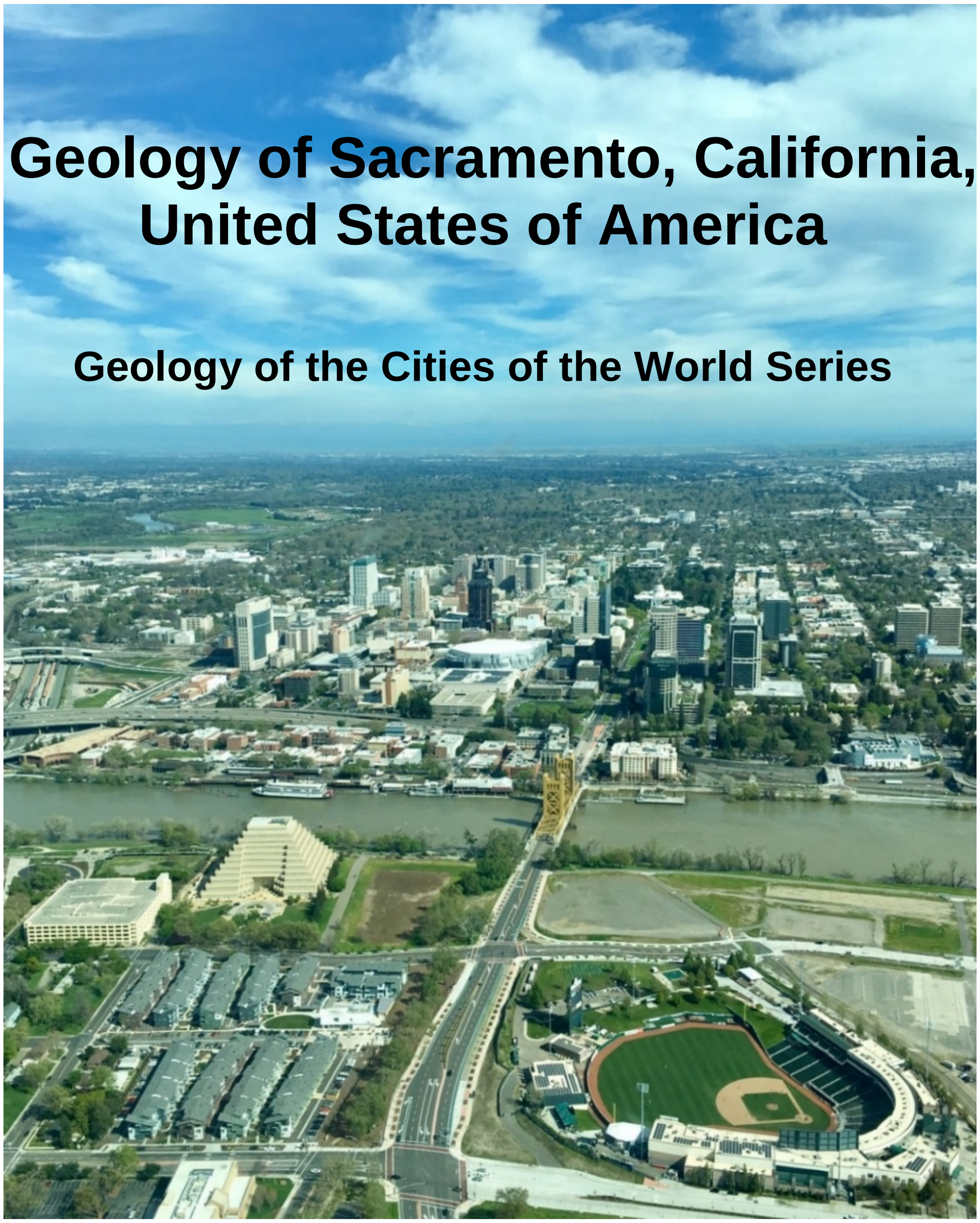
Geology of Sacramento, California, United States of America

Geology of the Cities of the World Series



Cover photo courtesy of Ricardo Goñi

Robert Anderson, Mike Anderson, Tom Barry, Meredith Beswick, Chris Bonds, Mike Conway, Christopher Dennis, William A. Fraser, Fred Gius, Jeffrey Hess, Richard Hilton, Jonathan Manke, Garry Maurath, Eldridge Moores, Matt O'Neal, Kent Parrish, Nicholas Pinter, Roy J. Shlemon, Stephen Testa, Jeff Unruh, John Wakabayashi, and Jeremy Zorne

This paper is being released as part of the XIII IAEG Congress and AEG Annual meeting held in San Francisco, 17-21 September 2018.

A generous grant from the AEG Foundation, Robert F. Legget Fund, helped make this publication possible. Founded in 1993, the Robert F Legget Fund of the AEG foundation supports publications and public outreach in engineering geology and environmental geology that serve as information resources for the professional practitioner, students, faculty, and the public. The fund also supports education about the interactions between the works of mankind and the geologic environment.

Author Affiliations

Alfred E. Alquist Seismic Safety Commission
Robert Anderson

California Division of Oil, Gas, and Geothermal Resources
Tom Barry

California Department of Water Resources
Mike Anderson
Chris Bonds

California Energy Commission
Mike Conway
Chris Dennis
Garry Maurath

California Division of Safety of Dams
William A. Fraser

California Geological Survey
Fred Gius
Matt O'Neal

California State University, Fresno
John Wakabayashi

Geocon Consultants, Inc.
Jeremy Zorne

Geopier Foundation Company, Inc.
Jonathan Manke

Gilbane Incorporated
Jeff Hess

Kleinfelder Engineering, Inc,
Meredith Beswick

Sierra College
Richard Hilton

University of California, Davis
Eldridge Moores
Nicholas Pinter

Wood Engineering
Kent Parrish

Private Consultant
Roy J. Shlemon
Steve Testa

Lettis Consultants
Jeff Unruh

Cities of the World, Geology of Sacramento, California, United States of America

Table of Contents

PREFACE

The *Geology of the Cities of the World* series of papers continues to grow with the addition of the *Geology of Sacramento, California, United States of America.* This paper is intended to be a general reference for students, practitioners, as well as persons not familiar with the geology of the city and surrounding area. Generally, the papers in this series were published in journals as paper copies, with a restrictive length requirement or more recently as electronic publications. However, the Sacramento paper was developed specifically for electronic publication. This has allowed the authors to expand the paper to include not only the Sacramento area but also select topics such as the Sierra foothills and the relationship between Sacramento, the Mother Lode, natural gas fields and the western starting point of the Pacific (Transcontinental) Railroad.

The Geology of Sacramento team wish to thank Dr. Allen Hatheway for originating and shepherding the series for most of its existence. We also thank Joseph Krupansky for taking over as series editor after Dr. Hatheway retired.

Sacramento is not without its problems. The Sacramento and American Rivers are prone to flooding and the town experienced several major floods. Despite the potential for flooding Sacramento has grown to be the sixth largest city in the State with a population of approximately 500,000. Without the geographic and geologic setting and resources of the Sacramento Metropolitan Region, the history and the development of the city and region may have been significantly different.

Robert L. Anderson, Series Editor
Alfred E. Alquist Seismic Safety Commission,
Sacramento, California
Bobanderson816@gmail.com

Listing of published papers in the series:

Albuquerque, New Mexico – 1984
Boston, Massachusetts - 1991
Boulder, Colorado – 1987
Cairo, Egypt - 1988
Christchurch, New Zealand -1995
Dallas, Texas – 1986
Denver, Colorado – 1982
Granada, Spain - 2012
Hong Kong, China – 1989
Indianapolis, Indiana – 1983
Johannesburg, Republic of South Africa – 1986
Kansas City, Misourri and Kansas – 1988
Las Vegas, Nevada – 1993
Lima, Perú - 1997
Long Beach, California – 1983
Los Angeles, California – 2007
Memphis, Tennessee - 2012
Montreal, Quebec, Canada – 1985
Pittsburg, Pennsylvania – 2015
Port Elizabeth, Republic of South Africa – 1987
Plymouth, England – 2001
Reno, Nevada – 1992
Rome, Italy - 1989
Sacramento, California – 2018
Salt Lake City, Utah – 1990
San Francisco, California – 2018
Seattle, Washington - 1991

Key Terms: Transportation, Sacramento River, Gold, Mining, Mother Lode, Natural Gas, Central Valley, Geology, Paleontology, Natural Hazards, Flooding, Faulting, Dams, Levees, Liquefaction, Subsidence, Environmental Hazards, Military Bases, Surface Water and Groundwater Resources, Sustainable Groundwater Management Act.

ABSTRACT

Sacramento is the state capitol of California. Local and regional geology played a large role in the history and development of the city and its adjacent areas. The city is in the southern portion of the Sacramento Valley at the confluence of the Sacramento and American rivers. Its location and proximity to the Mother Lode made it a bridgehead for the California Gold Rush in the mid-1800s and subsequent post-civil war expansion for the western United States.

The purpose of this paper is to convey background information useful for discovering and understanding geology and geologic issues in the Sacramento region to practitioners, government officials, graduate students and the public. The following is a limited overview of the history, geology, paleontology, hydrogeology, dams, natural resources, as well as geologic hazards, with a focus on flooding and flood protection in the Sacramento region. Also included is an overview of the impacts of climate change, and environmental issues including impacts from past mining activities and military base operations.

I. INTRODUCTION

Sacramento has a population of about 500,000, making it the sixth largest city in California and the 27th largest city in the United States. Its footprint covers approximately 2,449 square kilometers (km^2) (SCMHMP, 2004). Sacramento lies in the approximate center of the Central Valley of California, located along the eastern edge of the southern Sacramento Valley near the confluence of the Sacramento and American Rivers, between the foothills of the Sierra Nevada mountain range to the east and the Coast Range Mountains to the west (Figure 1). Sacramento is the largest city in the Sacramento region. It is located along Interstate 80 midway between Lake Tahoe and San Francisco. The Sacramento region is made up primarily of seven counties including Sacramento, Yolo, Sutter, Placer, El Dorado, Amador, and San Joaquin Counties. The region has a population of over 2.5 million. The geographic limits of the paper in general are: from Sacramento north to the Sutter Buttes, west to the Vacaville-Winters area, south towards the town of Galt, and east towards Auburn and Colfax. Each direction has specific resources and hazards that affect the Sacramento region.

The city was founded mainly on floodplain and glacial outwash deposits as well as deep deposits of alluvium and marine sediments. The city's location and the presence of both Sacramento, and American Rivers, as well as the Yolo Bypass, drives the primary natural hazard potential as Sacramento and nearby communities are highly prone to flooding.

To the southwest of Sacramento lies the Sacramento-San Joaquin Delta, the largest inverted delta in the United States and a natural conduit for most of Northern California's water for shipment to the Central Valley and Southern California. The Sacramento-San Joaquin Delta is a complex subject that has been the object of extensive scientific research for more than a century and a half. The region is still under study and will not be a feature discussed in this volume.

A detailed regional map (Plate A) depicting selected locations is presented in Appendix A, which contains oversize figures for this paper.

Geodetic Datum

primary author: Mike Conway

This paper covers more than 180 years of recorded history throughout which numerous vertical and horizontal datums have been used. Historically, vertical elevations were often referenced as feet above or below mean sea level. With the accuracy and precision of geodetic measurements available today, this datum referencing convention has evolved and been redefined.

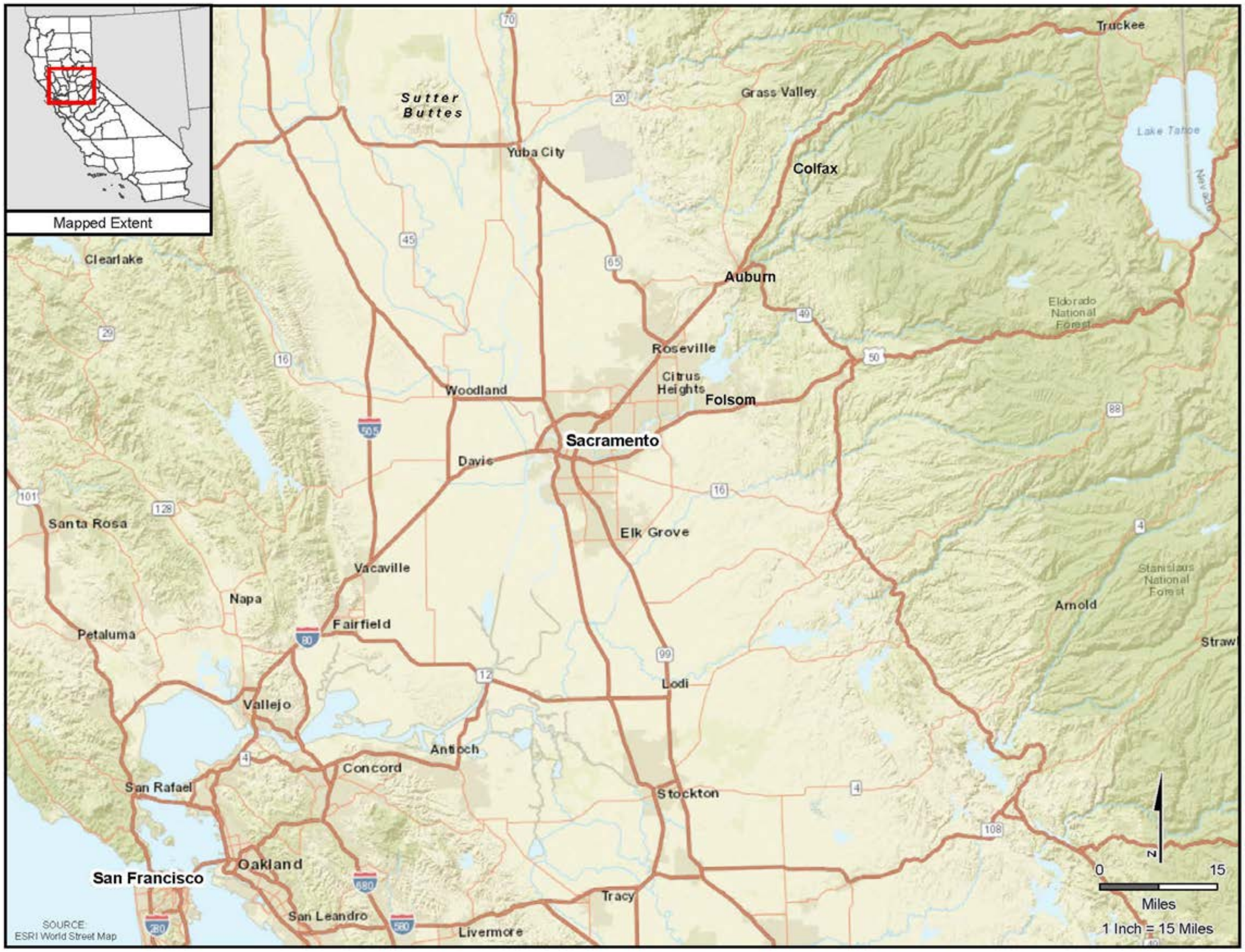


Figure 1. General Location Map (Source: ESRI World Street Map).

The Sea Level Datum of 1929 represented a significant adjustment of the nation vertical control network. *Mean sea level* was held fixed at the sites of 26 tide gauges, 21 in the United States and 5 in Canada and used to establish this updated datum. A total of 106,724 km of leveling was involved, constituting 246 closed circuits and 25 circuits at sea level. However, this datum did not actually represent the tidal mean sea level, the geoid, or any other equipotential surface, and it was renamed in 1973, to the National Geodetic Vertical Datum on 1929 (Zilkoski and others, 1992).

The North American Vertical Datum of 1988 (NAVD 88) is the vertical control datum established in 1991 by the minimum-constraint adjustment of the Canadian-Mexican-United States leveling observations. It fixed the height of the primary tidal bench mark, referenced to the new International Great Lakes Datum of 1985 local mean sea level height value, at Father Point/Rimouski, Quebec, Canada. Additional tidal bench mark elevations were not used due to the demonstrated variations in sea surface topography; mean sea level is not the same equipotential surface at all tidal bench marks (Zilkoski and others, 1992). Figure 2 presents the relationships between various heights used to develop the modern standard vertical datum, NAVD 88.

NGS develops and maintains the current national geodetic vertical datum, NAVD 88. In addition, NGS provides the relationships between past and current geodetic vertical datums, e.g., NGVD 29 and NAVD 88. The Center for Operational Oceanographic Products and Services (CO-OPS) published tidal bench mark information and the relationship between NAVD 88 and various water level/tidal datums (e.g., Mean Lower Low Water, Mean High Water, Mean Tide Level, etc.). The relationships to NGVD 29 are not published but may be calculated independently using tidal bench mark information from the NGS database. Tidal bench mark information, water level/tidal datum, and their relationship to geodetic vertical datums are available at the CO-OPS website (NOAA, 2018). There is also an effort underway to provide a unifying structure for all national elevation efforts in the United States that includes providing a consistent set of standards. This is being led by the National Oceanic and Atmospheric Administration (NOAA) office of Coast Survey and the U.S. Geological Survey (USGS) National Geospatial Program.

Geographic Setting

primary author: Robert Anderson

Sacramento and its metropolitan area are in two distinct geologic provinces, the Great Valley, which is made up of the Sacramento and San Joaquin Valleys, and the foothills of the Sierra Nevada mountain range. The Central Valley Province, can be subdivided into the Sacramento Valley in the north and the San Joaquin Valley in the south, separated by the Sacramento/San Joaquin Delta (Figure 3). The Southern Sacramento Valley basin is made up of alluvium and deep marine deposits

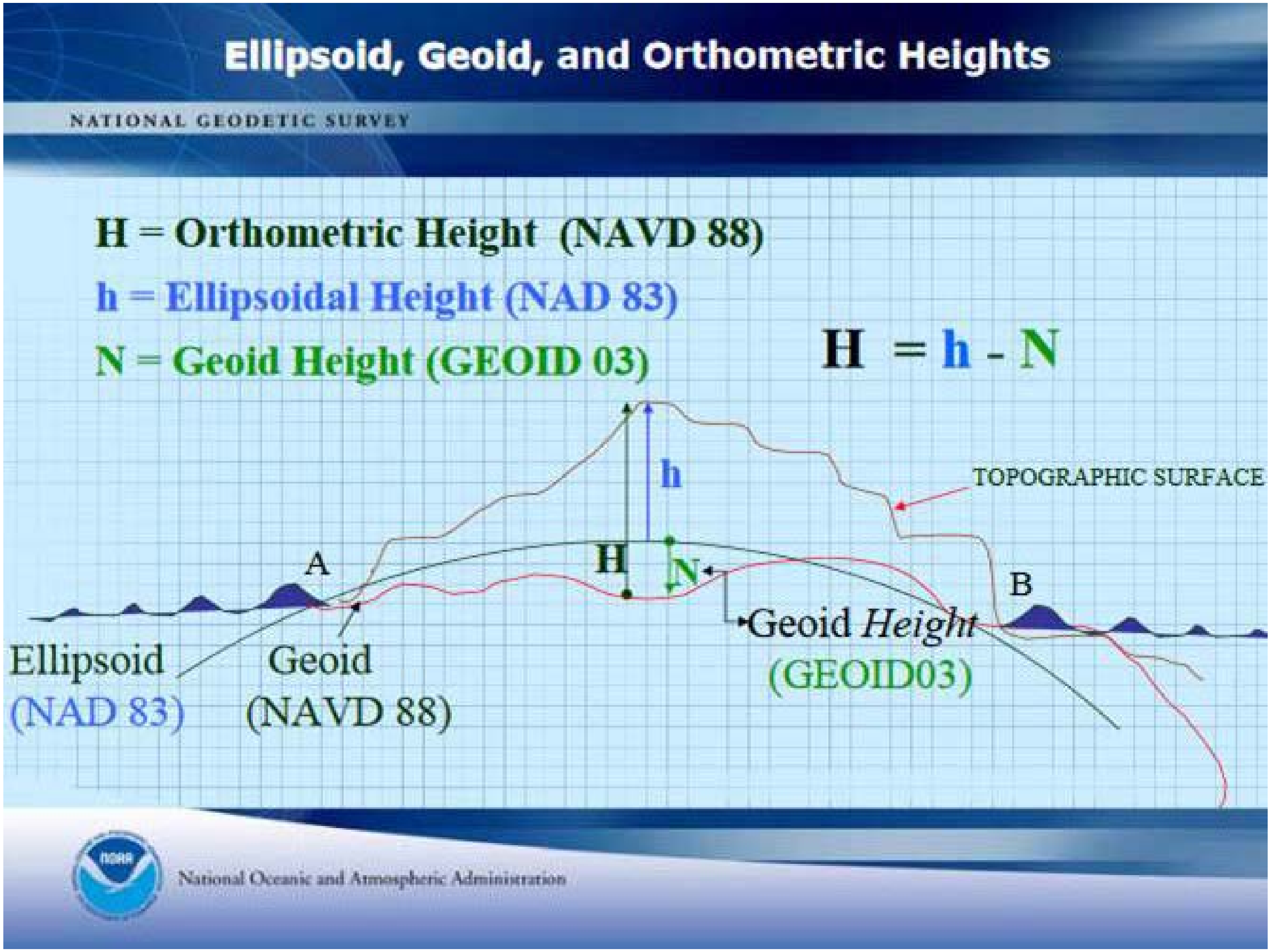


Figure 2. Relationship between ellipsoid, geoid, and orthometric heights (National Geodetic Survey, 2007).

Figure 3. Geomorphic provinces of California (CGS, 2002).

with several major features such as subsurface canyons and faults. It is flanked to the east by diorite and volcanic deposits including lahars, ash, and basalt. The city of Sacramento and its surrounding urban areas are built on late Cenozoic sediments of the Sacramento and American Rivers as well as glacial outwash deposits, which have locally buried the basement rocks of the Sierra Nevada and the overlying Superjacent Series sediments.

Figure 4 presents a generalized geology map. Detailed 1:100,000 scale geologic maps (30x60 minute quadrangles) are available at the California Geologic Survey website (CGS, 2009; CGS 2011, and CGS 2018). The principal natural resources of the area include: surface and ground water, construction aggregate, sand and gravel, building stone, clay, natural gas and gold. The principal hazards include: flooding, wildfire, expansive soils, liquefiable soils, subsidence, long period strong ground shaking, and to the east in the Sierra Nevada mountain range, landslides. In addition, Sacramento has several sites that have issues with soil and groundwater contamination.

II. HISTORY AND FOUNDING

primary author: Robert Anderson

The Sacramento area was populated long before its formal designation as a city. There is evidence of inhabitants in the area for at least the last 12,000-years and evidence of people living in what is now downtown Sacramento 4,500-years ago. The Native American Nisenan (one of the Maidu groups) is the first formally designated tribal group that lived in Sacramento (ARNHA, 2005). The Nisenan were also known to dwell within close proximity of the Lower American River as recently as 1832 (Peper, 2014). The Nisenan occupied areas east of the Sacramento River, along the American River, but did not establish permeant dwellings above an elevation of 900 m. They were hunters and gathers that lived above the frequently flooded Central Valley, but generally below the more rugged mountain terrain of the Sierras. This region was also capable of providing a year-round food supply, the majestic oaks trees that still define the region today yield acorns with substantial nutritional value. The river provided fresh water mollusks and salmon. The surrounding landscape was rich with antelope and deer (ARNHA, 2005).

The city of Sacramento is named after the Sacramento River, which was named in 1808 by the Spanish explorer Gabriel Moraga. John Sutter Sr. arrived in the area on August 13, 1839 with a Mexican land grant of nearly 20,234 ha. He established Sutter’s Fort in 1840 and named the new settlement New Helvetia, inspired by his Swiss ancestry. When gold was discovered by James W. Marshall in 1848 at Sutter’s Mill, in Coloma, about 80.5 km northeast of Sutter’s Fort, John Sutter Jr. arrived to assist his father, and together with Samuel Brannan officially founded Sacramento in 1850. It was the first incorporated city in the Great Valley.

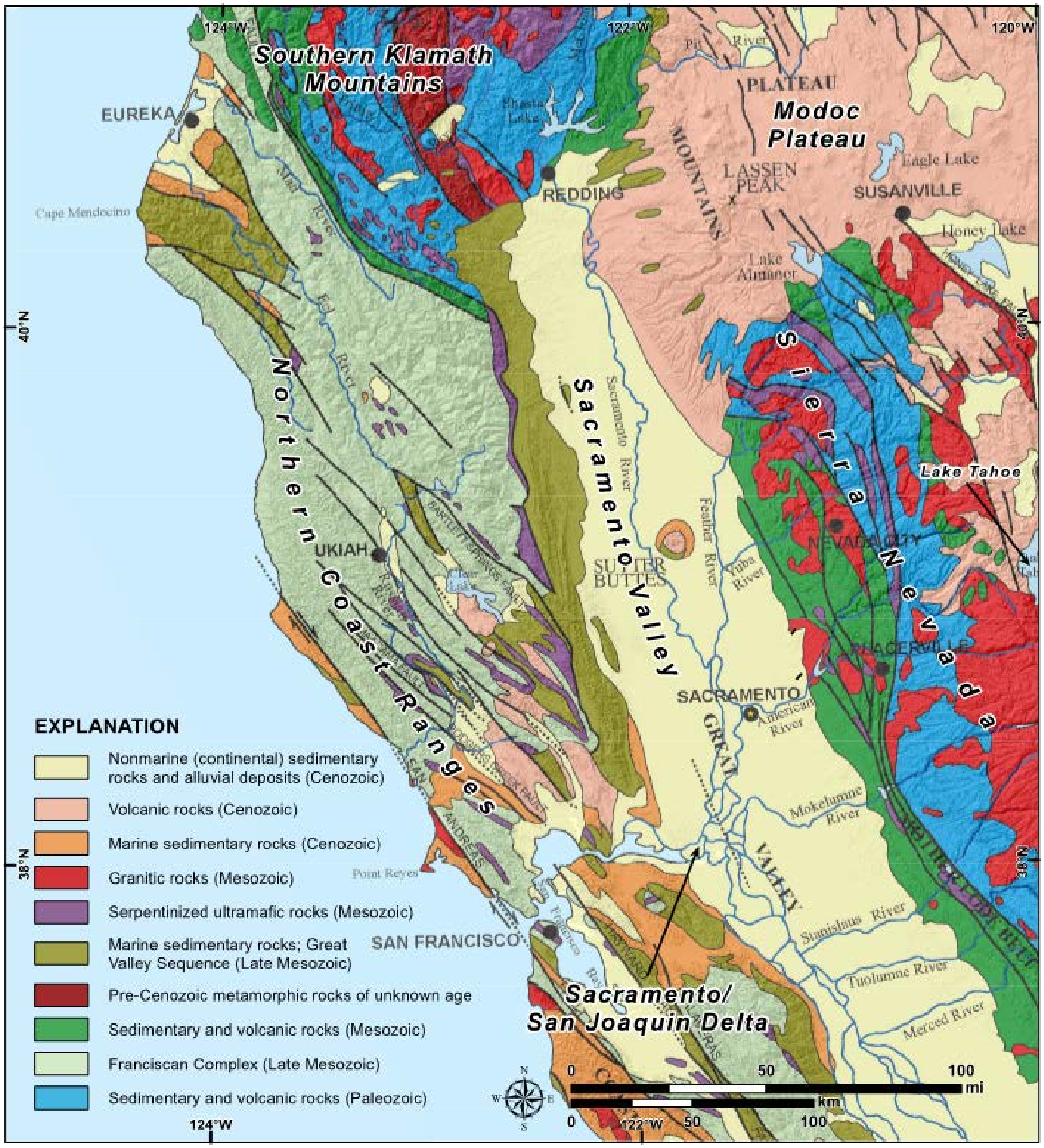


Figure 4. Generalized geologic map of part of northern California. Map projection: NAD 1983 UTM Zone 10N.

Early Transportation Hub

Sacramento's location along the Sacramento and American rivers allowed the city to be a bridgehead into the goldfields in the Sierra foothills. This was due in part to the ease of navigation of the Sacramento River from San Francisco Bay, through the Sacramento-San Joaquin estuary to the riverside docks in Sacramento. Sacramento also served as a transfer point between deeper draft river boats (steam and sail) serving San Francisco and shallower-draft boats serving towns up river. In season, some boats could reach Redding, 260 km to the northwest. Shallow draft boats could also run part way up the American and Feather Rivers.

The first stagecoach lines in California started in 1849, during the Gold Rush, and ran out of Sacramento to the goldfields. Beginning in 1857, the original Overland Stage route from the East to California came via the Southern route, through New Mexico and Arizona, crossing the Colorado River at Yuma to Southern California, and thence to San Francisco, by sea or by land (Wyatt, 2018).

The discovery of the Comstock Lode in Virginia City, Nevada, in 1859, led to the initiation of a stage coach route starting in Sacramento and heading east through Placerville across the Sierra Nevada, where several routes branched off and passed through Lake Tahoe to Carson City and Virginia City (Wyatt, 2018).

The Gold Rush also helped prompt the Federal government to prepare one of the earliest statewide geologic maps of California as part of a U.S. Topographic Engineer expedition. William P. Blanke was the geologist and mineralogist for the expedition and his map was published in 1853 (Blake, 1853) (Figure 5).

A railroad route over the Sierra Nevadas via Donner Pass was discovered in 1860. The discovery led local merchants to push for the creation of a railroad that would connect California markets with the east.

Railroads and Development of California and Western Nevada

In 1852, the Sacramento Valley Railroad was formed to build a rail line from Sacramento to Folsom. Theodore Judah surveyed a route from Sacramento to Folsom. The route is now the light rail gold line of the Sacramento regional transit district. The railroad was completed in 1856, becoming the first steam railroad in California (Noble, 2010). The railroad ran from Sacramento to Folsom, with the eastern terminus of the line located at the western edge of the Sierra Nevada foothills. The railroad brought

Figure 5. Geologic map of California from the U.S. Topographic Expedition of 1855 led by Lt. R.S. Williamson, William P. Blake, Geologist and mineralogist of the expedition (Blake, 1855).

supplies and materials to Folsom whereupon miners would then take them to various mines in the Sierras and eventually to the Comstock Lode in western Nevada. The railroad was later extended east to Placerville as the Sacramento Valley and Placerville Railroad.

The Central Pacific Railroad and the First Transcontinental Rail Way

A transcontinental railroad was initially proposed in the late 1830s. The western end of the first transcontinental railroad began near front and K streets in Sacramento and was built by Central Pacific Rail Railroad (Wyatt, 2018). From 1863 to1869 the western portion of the first transcontinental railroad was built between Sacramento and Promontory, Utah where the Central Pacific and Union Pacific railroads met. The entire line went from Sacramento to Omaha, Nebraska. The western terminus allowed goods and material to be offloaded from ships and onto railcars. Once the railroad was operational, it helped deliver goods and personnel to the Mother Lode for mining of gold and into the Comstock Lode where silver was mined. It also was used to move California produce and manufactured goods to eastern markets. Figure 6 depicts the general alignment of the transcontinental railroad from Sacramento to Colfax.

Engineering Geologic Challenges and the First Transcontinental Railroad from Sacramento to Auburn, California

Discovery of gold at Sutter's Mill in 1848 brought hundreds of thousands of people to and phenomenal growth of business in California. Goods needed to be transported in and out of California, but boats and wagon trains were slow. Communication was slow. It could take months for goods and people to arrive and leave California, and 10 days for letters to travel the nearly 3,100 km between St. Joseph, Missouri and Sacramento, California via pony express (NPS, 2012). A transcontinental railway and telegraph line were urgently needed for trade and development.

Conflict surrounded the decision to make the route either a northern route or a southern route (Galloway, 1950). The Civil War begun in April 1861 and almost by default it was decided that the route would be a northern transcontinental railway alignment and telegraph line. Construction of the railway, supporting infrastructure, and the telegraph line would cost millions of dollars, a cost the existing corporations were not willing to pay, even after the federal government funded the necessary topographic surveys. To facilitate construction, Congress passed a series of eleven acts, called the Pacific Railroad Acts, between 1862 and 1874. The first of these acts signed by President Lincoln became effective in July 1862. This act authorized the Union Pacific Railroad and the Central Pacific Railroad to build a railroad and a telegraph line from Omaha, Nebraska to Sacramento, California. The act also provided federal government land and government bonds to help pay for the construction. The government incentives for the railroad companies were as follows:

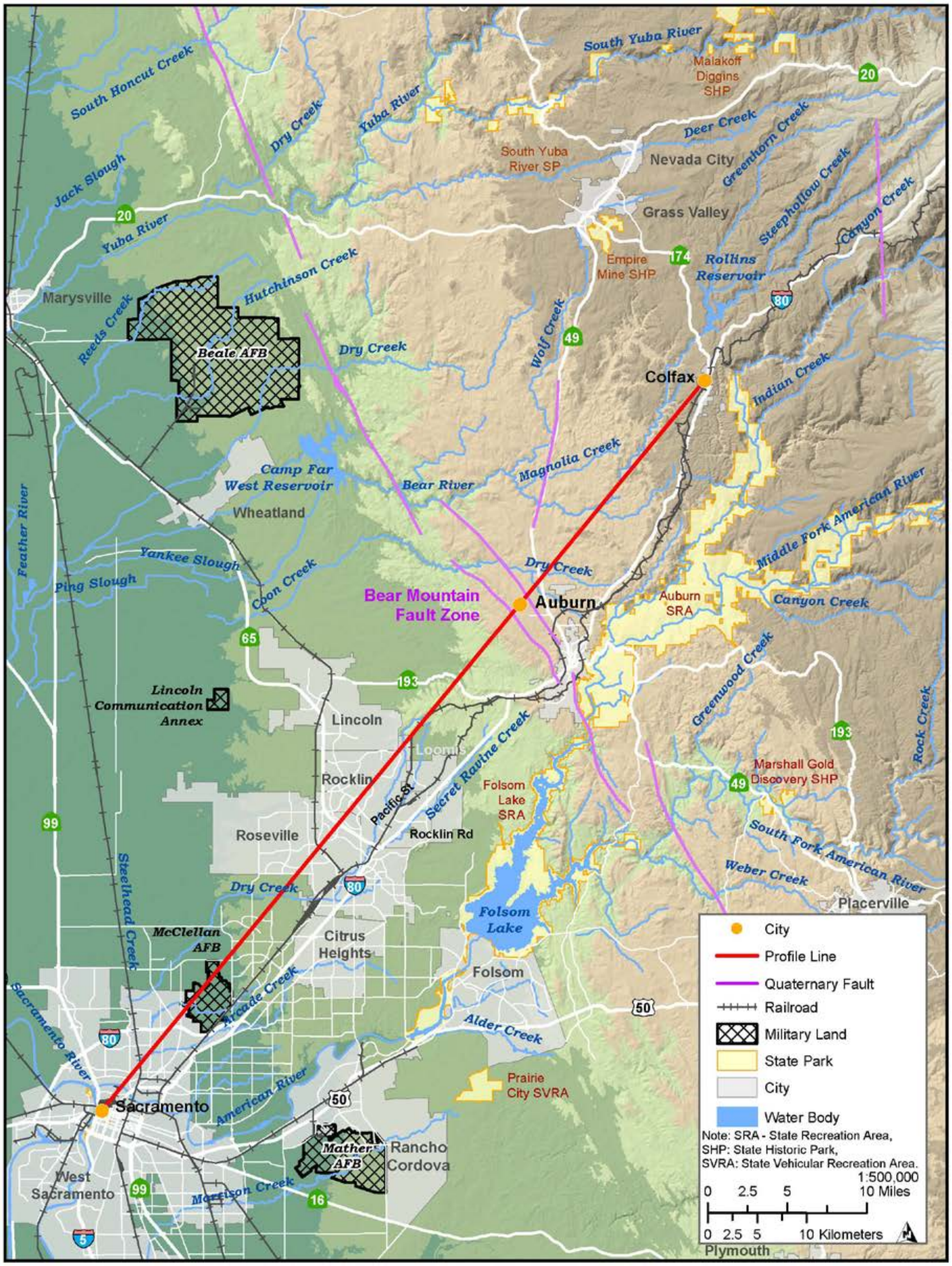


Figure 6. General alignment of the transcontinental railroad and location of topographic cross section (UAGS 2017, TeleAtlas 2009, ESRI 2016, DoD 2017, Caltrans 2017 and California Park and Recreation 2017).

- 30-year bonds for every kilometer of track offered at two rates: in the flat plains, $9,942 per kilometer ($16,000 per mile), and in the mountains of the Great Basin, and Sierra and Rocky Mountains, $29,826 per kilometer ($48,000 per mile).
- Land grants for rights to the land within 61 meters on either side of the track.
- Using a checkerboard system, the railroads received 16 km^2 of land alternating along the railroad track for every kilometer of track laid.

Because the bond rate was three times higher in the mountain areas, it became very important for the railroads to identify the starting and ending locations of the mountains. Given the steep differential in costs, there was a dispute about where the boundary between the plain and mountains was. Outcrops of the Sierra Nevada began in Rocklin, but according to the surveyors the mountain grade began at Arcade Creek. Thus, with respect to construction, the mountains began at Rocklin. However, it was in the interest of the railroad financiers to have a mountain base as close to Sacramento as possible (Galloway, 1950).

Two locations, 24 km apart, were identified as the likely boundary between the Great Valley and the beginning of the Sierra Nevada mountain range: (1) Arcade Creek in northeast Sacramento near Fulton Avenue, and (2) the City of Rocklin near Pacific Street and Rocklin Road. Figure 7 presents an approximate topographic cross section from Sacramento to Colfax along the general alignment of the transcontinental railroad. The original alignment of the transcontinental railroad has changed because of land development over the past 150 years.

The controlling managers of the Central Pacific Railroad, known as The Associates, were Leland Stanford, Collis Huntington, Mark Hopkins, EB Crocker, and Charles Crocker. To settle the matter of where the Sierra Nevada mountain range began, reputable geologists testified that the alluvial valley changed to a mountain formation at Arcade Creek (J. W. Whitney, the state geologist, and J. F. Houghton, state surveyor general). E. F. Beale, United States surveyor general for California, testified that the base of the mountains began approximately midway between Sacramento and Folsom (Galloway, 1950). Disregarding the latter testimony President Lincoln signed a paper fixing Arcade Creek as the beginning of the Sierra Nevada mountain range (Galloway, 1950).

On the day that construction began, the construction company building the Central Pacific Rail Road began pile driving for a bridge to cross at the American River in Sacramento. The western Terminus of the railroad was sited on uncontrolled fill and alluvium. The Sierra Nevada actually day-lighted in Junction City (present day Roseville) and is represented by the Rocklin Pluton, which is composed of quartz diorite.

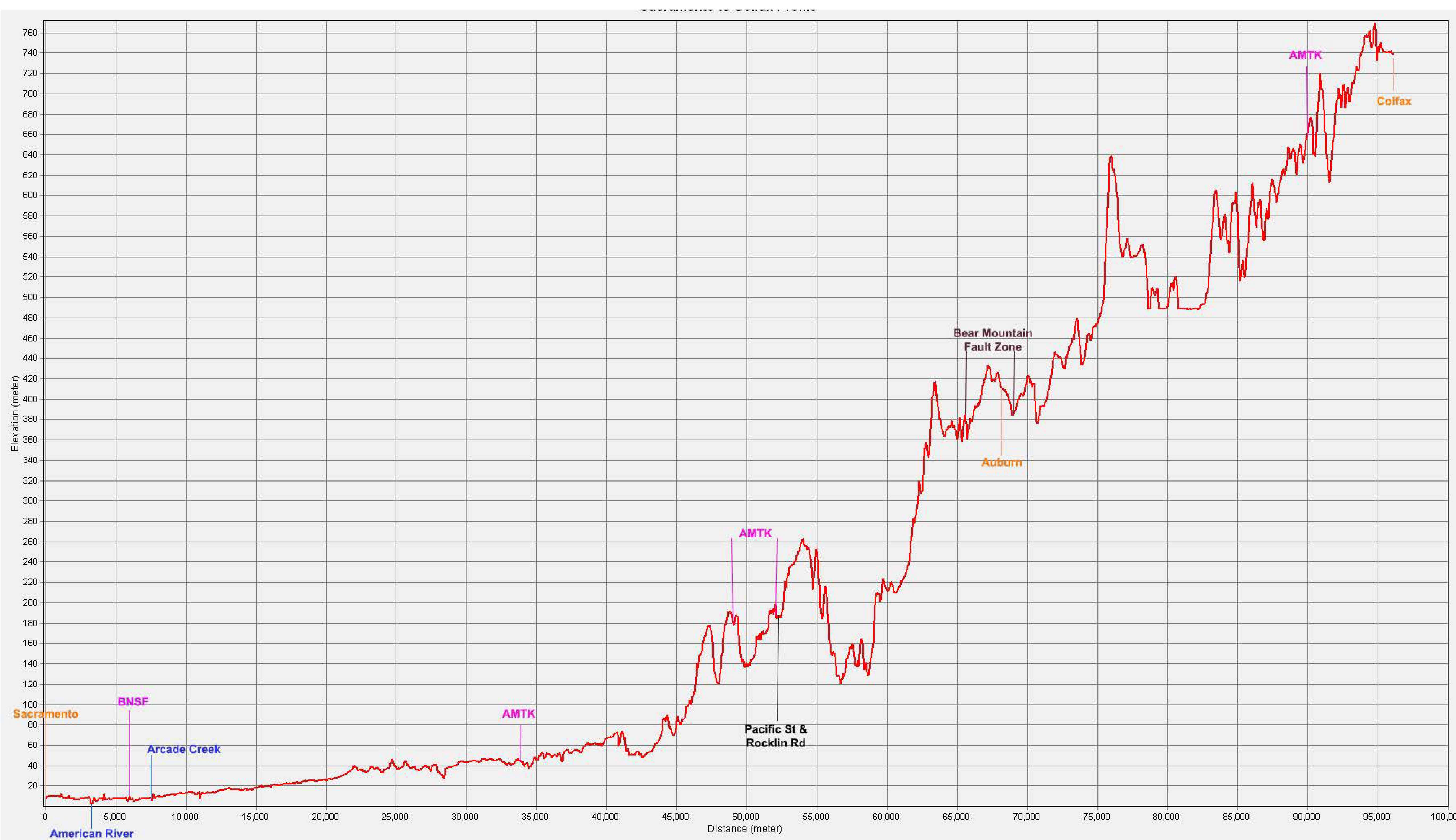


Figure 7. Approximate topographic profile along the transcontinental railroad alignment between Sacramento and Colfax.

An early obstacle was the Bloomer Cut just west of Auburn. The near vertical cut was carved out of rock by railroad workers. The 244-meter long by 20-meter deep cut was very difficult to hand chisel and blast with black powder (Moulton, 2016). At this point, black powder in large quantities was hard to come by since the American Civil War was on going in earnest. Further east, various rock types were encountered including volcanic rocks and quartz diorite. Topography, rock type, the stability of cut and fill slopes, as well as design grade and location of obstacles, controlled the alignment of the railroad. The original alignment of the railway is no longer followed in some locations from Sacramento to the crest of the Sierra Nevada.

During construction of the railway, modern techniques of soil testing did not yet exist. In some locations fill materials were scarce since the rock had only a thin veneer of soil. Trial and error was the only guide for developing cut and fill slopes. In some cases, cuts were vertical as was the case at the Bloomer Cut near Auburn (Figures 8-A and 8-B). Static and dynamic slope stability analysis tools had not yet been developed. Cut slopes were normally not benched. In addition, it is not known if some fill slopes were keyed into soil or rock. Some fills used in bridge approaches were made up of both soils and debris. The amount of large debris and its placement in the fill was not determined in a quantitative manner. Compaction and moisture conditioning of soils was not done by today's standards. Indeed, most fill was moved by horse drawn carts on wagon wheels or by shovel.

Decline in River Traffic Due to Hydraulic Mining

Hydraulic mining came into use in the Sierra Nevada and its foothills in the 1850s. The runoff from the hydraulic mining operations contained large quantities of sediment and debris of various sizes. The sediments would end up in part in the major streams and rivers of the area as well as in San Francisco Bay. The sediments that were not flushed out of the streams and rivers caused changes in their depth. This caused problems for larger deep-draft riverboats, which forced a reduction in the draft and size of the boats servicing different communities along the waterways.

Throughout the years, Sacramento has continued to flourish despite changes and advances in transportation methods. In addition to being a historic location in the development of the United States during the 1800s Sacramento played a key role in the historic development of engineering and environmental geology. Sacramento serves as a birthplace of the Association of Environmental and Engineering Geologists.

Figure 8-A. Midway in Bloomer Cut looking east ca. 2015. Note that the cut is not terraced, and the walls are near vertical. (Courtesy of Bruce C. Cooper, CPRR.org).

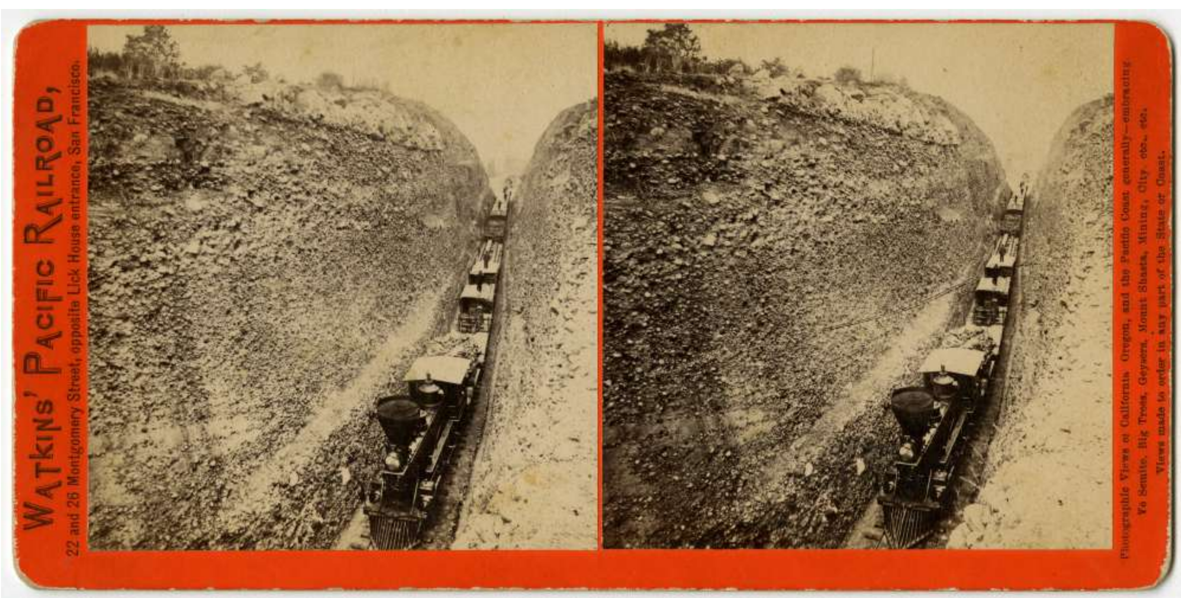


Figure 8-B. Stereoscopic image of Bloomer Cut ca. May 1863 (Courtesy of Bruce C. Cooper, CPRR.org).

Sacramento – Birthplace of AEG

primary author: Garry Maurath

In June of 1957, 13 local engineering geologists met in Sacramento to discuss the need to organize a society in the specific field of engineering geology. During the next eight months, this group set up the framework of the California Association of Engineering Geologists by formulating the aims of the organization, a definition of Engineering Geology, and membership qualifications. In February of 1958 membership recruitment began with by establishing three Sections representing the Los Angeles, Sacramento and San Francisco areas. The Association was incorporated according to the laws of the State of California on May 7, 1963.

During the early years of the Association, it became immediately apparent that there was a need for a similar organization with engineering geologists everywhere, not just in California. Some geologists outside California, concerned with the application of geology to problems of civil engineering, showed a marked interest in the organization. In recognition of this need and interest, the membership voted in late 1962 to remove all geographical limitations on the organization and to change the name to the Association of Engineering Geologists.

In 1963, the first Section outside of California (Washington State) was established. In 1964, AEG was accepted as a member society of the American Geological Institute. Later that same year the International Association for Engineering Geology and the Environment (IAEG) was founded and is affiliated to the International Union of Geological Sciences (IUGS). IAEG is a worldwide scientific society with more than 5,200 members and 59 national groups. By 1973, seventeen Sections were recognized, including two outside the United States. By the Associations 25th birthday it had grown to twenty-two sections, which were grouped into regional units of the Association.

In September of 2005 the name of the organization was changed to the Association of Environmental & Engineering Geologists. By 2017, 60 years after the founding of the organization, membership has grown to more than 2,100 scientists and engineers, with members from all 50 states, Puerto Rico, the District of Columbia, and 15 other countries.

Throughout the years AEG has produced many peer-reviewed papers and several standalone publications to share ideas on practice as well as case histories with practitioners and those interested in Engineering Geology. This practice continues today. AEG works with sister organizations such as the Geological Society of America and the Groundwater Resources Association of California to continue to improve the practice of engineering and environmental geology.

III. QUATERNARY GEOLOGY

primary author: Roy J. Shlemon

The following section summarizes the Quaternary geology of the Sacramento region by pointing out the geomorphic setting, the impact of regional climatic change, the indirect influence of Sierra Nevada glaciations and eustatic base level changes, the various Quaternary stratigraphic formations, the use of pedogenic soils for stratigraphic markers and for relative dating, and the course of several lower American River channels. Although much has been learned about the Quaternary stratigraphic framework, most deduced about 50-years ago (Shlemon, 1967a; 1967b), details remain tenuous. Hence, generations of future students and professionals may eventually refine, if not totally change, the existing model, a benefit for society in general and the geosciences in particular.

To the casual viewer, the modern landscape of the Sacramento region is a featureless and relatively flat surface on which has been superimposed a modern urban agglomeration; namely, an older (and redeveloped) downtown focusing on the State Capitol, accompanied by State and Federal buildings, light industry, four major highways, several major roads and bridges, numerous housing tracts and shopping centers, a nearby major railyard, and three major airports. The Sacramento and American rivers pass through the Sacramento region and flank the central business district (CBD) (Figure 9). The rivers are the main natural drainages, presently lined by flood-control levees, parks, and bicycle pathways. However, Sacramento's location comes with a price. At the confluence of two major rivers and with much urban development in the respective floodplains, it has historically been subject to floods. Less than 160-years ago, massive floods almost seasonally inundated the "old town." The great flood of 1862 inundated Sacramento and turned part of the Great Valley into a lake. Later floods were exacerbated by upstream hydraulic mining that produced huge sediment fluxes that raised river beds and ultimately surged through the California Delta to San Francisco Bay and thence offshore through the Golden Gate (Gilbert, 1917; Jaffe and others, 2007; Figure 1). Major floods still periodically occur in the Sacramento region and potential levee failure is of on-going geological and political concern (see the "flooding section" for additional information.).

Yet, massive floods and channel cutting-and-filling periodically beset the Sacramento region during the Quaternary. This is illustrated by the seemingly insignificant (1.0 -1.5 m) low-sloping escarpments, now degraded by road and house construction, that mark former pathways and bluffs of ancestral channels of the lower American River. Indeed, the glacial history of the nearby Sierra Nevada is not in the mountains where successive glaciations typically destroyed evidence of early ones; but rather in the Sacramento Valley where Pleistocene "outwash rivers" are preserved as fill terraces grading into readily traceable buried channels. The old channels are stratigraphically recognized by their

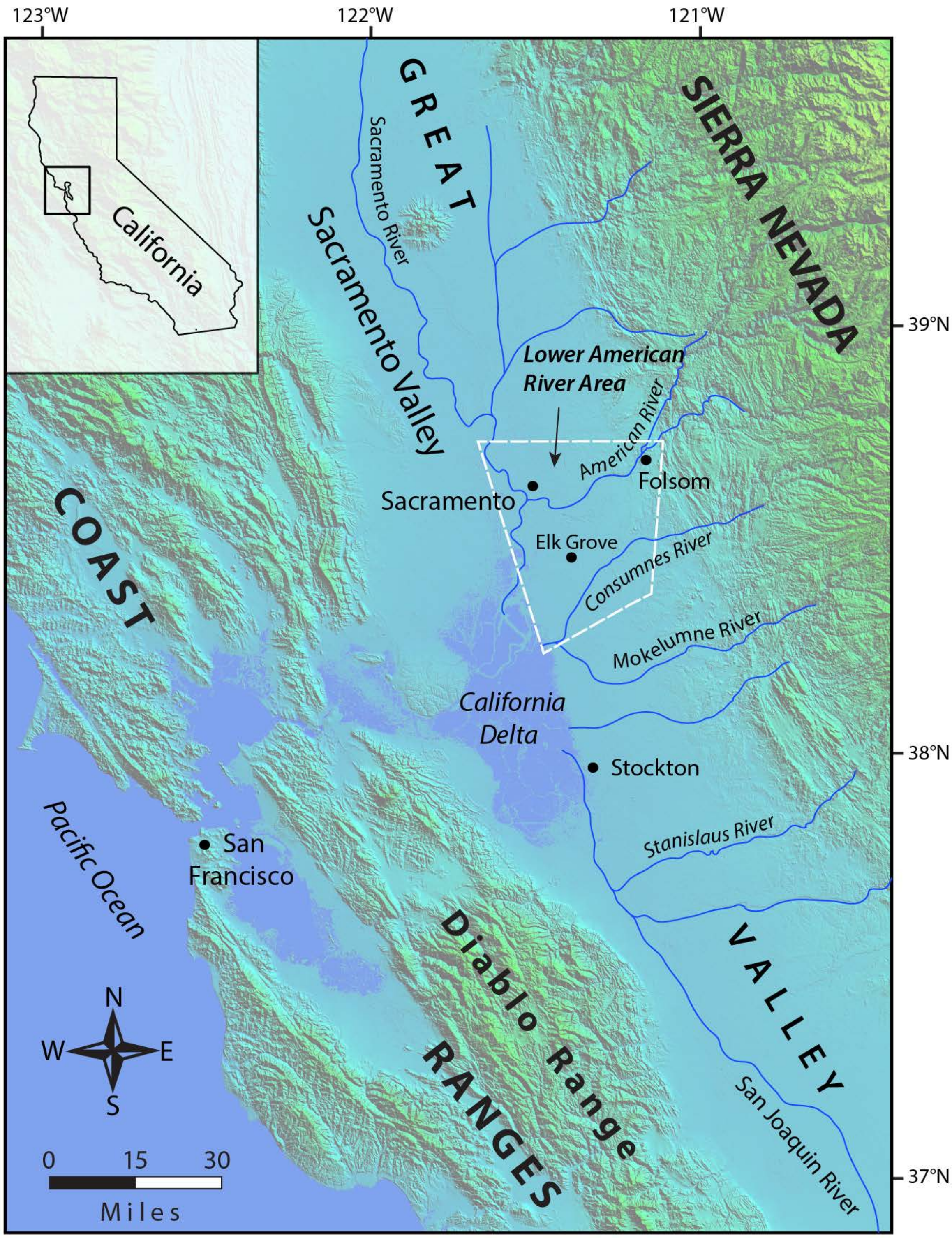


Figure 9. Map showing the location of Sacramento, the lower American River area and various drainages and place names noted in the text (courtesy of Yannick Wirtz).

grossly fining-upward basal gravels, covering sands, and overbank fine sand and silt. The surface sediments typically weathered to form relict paleosols on terrace surfaces and extending into subsurface as buried paleosols, markers of interglacial and interstadial environments. Accordingly, the combination of urban road cuts, geomorphic mapping, soils (pedogenic profiles), water-well logs and bridge borings provides multi-disciplinary data to construct the Quaternary geologic history of the Sacramento region, much more so than in “pristine,” non-urban environments.

Quaternary Mapping in the Sacramento Region

The first well-known geologic map of the Sacramento region was that of Lindgren (1894) who portrayed the local sediments as either “Earlier Pleistocene,” referring to deposits underlying flat-topped hills (such as inverted topography and dissected river terraces and plains discussed later in this section), mainly in the Rocklin and Folsom areas, or as “Alluvium,” for the fluvial deposits in and around Sacramento. Lindgren (1911) later provided more detail about local Quaternary deposits based on his analysis of gold dredging in the Folsom area.

Piper and others (1939) provided the first modern description and division of Quaternary deposits in the Sacramento region. They identified three major Quaternary units (Table 1; Figure 9) from about the Cosumnes River south to the Mokelumne: (1) The Arroyo Seco Gravels (oldest); (2) the Laguna Formation; and (3) the Victor Formation, mostly based on exposures and type localities near the Mokelumne River in San Joaquin and adjacent Amador counties. In the Sacramento area, the Victor, based largely on soil-stratigraphy, has since been subdivided into the Riverbank (older) and Modesto Formations, while the Arroyo Seco and Laguna Formations remain as distinct mapped units (Shlemon, 1967a; 1967b; Helley and Harwood, 1985; Table 1).

The 1960s proved to be the halcyon days of Quaternary investigations in the Central Valley. Encouraged by the late Clyde Warhaftig at the University of California at Berkeley, several graduate students mapped the lower San Joaquin River area (Janda, 1965; Janda and Croft, 1967), the Chowchilla fan (Helley, 1978) and the lower American River at Sacramento (Shlemon, 1967a; 1967b). The resulting dissertations and papers relied greatly on soil-geomorphic concepts established earlier by soil scientists working in the Central Valley (Arkley, 1954; 1959; Arkley and others, 1962; Cole and others, 1954; Ulrich and Stromberg, 1962; Huntington, 1971). A particularly influential, though little cited, paper was that of Arkley (1962) who, from his previous soil-survey in eastern Stanislaus County, developed associations between geomorphic surfaces and the relative development of capping soils (pedogenic profiles). Based on Arkley’s work, the existing Quaternary formations were then readily subdivided, thus providing much more detail about local landscape evolution in the Central Valley of California. It was also in eastern Stanislaus and adjacent counties that Davis and Hall (1959), from their groundwater assessments, described the Turlock Lake Formation

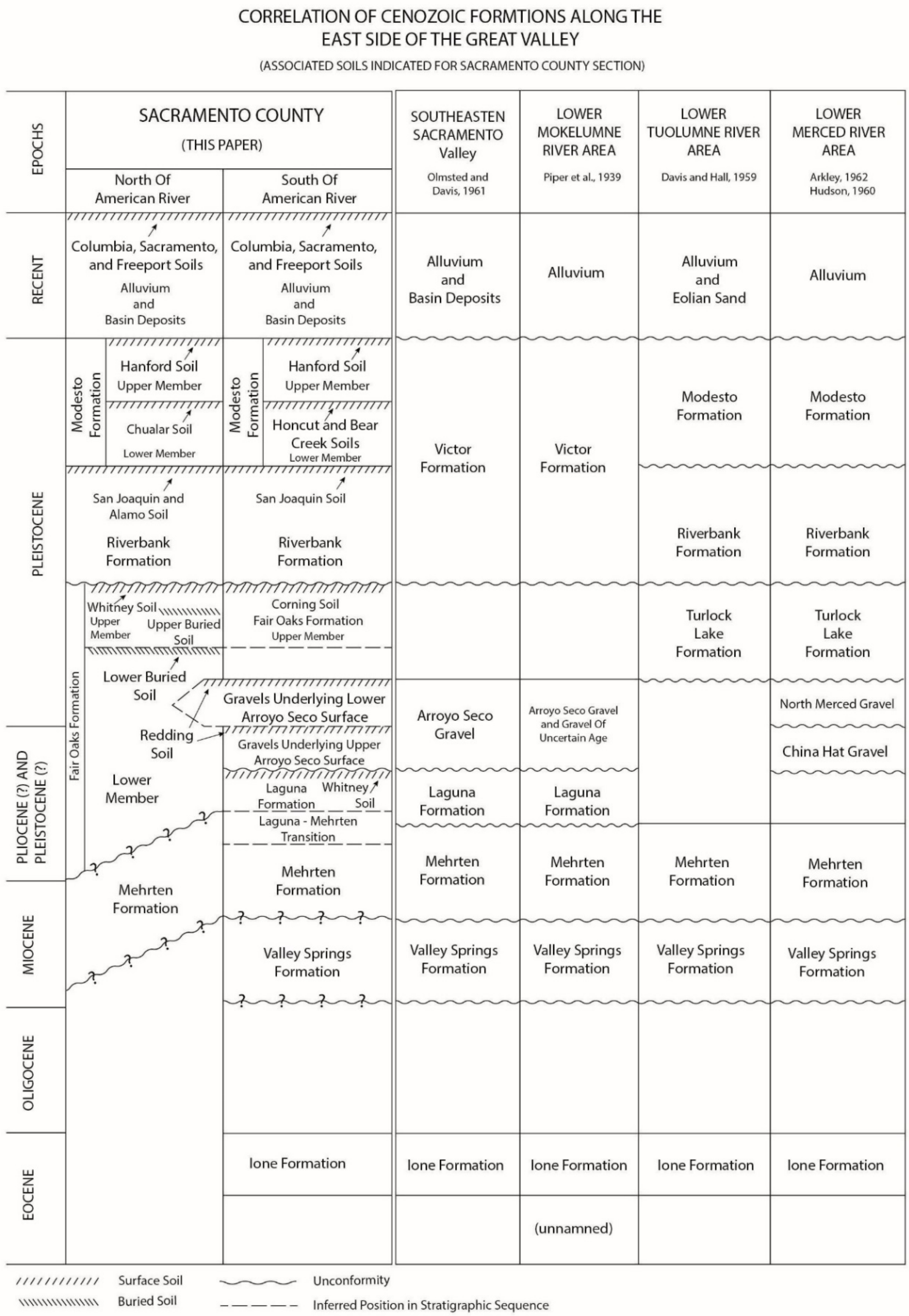


Table 1. Inferred correlation of Cenozoic formations along the east side of the Great Valley. Associated soils indicated for Sacramento county section (after Shlemon, 1967b).

(oldest) from cuts at the Turlock Lake Reservoir, the Riverbank Formation from exposures along the Stanislaus River near the town of Riverbank, and the Modesto Formation from bluffs along the Tuolumne River (Figure 9; Table 1). These formation names have now been extended throughout the Central Valley (Huntington, 1971; Huntington and others, 1977; Marchand, 1977; Marchand and Allwardt, 1981; Harwood and others, 1980; Wagner and others, 1981; Helley and Harwood, 1985; Harden, 1987; Busacca and others, 1989; Bartow, 1991; Lettis, 1982; Lettis and Unruh, 1991; Burow and others, 1997; 2004; Blake and others, 1999; Weissman and others, 2002; 2005; Staton and Spangler, 2014).

These formations can be cross-referenced with the fossil flora and fauna in these formations as described in Section IV, Paleontology. The depositional environments and corresponding geologic time of these formations older formations are described in Appendix A, Plate B, Summary of Geologic History of Sacramento and the Surrounding Area.

In addition to readily available published literature, the Sacramento area is blessed by an abundance of Quaternary-related “gray” literature. These are typically field-trip Guidebooks and road logs, usually of limited distribution, prepared by local geological, engineering, and soil-science organizations (Lydon, 1962; Shlemon, 1967b; 1998; Shlemon and others; 2000; 2009; Hauge, 1973; Moores, 1993; Franks and Moss, 1995). The Guidebooks are particularly valuable, for many contain photographs of road cuts and landscapes now destroyed or substantially modified by urbanization. Several Sacramento-area, “key” guidebook stops are shown on Figure 10 and identified by numeric symbols. Some or all exposures and landscape viewpoints may still be available for field examination.

Geomorphic Setting

The Sacramento region, for purposes of this paper extends primarily across nine California counties: Sacramento, Yolo, Sutter, Sierra, Nevada, Placer, El Dorado, Amador, Calaveras. Although Solano, Contra Costa, and San Joaquin counties border Sacramento County to the south they are paimarly part of the Sacramento / San Joaquin Delta, and not addressed in detail in this paper. The Sacramento urban area covers most of the northeastern part of Sacramento County, spreading northeast into Placer County and west, across the Sacramento River, into Yolo County (Figure 1). The major drainages are the Sacramento River on the west, the American, Feather, Yuba, and Bear Rivers on the north and the Cosumnes River on the south. Smaller drainage, such as Arcade Creek north of the American River, and Elder and Laguna (north) creeks, south of the River, are now mostly channelized to carry off storm and return irrigation water (Figure 10).

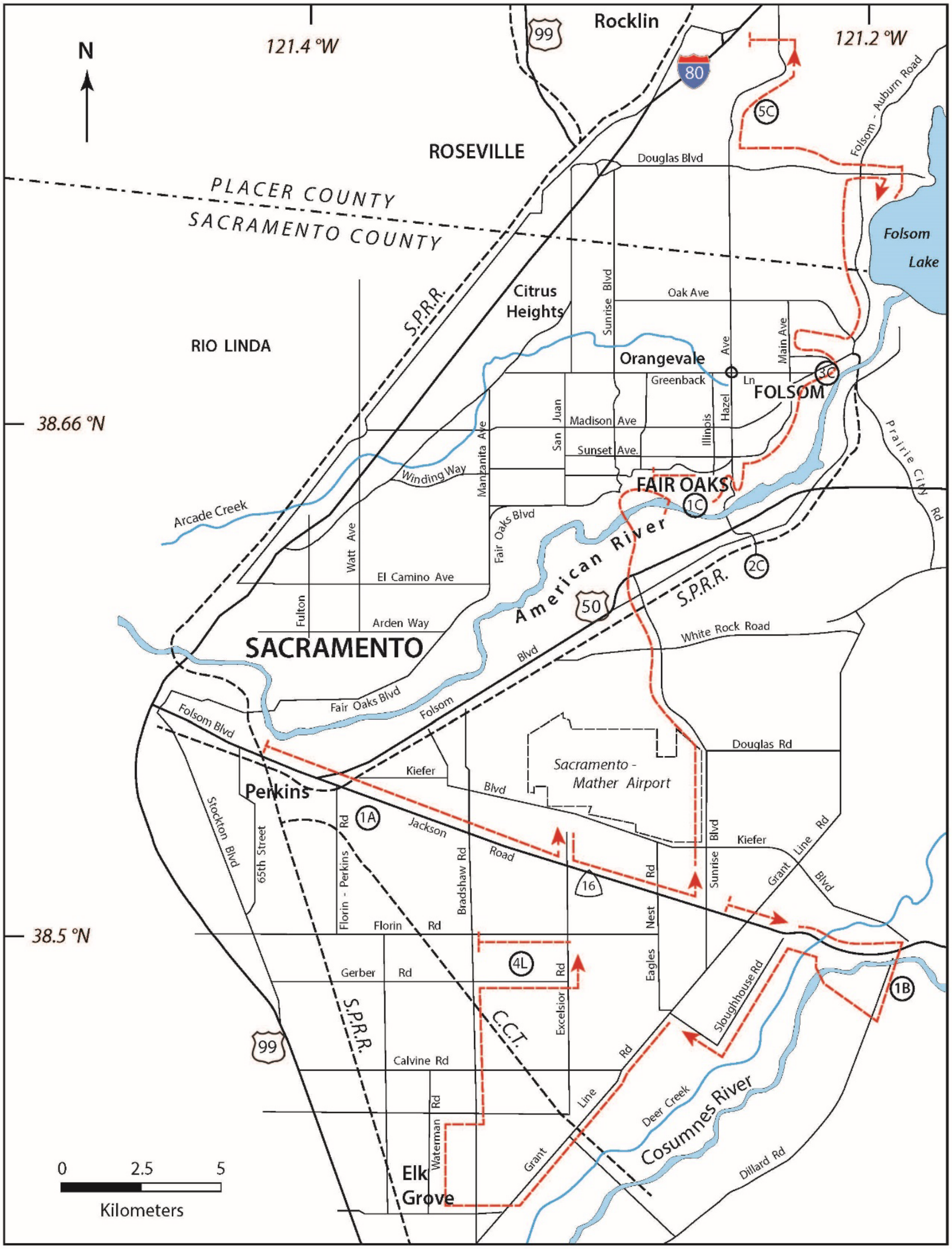


Figure 10. Sacramento area place names referred to in the text. Traditional field guidebook stops (see references) are identified by circled symbols (modified from Shlemon, 1998).

The Sacramento area ranges in elevation from about 7 meters (NAVD88) at the American-Sacramento River confluence, to about 66 meters at Folsom (Figure 10). Except for natural and now man-made levees along the American, Sacramento and Cosumnes rivers, local relief is generally less than about 2 meters, but increases east toward the Sierra Nevada foothills. The Cosumnes River and tributaries incise the Mehrten and older formations some 15-30 meters, giving rise to local “haystack hills” that are particularly observable along Jackson Road, east of Sloughhouse (Figure 10). An exception to the generally low relief are the 45-meter-high bluffs along the north side of the American River at Fair Oaks that expose complex fluvial stratigraphy and buried paleosols within the Fair Oaks Formation (Figures 10 and 11).

South of the American River, previously dredged gravels and now urbanized fill terraces step up to the east where each successive terrace is underlain by increasing older fluvial deposits (Figures 12 and 13). The older terraces are increasingly dissected and those more than about 100,000-years old, which are particularly prevalent east of the former Mather Air Force Base (decommissioned in 1993 and now known as “Sacramento Mather Airport”), are replete with ephemeral internal drainage (vernal pools) and surrounding mima mounds that were once extensive especially near Grant Line and Kiefer roads (Figure 10).

Topographic relief of about 1.0 - 1.5 meters typically marks each terrace step, many of which are only discernible as minor escarpments in local roads (Figure 14). The terraces and their underlying American River fluvial deposits merge southwestward into the subsurface where they are traced as Pleistocene American River channels now buried by successively younger fan and fluvial sediments (Figure 12).

The Cosumnes River is bordered by flights of fluvial terraces similar in age to those of the lower American River (Figures 12 and 15). However, the Cosumnes River drainage area (1,865 sq. km) is only a third of the American (5,568 sq. km); and this is reflected by associated geomorphic features: The terraces are narrower, generally less than 10-meters wide and the risers are usually only a few meters high. The modern Cosumnes floodplain, known for its historic production of hops at Sloughhouse (California Historical Landmark 575), is now intensively cultivated for vineyards, corn, and alfalfa. The floodplain is bordered by low natural, and now artificial levees about 5-7 meters high. The lower Cosumnes geomorphology similarly reflects the impact of Pleistocene climatic change, for the various river courses were also deeply incised during the last major Sierra glaciations and affected by glacio-eustatic lowering of base level. This is topographically expressed by still preserved side-stream gullies that graded to a former (about 15-20 thousands of years ago [Ka]) Cosumnes, gravel-filled channel some about 6-7 meters below the present, now backfilled by post-glacial sedimentation in the main channel (Shlemon, 1972; Figure 16).

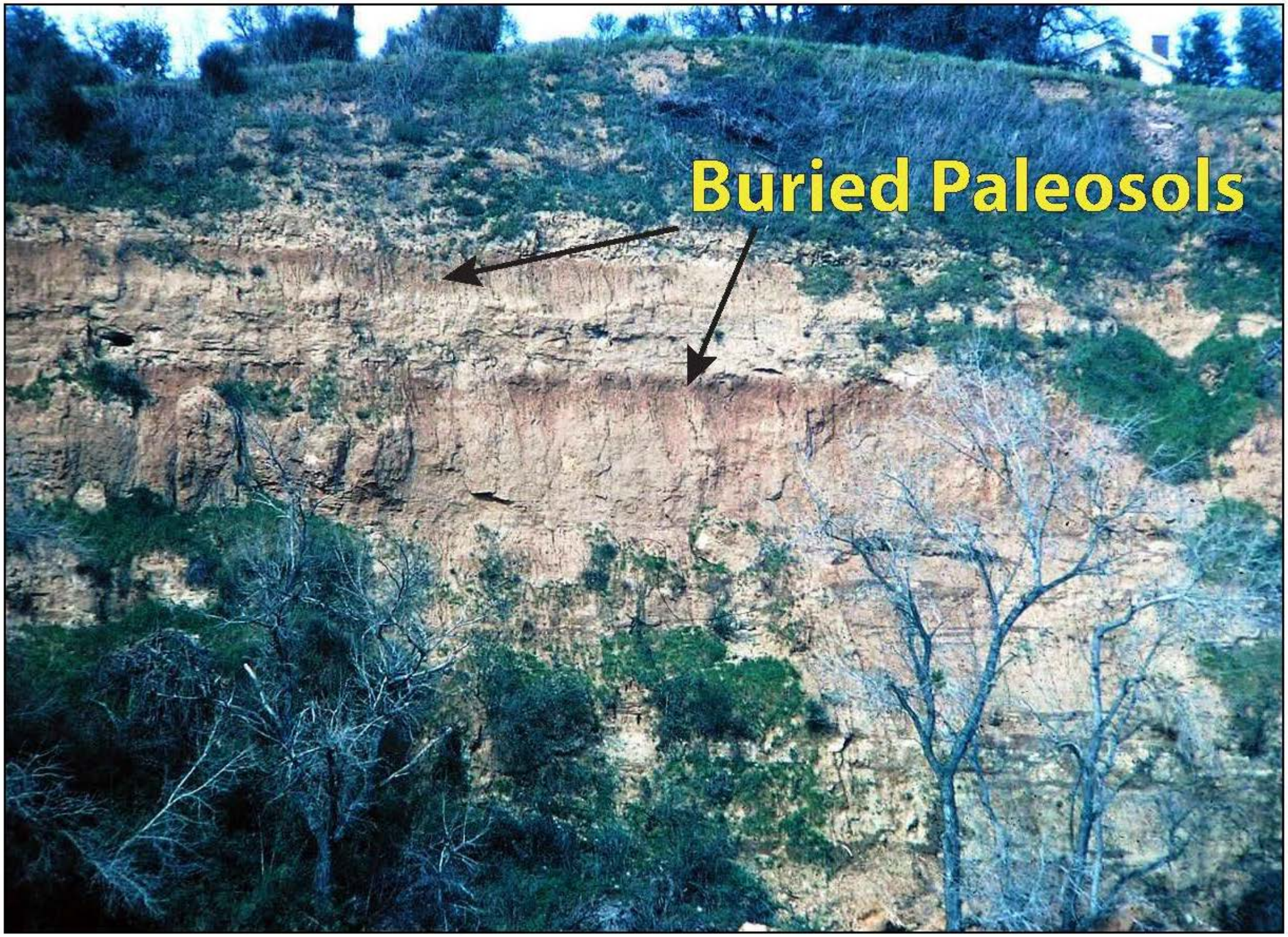


Figure 11. Photograph showing upper-two, strongly developed buried paleosols in the Fair Oaks Formation exposed in the north bluffs of the American River between the “old” and “new” Sunrise Avenue bridges (Source: image and annotation courtesy of Robert Sydnor).

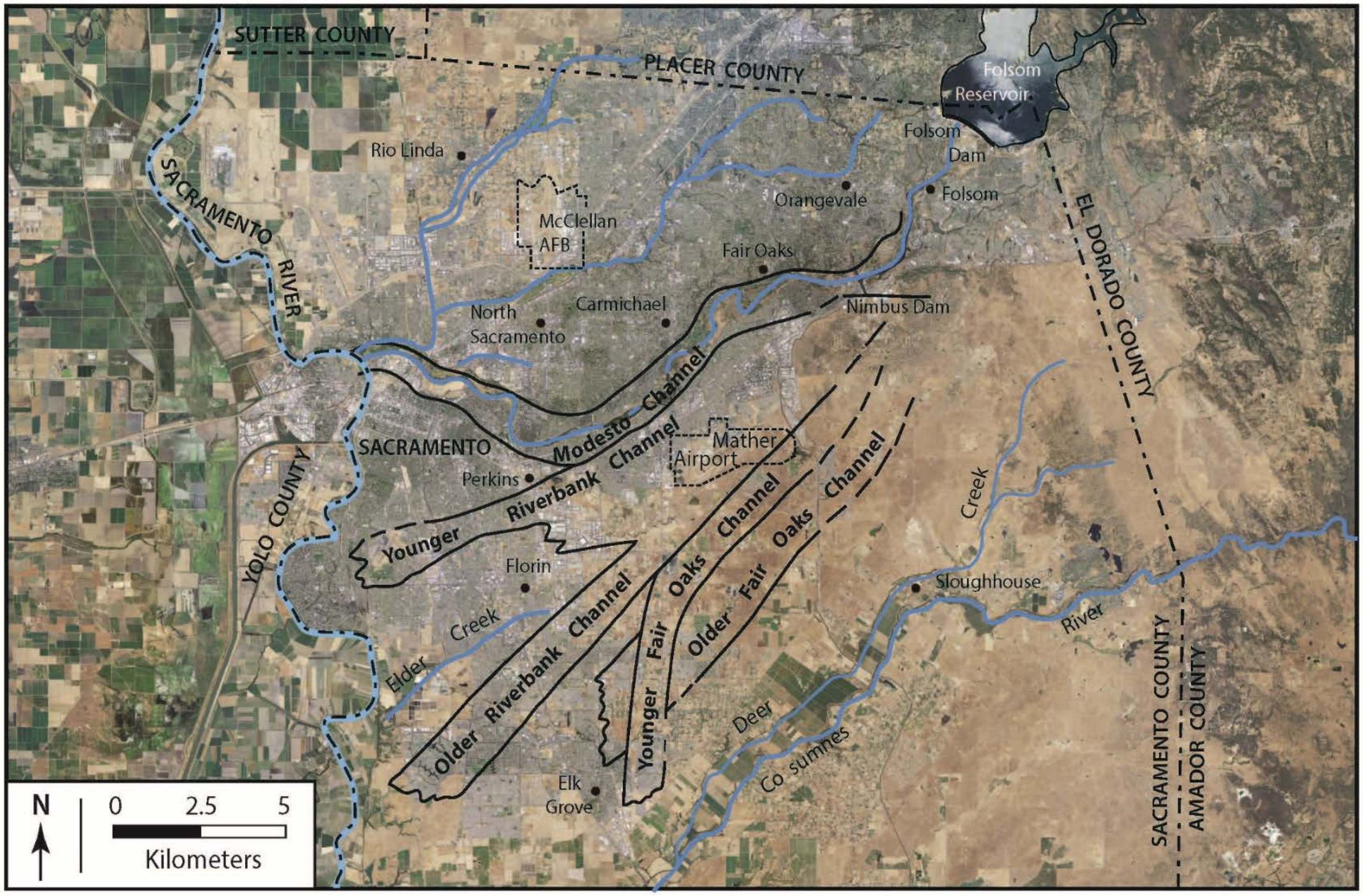


Figure 12. Paleo-channels of the lower American River that have migrated ("jumped") northward during successive Pleistocene glaciations (Older Fair Oaks = oldest; Modesto = youngest). All channels emanate from an apex near Folsom and are geomorphically expressed as fill terraces upstream from about the Sacramento-Mather Airport; and as buried fluvial gravels increasing in depth downstream where they graded to or were cut off by paleo-channels of the lower Sacramento River. Similar, but smaller paleo-channels flank and underlie the present Cosumnes River (see text for discussion). Channel form and extent modified from Shlemon (1967b) and superimposed on Google images courtesy of Yannick Wirtz.

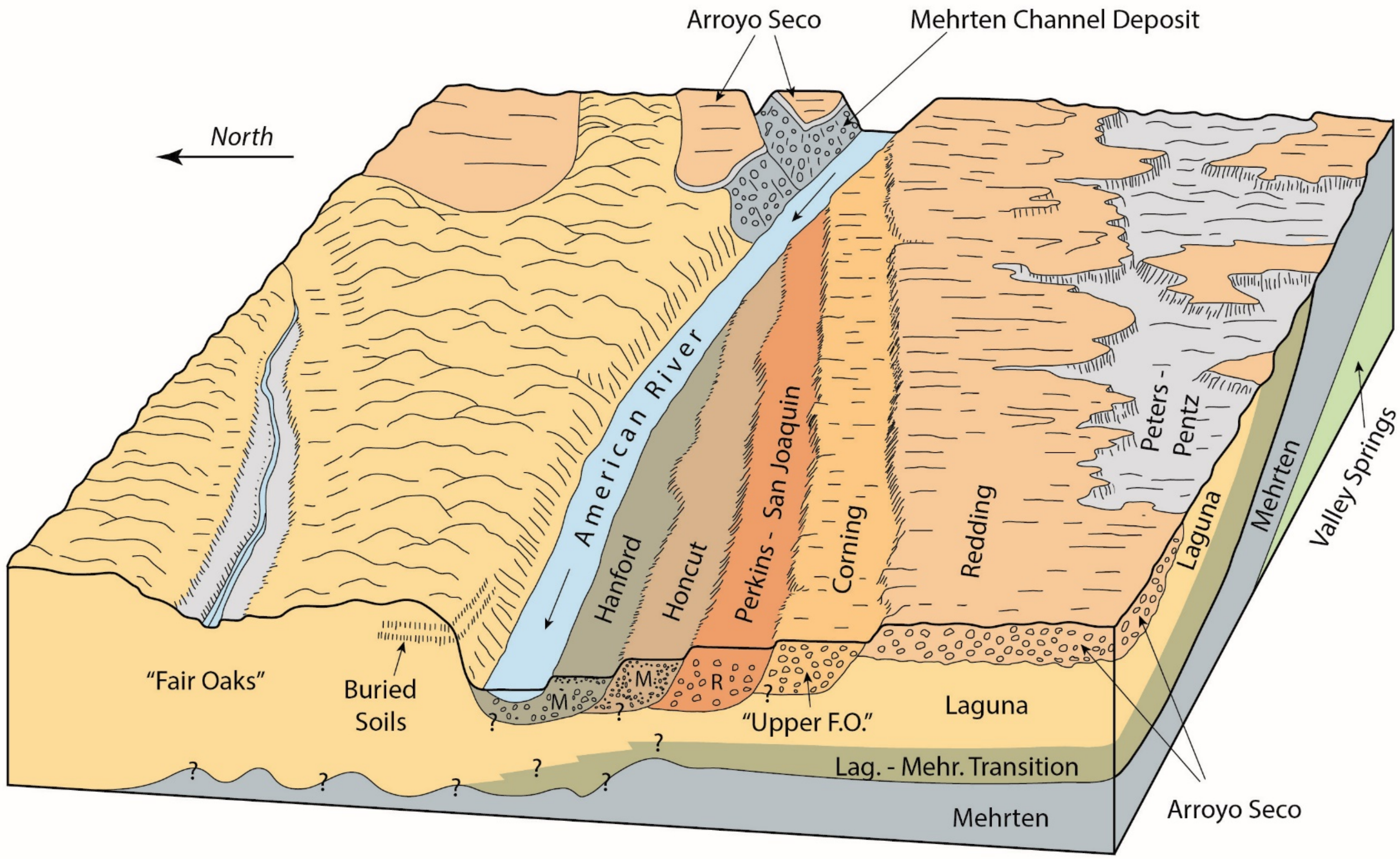


Figure 13. Schematic (not to scale) diagram in the latitude of Fair Oaks showing nested fill terraces south of the American River and their associated Quaternary formations. Characteristic soil series indicated on landform surface; geologic unit identified below surface: (M = Modesto Formation, R = Riverbank Formation, F.O. = Fair Oaks Formation, A.S. = Arroyo Seco Gravel, Lag. = Laguna Formation, Mehr. = Mehrten Formation). Also shown are representative soil series from Cole and others (1954); e.g., Hanford, Honcut, Perkins-San Joaquin, etc.). Upper buried paleosols at Fair Oaks shown on Figure 11 (modified from Shlemon, 1967b; courtesy of Yannick Wirtz).

Figure 14. Typical 1-meter topographic rise south of the American River marking Riverbank-age sediments (right) from the lower Fair Oaks (left) looking east on Jackson Road (Highway 16) near the Excelsior Road junction (Fig. 10), about 2.0 km south of the Sacramento-Mather Airport near stop “1C” (Figure 10) (Source: image courtesy of Robert Sydnor).

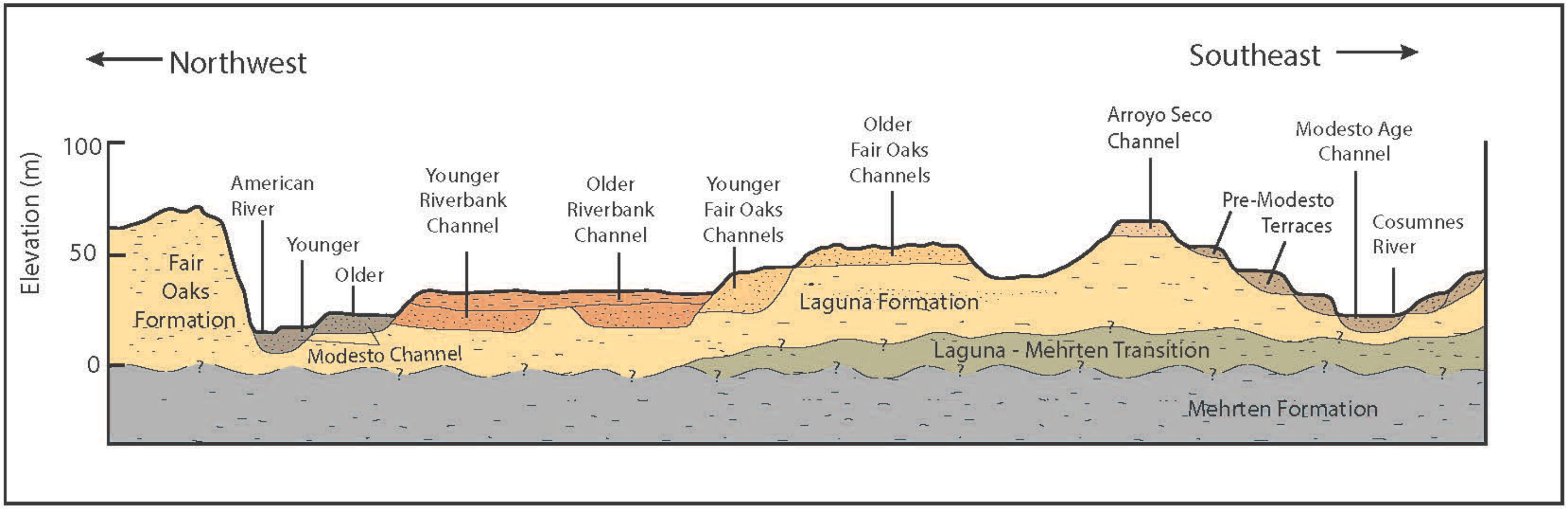


Figure 15. Generalized cross section across the American River between approximately Carmichael on the northwest and Sloughhouse on the southeast (Figure 10) showing principal Quaternary formations and relative scale of the American and Cosumnes River terraces (modified from Shlemon, 1967b; diagram courtesy of Yannick Wirtz).

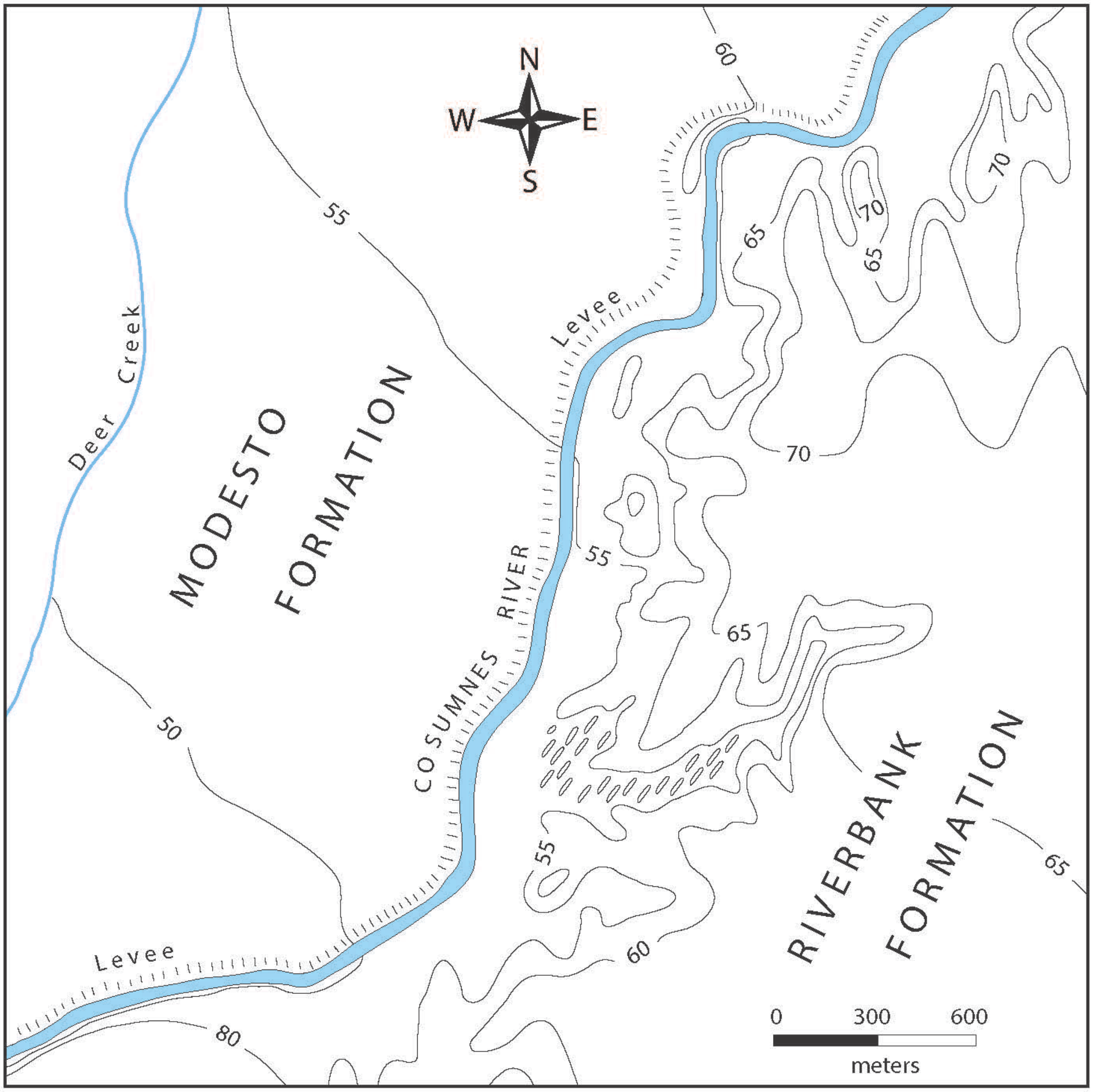


Figure 16. Backfilled side-stream gullies on the Riverbank Formation near Sloughhouse (Figure 10) reflecting incision about 15-20 Ka to a Modesto-age, gravel-filled, Cosumnes River channel 6-7 m below the present (Contours in feet; modified from Shlemon, 1972).

The lower Cosumnes River area is relatively undisturbed (Florsheim and Mount, 2003) compared with the lower American River and thus preserves a relatively rare geomorphic feature; *viz.,* a “Yazoo stream” in the form of Deer Creek (Figure 16). Deer Creek flows within in the historic Cosumnes floodplain paralleling the river on the northwest for almost 32 km before “breaching” natural levees and entering the main stream (Figure 10).

Impact of Regional Climatic and Land Use Change

The modern geomorphic setting of the Sacramento area owes its origin to three major processes: Channel incision and sediment filling associated with climatic change in the adjacent high Sierra Nevada; the influence of glacio-eustatic lowering of sea level and its effects extending “upstream” through San Francisco Bay and the California Delta; and the accelerated sedimentation stemming mainly from late 19th Century upstream deforestation and hydraulic mining and downstream gold dredging.

Regional Climate Change

Sierra Nevada Glaciations

Throughout the Quaternary, the adjacent Sierra Nevada mountain range was periodically glaciated. Major glacial advances younger than about 1 million-years-old (m.y.o.) are amenable to dating by several numeric techniques ranging from radiocarbon assay for younger moraines, to cosmogenic assessments, for rates of boulder weathering, and to lake sediment records (Benson and others, 1996, 1998; Phillips and others, 1996; Bischoff and Cummins, 2001; Bischoff and others, 1997; Ehlers an Gibbard, 2004; summaries in Gillespie and Zehfuss, 2004). Evidence for earlier mountain glaciations has now been largely lost owing to subsequent erosion; however, indirect evidence is still preserved in the Sacramento area by deep subsurface channels documented to be significant sources of groundwater (Ford and others, 1974).

Relative dating techniques have also proven extremely useful to judge the age of younger Sierra Nevada glaciations; namely, relative soil profile development and association with the marine-isotope stage chronology (Warhaftig and Birman, 1966; Burke and Birkeland, 1979; Birkeland and others, 1980; Cherven, 1984; Atwater and others, 1986; Fullerton, 1986; Birkeland and Burke, 1988; Phillips and others, 1996; Benson and others, 1998; Gillespie and Clark, 2011). The timing of respective Sierra glaciations has now likewise been associated with similar events in the mid-Continent and with various pluvial events in the Great Basin and in the Central Valley of California (Morrison, 1965; Helley, 1978; Sowers, 2000; Ehlers and Gibbard, 2004).

Both continental and alpine glaciations generally coincide with world-wide sea level lowering. With onset of the Sierra glaciations, most west-flank streams deeply incised their lower courses grading to now lowered base levels, thus giving rise to adjacent fill terraces, geomorphic surfaces subject to weathering, and ultimately soil (pedogenic) formation. This occurred several times in the past million years or so in the Sacramento area and is portrayed by a schematic model of regional landscape evolution (Shlemon, 1972; Figure 17). In brief, initial incision of the lower "glacial channels" was succeeded by filling with basal, coarse-grained, outwash and followed by fining-upward sequences of coarse to fine sand and silt. The Sacramento-area topography was unlike that of the present. During glacial events, the lower American, Cosumnes, Mokelumne, Sacramento and probably other drainages traversing the Delta (Figure 9) were incised more than 20 meters, thus forming local "canyons." Today, however, this local relief has been backfilled giving rise to the relatively featureless plains, now characteristic of the area. With general deglaciation and rising base (sea) levels, relative landscape stability ensued during interstadial and interglacial time resulting in surface weathering and soil formation. Accordingly, the Sacramento area Quaternary sediments, as elsewhere along the east side of the Central Valley, preserve not only evidence of successive Sierra Nevada glaciations, but also relict (surface) and buried paleosols, stratigraphic markers of interglacial weathering.

Glacio-Eustatic Sea Level Change

Sierra Nevada glaciations generally correlate with world-wide glacio-eustatic sea level fluctuations (Morrison, 1965; Sowers, 2000). This is well illustrated by the geomorphic evolution of the lower Sacramento and San Joaquin Rivers that form the nexus of an inland, broad upper-estuarine plain generally called the "Delta" (Figure 9). During Pleistocene glaciations, lower world-wide sea levels caused deep fluvial incision of the then Sacramento-San Joaquin Delta, by ancestral Sacramento rivers flowing through the modern San Francisco Bay and then offshore through the Golden Gate to glacio-eustatic base levels about 100 m below the present (Shlemon, 1971; Shlemon and Begg, 1975; Atwater, 1982; Band, 1988; Drexler and others, 2009). But the Quaternary history of Delta glacio-eustatic changes is complex, for differential subsidence continues regionally, due to peat and sediment compaction (Weir, 1950; Rojstaczer and Deverel, 1995; Ingebritsen and Ikehara, 1999; Reed, 2002; Miller and others, 2008) and locally, due to probable Holocene faulting (Shlemon and Begg, 1975; Band, 1988; Verosub and others, 2009).

Even today, tidal impacts extend through the Delta and upstream to the Sacramento area. And during the Pleistocene, ancestral American River channels graded to the eustatically lowered base levels, reaching about -18 meters at the modern confluence with the Sacramento River (Figure 12).

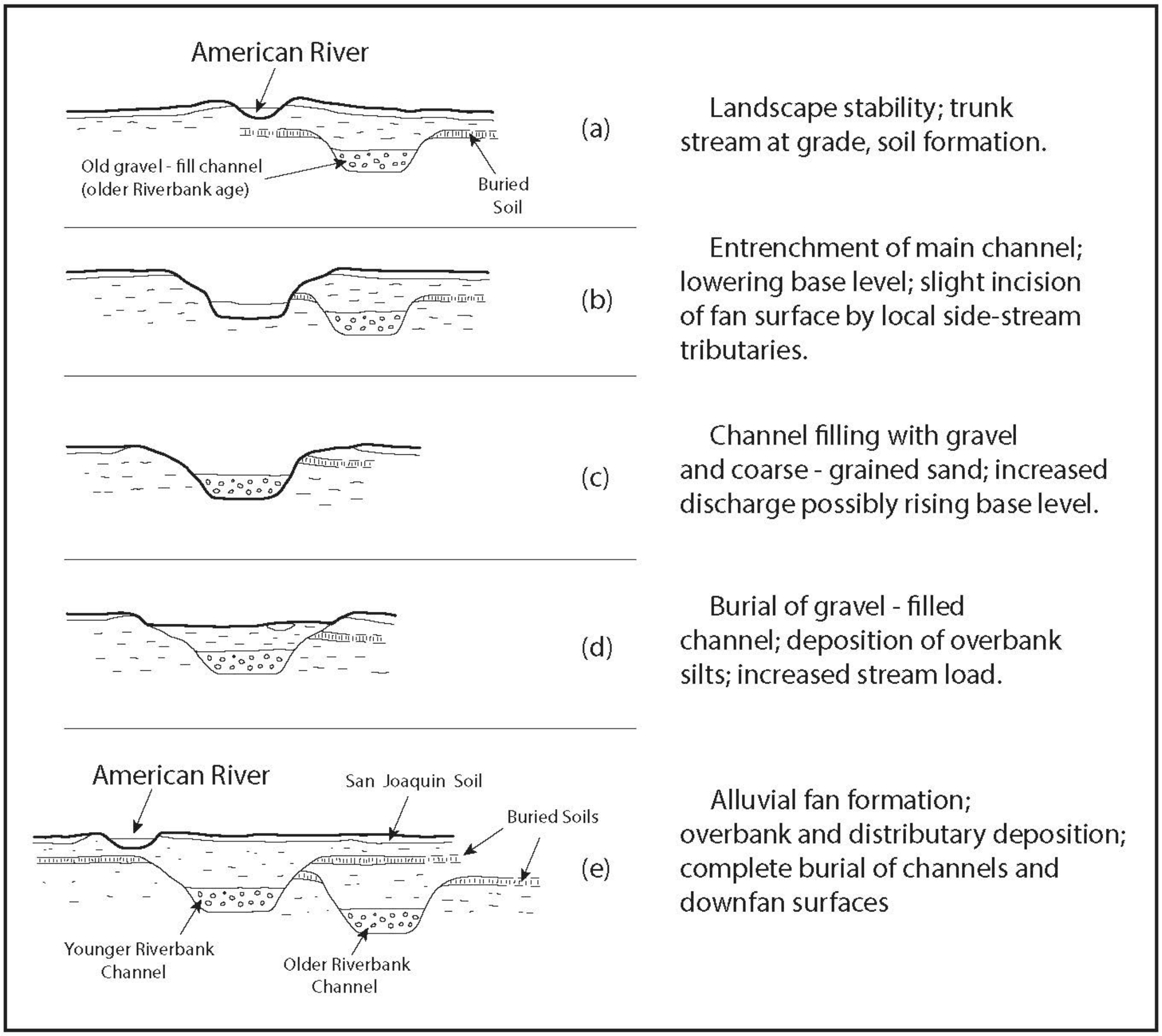


Figure 17. Conceptual model of Pleistocene landscape evolution in the Sacramento area controlled by regional climatic change: Initial fluvial incision followed by deglacial gravel and overbank filling and interglacial/interstadial stability and soil formation (after Shlemon, 1972).

Land Use Change

Hydraulic Mining and Dredging

The latter part of the 19th century saw extensive hydraulic and placer mining in tributaries of the American and other Sierra Nevada streams. The resulting deforestation and accelerated erosion filled most streams with debris, clogging channels, raising flood-plains and causing massive floods in the Central Valley (Kelley, 1959; James, 1989; 1999). Hydraulic mining was, locally, probably as important as Pleistocene climatic change in affecting sedimentation rates (Gilbert, 1917; Averill, 1946; Jaffe and others, 2007). In the Sacramento area, the heyday of hydraulic mining was followed by gold dredging within the active American River channel and on the adjacent Pleistocene gravel-filled terraces, particularly in the Nimbus area (Figures 12 and 18). The first of the famous Yuba-type, bucket-line dredges commenced commercial operation in 1898 (Farina and Carpenter, 1973; Kirshenbaum, 2000). Dredges, mainly from the Natomas Company, intermittently operated until about 1962, creating the classic tailings topography between Folsom on the northeast and the Sacramento Mather Airport on the southwest (Clark, 1970; Figures 10 and 12). Additional information and photographs are provided in "Chapter VII – Natural Resources [Metal Mining]" of this document.

Though appearing "pristine" and generally barren to the casual viewer, the old tailing topography has been substantially modified over the years. Indeed, the tailings have had many uses, ranging from early 20th Century orange groves near Natomas and olives near Folsom (remnants of which were visible in the late 1960s), to revetments for rocket-motor testing in the 1950s (Aerojet General), to sand and gravel exploitation for local highway construction (Rapp, 1975), and to urban suburban-development fill. But the tailings are not just simple "piles of rock" amenable for traditional grading and urban construction with modification. Tailings can contain an internally complex lenticular stratigraphy owing to the mixing of dredge side-sluice sand, silt and clay then usually covered by gravels emanating from the stern, side-swinging dredge stacker (Romanowitz, 1970; Shlemon and Phelps, 1971). Too often, under load, tailing clays and sand are differentially compressed, resulting in potential surface subsidence and substantial structural damage. Likewise, the tailings are generally very permeable and thus enhance contaminant migration from the 1950s "rocket testing sites," toward nearby water wells, and ultimately into the American River. The result has been a long-lasting and expensive "Superfund" cleanup (EPA, 2016). In sum, though not as geomorphically impactful as Sierra Nevada glaciations, the American River dredging also affected downstream sedimentation patterns, contributing to channel filling and increasing flood frequency.

Figure 18. View from the Fair Oaks bluffs looking south across the American River and Nimbus Dam showing multiple, now dredged, Pleistocene nested terraces on the skyline (Source: image courtesy of Robert Sydnor).

Stratigraphic Setting

The general stratigraphy of the Sacramento area is reconstructed from several main sources and specifically; early economic-geologic assessments in the adjacent gold-bearing foothills (Lindgren, 1911), engineering-geological investigations for Folsom Dam (Kiersch and Threasher, 1955), general mapping, particularly in the Roseville-Rocklin area (Figure 10; Olmsted, 1971), and site-specific observations and soil-stratigraphic descriptions and measurements of river and road cuts in the 1960s, with the related subsurface stratigraphy deduced from hundreds of then-available water-well logs and bridge borings (Shlemon, 1967a; 1967b), and from soil-geomorphic relations interpreted from soil surveys (Weir, 1950; Cole and others, 1954; Bartow and Helley, 1979; Tugel, 1993).

Pre-Quaternary Units

Two major pre-Quaternary rock and sediments units occur mainly in the eastern part of the Sacramento area: Granitic rocks near Folsom Dam and in the Roseville-Rocklin area in adjacent Placer County; and andesitic lahars and old channel gravels of the Mehrten Formation north of the American River and generally reworked andesitic sediments south of the river (Figure13). Earlier sediments pertaining to the Eocene Ione Formation and the Valley Springs Formation crop out in foothills immediately east of the Sacramento area (Figure 13; Table 1).

Granitic Rocks

The Sacramento area is abutted by and underlain by pre-Quaternary rocks and sediments. Specifically, as illustrated on a generalized diagram (Figure 19), granitic rocks are represented by quartz diorite and crop out in Rocklin as a part of the Rocklin Pluton in Placer County (Swanson, 1978). Weathering along joints and fractures has given rise to a broad, low-relief undulating plain informally named “Roseville Surface” between about Auburn on the northeast, and Roseville on the southwest (Shlemon, 1967a; 1967b; Aune, 1973). It is this relatively gentle-gradient Roseville Surface upon which the first railroad, byways, and now Interstate Highway 80 ascended from the Sacramento area eastward through the metamorphic foothills and thence across the Sierra Nevada mountain range (Figure 19). Granitic rocks are likewise exposed beneath ancestral channels of the Mehrten Formation in the Rocklin and Folsom Dam areas (Kiersch and Threasher, 1955).

Mehrten Formation

The most extensive pre-Quaternary sediments pertain mainly to the Mio-Pliocene Mehrten Formation, a massive accumulation of generally andesitic lahars and fluvial

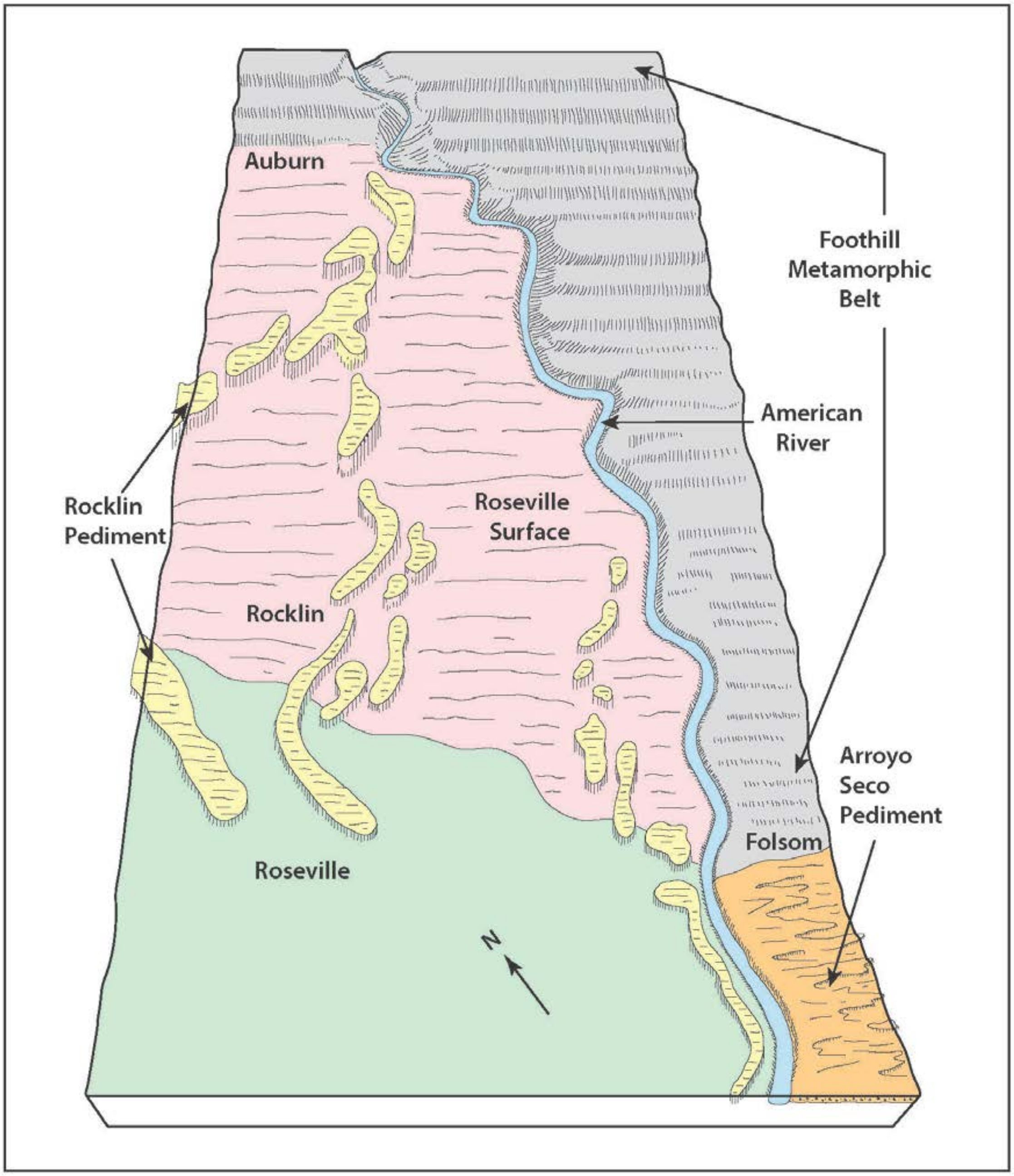


Figure 19. Generalized diagram (not to scale) illustrating the topographic relationship of the informally named Arroyo Seco Pediment (Piper and others, 1939), Rocklin Pediment and Roseville Surface in northeastern Sacramento and southwestern Placer counties. The Rocklin Pediment is generally underlain by Mehrten-age andesitic gravels (Figure 20; inversion of topography; see text). Granitic rocks of the Roseville Surface merge imperceptibly into the dissected alluvial plains of the Fair Oaks Formation near Roseville providing a relatively low gradient, geomorphic “ramp” for construction of the first transcontinental railroad (Figure 6), and now traversed by Interstate 80 (Figure 10). Diagram modified after Shlemon (1967a; 1967b).

sediments emanating from near the crest of the Sierra Nevada. Sweeping down the western Sierra slopes, the lahars deflected and filled pre-existing channels (Curtis, 1954; Slemmons, 1966). Several former Mehrten fluvial channels now stand as inversions of topography, often about 30 meters above the surrounding Roseville surface, particularly at Mooney Ridge on the west side of the Folsom Reservoir (Shlemon, 1967b). The broadly correlative, west-dipping surfaces are informally designated as the “Rocklin Pediment” (Figure 19). One such Mehrten channel extends along the north side of the American River as far west as Hazel Avenue (Figure 13) where, during the early 1960s, it was clearly exposed in the then-fresh road cuts. A detailed depositional and mineralogical description is provided by Horner and Giorgis (2000). Today, the channel gravels are partially visible along trails descending to the nearby Nimbus Dam and Fish Hatchery (Figure 20).

An entire sequence of the Mehrten Formation, about 6.1 meters of basal andesitic channel gravel overlain by up to about 14-meters of tuff breccia, was clearly visible in then new, late 1960s road cuts for Douglas and Sierra College boulevards, about 3.2 km east of Roseville (Figure 10, “stop 5C”). Prior to recent urbanization, the Mehrten surface in this area was replete with thousands of generally northwest-trending subparallel “lines and dots.” The lines proved to be subtle ridges, about 0.3 meters high and about 1.0-meter-wide; and the dots were classic mima mounds, the largest about 7 meters in diameter and 1-meter high. The nearby fresh road cuts showed that the “lines-and-dots” topography were expressions of fracture traces that extended through the entire tuff breccia but not into underlying granitic rocks. Various hypotheses for the origin of this unusual Mehrten micro-topography range from lahar cooling and surface dilation to impact of seismic ground shaking; but these ideas remain untested (Shlemon and others, 1973).

Quaternary Deposits

Mehrten-Laguna Transition Zone

Unfortunately, the term “Mehrten” is generally applied to any sediments that are primarily andesitic. Accordingly, many geologists observing Sacramento area road cuts and water wells encountering andesitic sediments designate these as “Mehrten,” implying a late Miocene age. But most andesitic fluvial sediments in the Sacramento area are reworked and thus post-Mehrten in age. This is well illustrated by the Dillard Road exposures near the Cosumnes River and the intersection of Jackson Road (Highway 16; Figure 10, stop “1B;” and Figure 21). The Dillard Road cuts were new in the early 1960s and then quite visible as basal cross-bedded andesitic sediments interfingering and transitioning upward into granitic-derived sediments (Laguna Formation [see description below]; Table 1; Figure 22). The original cuts also exposed two moderately-to-strongly developed buried soils in the granitic section, comparable in

Figure 20. Trail cut exposing andesitic fluvial gravels of the Mehrten Formation in the north bluff of the American River, 0.2 km east of Nimbus Dam (2017) (Source: image courtesy of Robert Sydnor).

Figure 21. A once-clean (late 1960s) road cut on the east side of Dillard Road near Sloughhouse (Figure 10, stop "1B) exposing Laguna-Formation granitic sediments (upper cut) interfingering with Mehrten andesitic (lower cut) forming the "Laguna-Mehrten transition." Cross-bedded granitic (Laguna) sediments and two "moderately developed" buried paleosols crop out in the upper-cut exposures (Source: image and annotation courtesy of Robert Sydnor).

Figure 22. Close-up of the Dillard road-cut showing typical andesitic cross-bedded fluvial sediment at the base of the Laguna-Mehrten transition (Source: image courtesy of Robert Sydnor).

relative development to a similar pair exposed in the Fair Oaks bluffs (Table 1), suggesting possible regional correlation (Shlemon, 1967a; 1967b). The "Mehrten-Laguna transition zone" is likewise identified in water-well logs, in cores, and in road cuts elsewhere in the Sacramento area. Regrettably, the Dillard Road exposures have since been degraded over the years owing to fluvial erosion, to vegetation growth, and to generations of geology students picking away at the cut.

Arroyo Seco Gravels

First described in the Mokelumne River area (San Joaquin and adjacent Amador counties) as a Pleistocene veneer of generally quartzitic and mixed granitic rocks overlying progressively older formations, Piper and others (1939) postulated that the Arroyo Seco Gravels were laid down on a once-extensive "pediment surface" that locally truncated the Laguna, Mehrten, Valley Springs and Ione Formations (Table 1). Other "high-level" gravel-strewn surfaces occur at elevations slightly above and below the Arroyo Seco (for example, the "North Merced" and China Hat" gravels of Hudson, [1960] and Arkley [1962]), and were later combined with the Arroyo Seco and extrapolated throughout much of the eastern Sacramento and San Joaquin valleys (Olmstead and Davis, 1961; Harden and Marchand, 1977; Marchand and Allwardt, 1981; Busacca and others, 1989; Table 1). From their stratigraphic position, variability in thickness and geographic proximity to major streams, many Arroyo Seco gravels are probably remnants of former early Pleistocene (> about 1 million years ago [Ma]) river fill terraces rather than a once regionally extensive pediment veneer. Locally, some "Arroyo Seco gravels," especially south of the American River, cover fluvial granitic sediments identified as the Laguna of Piper and others (1939) and some are overlain by sediments with similar lithologies.

In the Sacramento area, the Arroyo Seco Gravels were particularly well exposed during the 1960s in ephemeral cuts within the Gerber Road Landfill, about 8 km southeast of the Sacramento-Mather Airport near the junction of Gerber and Excelsior roads (Figure 10). Here, a typical 3-meter section of Arroyo Seco Gravels overlay, with undulating contact, the underlying Laguna Formation (Shlemon, 1967a; 1967b). Elsewhere, the Arroyo Seco Gravels are locally preserved as the highest terrace remnants forming the drainage between the American and Cosumnes Rivers and as a thin veneer capping Mehrten-age channel deposits adjacent to and north of the American River between about Nimbus Dam and Folsom (Horner and Giorgis, 2000; Figures 10, 12, and 13). The Arroyo Seco Gravels, between the American and Cosumnes rivers, is typically capped by the widespread "Redding soil" (Cole and others, 1954; Rogers and others, 2009). But simple correlation of mapped soil series with underlying geologic formations can be misleading, for the Redding is mapped on several discrete "high surfaces," some of which are underlain by American River Pleistocene channels and some by a thin veneer of so-called pediment gravels (Figure 13).

Laguna, Turlock Lake, and Fair Oaks Formations

These three Pleistocene formations, originally described in 1939 (Laguna; Piper and others), in 1959 (Turlock Lake; Davis and Hall), and in 1967 (Fair Oaks; Shlemon, 1967a; 1967b), respectively, have now been identified, mapped, and widely extrapolated throughout the Central Valley as mainly deduced on interpretations of previously published soil surveys (Arkley, 1962; Shlemon, 1967a, 1967b; Harden and Marchand, 1977; Marchand and Allwardt, 1981; Cherven, 1984; Helley and Harwood, 1985; Busacca and others 1989; Weissman and others, 2005). Most sediments are fluvial fine sand and silt, though gravels associated with ancestral river channels are common, especially in the lower American and Stanislaus river areas (Figure 9). Though not specifically identified in the Sacramento area, the Turlock Lake Formation (Davis and Hall, 1959), described from exposures around Turlock Lake Reservoir in eastern Stanislaus County, has been extrapolated elsewhere along the east side of the Central Valley (Marchand and Allwardt, 1981). Heretofore, no unequivocal numeric dates provide age estimates for the Laguna and Turlock Lake Formations, and they are both generally deemed to be Pleistocene (Table 1). In contrast, the stratigraphic position and magnetically reversed (about 780 Ka) sediments in the lower part of the Fair Oaks suggests a “middle Pleistocene” age.

Laguna and Turlock Lake Formations

The Laguna Formation was first described and measured by Piper and others (1939) from exposures along the Laguna Creek south of the Cosumnes River in southern Sacramento County (Figure 10). Described as consisting of granitic fluvial sediments generally west of and overlying Mehrten andesitic deposits, the Laguna Formation is generally correlative with the Turlock Lake Formation in that both are generally comprised of fluvial, interfingering granitic sand and silt immediately overlying the Mehrten Formation (Table 1). Arkley (1957; 1962) mapped and described typical soil series forming on the Turlock Lake Formation and these were similar in relative profile development to those identified on the Laguna Formation. In the Sacramento area, the Laguna of Piper and others (1939) is recognized only south of the Cosumnes River. However, in the subsurface it may interfinger with basal sections of the Fair Oaks Formation north of the American River (Figures 13 and 15).

Fair Oaks Formation

The “Fair Oaks Formation” was informally named (Shlemon, 1967a, 1967b) from road and river-cut exposures at the type locality north of the American River at the town of Fair Oaks (Figure 10). The Fair Oaks Formation seemingly occurs at or near the same stratigraphic interval as the Laguna Formation south of the Cosumnes River. But direct physical association is not possible owing to the, about 25 km, distance between the Fair Oaks bluffs north of the American River and the minor Laguna-age outcrops south of the Cosumnes River (Figures 10 and 15). A later regional Quaternary map (Helley and Harwood, 1985) used soil-geomorphic relations developed elsewhere and therefore omitted the Fair Oaks Formation, deeming the bluff and north bank sediments as pertaining to the Laguna Formation.

Two distinct Fair Oaks-age deposits are recognized in the Sacramento area: North of the American River, as exposed mainly in the 45-m high bluffs between the “old” and “new” Sunrise Avenue bridges (Figures 10 and 11), are interbedded, fine fluvial sands and silts interpreted to be braided stream deposits (Horner and Giorgis, 2000). Four distinct buried paleosols occur within this section. The upper two, near the top of the bluffs (Figure 11), each bear a strongly developed argillic horizon, typified by reddish-brown (Munsell 5YR 4/3), common thick and continuous clay films that line ped faces, bridge mineral grains and fill root pores. As shown in Figure 11, the uppermost soil developed on slightly undulating relief and locally is superimposed on the lower paleosol forming a composite or “two-storied” profile. Both paleosols represent long periods of weathering, which likely took place during epochs of regional, relative landscape stability typical of interstadial or interglacial epochs (Shlemon, 1967a; 1972).

The lower two soils were previously exposed only during extremely low water levels. Now, with higher water levels (controlled by release from Folsom Dam) and vegetation growth, the soils are seldom visible in the bluffs today. They were, however, originally described as similarly strongly developed, though semi-permanent saturation gave rise to reduced (redox) colors (Shlemon, 1967a). Ostensibly, therefore, these two paleosols likewise represent interstadial or interglacial epochs within the Pleistocene.

Paleo-magnetic assays in the early ‘70s (unpublished) indicate that sediments enclosing the upper paleosols are normally polarized, and hence most likely pertain to the Brunhes magnetochron. In contrast, the base of the lower paleosols is magnetically reversed, presumably recording the Matuyama chron. Accordingly, the base of the Fair Oaks Formation, as exposed at the Fair Oaks bluffs, is judged to be about 780-thousand years old. The underlying, older sediments ostensibly merge with Laguna sediments south of the American River and thus provide a minimum age estimate for the Laguna, the basal Fair Oaks and ostensibly also for the Turlock Lake Formations (Figure 13; Table 1).

South of the American River the Fair Oaks Formation is represented by at least two discrete gravel-filled channels (Figure 12). Geomorphically expressed as subtle nested terraces, the upstream surface deposits are comprised almost exclusively of Sierra-derived, highly-weathered mixed granitic and metamorphic clasts. Granitic cobbles are typically weathered to grus, and thick, reddish-brown pedogenic clay extends through the profile to at least 2 meters (Rogers and others, 2009, p. 13). In fact, road cuts along

Excelsior Road, immediately south of the Sacramento Mather Airport (Figure 10) expose superimposed soil profiles locally separated by a possible thin veneer of reworked loess. Downstream, the Fair Oaks channels extend into the subsurface where, to the southwest, they are covered by an increasing thickness of overbank sand and silt (Figure 12).

In brief, it appears that the Fair Oaks Formation north of the American River was periodically laid down primarily as locally derived fluvial sand and silt. Together with its four buried paleosols, the Fair Oaks Formation here represents an estimated 400 thousand years of mid-Pleistocene deposition and soil formation. The stratigraphic equivalent south of the American River reflects major channel incision, filling and overbank deposition, the impact of discrete Sierra Nevada glaciations and "downstream" eustatically lowered base-level at and near the confluence with an ancestral channel of the lower Sacramento River.

Riverbank Formation

The Riverbank Formation is the most extensive Quaternary unit in the Sacramento area (Figure 12; see geological maps in Shlemon, 1967a, 1967b; Helley and Harwood, 1985). It lies topographically lower but stratigraphically above the Fair Oaks Formation north of the American River and the Laguna Formation south of the American River. It has several distinct facies. South of the American River, at least two ancestral Riverbank gravel-filled channels are well expressed on the surface as nested fill terraces and in the subsurface as distinct buried channels. Both terraces are covered to the southwest by an increasing thickness of overbank sands and silts (Figure 12). The terrace gravels are much less weathered compared with the adjacent older Fair Oaks and probable Arroyo Seco deposits. As a result, where readily accessible, many Riverbank channels were, and still are, actively quarried as observed in several sand and gravel pits, particularly along Jackson Road (Highway 16) in the Perkins area (Figure 10; stop "1A"). The Riverbank terrace gravels were also extensively dredged for gold, principally from Folsom southwest to the boundary with the Sacramento Mather Airport (Figure 10).

The gravel facies of the Riverbank Formation are generally identified by the "Perkins" soil of Cole and others (1954). A later, more detailed survey (Tugel, 1993) delimited several additional soil series typical of Riverbank channel deposits, each marking minor facies changes (usually surface and near-surface grain size) within the gravels. These soils are usually well drained and are typically "moderately to strongly developed."

Elsewhere, Riverbank fine-grained overbank and distributary fine-grained sand and silt are usually capped by very strongly developed soils. This is typified by the San Joaquin series as ephemerally exposed in the various Teichert gravel quarries in the Perkins area. The San Joaquin series (*Abruptic durixeralf)*, now designated as the “California State Soil” (Soil Science Society America, 2017), has a typical siliceous duripan (silcrete; Bqm horizon) that impedes gravitational water and thus gives rise to an accumulation of *in situ* as well as translocated (illuvial) clay in the overlying claypan (argillic) horizon (Rogers and others, 2009, p. 10-11). Locally, however, as observed in the Teichert quarries, the duripan is breached by about 5-m wide and about 2-m deep, V-shaped “fractures” in which illuvial clay extends far below the normal claypan. These clay-filled fractures may reflect former root systems or even possible regional seismic ground shaking, but their origin remains unknown (Shlemon, 1967a, 1967b).

Where locally buried by sediments of the Modesto Formation, particularly adjacent to the Sacramento River, the San Joaquin and related profiles are identified in water-well logs and serve as distinct soil-stratigraphic markers for regional subsurface correlation (Shlemon, 1967a).

Fine-grained facies of the Riverbank and older deposits often give rise to mima-mound and vernal pool topography, a microrelief now mostly destroyed by farming and urban development. Often informally called “hog-wallows” or “vernal pools,” the mound-and-pool topography once extended over many tens of thousands of hectares in California (Smith and Verrill, 1998). In the Sacramento area, particularly near Highway 16 along the American-Cosumnes River divide (Figure 10), artificial mound-and-pool topography is increasingly constructed to mitigate land “lost” to urban development (Davis and others, 2009).

Various hypotheses have been proposed accounting for the origin and age of the San Joaquin and similar silcrete and claypan soils, the most notable being that of Nikiforoff (1941) who envisioned ash influx “several thousand years ago” as the source of the silica. Now, however, numeric dating suggests that the strongly developed soils cap various facies of the Riverbank Formation are probably at least about 100,000-years old (marine isotope stage 5). This estimate was originally confirmed by the first uranium-decay date for Central Valley Quaternary sediments, based on samples collected immediately below the San Joaquin soil at one of the Teichert quarries in the Perkins area (Shlemon and Hansen, 1969; Hansen and Begg, 1970). Based on the marine isotope chronology, the underlying “younger Riverbank channel” gravels (Figure 12) are thus estimated as about 150 Ka (marine isotope stage 6), and those underlying the “older Riverbank” as about 250 Ka (stage 8).

Modesto Formation

The Modesto Formation generally pertains to sediments associated with the last two major Sierra Nevada glaciations (Tahoe and Tioga; marine isotope stages 4 and 2, respectively), about 60- and 20-thousand years old, respectively (Table 1). In the

Sacramento area, the Modesto Formation is confined mainly to floodplains and lowest terraces along the American and Cosumnes rivers and to natural levees of the Sacramento River (Figure 12). Where still preserved, the early Modesto sediments bear "slightly developed" soils typified by incipient reddening (rubification) of the subsoil (Bw horizon) or by local development of an initial argillic (Bt) horizon (e.g., "Honcut series;" Cole and others, 1954; Figure 13). In contrast, late Modesto sediments typically bear a surface organic horizon directly forming on relatively unweathered "parent material;" for example, the "Hanford soil" (Table 1). Both early and late Modesto sediments have been largely altered in the Sacramento area by gold and gravel mining and hence are not readily distinct from anthropogenically altered Holocene deposits.

The American River has not produced large, Modesto-age alluvial fans in contrast to the Mokelumne, Stanislaus, Tuolumne and other major fluvial systems to the south in the Central Valley (Figure 9; Janda, 1965; Helley, 1966; Shlemon, 1971; Atwater and others, 1986; Bartow, 1991; Burrow and others, 1997; 2004; Weismann and others, 2002). Rather, apparently because of eastward migration of the Sacramento-American River confluence or continued subsidence in the adjacent basin (Figure 12), the Modesto-age sediments are confined almost exclusively to the modern floodplain, natural levees and adjacent low terraces.

Pleistocene Channels of the Lower American and Cosumnes Rivers

The American River channels dominate the Quaternary landscape (and hydrology) of the Sacramento area. From the southern known extent of the "older Fair Oaks channel" to the modern Sacramento River confluence, the American has "migrated" some 25 km to the north (Figure 12). In contrast, the Cosumnes River channels are small and have occupied the same general area throughout much of the Quaternary (Figure 15). The channels, identified as upstream nested fill terraces and downstream buried fluvial systems, owe their origin to incision during early stages of Sierra Nevada glaciation. Ostensibly, during full glacial events, hydraulic competence increased, resulting in gravel-laden, braided stream deposits filling the channels. With the onset of deglaciation vast quantities of overbank sand and silt were carried far downstream, eventually burying the channels and spilling outward along distributaries to build up broad, coalescing alluvial fans.

At least six, post-Mehrten, American River channel systems are recognized, all extending southwest and west from a general apex in the Folsom area (Figure 10). Based on well-log data and on exposures in the Teichert and other quarries, some channels were over 0.6 km wide and up to 12-meter deep incising deep chasms into a relatively featureless plain (Figure 12).

The inferred oldest channel(s) have no distinct terrace form but are probably embodied by remnants of the Arroyo Seco fluvial gravels capping the drainage divide between the

American and Cosumnes River (Figure 15). These gravels are observed in cuts along Jackson and Grant Line roads near Sloughhouse and along Jackson Road (Highway 16) at the divide before descent into the Cosumnes River drainage (Figure 10). Even older channels are apparent, identified in water well logs (Ford and others, 1974) and formerly visible in the Folsom South canal cuts at and south of the Sunrise Boulevard and Jackson Road intersection (Figure 10). These deposits have no obvious surface expression, at least in the Sacramento area, and thus yet cannot be unequivocally associated with a specific Quaternary channel of the lower American River. Though now dissected (Figure 23), remnants of the Arroyo Seco channel systems still bear very strongly developed soil profiles, typically variants of the Redding series (Figure 13). Based solely on stratigraphic position below the paleo-magnetically dated Fair Oaks Formation, the high-level channel deposits are an estimated 1 ma old.

The "older Fair Oaks channel" is topographically lower and incised within the Arroyo Seco system. The channel is geomorphically expressed upstream by, probably, two nested fill terraces (Figure 23A) and downstream by at least one (Figure 23B). The terrace(s) extend into the subsurface as a distinct channel traced by well logs almost to the Elk Grove area (Shlemon, 1967a; Figures 10 and 12).

The "younger Fair Oaks channel" is even lower topographically. At the surface, the channel is geomorphically expressed as a gravel-filled terrace (Figure 23B), bearing strongly developed soils (e.g., the "Corning" of Cole and others, 1954). Based on water-well log identification, the subsurface gravels incise and cross the older Fair Oaks east of Elk Grove and extend to, and probably under, the modern Cosumnes River floodplain (Figure 12).

At least two Riverbank-age channels are identified on the surface as nested, gravel-filled terraces (Figure 23a). These project into the subsurface where they are traced to, and near, the Sacramento River confluence (Figure 12). Upstream, both channels carried boulders and cobbles. Downstream, channel fill decreased to smaller cobbles and pebbles downstream with increasing admixtures of coarse sand. Although not readily identifiable in water-well logs, the channels may have extended west of the present Sacramento River during epochs of glacial-eustatic lowered base level.

The older Riverbank channel trends southwest from the Sacramento-Mather Airport nearly to Franklin in the southeastern part of Sacramento County (Figures 10 and 12). The younger Riverbank steps north near the town of Florin and is traced beneath the present Sacramento Metropolitan Airport (Figure 12). The younger Riverbank is particularly well exposed in the Teichert quarries on both sides of Jackson Road (Highway 16; Figure 10, stop "1C") and it was here where near-surface overbank sands and silts yielded wood fragments, radiocarbon dated as >about 35 thousand years, and abundant specimens of *Camelops, Mammuthus* and *Equus* (Shlemon and Hansen, 1969).

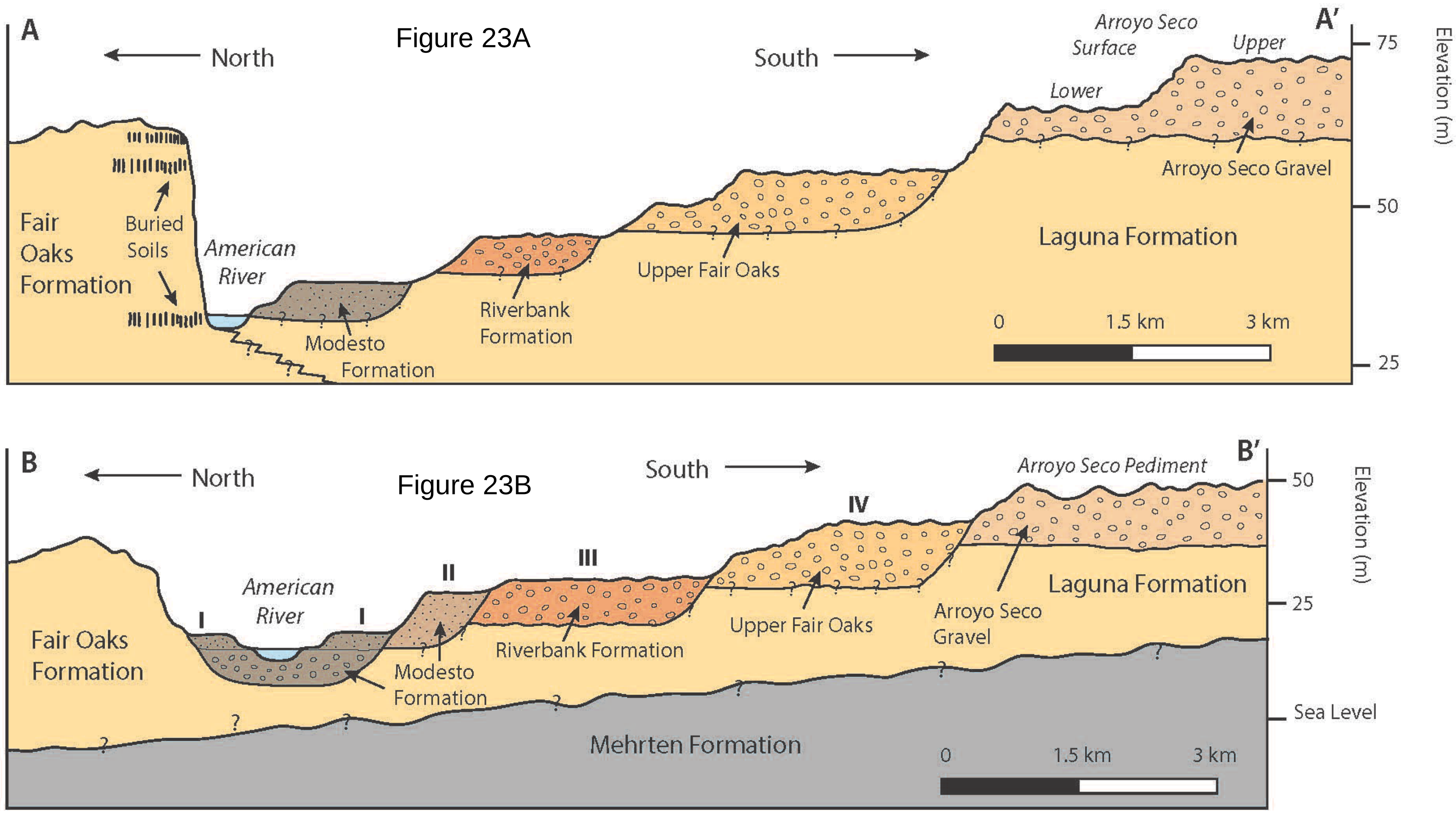


Figure 23. General sections across the American "upstream" at Fair Oaks (Figure 23A) and "downstream" near Bradshaw (Figure 23B) showing representative sediments and fill-terrace surfaces (I through IV) and inferred association of Laguna and Fair Oaks Formations (regional location map, Figure 10). The Fair Oaks buried paleosols (bluff exposures, Figure 11) are shown schematically in Figure 23A; the "jagged line" (Figure 23A) identifies the inferred correlation of basal Fair Oaks and the Laguna Formations. Subdivisions of the Fair Oaks and Riverbank channel are not shown (see text; adapted, from Shlemon, 1967b; courtesy of Yannick Wirtz).

A single Modesto-age channel essentially underlies the modern American River from Folsom and downstream to the Sacramento River confluence (Figure 12). This contrasts with the lower Stanislaus and Tuolumne Rivers where at least two discrete Modesto-age channels have been identified (Marchand and Allwardt, 1981). In the Sacramento area, the Modesto channel mainly underlies the modern American River and is identified as an approximately 8-10 m-thick basal gravel overlain by fining-upward coarse sand and silt. The gravels have been mined extensively upstream, especially between Folsom on the northeast and below Fair Oaks on the southwest (Figure 10). Dredge tailings and old sluice sands abound in this area and, accordingly, possible "upper" and "lower" Modesto-age channels have since been thoroughly mixed and hence are not readily distinguished.

The Modesto-age gravels are also identified in borings of the several bridges that cross the American River (Shlemon, 1967b). In contrast to the older American River channel, the Modesto-age basal gravels are confined to an increasingly narrowing channel downstream at the Sacramento River confluence (Figure 12). This geometry suggests that a Modesto-age American River once extended farther west and has since been "truncated" by later, eastern migration of the Sacramento River.

The Sacramento Area Quaternary: Unresolved Problems

Some 50-yrs ago, abundant well-log, road-cut, engineering and pedogenic data led to a general understanding about the origin of Sacramento area landforms and the age and distribution of Quaternary deposits (Shlemon, 1967a). Nevertheless, questions remain. Four have been awaiting resolution for at least the past half century: (1) Why has the lower American River migrated, or seemingly "jumped" north during the Quaternary; (2) where are the Pleistocene channels of the adjacent Sacramento River; (3) what is, or has been, the impact of neotectonics and regional subsidence; and (4) where is the loess that ostensibly emanated from glacial-age ancestral channels of the lower American River?

Many hypotheses have been informally advanced for the northward "jumps" of the American River during the Pleistocene (Figure 12; Shlemon, 1967b; 1998). These range from the impact of Coriolis force in the northern hemisphere (somewhat tongue in cheek), to eastern migration of the Sacramento River confluence, and to perhaps fault-controlled subsidence. No other Valley-flowing major drainage has a similar migration pattern. Typically, major west-flowing drainages, such as the San Joaquin, Merced, Tuolumne, Stanislaus, and Mokelumne rivers, all repeatedly incised their previous courses during the Quaternary and eventually extended their fans westward into the Central Valley; but not so for the lower American River. An early suggestion (Shlemon, 1967a) was that the 'Younger Fair Oaks channel," trending almost due south near Elk Grove, may have graded to a base level prior to development of the modern Carquinez

Strait and Sacramento River drainage through the Golden Gate. To date, however, no supporting regional evidence has been reported.

A more plausible cause of American River northward “jumps” may relate to differential subsidence along one or more subsurface faults. Many generally northwest-trending faults have been identified along the Valley margins, and some are known or judged to have had Quaternary offsets (Reynolds and Reynolds, 1963; Hart and Rapp, 1975; Bryant, 1982; Bennett, 1987; Harwood and Helley, 1987; Unruh and Moores, 1992; Unruh and others, 1995). Whether such fault-controlled subsidence can explain the apparently unique American River changes in course, awaits the interest, pluck and resources of present and future geomorphologists, Quaternary geologists and hydrologists.

Despite the myriad of bridge borings and near-surface geophysical data, nobody has yet published or at least identified Pleistocene channels of the lower Sacramento River. Such information can help determine rates of geological subsidence and sedimentation, especially for comparison with anthropic impacts. Also, migration of “glacial-age” Sacramento River channels might reasonably explain movement of the lower American River during the Quaternary.

Determining geologic rates of subsidence during the Quaternary is typically based on identifying and dating a specific marker horizon, in this area subsurface channel deposits or buried paleosols. Faults and peat compaction control the location and rates of subsidence in the Delta, where Mokelumne River channels (Figure 9) have proven to be distinct markers (Shlemon, 1971; Shlemon and Begg, 1974; Atwater and others, 1977; Drexler and others, 2009; Verosub and others, 2009). But whether Quaternary faults or other control of differential subsidence occur in the Sacramento area is still unknown.

Almost every large drainage emanating from mid-western continental glaciation or from floodplains downstream from major alpine glaciers has produced major, downwind loess deposits. But where is the loess produced from the major outwash streams in the Central Valley in general and from the American River channels in particular? Were such deposits so sparse that they were ultimately deposited downwind as a thin veneer of eolian sediments and incorporated into the then-surface soils (cumulic profiles) without leaving any stratigraphic evidence? This is strange, for the modern Merced, Tuolumne, and Stanislaus rivers, for example, are all flanked by Holocene dunes on the lee side (south) of their floodplains (Arkley, 1954, 1959; Arkley and others, 1962). But no such, presumably larger, Pleistocene deposits are yet recognized in the Sacramento area, either from geomorphic expression or from soil-profile characteristics. This is yet another enigma awaiting answers from future Quaternary geologists, geomorphologists and pedologists.

IV. PALEONTOLOGY

primary author: Richard Hilton

There have been thousands of fossils found in the greater Sacramento region within many local formations, from rocks ranging in age from the Paleozoic to the Holocene. The oldest fossils come from the Sierra foothills in indurated rock that was added to the area by the activities of plate tectonics. Many of these rocks originated as sediment in a marine environment that is often far from shore and in deep water. Carbonate rocks in this area that are associated with shallow reef environments rarely contain fossils. Almost all of them were obliterated from the heat and pressure that was created when these rocks were added to the edge of North America in plate tectonic settings. Metamorphism has indurated, deformed, and even changed the mineralogy of the rocks. With some it was not quite enough to erase all the fossil evidence, but fossils from the bedrock of the Sierra are still very rare.

Fossils are also found in the thick sedimentary sequences of the Central Valley and eastern folded edges of the topographic Coast Range. New grass comes up in these areas every year and blankets almost everything exposed to the sun, so most of the fossils here are found either in stream beds or when excavations are in progress. Roads and highway construction often expose fossils for a short time, allowing for large collections to be made. Urban and agricultural development encompass much of the Sacramento region. Finding fossils here usually requires excavation activity, and occasionally when a foundation or ditch goes some bit deeper fossils can be recovered.

Fossils are a window into the past. The types of fossils, the rocks they come from, and the age of those rocks, provide us with a glimpse not only of the life forms that existed at the time, but the environment and climate in which they lived. Fossil evidence records the change of life through time giving us hard evidence of life from the past and the pace of evolutionary change.

The greater Sacramento area is here defined for the purposes of paleontological resources as being west of the Gold Rush towns of Grass Valley, Colfax, and Coloma. The south-western border starts at the western edge of the Montezuma Hills and stretches north to border I- 505 and then I-5, to include the fossils of Dunnigan Hills. The northern border reaches to the northern extent of the Sutter Buttes. The southern border is where the Montezuma Hills meet the Sacramento/San Joaquin Delta. Portions, or all, of the following counties lie within the borders: Colusa, El Dorado, Nevada, Placer, Sacramento, Solano, Sutter, Yolo, and Yuba.

Appendix B provides a detailed description of specific fossil locations and summaries of the types and locations of fossils to be found in individual stratigraphic units throughout the area. The depositional environments and corresponding geologic time of the formations in which these fossils occur are described in Appendix A, Plate B, Summary of Geologic History of Sacramento and the Surrounding Area.

V. BEDROCK GEOLOGY

primary authors: Eldridge Moores, Jeff Unruh, and John Wakabayashi

The Central Valley is bounded on the east by the Sierra Nevada mountain range, which rises eastward from low foothills along the western flank of the range at an average slope of about 1.3 degrees to culminate at elevations of about 2500 meters at the latitude of Sacramento (Figure 24). In contrast to the gentle slope of the western Sierra Nevada, the northern Coast Ranges rise abruptly along the western margin of the Central Valley to summit elevations of about 500 meters.

Sacramento gives its name to the Sacramento Valley, the northern arm of the Central Valley. The southern Sacramento Valley at the latitude of Sacramento is near sea level. To the south, elevations in the Delta region where the Sacramento Valley meets the San Joaquin Valley (the southern arm of the Central Valley) are on average below sea level. This is primarily a consequence of oxidation and deflation of peat soils that formed in the Delta wetlands and, beginning in the mid-19th century, were drained for farming. The Sacramento Valley floor rises northward for 225 km to an average elevation of about 150 meters at its northern end, approximately replicating the slope of the mid-Atlantic spreading ridge.

The modern geology of the Sacramento region is the result of an extended history of active plate-margin interactions spanning some 500 million years. Over the course of this period, countless numbers of large earthquakes of different types accommodated tens of thousands of kilometers of movement between the tectonic plates and microplates that eventually came together to form the rocks of northern California as we see them today.

For most of its geologic history, the Sacramento region has lain adjacent to a convergent plate boundary. Oceanic plate subduction, a process still active north of Cape Mendocino in northwestern California, dominated the geologic history of western North America from ca. 500–18 million years ago (Ma) (Figure 25). During this period, several subduction zones and volcanic arcs were active, and ocean basins thousands of kilometers wide were consumed as plate convergence swept together a vast collage of rocks from far-flung locations and progressively added them to the western edge of California. Some of this collage incorporates subduction zones that actually dipped away from, and collided with the continental margin as they arrived (Moores and others, 2002; 2006).

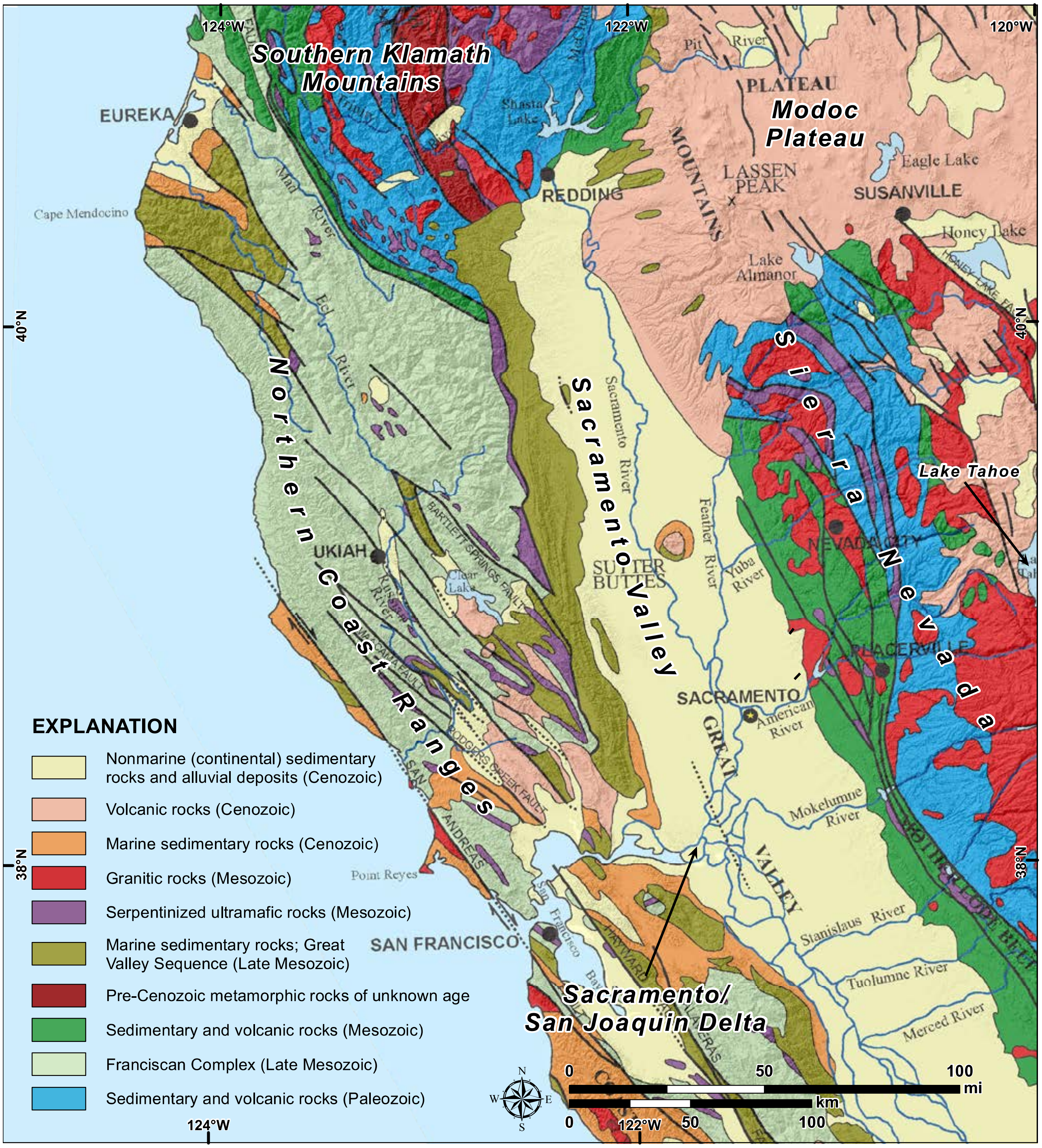


Figure 24. Generalized geologic map of part of northern California, showing the northern Coast Ranges, Sierra Nevada, and Sacramento Valley. Note location of Sacramento. Sacramento-San Joaquin Delta is the confluence of rivers at the east end of Suisun Bay, a branch of the greater San Francisco Bay. After the California Geological Survey.

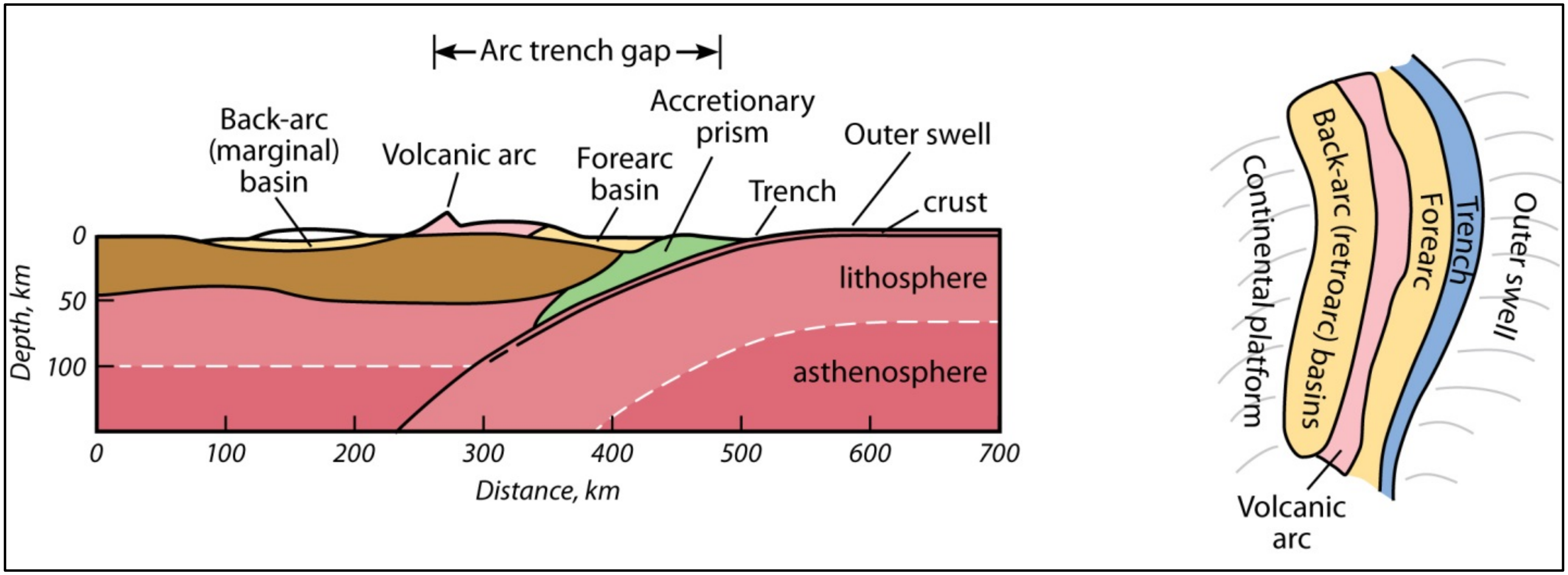


Figure 25. Schematic map and cross section of a typical subduction zone at a continental margin. Modified after Moores and others, 2013, Figure 18B.

Remnants of the most ancient of these subduction zones and collided blocks (typically called terranes) are preserved in the northern Sierra Nevada and beneath the Sacramento Valley. The active plate margin has progressively shifted west through time. The most recent episode of subduction along western California involved the Farallon plate, an oceanic plate that lay east of the Pacific plate and was separated from it by a spreading mid-oceanic ridge. The rocks that were added to the western margin of California during this subduction episode are now preserved in the Coast Ranges. In Neogene time, the down-going Farallon slab triggered arc magmatism on top of what is now the Sierra Nevada (e.g., Hamilton, 1969, Dickinson, 1970), blanketing the Paleozoic-Mesozoic ancestral Sierran terranes and Mesozoic intrusive rocks with a carapace of volcanic rocks similar to the modern Cascades arc in the Pacific Northwest. The depositional environments and corresponding geologic time of these bedrock formations are described in Appendix A, Plate B, Summary of Geologic History of Sacramento and the Surrounding Area.

As the spreading ridge between the Farallon and Pacific plates obliquely contacted the subduction zone off California, the plate boundary changed from convergence to transform motion. For the past approximately 18 million years, subduction has progressively been replaced from south to north by right-lateral strike-slip faulting, gradually extinguishing the volcanic arc to the east. The evolution of the landscape followed the plate tectonic evolution. Prior to the establishment of a transform plate boundary, most of the region west of the present Sierra Nevada foothills lay submerged beneath the ocean. After conversion to a transform plate boundary the Coast Ranges and Central Valley rose above sea level. Where the linkage between the recent tectonic environment and earthquake hazard is obvious, there are subtler connections between the bedrock geology and applied geologic practice, some of which will be discussed in this paper.

The single most important strike-slip structure of the new transform plate boundary is the San Andreas fault, which produced the great 1906 earthquake that destroyed San Francisco. The San Andreas fault and related structures of the modern plate boundary are responsible for generating the largest and most frequent earthquakes at the latitude of Sacramento. The pre-existing complexity of the western California crust due to the earlier tectonic history probably influenced the development and location of many active fault zones (Figure 26-A and 26-B).

Present Day Plate Motions

Modern satellite-based geodesy reveals that right-lateral motion between the Pacific plate and stable North America (generally east of the Rockies) extends across a region at least 750 km wide (Figure 27); approximately from San Francisco to central Nevada. The plate motion is concentrated in two active zones: (1) the San Andreas fault system in the California Coast Ranges, which accommodates about 75 percent (%) of total

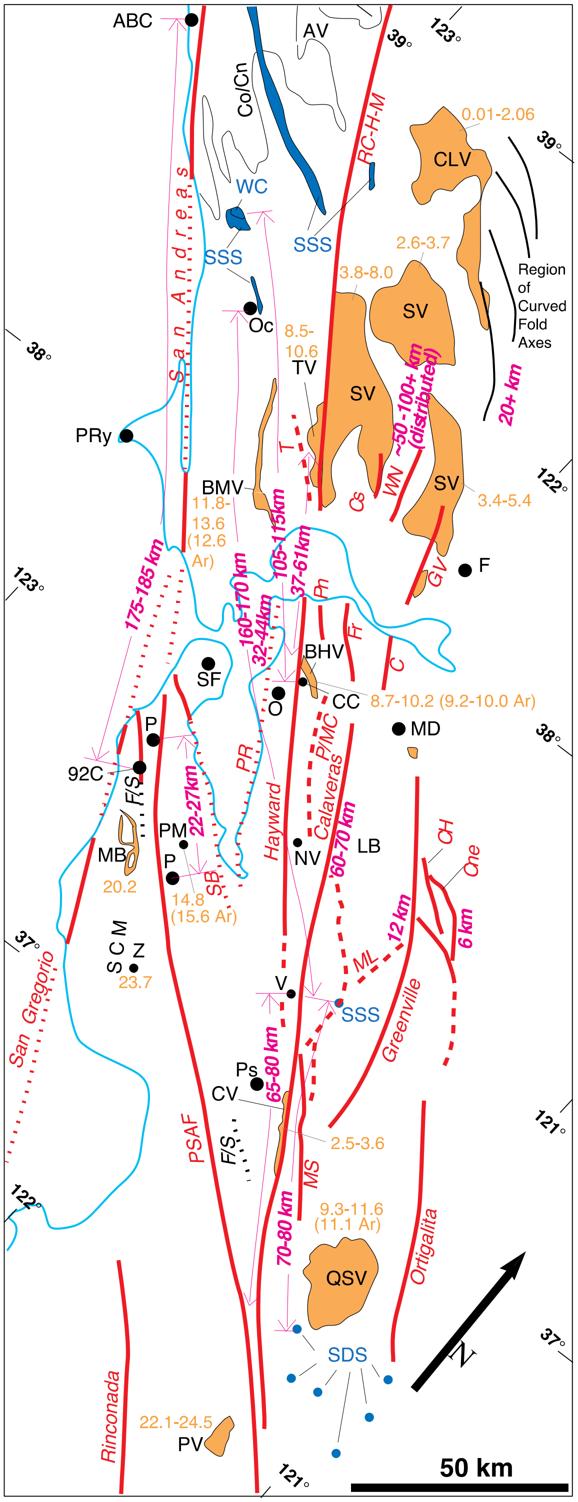


Figure 26-A. Present configuration of the north-central San Andreas fault system. Symbols and fills are as follows: Bold red lines are dextral faults, dashed where uncertain and dotted where concealed beneath sediment or water. Light blue line is the coastline. Orange filled areas are late Cenozoic volcanic rocks coeval with the San Andreas fault system. Dark blue filled areas are major outcrops of the Skaggs Springs schist of the Franciscan Complex. Orange lettering are K/Ar dates of volcanic rocks in millions of years, with 40Ar/39Ar step-heating ages in parentheses. Abbreviations: ABC=Anchor Bay conglomerate; AV=Anderson Valley; BHV=Berkeley Hills volcanics; BMV=Burdell Mtn. volcanics; BS=Bartlett Springs fault; C=Concord fault; CC=Contra Costa Group conglomerate beneath Berkeley Hills volcanics; CH=Corral Hollow fault; CLV=Clear Lake volcanics Cne=Carnegie fault; Co/Cn=Coastal Belt-Central Belt contact of Franciscan Complex; Cs=Carneros fault; CV=Coyote volcanics; ERP=Eagle's Rest Peak; F=Fairfield; Fr=Franklin fault; F/S=Franciscan-Salinian contact; GH=Gold Hill; GHF=Gold Hill fault; GV=Green Valley fault; LB=Livermore Basin; MB=Mindego basalt; MD=Mt. Diablo; ML=Mt. Lewis trend; MS=Madrone Springs fault; N=Neenach volcanics; ND=Navarro discontinuity NV=volcanics north of Niles Canyon; O=Oakland; Oc=Occidental; P=offset Permanente terrane nappes; PM=Page Mill basalt; Pn=Pinole fault; PR=Point Richmond fault; PRy=Point Reyes; Ps=south cutoff, Permanente terrane; PSAF=Peninsula San Andreas fault; PV=Pinnacles volcanics; RC-H-M= Rodgers Creek-Healdsburg-Maacama fault; SB=San Bruno fault; SCM=Santa Cruz mountains; SDS=Schist klippen, south Diablo Range; SF=San Francisco; SSS=Skaggs Springs schist; SV=Sonoma volcanics; T=Tolay fault; TV=Tolay volcanics; V=volcanics along Mt. Hamilton road; WC=blueschists at Ward Creek; WN=West Napa fault; Z=Zayante Creek basalt; 92C=Conglomerate along State Highway 92.

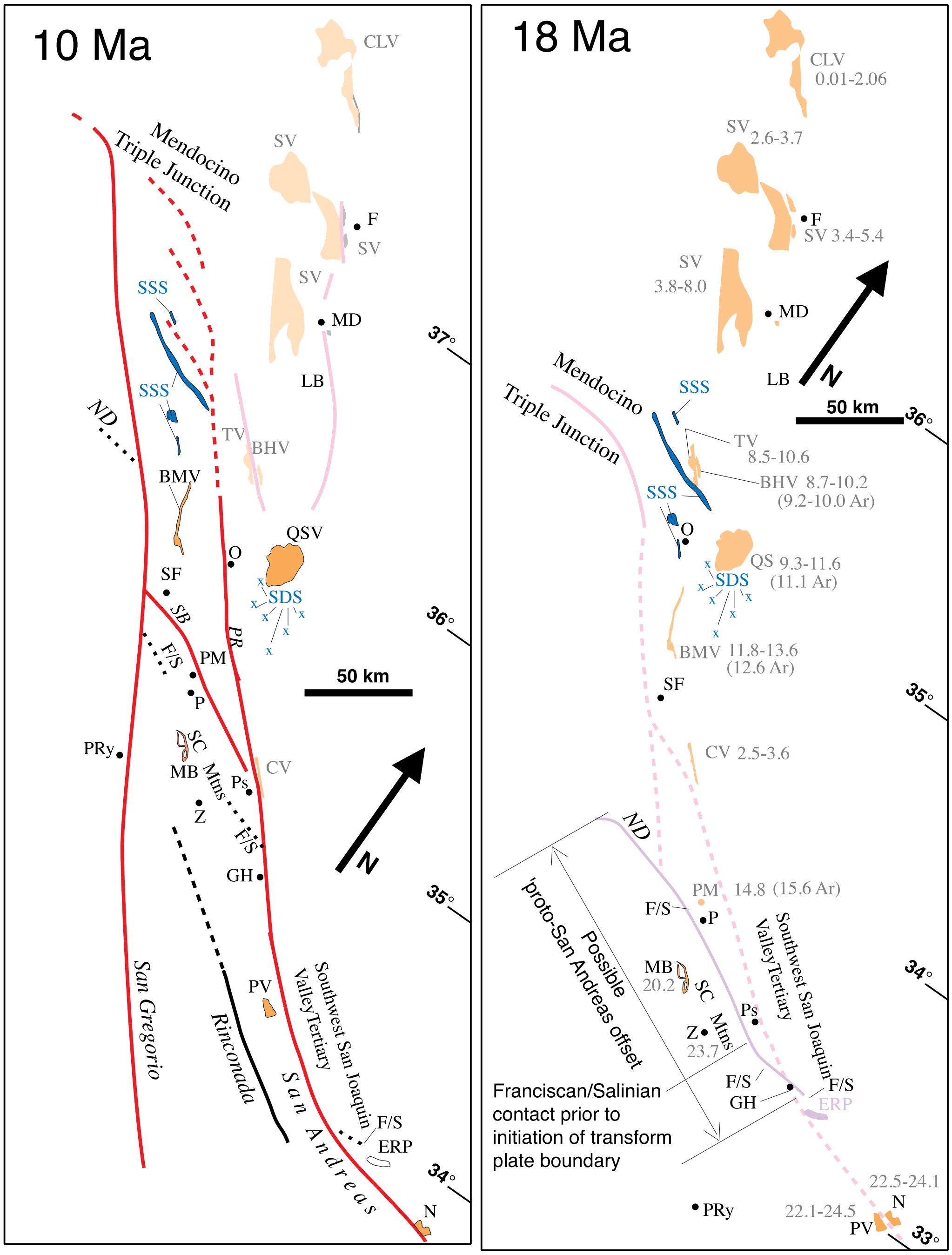


Figure 26-B. Reconstruction of the northern San Andreas fault system at 10 and 18 Ma. Abbreviations and symbols the same as Figure 26-A except: Grayed letters and lighter orange areas indicate that specific volcanic units were not present at that time; this is the future position of these volcanics for reference purposes. Pink faults correspond to faults that may not have existed at the time of the reconstruction. Note that the latitude on the eastern margin of these reconstructions also shifts southward because of dextral displacement east of the Sierra Nevada. Figures 26-A and 26-B adapted from Wakabayashi (1999).

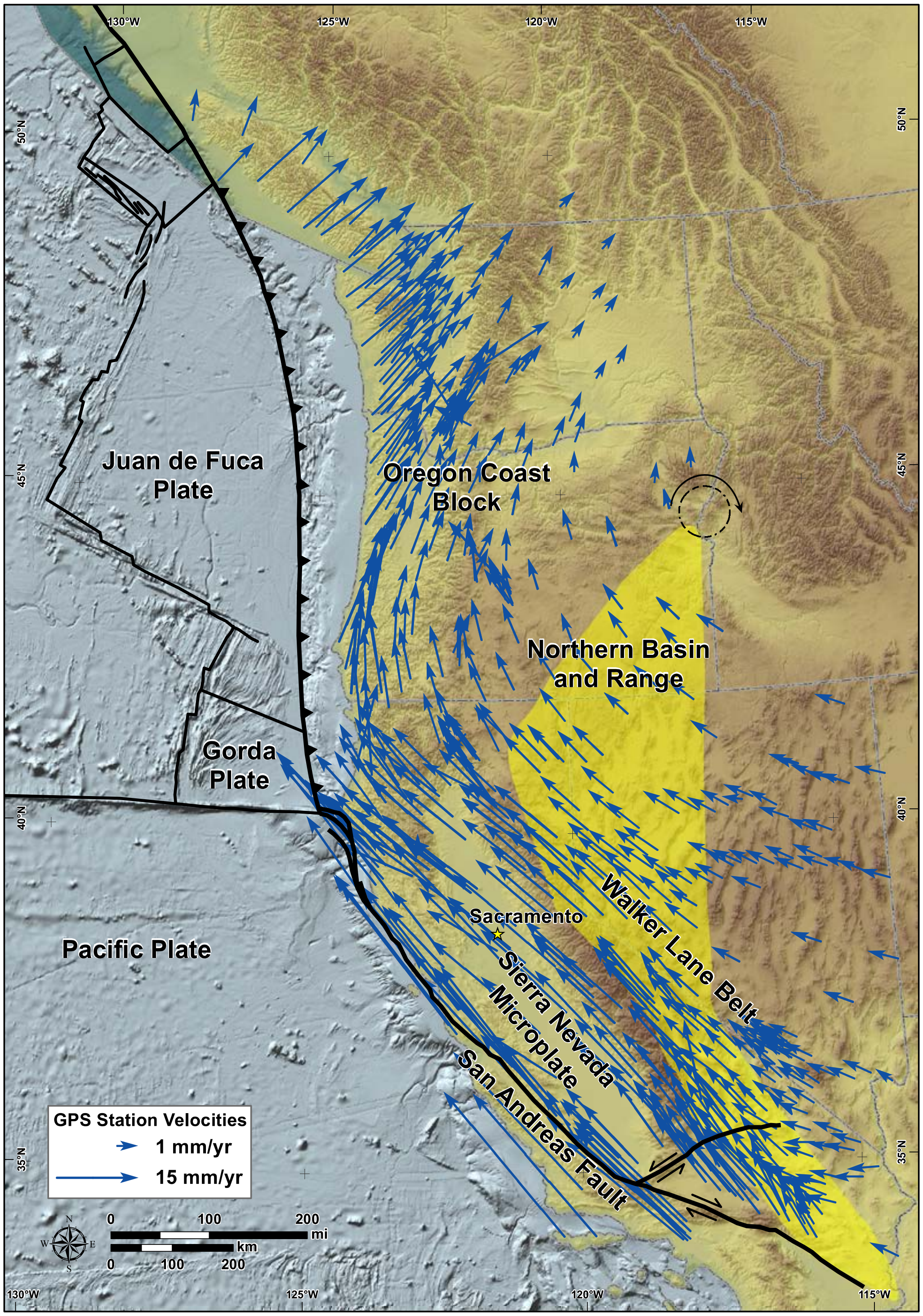


Figure 27. Global Positioning System (GPS) velocity field for the western United States. Arrows show the motion of individual GPS stations relative to stable North America (arrow lengths are scaled to velocities). The yellow region east of the Sierran microplate (including the Walker Lane Belt and northern Basin and Range) represents the extent of distributed northwest-directed motion east of the Pacific plate (Unruh and Humphrey, 2017).

Pacific-North American plate motion; and (2) a broad zone east of the Sierra Nevada that includes right-lateral faulting in the Walker Lane and mixed strike-slip and normal faults of the Basin and Range province (Unruh and Humphrey, 2017; Figure 4). About 25-% of total Pacific-North American motion is accommodated by distributed deformation east of the Sierra Nevada (Argus and Gordon, 1991; 2001). Between these branches of the plate boundary is a comparatively unfaulted block known as the Sierra Nevada microplate that includes the Central Valley and the Sierra Nevada. Sacramento is situated near the center of this microplate and relatively distant from major active faults.

The transfer of part of the Pacific-North American plate motion from the San Andreas and related faults to regions east of the Sierra Nevada occurred progressively during the past 12 million years (Atwater and Stock, 1998; McQuarrie and Wernicke, 2005), and primarily during opening of the Gulf of California and transfer of Baja California to the Pacific plate at about 6 Ma (Oskin and others, 2001). This process effectively separated central and western California from stable North America. The Sierran microplate currently moves about 12-14 mm/yr to the northwest with respect to North America as an independent block (Argus and Gordon, 1991; 2001). Most earthquake activity in California is concentrated along the eastern and western margins of the Sierran microplate, although very low rates of background seismicity are recorded within the block (Wong and Savage, 1983), and Mesozoic faults within the western Sierra Nevada foothills locally show evidence for reactivation as strike-slip and normal faults during the past several million years. These reactivated faults are the closest sources of moderate to large earthquakes to Sacramento, but large earthquakes on the more distant faults on the west and east margins, respectively, of the Sierran microplate also can produce felt effects and strong shaking at long distances.

Due to the west-directed extension in the eastern part of the Basin and Range (Figure 27), the Sierran microplate moves slightly more toward the west relative to stable North America than the Pacific plate, resulting in a component of oblique convergence or “transpression” along the Pacific-Sierran plate boundary (Figure 27). The transpressional deformation in western California is accommodated by mixed strike-slip and thrust faulting in the Coast Ranges and along the western margin of the Central Valley, and probably has been the driving mechanism for uplift of the Coast Ranges during the past 6-8 million years (Argus and Gordon, 2001). At the latitude of Sacramento, the long-term average uplift rate of the Coast Ranges over the past several million years is on the order of tenths of millimeters per year.

Studies of geomorphic and stratigraphic relationships suggest that the Sierra Nevada east of Sacramento has increased 1-2 km in elevation, which is associated with a westward tilting of the western flank of the range, within the last ca. 5 million years (Unruh, 1991; Wakabayashi and Sawyer, 2001; Wakabayashi, 2013a; and references therein). In contrast, many studies from 1996 and onward have concluded that the

Sierra Nevada has decreased in elevation or stayed at approximately the same elevation over about the last 30 million years, based primarily on low-temperature thermochronologic (e.g., House and others, 1997; 1998) and stable isotopic data and stable isotopic data (Poage and Chamberlain, 2002; Mulch and others. 2006; Cassel and others 2012), as well as a reinterpretation of regional stratigraphic and geomorphic relations (e.g., Gabet, 2014). These alternative models suggest that the northern Sierra, at least, may have been a high-standing range since early Tertiary, and possibly abutted an orogenic plateau to the east that once occupied much of what is now the Basin and Range during late Cretaceous and early Tertiary time (Dilek and others, 1988). In this model, the high gravitational potential energy of the orogenic plateau caused it to collapse into the extensional Basin and Range province during the Oligocene and Miocene, and leaving the Sierra Nevada and its gently sloping western slope as a relic of the high early Tertiary Cordilleran topography. The models advocating late Cenozoic uplift of the Sierra Nevada also support the existence of high Cordilleran elevations in the early Tertiary but postulate the region of the modern Sierra Nevada was part of the lower western flank of this high region (e.g., Wakabayashi, 2013a).

Geodetic studies of the southern Sierra Nevada show that it is undergoing active uplift at a rate of about 1 mm/yr, but this may be a primary consequence of elastic rebound from anthropogenic groundwater withdrawal in the Central Valley, rather than tectonic uplift process (Amos and others, 2014; Hammond and others 2016). Longer-term (hundreds of thousands of years and more) geomorphic-stratigraphic relationships indicate that tectonic uplift has slowed or stopped in the Sierra Nevada exclusive of the northernmost part of the range in the Feather River drainage (Stock and others, 2005; Wakabayashi, 2013a).

Bedrock Geology

The bedrock geology of the Sacramento region is the history of the convergent tectonics of California through collision and accretion of exotic rocks to the edge of western North America. In the following sections, we summarize this history by describing and interpreting the rocks that comprise the modern Sierra Nevada, the Sacramento Valley and the Coast Ranges.

Sierra Nevada Pre-Batholithic Rocks

In the northern Sierra Nevada, rocks that predate the Mesozoic intrusions of granitic rocks were originally referred to as the “Subjacent Series” (Turner, 1896), and are grouped into four generally recognized belts. From west to east, these belts include the following (Figures 28 and 29):

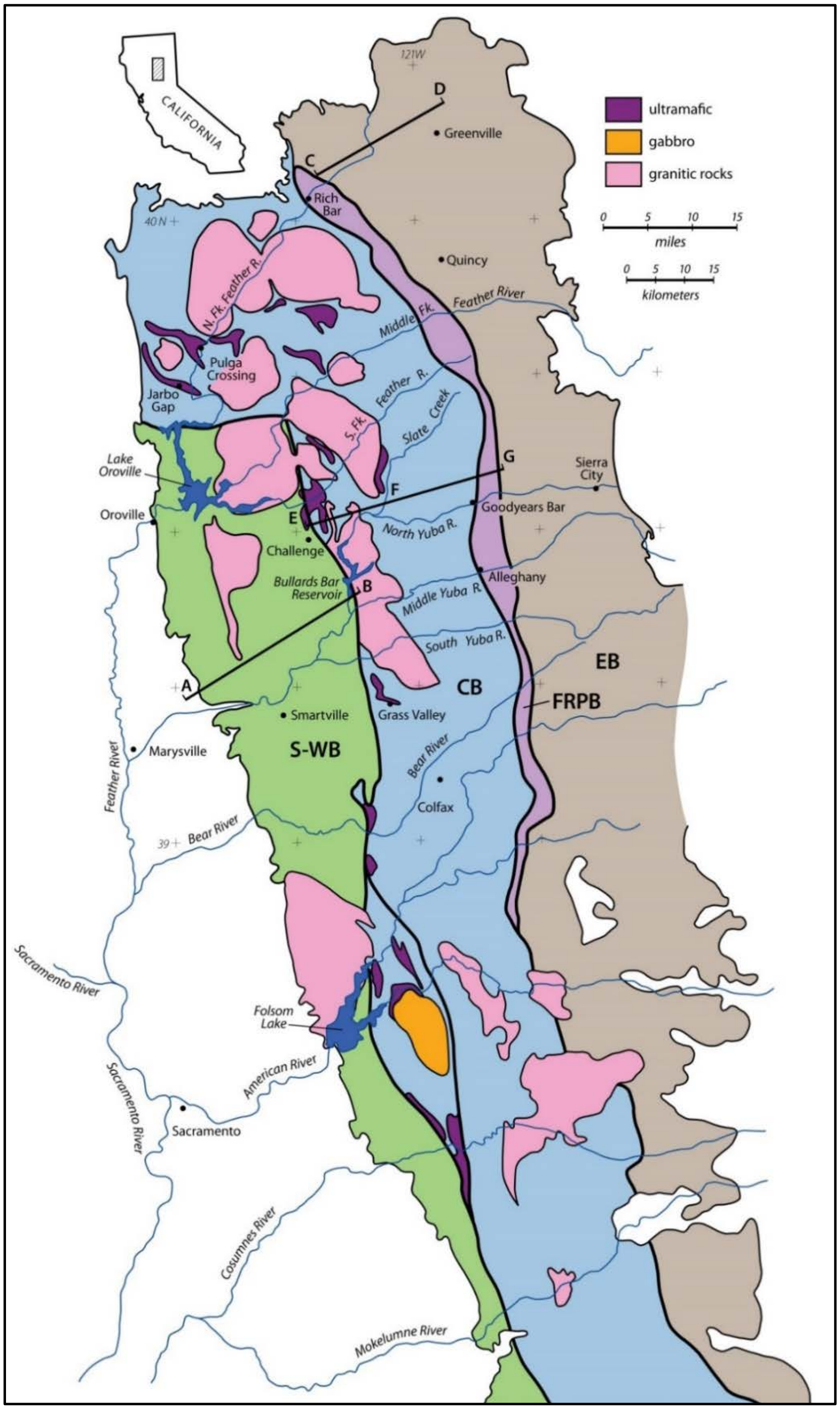


Figure 28. Generalized geologic map of the northern Sierra Nevada, showing four principal tectonic belts. Symbols: CB Central Belt, EB Eastern Belt, FRPB Feather River Peridotite belt, S-WB: Smartville-Western Belt. Redrawn from California Geological Survey, Geological Map of California.

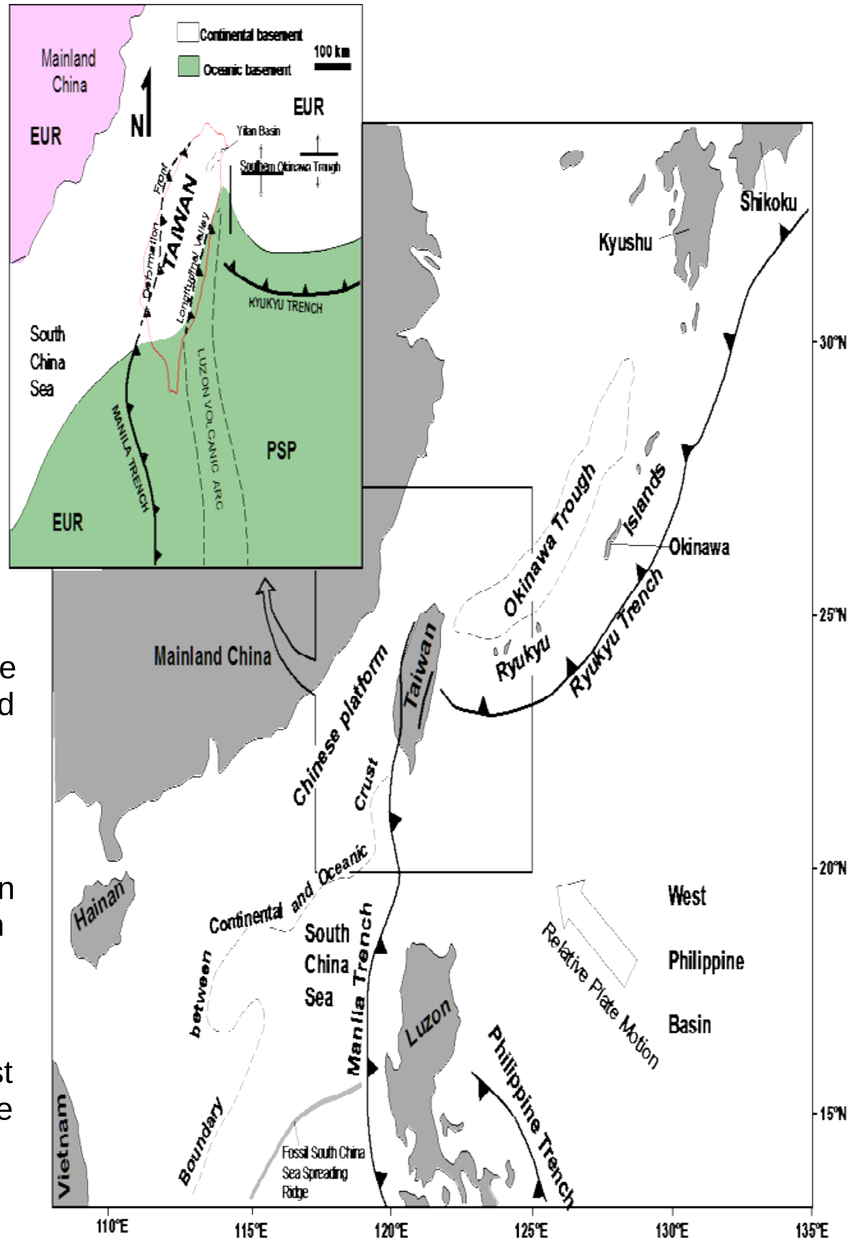


Figure 29. Plate tectonic context of Taiwan, one of the world's best examples of a subduction zone that dips away from a continent. In this case it is the subduction zone that reaches the sea floor at the Manila Trench; it dips eastward away from the Asian mainland. Plate acronyms: EUR=Eurasian Plate, PSP=Philippine Sea Plate. The southern part of the Manila Trench subducts oceanic crust of the South China Sea that formed at a now-dormant spreading center (the fossil spreading ridge shown on the figure). To the north, the continental margin enters the subduction zone and arrests subduction (collision) resulting in the shortening and uplift that forms the island of Taiwan, including uplifting the highest mountains in Asia east of the Himalaya (highest peak: Yushan: 3,952 m/12,966 ft., compared with Japan's Mt. Fuji: 3,776 m/12,388 ft.). In addition to the partial subduction of the continental margin, the volcanic arc associated with the Manila Trench, the Luzon Volcanic Arc, is also thrust onto land as the eastern part of Taiwan, east of the Longitudinal Valley (see inset). To the north the thickened crust from the earlier collision has already begun to rift with the extension focused in the Okinawa Trough. The southernmost extension of the Okinawa Trough has already begun to rift Taiwan itself; the trough comes onto the island as the Yilan Basin (see inset). Redrawn from Lallemand (2001).

- The Western Jurassic Belt extends some 200 km southward from the northern end of the Sierra Nevada (e.g., Schweickert, 1981; Beard and Day, 1987) and consists of andesitic volcanic rocks (similar in composition to Mount Shasta), shallow and related intrusive ("plutonic") rocks, and sedimentary rocks. North of Sacramento, this belt is represented by the Smartville complex, part of a 185–160 m.y.o oceanic-island arc that formed above an intra-oceanic subduction zone that was separate from the ancestral subduction zone along the California margin. The Smartville oceanic-island arc developed on older (200–220 m.y.o.) oceanic crust now represented in the northern Sierra Nevada by exposures of serpentinite, gabbro, and various dikes (Saleeby and others, 1989; Bickford and Day, 2001; Dilek and Moores, 1992, Dilek and others, 1991).

- The Central Belt consists of the 225–175 m.y.o. Jarbo Gap and Slate Creek ophiolites, which are represented by serpentinite, gabbro, diabase dikes, basaltic breccia, and volcanic rocks. The youngest Central Belt units correlate with the oceanic crust beneath the Smartville Complex. A Mesozoic chert-argillite unit (a dark, hard rock made up of firmly cemented, poorly bedded mud rocks), with disordered and discontinuous beds (a so-called "chaotic" unit), contains blocks of Carboniferous-Permian (360–250 m.y.o.) limestone that possibly formed on top of extinct submarine volcanoes (seamounts). In some places, the chert-argillite unit has been overthrust by ophiolitic rocks, but is also intruded by rocks of the ophiolite.

  The thrust contact between the ophiolitic rocks (Slate Creek ophiolite and related rocks) and the chert-argillite unit is intruded by a 165 m.y.o. pluton (Edelman and Sharp, 1989). This relationship indicates that the thrusting of the Slate Creek ophiolite over the chert-argillite occurred before 165 Ma (middle Jurassic). Ophiolitic remnants are common within and along the western margin of the Central Belt but not in its eastern part. This fact implies that the chaotic chert-argillite unit and included blocks of the Central Belt formed in a west-dipping subduction zone (Moores, 1970; Day, Moores, and Tuminas, 1984). Some workers have proposed that the Central Belt consists of two subduction complexes, the western part of which was associated with west-dipping subduction and the eastern part with east-dipping subduction (e.g., Moores, 1970; Schweickert and Cowan, 1975).

- The Feather River complex and associated Devils Gate ophiolite comprise a 6- to 10-km-wide zone that extends southward for more than 100 km from the north end of the Sierra Nevada, and contains basalt, diabase, and gabbro (now metamorphosed to amphibole-containing rocks, "amphibolites"), and ultramafic rocks (fresh peridotites and serpentinites). Magmatic rocks exhibit two ages: an earlier Devonian age (416–359 Ma), and a later Carboniferous age (ca. 300–320 Ma (Saleeby and others, 1989). Metamorphic rocks in the Feather River Belt range in age from 240 to 390 m.y.o. (Devonian-Triassic; see Hacker and Peacock, 1990). Coarsely crystalline metamorphic rocks containing garnet and amphibole, including blue amphiboles, border the ultramafic rocks on the west and appear to dip eastward beneath them. This relationship suggests that east-dipping subduction occurred beneath the Feather River complex (e.g., Hacker and Peacock, 1990). If this is correct, then it may coincide with the east-dipping subduction zone along the eastern margin of the Central Belt proposed by Moores (1970) and Schweickert and Cowan (1975).

- The Eastern Belt is a thick sequence of metamorphosed sedimentary and volcanic rocks with a few granitic intrusive bodies. It ranges in age from early Paleozoic to Jurassic (542–146 Ma). The lowermost unit is the lower Paleozoic Shoo Fly complex, containing fault-bounded slices of quartz-rich turbidites, mafic volcanics, a fault zone containing slivers of serpentinite, and a mélange containing blocks of chert and Ordovician (488–444 Ma) limestone (Hannah and Moores, 1986). These rocks have been deformed more than once. Early east-northeast–trending "isoclinal" folds (folds where both sides are parallel to each other, indicating that the originally horizontal layers have been bent about 180º) are present in these rocks (Varga and Moores, 1981). The largest serpentinite exposure is only a few hundred meters thick in outcrop, but gravity and magnetic data indicate that it becomes several kilometers thick at depth (Griscom in Blake and others, 1989).

  Turbidites and mélange may represent a lower Paleozoic subduction complex. The serpentinite may represent remnants of an ophiolite that was emplaced over the Shoo Fly rocks in mid-late Devonian time (398–360 Ma; Varga and Moores, 1981). Discordantly (or "unconformably") overlying the Shoo Fly rocks are three volcanic complexes: (1) the Devonian-Mississippian (416–318 Ma) units of the Sierra Buttes, Taylor, Elwell, Keddie, and Peale Formations, interpreted as the remnants of a chain of oceanic volcanoes formed above an intra-oceanic subduction zone; (2) the Permian–Triassic (299–200 Ma) units of the Robinson, Reeve, Arlington, and Cedar Formations also may represent an oceanic volcanic sequence similarly formed above one or more oceanic subduction zone(s); and (3) the Jurassic (200–146 Ma) Mount Jura and Milton sequences that may represent remnants of a volcanic chain that formed above a subduction zone near to, or along, the continental margin (e.g., Hannah and Moores, 1986). These units all feature andesitic volcanic rocks (which are more silica-rich than a basalt), submarine lavas with pillow forms, and fragmental volcanic rocks derived from volcanic explosions. For much of the length of their exposure, the rocks are primarily older in the west and younger in the east ("east-facing"). In addition, they have been tilted more than 90° to the east from their original horizontal orientation, suggesting that the forces producing the tilting came from the west.

> Near the northern end of the Sierra Nevada, however, the rocks are highly folded and deformed by east-directed thrust faults.
>
> Along the western margin of the Eastern Belt, an enigmatic sequence of Devonian (?)-Jurassic (416–146 Ma) rocks crop out that show affinities with rocks in the Klamath Mountains (Harwood, 1992; Jayko, 1988, 1990; Hannah and Moores, 1986).

Three major fault blocks are present in the Eastern Belt that are separated from each other by east-directed (west-dipping) thrust faults (Figure 30). The degree of deformation in Eastern Belt rocks increases in complexity from east to west. In the east, post–Shoo Fly rocks are generally non-foliated (that is, their metamorphic minerals are not formed parallel to each other) and little metamorphosed. To the west, however, post–Shoo Fly rocks become progressively more intensely folded as one approaches the contact with the Feather River peridotite. In addition, the rocks become more metamorphosed and the minerals thus formed are aligned, producing a preferential plane of parting in the rocks, or “cleavage.” The cleavage dips westward in the east, but gradually becomes east-dipping as one approaches the Feather River peridotite. This relationship may reflect a change in subduction dip or in polarity of subduction (e.g. Roeder, 1973; Figure 30).

The four major belts of rocks described above record an “archipelago” style of orogeny along and adjacent to the Paleozoic and early Mesozoic western California margin. An archipelago is a group of islands in a sea or an ocean. Modern examples include the Aleutians, the Greater Antilles, the Philippines, Indonesia, or the Marianas (e.g., Hall, 1996, Sigloch and Mihalynuk, 2017), all of which are chains of islands that involve active subduction of one oceanic plate beneath another. As subduction proceeds along a continental margin, it would not be surprising if one or more oceanic archipelagoes were swept against the continent and the remnants preserved there as subduction proceeded.

The geology of the remnants of separate islands is different from the rocks adjoining them. It is common to call such regions with different geology a “terrane.” A terrane is a region with a specific geologic history, which is separated by faults from surrounding regions with their own distinct geologic history. The Sierran terranes began their existence in different locations and migrated separately, coming together at various times, and then becoming attached to the western margin of the continent at different times. This complex history can be read in a study of the geology of the individual and combined terranes. A **suture**, that is, a site of a disappeared ocean, characteristically marks the boundary between terranes (e.g., Moores, 1981).

The tectonic development of the northern Sierra is complex, involving a number of fossil subduction zones. Some of these zones dipped to the east, some to the west, and one

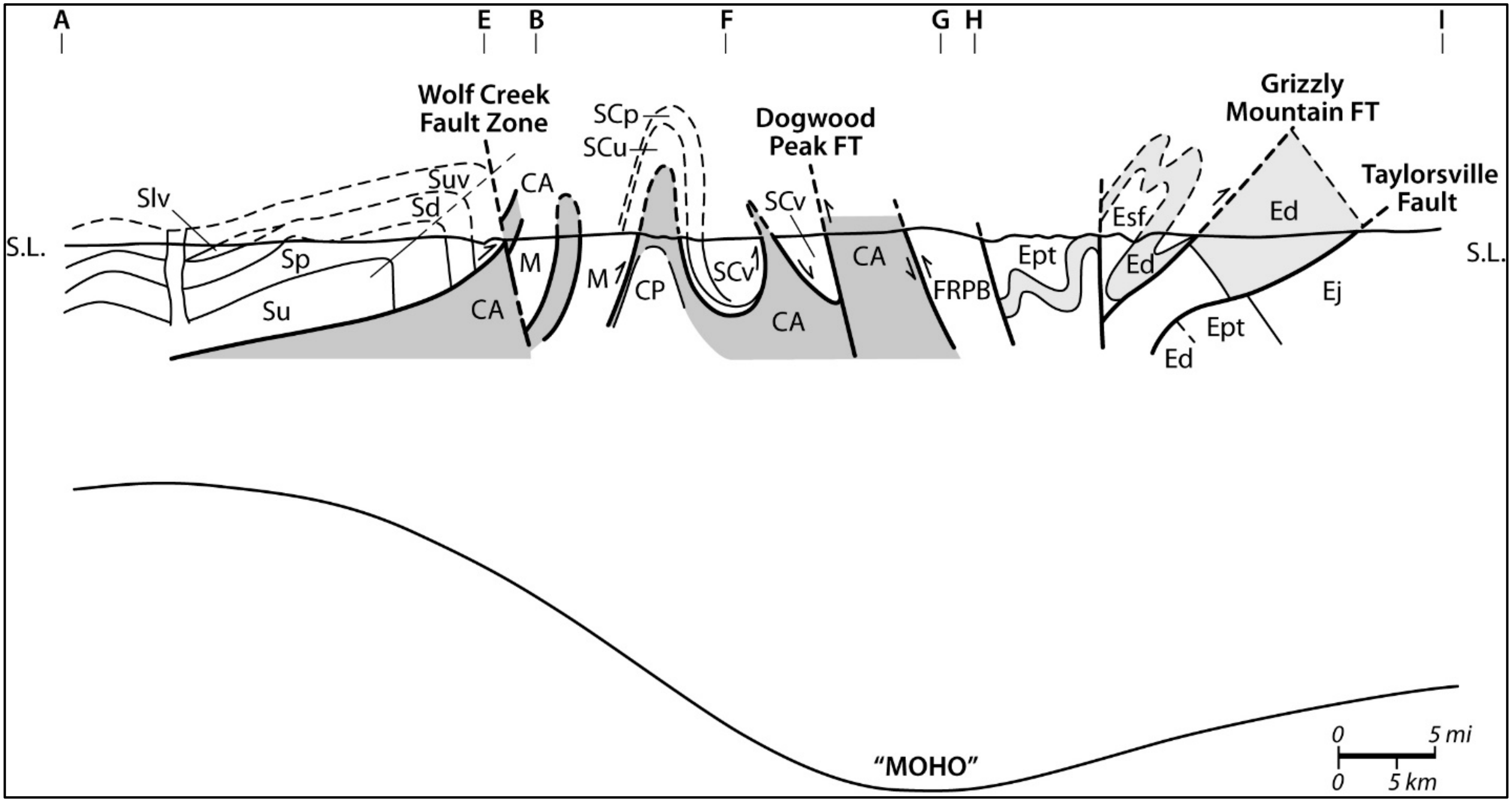


Figure 30. Generalized cross section of northern Sierra Nevada. Symbols: CA Calaveras Complex, CP Cascade Pluton, Ed Eastern Belt Devonian-Carboniferous rocks, Ept Eastern Belt Permian, Triassic, Jurassic rocks, Esf Lower Paleozoic Shoo Fly rocks. M undifferentiated mafic rocks, SCp Slate Creek plutonic rocks, SCu Slate Creek ultramafic rocks, SCv Slate Creek volcanic rocks, Sd Smartville diabase dike rocks, Slv Smartville lower volcanic unit of mostly pillow lavas, Sp Smartville plutonic rocks, Suv Smartville upper volcanic unit. Letters on top: Ends of cross sections in Day and others, 1985.

possibly to the northwest (in present coordinates). The dipping of subduction zones to the west is perhaps difficult to understand by workers who are typically exposed to tectonic cross sections showing unvarying eastward subduction (probably incorrectly) against the North American western margin. There is no reason, however, to assume that subduction zones dipping away from the continental margin began there. They likely migrated from an oceanic position towards the continental margin and collided there. Tectonic models involving collisions of the North American continental margin with subduction zones dipping away from it are fairly common in the literature, starting over 40-years ago (Moores, 1970), and continuing to the present (e.g. Hildebrand, 2009, 2014; Johnston, S. T., 2001, 2008; Moores, 2009; Moores and others, 2006; Sigloch and Mihalynuk, 2013, 2017).

The plate tectonic situation in present-day Taiwan is an outstanding example of the process of collision of a continent with a seaward-dipping subduction zone, succeeded by one dipping under the continent (Lallemand and others, 2001). In southern Taiwan, the eastern margin of Asia (China) is colliding with an E-dipping subduction zone associated with the West Luzon arc. In northern Taiwan, the NW dipping (beneath the continent) Ryuku subduction zone is propagating southward at the expense of the E-dipping subduction zone (west Luzon; see Figure 29)

Moores (1998) proposed a model for an “archipelago” style of orogenic development, involving convergence and collision of already complexly deformed oceanic island arcs or collections of terranes (“super terranes”) during Mesozoic and Cenozoic time along the western margins of North America and northern South America. Figures 31 A-E show generalized tectonic sketch maps from 180 to 40 Ma, starting in the early Jurassic period, just prior to one collision in the mid-Jurassic period (ca. 185–160 Ma). An oceanic island arc represented by the Jarbo Gap, Smartville–Slate Creek ophiolites, and similar rocks now in Mexico (the Guerrero terrane) and in the Caribbean (Cuba, Hispaniola, Puerto Rico) and in northern South America (Venezuelan Coast Ranges, NW Colombia) was separated from the North American margin by a plate that was consumed on both its margins. This plate may be the oceanic “Mescalera plate” of Dickinson and Lawton (2001). This plate has essentially disappeared as a result of subduction, leaving only a few small pieces that were scraped off and added to the overlying crust. This model implies the idea that western North America in general, and the basement rocks of the northern Sierra Nevada in particular, is oceanic in origin and became attached to the continent at various times in the past. The model also implies that many of the major Caribbean islands originated in the Pacific Ocean. Sigloch and Mihalynuk (2017) vividly portray a comparison between western North American tectonic history and ongoing processes in the Indonesia-Australia region.

We interpret the thrust faults at the base of the northern Sierra ophiolite complexes to represent major sutures (former positions of subduction zones and/or disappeared

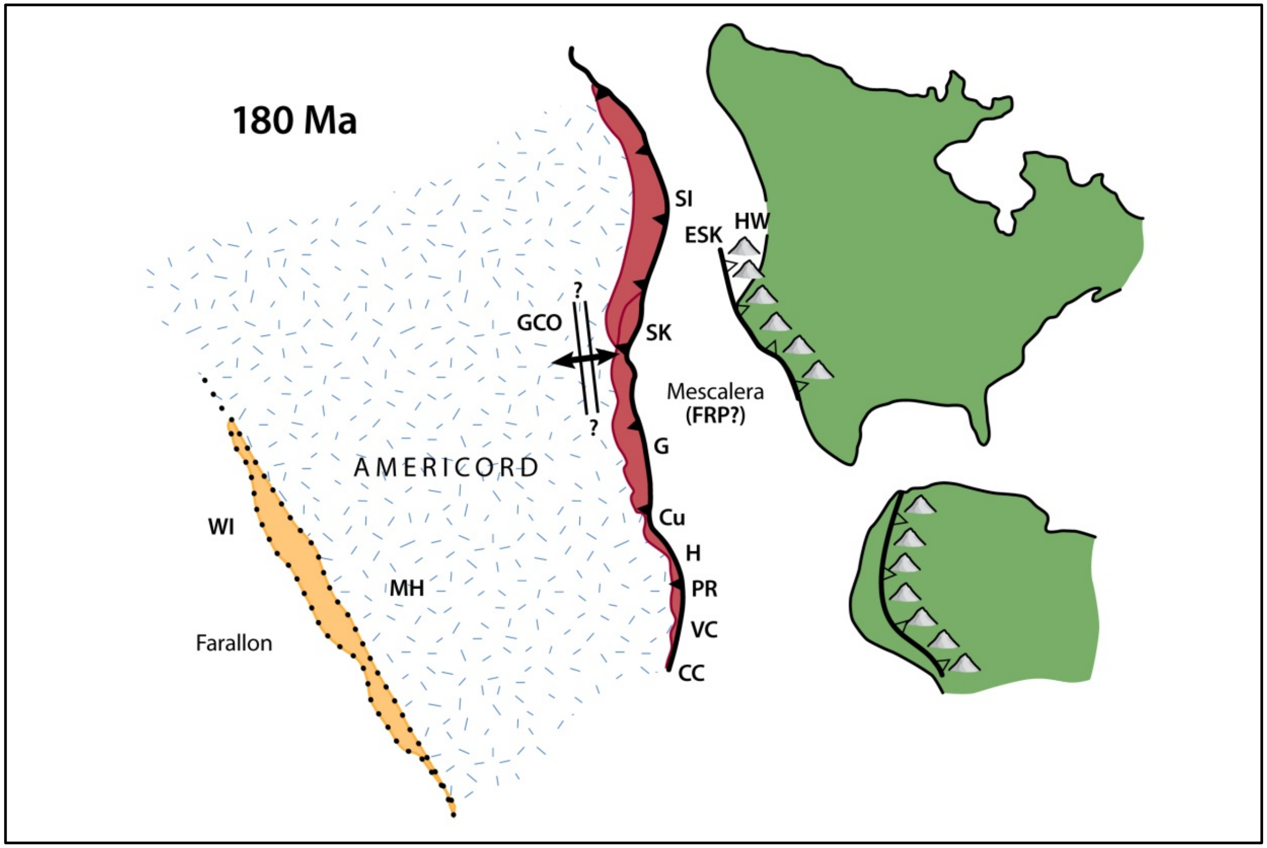


Figure 31-A. Generalized tectonic maps of Western North America and South America showing positions of off-shore archipelagoes at 180Ma, Symbols: C Calera, CC Cordillera Central, Colombia, CH Chortis block, Central America, Cu Cuba, ESK Eastern Sierra =Klamath region, FRP Feather River Peridotite Belt, G Guerrero terrane, Mexico, GCO Great Valley-Coast Range ophiolite. H Hispaniola, HW Humboldt-Walker basin, LA Laytonville limestone, PE Permanente Terrane. PR Puerto Rico, SI Stikine Intermontane superterrane, SK Sierra Nevada western and central belts and related rocks in Klamath Mountains, V Venezuelan Basin, VC Venezuelan Coast Ranges, Y Yucatan Basin. WI Wrangell-Insular superterrane. Toothed line: subduction zone showing direction of dip; Dashed line: terrane boundary with uncertain nature, either transform fault or subduction zone. After Moores and others, 2006.

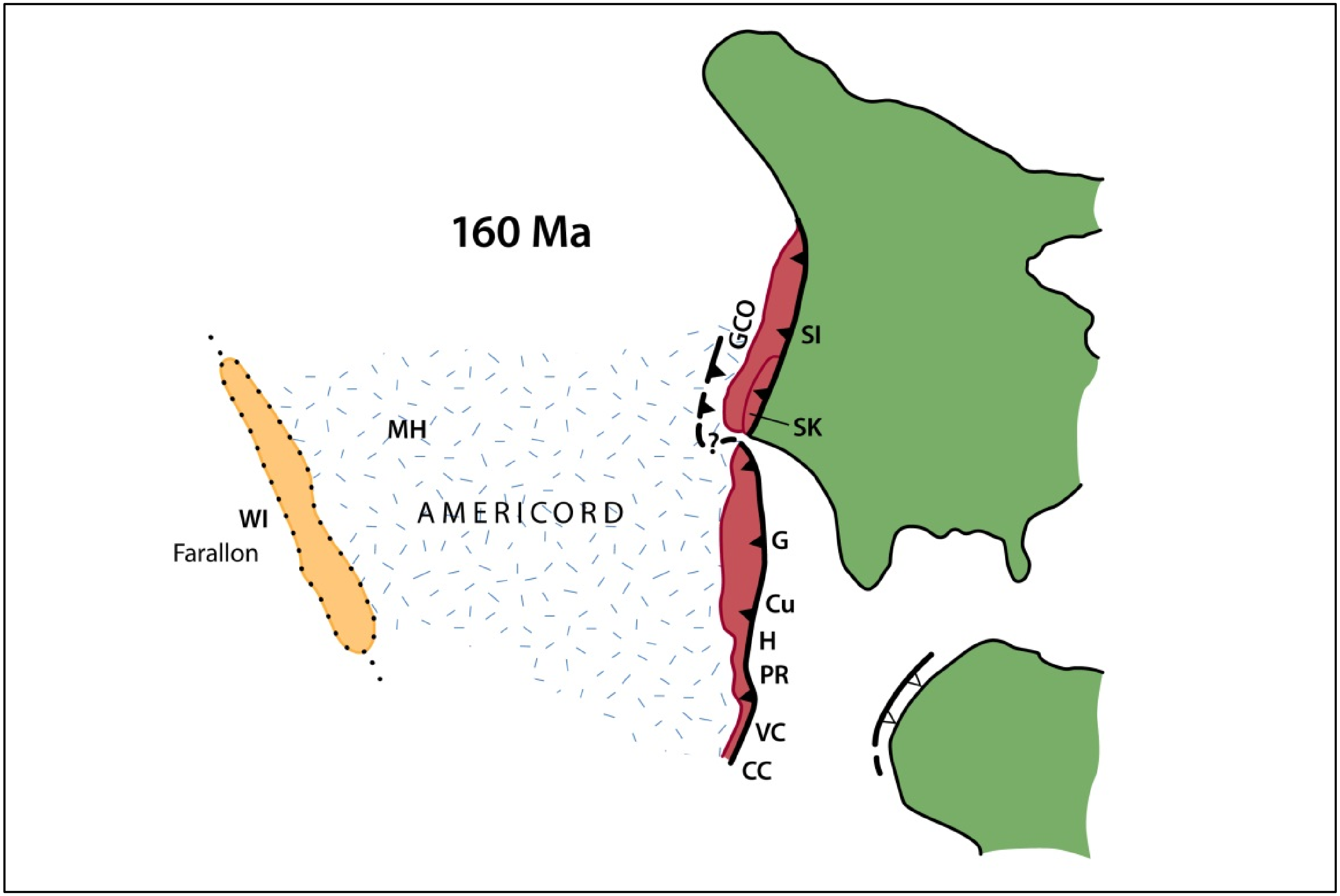


Figure 31-B. Generalized tectonic maps of Western North America and South America showing positions of off-shore archipelagoes at 160Ma. Symbols as in Figure 31-A. After Moores and others, 2006.

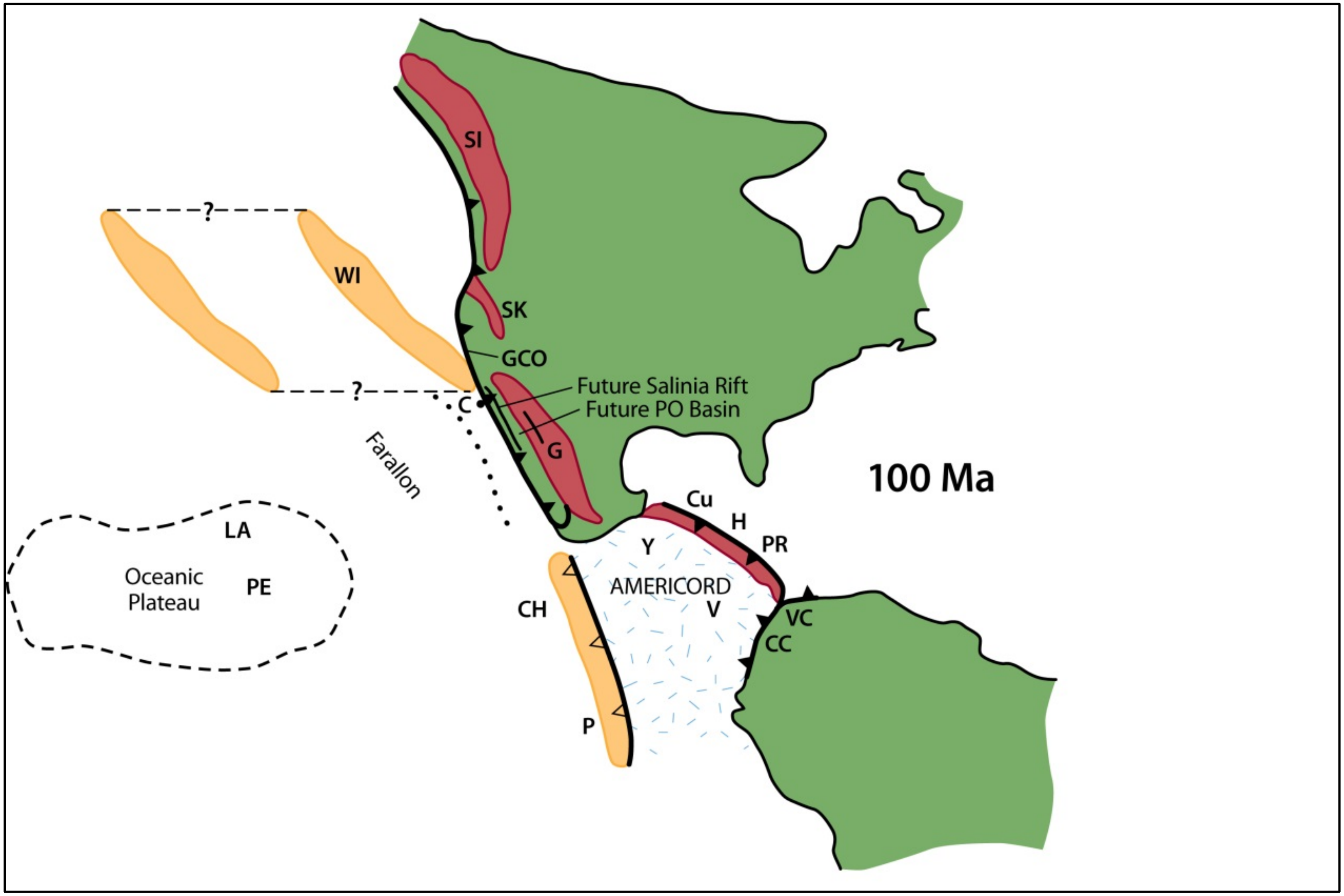


Figure 31-C. Generalized tectonic maps of Western North America and South America showing positions of off-shore archipelagoes at 100Ma. Symbols as in Figure 31-A. After Moores and others, 2006.

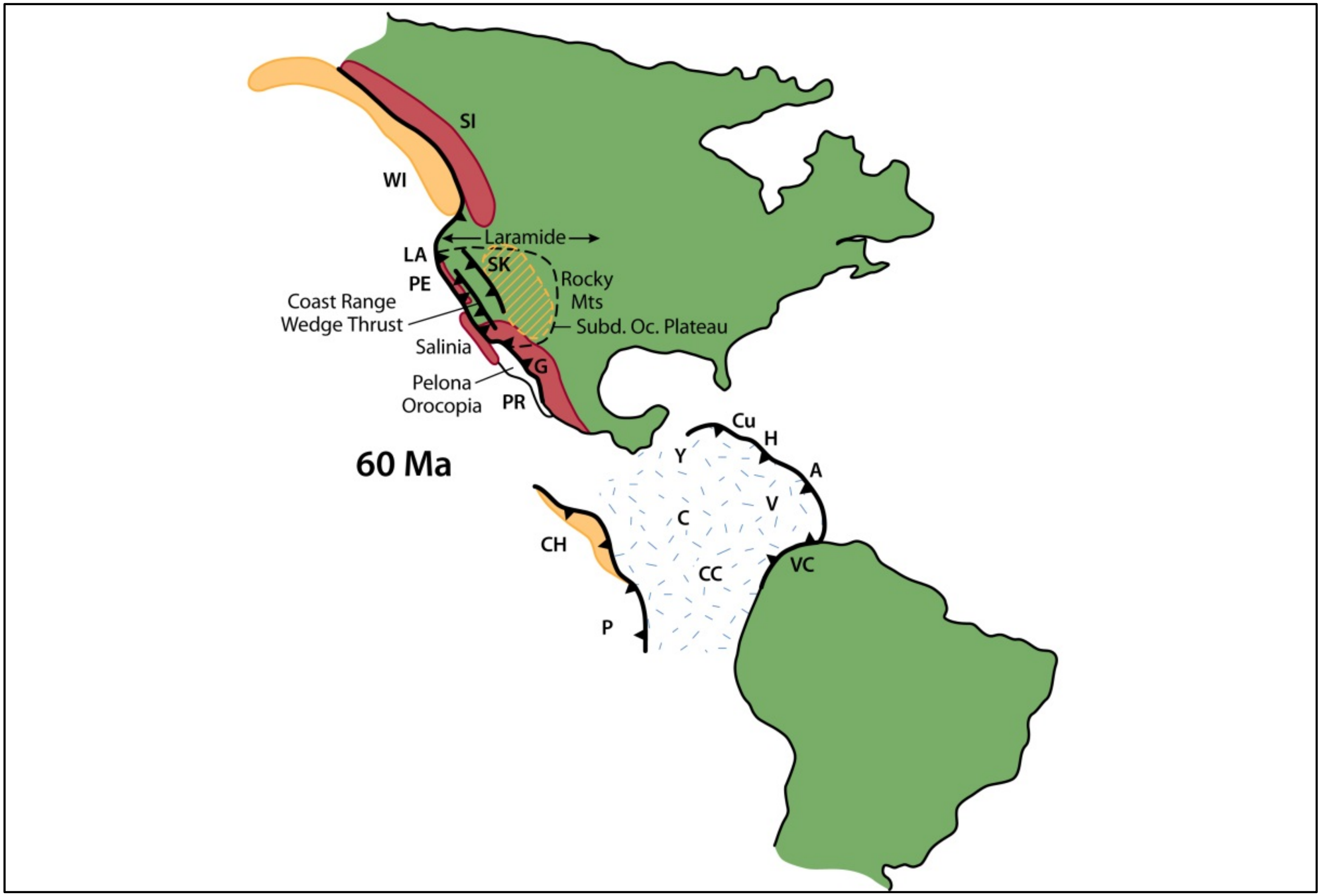


Figure 31-D. Generalized tectonic maps of Western North America and South America showing positions of off-shore archipelagoes at 60Ma. Symbols as in Figure 31-A. After Moores and others, 2006.

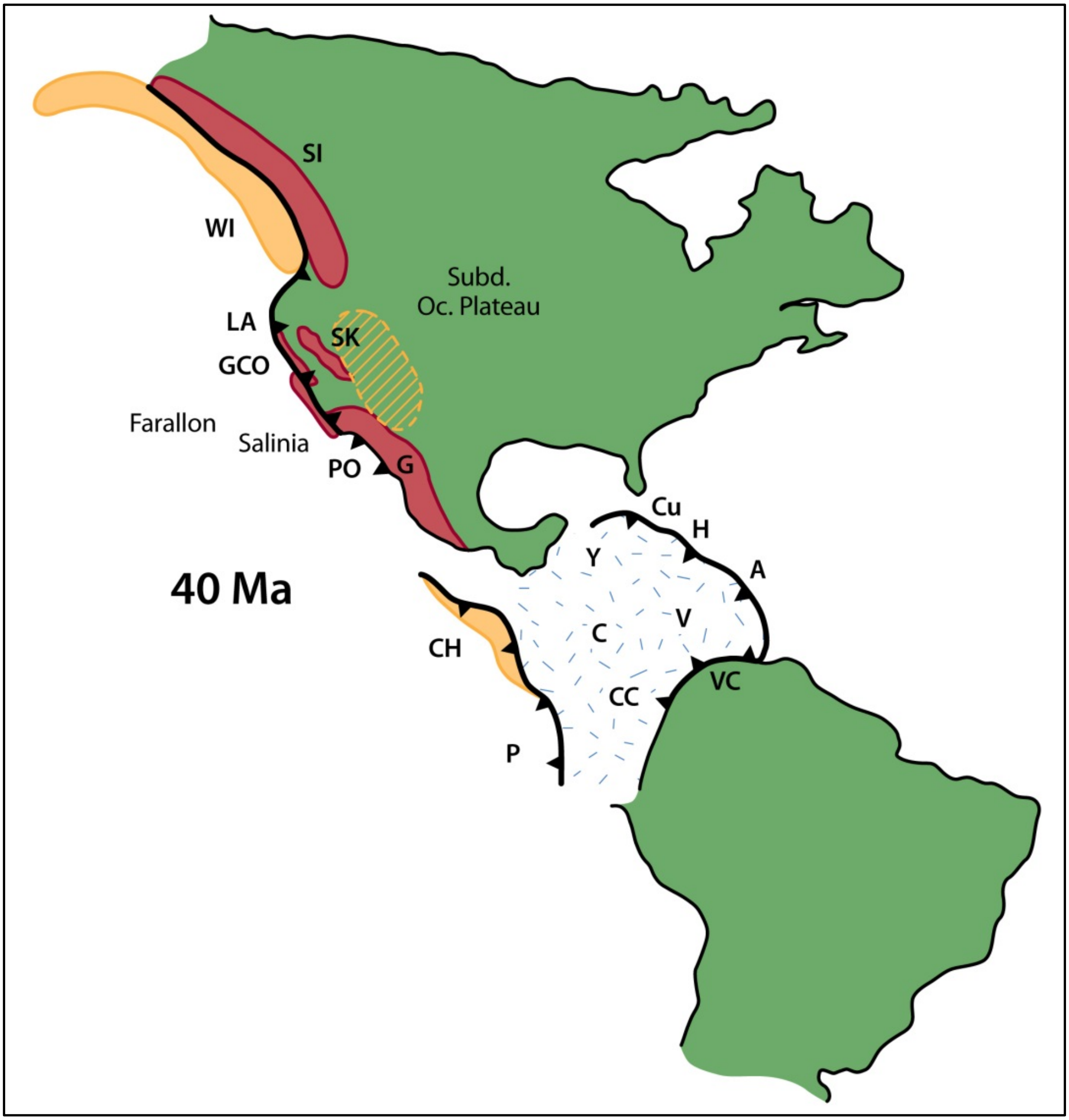


Figure 31-E. Generalized tectonic maps of Western North America and South America showing positions of off-shore archipelagoes at 40Ma. Symbols as in Figure 31-A. After Moores and others, 2006.

oceans; Moores, 1981). The subduction zone(s) dipped west beneath the colliding arc, as shown in Figure 30. In this manner, the Central Belt rocks were likely scraped off a subducting plate. The fault west of and structurally beneath the Feather River peridotite, the largest body of ultramafic rocks in the Sierra Nevada, represents a major east-dipping suture, and is illustrated in Figure 30 as the east-dipping subduction zone beneath the Central Belt.

Batholithic and Superjacent Rocks of the Sierra Nevada

Following the collision of the Western belt rocks with the ancestral California margin during the Jurassic period, the convergent plate boundary jumped west, and an east-dipping subduction zone was established in the ancestral offshore region now occupied by the California Coast Ranges. Arc volcanism triggered by fluids liberated from the down-going oceanic slab was accompanied by pervasive magmatic intrusions into the accreted Sierran terranes east of the trench. These intrusions subsequently cooled to form what is now known as the Sierra Nevada granitic batholith, the rocks that inspired John Muir to call the Sierra Nevada "the Range of Light". On Figure 28, the batholith is shown modified from Godfrey and Dilek (2000). The Rocklin pluton is an example of the Sierran batholithic rocks in the Sacramento region. During the early Cretaceous, fluids heated by the intrusions, mobilized metals, including gold, from the rocks of the accreted terranes, migrated upward along fault zones, resulting in the crystallization of gold-bearing quartz veins (Böhlke, 1999 and references therein). These gold deposits are known as the Mother Lode and, along with gold found at the base of Eocene paleochannel deposits (see below) drove the Gold Rush to California beginning in 1849.

During the time that the Sierran batholithic rocks were being intruded as magma into the collage of accreted terranes, the Sacramento region was a part of a forearc basin, an ocean basin that lay between the volcanic arc to the east and the new subduction zone to the west. The modern Central Valley has inherited at least some of its elongate shape and present location from the ancestral forearc basin. Rivers draining west from the volcanic arc initially deposited volcanic-rich sediments in the forearc basin as a series of submarine alluvial fans. Analysis of the composition of sandstone rocks from the forearc basin, now uplifted and exposed along the western margin of the Sacramento Valley, reveals a progressive transition from volcanic sources to intrusive sources (Dickinson and Rich, 1972), suggesting that the rivers eventually incised through the volcanic rocks into the rocks of the underlying—and by then solid—granitic batholith. The Upper Jurassic and Cretaceous sandstones and shales of the ancestral forearc basin are known collectively as the Great Valley Group, and they comprise one of the best-exposed and studied sequences of forearc basin deposits in the world. In the Sierra foothill region exposures are of only the late Cretaceous part of the Great Valley Group, whereas more extensive deposits are present on the western margin of the Central Valley, as will be discussed later.

By early Cenozoic era, the rivers draining eastward into the Great Valley forearc basin eventually cut down approximately to the current erosional level of the pre-batholithic and batholithic rocks exposed on the upland interfluves of the western Sierran slope. Deposits of these rivers, as well as younger volcanic rocks, are locally preserved in the Sierran foothills and have been referred to as the “Superjacent Series” (Turner, 1896; Bateman and Wahrhaftig, 1966; Durrell, 1966). The oldest Superjacent rocks in the Sacramento region are the Eocene Auriferous (gold-bearing) gravels, which were extensively mined by hydraulic methods in the Sierra Nevada from 1860 to 1884. Debris from this mining filled the streams coming off the Sierra, especially the Yuba and Sacramento Rivers. Hydraulic mining ceased after the "Sawyer Decision,", a decision by Judge Lorenzo Sawyer of the 9th Circuit Court that debris from mining could not exit the miners' property. This decision has been called California's first environmental act. For a more extensive explanation of the effect of mining on California water law, please refer to “Chapter VII – Natural Resources [How Mining Practices Shaped California Water Law]” of this paper.

The Auriferous gravels interfinger westward with nearshore and shallow marine deposits of the Ione Formation, which are locally preserved in the western Sierran foothills north and east of Sacramento, near the towns of Lincoln and Ione. The Ione Formation can be traced westward in the subsurface of the Sacramento Valley, and its deep-water stratigraphic equivalents are uplifted and exposed along the eastern flank of the Coast Ranges.

Younger Superjacent Series rocks of the Sierra Nevada that overlie the Ione Formation are primarily Oligocene and Miocene-Pliocene volcanic rocks (Slemmons, 1966) most of which were associated with Cenozoic plate convergence and arc magmatism. The much less voluminous Oligocene rocks consist of rhyolite ashflow tuffs that erupted from vents far east of the present Sierra Nevada and flowed down some of the same channels filled by the Eocene gravels (Henry and others, 2012). The much more extensive Miocene-Pliocene rocks include the Mehrten Formation, which was largely sourced from volcanic centers near the modern Sierran crest (Slemmons, 1966; Busby and others, 2008). These deposits are a mix of river gravels sometimes referred to as “intervolcanic gravels” to distinguish them from the Eocene gravels (e.g., Bateman and Wahrhaftig, 1966), and volcanic flows and “lahars”, i.e., mudflows of volcanic sediments that were capable of traveling great distances under the force of gravity. These volcanic deposits filled existing river channels on the western Sierran slopes so that older granitic and metamorphic high points only rose locally to be above the tops of these younger deposits (Wakabayashi and Sawyer, 2001). Following deposition of the volcanic deposits, fluvial erosion of adjacent rocks that formed the original canyon walls left them capping ridges, commonly forming “inverted topography”, i.e., elongate mesas with relatively flat tops where the valleys once were (Bateman and Wahrhaftig, 1966).

An example of one of these superjacent volcanic mesas is Boulder Ridge, about 40 km northeast of Sacramento near the town of Penryn (Figure 32).

Coast Ranges

The Great Valley Group strata and stratigraphic equivalents of the overlying Superjacent Series rocks are dramatically exposed as an uplifted, east-tilted section along the western margin of the Central Valley west of Sacramento (Figure 33).

These rocks represent the common elements of the otherwise very different geologic histories of the Sierra Nevada and the Coast Ranges. The Great Valley Group rocks overlie mafic and ultramafic rocks of the so-called Coast Range ophiolite (CRO; green) and its continuation beneath the Central Valley, the Great Valley ophiolite (GVO; green). West of and structurally below the Coast Range ophiolite is the Franciscan Complex, the product of subduction beneath North America.

Franciscan Complex

The Franciscan Complex is regarded as the world's best example of a subduction complex, which represent rocks that are physically transferred from the subducting plate to the upper plate (e.g., Wakabayashi, 2015). The Franciscan Complex formed during the most recent subduction episode in California, a chapter in geologic history that spanned the period from ca.140 Ma to 20 Ma at the latitude of Sacramento. Franciscan rock units consist of trench sediments shed from the continent (now sandstones and shales), as well as smaller amounts of far-traveled pieces that represent the top of the subducted oceanic crust, such as cherts, limestones, and basalts (Hamilton, 1969, Blake and others, 1988; Wakabayashi, 2015). The main rock units of the Franciscan are bounded by faulted contacts that have a relatively low-angle geometry when viewed at scales of tens of kilometers, but these contacts are deformed by tight isoclinal and commonly overturned folds at scales of kilometers to hundreds of meters so that the dips of most Franciscan contacts are steep (Wakabayashi, 2015). The belt-like geometry of exposures of many Franciscan units, including parallel exposures of the same geologic subunits seen on all regional scale geologic maps, illustrates this general structural architecture.

The Franciscan rocks were scraped off from the eastward-subducting Farallon plate beneath oceanic crust and mantle now exposed as the Coast Range ophiolite. The off-scraping or 'accretion' process, which is the transferring of material from the subducting to the upper plate, that formed the Franciscan Complex units resulted in much more deformation and metamorphism than that present in the structurally overlying Coast Range ophiolite and Great Valley Group rocks. The Franciscan is one of the type

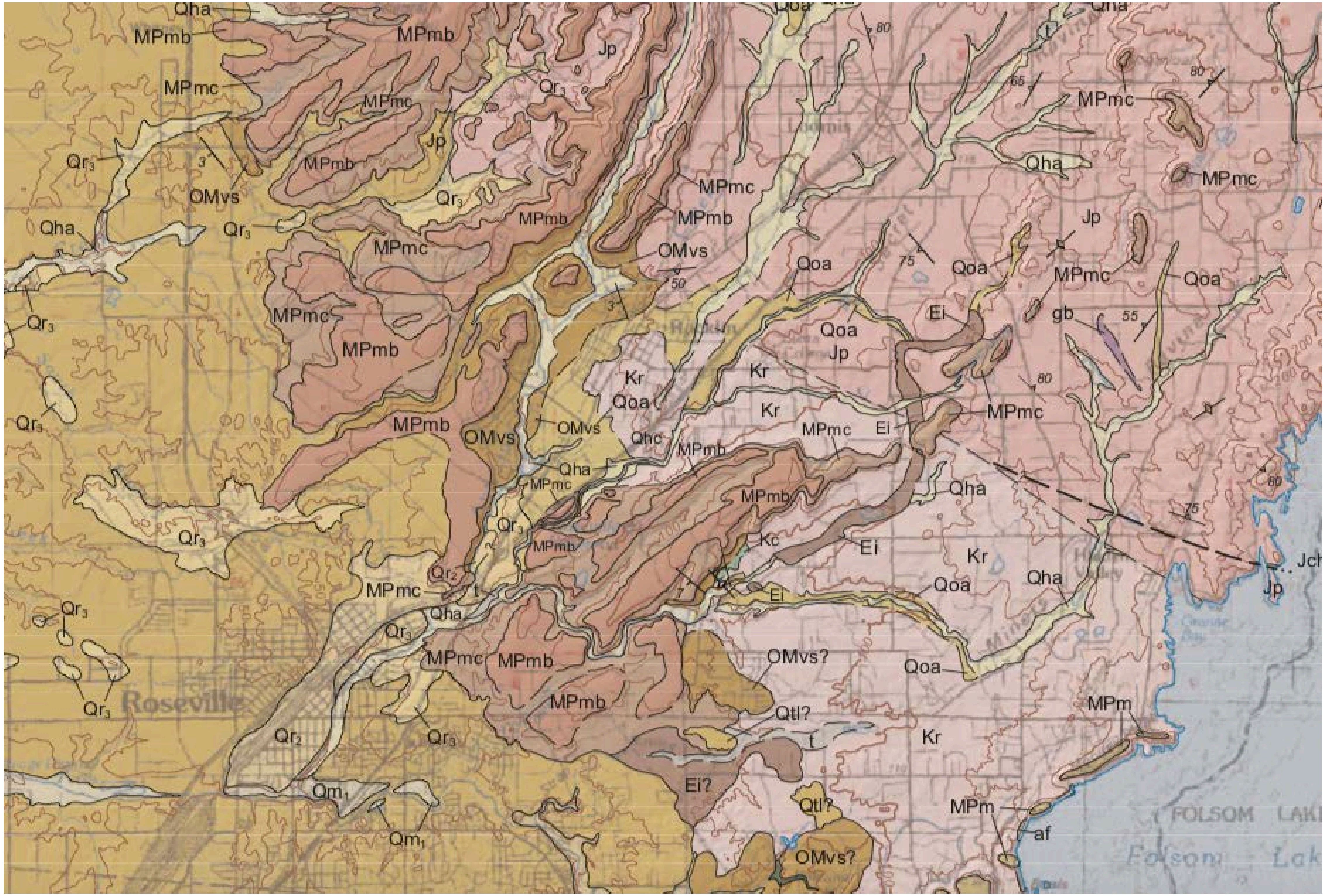


Figure 32. Part of the California Geological Survey 30' x 60' 1:100,000 Sacramento Map Sheet (Gutierrez, 2011), showing various geological units in the eastern Sacramento Valley and western Sierra foothills near Folsom Lake. Light yellow-yellow-brown Qxx: Quaternary sediments; MPm: Mio-Pliocene Mehrten formation andesitic volcanogenic sediments and tuff breccia derived from Sierra crest; OMvs Oligo-Miocene Valley Springs rhyolite and associated sediments; Ei Ione formation; Kr: Rocklin pluton; Jp Penryn pluton; [note: the entire map sheet and detailed legend are available online from the California Geologic Survey (Gutier

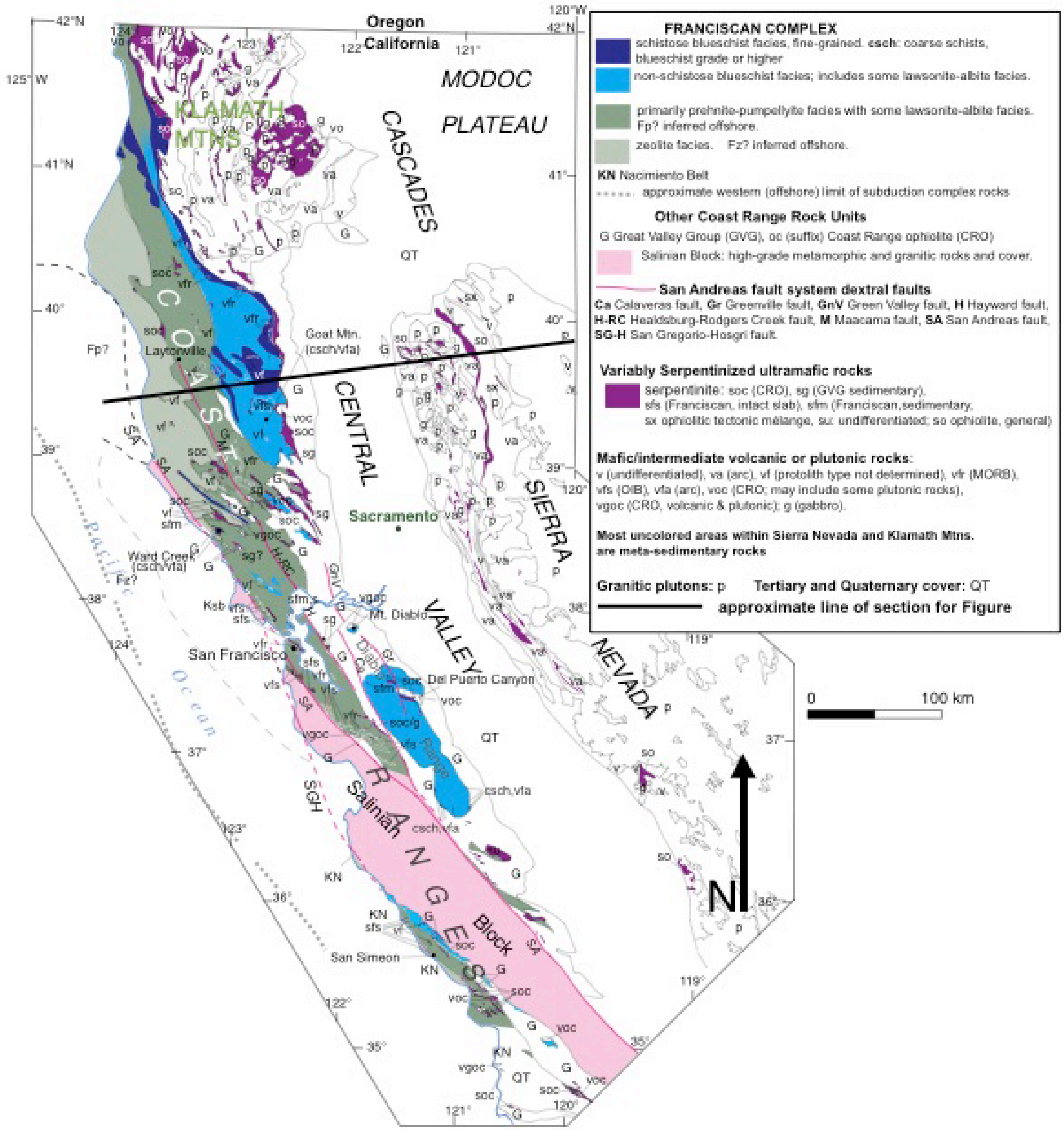


Figure 33. Geologic map emphasizing the basement (pre-transform margin) geology of the California Coast Ranges and adjacent regions. Also emphasized on this map are serpentinized ultramafic rocks derived from oceanic mantle, volcanic rocks, as well as the different degrees of metamorphism of the Franciscan subduction complex. Adapted from Wakabayashi (2017a).

examples of high-pressure/low-temperature metamorphic rocks such as blueschist facies rocks (Ernst, 1970), and block-in-matrix units known as “mélanges” (after a French word meaning “mixture”; Hsü, 1968). Mélanges consist of variably deformed matrix of shale, sandstone, conglomerate, and serpentinite with included blocks of a wide range of rock types. They differ dramatically from the “layer cake” stratigraphy one associates with areas such as the Grand Canyon (Hsü, 1968, Maxwell, 1974; Cloos, 1984; Cowan, 1985; Wakabayashi, 2015).

Mélanges have engineering properties that differ markedly from layered or comparatively isotropic units. Their block-in-matrix nature, termed “Bimrocks” for “block-in-matrix rocks”, requires a different field approach for projects engineered on such bedrock (e.g. Medley and Zekkos, 2011 and references therein). Whereas the initial studies on the engineering properties of Bimrocks were undertaken in the mélanges of the Franciscan Complex, mélanges are common in other units of California, including the Great Valley Group and several bedrock units in the Sierra Nevada. Such units include a significant fraction of the bedrock on either side of the Central Valley at the latitude of Sacramento.

Whereas mélanges are thought by many to represent extreme faulting along the subduction interface, sometimes referred to as the “subduction channel” (e.g. Cloos, 1984; Cloos and Shreve, 1988; Gerya and others, 2002), various lines of field evidence suggest that most of the mixing of blocks into matrix occurred as a result of submarine landslides (olistostromes) into the trench with deformation imposed later during subduction (Aalto, 2014; Cowan, 1978; Macpherson and others, 1990; Wakabayashi, 2015). Large submarine landslides into trenches are commonly triggered by great megathrust earthquakes, such as the M 9 Tohoku earthquake off northeastern Japan (Kawamura and others, 2012). Whereas mélanges and non-mélanges (informally called “coherent units”) were once distinguished with the presumption of a different origin (e.g., Wakabayashi, 1992), recent field studies have shown mélanges to be interbedded and interfingered with bedded turbidite deposits, so they are part of larger accretionary units, rather than shear zones that separate them (Wakabayashi, 2017a). Tectonically (fault)-generated block-in-matrix deformation locally overprints Franciscan units, but this deformation is not of the sort that introduces truly exotic blocks into matrix. Rather, it is deformation that is part of progressive deformation of the upper part of the subducting plate, usually involving basalt, chert, and clastic sedimentary rocks, with the latter component being dominant (Wakabayashi, 2017a).

The subduction-accretion process has produced a complex pattern of age distribution of rocks in the Franciscan because the various accreted units were brought together by faulting, primarily movement along the subduction interface, rather than deposition. Each actively accreting unit is shingled beneath earlier accreted ones, resulting in a pattern of downward younging rather than upward younging as in a normal stratigraphic sequence (e.g., Wakabayashi, 1992; 2015). Each unit that is accreted initially goes down attached to the subducting plate so that the subduction interface is above it. During accretion the unit is added to the upper plate as the subduction interface jumps to a position below the unit (that is, it cuts into the subducting plate). Accordingly, the primary faults that shorten the accreted units of the Franciscan accommodated the subduction megathrust slip during the time the units accreted, whereas the faults bounding each accreted unit accommodated megathrust slip when nothing was accreting (Wakabayashi, 2017a). The rocks of the Franciscan record over 10,000 km of subduction megathrust slip.

The Franciscan Complex provides the opportunity to examine the nature of a subduction megathrust fault exhumed from depths of about 10 to 30 km beneath the sea floor, which is within depth range of the part of the subduction interface that ruptures in great subduction zone earthquakes. As noted earlier, the subduction interface in this depth zone is commonly visualized as a very broad (kilometers wide) zone of distributed shear known as the subduction channel, the rock equivalent of which are mélanges. Detailed field studies show that these mélanges, however, are much thinner (commonly hundreds of meters in thickness) and are actually sedimentary deposits rather than shear zones. Megathrust slip in the 10-30 km depth range appears to be accommodated on a network of discrete faults, each of <20m thickness, distributed across the full structural thickness of an accreted unit (up to 3 km) that accommodated the slip during accretion of a unit or on discrete faults of <50 meters thick that accommodated subduction slip when accretion was not taking place (Wakabayashi and Rowe, 2015; Wakabayashi, 2017a).

It is important to realize that in a subduction complex the age of incorporation may have little to do with the age of formation of the rocks. For instance, the oldest known rocks in the Franciscan, from the standpoint of origin, are the basalts of the Marin Headlands and related units that formed ca. 195 Ma at a mid-oceanic spreading center and were incorporated into the Franciscan Complex ca. 95 Ma (Wahrhaftig, 1984). In contrast, the first rocks incorporated into the subduction complex are “high-grade” (formed at great depth and pressure) metamorphic blocks that mark the beginning of Franciscan subduction ca. 165 Ma and whose basaltic parents probably formed only a few million years before that (Wakabayashi and others 2010). Thus, the formational age of exposed Franciscan rocks at the latitude of Sacramento ranges from ca. 200 Ma to perhaps 50 Ma, whereas the incorporation ages (that track the time of subduction itself) range from ca. 165 Ma to 50 Ma; rocks accreted as recently as ca. 20 Ma may be offshore (Wakabayashi, 2015).

About a third of the exposed Franciscan rocks were once buried to sufficient depths (>20 km) during the subduction process to cause minerals to form at high pressure and low temperature under metamorphic pressure-temperature conditions, known as the blueschist facies (Blake and others, 1988; Ernst, 1993; Wakabayashi, 2015). The terms “blueschist facies” and “blueschist” are not synonymous in the Franciscan, however.

Most blueschist facies rocks of the Franciscan lack or have very minor amounts of the blue amphibole (glaucophane-riebeckite) that give blueschists their characteristic color and few are truly schistose, and thus most blueschist facies rocks are neither blue nor schist. Most of the blueschist facies rocks are metasandstones (metagraywackes) that have the appearance of ordinary sandstones with variable intensity of cleavage and foliation. The characteristic high-pressure metamorphic minerals in such rocks are commonly too small (tenths of millimeters and smaller) to be visible to the naked eye. A small fraction (much less than 1%) of Franciscan metamorphic rocks are coarse-grained with macroscopic metamorphic minerals of 1 mm in size or larger. Such rocks comprise amphibolites, garnet-amphibolites, and eclogites, with slight to near total replacement of these assemblages by blueschist facies minerals. They crop out mostly as blocks-in-mélange of about 200 meters and smaller and are widely distributed and numerous (many thousands or more blocks), although volumetrically minor. Rare intact fault-bounded sheets of such rocks are also present, ranging in size to 1.3 x 2.2 km in map dimension (Wakabayashi, 2015).

Nomenclature in the Franciscan has changed greatly through time, is currently in a state of flux, and remains very confusing for most readers (see Wakabayashi, 2015; Raymond, 2015 for details). Problematic nomenclature includes various changing terrane names as well as some variation in the use of belt names.

North of the San Francisco Bay region, the Franciscan complex has traditionally been divided into three principal belts, the Eastern, Central, and Coastal Belts, that become younger in incorporation age from east to west and from structurally highest to lowest (e.g., Berkland and others, 1972; Blake and others, 1988; Figure 3). Whereas this grouping of Franciscan is useful in the northern Coast Ranges, where the three units also correspond to different metamorphic conditions of blueschist, prehnite-pumpellyite, and zeolite facies, respectively, the belt division does not work well in other parts of the Franciscan (Wakabayashi, 1992; 2015; Raymond, 2015). In the cross section, the three belts are shown modified after the reconstruction of Wakabayashi and Unruh (1995).

There is considerable along-strike variation in the Franciscan, as should be expected for a unit that extends some 1000 km along strike. The accretion of various units is not expected to be continuous along the entire length of a subduction zone, so the specific accretionary units making up the Franciscan tectonic stack varies on scales of tens to hundreds of kilometers along strike (Wakabayashi, 1992; 2015). Most significant, is the transition from net accretion in the “type” Franciscan exposed east of the Salinian block compared to net subduction erosion recorded in the Franciscan Nacimiento Belt, west of the Salinian block (Wakabayashi, 2015). The Nacimiento Belt restores south of the southern limit of “type” Franciscan after restoration of slip on the faults of the San Andreas system. The arc-trench gap is well preserved for the type Franciscan whereas it has been removed for the Nacimiento Belt.

Coast Range-Great Valley Ophiolite

The oceanic crust remnant, known as the Coast Range ophiolite structurally overlies the Franciscan Complex. In general, the ophiolite is the basement that Great Valley Group forearc basin strata were deposited on, although the original depositional contact between the two units has been overprinted by faulting in many places (Hopson and others, 1981, 2008; McLaughlin and others, 1988). Geophysical evidence indicates that beneath the Central Valley itself, a slab of oceanic crust and mantle underlies the buried Great Valley sediments (the so-called Great Valley ophiolite; Godfrey and Klemperer, 1998; Godfrey and others, 1997). Most exposures of the ophiolite along the eastern flank of the Coast Ranges comprise one or more of the following rock types: serpentinite, gabbro, quartz diorite, diabase, basalt, and felsic volcanic rocks (Hopson and others, 1981). The age of the Coast Range ophiolite is ca. 165–172 m.y.o. (Hopson and others, 1996; 2008; Shervais and others, 2005; Pessagno and others, 2000). Individual remnants of the ophiolite extend up to 50 km along strike and reach a maximum thickness of about 5 km (Hopson and others, 1981; 2008). Nearly all of the Coast Range ophiolite remnants are “incomplete,” in comparison to the so-called "Penrose" definition of an ophiolite (Anonymous, 1972), but they fit subsequent designations as magma-poor (Hess-type; e.g. Moores, 2002, Dilek and Furness, 2011). Although the lack of sheeted dikes or other components in ophiolites was once attributed to post-formational faulting during and after emplacement above the Franciscan Complex, recent ocean floor research has revealed that “incomplete” oceanic crustal sections are common, so Coast Range ophiolite remnants may largely reflect their original oceanic crustal character (e.g., Hopson and others, 2008).

In contrast to the Franciscan Complex, most of the Coast Range ophiolite exhibits moderate deformation and negligible burial metamorphism (Hopson and others, 1981). The Coast Range ophiolite has been overprinted with low-pressure metamorphism associated with fluid flow at or near the original spreading center. The grade of metamorphism increases downward, with local lower amphibolite metamorphism in the gabbro (Evarts and Schiffman, 1983). Whereas many of the serpentinite exposures are massive, the serpentinite component of the ophiolite remnants is locally deformed and foliated, particularly along the contacts with the underlying Franciscan Complex (Wakabayashi, in press). Many exposures of gabbro of the Coast Range ophiolite are laced with brittle and ductile shear zones associated metamorphic mineral growth of the spreading-center type noted above. These shear zones do not affect the overlying Great Valley Group and the associated metamorphism is not found in the underlying Franciscan Complex. Accordingly, much of the deformation seen in Coast Range ophiolite remnants took place during formation of the oceanic crust at or near a spreading center and prior to emplacement over the Franciscan and burial beneath the Great Valley Group (Wakabayashi, 2013b).

Great Valley Group

The Great Valley Group may be the best example of an exhumed marine forearc basin preserved on Earth. Unlike the Franciscan Complex and the basement units of the Sierra Nevada, it has extensive oil and gas resources (e.g., Dickinson, 1970; Ingersoll, 1978, 1983). The main outcrop belt of the Great Valley Group is along the western margin of the Central Valley. Other exposures, which are generally less extensive, are found along the eastern margin on the Sacramento Valley, as well as in several outliers to the west of the main exposure belt. In the Coast Ranges, the Great Valley Group overlies the Coast Range ophiolite and, consistent with this relationship, exhibits negligible burial metamorphism. Only its stratigraphically lowest levels have zeolite grade metamorphism (Dickinson and others, 1969), in stark contrast to the high-pressure metamorphism recorded by much of the Franciscan Complex. The Great Valley Group also shows much less deformation than the Franciscan Complex. None of the Great Valley Group units have penetrative deformation (cleavage or foliation) and most strata consist of well-bedded sandstone, shale, and conglomerate.

The Great Valley Group has extensive basal deposits of sedimentary serpentinite mélange (olistostromes), as well as associated sandstone and shale matrix sedimentary mélange (Lockwood; Phipps, 1984; Wakabayashi, 2017b). The more extensive exposure belts of sedimentary serpentinite extend for at least 40 km along strike with thicknesses that reach 1 kilometer or slightly more (Phipps, 1984). Some of the shale and sandstone matrix olistostrome deposits may attain similar maximum dimensions (Wakabayashi, 2017b). The best exposures of these units are in the southern part of the western margin of the Sacramento Valley, the part of the Great Valley Group outcrop belt that is closest to Sacramento. The blocks of these mélanges include abundant mafic, ultramafic, and chert blocks, likely derived from the underlying Coast Range ophiolite, as well as high-pressure metamorphic blocks, such as blueschist and high-pressure amphibolites (Wakabayashi, 2017b).

Whereas most of the Great Valley Group consists of clastic sedimentary rocks, whose sediment sources were primarily the inboard magmatic arc and associated basement rocks (Surpless 2015; Sharman and others 2015), the olistostromal deposits may have originated as submarine forearc mud volcano deposits that are similar in setting, lithology, and scale to those found in the modern Mariana forearc (Fryer and others, 2000). Although comparatively undeformed at outcrop scale, the Great Valley Group has been folded and shortened by fold and thrust deformation, primarily localized in the eastern Coast Ranges that took place periodically from the late Cretaceous or earlier to the present (Wentworth and others, 1984; Unruh and Moores, 1992; Unruh and others, 1991; 1995; 2004). This large scale thrust system apparently dipped west and rooted in the subduction zone, so that the overall vergence (thrusting direction) was the opposite of that of the subduction zone (top to the east instead of top to the west). The blind, east-vergent thrust, locally, is paired with a west-vergent backthrust to form a passive roof duplex (Unruh and others, 1995). This style of deformation also has been called "tectonic wedging" (e.g., Wentworth and others 1984; Unruh and others, 1991). Such structures form many of the traps for the petroleum deposits hosted within the western Central Valley.

Coast Range Fault and Other Exhumation Structures

Unlike the Franciscan Complex, the Coast Range ophiolite and Great Valley Group were never part of or deposited on the downward moving plate of a subduction zone. For that reason, the fault that places the Coast Range ophiolite and/or the Great Valley Group on the Franciscan is a regionally important tectonic contact. Based partly on its regional low-angle orientation, although it is steeply-dipping in many local exposures, and its position as a fault above a subduction complex, this fault was originally called the "Coast Range Thrust," even though it was recognized that the fault places rocks without significant burial metamorphism over those exhumed from significant depth (e.g., Suppe, 1973), or it cuts out crustal section rather than repeats it. Along much of the western margin of the Sacramento Valley, this fault is locally known as the Stony Creek fault (Lawton, 1956; Chuber, 1962). The regional-scale structural contact at the top of the Franciscan Complex was renamed the "Coast Range Fault" (Jayko and others, 1987) following the recognition by Platt (1986) that the most recent movement on the fault effectively raised the Franciscan in the footwall 15 to 20 km upward in burial depth compared to the Coast Range ophiolite and Great Valley Group on the hanging wall. Accordingly, the Coast Range fault accommodated east-down normal fault movement and is interpreted to be responsible for much of the exhumation of the blueschist facies rocks of the Franciscan from burial depths of 20-35 km or more. The original upper contact of the Franciscan, prior to its reactivation as a normal fault, must have been the structurally highest and oldest paleo megathrust horizon. This would have been the horizon along which Franciscan subduction initiated (Cloos, 1984; Wakabayashi, 1992; 2015).

Normal separation on the Coast Range fault was associated with extensional faults dismembering and separating tracts of Coast Range ophiolite and Great Valley Group (Harms and others, 1992) as well as normal faults locally thinning the Great Valley Group (Unruh and others, 2007). An indication of the amount of extension and thinning of the Great Valley Group, Coast Range ophiolite, and especially the mantle wedge that underlay the latter may be visualized by noting that these rocks, with a thickness of <5 km, directly overlie Franciscan rocks exhumed from 30 km or more depth along an across strike distance of more than 80 km (Wakabayashi, 2015). In other words, an assemblage of crust and mantle that once exceeded 30 km in thickness is now less than 5 km thick, over an across strike distance of at least 80 km. Accordingly, significant extension of the upper plate accompanied normal fault movement on Coast Range faults, and this is the primary mechanism that brought the Franciscan Complex toward the surface from great depth in the subduction zone (Platt, 1986). This exhumation, however, appears to have paired with thrust faulting of the Franciscan blueschist facies rocks over lower-pressure Franciscan prehnite-pumpellyite facies rocks, so that the high-pressure metamorphic rocks were brought to the surface by significant extension in the upper plate combined with thrust movement of these rocks over less buried subduction complex rocks. This is similar to the fault geometry and movement directions observed during and shortly after the 2011 M9 Tohoku earthquake off of northeastern Japan (Wakabayashi, 2015).

The regional east-dipping nature of the Coast Range fault is complicated by the fact that it has been deformed by the east-vergent, west-dipping thrust system ("tectonic wedging") noted earlier. It is for this reason that most of the extension has been proposed as having taken place prior to the start of tectonic wedging, otherwise the blueschist facies rocks would not have been exhumed (Wakabayashi and Unruh, 1995).

Structure Beneath the Great Valley

Based on analysis of geophysical data, the Great Valley Group rocks underlie the Sacramento Valley itself and define a broad, asymmetric syncline (see Figure 34). In the east, the rocks dip gently westward. To the west, the Great Valley rocks dip moderately to steeply east and, as mentioned above, overlie ophiolitic rocks, including crustal and mantle rocks (Godfrey and Dilek, 2000). The sedimentary rocks thicken westward, and beneath the western part of the Great Valley, they are deformed by several east-vergent thrusts. The ophiolitic rocks beneath the Sacramento Valley structurally overlie continental crust and mantle belonging to the Sierra Nevada along one of the master faults of this tectonic wedge system. The Sacramento Valley effectively possesses two crust-mantle boundaries (this boundary is also called the Moho discontinuity). The presence of two Mohos and the high density of the oceanic rocks may help explain the long-standing enigma of the existence of the low-lying Central Valley basin surrounded by rising regions—the Coast Ranges, the Klamath Mountains, the Sierra Nevada, and the Tehachapis. The Great Valley and Coast Range ophiolites may have been emplaced by a collision of the continental margin with a west-dipping subduction zone (e.g. Godfrey and Dilek, 2000).

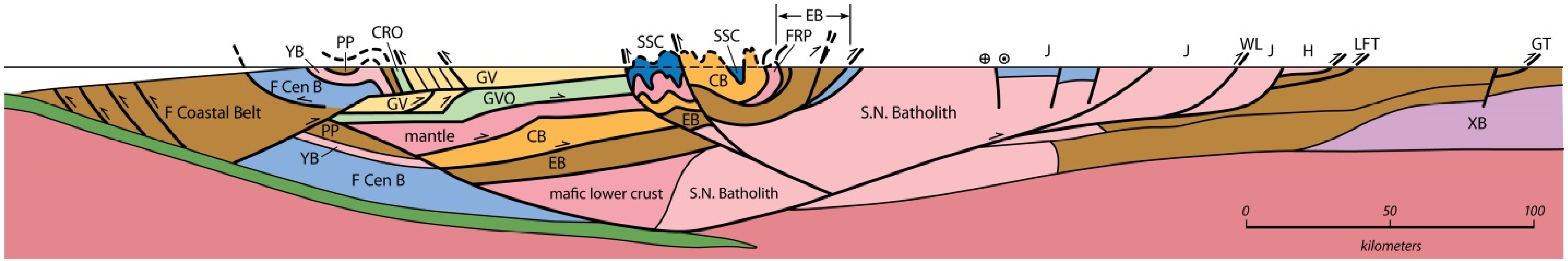


Figure 34. Crustal-scale cross section of the western United States along a ling through northern California north of Sacramento, just before development of San Andreas fault system. Symbols: CB Sierra Nevada Central Belt, CRO Coast Range Opholite, EB. Sierra Nevada Eastern Belt, F. Coastal Belt, F Cen B Franciscan Central Belt, Franciscan Coastal Belt, FRP Feather River Peridotite belt, GT Golconda thrust, GV Great Valley sediments, GVO Great Valley Ophiolite, H Humboldt complex, LFT Luning Fencemeaker Thrusts, PP Franciscan Picket Peak unit, XB North American Precambrian crystalline basement, YB Franciscan Yolla Bolly unit (after Moores and others, 2006, Figure 5.)

VI. CLIMATE AND CLIMATE CHANGE IMPACTS

primary author: Mike Anderson

Sacramento possesses a Mediterranean climate with warm, dry summers and cool, wet winters. Summer temperatures are modulated by the Delta Breeze, which brings an influx of cooler air from the San Francisco Bay region, cooling evening temperatures from mid-day highs. The combination of wintertime temperatures and available moisture can, on occasion, result in radiation fog or Tule fog, named for the Tule reeds that grow in the Delta.

In this section, the average distribution of temperature and precipitation over the year are presented along with a discussion of the variability over different time scales. Precipitation and temperature data for Sacramento come from Western Region Climate Center's archive of National Weather Service Cooperative Observer Data. The analyses presented here utilize data collected from the Sacramento station 047633 – Sacramento 5ESE. Variability in precipitation is presented from the perspective of the role of atmospheric rivers. Atmospheric rivers and the contributions that these climate features offer to seasonal accumulations and extremes are described and presented. A final section discusses observed changes in the historical record and projected changes with climate change.

Temperature

Sacramento has an annual average maximum temperature of 22.8 degrees Celsius (^{o}C) and an annual average minimum temperature of 9.9 ^{o}C. Maximum temperatures peak in July with a monthly average of 33.2 ^{o}C and reach their minimum in January averaging 11.9 ^{o}C. The highest minimum average temperature is in July at 15.1 ^{o}C and the lowest minimum average temperature is in January at 4.2 ^{o}C. The monthly variation of maximum and minimum temperatures over the year is shown in Figure 35. Sacramento's highest maximum temperature was 45.5 ^{o}C, which was set on July 17, 1925. Sacramento's lowest minimum temperature of negative 8.3 ^{o}C, which was set on December 11, 1932.

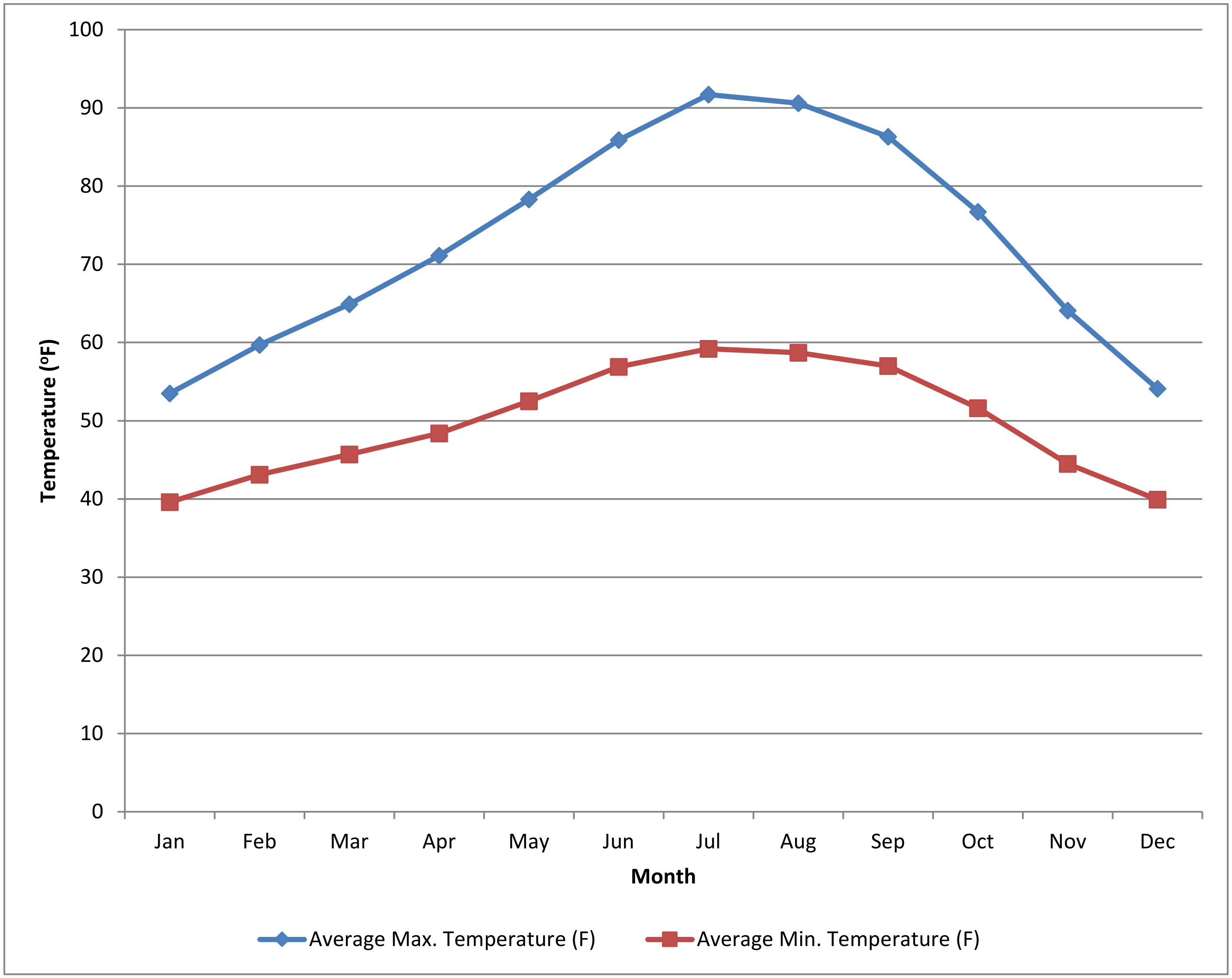


Figure 35 – Monthly maximum and minimum average temperatures for Sacramento (Source: Sacramento station 047633 – Sacramento 5ESE).

Figure 36 shows a time series of annual average temperatures for the period of record from 1877 to 2016. There is large year-to-year variability and some evidence of decadal scale variability in the record that can be seen in Figure 36. Note that early in the record, annual temperatures exceeding 16.7 ^{o}C were rare. An annual temperature above 17.8 ^{o}C wasn't seen until 1976, but Sacramento did reach an average of 18.9 ^{o}C just a few years ago. Over the period of record Sacramento's average temperature has risen by about 1.7 ^{o}C. Average maximum temperatures have increased more than average minimum temperatures, 2.8 ^{o}C versus 1.7 ^{o}C. More information on continued warming through the 21st century with climate change is presented after the section on precipitation.

Precipitation

Approximately 45.7 centimeters (cm) of precipitation falls on Sacramento in an average year. Precipitation falls primarily in the winter months, with 50% of the annual total falling in the months of December/January/February, and 90% between October and April. Almost no precipitation falls in July and August. A plot of the monthly distribution of precipitation is shown in Figure 37. Snow does not normally fall in Sacramento, although there have been some instances of snow falling during cold weather outbreaks. Accumulations have been negligible with only a trace as the record accumulation.

The period of record (1877-2016) time series of annual accumulation of precipitation is shown in Figure 38. Note the large year-to-year variability as well as a suggestion of some type of decadal scale variation in precipitation totals. Dettinger and others (2011) show that California has the largest year-to-year variability in precipitation for the conterminous United States with fluctuations between 30% and 50%. Due to the large variability on multiple scales, it is hard to discern if there is a trend in annual precipitation accumulation for Sacramento. For extremes, Sacramento's wettest year was in 1983 when 95.6 centimeters (cm) fell. The driest year was 2013 when only15.7 cm fell. The wettest month was set in April of 1880 when 36 cm was recorded. Sacramento's largest single day rainfall total is 13.4 cm set on April 20, 1880. The heavy accumulations are associated with the passage of atmospheric river events, which are described below.

Atmospheric river events are winter storms that entrain an atmospheric river into the circulation ahead of the cold front. Atmospheric rivers are intense bands of water vapor transport that extend from tropical regions into the middle latitude regions. According to Zhu and Newell (1998), 90% of the equator-to-pole transport of water vapor occurs with atmospheric rivers. Dettinger and others (2011) show that up to 50% of Sacramento's

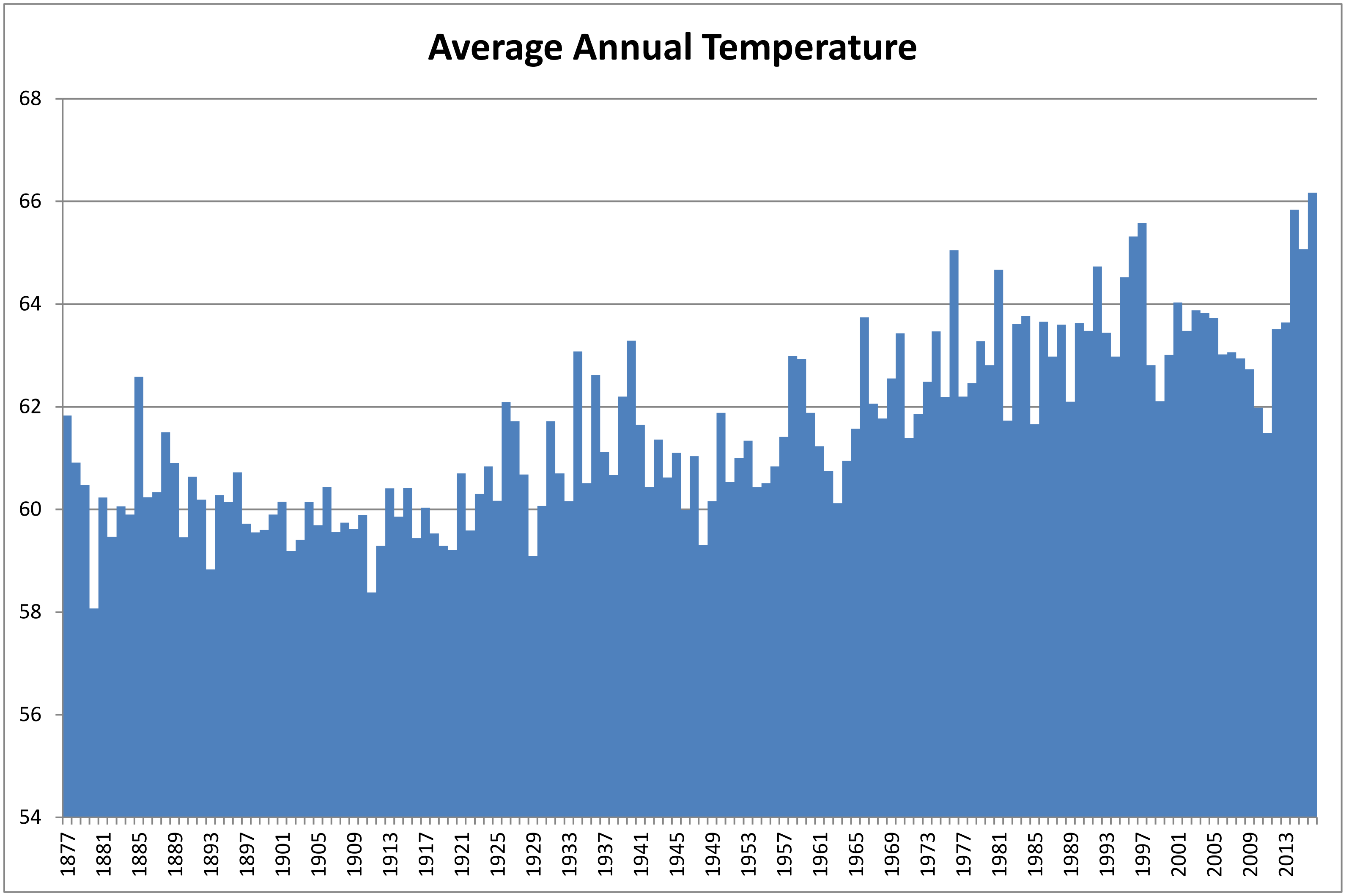


Figure 36. Time series of annual average temperature from 1877 to 2016 (Source: Sacramento station 047633 – Sacramento 5ESE).

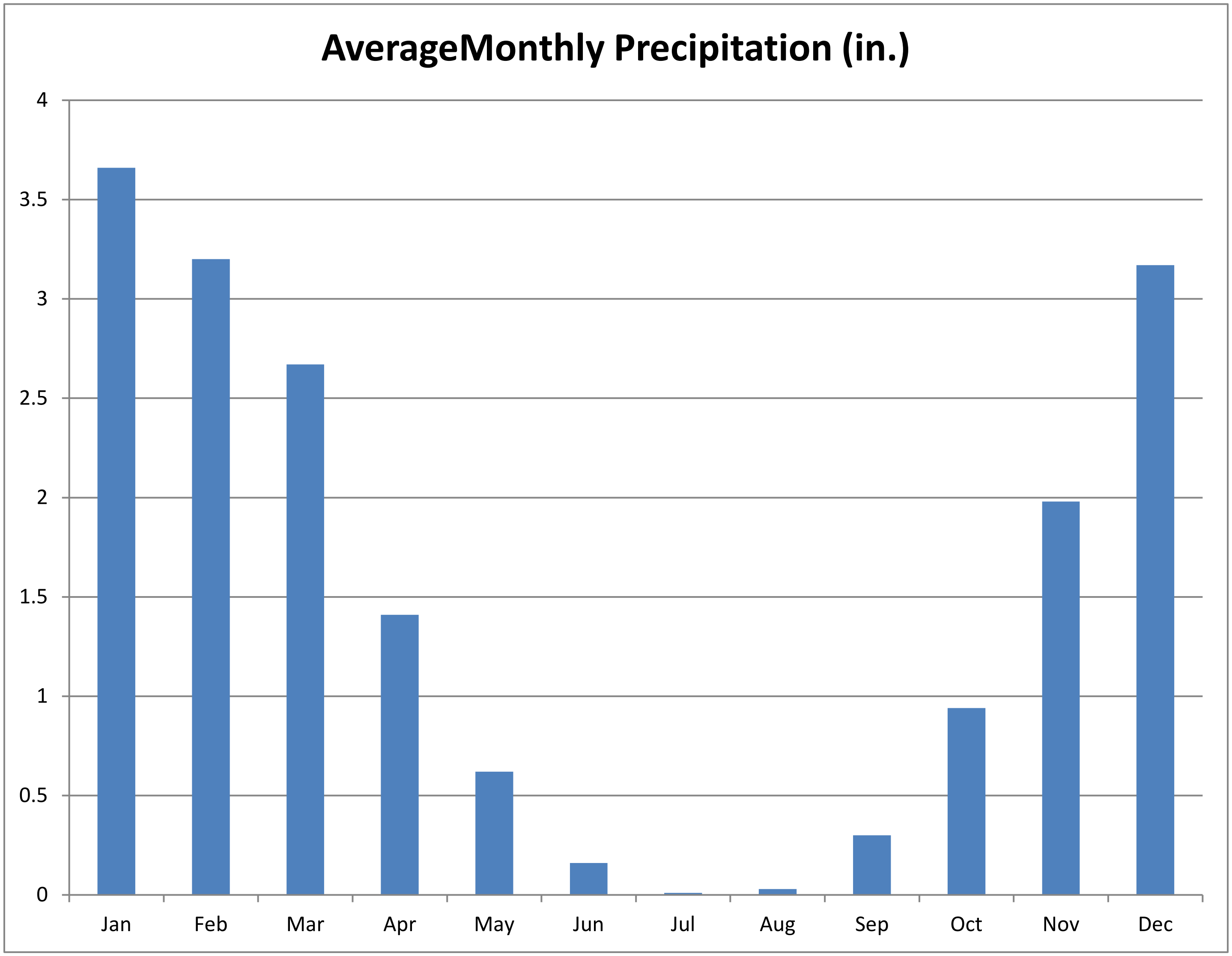


Figure 37. Monthly distribution of average precipitation (Source: Sacramento station 047633 – Sacramento 5ESE).

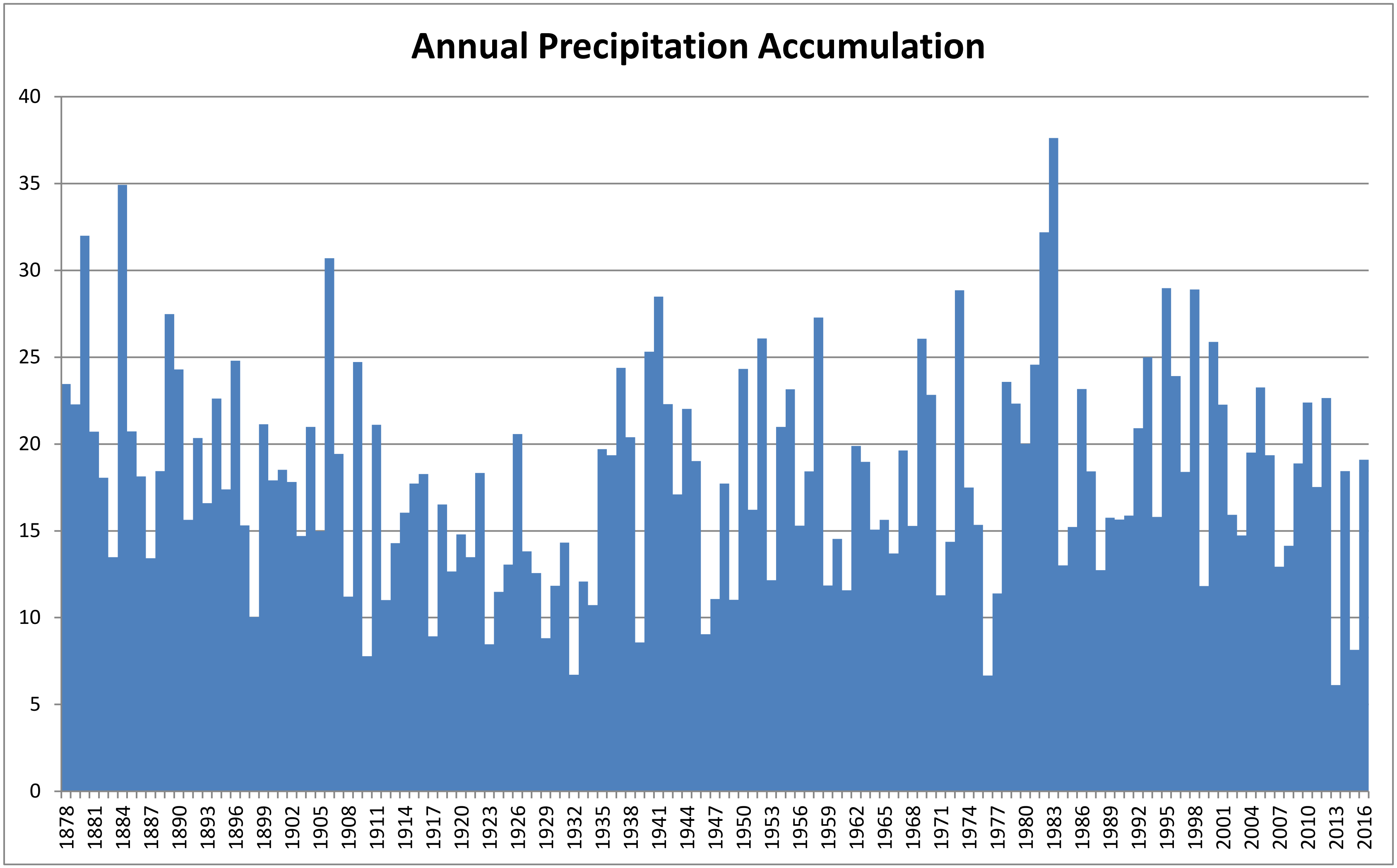


Figure 38, Time series of annual accumulation of precipitation from1878 to 2016 (Source: Sacramento station 047633 – Sacramento 5ESE).

annual precipitation comes from rainfall associated with atmospheric river events. These storms make landfall over California between October and April with the stronger events tending to hit during the month of January. The number, strength, timing, and duration of these atmospheric rivers play a large role in determining if the Sacramento region faces flood or drought. This is detailed in Dettinger (2016).

Climate Change

As the 21st century unfolds, climate change is expected to result in further average temperature increases ranging from 2.2 to 5.6 ^{o}C by the end of the century. This would result in fewer days below freezing and a greater number of days where summer temperatures can exceed 37.8 ^{o}C. For Sacramento, there would likely be fewer days with fog and fewer cooling degree days for some fruit and nut trees. Projections of future average temperatures can be found at Cal-Adapt, an online resource for climate change information (Cal-Adapt website, 2018). The California Energy Commission funded a number of studies related to climate change and impacts to California. The studies were published under the Public Interest in Energy Research Program (Energy Commission, 2018).

Anticipating health impacts from future temperature extremes, the heat adaptation work group, as part of the public health workgroup of the State's Climate Action Team, published a guidance document in 2013 on preparing for extreme heat (Climate Action Team, 2013). The document contains a number of references on temperature and climate change, including Gershunov and Guirguis (2012), and Hayhoe and others (2004).

As the atmosphere warms, new precipitation extremes are expected. Atmospheric rivers may become stronger, but it is uncertain if the total number would increase or decrease. Large internal and decadal scale variability is expected to continue. The seasonal cycle of winter-dominated precipitation is expected to continue. The opportunity for thunderstorms including heavy rainfall, hail, tornadoes, and damaging winds may increase with warming temperatures. The influence of rising temperatures on the physical processes that drive atmospheric river formation and organization would ultimately define how precipitation accumulation would change for Sacramento (Dettinger, 2016). More research is needed to understand these processes and their expected changes with climate change. Also, research is needed to determine the potential for increased convective activity and the formation of thunderstorms in the Central Valley.

VII. NATURAL RESOURCES

Non-metal Mining

Construction Aggregate

primary author: Matt O'Neal

Construction aggregate is the most economically important non-fuel mineral commodity produced in California. Construction aggregate includes sand, gravel, and crushed stone that is used to provide bulk and strength to Portland Cement Concrete (PCC), asphaltic concrete (AC), plaster, mortar, and stucco, and is also used as road base, subbase, and rip rap. These construction materials are ubiquitous in, and essential to, the construction of our modern cities and infrastructure.

Specifications for PCC, AC, and various other aggregate applications have been established by several agencies, such as the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, and the California Department of Transportation to ensure that aggregate is satisfactory for the given application. Most PCC and AC aggregate specifications have been established to ensure the construction of strong, durable structures capable of withstanding the physical and chemical effects of weathering, loads, and use. Every potential deposit must be tested to determine how much of the aggregate can meet specifications for a particular use, and what processing is required.

The major factors that affect the grade of construction aggregate are the rock type and the degree of weathering of the deposit. Rock type determines the hardness, durability, and potential chemical reactivity of the rock when mixed with cement to make concrete. Weathering involves physical and chemical changes which may make the aggregate unsuitable for applications requiring high strength and durability. More extensive weathering typically necessitates more extensive processing and a correspondingly higher waste percentage, to meet specifications.

An important difference between construction aggregate and other non-fuel mineral commodities is the extent to which transportation contributes to the cost of aggregate to the consumer. Aggregate is a low-unit-value, high-bulk-weight commodity, and it must be obtained from nearby sources to minimize the cost to the aggregate consumer and the environmental and societal impacts associated with transportation. If nearby sources do not exist, then transportation costs may significantly increase the cost of the aggregate by the time it reaches the consumer.

The first recorded commercial mining of construction aggregates in the Sacramento Region began in the early 1900s in response to the need for materials for roads, highways and other infrastructure (Tucker and Waring, 1917; Logan, 1925). Starting around 1909, gold dredge tailings were utilized in the Fair Oaks-Folsom area of Sacramento County for sand, gravel, and crushed stone (Carlson, 1955). Many of the early sand and gravel operations in the Sacramento County were located in, and adjacent to, the American River between Folsom and Sacramento. Similarly, in the first quarter of the 20th century, aggregate mining began in the Cache Creek area and on the Yuba River, near Marysville, to acquire material for roadwork and highway construction (Bradley, 1917; O'Brien, 1950; Tucker and Waring, 1917).

While established in the early history of California, the communities of the Sacramento region have undergone dramatic growth since the middle of the last century. Almost nine-tenths of Sacramento's current urbanized region was developed between 1950 and 2010 (Wheeler and Beebe, 2011). During this growth period, construction was fed by a series of aggregate mines in the region. The geographic distribution of aggregate mines in the Sacramento region has evolved with time as the area has grown. Though a small number of aggregate mines are distributed diffusely throughout the region, there are three conspicuous concentrations of mines: South of the American River in Sacramento, along the Cache Creek at the valley margin, and along the Yuba River approximately 9.6 km upstream of Marysville (Figure 39).

Mines in, and south of, the American River in Sacramento have been producing construction aggregate from Pleistocene Age Riverbank Formation and younger alluvium since the 1910s. In general, mining began in the northwest, in and adjacent to the active channel. As individual mines became depleted and land near the river became urbanized, mining migrated away from the active channel and to the southeast. Typically, the mined deposits 9 to 14 meters thick with 1.5 to 3 meters of soil overburden.

Riverbank Formation and younger alluvium is mined because of clast lithology, and because the extent of weathering is typically suitable for all aggregate commodities up to and including PCC. The underlying and adjacent Pliocene age alluvium of the Laguna Formation is lithologically similar to the Riverbank Formation, but has been more extensively weathered, resulting in a significantly higher proportion of friable clasts, and clasts with silica rinds which can result in alkali-silica reactivity issues. Use of this material requires additional processing and results in a higher percentage of waste when compared to the younger Riverbank deposits. Currently, mining is conducted by open pit methods.

The operations along the Yuba River, approximately 9.6 km upstream of Marysville, are mining predominantly Quaternary alluvium, including the Riverbank Formation and younger deposits. Some of the mines are located within the Hammonton Dredge Field (Figure 40) and produce aggregate from dredge tailings. The operations upstream and downstream of the dredge field mine native alluvium. This is notably the largest deposit

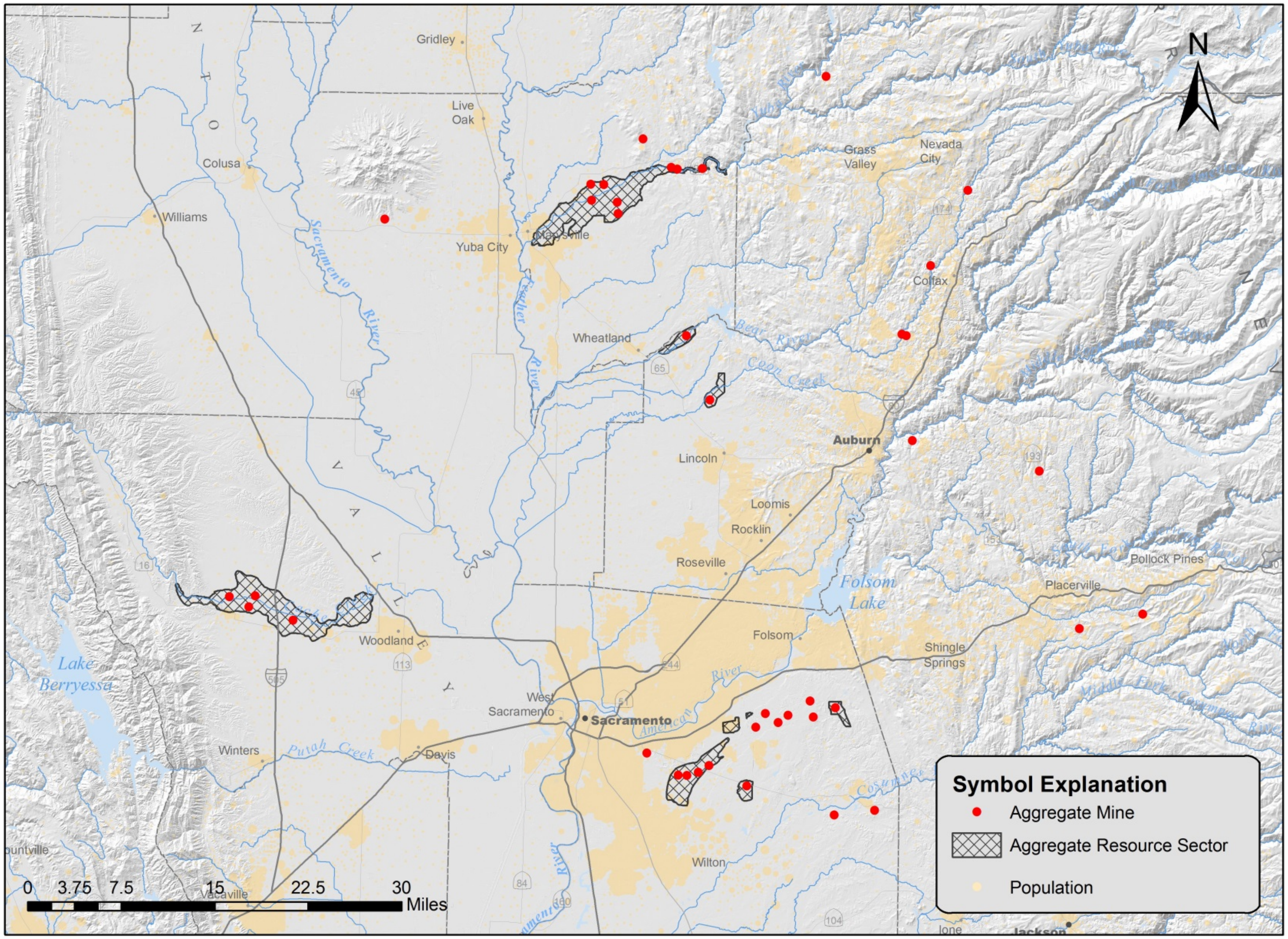


Figure 39. Map of population and construction aggregate resource sectors and mines in the greater Sacramento region.

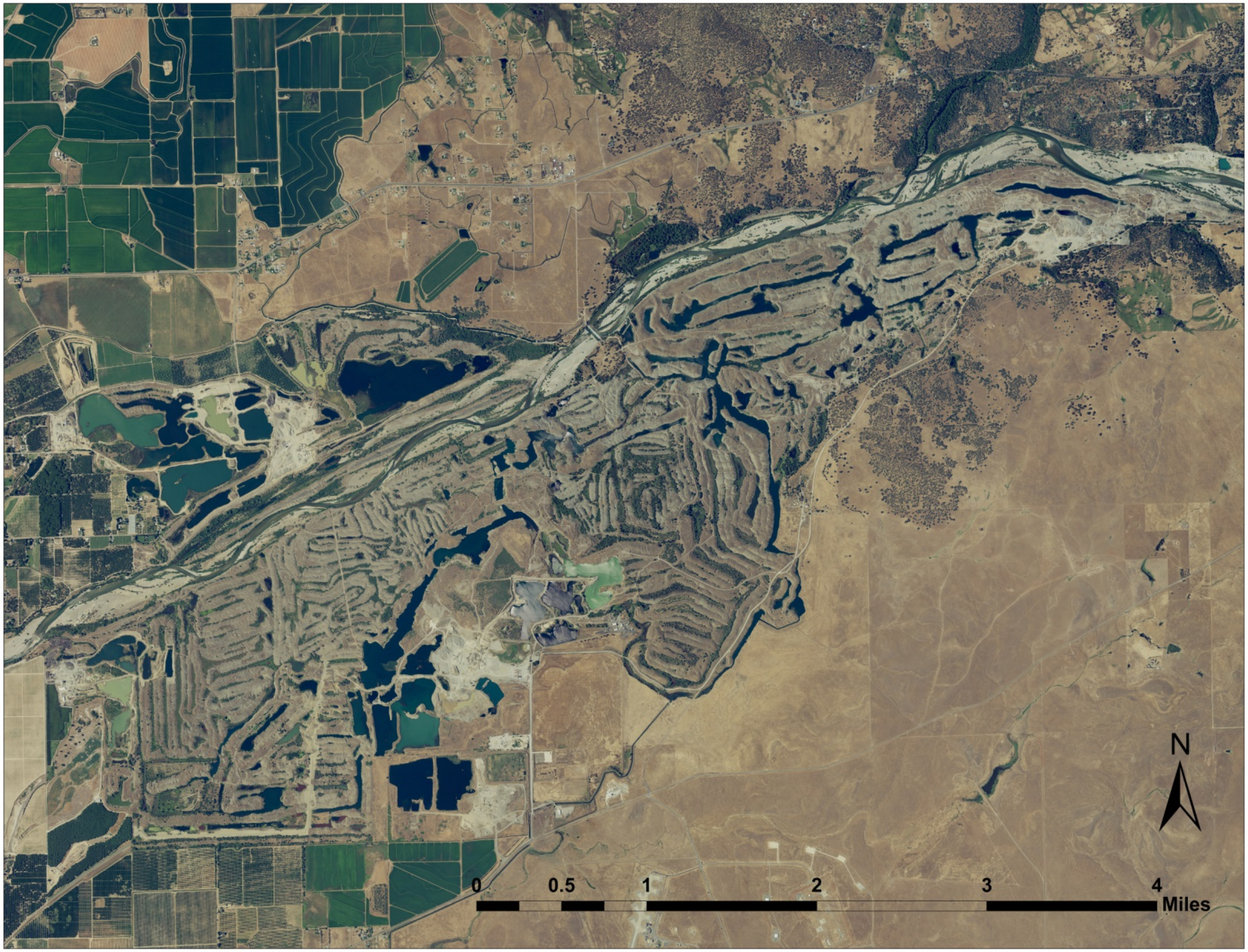


Figure 40. Aerial photograph of the Hammonton Dredge Field (California NAIP Imagery, 2016).

of sand and gravel suitable for use in construction aggregate in the region, with an estimated 1.9 billion metric tons of resources and approximately 544 million metric tons of currently permitted reserves. The deposit varies in thickness from 18 to 24 meters on the upstream end and in excess of 61 meters on the downstream end. Mining is conducted by open pit, clamshell dredge, and dragline methods.

The mines along the Cache Creek, at the western valley margin, produce aggregate from Quaternary age alluvial deposits. This alluvium, sourced from the Coast Ranges, is compositionally distinct from the alluvium of the American and Yuba Rivers, and consists primarily of graywacke, chert, and other metamorphic and sedimentary lithologies. Because this deposit is relatively high up on the alluvial fan, the grain size tends to be relatively coarse, with a high proportion of pebble-sized clasts. The American River deposit mentioned above is deficient in medium-coarse grained sediment, and material from the Cache Creek area fills some of this regional need. Mining is conducted by open pit, clamshell dredge, and dragline methods.

In addition to the three major aggregate production areas mentioned above, aggregate is, or has been, mined in other areas and from other formations within the Sacramento region for a variety of applications up to and including use in concrete. Many of these deposits supply aggregate to meet local demand in the less urbanized areas within the region. For example, on the lower flanks of the Sutter Buttes, volcaniclastic sediments are mined and marketed as road base, decorative stone, mortar sand, and for other uses. In the past, andesitic cobble conglomerate of the Mehrten Formation, near Rocklin, was crushed and used for road base and AC. In the foothill areas of the Sacramento region (western Nevada, Placer, and El Dorado counties), sand and gravel has been mined from deposits along local rivers and streams, including materials derived from past hydraulic mining. In addition, crushed stone has been produced from quarries in the igneous and metamorphic bedrock of the region. Dredge tailings are currently being mined for construction aggregate both in the Sacramento area (Folsom-American River dredge field) and the Yuba City-Marysville area (Hammonton dredge field) within the Sacramento region.

The process of gold dredging produces tailings that are unconsolidated and recently washed, but also involves the separation of coarse cobbles from fine sediments, which are then redeposited as alternating layers of coarse and fine materials. Consequently, the material being mined at any point in time is typically too coarse or too fine, necessitating additional stockpiling and blending to achieve an aggregate product with appropriate grain size distribution. Scrap metal from dredges are sometimes buried in tailings, making it necessary to conduct magnetic surveys to locate such potentially damaging objects before mining. Where dredged sediments include overlying soils and/or underlying older, more weathered and less competent alluvium, these strata are typically mixed together by the dredging process. Such mixed deposits typically require additional processing to meet aggregate quality specifications and production of PCC-or AC-grade aggregate may not be economical. The Hammonton dredge field tailings contain a high percentage of hard durable material and relatively little heavily weathered or otherwise potentially detrimental materials that would require significant additional processing to produce a wide range of aggregate products. In contrast, the tailings of the Folsom–American River dredge field have considerable soil overburden and more extensively-weathered Pliocene Laguna Formation sediments mixed into the younger Riverbank Formation sediments. These tailings have only recently begun to be utilized for construction aggregate because of market pressure driven partly by the depletion of other higher quality and more economical deposits in the area.

The temporal and spatial migration of mines in the Sacramento region reflects a gradual depletion of the most desirable or economical deposits. As local deposits of clean, young and well-graded alluvium become depleted, or access becomes restricted due to increasing property values and urbanization, the older, more weathered and friable alluvium of the Laguna Formation, as well as dredge tailings with soil and Laguna Formation clasts, have become economical for some uses. Importation of aggregate from the Cache Creek production area into the Sacramento region began several decades ago to supplement the local deficiency of pea-sized gravel. Importation of aggregate from the Yuba River production area also began several decades ago due to the rising costs of local aggregate and a growing deficiency of sand-sized aggregate. Production of crushed stone from igneous and metamorphic bedrock near Folsom is expected to begin in the near future. A few decades ago, the importation of aggregate from the Yuba City-Marysville area into the greater Sacramento urban area, utilization of much of the Folsom-American River dredge tailings, and utilization of local lode deposits were all considered uneconomical. Their economic feasibility has improved due to changing market conditions, depletion of local resources, growth, and urbanization.

Dimension Stone

primary author: Chris Dennis

Building stone has been mined in open-pit mines in Folsom, Penryn, and Rocklin just east of Sacramento since 1864, and possibly as early as 1850 (Day, 2014). The Folsom State Prison Granite Quarry is located on the east bank of the American River at Folsom State Prison (CSMB, 2011). The material removed from the quarry was granodiorite and diabase. Blocks of the “granite” have been used in the prison buildings, walks, and Folsom dam, and about 8,000 tons per year was used as railroad ballast (CSMB, 2011). The quarry ceased operations in 1944.

The Rocklin quarries were used as a source of “granite” building stone in San Francisco and Sacramento, including such projects as the California State Capital building, San Francisco’s Palace Hotel, and the Central Pacific railroad. As many as 62 quarry pits were opened and abandoned. Rocklin’s largest 19th Century quarry was the Rocklin

Granite Company quarry near Granite Street and Rocklin Road. Another quarry nearby was later used as a dump and is now a California Department of Toxic Substances Control cleanup site, posing environmental concerns for organic solids, pesticides, tank bottom wastes, and unspecified alkaline solutions (Geotracker, 2018: https://geotracker.waterboards.ca.gov). Many quarries are filled with runoff rainwater and debris, hidden in weedy fields. The Big Gun (Capitol Quarry) is being turned into a city recreational park, scheduled to open in 2018. Material from the Griffith Quarry, now also a park, was used in the construction of the U.S. Mint and San Francisco's primary post office.

The material from the Rocklin quarries is quartz diorite from the Rocklin pluton, a Lower Cretaceous intrusion into the Upper Jurassic plutonic (Penryn pluton) and metamorphic rocks (Swanson, 1978). The Rocklin pluton varies from hornblende quartz diorite near Folsom to leucocratic, muscovite-bearing granodiorite in the quarry exposures at Rocklin. The mineral zonation is very regular and is interpreted to be the result of fractional crystallization beginning near Folsom and ending at Rocklin. Intrusion of the Rocklin pluton followed a period of complex deformation in the Sierra Nevada that is referred to as the Nevadan orogeny (Swanson, 1978).

Clay

primary author: Fred Gius

Like many cities, the clay mining industry played a key role in the early development of the Sacramento region. A series of destructive fires between 1850 and 1852 created a demand for common brick as an alternative to wood building materials. Mining numerous local clay sources, ranging from the banks and floodplains of the Sacramento River to 'hardpan' deposits of the older terraces occupied by the river, met this demand (Watts, 1890). Clay from these sources were typically low-grade, sandy clays with impurities that act as fluxes allowing them to develop hardness and strength at as low a firing temperature as possible.

By 1856, Sacramento had 30 brick yards producing 250,000 bricks a day and 500 brick frame buildings, most built after the 1852 fire (Severson, 1973). Bricks from Sacramento were also shipped to San Francisco to meet needs there. Around the turn of the century, neighborhoods encroached closer to the kilns and complained about the smoke and pollution produced by them and forced many independent brick makers out of the business (Mosier, 2003). Others were forced to close or relocate their operations further away from the cities that depended on their product because their land became more valuable for real estate development.

Following the 1906 earthquake, the use of common brick as a structural building material began to decline as building codes were modified to require stronger construction materials better able to withstand seismic events. For example, increased use of reinforced concrete ultimately displaced the need for bricks in the building market. Although brick continues to be manufactured in the Sacramento region today, they are used primarily as pavers and non-structural veneers.

Deposits of high grade clays also occur in the Sacramento region. High-grade clays are perfect for use in manufacturing fire clay products (furnace liners, tiles, pipes) and architectural terra cotta because of the following qualities:

- Refractiveness under high temperatures
- Permanence and durability after burning
- Ability to be molded in the wet plastic condition

Economic deposits of high-grade, kaolinitic clays were discovered and mined in the Eocene Ione Formation in Sacramento, Amador, and Placer counties at least as early as 1864 (Jenkins, 1954). The Ione Formation became an important source of high-grade clay, with deposits from the Ione district (Amador Co) and the Lincoln district (Placer County), along with similar Eocene age deposits from the Alberhill-Corona district (Riverside County). These districts supplied 90 percent of the high-grade clays of the state in the early 1900s (Dietrich, 1928). Figure 41 shows the ground surface expression of the Ione Formation in the Sacramento region.

Due to their desirable ceramic properties, products manufactured from the clays mined from the Ione Formation were used in Sacramento, San Francisco, Los Angeles, and other large cities throughout the nation. For example, Stanford University used the clay roofing tile manufactured in the Lincoln district on most of their major structures and is used today for campus additions. Some companies, like Gladding McBean and H.C. Muddox, which began mining high-grade local deposits and producing clay products in 1875 and 1878, respectively, are still mining and manufacturing clay products today.

The geology of the Ione Formation has been studied in detail throughout the years (Creely and Force, 2007; Wood, 1994; Pask and Turner, 1952; Allen, 1929). During the Eocene Epoch, the Sierra Nevada had become deeply eroded and a subtropical climate had developed. Under the influence of reduced elevations and humid climate, chemical decay of the alumina-rich bedrock proceeded slowly but deeply. The finer products of this erosion, such as quartz sand and clay, were deposited primarily under non-marine conditions, with lesser parts deposited under marine and estuarine conditions, along the margin of the Eocene sea. These conditions gave rise to the valuable kaolinitic clay, quartz sand, and lignite deposits of the Ione Formation (Jenkins, 1955).

Although considered unique by modern standards, the kaolinite and quartz mineral suite of the Ione Formation fluvial deposits is an expected result of geologic factors which do not all coexist today (Wood, 1994). These factors include:

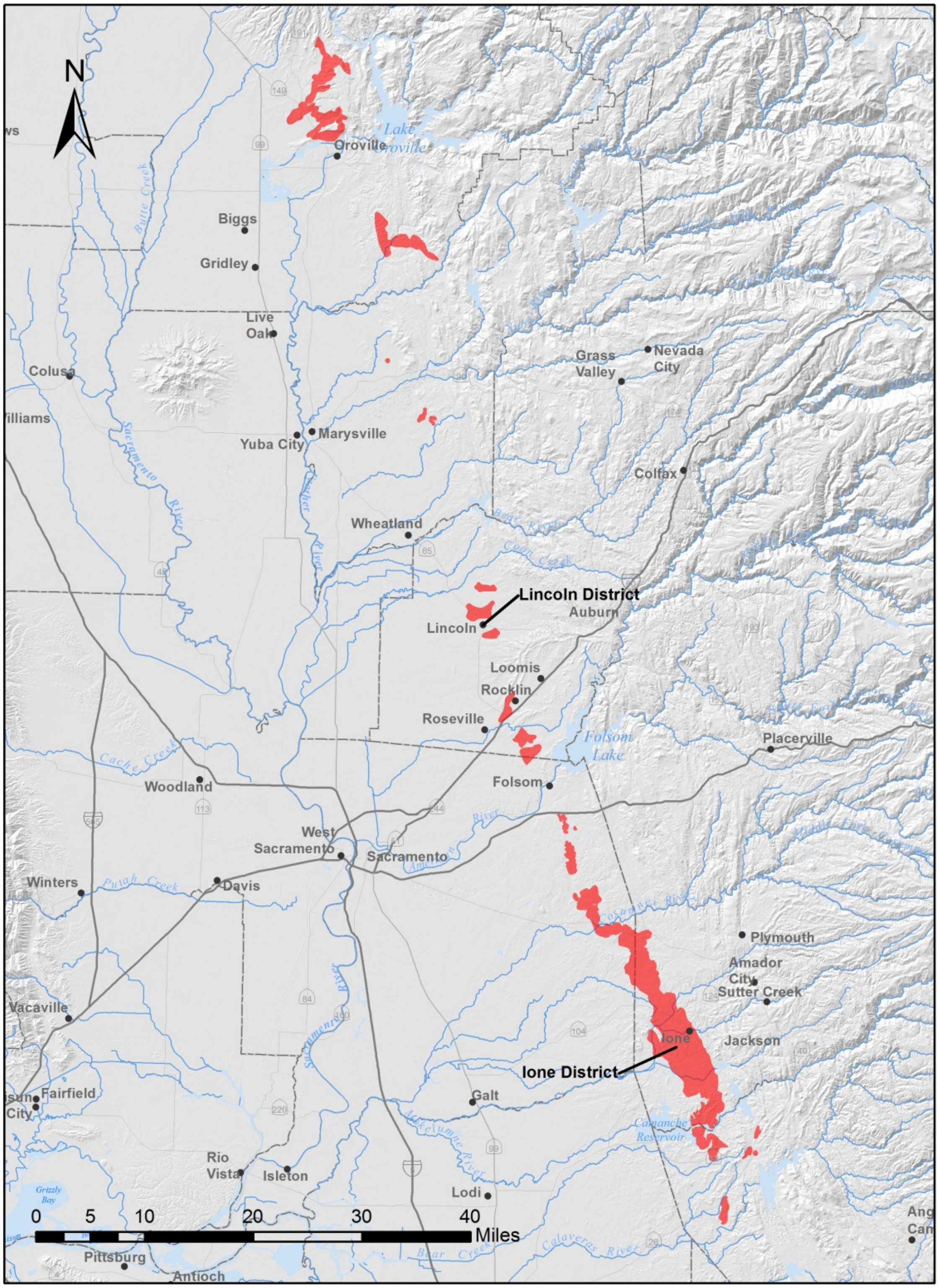


Figure 41. Areal distribution of the Ione Formation showing the Ione and Lincoln districts.

- A prolonged period of chemical weathering producing kaolinitic tropical soils of regional extent
- A significant sea level low-stand leading to erosion and transport of tropical soil material by fluvial systems
- The modification of the fluvial sediment composition through post-depositional weathering and sediment reworking (Wood, 1994).

A detailed geologic map of the Ione Formation in its type area is shown in the 30x60 minute geologic quadrangle map of Sacramento available online from at the California Geological Survey website (Gutierrez, 2011).

Metal Mining

primary authors: Matt O'Neal, Stephen Testa and Chris Dennis

Metal Mining had a profound influence on the physical development of Sacramento and economy of not only Sacramento and the surrounding regions, but California and the United States. Geologically, the various economic ore deposits of the Sacramento region are tied to the Sierra Nevada mountain range, metamorphism associated with the Melones and Bear Mountains fault systems, and erosion of these two features. However, economic development of these ore deposits follows a chronology unrelated to the chronology of their geologic formation.

The three most important metals, based upon economic value, mined in the Sacramento region: gold, copper, and chromium. The impact of gold has been significantly greater than either copper or chromium. Chromium is included in this list, not because it had a major economic impact on the Sacramento region, because it was generally only produced during the world wars as a strategic commodity for defense, but because most Californians' are unaware of its place in California history. Similarly, copper production was a major commodity during the Civil-way with California accounting for more than 15% of the entire United States production. After the 1930s production declined significantly, and after 1964 copper was mostly produced as a by-product of mining other metals such as tungsten (Fred Gius, personal communication, 2018). Other metals have been extracted, but these three metals have had the greatest impact on the development of Sacramento and the surrounding region. They will be discussed in chronological order based on their prominence during development. The first major metal deposits to be mined in the area are, of course, the placer gold deposits that precipitated the California Gold Rush in 1848. The initial development of these deposits lasted only a short while, to be replaced by hydraulic mining (1853-1884). At the same time the Mother Lode was discovered and hardrock mining (1850-1942) started to flourish. In the 1860s copper was discovered, and California became a major copper producer (1860-1946). The last major metal mines to be developed were the chromium mines near Folsom (1894-1955).

There are an estimated 47,000 abandoned mine sites in California, and most of these were gold mines. However, this includes prospects, so the actual number of abandoned mines is much smaller. The number of abandoned mines on state-owned land is 341 (CNRA, 2009). Many of the gold mines recovered little if any gold, but at least eight mines were known to have each recovered more than 1,000,000 ounces of gold. Hardrock mining is thought to account for more than 60% of the gold produced from the Mother Lode. Notably, these operations (from north to south) include the historic lode gold mining associated with the Alleghany mining district (Sierra County), Grass Valley district and Malakoff Diggings (Nevada County), and the Argonaut and Kennedy mines (Amador County). The associated aggregate and gold dredging operations in what is referred to as the Yuba Goldfields (Yuba County) would also contribute significantly to overall gold production in the Mother Lode.

These mining areas, along with other notable mining areas, such as the Pillikin chromite mining district (El Dorado County) and the copper mines of Copperopolis (Calaveras County), have played key roles in the historical development of the Sacramento region and resulted in tremendous growth and impact on the Sacramento region. The environmental legacy of these operations is discussed in “Chapter VIII - Environmental Concerns [Mining]” of this paper.

Gold

Placer Mining

primary author: Matt O’Neal

Although the first known discovery of gold in California was in the late 1700s in Imperial County (Clark, 2005), the California Gold Rush was prompted by James Marshall’s discovery of gold at Sutter’s Mill in 1848. The initial influx of miners used pans, rockers, and sluices to mine placer gold deposits in active channels that drained from the Sierra Nevada mountain range. Despite the relatively primitive nature of these methods, the sheer number of miners coupled with the abundance of easily-accessible placer gold resulted in a still-unsurpassed peak in statewide annual gold production of nearly four million ounces only four years after Marshall’s discovery (Figure 42). As these rich surface placers became depleted, some of the miners moved upslope to lode deposits, while others turned their focus from the active channels to older alluvial deposits. The older alluvium was targeted in two waves. In the first wave, predominantly Eocene age alluvium present in paleochannels outcropping as terraces in the Sierra Nevada mountain range and foothills was targeted by hydraulic mining and (to a much lesser extent) drift mining. In the second wave, Pliocene to

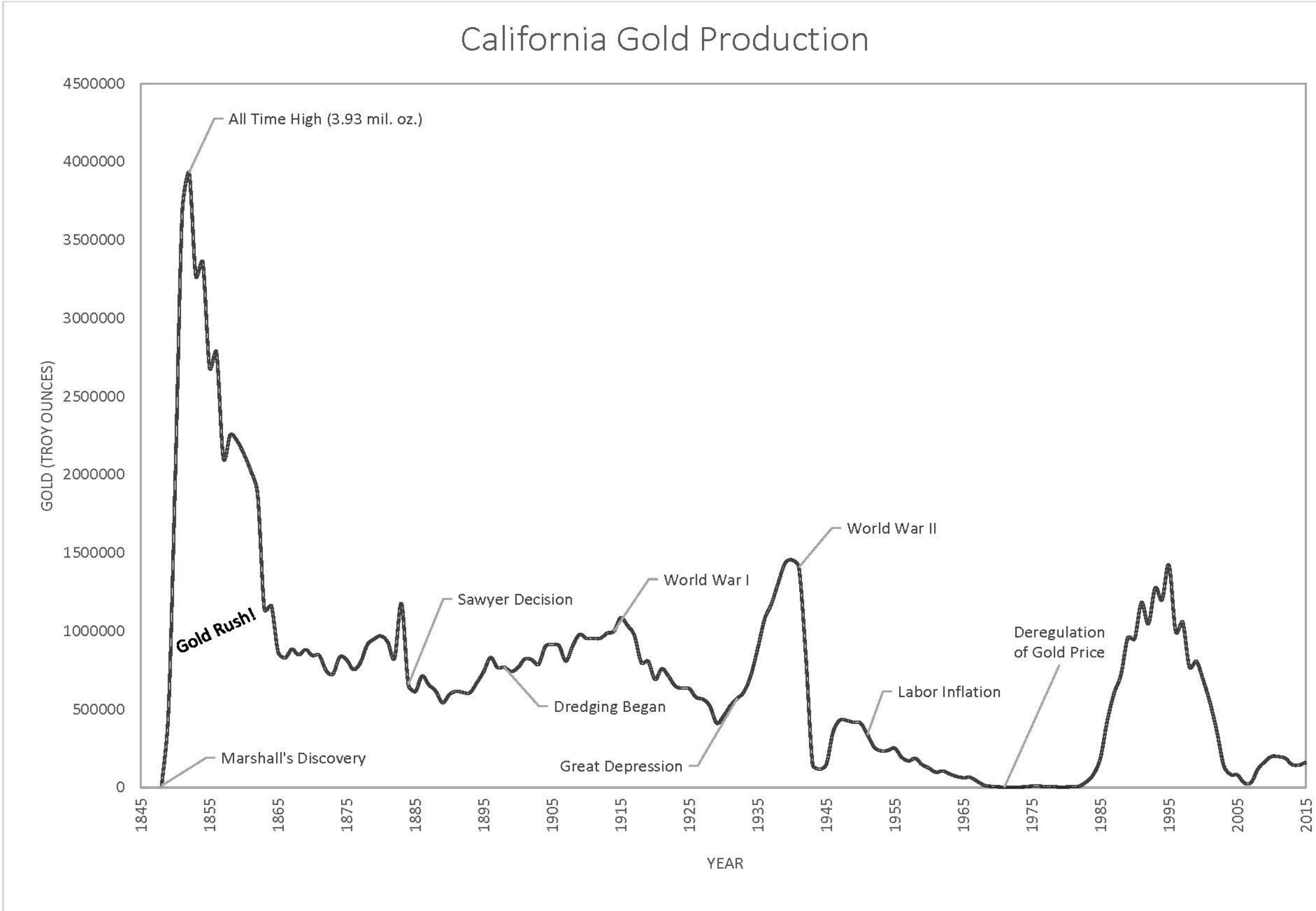


Figure 42. Graph of gold production in California from 1845 to 2015 Data Sources: California Division of Mines Bulletin 144 (years 1848 to 1938); USGS Mineral Yearbook (years 1939 to 1990); Division of Mine Reclamation (years 1991 to 2015).

Quaternary age alluvium present in alluvial fans along the eastern margin of the Great Valley was targeted by off-channel gold dredging (Averill, 1946).

The first significant placer gold target after active surface placers were depleted were what are termed the “auriferous gravels” (Whitney, 1880). These Eocene auriferous gravels are thick and widespread in the northern Sierra Nevada but are largely or wholly absent in the Southern Sierra Nevada. Though the term “auriferous gravels” is only vaguely defined, it primarily refers to gold-bearing Eocene age sands, gravels, silts and clays. The gravel fraction is compositionally dominated by quartz with lesser amounts of Paleozoic to Mesozoic metamorphic and igneous rocks, and the clay fraction is dominantly kaolinite. It is thought to be the upstream-equivalent of the Ione Formation sediments.

These fluvial sediments were deposited in west trending Cretaceous to Eocene age channels which drained the Nevadaplano (DeCelles, 2004; Henry and others, 2012), an extensive Tibetan-like plateau created by Cretaceous to Paleogene crustal thickening associated with the Laramide and Sevier orogenies (Figure 43). The watersheds that fed the paleochannels now present in the Sierra Nevada extended east to a North-South paleodivide in what is now in eastern Nevada (Henry and others, 2012), resulting in extensive and varied sediment sources. The quartz and kaolinite-dominated composition of these deposits is thought to be the result of moderate- to high-intensity chemical weathering during the tropical climate of the Early Eocene Climatic Optimum (Wood, 1994; Zachos and others, 2001). The large geographic extent of the source watersheds and the presence of other gold deposits east of the Sierra Nevada, together with the spatial distribution of auriferous gravels, suggest the gold itself was derived from the weathering of local lode deposits (e.g., the Mother Lode) as well as present or past lode gold deposits as far away as north and central Nevada (Garside and others, 2005; Christensen and others, 2015). Studies of stratigraphic variations in gold concentration in the auriferous gravels indicate a strong pattern of gold concentration in the lowermost sections of the paleochannels (Yeend, 1974). It has also been suggested that placer gold may undergo secondary concentration by microbial processes (e.g., Southam and others, 2009) or by inorganic pedogenic processes (e.g. Christensen and others, 2015). The auriferous-gravel-bearing paleochannels were later deformed by Neogene to Quaternary extensional, transtensional, and dextral strike-slip faulting (e.g., Wakabayashi, 2013; Busby, 2013; Busby and others, 2016).

The auriferous gravels were most efficiently mined by hydraulic methods, which involved the use of high-pressure streams of water to break apart the sediment and transport it into a series of sluices for gold recovery (Figure 44). The water stream was generated by a gravity-

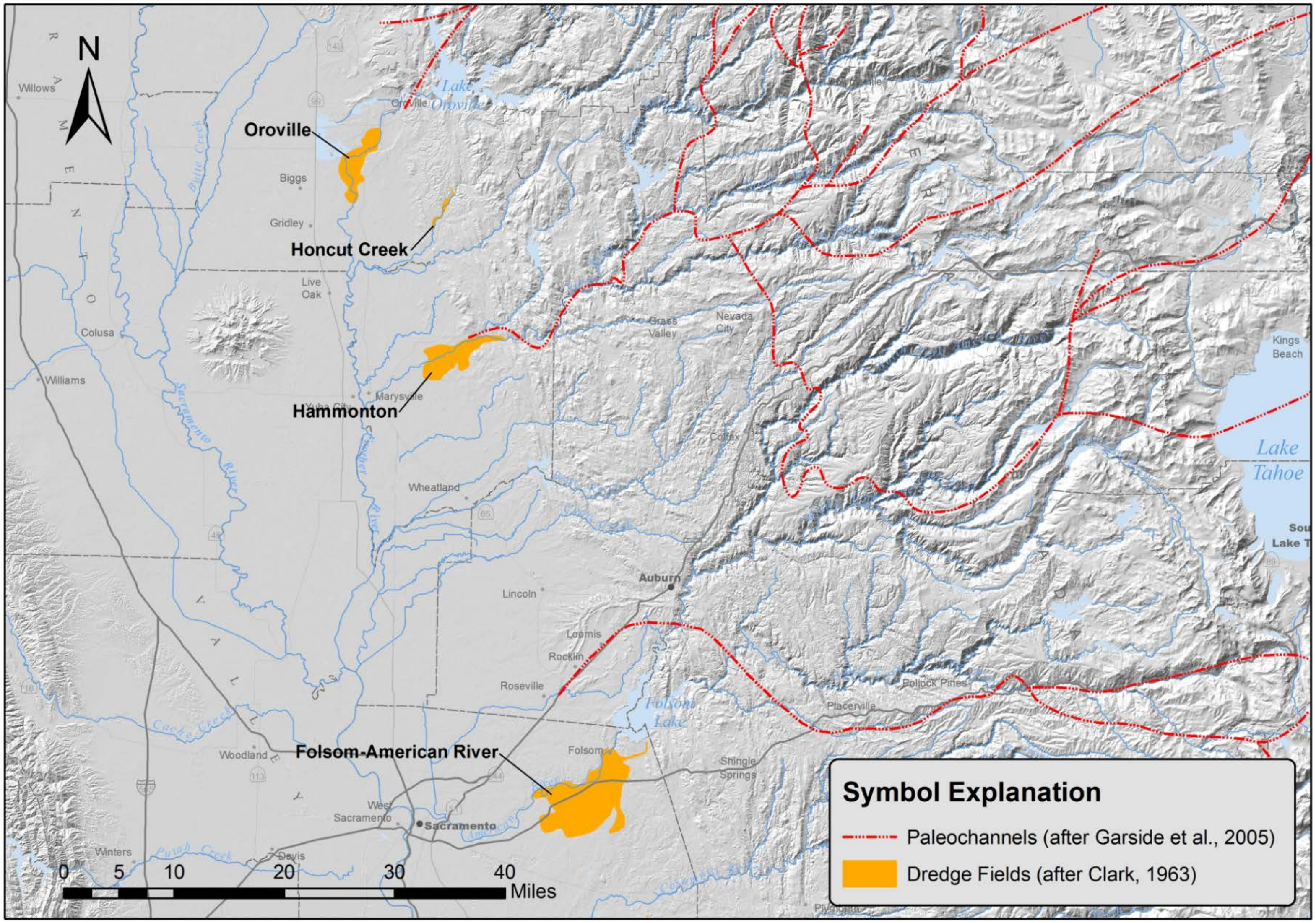


Figure 43. Map of paleochannel paths (after Garside and others, 2005) and dredge fields (after Clark, 1963).

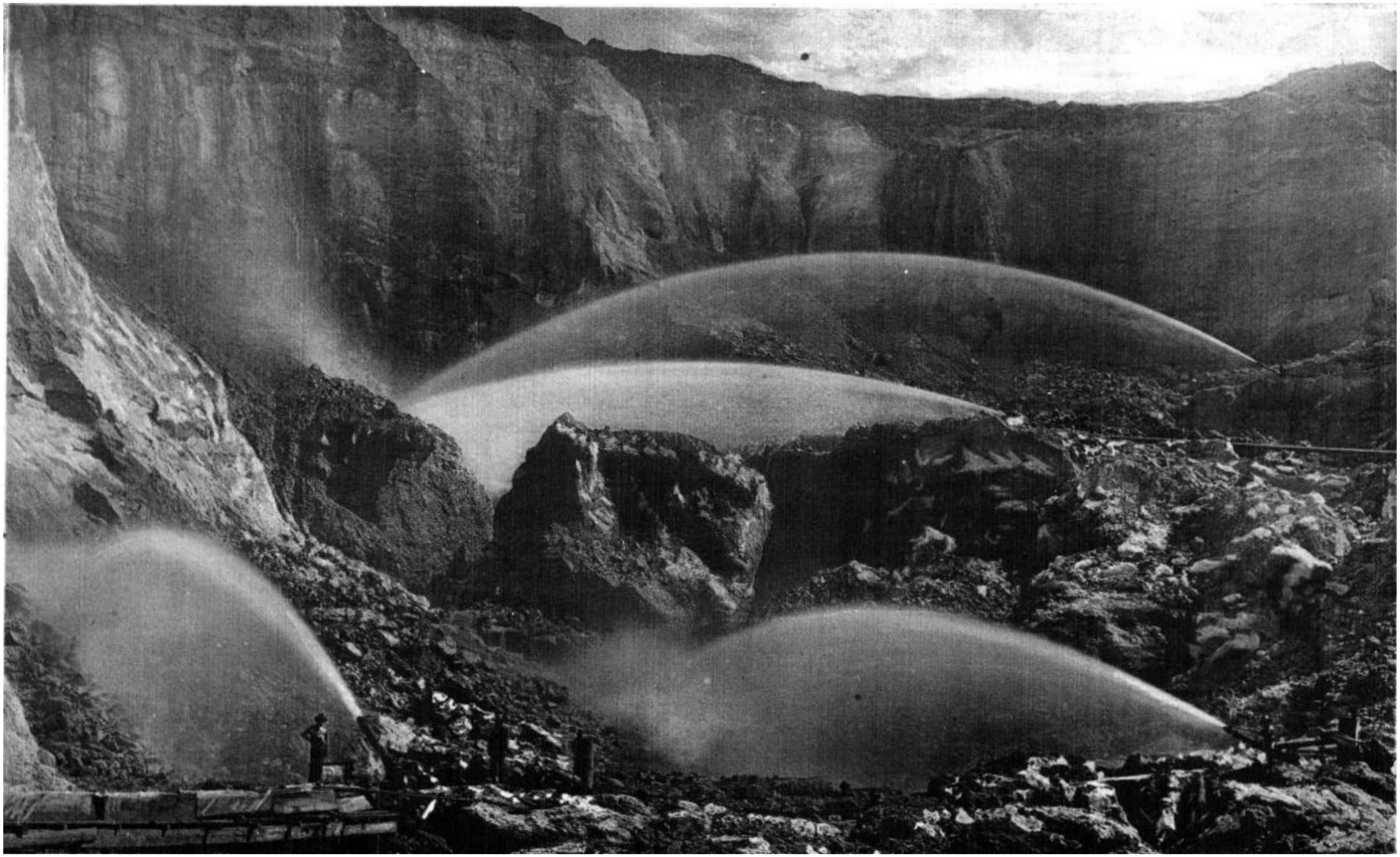


Figure 44. Photograph of hydraulic mining at North Bloomfield (Malakoff Diggins), Nevada County, mid to late 1800s (from Hammond, 1889).

powered water cannon, or monitor. Dams and substantial networks of flumes, ditches, and canals were built to deliver water to the monitors. Hydraulic mining was introduced in 1853. Owing to its ability to process very large amounts of low grade material, hydraulic mining became the dominant mode of placer mining, and even the dominant mode of gold production in the state, from the mid-1850s until 1884 (Testa and Arcand, 2016). This type of mining also created an extreme environmental impact that affected the entire Sacramento region. Details of the environmental impact are presented in "Chapter VIII - Environmental Concerns - [Mining]" of this paper.

A little more than a decade after hydraulic mining in the region was curtailed by the Sawyer Decision, discussed in "Chapter VII – Natural Resources [How Mining Practices Shaped California Water Law]" of this paper, gold dredging became the dominant method of mining placer gold deposits. Though primitive types of gold dredges such as spoon dredges and current-wheel dredges had worked active channels in California since the 1850s, gold production by dredging did not become significant until R.H. Postlethwaite introduced the modern continuous-bucket dredge (Figure 45) to California in 1897. The first such dredge operated on the Yuba River near Smartsville in 1897, but soon sank due to turbulence (Doolittle, 1905). A year later, a second bucket-line dredge began successful operations on the Feather River near Oroville. Gold dredging then began to rapidly proliferate in California. By 1910, several dozen dredges were active in at least 14 different dredge fields. At its peak, more than 70 dredges were operating (Testa and Arcand, 2016). The two most significant dredge fields, in terms of volume of alluvium dredged and amount of gold recovered, are the Folsom–American River and Hammonton dredge fields. Both are located within the Sacramento region.

Dredging of the Folsom–American River dredge field began in 1899, at Mississippi Bar, and continued with little interruption until 1962. Over this time, the dredge field expanded and ultimately encompassed land from Folsom downstream about 16 km to Rancho Cordova, and up to 8 km south and inland of the river (Figure 46). Bluffs along the north bank of the river, and the accompanying change in both geology and topography, restricted all dredging to south of the river, with the exception of Sacramento, Sailor, and Mississippi Bars. The dredging targeted fluvial sediments of the Pliocene and younger, including the sediments of the Laguna, Turlock Lake, and Riverbank Formations. These units are compositionally similar and are predominantly composed of arkosic sand, gravel, silt and clay, with volcanic clasts sourced from the Valley Springs and Mehrten Formations intermixed with Jurassic to Cretaceous igneous rocks from the Sierra Nevada Batholith, and Paleozoic to Mesozoic metamorphic rocks from the foothills metamorphic belt. The gold present in the alluvium was derived from the weathering of lode gold in the Sierra Nevada mountain range and foothills, and from fluvial erosion and remobilization of the older auriferous gravels. The Folsom–American River dredge field was dredged to a maximum depth of 33.5 meters and an average

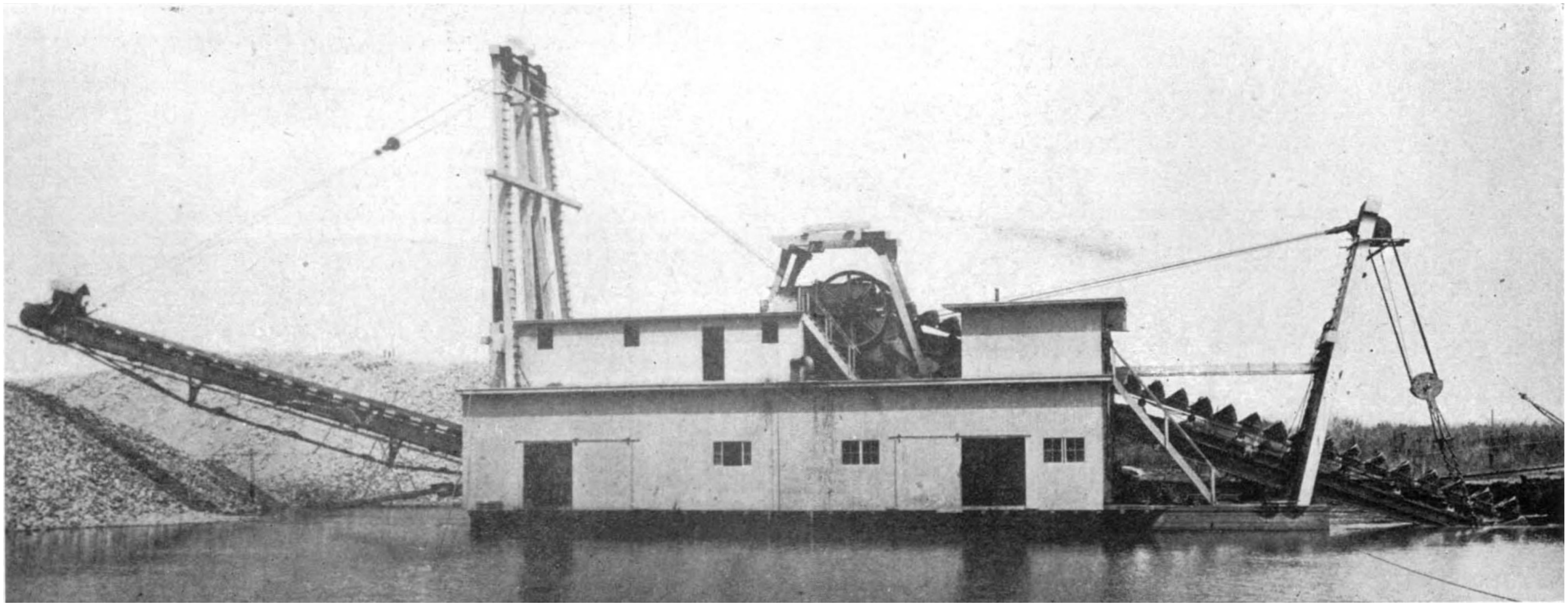


Figure 45. Viloro No. 2 Dredge with 7 cu. ft. buckets, Oroville District (Photo No. 100, Winston and Janin, 1910).

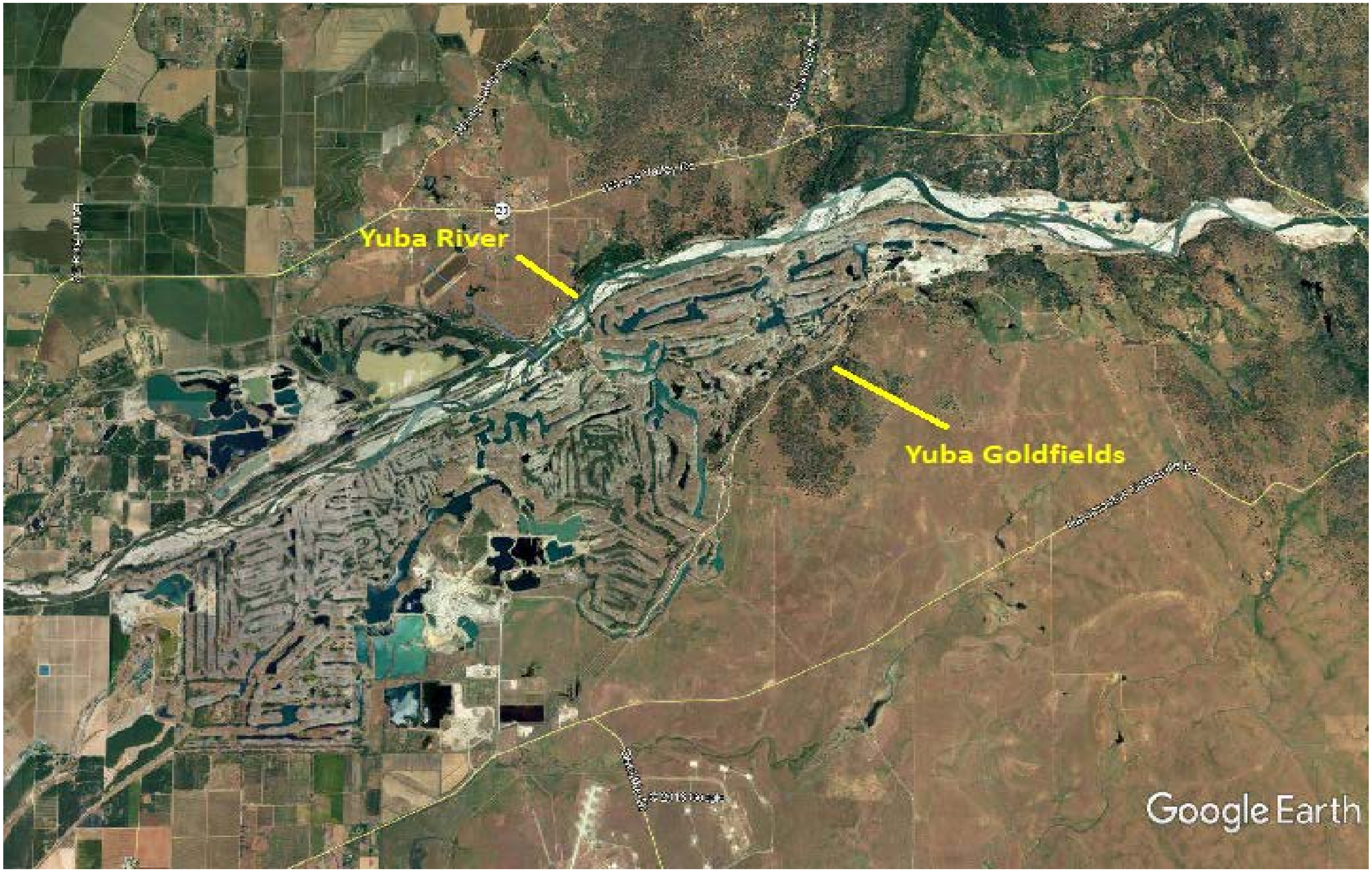


Figure 46. Aerial photograph of the Yuba Goldfields along the westerly flowing Yuba River from Smartsville to Marysville.

depth of approximately 18 meters. Approximately 765 million cubic meters (Mm^3) of alluvium were dredged, and 3.6 million ounces of gold were recovered (Clark, 2005; Long and others, 1998).

Dredging of the Hammonton field began in 1904 and continued essentially uninterrupted until 1968. The Hammonton field (Figure 46), also known as the Yuba Goldfields, is located on the Yuba River approximately 9.6 km upstream of Marysville (Figure 43). This is the most voluminous dredge field in the state, with more than 765 Mm^3 of sediment dredged and an estimated 5.14 million ounces of gold recovered (Clark, 2005; Long and others, 1998).

The alluvium is compositionally similar to that of the Folsom–American River dredge field. Though dredging activity slowed to a halt in 1968, one dredge – the mammoth Yuba 21, has operated intermittently from 1981 to present. This dredge was retrofitted to increase maximum mining depth to 43 meters below water level. One noteworthy feature of the alluvium dredged in this field is its thickness. Alluvium of probable Pliocene age and younger is present to depths of 18 to 24 meters on the upstream end and in excess of 61 meters on the downstream end of the field. The exceptional thickness of gold-bearing alluvium is probably a result of the relatively sharp transition from narrow canyon to fan, resulting in a particularly focused concentration of alluvium. Normal (down-to-the-west) faulting may also be a factor, but this has not yet been adequately evaluated. Historic upstream hydraulic mining also resulted in the deposition of 3 to 12 meters of hydraulic mine tailings ("slickens") in this area, which was regarded as undesirable and uneconomical overburden (Winston and Janin, 1910).

Lode Gold

primary authors: Stephen Testa and Chris Dennis

Extensive hardrock mining was utilized in the foothills east of Sacramento in the metamorphic belt of the Sierra Nevada mountain range (Figure 47). Hardrock mining began in 1850, the same year California became a state, when gold bearing quartz was discovered on Gold Hill in Grass Valley (Wagner, 1980). The gold-bearing quartz was found in a zone called the Mother Lode, which ranges from Tuolumne to Sierra County, and is defined as the richest, most productive lode gold producing area in the State (Wagner, 1980). The Mother Lode is a 2- to 6-km wide by and 193 km long system of linked or en-echelon gold-bearing quartz veins and mineralized country rock that extends from the town of Mariposa north-northwest to northern El Dorado County (Figure 47 and Plate A) (Clark, 1970).

Productive quartz veins are typical of the northern portion, while gold deposits in large bodies of carbonate rock are more common in the south. Typically, quartz veins and ore bodies are tabular and dip steeply to the northeast. The veins consist mostly of white

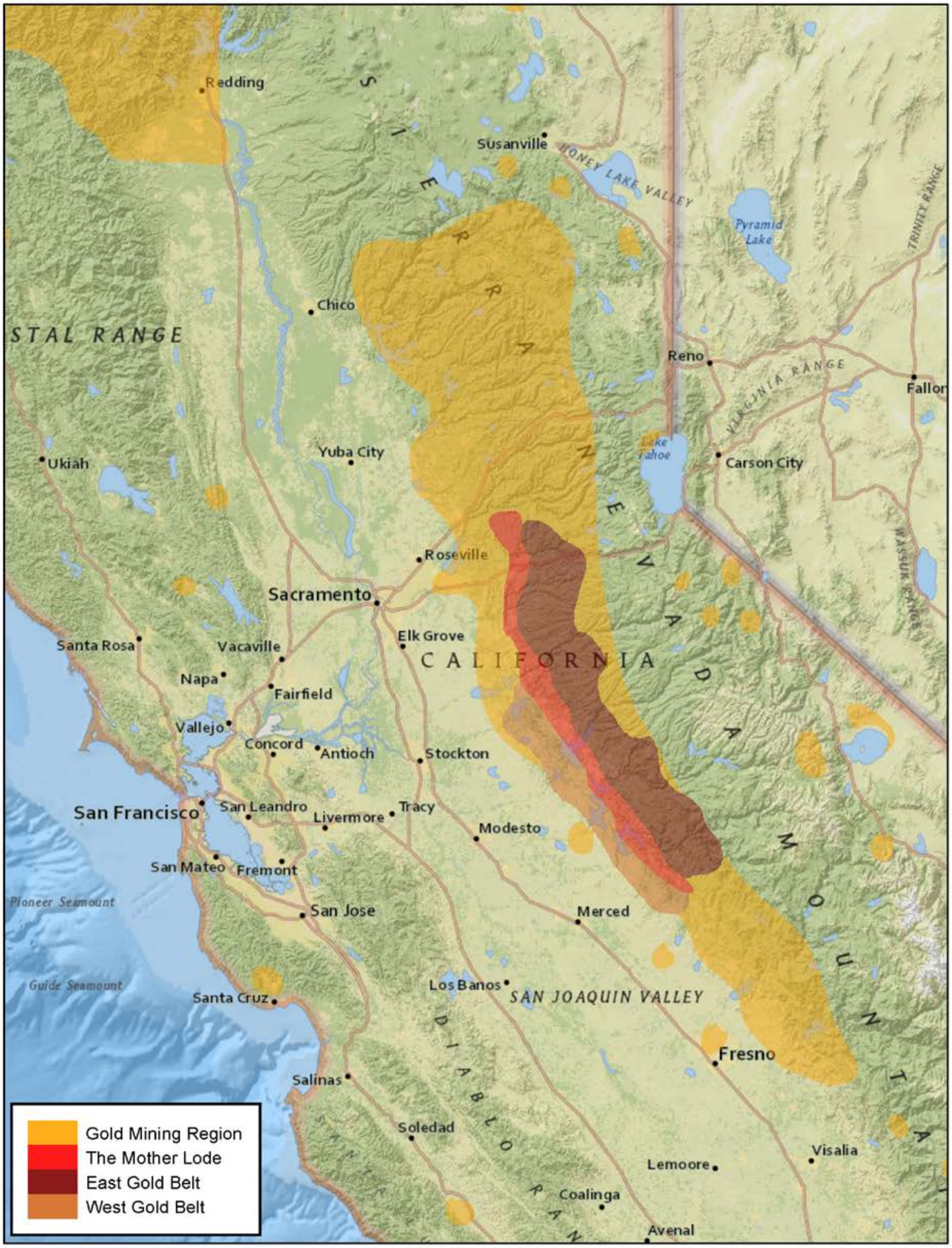


Figure 47. Map of Mother Lode (Source: Christopher Dennis).

quartz ribboned with bands of slate or schist and minor amounts of iron pyrite (fool's gold) with pure gold (Dodge and Loyd, 1984). Between 1848 to 1978, nearly $2.5 billion in gold was produced from this area.

The Sierra Nevada was created during the Nevadan orogeny and contains some of the tallest mountains in the continental United States. This mountain range represents what used to be the western shoulder of a Tibetan-like plateau, called the Nevadaplano, centered over Nevada (Busbya and Putirka, 2009).

The Nevadan orogeny began as an Andean-type continental magmatic arc along the western margin of North America due to subduction of an oceanic plate beneath the North American Plate. Over time, multiple oceanic arc terranes accreted onto this terrane in a Cordilleran-type accretionary orogeny, developing a broad metamorphic belt on the western side of the Sierra Nevada mountain range, east of Sacramento. This metamorphic belt extends approximately 290 km through the foothills of the central and northern Sierra Nevada with a varying thickness of about 32 to 64 km (Clark, 1976).

The metamorphic belt can be divided into two main groups of rocks: an older complex of faulted and folded Paleozoic and Jurassic metavolcanics and metasedimentary rocks with intrusions, and a younger sequence of low-dipping, relatively flat, volcanic and sedimentary deposits of Tertiary and Quaternary age. The latter younger series unconformably overlie the older series. Recent research shows that the Sierra Nevada landscape was shaped, at least in part, by Miocene structural and magmatic events (Busbya and Putirka, 2009).

These rocks have been grouped and classified into various terranes and complexes by different researches over time. Recently, Snow and Scherer (2006) re-evaluated the various groupings and classifications, summarizing them in five geological zones:

- Northern Sierra terrane
- Feather River terrane
- Calaveras Complex
- Jura-Triassic arc belt
- Middle-Late Jurassic arc sequence

These geologic zones are bounded mostly by the Foothills fault system, which includes steep dipping, late Jurassic faults, and the Melones and Bear Mountains fault zones, and are locally juxtaposed along earlier, highly deformed, low-angle faults that are remnants of major terrane-bounding faults (Eldelman and Sharp, 1989). The accretionary history of these geologic zones is complex, especially with the entire Sierra

Nevada metamorphic belt likely accreted by the late Jurassic (Snow and Scherer, 2006).

$^{40}Ar/^{39}Ar$ dating of mariposite that was formed during metasomatic replacement of serpentinite in the metamorphic belt yield ages of 152 million years to at least 122 million years, demonstrating that gold-quartz-carbonate mineralization occurred during this time (Snow and others, 2010). Their research indicated that gold mineralization began in the Grass Valley District and migrated southward along the Melones fault zone, forming the Mother Lode gold belt, with the mineralization of gold corresponding to a period of plutonic inactivity and periods of ductile deformation along the Melones and related fault zones. Based on this finding, the gold-quartz-carbonate mineralization was related to changes in plate dynamics and migration of CO_2-rich ore-forming metamorphic fluids.

From an economic perspective, several surrounding mining districts and operations in the metamorphic belt had a profound economic influence on the Sacramento region and the nation. Notably, these operations include the certain gold districts such as the Jackson-Plymouth gold district in Amador and Calaveras Counties, the North Bloomfield gold district in Nevada County, the Grass Valley gold district in Nevada County, and the Hammonton gold district in Yuba County.

These districts all lie within or adjacent to the historic northwest-southeast trending Mother Lode gold belt. Also, along the foothills of the western slope of the Sierra Nevada, between the valley and west of the Mother Lode gold belt is a belt of copper-zinc mineralization. This belt is about 402 km long and extends through eleven counties, generally parallel to the Mother Lode belt to the east. Significant deposits within this belt include the copper mines of Copperopolis in Calaveras County and the Spenceville Copper Mine in Nevada County. Although these three distinctive areas are noteworthy in their historical development at a time of tremendous growth and influence, their environmental legacy remains with us to this day.

Allegany-Forest City District

Of the Mother Lode gold field, two of the most productive gold mining districts in the Mother Lode are the Allegany-Forest City district and the Grass Valley district. The Allegany-Forest City district is located in Sierra County at the northern end of the Mother Lode (Wittkopp and Babros, 2015). The district is often referred to as the Northern Mines and is uniquely known for its rich high-grade pockets of gold, one of the richest pocket belts in the world. This area differs from the other areas in that nearly all production is obtained from small shoots of high grade ore, which can yield several thousands of dollars per ton. Very little gold is obtained from the low-grade ore. The Allegany-Forest City district differs from the Grass Valley district, where large bodies of lower grade ore are found with only occasional high-grade ore. Mark Twain noted that experienced miners could identify the differences in high grade ore from the differing mines. The district is widely reported to have produced about 2 million ounces of gold, but due to high-grading, as well as the gold that was stolen and never reported, the total amount produced is unknown.

One of the most productive mines in the Allegany-Forest City district is the Sixteen-to-One (Figure 48). The Sixteen-to-One started in 1851, when a group of Hawaiian sailors discovered coarse gold nuggets in a streambed of what is now called the Kanaka Creek. The lode gold mine started in 1896, the same year William Jennings Bryan, as a delegate to the National Democratic Convention, wrote the “Silver Plank” in the platform advocating the free and unlimited coinage of silver at the ratio of 16:1 and inadvertently gave the Sixteen-to-One its name.

The structural setting and the ore-bearing fluids is the same for the Allegany-Forest City and Grass Valley districts. The Allegany-Forest City district is underlain by north and northwest trend beds of metamorphic rocks of the Carboniferous age Calaveras Group. The most abundant rock types within this group are gabbro (often alerted to amphibolite), chlorite schist, conglomerate, quartzite, chert, phyllite, and slate. Numerous north-trending serpentine bodies occur within these rocks. Notably, the amount of granite in the district is minor. However, granite of Jurassic age does form the rock wall of a portion of the Oriental mine vein in the district. A few fine to medium grained dikes have also been described in the district.

Unconformably overlying the Calaveras Group and capping the higher ridges are andesite flows, mud flows, volcanic ash, and inter-volcanic locally auriferous ancient river channels of the Tertiary age Mehrten formation. Palm tree fossils are present in the Mehrten formation, which provide an indication of the paleoclimate during its deposition. The highest gold content occurs at the base of the Mehrten formation in the ancient river gravels, especially where the river once flowed over a quartz vein in the underlying Calaveras Group. Also, at the base of the Mehrten formation is perched groundwater, which results in many surface springs along this contact. In an inversion of topography, the river channels with their gravels and boulders were once the bottom of valleys, but now occur as outcrops high on the mountain ridges, capped by erosion resistant volcanics.

The main structural feature within the Allegany-Forest City district is the north trending Melones fault zone. The zone extends from north of Downeyville to the southern end of the Mother Lode and is the remnant of a compressive or transpressional environment common to convergent plate margins (Original Sixteen to One Mine, 2018). The Melones fault is the conduit for the large volume of hydrothermal fluid that formed the gold vein system. Along this fault zone are numerous bodies of serpentine. The quartz veins that contain gold are associated with the serpentine bodies. Approximately 80 % of the gold produced from quartz veins occurs within 30.5 meters of serpentine.

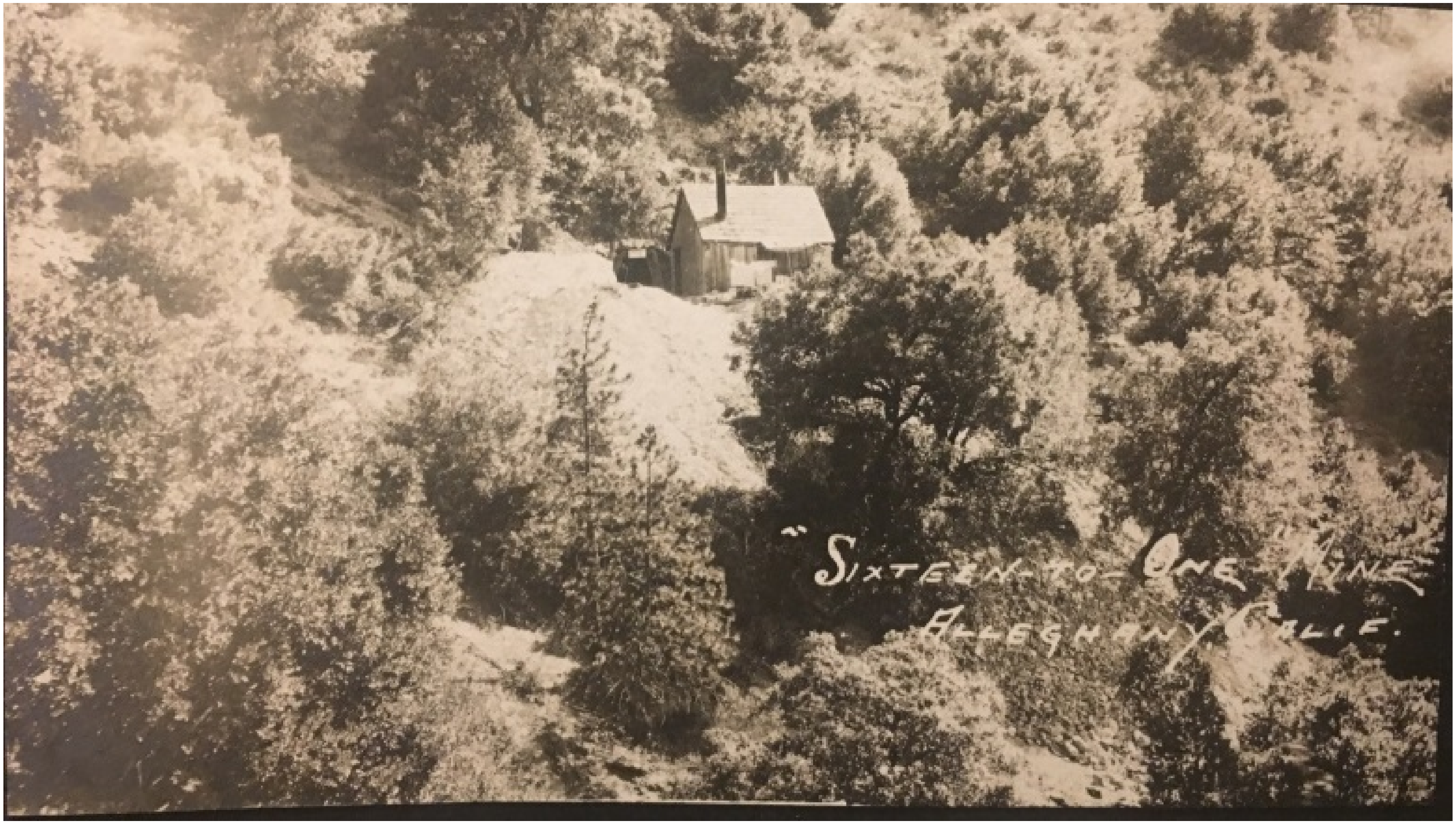


Figure 48. Sixteen-to-One Mine, ca. 1900 (Source: image courtesy of Chris Dennis).

The Grass Valley District, Nevada County

Empire Vein

The Grass Valley mining district in western Nevada County adjoins the Nevada City district to the northeast and the Rough-and-Ready district to the west and was the richest and most famous gold-mining district in California. There are several important mines throughout the Grass Valley district including the Empire (Figure 49), Idaho-Maryland, North Star, Pennsylvania and W.Y.O.D. All these mines were highly productive and many important inventions and improvements in mining and milling equipment were made in the region. Although these mines were all shut down during World War II, all but the W.Y.O.D. reopened shortly thereafter. The Empire Star mine reached a depth of 3,355 meters, making it one of the deepest mines in California, and it contains more than 591 km of underground passages.

The gold district is underlain by metamorphic rocks that were intruded by an elongated granodiorite body approximately 8-km long and up to 3-km wide and cut by various intrusive dikes. East and west of the intrusion are greenstones (metadiabase and metadiabase porphyry) and continuing northeast are amphibolite schists, serpentine, gabbro, diorite and slate.

The ore deposit is heavily mineralized with a very large number of productive veins, which fall into two general groups: those of the granodiorite-greenstone area and those of the serpentine-amphibolite area (Clark,1970). Veins of the granodiorite area intrude the granodiorite or in adjacent greenstones entering the granodiorites at depth, and have gentle dips on the order of 35^o toward the east or west. High producing veins included the Empire, Pennsylvania, Osborne Hill, Omaha, W.Y.O.D., and Allison Ranch veins. Veins of the serpentinite-amphibolite area strike northwest and dip steeply toward the southwest with a few dipping toward the northeast, and include the Idaho-Maryland, Brunswick, and Union Hill veins.

The veins range up to 3 m in thickness and fill minor thrust faults. Ore shoots vary in size and shape, exhibit several generations of quartz, with gold distribution within the shoots erratic. Veins consist of quartz with some calcite and ankerite, free gold, along with varying amounts of sulfides (chiefly pyrite), and smaller amounts of galena, chalcopyrite, arsenopyrite, scheelite, sphalerite and pyrrhotite. Today most of the underground workings are filled with groundwater. In 1975, the State purchased the surface property at the Empire Mine and created the Empire Mine State Historic Park. A more detailed discussion of the park is included below in the Empire Mine State Park section of this paper.

Figure 49. The Empire Mine located immediately east of downtown Grass Valley is on the National Register of Historic Places, a federal Historic District and a California Historical Landmark and Park (viewing southeast). (Source: image courtesy of Stephen Testa).

North Bloomfield Gold District, Nevada County

Malakoff Mine

Some of the largest and most productive mines in California operated in the Tertiary age, gold-bearing gravels between the South Fork and Middle Fork of the Yuba River in Nevada County. Most of the hydraulic gold was mined from gravel that was deposited by the Yuba River during the Eocene. These Eocene river gravels are thick and widespread in the northern Sierra but were not present in the southern Sierra. The region was subjected to significant erosion and environmental damage caused by hydraulic mining, and there was no larger hydraulic mining operation than that which occurred at the Malakoff mine. located in the North Bloomfield district.

The North Bloomfield gold district was discovered in 1851, with hydraulic mining beginning in1853. The Malakoff mine is more than 2,134 m long, 915 m wide, 183 m deep (Figure 50). The Yuba River entered this district from the northeast, and Tertiary gravels overlie bedrock of slate, schist and phyllites (Figure 51). Despite the thickness, most of the gold was from the lower 40 m of blue gravel. Hydraulic mining became the predominant form of mining from the mid-1850s until 1884 (Testa and Arcand, 2016). The section of this paper titled Placer Gold Mining presents additional detail about the Malakoff mine.

Jackson-Plymouth Gold District, Amador and Calaveras Counties

Argonaut and Kennedy Mines County

Most of the important lode gold deposits in Amador County were discovered in the 1850s concurrent with the working of rich Tertiary placer deposits. During this period, a 32 km long belt of gold mineralization, part of the famous Mother Lode, was identified running through western Amador County. The nearby towns of Jackson, Sutter Creek, Amador City and Plymouth flourished in support of the new mines. While many of the local mines had been discovered and several had become large and profitable by 1875, several of the more important mines, including the Argonaut, Kennedy, Central Eureka, Bunker Hill, Fremont-Gover and Lincoln Consolidated Mines, did not become important producers until the 1880s and 1890s.

The Argonaut and Kennedy mines are also located in the Mother Lode of the western Sierra foothills approximately one-mile northwest of the town of Jackson, western Amador County (Figures 52 and 53). The area between the town of Jackson and

Figure 50. Current view of the Malakoff mine (viewing east) (Source: image courtesy of Stephen Testa).

Figure 51. Current view of the ancestral Tertiary Yuba River deposits at the Malakoff mine viewing north (Source: image courtesy of Stephen Testa).

Figure 52. The Argonaut Mine viewing north (Source: image courtesy of Stephen Testa).

Figure 53. View from the Argonaut mine toward the Sierra foothills with the Kennedy Mine headframe visible in the background (viewing northeast) (Source: image courtesy of Stephen Testa).

Plymouth to the north historically was the most productive gold district of the Mother Lode. Between the 1880s until 1942, the mines in this district were producing $2 to $4 million dollars annually with an estimated total production of about $180 million (Clark, 1970). The Argonaut mine was discovered in the 1850s by two freed slaves, William Tudor and James Hager. The mine was largely undeveloped following its discovery until the purchased by the Argonaut Mining Company in 1893. After the purchase, the mine remained in continuous operation until 1942, with exception to three years where the mine was shut down due to fires. The Argonaut mine was one of the deepest gold mines in the country with a bottom depth of 1,698 m. The nearby Kennedy mine also surpassed this depth. Operations at these two mines resulted in many changes in mining methods. In 1922, 47 miners perished in a fire 1,417 m below ground at the Argonaut mine. The unfortunate incident remains one of the worst gold-mining disasters in California history.

The nearby Kennedy claims covered 945 m along strike of the Mother Lode between the adjoining Oneida mine to the north and the Argonaut mine to the south. The Kennedy mine is noteworthy for being the most productive mine in the Mother Lode and for being one of the deepest gold mines in North America, with a vertical depth of 1,792 m. The Empire mine in Grass Valley, which is the deepest lode gold mine in California reached a depth of 3,355 m.

While discovered in 1856, the Kennedy Mine did not become a major producer until after 1885 when the mine was purchased by well capitalized investors and the Kennedy Mining and Milling Company was incorporated. The mine was then operated continuously until 1942. The mine is currently owned by the Kennedy Mine Foundation, an historical preservation organization that offers tours of the remaining historic surface facilities.

The Argonaut and Kennedy mines produced from typical Mother Lode type low sulfide mesothermal gold quartz veins. The producing veins are part of a single NNW-SSE striking, steeply dipping vein system that extends northward through the Kennedy Mine and adjoining Argonaut Mine to the south. In Amador County, the Mother Lode approximately parallels Highway 49 southeastward from Plymouth through the town of

Jackson and referred to as the Plymouth-Jackson district. Bedrock consists of north trending tectonostratigraphic belts of metamorphosed sedimentary, volcanic, and intrusive rocks that range in age from late Paleozoic to Mesozoic. Locally, the Mesozoic rocks are capped by erosional remnants of Eocene auriferous gravels and once extensive volcanic rocks of Tertiary age. The structural belts, which extend about 378 km along the western side of the Sierra, are flanked to the east by the Sierra Nevada Batholith and to the west by sedimentary rocks of the Cretaceous and Jurassic Great Valley sequence. In Amador County, the structural belts are internally bounded by the Melones and Bear Mountains fault zones. Gold deposits in the Plymouth-Jackson district, which incorporates both mines, is dominated by gray to black slate of the Upper Jurassic Mariposa Formation and associated greenstone and amphibolite schist bodies assigned to its Brower Creek Volcanics member.

The Amador County portion of the belt was one of the most productive gold mining areas in the United States, and the Plymouth-Jackson district in Amador County was the most productive part of the County. Mineralization is characterized by steeply dipping massive gold-bearing tabular quartz veins striking north to northwest and dipping between 50º to 80º east. Veins are discontinuous along both strike and dip, with maximum observed unbroken dimensions of 1,981 m in either direction (Zimmerman, 1983), but individual veins more commonly range from structures 915 m long and 3-15 m wide to tiny veinlets. In rare instances, veins are known to reach as much as 61 m thick (i.e., Keystone Vein). Veins may be parallel, linked, convergent, or en echelon, and commonly pinch and swell. Few can be traced more than several hundred meters. At their terminations, veins pass into stringer zones composed of numerous thin quartz veinlets or into gouge filled fissures (Knopf, 1929). Quartz is the dominant mineral component in the veins, comprising 80-90% or more with ankerite, arsenopyrite, pyrite, albite, calcite, dolomite, sericite, apatite, chlorite, sphalerite, galena, and chalcopyrite in lesser amounts of a few percent or less.

The principal producing vein, known as the Argonaut or Pioneer vein, is a fracture-filling quartz vein that strikes N 10º– 18º W and dips between 40º and 63º NE. The same vein is known as the Kennedy footwall vein in the adjoining Kennedy mine where it is also the major producing vein. The Argonaut vein ranges from 2.4 – 3 m wide in the upper workings, but reached as much as 21 m wide on the 1,463-m level. Essentially, all ore was contained in the single large vein, but there were numerous splits from the main vein into the hanging wall (Zimmerman, 1983). The best ore consisted of a ribbon structure of quartz, crushed slate, free gold, and sulfides, which was found within a meter of the foot wall. Auriferous sulfides, primarily pyrite, and to a lesser extent galena and arsenopyrite, comprised about 2 to 2-1/2% of the ore. Other ore materials included pyrite, galena, pyrrhotite, chalcopyrite and tetrahedrite. Gangue materials included quartz, slate, greenstone, amphibolite schist, pyrrhotite, chalcopyrite and tetrahedrite.

The main quartz ore body in the Argonaut mine was locally over 305 m long horizontally and about 1,524 m long vertically, but included barren or low-grade zones (Logan, 1934). Individual ore shoots ranged from 0.3 – 18 m wide with an average of about 1.8 – 3.6 m (Knopf, 1929). The main ore shoot, which had been the mainstay of the Argonaut and Kennedy mines, did not appear until about 427 m downdip from the surface where the upper portion of the veins fissure system intersected a slate-greenstone contact (Zimmerman, 1983). The ore was free milling and most of the gold was recovered by crushing and amalgamation (Clark, 1952).

Technical Advances in Hardrock Mining

In addition to the minerals extracted from the Sierra Nevada mountain range, California also contributed to the advancement of mining technology. California-designed machines and systems found use all over the world. Mucking machines were designed to speed up the process of moving ore and spoils from the cut face (Figure 54). One of the most innovative and important inventions was the Pelton wheel (Figure 55). The Pelton wheel came about when Lester Pelton sold his idea for a new water wheel using cups instead of flat paddles, and directed flow of water directly into the cups, which significantly increased the efficiency of existing water wheel technology. The Pelton wheel, which has remained essentially unchanged from the original design, is in use all over the world today as the primary drive system for non-variable speed turbines for hydroelectric power generation (Green Energy, 2018).

End of a Mining Era

The Empire Mine, and all other mines in the Mother Lode closed during World War II due to the War Production Board Order L-208, which classified gold as a “non-essential resource. At this time, many miners ended up enlisting into the armed services. Order L-208 gave copper a priority because of its military applications, primarily for production of shell casings. In 1945, the Empire Mine reopened, but gold was still at its 1934 gold standard price, $35 per troy ounce. Unfortunately, at that time it cost more to bring gold to the surface than it was worth to mine it. Regardless, mining efforts continued for another decade. In 1956, the Empire closed, but had yielded nearly six million troy ounces of gold. From the discovery of gold bearing quartz on Gold Hill in the Grass Valley district in 1850 to December 31, 1965, when the Sixteen-to-One Mine closed, California was world renown as one of the most important gold fields. Although no longer producing gold bullion the Sixteen-to-One Mine has limited production from the upper (non-flooded) reaches of the mine, and the small quantity produced is destined for jewelry and private mineral collections (Arbogast, 2015).

In the Grass Valley district, groundwater needs constant removal and treatment. Disposal of the water requires government permitting, carries environmental concerns, and could cause losses in efficiency in nearby water supply wells. The rock waste would also need disposal. At the Sixteen-to-One Mine, the gold to rock ratio is higher, resulting in a richer ore. Perhaps new technologies would allow these mines to reopen sometime in the future.

The Argonaut and Kennedy mines closed in 1942. The upper part of the Argonaut mine was kept dewatered and in repair, in hopes of eventual reopening. Due to escalating costs and the government imposed fixed gold price, the mine never reopened, and the Argonaut Mining Company was dissolved in 1948.

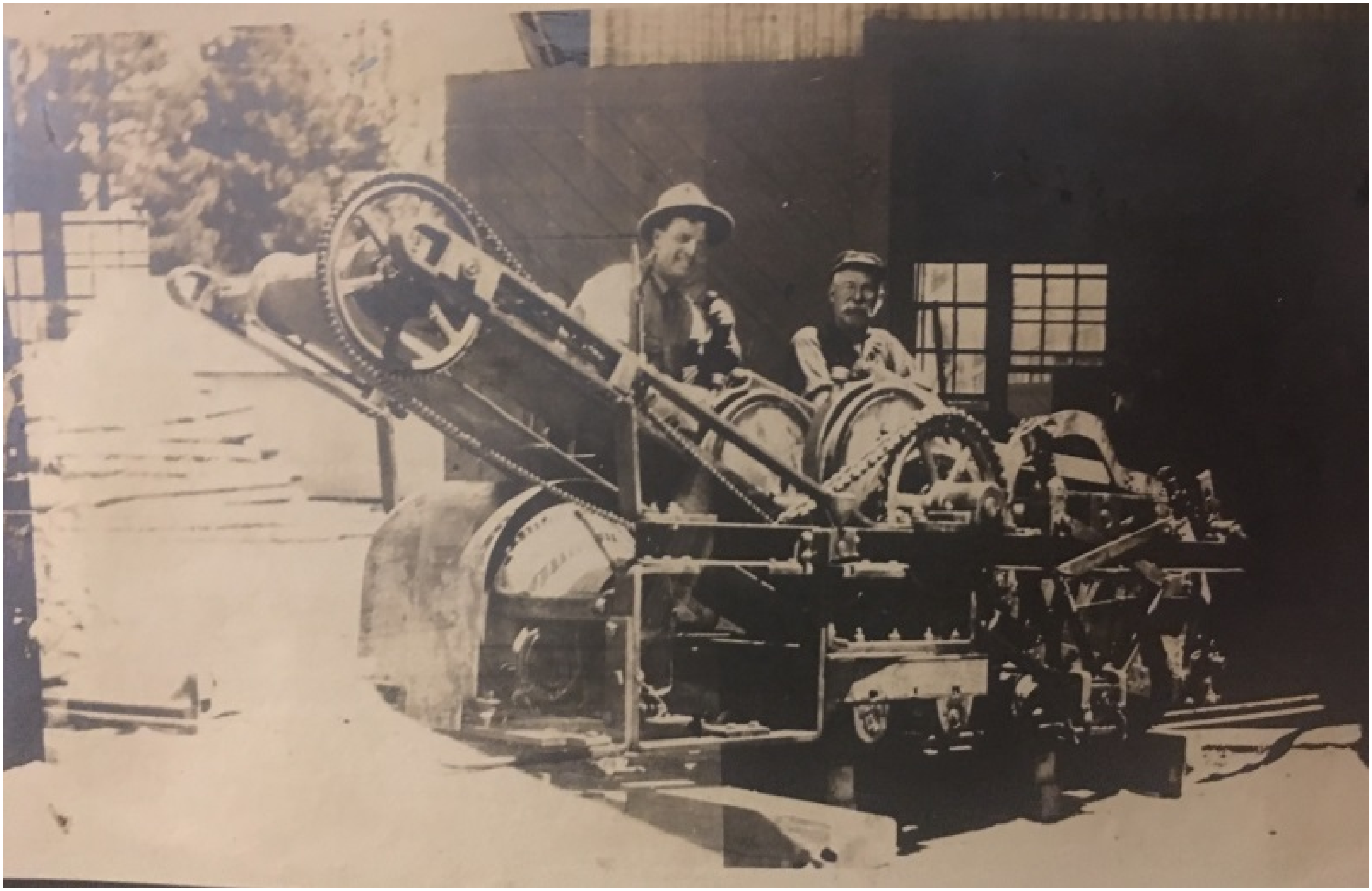


Figure 54. Empire Mine about 1921. Mucking machine developed by Howard Dennis, the grandfather of an author of this paper (Chris Dennis), was used to replace costly hand mucking of ore (Source: image courtesy of Chris Dennis).

Figure 55. Pelton wheel at the North Star Mine and Powerhouse about 1950. (Source: image courtesy of The Union newspaper, Grass Valley, CA).

Foothill Copper-Zinc Belt

primary author: Stephen Testa

Along the foothills of the western slope of the Sierra Nevada west of the Mother Lode is a belt of copper-zinc mineralization. This belt is about 400 km long and extends through eleven counties, generally parallel to the Mother Lode belt to the east. These deposits typically form lenticular sulfide bodies formed by replacement along fault and shear zones and developed by hydrothermal alteration.

Copperopolis, Calaveras County

The largest and most influential copper mines were in the vicinity of the town of Copperopolis in Calaveras County. The town of Copperopolis, located in Calaveras County, is derived from the word “Copper” and the Greek word for city “polis”. From its beginnings in 1860 to the end of World War II, Copperopolis has been directly related to, and affected by, the extraction and production of copper ore. Following the discovery of copper at various locations in 1860 by Hiram Hughes on Gopher Ridge at Quail Hill, other discoveries immediately followed: Napoleon Mine on Hog Hill, Copper Canon Mining District, Union Copper Claim and the Keystone, Calaveras and Empire Claims. Almost overnight the rolling hills of the Sierra foothills were transformed into a booming community reflecting the extraordinary need for munitions and shell casings for the Civil War (1860-1864). This would lead Copperopolis to become the second-most important copper district in the U.S. during this period.

The center of town was destroyed in a conflagration in 1867. With the cessations of the Civil War, and therefore a diminished demand for copper for shell casings, the town was never completely rebuilt. Copper prices soon declined worldwide, and along with high transportation costs and the more readily accessible ore being mined, the town became virtually deserted. In the late 1880s, a modest copper boom revisited the area. The Union Mine was dewatered, and a new smelter was constructed by the Ames Tool Company. These operations curtailed in 1902, and in 1909, the Calaveras Copper Company purchased the Union interests along with most of the town, and operations rebounded. The mine was again de-watered, and a new smelter constructed. Although Copperopolis was no longer the leading producer of copper in California, it did continue as second or third largest producer through the year 1930. Copper prices fluctuated during this period, but the company continued to operate on a small scale, increasing during World War II at the Keystone Mine. All mining ceased in 1945 and mining has been idle since.

Rocks in the Copperopolis area regional strike N 42º W. and bedding, cleavage and schistosity all dip steeply to the northeast. A narrow fault zone approximately parallels the regional strike, dips steeply northeast and includes two major en-echelon faults: the

Foothill fault to the northeast, and the Calaveras fault to the southwest (Clark and Lydon, 1962). Intense chloritization is encountered as a discontinuous belt about 2,743 m long and up to 91 m wide. Mineralization is a replacement deposit consisting of volcanogenic massive sulfides hosted in slate, metavolcanic rock and schist (Clark, 1970). All of these deposits are steeply plunging lenticular deposits in shear zones (Heyl, 1948). The sulfides commonly replaced chloritized metavolcanic rocks, in addition to replacing chloritized granodiorite and slate. The chief sulfides were pyrite and chalcocite, but also included pyrrhotite, galena, tetrahedrite, sphalerite, bornite, magnetite, ilmenite, gold, and silver.

Mine workings included underground openings with an overall depth of about 411 m. The six shafts from north to south were the Keystone-Discovery, the Keystone, the Union No. 1, the Union No. 2, the Union No. 3, and the South Union. These were developed along a 609 m foot length of the mineralized zone.

The total copper production of the Copperopolis copper mines for the period from 1861 to 1946, primarily from the Keystone and Union mines, was approximately 33,000,000 kg (Heyl, 1948). Rich ore containing 10 to >20 percent copper was smelted onsite or shipped to smelters. During the period of 1865 to 1866, approximately 20,865 metric tons per year of rich ore were shipped to Swansea, Wales, for smelting. However, some ore was partially smelted locally, then shipped to other smelters for refining. Low-grade ore (approximately 2 percent copper) was concentrated by flotation, with the concentrates shipped to smelters such as in Tacoma, Washington, or smelted onsite (Robie 1921).

Today, not much is left of the times where copper was king. Large slag and mine waste piles, exhibiting the distinctive rust color of copper gossan remain evident (Figure 56). The large headframes and mill buildings have vanished, although a few buildings from the 1860s survived the 1867 fire, and basement foundations and depressions occasionally observed. Of the more than 60 commercial establishments which once lined the streets of the community in the 1860s, only seven were constructed of brick, and only four are extant: two stores, a church, and the armory. The land today is slowly coming back as subdivisions.

Spenceville Copper Mine, Nevada County

The Spenceville mine was discovered in 1863 and operated between 1863 and 1918. Although of low ore grade, it was one of the longest running copper mines in the state. The ore consisted of massive chalcopyrite with bornite and pyrite, occurring in irregular fissures in a mineralized vein deposit hosted in diabase and granodiorite near the contact with adjacent diorite and granodiorite. The mine was originally known as the Well Lode Copper mine and early efforts from 1863 to 1865 were limited. After several

Figure 56. Surface plant of the Keystone-Union copper mine viewing southeast, with the concrete piers which held the headframe visible in foreground (Source: image courtesy of Stephen Testa).

years of inactivity efforts were revived and expanded in 1877. Up to about 1887, the mine produced about 136,000 metric tons of copper (at about 5% copper) (Russell, 2008). Overall, this mine has produced more than 450,000 kg of Cu. The Imperial Paint Company (1890-1897) did not conduct any mining in 1890, but produced paint from roasted ores on the dumps. This company continued working the mine until 1897. The Spenceville Mineral Company (1904-1915) shipped 13.6 metric tons of pyrite a day to San Francisco to produce sulfuric acid.

There were 15 copper mines within 16 km of town of Spenceville. The ore body at the mine is a mineralized vein deposit hosted in diabase and granodiorite. Irregular in form, the ore body has a length of 91.44 meters and a thickness of about 16.76 meters. Workings include surface and underground openings with an overall depth of 45.72 meters and comprised of a 55-m shaft with levels at 18, 30, and 46 m, also being worked as an open cut.

The legacy of the Spenceville mine was a 4-ha site with 60,000 cubic yards of mine waste and a 2-ha water-filled mine pit (Figure 57). Remediation required a cooperative approach, which included the interaction of various local, state, and federal government agencies, as well as community environmental groups and residents who worked together to accomplish ecosystem restoration. Reclamation goals included the improvement of surface-and groundwater quality, the removal of physical and chemical hazards, the restoration of Little Dry Creek, the retrieval and archiving of historic and cultural artifacts, the development long-term water quality and vegetation monitoring programs and to restore the site for public recreational use. During site restoration of the mine site, cultural and mining-related artifacts were exhumed, surveyed, catalogued, and preserved (Reynolds, 2008).

The restoration required the treatment of the mine wastes and a flooded mine pit filled with acid mine drainage having a pH of 2.5. The pit was dewatered and then backfilled with stabilized waste (Figure 58). Acidic mine-pit water was removed and treated, and treated water was used to irrigate the revegetation forage area. Acidic water underwent a single-phase neutralization process. About 27,634 m^3 of affected water was treated and 708 m^3 of sludge was generated. Tailings were treated with a sugar beet waste as a liming agent for long-term buffering and pH control, with about 10% hematite and 30% jarosite by volume as an amendment. This was complimented by a layer of limestone rock lining the pit, 90% compaction of treated materials, a cover of native soil and revegetated with native species, and reconfiguration of the landscape integrated with the surrounding area based on geomorphic analysis.

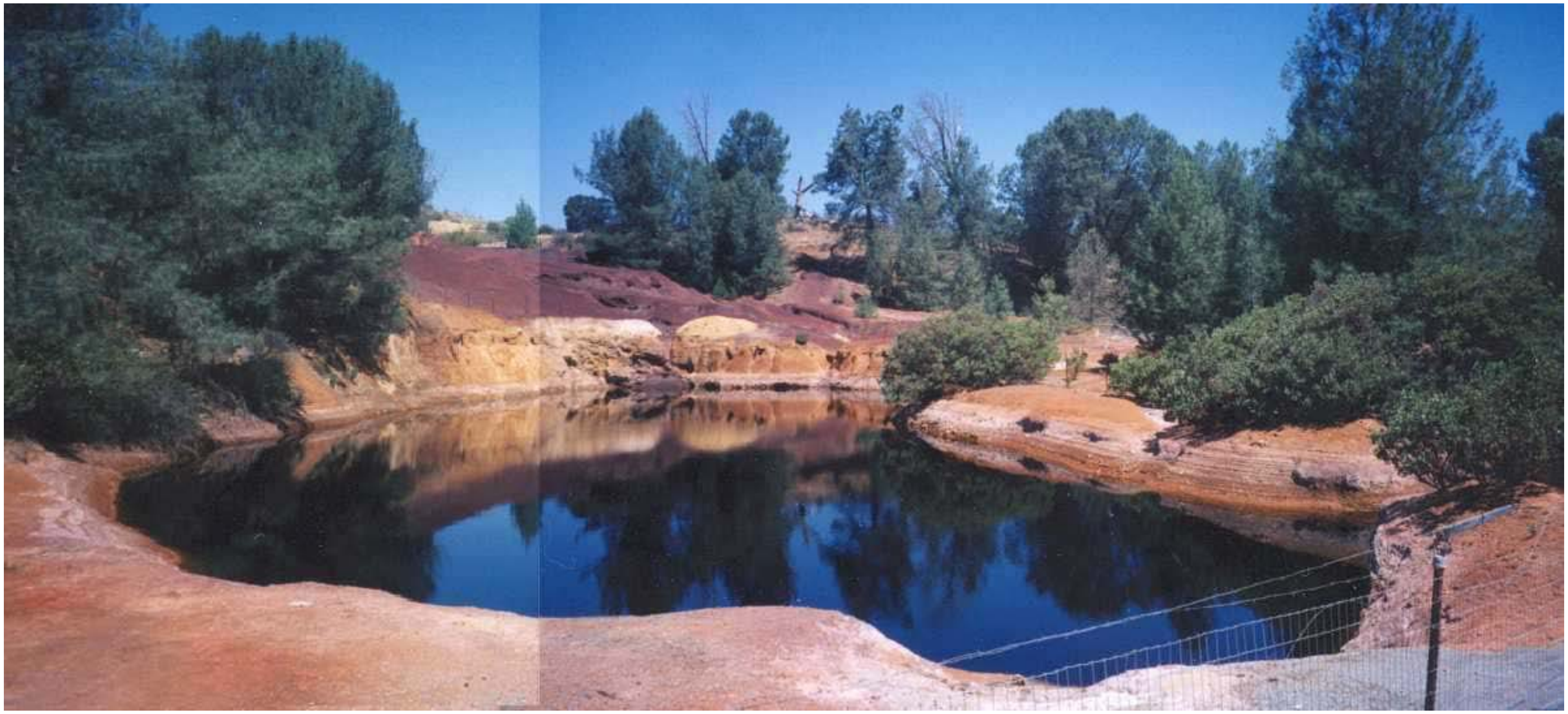


Figure 57. Image showing the 26,500 m^3 pit lake surrounded by 49,670 m^3 of acidic, heavy-metal laden mine waste (Source: image courtesy of the California Department of Conservation, Office of Mine Reclamation).

Figure 58. Image showing the pit lake in 2000 (left) and following reclamation in 2006 (right) (image courtesy of the California Department of Conservation, Office of Mine Reclamation).

Chromium

primary author: Chris Dennis

The Sacramento region is known for its history and unique geologic features, but not for its economic deposits of chromite. Economic deposits of chromite occur in the ultramafic (ultrabasic) rock of the Sierra Nevada mountain foothills in the Folsom dam, Flagstaff Hill area (USGS, 1940). These deposits of chromite were considered strategic mineral deposits during the war efforts of World War I and World War II. The demand for chrome during this time led to higher chrome prices, high enough to make mining the ore in the area profitable. Estimates of the amount of ore mined from 1894 to 1955 range from 34,545 to 44,742 metric tons, depending on the ore grade considered (CDMG, 1951; Loyd, 1984).

Chromite is iron chromium oxide, $FeCr_2O_4$. The chromite deposits in the Folsom quadrangle occur in primarily late Cretaceous ultramafic rocks, which are rich in magnesium and iron and deficient in alkalis and silica (USGS, 1940, CDMG, 1951). Defining minerals of ultramafic rocks are olivine and pyroxene. Other minerals may be present such as minor amounts of nickel, talc, and asbestos.

Economic concentrations of chromite in the ultramafic rocks in the Folsom quadrangle generally occur as podiform deposits within dunitic masses. Concentrations of magmatic ore deposits, such as these, form during crystallization and differentiation and occur as magmatic segregations and disseminations in layered and alpine-type ultramafic intrusive rocks (Loyd, 1984). The chromite deposits in the Folsom quadrangle occur in alpine-type ultramafic rocks associated with the Pine Hill layered gabbro complex and ultramafic rocks of the Sierra Nevada metamorphic belt (Loyd, 1984; GSA, 1980). These rocks also mark the trace of the Bear Mountains fault zone (Loyd, 1984).

The Folsom quadrangle alpine-type ultramafic deposits occur in ophiolitic terranes. These terranes represent oceanic crust and upper mantle rocks generated at a spreading center where the ultramafic rocks and chromite bodies formed from the same silicate melt (CDMG, 1984).

The most prolific mine in the area was the Pillikin Mine, which extracted about 27,579 metric tons of ore from 1916 to 1945 (CDMG, 1951). The Pillikin chromite deposits occur in tabular, podiform deposits in steeply dipping body of ultramafic rock (USGS, 1940). A rough estimate of the chromite milling ore reserves containing over 20 % of chromite is at least 498,950 metric tons (USGS, 1940). This estimate includes an estimated 9,071 metric tons of ore containing over 50-% chromite and 489,880 metric tons of ore containing 20% to 50 % chromite (USGS, 1940). In addition, it was estimated that there may be 3,737,602 metric tons of ore containing 10 to 20 % chromite.

How Mining Practices Shaped California Water Law

primary author: Chris Dennis

Prior to the in 1848, the population of non-native Americans in California was about 5,000 to 6,000 people (Kinney, 1912). One year later, the population swelled to about 110,000 people. The law of the land was Hispanic (Spanish and Mexican law). The Treaty of Guadalupe Hidalgo transferred ownership of California (and other land as well) to the United States in 1848 and preserved Mexican property rights. After California became a territory, Hispanic law was still pervasive but there were jurisdictional issues until U.S. law became firmly established in the new territory (Shaw, 1922). The resulting confusion made conflicts inevitable, but the miners improvised by setting up their own mining districts between 1848 and 1850. These districts adopted rules and regulations to govern themselves, their mining claims, and their use of the water (Shaw, 1922). The rules and regulations controlling the use of water were based on a sense of fairness, which generally allowed the miners, as non-riparian owners (non-water bearing land owners), to appropriate all of a stream water flow for their own use in what later became the *arid region doctrine* (Kinney, 1912). This doctrine prescribed the relationship between a trespasser, who claimed possessory rights, to the water of another person's land (Kinney, 1912). According to the miner's rules and regulations, anyone working a mining claim who was the first to use the water, had right to that water (Kinney, 1912). Under this doctrine, there was no equality among users. Those prior in time had a superior right and could divert and use all of the water. (Kinney, 1912; Irwin, 1855). However, as an important exception, the trespasser's right was valid only against other trespassers and not against the real landowners, such as the federal government, even if the real landowners were not taking action against the trespassers.

These possessory rights conflicted with the old English common law and the common law of the eastern states, which allowed land owners to use the water flowing on their property as long as they did not diminish the supply of water available to persons downstream or unreasonably disrupt the flow and adversely affect users and landowners upstream (Shaw, 1922). This was the *doctrine of riparian rights*, which arose out of equality among all riparian users and land ownership (Shaw, 1922). Under this doctrine, a disruption, diversion, or unreasonable detention of the flow of water from its natural channel was a trespass (Shaw, 1922).

Just after California was admitted to the Union in 1850, California adopted two far-reaching statutes. The first statute stated that the common law (doctrine of riparian rights) would be used to the extent it was consistent with the state and federal constitutions and the laws of California (Kinney, 1912). The second statute stated that the mining rules, regulations, and customs of the State of California (*arid region doctrine*) would be used to address water rights. These two far-reaching statues were in direct conflict (Kinney, 1912). However, because the federal government owned all the land comprising the mining districts but did not take any action against the trespassing miners, the common law doctrine of riparian rights was not enforced (Kinney, 1912; Shaw, 1922; Atchison, 1874). The courts, however, worked out disputes between the miners using common law property concepts, and brought a degree of equality to the miner's appropriation right (*first in time, first in right*) (Wiel, 1912). The miner's right to water became restricted to the quality and quantity for which it was appropriated (Atchison, 1874).

The California Supreme Court was not passing judgment on the trespasses by the miners because the owner in interest, the federal government, had not pressed a claim (Shaw, 1922). No case was brought to the California Supreme Court. In further support of the miners in the aftermath of the Civil War, many western congressmen persuaded the rest of Congress to pass an Act precluding the federal government from asserting its rights against the trespassing miners, ejecting the miners, and selling the land as a method paying off the war debt (Kinney, 1912). This Act, the Revised Statutes of the United States related to Mineral Lands and Mining Resources, opened the "mineral lands" for exploration to any citizen subject to, among other things, the "local customs or rules of miners in the several mining districts" (Kinney, 1912). The mining rules and regulations were now codified at the federal level.

As irrigation agricultural production rapidly increased during the 1870s with California's population, California's economy shifted toward agriculture with its own demands for water and flood protection. Agricultural interest soon became influential and inevitable tension developed between mining and agriculture due to the debris discharged down the rivers from hydraulic mining operations (Tarlock, 1994). Miners appropriative rights and riparian rights were, once again, in conflict.

In the seminal case, *Woodruff v. North Bloomfield Gravel Mining Co.* (1884), known as the Sawyer Decision, several mining companies were permanently enjoined from hydraulic mining (Woodruff, 1884). The advent of hydraulic mining had grown from the use of water hoses 2.6 centimeters in diameter, in 1855, to hoses 10.2 to 22.9 centimeters in diameter at the time of the lawsuit (Woodruff, 1884). The hydraulic mines operated day and night using nozzles called "monitors" to discharge water at a pressure of 3,447 to 6,895 kilopascals from 91 to 152 meters away (Woodruff, 1884). As the court noted, "The amount of debris discharged into the rivers by these operations can only be duly appreciated by actual observation" (Woodruff, 1884). The debris from these mining operations were interfering with domestic and agriculture water consumption and navigation of some of the lower rivers such as the Sacramento, Yuba, Bear, Feather, and American (Woodruff, 1884). The river beds were filling with debris, changing the gradient of the rivers and decreased their freeboard and depth. Dams up to 15-meters high were constructed to contain the debris and mitigate the effect the debris would have on the rivers (Woodruff, 1884).

The hydraulic mining displaced more than 1,555 Mm^3 of material (Gilbert, 1917). From 1849 to 1909, it was estimated that the volume of material displaced in total, was:

- 1,555 Mm^3 from hydraulic mining (Upper Feather River, Yuba River, Bear River, American River, and streams tributary to lateral basins of Sacramento River and, Mokelumne River to Tuolumne River).
- 1,394 Mm^3 from all mining tributary to Sacramento River (including ordinary placer mining, quartz mining, and drifting).
- 1,665 Mm^3 from all mining tributary to Suisun Bay (including ordinary placer mining, quartz mining, and drifting).

The amount of materials displaced by hydraulic mining was nearly eight times the volume of material moved in making the Panama Canal (Gilbert, 1917). The debris washed down the rivers to the Sacramento Valley and the apex of the debris flood moved through the Delta and into San Francisco Bay (Gilbert 1917). The apex of the debris flood left the mines in 1883, moving past the mouth of the mountain canyons in about the year 1900, and past the mouth of the Yuba River in about 1905 (Gilbert, 1917). The rivers became choked, reduced flow, resulting in periodic flooding downstream, including Sacramento. Minor flooding became amplified by the mining debris raising the elevation of the river beds. For example, in 1862, due to heavy precipitation, both Northern and Southern California flooded, forming an inland sea more than 322 kilometers long and 97 kilometers wide (Kelley, 1989). The flooding caused widespread death and destruction in the central Valley. Mining debris covered the agriculture fields in the Sacramento Valley (Kelley, 1989).

Landowners built levees in response to the repeated flooding caused by the mining debris coming down the rivers and then they formed local governments to address flood problems (Kelley, 1989). In 1868, the California legislature authorized the creation of local reclamation districts, which allowed the formation of hundreds of reclamation districts throughout the state and a boon to agriculture (Kelley, 1989). These reclamation districts were responsible for managing and maintaining the levees, fresh water channels, or sloughs, canals, pumps, and other flood protection structures in the district boundary. Many of the reclamation districts are still in existence today. A more detailed discussion of the levee system in the Sacramento drainage basin is provided in "Chapter X – Major Engineering Structures [Levees and Levee Flood Control System]" of this paper.

As California's population continued to grow during the late 1800s and early 1900s, the use of groundwater became increasingly important as a water supply for agriculture industries. A deviation from the groundwater common law of *to whom belongs the bottom, belongs every point to the bottom* became necessary (Katz, 1902). The common law rule was causing increasing injustice and so was overturned in favor of a rule confining each landowner to a reasonable use of groundwater (Katz, 1902). The courts considered this modification of the common law rule necessary to further California's policy of developing resources for future growth (Wiel, 1912). This reasonable use meant that a landowner could use groundwater so long as it did not interfere with a neighbor's reasonable use of groundwater. This became known as the *correlative rights doctrine* (Wiel, 1912). In the Central Valley litigation, Katz v. Walkinshaw (1902), the court also held that the rules for appropriation rights as applied to surface water users were the same to be applied to groundwater appropriators (Katz, 1902).

However, the Katz rule in the Central Valley did not produce the same effect as it did in Southern California where the doctrine of correlative rights was further developed (Wiel, 1912; Tarlock, 1994). In the Central Valley, the groundwater management system was more centralized and as a result, the farmers effectively blocked any adjudication or a state administered groundwater system. The result was that groundwater withdrawal occurred to a point beyond significant overdraft (Wiel, 1912; Tarlock, 1994). Irreversible groundwater extraction, partial collapse of aquifer(s), and groundwater induced land subsidence occurred in the Santa Clara Valley, up to about 4 meters of aquifer collapse occurred. In the San Joaquin Valley, up to 8.8 meters of aquifer collapse occurred (Poland, 1988). The problem appeared to have been alleviated through state intervention in 1967 when large amounts of surface water was supplied to the region through the State Water Project, in an effort to reduce groundwater consumption (Poland, 1988). However, the recent drought and environmental concerns in the Sacramento-San Joaquin River Delta have demonstrated that the problem of overdraft continues. Land subsidence continues and even the State Water Project and flood channels in the San Joaquin Valley have lost conveyance capacity due to this groundwater-pumping induced land subsidence.

Riparian rights and the prior appropriation doctrine butted heads again in the Lux v. Haggin (1886) litigation (Lux, 1886; Freyfogle, 1985). The court decided that although prior appropriation gave possessory rights to the first appropriator, it did not give better rights against a riparian landowner (Shaw, 1922; (Woodruff, 1884), except in the case of some municipalities such as Los Angeles and San Diego, which asserted *pueblo water rights* as being superior to riparian rights because they were derived from Hispanic law (Vernon, 1895). The influence of Hispanic law in California was more convenient than an actual foundation from which California courts based their decisions. American romanticizing of the Spanish missions, pueblos, and law influenced judicial decisions beginning in the 1880s (Reich, 1994). There is also evidence that the California courts intentionally misconstrued Hispanic law to support the prevailing policy of future land development in California (Reich, 1994). Through a series of cases, this resulted in the development of a doctrine called *pueblo water rights*. These rights were attributed to Hispanic law, and gave municipalities, like Los Angeles and San Diego, rights to appropriate water over other users. This doctrine was crystallized in 1895 in Vernon

Irrigation Co. v. Los Angeles litigation, where the city's interest in the water was given priority to all other riparian users upstream and downstream (Vernon, 1895). The only limitation imposed on the city was its own needs.

The *pueblo water doctrine* was later extended to apply to areas outside the original pueblo boundary to newly incorporated parts of the city, to groundwater, and gave these municipalities absolute and exclusive water rights. In the Los Angeles v. Glendale (1943) litigation, Los Angeles' monopoly over the water was furthered, giving Los Angeles rights to all the water from the Los Angeles River and its tributaries, all reclaimed flood water, all stored and unused agricultural water from the Owens Valley (Los Angeles, 1943; Reich, 1994). In 1975, in the Los Angeles v. San Fernando litigation, Los Angeles acquired the right to the entire Los Angeles water basin including groundwater, all under the rubric of *pueblo water rights* (Los Angeles, 1975). The only limitation imposed was that Los Angeles did not have a right to groundwater in a groundwater basin hydraulically independent from the Los Angeles River (Los Angeles, 1975).

The doctrines of appropriative rights and the public trust also give rise to conflict. The *public trust doctrine* not only authorizes the state to take public trusts into account, but compels it to do so (Dorrity, 1992). In National Audubon Society v. Superior Court, the California Supreme Court precluded the appropriative use of stream flows for water supply purposes without taking into account the *public trust doctrine* (National Audubon Society, 1983). In California, the public trust includes the areas of environment, recreation, navigation, commerce, and fishing (National Audubon Society, 1983).

Although the early anti-hydraulic mining cases were primarily designed to protect agricultural and navigational water use, they had the additional effect of limiting the ecologically damaging practice of hydraulic mining (Los Angeles, 1975). Express consideration of environmental uses as beneficial, developed out of the growth of other legal doctrines and legislatively (state and federal) imposed requirements. At the state level, these legislative requirements include the California Environmental Quality Act and the Porter-Cologne Act. At the federal level, they include the Clean Water Act and the National Environmental Protection Act. A discussion on the development of water supply and management in the Sacramento region and the current regulatory framework in California is presented below in “Chapter VII – Natural Resources – [Current Regulatory Framework]”.

Water Resources

primary authors: Chris Bonds and Kent Parrish

History of Water Resources Development in the Sacramento Region

The California Department of Water Resources (DWR) published an excellent evaluation of groundwater resources in Sacramento County from 1849 into the 1960s (DWR, 1974). Much of the information on water use history from that report is summarized below.

Sacramento County's historical water use centered on Sutter's fort and the beginnings of the California Gold Rush in 1849. John Sutter Sr. used water from the Sacramento and American Rivers to irrigate his lands and agricultural enterprises (grains, a ten-acre orchard, a heard of thirteen thousand cattle, and two acres of Castile roses) (PBS, 2001). The first water supply facilities were constructed in 1849 and 1850 at the current "I" Street in Sacramento. The historical facilities consisted of pumps to lift Sacramento River water into elevated storage tanks. Water was sold by the gallon and transported in wagons (DWR, 1974).

The crude water supply infrastructure provided only a limited amount of water for fire control. In 1852, fire destroyed many Sacramento settlements. As a result, Sacramento citizens organized the first municipal water company on the west coast of the continent. This newly created water company acquired the 1850 water system and began operations in April 1854 (DWR, 1974).

In the 1850s, hydraulic mining in the eastern portion of Sacramento also created a need for water supply and distribution systems development. The American Ditch Company was organized in 1854, and a 53 km long canal was constructed, which terminated at the community of Folsom, to supply American River water for placer mining uses. When hydraulic mining in the Sierra Nevada declined (ending in the historic Sawyer Decision in 1884), the water from the canal began to be used for crop irrigation. In the 1880s, the American Ditch Company was acquired by the Cox and Clarke cattle firm. Cox and Clarke reorganized the company into the North Fork Ditch Company and this private water company was the sole supplier of surface water to what is now the wholesale water service area of the San Juan Suburban Water District. Other water districts were formed during the last part of the 19^{th} and early part of the 20^{th} centuries (DWR, 1974).

The lack of efficient pumps and power supply prevented well use for irrigation until about 1879. During that year, an irrigation well was drilled (approximately 46 cm in diameter and 7 m deep) near Woodland, California and its success led to further well drilling. By 1913, approximately 4,330 hectares (ha) of land in Sacramento County were irrigated by groundwater. The increasing use of groundwater resulted in the groundwater table dropping about one foot per year. By 1928, approximately 28 % of the irrigated land was supplied by groundwater, and the groundwater table continued to drop (DWR, 1974). The Great Depression of the 1930s temporarily slowed the spread of farming and irrigation demand. But shortly after the start of World War II the water needs of Carmichael, Citrus Heights, and Fair Oaks Irrigation Districts exceeded their surface water supplies. As a result, they began using groundwater during peak demand periods (DWR, 1974).

The City of Sacramento began utilizing groundwater in the 1940s and annexed other areas served by groundwater. Groundwater use in Sacramento County has increased steadily from the early domestic wells of the 1850s, through the expanding irrigated agriculture of the early 1900s, to the increased urbanization of the 1950s, and to the present time (DWR, 1974).

Water Supply and Demand

Successful water management in the Sacramento Region continues to be an important part of a thriving economy and culture. But the current collaboration and successes regarding sustainable water management have not always existed (SGA, 2014). During the 1970s and 1980s, significant growth occurred in the greater Sacramento region, resulting in continued and increasing demands on surface water and groundwater resources. Proposals to increase surface water diversions faced potentially prolonged legal challenges because of stressed habitats along the Lower American River (Water Education Foundation, 2002). Groundwater levels in much of the Sacramento region continued to decline until the California Department of Water Resources identified Sacramento County as being in a state of groundwater overdraft (DWR, 1980). This necessitated the development of a new water management process that became known as the Water Forum (SGA, 2014). The formation of the Water Forum is discussed in further detail in a following part of this section. The following text is from the Water Forum web page (Water Forum, 2015)

“Water purveyors in the Sacramento region primarily pump groundwater and divert surface water to meet their customer’s needs. Surface water is obtained from the American and Sacramento rivers and from Folsom Reservoir. Collective efforts on the parts of the regional water purveyors have increased the regions ability to strategically manage surface water diversions to augment groundwater supplies.” (Water Forum, 2015) (Figure 59). Figure 59 illustrates the source of water for the region’s water purveyors (Water Forum, 2012). The Water Forum Agreement (WFA) outlined diversion limits for each supplier and the facilities that would likely be needed to divert, treat, and distribute this water. The number and scope of completed water projects demonstrates the power of regional collaboration (Water Forum, 2012). One example is the Freeport

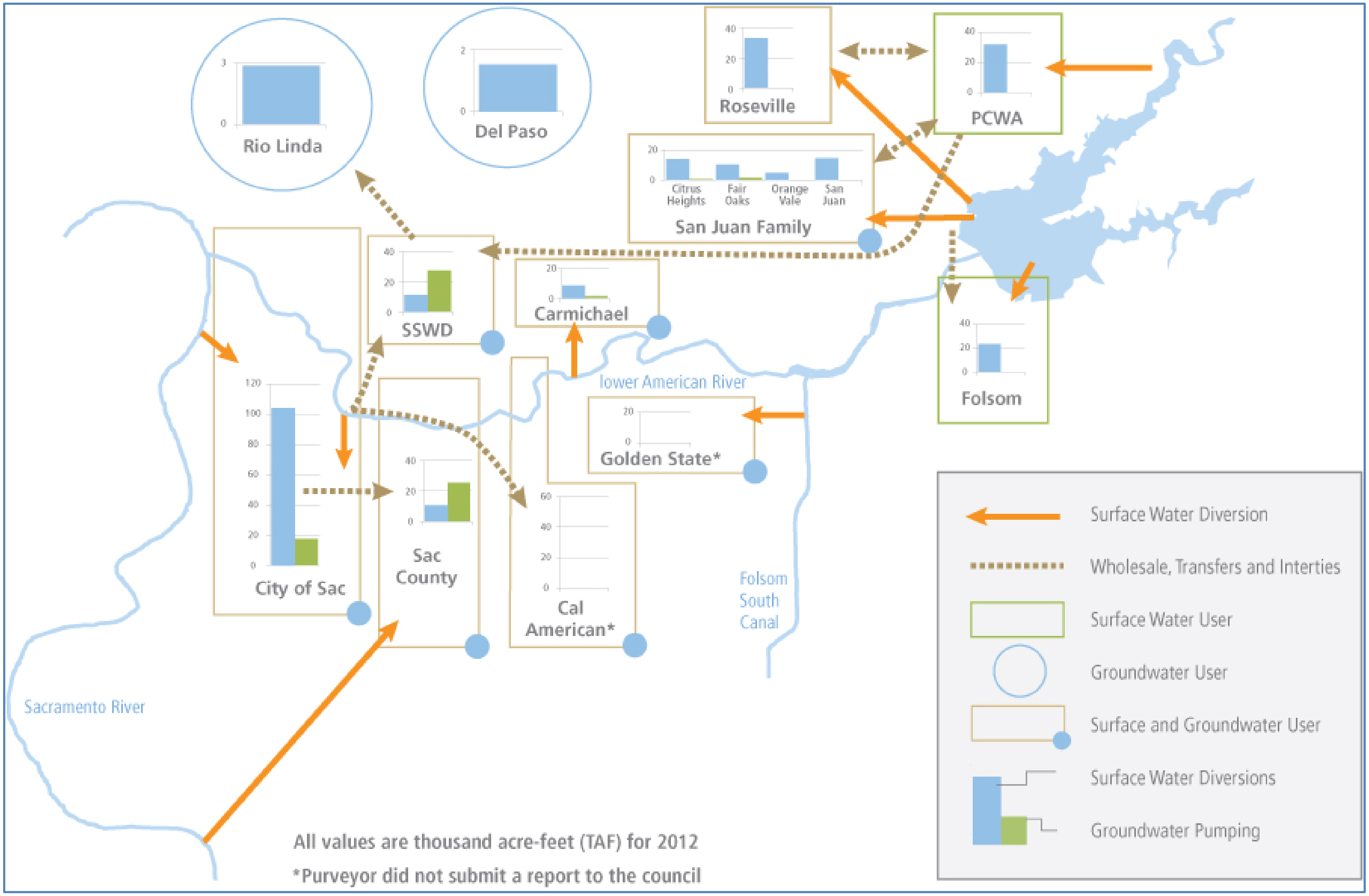


Figure 59. Source of water for the region's water purveyors (Figure 13 from Water Forum, 2012).

Regional Water Project [*see Local Water Projects below*], which is a collaboration between Sacramento County and the East Bay Municipal Utility District.

Federal, State, and Local Water Projects

California has a multitude of Federal, State, and locally funded water supply projects across the state. Several of the largest are presented in the following sections.

Federal Water Project

The Central Valley Project (CVP) is a U.S. federal government water management project under the supervision of the U.S. Bureau of Reclamation (Figure 60). It was devised in 1933 to provide irrigation and municipal water to much of California's Central Valley. It does so by regulating and storing water in reservoirs in the water-rich northern half of California and transporting it to the water-poor San Joaquin Valley. Water is moved through a series of canals, aqueducts, and pumping plants with some of these facilities shared with the California State Water Project (Wiki, 2017).

The CVP was built primarily to integrate California's water infrastructure and protect against water shortages and hazardous floods. It also produces hydroelectric power and provides flood protection, navigation, recreation, and water quality benefits. The CVP serves farms, homes, and industry in the Sacramento and San Joaquin Valleys as well as in the San Francisco Bay Area. The CVP is the largest single source of irrigation water in California while also dedicating 0.987 km^3 per year (800,000 acre-feet per year [AFY]) to fish and wildlife pursuant to the 1992 Central Valley Project Improvement Act (USBR, 2017a).

The CVP was originally conceived as a State project. The basic concept and facilities were included in the State Water Project formulated in the 1930s. However, during the Great Depression, the State of California was unable to finance the project. Most of the water development envisioned by the State of California was accomplished by the CVP beginning with its initial Congressional authorization in 1935 (USBR, 2017b).

California State Water Project

The California State Water Project (SWP) is a water storage and delivery system of reservoirs, aqueducts, power plants, and pumping plants that deliver water to about two-thirds of California's population and is maintained by DWR (DWR, 2017a). Its main purpose is to store water and distribute it to 29 urban and agricultural water suppliers in Northern California, the San Francisco Bay Area, the San Joaquin Valley, the Central Coast, and Southern California. Of the contracted water supply, approximately 70% goes to urban users and approximately 30% goes to agricultural users.

Figure 60. Major water conveyance facilities in California (Figure 6.4.2 in MWD, 2012).

The SWP includes 34 storage facilities, reservoirs, and lakes; 20 pumping plants; four pumping-generating plants; five hydroelectric power plants; and about 1,128 km of open canals and pipelines. It supplies supplemental water to approximately 25 million Californians and about 303,514 ha of irrigated farmland (DWR, 2017a). Additional information about the management of the SWP is provided through annual reports (DWR, 2015a).

Local Water Projects in the Sacramento Region

In November of 2014, DWR awarded the Sacramento Regional Water Authority (RWA) and member agencies $9.7 million in state grants, via the Proposition 84 Grant Program, for projects designed to help support the area's water supply reliability during drought (RWA, 2016). Seventeen local projects received grant funding. Many projects focus on reducing the Sacramento region's reliance on Folsom Reservoir by expanding the ability to recharge, store, extract, and move groundwater around the region (Table 2) (RWA, 2017).

There are many other projects underway in the Sacramento region to secure water supply reliability during drought periods and over the longer term. One example is the Freeport Regional Water Authority (FRWA) Project, which is a groundbreaking collaboration between Sacramento County and the East Bay Municipal Utility District (EBMUD) that provides surface water to the central Sacramento County area as well as EBMUD customers in dry years (FRWA, 2017a). By diverting their American River water supply from the Sacramento River downstream, both agencies avoid diversion impacts to the lower American River. Sacramento County's diversions at Freeport on the Sacramento River would be pumped to the new Vineyard Surface Water Treatment Plant in south Sacramento County. With capacity to treat up to 378,550 m^3 (307 acre-feet [AF]) of surface water per day, the Vineyard Plant is the biggest project ever undertaken by the Sacramento County Water Agency and will play a critical role in helping preserve and sustain groundwater resources in the Sacramento Region (FRWA, 2017b).

Surface Water Supply

Surface water for the Sacramento region comes primarily from three river watersheds: the Sacramento, American, and Cosumnes Rivers. The Sacramento region also includes a portion of the Mokelumne River watershed south of the Cosumnes River (Figure 61).

Project	Purveyor	Completion Date
Lower American River Pipeline	Carmichael Water District	November 2016
Well #2 Reactivation	City of Lincoln	December 2015
Nelson Well Improvements	City of Lincoln	January 2015
PFE and Zone 4 Pump Stations	City of Roseville	July 2016
Phase 2B Well Rehabilitations;	City of Sacramento	December 2016
Sacramento River Pump Station Modifications	City of Sacramento	2015
Lower American River Pump Station Modifications	City of Sacramento	2015
American River Pump Station Improvements	Placer County Water Agency	October 2016
Agricultural Drought Response Incentives Program	Placer County Water Agency	Began January 2015
Regional Water Efficiency Drought Measures	Regional Water Authority	Began April 2015
Antelope Booster Pump Station Expansion	Sacramento Suburban Water District	November 2015
Barton Road Intertie	San Juan Water District	June 2016

Table 2. Selected local projects, water purveyors, and completion dates for the Proposition 84 Grant Program.

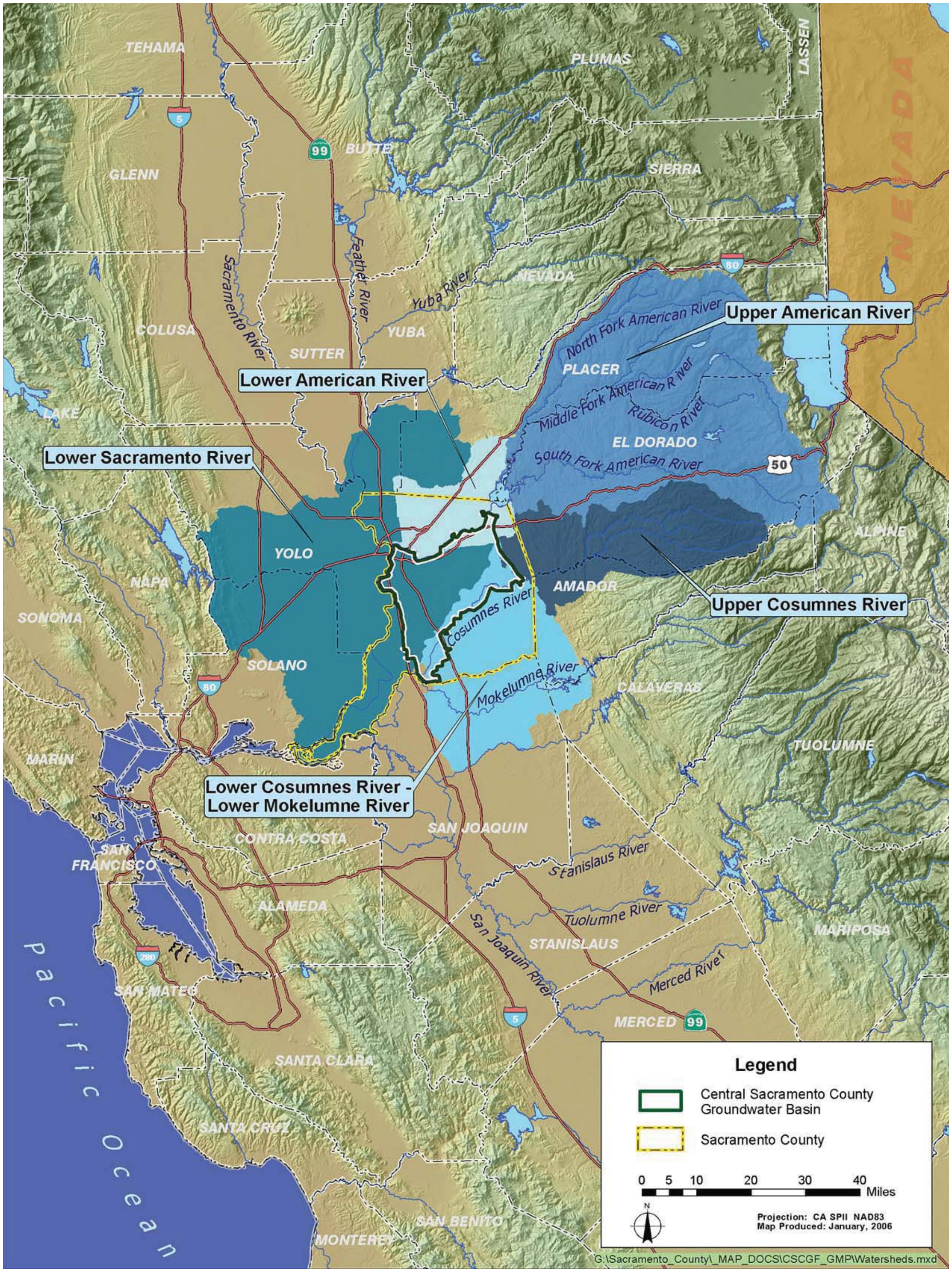


Figure 61. Major river watersheds (Figure 2-1 from CSCGMP, 2016)

Sacramento River Watershed

The Sacramento River watershed covers approximately 60,865 km^2 and produces an average annual runoff of about 20,969 km^3 (17 million-acre-feet [MAF]) as measured at the Freeport Gaging Station (below the confluence with the American River) (CSCGMPTF, 2006). Approximately 227 cubic meters per second (m^3/s) (8,000 cubic feet per second [cfs]) flows in the Sacramento River through Freeport, California in all seasons of the year (CSCGMPFT, 2006). The main reservoirs regulating flows in the Sacramento River include the following:

- Lake Shasta located on the Sacramento River upstream from Redding, California
    - Storage capacity approximately 5.62 km^3 (4.55 MAF)
- Trinity Lake, which regulates water deliveries to the Sacramento River from the Trinity River watershed
    - Storage capacity approximately 3.02 km^3 (2.45 MAF)
- Lake Oroville on the Feather River
    - Storage capacity approximately 4.36 km^3 (3.53 MAF)
- Folsom Reservoir on the American River
    - Storage capacity approximately 1.2 km^3 (0.97 MAF)

American River Watershed

The American River watershed covers approximately 4,920 km^2 to the east of Sacramento in the Sierra Nevada. Folsom Reservoir is the main reservoir in the watershed with a storage capacity of about 1.2 km^3 (0.972 MAF) (CSDGMOTF, 2006). Several smaller upstream reservoirs store up to approximately 1.01 km^3 (0.82 MAF) of water. The Nimbus Dam impounds Lake Natoma and is located immediately downstream from the Folsom Dam. This downstream dam regulates releases from Folsom Reservoir to the lower American River. The entrance facilities to the Folsom South Canal (a diversion canal running south and managed by the U.S. Bureau of Reclamation and part of the Central Valley Project) are located along the south shore of Lake Natoma immediately upstream from the Nimbus Dam. The mean annual flow in the lower American River (1968 to 1998) was approximately 93.45 m^3/s (3,300 cfs). The design capacity of the American River channel (for flood flows) is approximately 3,256 m^3/s (115,000 cfs) (CSDGMOTF, 2006).

Cosumnes River Watershed

The Cosumnes River watershed covers the area from the headwaters of the Cosumnes River on the western slope of the Sierra Nevada to its confluence with the Mokelumne River and is one of the last major rivers in northern California that has no large dam controlling its flow. Smaller dams on this river are used mostly for recreational purposes rather than for water supply or flood control (CSCGMPTF, 2006). Until the 1940s, the

Cosumnes River received baseflow (groundwater discharge) from its extensive floodplain. But historical data suggests that flow in the lower reaches of the river decreased steadily from about 1942 to 1982, with more frequent periods of little to no flow. Currently, the Cosumnes River flows cease in an 8- to 16-kilometer section of the river downstream from Michigan Bar nearly every year at or before the end of the dry season (August through October) (CSCGMPTF, 2006).

Groundwater Supply

Groundwater Basin and Subbasins in the Sacramento Area

The Sacramento area overlies the southern portion of the Sacramento Valley Groundwater Basin, a large alluvial basin spanning over 15,296 km^2 (DWR 2015b). This basin forms the northernmost part of California's Central Valley Aquifer System, which is the largest groundwater system and producer in the state and the second largest groundwater producer in the U.S. (USGS 2005). The basin generally extends north-south from the Red Bluff area to the Sacramento-San Joaquin River Delta and east-west from the Sierra Nevada Foothills to the Northern Coast Range. The metropolitan area overlying the Sacramento Valley Groundwater Basin is further divided into four subbasins: the North and South American Subbasins which encompass the eastern side of the valley and the Yolo and Solano Subbasins, which cover the western side of the valley (Figure 62).

The City of Sacramento, situated east of the Sacramento River and straddling the American River, overlies the North and South American Subbasins which encompass about 1,420 and 1,005 km^2, respectively (DWR 2003). Eastern suburbs of Sacramento include cities such as Citrus Heights, Elk Grove, and Roseville. Just to the west of the Sacramento River are the Yolo and Solano Subbasins, which cover about 1,035 and 1,720 km^2, respectively, and contain the western Sacramento suburban and rural areas of West Sacramento, Woodland, and Davis (DWR 2003).

Hydrostratigraphy of the Sacramento Region

The Sacramento region is underlain by a vast groundwater system that ranges from an unconfined aquifer in the shallow subsurface to progressively more confined aquifer conditions with depth. Since the Oligocene, the Sacramento Valley has been dominated by continental processes, namely alluvial and fluvial deposition (Hackell 1966). Due to these processes, the groundwater system consists of a minor amount of sinuous coarse-grained channel deposits (aquifers) interwoven (meandering and braiding) throughout a larger body (or matrix) of fine-grained interchannel deposits (aquitards). Modeling studies and research suggests that the interwoven nature of alluvial fan channel

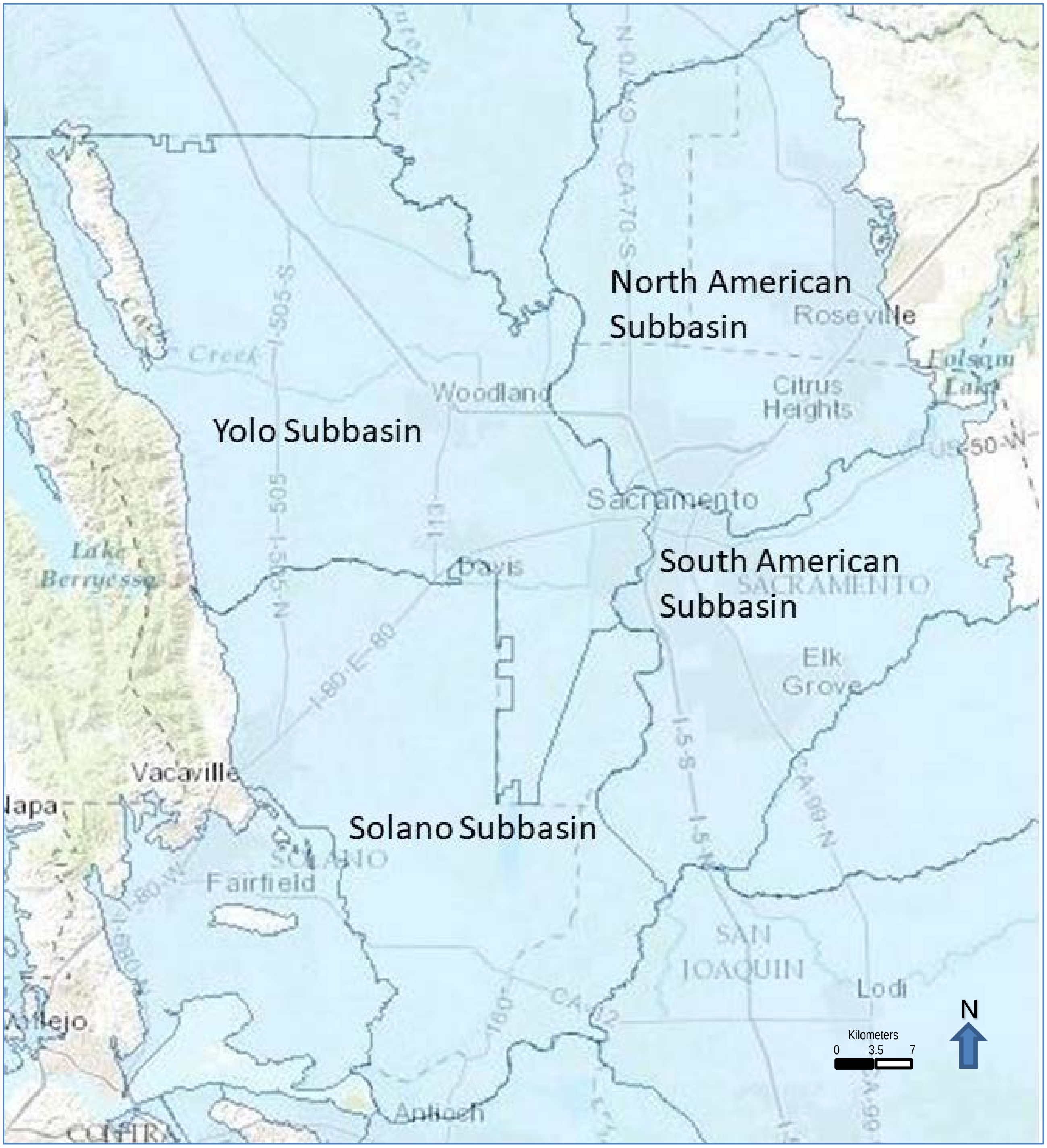


Figure 62. Groundwater Subbasins within the Sacramento region (Source: DWR SGMA Online Data Viewer).

deposits within a larger body of fine-grained interchannel deposits effectively creates a three-dimensional connected network or system (Fogg and others, 2000). The human body is a similar analog to this interconnected system, with fluid transfer between veins and arteries comprising the aquifers (high-flow zones) and all other soft tissues and bones comprising the aquitards (low-flow zones) (Fogg 2008). The paleochannel deposits (aquifers) generally follow the current alignment of the American, Cosumnes, and Sacramento Rivers and Cache and Putah Creeks which transect the area. As a result, these alluvial aquifers and aquitards are not continuous within or across the subbasins, making their lateral and vertical extent a challenge to locate and map accurately.

Significant geologic formations underlying the Sacramento region and containing the primary aquifers are as follows: (from youngest to oldest, including thickness in meters): Holocene (Recent) Alluvium and Modesto Formation (0-30.5± m); Pleistocene Victor (Riverbank) Formation (0-3.5 m) and Arroyo Seco Gravel (6-15 m); Pliocene to Pleistocene Fair Oaks Formation (0-69+ m) and Laguna Formation (38-61 m); and Pliocene Mehrten Formation (61-365 m) (DWR 1970, 1974) (Significant Geologic Formations in the Sacramento Area, Table 3). Aquifers within the Mehrten Formation are the most significant groundwater producers in the area. The Mehrten Formation consists of two distinct units: a gray-to-black andesitic sand (aquifer unit) commonly reported by drillers as “black sands” interbedded with blue to brown clay and a hard, gray tuff-breccia, commonly reported by drillers as “lava” (aquitard unit). A significant geologic formation found primarily to the west of the Sacramento River is the Tehama Formation (DWR 1978). This formation is sourced from erosion of the northern Coast Range and interfingers with the Laguna Formation near the valley center. The Tehama Formation is the principal water-bearing formation on the west side of the valley, due to its widespread distribution and thickness.

The effective base of the fresh groundwater system is typically found at the transition from the Mehrten Formation into the underlying Miocene Valley Springs Formation and Eocene Ione Formation, which typically have low to moderate hydraulic conductivities and contain brackish water.

Storage Capacity and Sustainable Perennial Yield of Subbasins in the Sacramento Region

Storage capacities of the North American, South American, and Yolo Subbasins are estimated to be 6.04, 5.92, and 8.02 km^3 (4.9, 4.8, and 6.5 MAF) respectively (DWR 2003). There are no published estimates of the storage capacity for the Solano Subbasin, although

Geologic Age			Formation	Thickness (feet)	Physical Characteristics	Water-Bearing Characteristics
CENOZOIC	QUATERNARY	HOLOCENE	Alluvium	0-100±	Unconsolidated gravel, sand, silt and clay deposited along stream channels, on terraces and floodplains, and in basins.	Gravels and sands act as important recharge areas and yield large amounts of water to wells. Silts and clays are of low permeability and yield little water.
CENOZOIC	QUATERNARY	PLEISTOCENE	Victor Formation	0-100+	Unconsolidated sand, silt, and clay. Hardpan present. Sand and gravel along old stream courses.	Generally yields little water. Yields larger amounts of water if old stream channels tapped.
CENOZOIC	QUATERNARY	PLEISTOCENE	Arroyo Seco Gravel	20-50	Sand and gravel in iron-cemented clay matrix.	Of relatively low permeability and thus would yield only small amounts of water to wells.
CENOZOIC	QUATERNARY / TERTIARY	PLIOCENE to PLEISTOCENE	Fair Oaks Formation	0-225+	Sand, silt, and clay. Hardpan present. Found principally north of American River. Cemented gravels south of the river.	Similar to the Victor Formation.
CENOZOIC	QUATERNARY / TERTIARY	PLIOCENE to PLEISTOCENE	Laguna Formation	125-200	Bedded silts, clays, and sands. Nonvolcanic.	Sand beds will yield moderate amounts of water to wells; clays yield little water.
CENOZOIC	TERTIARY	PLIOCENE	Mehrten Formation	200-1200	Beds of black volcanic sand, brown clay and sand; zones of volcanic tuff-breccia (lava). All of andestic origin.	Volcanic sands yield large quantities of water to wells. Brown sands yield lesser amounts; clays yield little water. Tuff-breccias yield no water.
CENOZOIC	TERTIARY	MIOCENE	Valley Springs Formation	75-125	Beds of light colored sand and ash, beds of greenish brown silty sand, few beds of gravel. All of rhyolitic origin.	Of low overall permeability. Yields only small amounts of water to wells.
CENOZOIC	TERTIARY	EOCENE	Ione Formation	100-400	Medium-grained quartz sand-stone, thick beds of white to red clay, blue to gray clay with lignite.	Of low overall permeability. Yields only small amounts of fresh to brackish water to wells.
MESOZOIC		CRETACEOUS	Chico Formation	200-15,000±	Brown marine fossiliferous sandstone and shale. Occurs principally in the subsurface.	Usually nonwater-bearing; contains salt water. Local areas may be flushed and now contain usable ground water.
Pre-TERTIARY			Basement Complex	?	Slate and sandstone of the Mariposa Formation. Green-stone, schist, and assorted metavolcanics of the Logtown Ridge Formation. Granodiorite and other intrusive rocks of the Sierra Nevada.	Essentially nonwater-bearing. Where sufficiently decomposed and/or fractured may yield small quantities of water to wells.

Table 3. Significant geologic formations in the Sacramento region (DWR, 1970; 1974)

estimates have been made for portions of the subbasin. For groundwater management planning purposes, the WFA (1993) subdivided portions of the three groundwater subbasins underlying Sacramento County into separate water management sub areas, including the North Basin (north of the American River) [southernmost portion of the North American Subbasin], Central Basin (between the American and Cosumnes Rivers) [South American Subbasin], and South Basin (south of the Cosumnes River) [Cosumnes Subbasin]. Sustainable yield was estimated in the WFA (1993) to be as follows: North Basin, 0.162 km^3/yr (131,000 AFY) (1990 amount) (Sacramento County portion); Central Basin, 0.337 km^3/yr (273,000 AFY) (2005 projected amount); and South Basin, 0.142 km^3/yr (115,000 AFY) (1990 amount) (WFA GW Management Sub Areas, Figure 63). The WFA defined sustainable yield as "the amount of groundwater which can be safely pumped from the groundwater basin over a long period of time while maintaining acceptable groundwater elevations and avoiding undesirable effects which might include increased pumping costs, accelerated movement of underground pollutants, etc."

The sustainable yield for the entire North American Subbasin was estimated to be 0.493 km^3 (400,000 AF) with the Placer, Sacramento, and Sutter County portions of the subbasin contributing 0.117, 0.162, and 0.216 km^3 (95,000, 131,000, and 175,000 AF), respectively (PCWA 2005). The Western Placer County Groundwater Management Plan (WPCGMP) defined "long-term average sustainable yield" as the average groundwater extractions calculated over the period of time commencing with the adoption of the GMP (WPCGMP 2007).

Perennial yield in Yolo County between 1963 and 1972 is estimated to have been 0.375 km^3 (304,500 AF). As defined in the report titled, Yolo County – Investigation of Groundwater Resources (Yolo County, 1976), the perennial yield of a groundwater basin is the amount of water that can be pumped annually from that basin, with no net change in storage over a selected period of time.

Groundwater Use Within the Sacramento Region Subbasins

North Basin

Reported annual groundwater extraction (1990-2013) in the North Basin for municipal and industrial (M&I) purposes ranged from a high of over 0.132 km^3 (107,000 AF) in 1998 to a low of about 0.076 km^3 (62,000 AF) in 2011 with an average of about 0.107 km^3 (87,000 AF) (SGA 2014). Groundwater pumping for agricultural and domestic purposes is not metered, but is assumed to be a minor component of the total. Recent groundwater modeling for 2004 indicates that M&I pumping constituted about 85% of the total with the balance of pumping being 8% agricultural, 4% domestic, and 3% remediation.

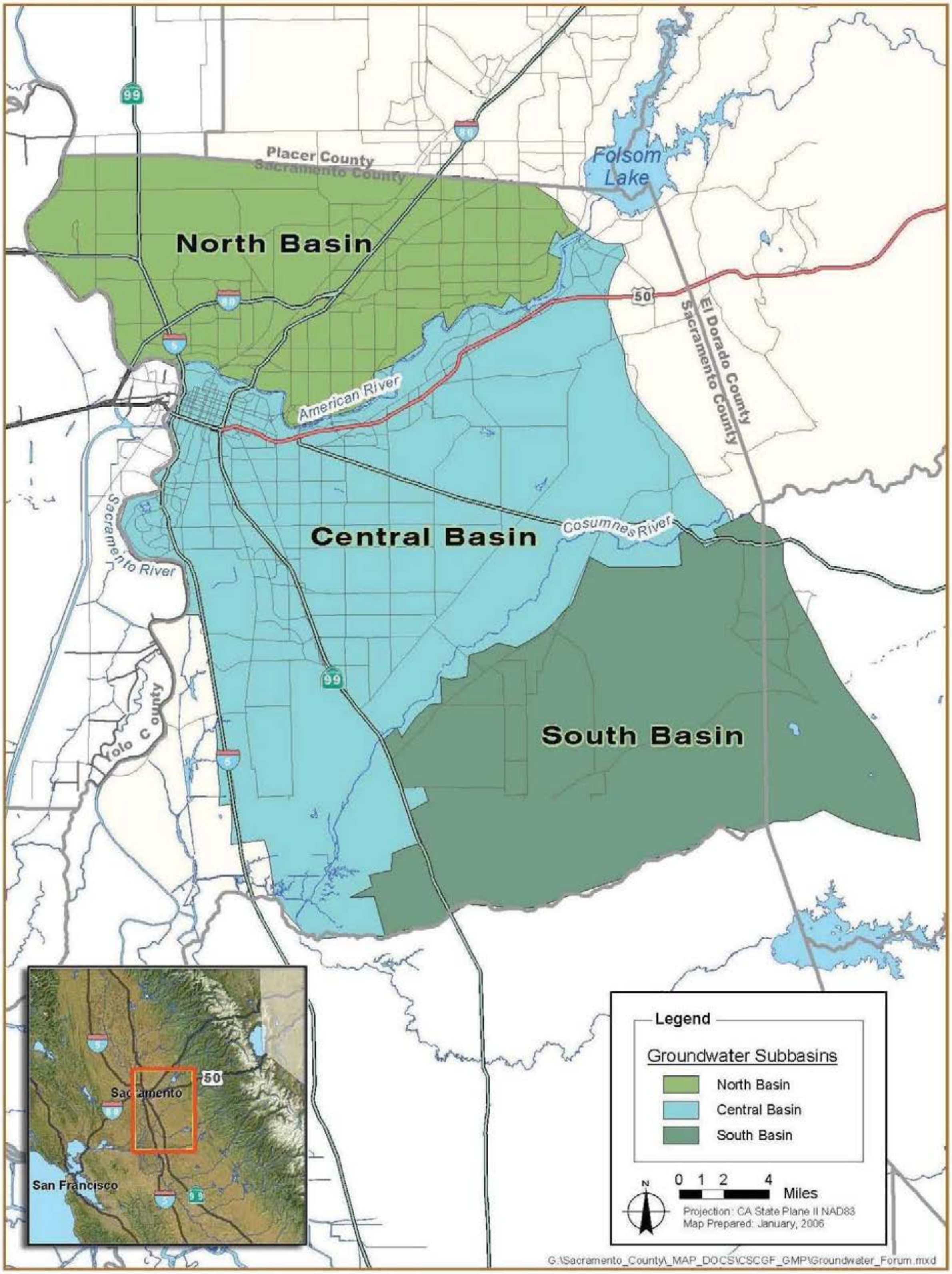


Figure 63. Groundwater management sub-areas in Sacramento County (WFA, 2000).

Central Basin

Reported and estimated groundwater extraction from the Central Basin over the period 2005-2015 ranged from about 0.249 to 0.317 km^3 (202,000 to 257,000 AF) and averaged about 0.292 km^3 (237,000 AF). On average, agricultural pumping constituted about 64% of the total with urban and rural domestic encompassing the balance at 30 and 6%, respectively (SCGA 2016).

South Basin

Groundwater pumping within the South Basin was estimated to be about 0.191 km3 (155,000 AF) per year, based on 1980-2004 data (SGA, 2011). This estimate suggests that overdraft may be occurring in the South Basin, since the sustainable yield for this area is 0.142 km3 (115,000 AF) (based on 1990 conditions).

North American Subbasin

Based on a 1990 level of development, groundwater extraction from the North American Subbasin was estimated to be about 0.494 km3 (400,000 AF) (DWR 2004). Based on 2011-15 data, groundwater extraction within South Sutter Water District by private agricultural pumpers was estimated to range from 0.044 km3 (36,062 AF) (2011) to 0.146 km3 (118,394 AF) (2015) averaging about 0.113 km3 (91,611 AF) (SSWD 2016).

Yolo Subbasin

Based on 2011-15 data, the City of Davis utilized groundwater for municipal supply in amounts ranging from 0.114 km3 (9,212 AF) (2015) to 0.152 km3 (12,339 AF) (2013) averaging about 0.139 km3 (11,240 AF) (Brown and Caldwell, 2016). Based on 2011-15 data, the City of Woodland pumped groundwater for municipal supply in amounts ranging from 0.011 km^3 (8,650 AF) (2015) to 0.019 km^3 (15,160 AF) (2012) and averaging about 0.138 km^3 (12,120 AF) (Woodland 2016). The above volumes constitute the majority of the municipal groundwater pumping occurring in the Yolo Subbasin.

Based on 1997-2016 data, the University of California, Davis (UCD) pumped groundwater for all uses in amounts ranging from 0.005 km^3 (3,661 AF) (2016) to 0.007 km^3 (5,888 AF) (2007) averaging about 0.006 km^3 (5,092 AF) (Lew Pollock, personal communication 2017). UCD groundwater uses includes domestic, industrial, landscape, agriculture, and fisheries.

Based on 2013-15 data, Reclamation District 2035 (RD 2035) pumped groundwater for agricultural purposes in amounts ranging from 0.022 km^3 (17,600 AF) (2013) to 0.036 km^3 (29,110 AF) (2014) averaging about 0.027 km^3 (21,575 AF) (RD 2035, 2016).

The largest use of groundwater in the Yolo Subbasin is for agricultural purposes and most pumping is unmetered (except RD 2035), so the total quantity of agricultural groundwater extraction is unknown.

Solano Subbasin

Based on 2011-2015 data, the City of Dixon (Dixon District) pumped groundwater for municipal purposes in amounts ranging from 0.0014 km3 (1,151 AF) to 0.0019 km3 (1,547 AF) averaging 0.0016 km3 (1,388 AF) (CalWater 2016).

Based on 1995-2015 data, the City of Vacaville pumped groundwater for municipal purposes in amounts ranging from 0.004 km3 (3,230 AF) (1996) to 0.008 km3 (6,680 AF) (2005) averaging 0.0065 km3 (5,287 AF) (Vacaville 2016).

Based on 2011-2015 data, the City of Rio Vista pumped groundwater for municipal purposes in amounts ranging from 0.0022 km3 (1,793 AF) (2015) to 0.003 km3 (2,658 AF) (2014) averaging 0.0023 km3 (2,263 AF) (Rio Vista 2016).

Based on 1991-2014 data, groundwater extraction within Solano Irrigation District by private agricultural pumpers was estimated to range from 0.007 km3 (5.359 AF) (2001) to 0.67 km3 (54,193 AF) (1992) averaging about 0.020 km3 (16,487 AF) (SID 2016).

The above estimates constitute the reported groundwater pumping occurring in the Solano Subbasin; however, because private groundwater pumping is not measured or reported in most areas, these volumes are considered minimums.

Well Types and Construction Statistics for the Sacramento Region

A key aspect to understanding the region's groundwater supply and development is identifying the age, distribution, and type of wells that have been installed in the region. Well completion reports (WCRs) are a valuable source of well information, as are well logs and well information submitted by licensed well drillers to the well owner, local city, or county department of environmental health, and DWR. Among other things, WCRs commonly describe well location, installation date, construction details, borehole geology, estimated pumping rates, and well use type.

The six most common well-use types include domestic, irrigation, public supply, industrial, monitoring, and other. Public supply wells include all wells identified on the

WCR as municipal or public. Wells identified as “other” include a combination of the less common well types, such as stock wells, test wells, or unidentified wells (no information listed on the WCR). Since 1949, well drillers have been required by law to submit WCRs to the State. California Water Code Section 13751 requires drillers who construct, alter, abandon, or destroy a well, to submit a WCR to DWR within 60 days of the completed work. WCRs submitted to DWR for wells completed over a 34-year period from 1979 to 2013 were used to evaluate the age, distribution, and type of groundwater wells in the region encompassing the Sacramento Metropolitan Area, namely Sacramento, Placer, Yolo, and Solano Counties (DWR 2016).

Regionally, domestic well installations peaked in 1988 (955) (dry period) and were lowest in 2011 (77) (wet period) (Figure 64). Monitoring well installations (7) were first recorded in the region (Sacramento County) in 1981 and peaked in 1992 at 802 (Figure 65). Irrigation well installations peaked in 1979 (112) (dry period) and were lowest in 1983 (11) (wet period) (Figure 66). Municipal supply well installations peaked in 1986 (29) (wet period) and were lowest at 3 in both 1982 (wet) and 2012 (dry) (Figure 67).

The total number of wells reportedly installed in the region between 1979 and 2013 is 32,132. However, this number is likely to be a minimum due to a small number of drillers not submitting WCRs and not in compliance with state law. The most common well type in the region is domestic with 15,680 wells. Placer County contains the most of this type at 9,682 and Yolo contains the least at 1,217 (Figure 68). The second most frequent well type is monitoring with a total of 13,399. Sacramento County contains the most of this type at 8,879 and Placer contains the least at 1,096. The third most common well type is irrigation with 1,308 wells. Yolo County contains the most of this type at 697 and Placer contains the least at 739 (Figure 69). The fourth most frequent well type is other with 1,138 wells; Sacramento County contains the most of this type at 596 and Yolo contains the least at 107. The fifth most common well type is public supply at 493 wells. Sacramento County contains the most of this type at 201 and Solano contains the least at 52. The well type with the lowest frequency in the region is industrial at 114. Yolo County contains the most of this type at 43 and Placer contains the least at 5. By county, Sacramento contains the largest number of wells at 13,101 and Yolo contains the least number of wells at 3,567.

Irrigation Pump Performance Data in the Sacramento Region

Irrigation pump performance data from over 500 wells in the Sacramento Valley were compiled and evaluated by the Irrigation Training and Research Center (Burt 2011). These tests are commonly used to identify optimum well production rates, pumping plant efficiency and energy demands. However, these data can also be used to characterize general aquifer conditions and well performance. Of the 500 tests conducted, over 100 tests were conducted within the four subbasins underlying the Sacramento area. Average well flow rates ranged from 0.0787 m^3/s (2.78 cfs) in the

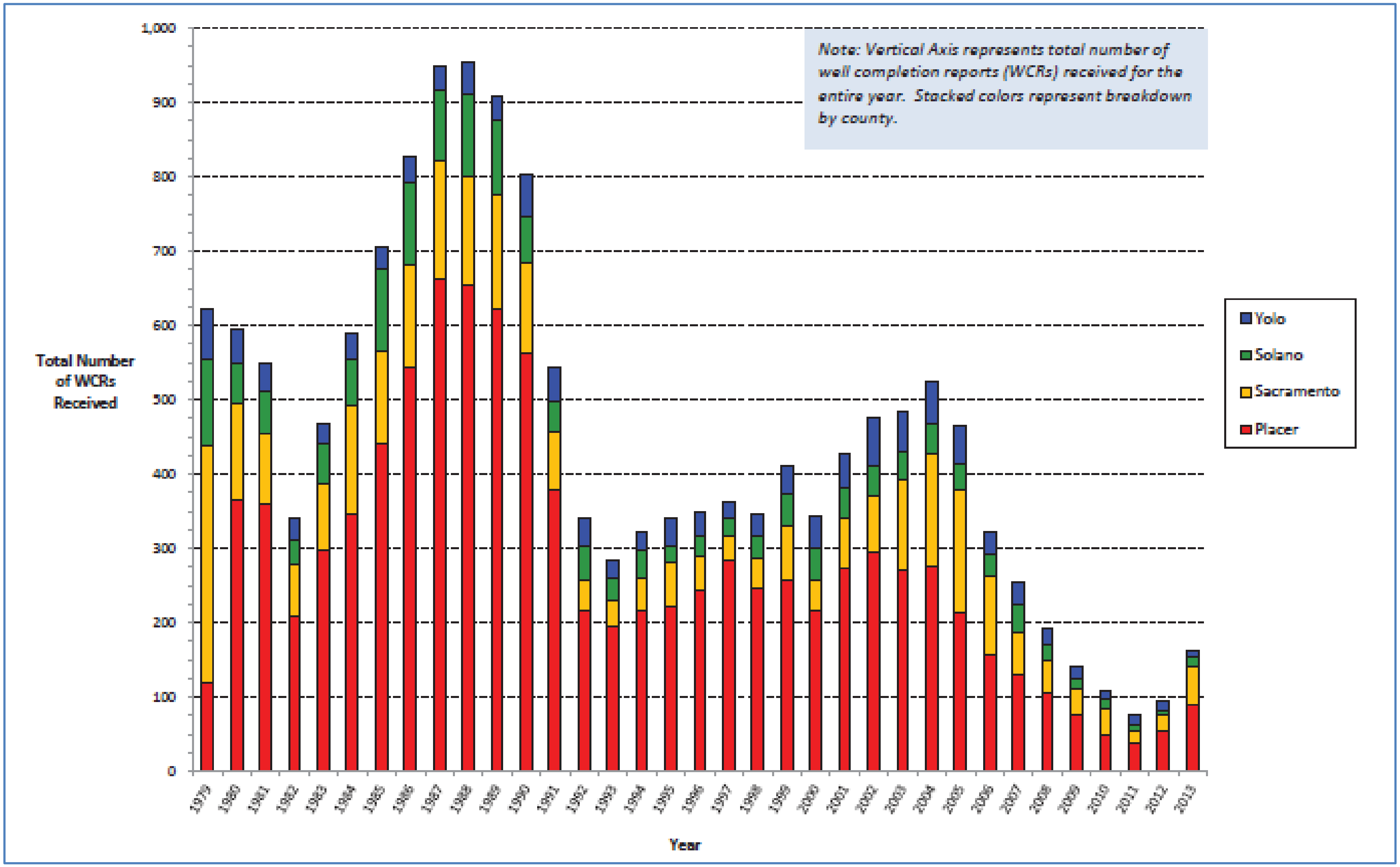


Figure 64. Domestic well completion reports received by DWR by county, Southern Sacramento Valley 1979 – 2013 (DWR, 2016).

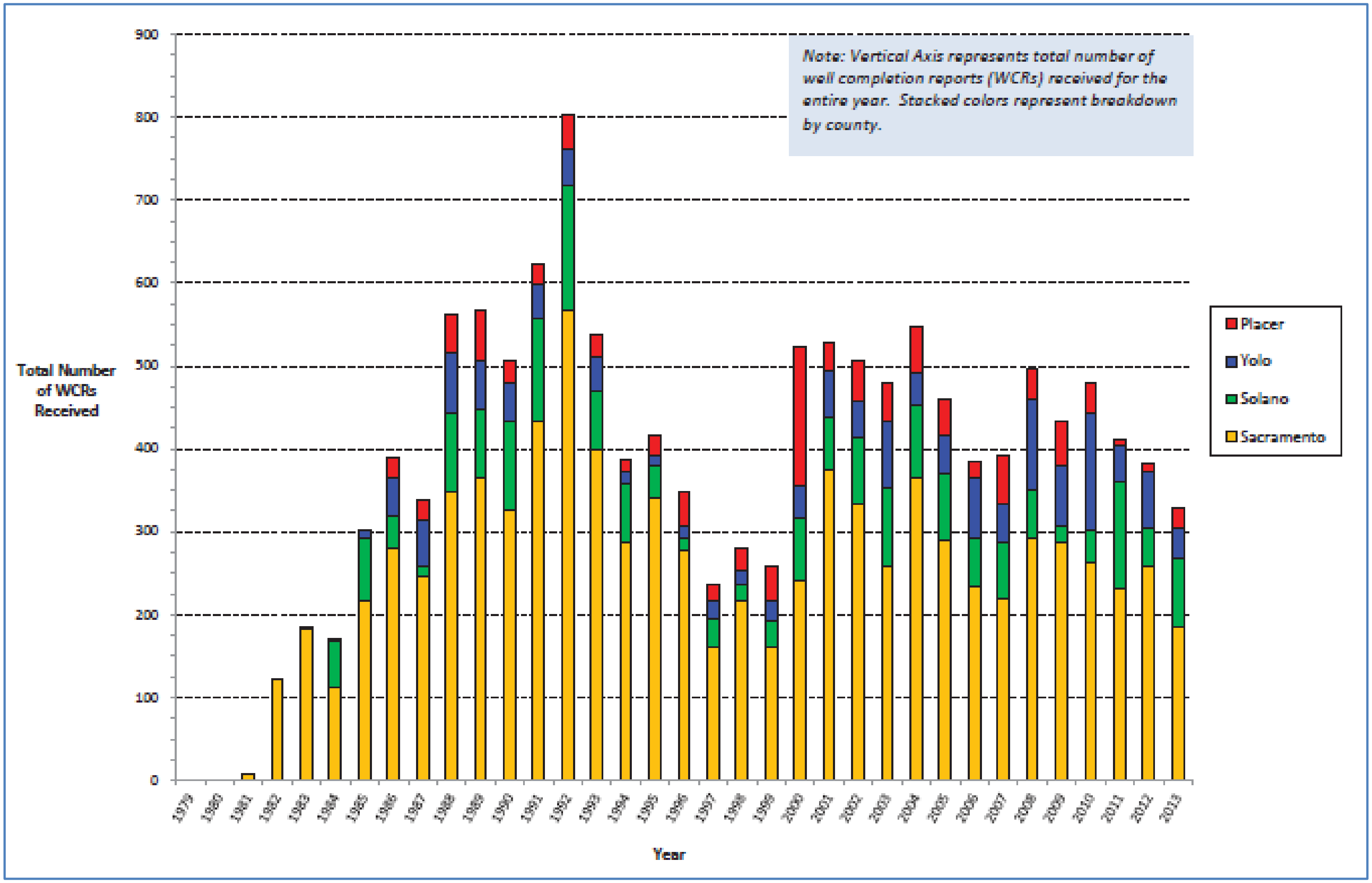


Figure 65. Monitoring well completion reports received by DWR by county, Southern Sacramento Valley 1979 – 2013 (DWR, 2016).

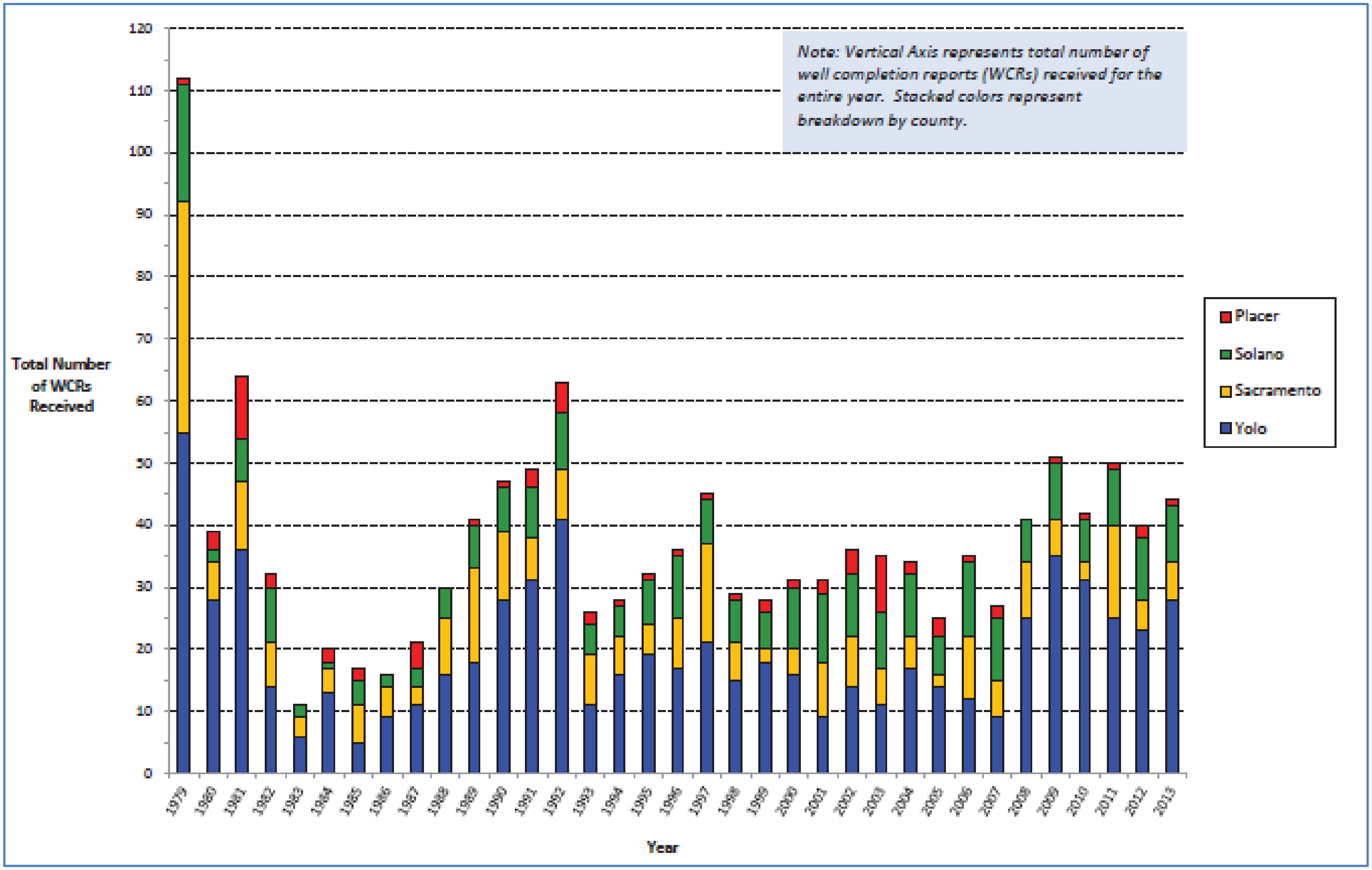


Figure 66. Irrigation well completion reports received by DWR by county, Southern Sacramento Valley 1979 – 2013 (DWR, 2016).

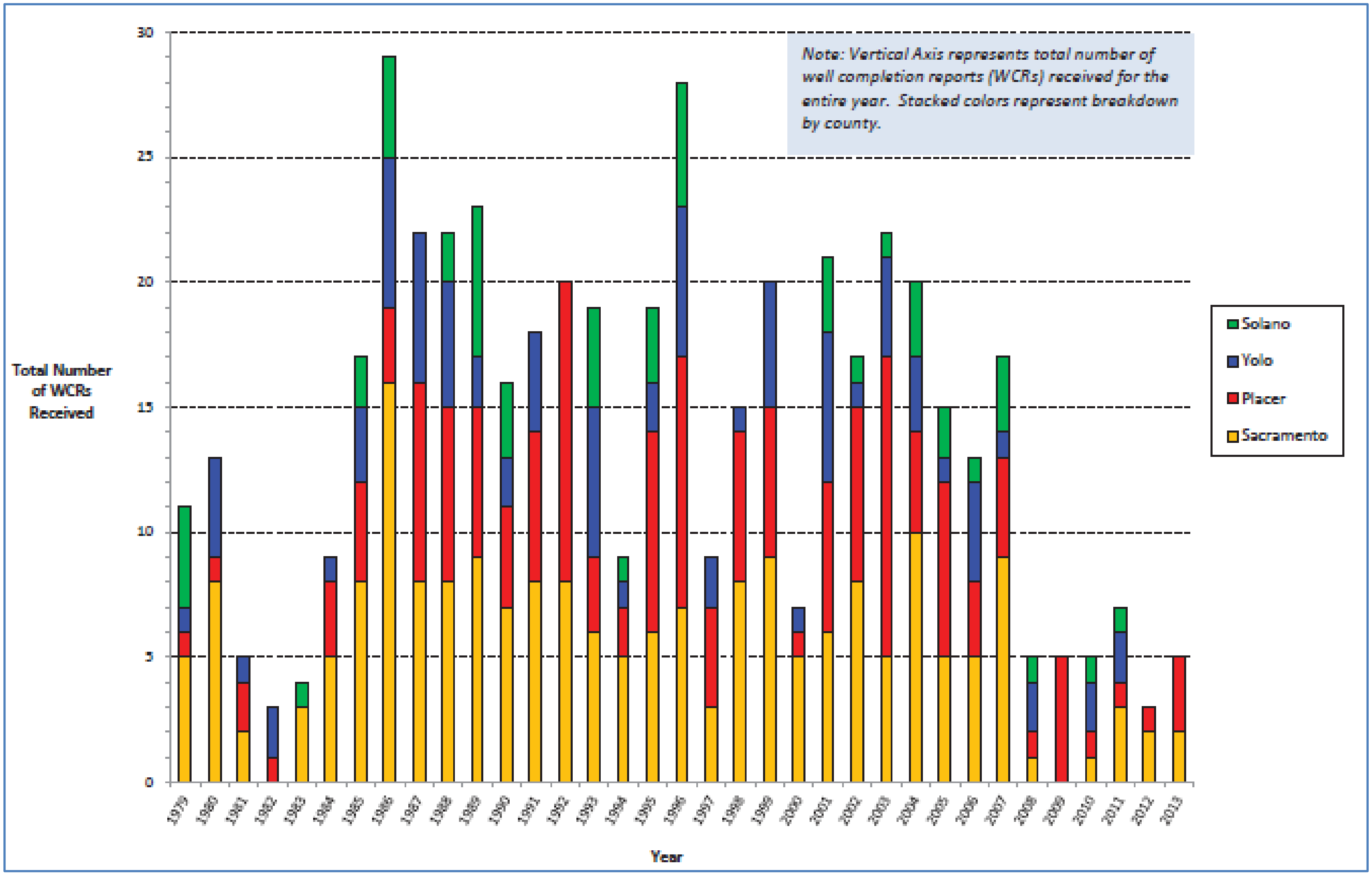


Figure 67. Municipal well completion reports received by DWR by county, Southern Sacramento Valley 1979 – 2013 (DWR, 2016).

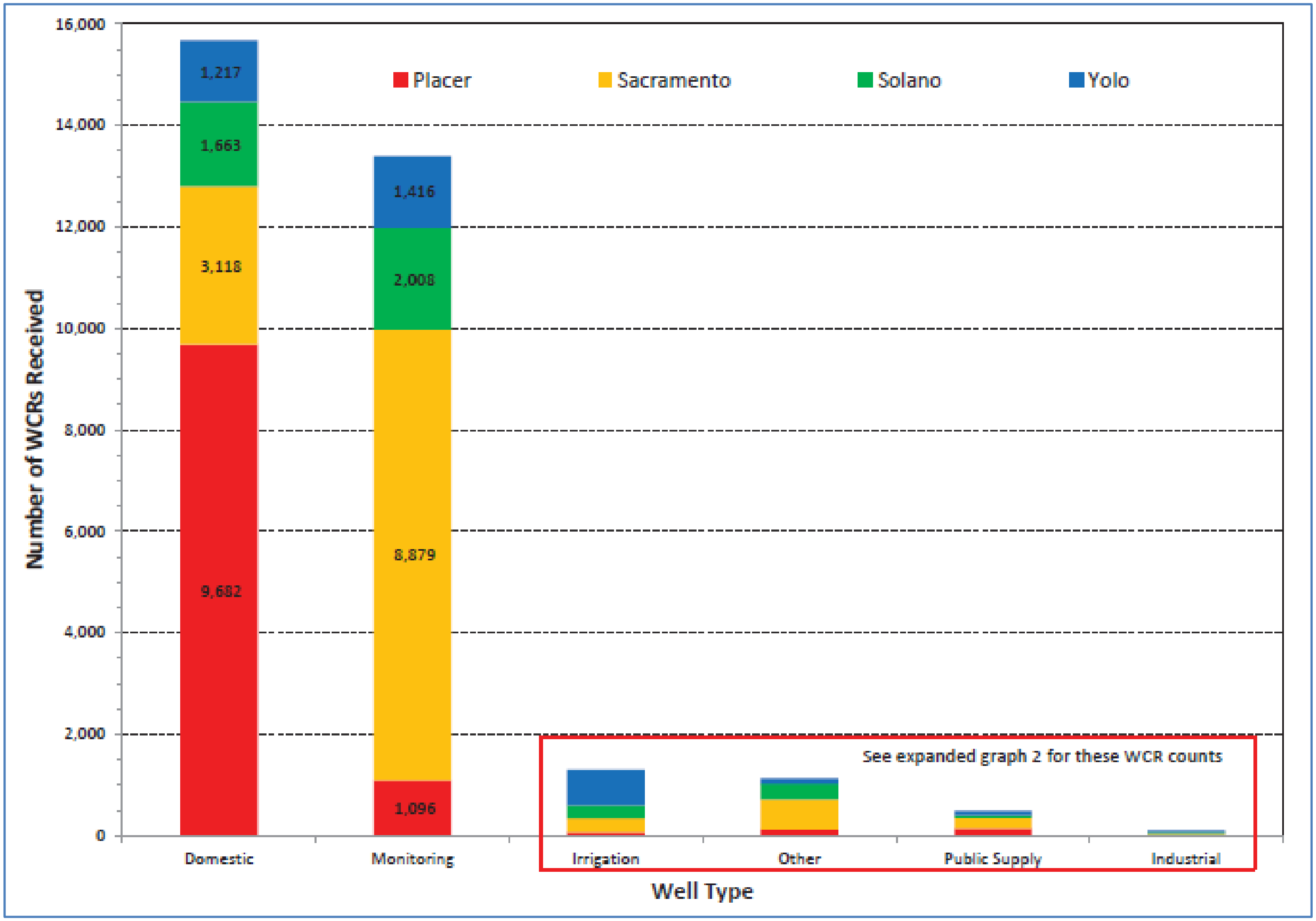


Figure 68. Distribution of well types by county (Sacramento Region) 1978-2013 (DWR, 2016).

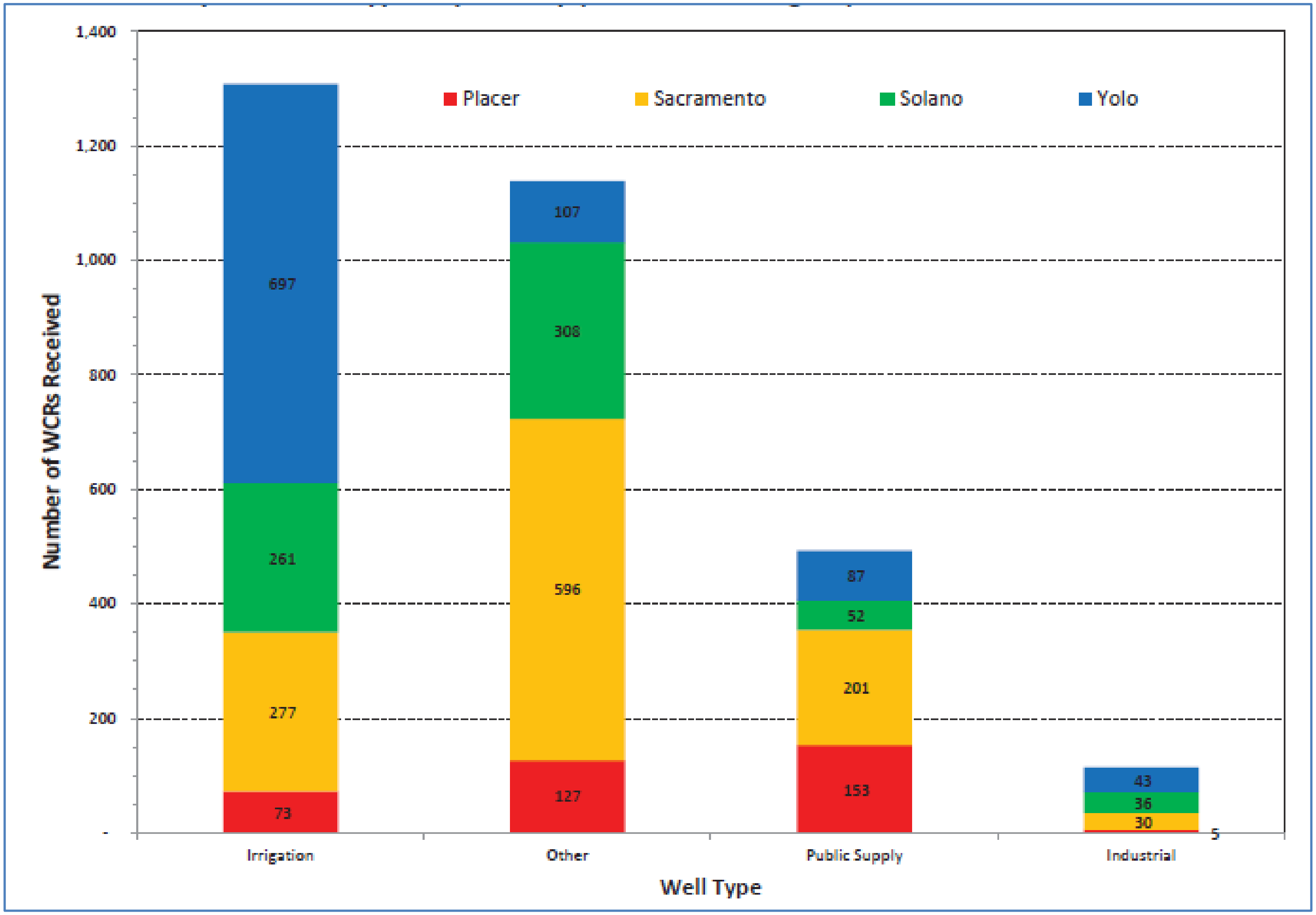


Figure 69. Expanded graph 2 (from Figure 68) showing selected well types by county (Sacramento Region) 1978-2013 (DWR, 2016).

Solano Subbasin to 0.160 m^3/s (5.66 cfs) in the South American Subbasin. Average static water levels ranged from 15 to 25 meters below ground surface. Average drawdown ranged from 9 to 13 meters below static water levels. Specific capacity ranged from an average of 590 $m^3/d/m$ (47,500 gpd/ft). in the North American and Yolo Subbasins to 270 $m^3/d/m$ (21,740 gpd/ft). in the South American Subbasin. Specific capacity is the measure of a well's pumping rate (cubic meters per day) divided by its drawdown (meters) and this measure yields insight into a well's production potential.

Groundwater Quality

The quality of groundwater in the Sacramento region is generally suitable for most uses, except for areas of contamination and localized water quality issues. Water quality concentrations can vary with depth and location with the Sacramento region. The California State Water Resources Control Board (SWRCB) Division of Drinking Water (DDW) maintains a database of public water systems' water quality analyses (referred to as the "DDW database") that has been useful in identifying potential water quality issues in the region (SGA, 2014).

Naturally Occurring Contaminants

This section presents a brief discussion of naturally occurring contaminants in groundwater. Human-introduced contaminants are discussed in "Chapter VIII – Environmental Concerns" of this paper.

Belitz and others (2015) recently published an assessment of public supply well groundwater quality in California. The 10-year study found that natural contaminants are more prevalent than human-introduced contaminants in California groundwater used for public supply. Belitz and others found that at a statewide scale, the trace elements that are most prevalent at higher concentrations in California groundwater are arsenic, manganese, and uranium (Figure 70).

Groundwater quality is typically evaluated using several water quality parameters of interest particular to a region. These parameters of interest may vary based upon local geologic conditions, land use practices, or a specific water user. For example, agricultural areas often evaluate dissolved boron concentrations in groundwater (SGA, 2014). The following sections briefly present information about several naturally-occurring contaminants found in Sacramento area groundwater: total dissolved solids, nitrate, arsenic, hexavalent chromium, iron, and manganese.

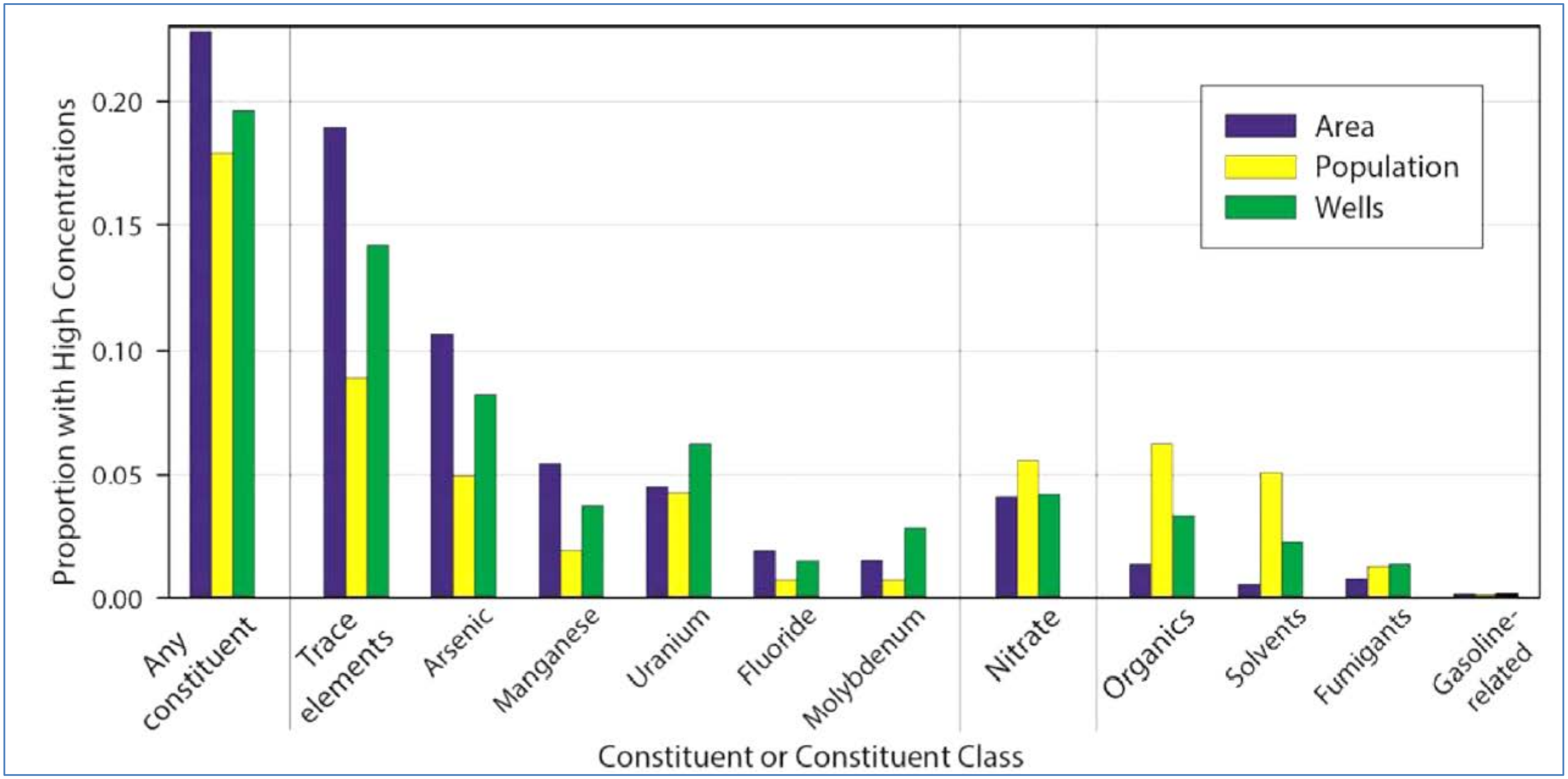


Figure 70. Naturally occurring and anthropogenic constituents or constituent classes in groundwater in the Sacramento area (Belitz and others, 2015; Figure 3).

Total Dissolved Solids

Total dissolved solids (TDS) are a measure of all dissolved constituents in a water sample. TDS units are typically represented in milligrams per liter (mg/L). The dissolved constituents result primarily from interaction of groundwater with the minerals making up the solid portion of an aquifer. TDS concentrations in the Sacramento Valley generally increase with depth below the land surface (SGA, 2014). At depths greater than approximately 366 meters, TDS in groundwater can typically exceed 1,000 mg/L (Berkstresser, 1973). While not representing human health concerns, water quality with TDS concentrations this high is undesirable because it typically tastes bad. Ideal TDS concentrations for human consumption are between 250 and 500 mg/L.

Nitrate

Nitrate is naturally present in groundwater. However, elevated nitrate concentrations in groundwater are often associated with human activities such as wastewater discharge, fertilizer application, and land application of animal wastes. The primary maximum contaminant level (MCL) allowed by federal and state regulations is 45 mg/L as nitrate (or 10 mg/L as nitrogen). Nitrate concentrations are not elevated to levels of human health concern within most of the urbanized Sacramento area (SGA, 2014). They can be of concern in predominantly agricultural areas (e.g., dairy and nitrogen-applied irrigated areas).

Arsenic

Arsenic is a naturally-occurring element in the Earth’s crust. Relatively high concentrations of arsenic have been noted in Sacramento Valley groundwater near the Sacramento and Feather Rivers (Bennett and others, 2011). Except for localized areas, groundwater in the urbanized region typically contains relatively low concentrations of arsenic (less than the CA primary MCL of 10 µg/L) (SGA, 2011; SGA, 2014).

Hexavalent Chromium

Hexavalent chromium is an oxidized form of chromium and can be found in low concentrations in drinking water. Naturally occurring hexavalent chromium in Sacramento area groundwater is typically found in very low concentrations, but has also been introduced into groundwater by historical industrial activities. The CA primary MCL of 10 micrograms per liter (µg/L) became effective on July 1, 2014. As a result of the recently lowered MCL, the Sacramento Groundwater Authority obtained hexavalent chromium results from the DDW database for the period 2001 to 2014. Of the 215 wells for which data were available, the average concentration was approximately 5.2 µg/L. Of the 215 wells, 19 had concentrations exceeding the MCL and another 25 were close to the MCL (>7.5 µg/L). The areas of biggest concern appear to the north of Interstate 80 near the communities of Rio Linda, Antelope, and North Highlands (SGA, 2014).

Iron

Iron is a naturally occurring element in the Earth's crust and is typically found in groundwater as a metallic ion. Iron has a California secondary MCL of 300 µg/L because at elevated concentrations, it tends to give water a bad taste. Dissolved iron can also precipitate as a red-brown solid on plumbing fixtures. In general, dissolved iron is not considered a significant problem in much of Sacramento-area public supply wells (SGA, 2014). However, iron is routinely encountered in this region's groundwater. In a study of 196 wells within the Sacramento area with available data, six wells were below the detection level of 10 µg/L. Of the wells with detections, 56 wells had concentrations exceeding the secondary MCL (SGA, 2011). The iron concentrations noted herein represent the maximum concentrations detected in a given well, so the individual wells may not routinely contain iron concentrations at these levels (SGA, 2014).

Manganese

Manganese is a naturally occurring element in the Earth's crust and is found in groundwater as a metallic ion. Manganese has a California secondary MCL of 50 µg/L because at elevated concentrations in water, it can also have a bad taste. Dissolved manganese can also precipitate as a black solid on plumbing fixtures (SGA, 2014). With a distribution similar to the occurrence of iron (but at relatively lower concentrations), wells in much of the Sacramento area produce water with elevated manganese concentrations (SGA, 2011). In a study of 183 wells sampled within the Sacramento area, 55 wells were below the detection level of 10 µg/L. Of the remaining wells, 35 wells had concentrations exceeding the secondary MCL (SGA, 2014).

Current Regulatory Framework – Water Resources

Groundwater Management in the Sacramento Region (pre-2015)

Numerous legislative and administrative efforts have laid the foundation for the development of the Sustainable Groundwater Management Act of 2014 (DWR 2015c).

Assembly Bill 3030 (AB 3030) - The Groundwater Management Act

The passage of AB 3030 in 1992 encouraged local agencies to prepare and adopt plans for managing their local groundwater resources, whether or not their groundwater basin exhibited overdraft conditions. This law is significant in that it greatly expanded the number of local agencies authorized to develop a groundwater management plan and set forth a common framework for management for local agencies throughout California.

Senate Bill 1938 (SB 1938) – The Local Groundwater Assistance Fund

In 2002, the legislature passed SB 1938, which expanded groundwater management plan requirements related to groundwater levels, groundwater quality, inelastic land subsidence, and surface water-groundwater interaction. SB 1938 requires local agencies to develop and adopt plans so groundwater projects can be eligible for receiving public funds.

Senate Bill x7-6 (SB x7-6) Statewide Groundwater Elevation Monitoring

SB x7-6, passed by the legislature in 2009, established collaboration between local monitoring entities and DWR to collect statewide groundwater elevations and to make these data available to the public. In response to the law, DWR developed the California Statewide Groundwater Elevation Monitoring (CASGEM) Program. The program's mission was to establish a permanent, locally-managed program of regular and systematic monitoring in all of California's alluvial groundwater basins. This early attempt to monitor groundwater continues to exist as a tool to help achieve the goals set out under the Sustainable Groundwater Management Act (discussed later in the section). Since 2009, the CASGEM Program has tracked seasonal and long-term groundwater elevation trends in groundwater basins statewide and made these data readily available to the public through DWRs website.

Assembly Bill 359 (AB 359) – The Groundwater Recharge Area Mapping Bill

In 2011, AB 359 was passed and signed into law, modified the California Water Code by requiring local agencies to provide a copy of their groundwater management plans to DWR and requires DWR to provide public access to those plans. The law also requires local agencies to provide a map of recharge areas to local planning agencies and notify DWR and other interested persons when a map is submitted.

Assembly Bill 1471 (AB 1471): Proposition 1, The Water Quality, Supply, and Infrastructure Improvement Act of 2014

On November 4, 2014, California voters approved Proposition 1 which authorized $7.545 billion in general-obligation bonds to fund ecosystems and watershed protection and restoration, water-supply infrastructure projects, including surface and groundwater storage, and drinking-water protection. Chapter 10 of the Act authorizes $900 million for projects that address groundwater sustainability, including $800 million for the prevention and cleanup of groundwater contamination and $100 million for projects that develop and implement groundwater plans.

Local Ordinances

Another method of managing groundwater is through ordinances adopted by local governments, such as cities or counties. DWR's Bulletin 118-2003 indicated that 27 counties in California adopted groundwater management ordinances and in the Sacramento area, two counties, Sacramento (Title 3 Section 3.40.090 Ground and Surface Water Export) and Yolo (Title 10, Chapter 7, Groundwater) have adopted groundwater management ordinances.

Water Forum Agreement (WFA)

As discussed in Section A.2., the 1970s and 80s were a period of significant growth in the Sacramento Region which resulted in increased demands on all of its water resources (SGA 2014). Groundwater levels in some parts of the region were steadily declining and, in some cases, were well below sea level. As a result, in 1980, Sacramento County was identified by DWR as being in a state of groundwater overdraft (DWR 1980). These conditions led local leaders in the Sacramento region to conclude that a process was needed to guide sustainable water resources management into the future. This process, which became known as the Water Forum, started in 1993. After six years of analysis, discussion, and negotiation, the WFA was signed in April of 2000 by 40 diverse stakeholder groups (WFA, 2000). The WFA formalized a collaborative, stakeholder-driven process for sustainable water management in Sacramento County with co-equal objectives of providing reliable water supplies and preserving the environment of the Lower American River. One of seven important elements of this process was to establish groundwater management governance structures in the region. In recognition of differences in the development and use of groundwater in Sacramento County, the WFA divided the county into three groundwater management areas: the North Basin, Central Basin, and South Basin (Figure 63). This gave rise to the *Sacramento North Area Groundwater Management Authority, Sacramento Central Groundwater Management Authority, and the Southeast Sacramento County Agricultural Water Authority.*

In preparation for the WFA, the Sacramento North Area Groundwater Management Authority (now known as the Sacramento Groundwater Authority [SGA]) was established in August 1998 through adoption of a joint powers authority using the existing authority of the Cities of Sacramento, Folsom, and Citrus Heights, and the County of Sacramento. SGAs purpose is to manage a portion of the North American Subbasin underlying Sacramento County north of the American River (North Basin).

SGA published its first groundwater management plan in 2003 with updates in 2008 and 2014 (Figure 71) (SGA 2014).

The Sacramento Central Groundwater Authority (SCGA) was formed in September of 2006 and approved its groundwater management plan in November 2006 (Figure 72) (SCGA 2006). SCGAs purpose is to manage a portion of the South American Subbasin between the American and Cosumnes Rivers (Central Basin). The Southeast Sacramento County Agricultural Water Authority (SSCAWA) was formed in 2002 and published its groundwater management plan in 2011 (Figure 73) (SGA, 2011). The purpose of this authority is to manage the Sacramento County portion of the Cosumnes Subbasin (South Basin).

Additional groundwater management plans developed in the Sacramento region include those developed by the following entities (Figure 74):

- Natomas Central Mutual Water Company
- South Sutter Water District
- Sutter County
- Western Placer County
- Yolo County Flood Control and Water Conservation District (Figure 74)

Groundwater Management in the Sacramento Region (post-January 2015)

<u>The Sustainable Groundwater Management Act (SGMA)</u>

On September 16, 2014, Governor Brown signed the following three-bill legislative package into law: AB 1739 (Dickenson), SB 1168 (Pavley), and SB 1319 (Pavley). These new laws are collectively known as the Sustainable Groundwater Management Act (SGMA) and became effective January 1, 2015. These laws define sustainable groundwater management as “the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results.”

Undesirable results are defined as any of the following effects caused by groundwater conditions occurring throughout the basin:

- Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply
- Significant and unreasonable reduction of groundwater storage
- Significant and unreasonable seawater intrusion

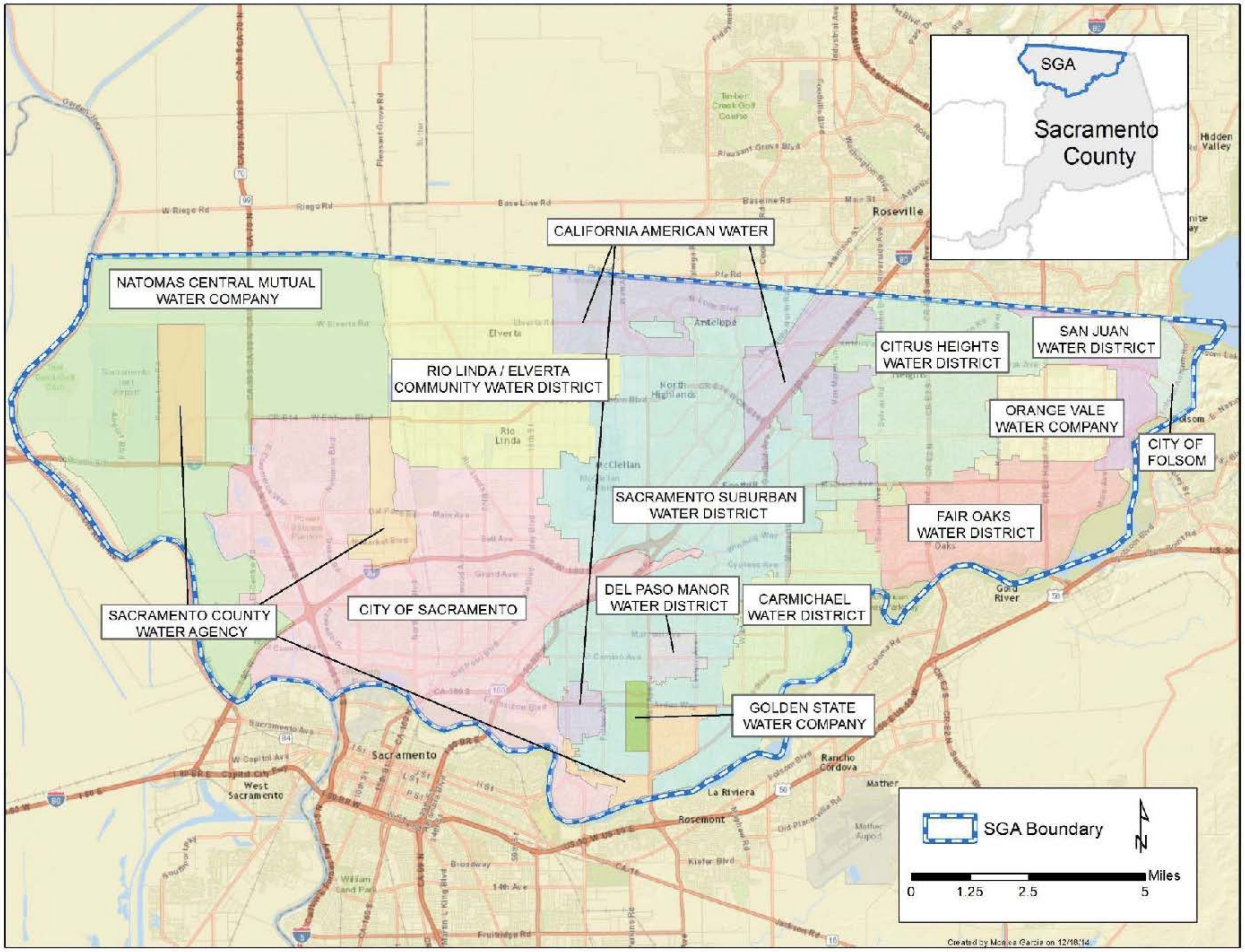


Figure 71. Water supplier service areas within the Sacramento Groundwater Authority's Jurisdiction (Figure A-13 from SGA, 2014).

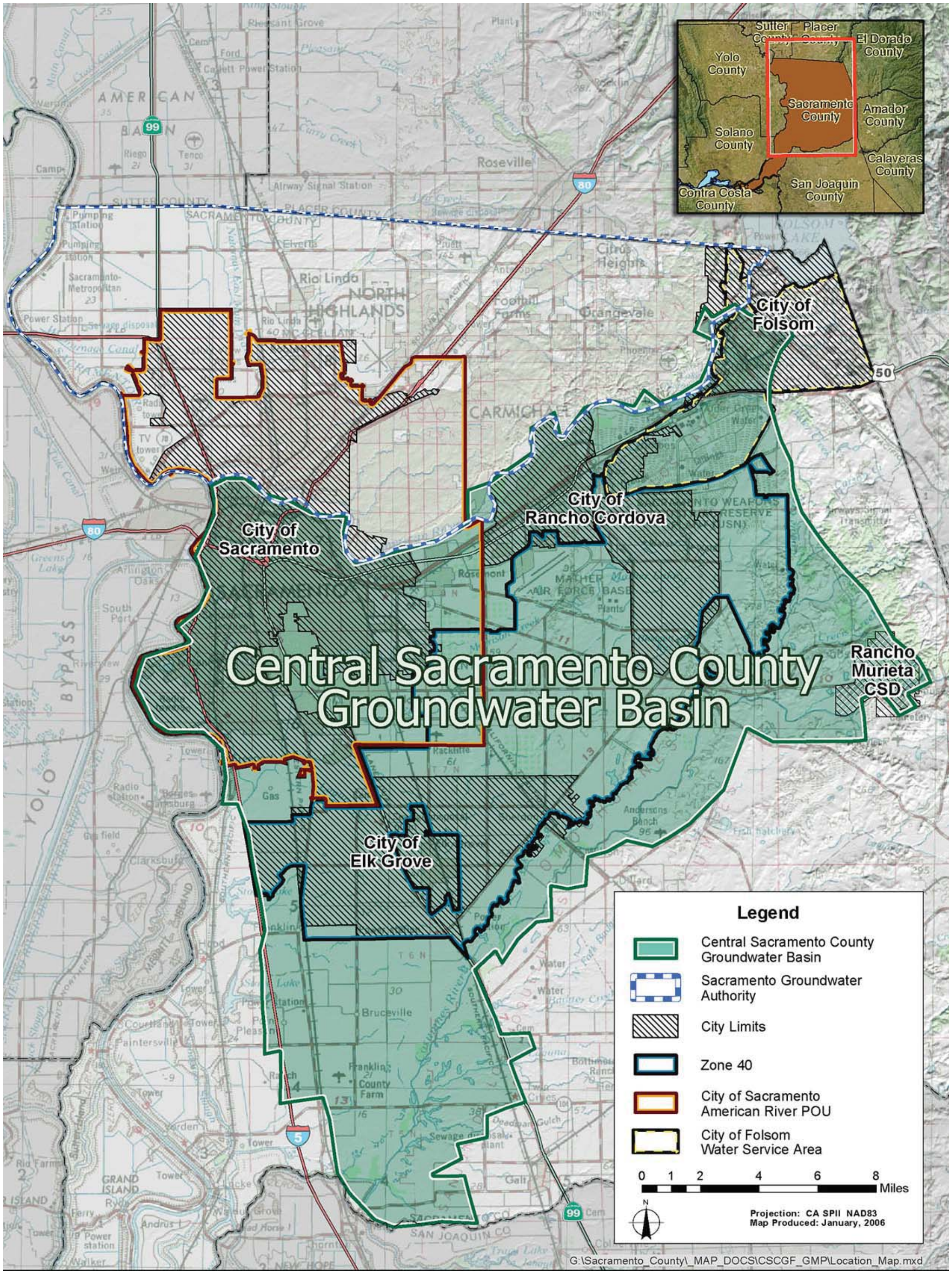


Figure 72. Location map of central Sacramento County groundwater basin (Figure 1.3 from CSCGMP (SCGA 2006).

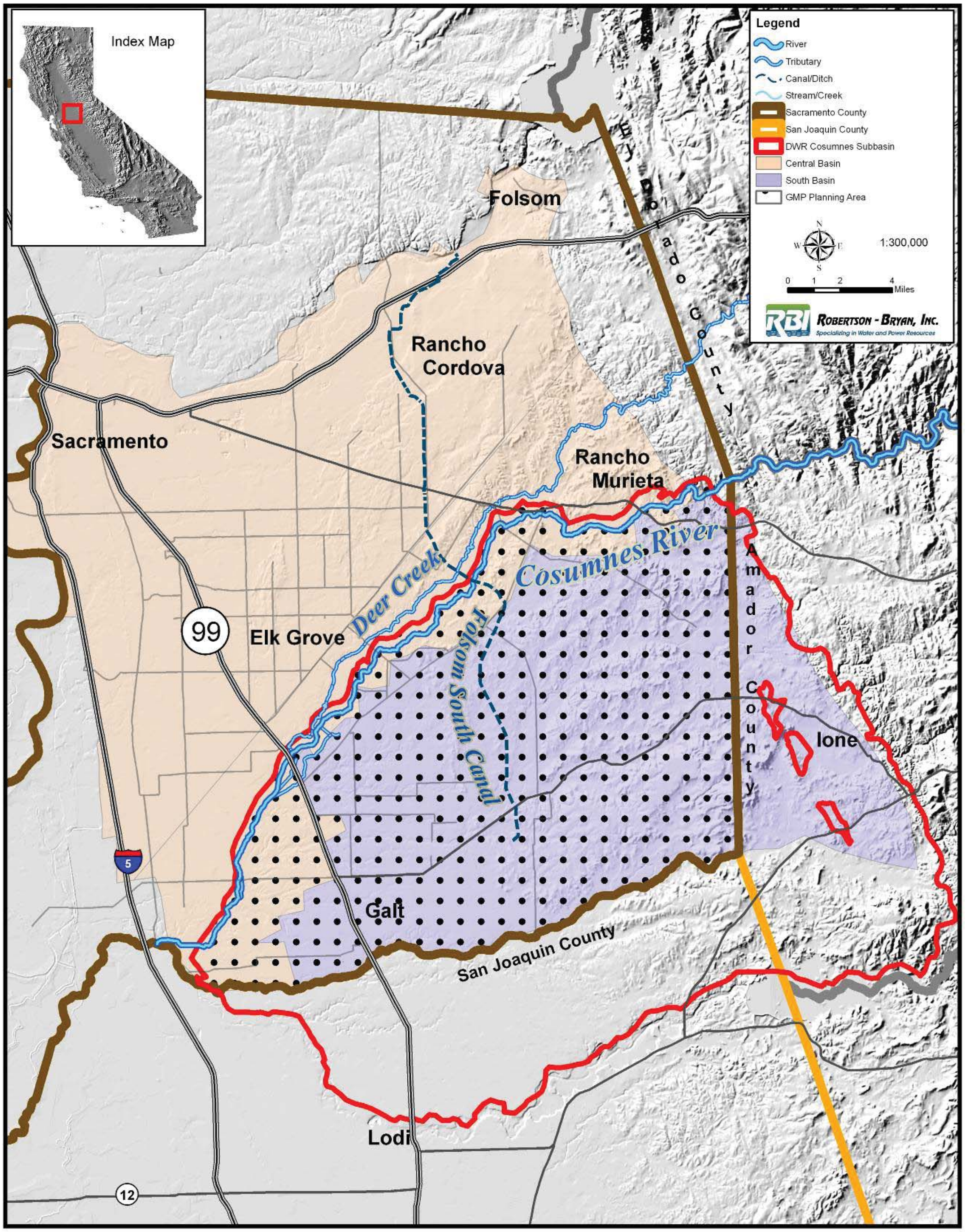


Figure 73. South Basin planning area for the South Sacramento County GMP (Figure 1-1 from (SGA, 2011).

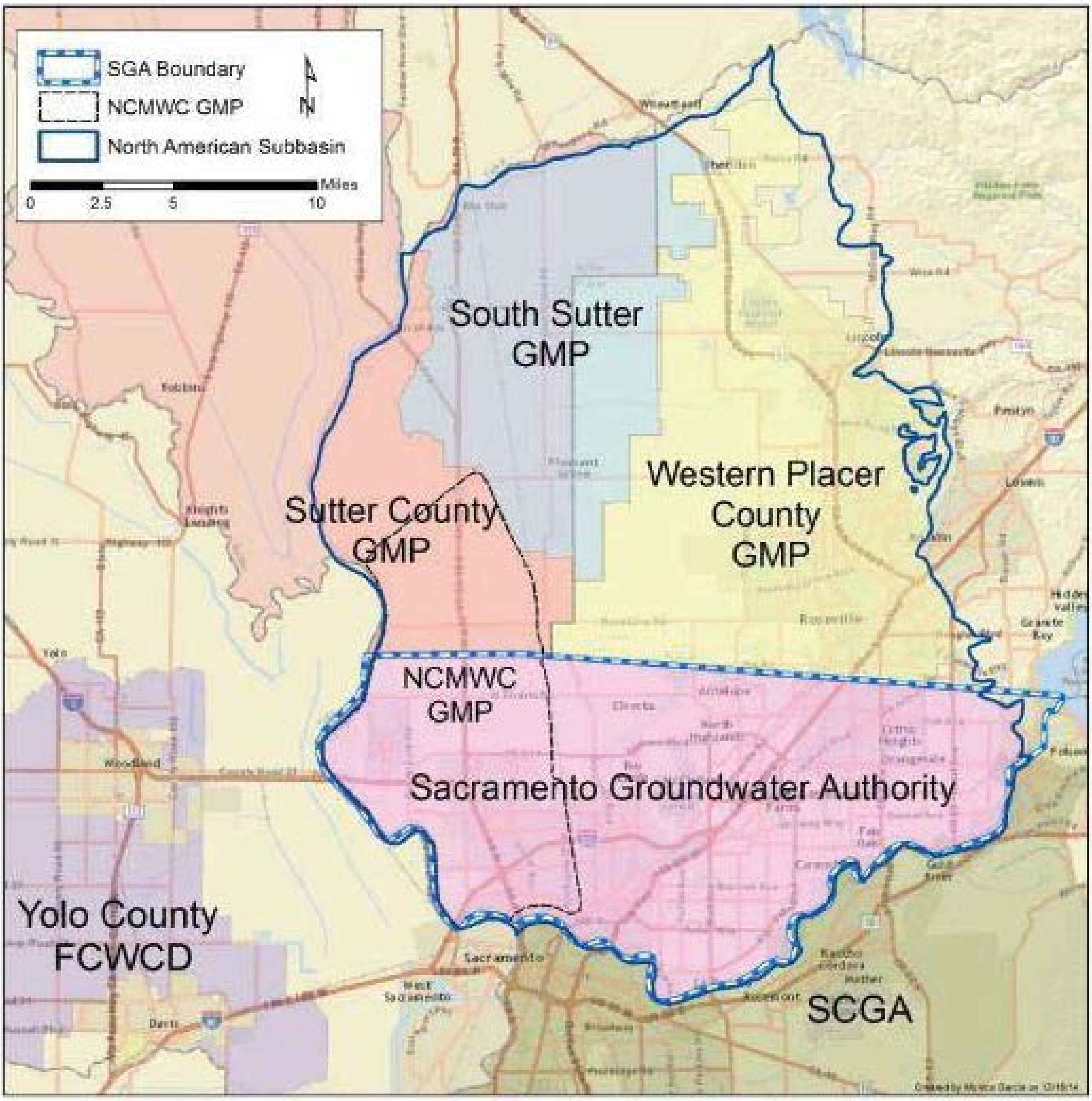


Figure 74. Additional groundwater management plans in the Sacramento area (SGA 2014).

- Significant and unreasonable degraded water quality
- Significant and unreasonable land subsidence
- Surface water depletions that have significant and unreasonable adverse impacts on beneficial uses of surface water.

The law requires high- and medium-priority basins under the CASGEM Program subject to critical conditions of overdraft to be managed under a groundwater sustainability plan (GSP) by January 31, 2020 and requires all other high- and medium-priority basins to be managed under a GSP by January 31, 2022. The four subbasins in the Sacramento area are high and medium priority and therefore, must comply with the SGMA (Figure 75). However, there are no critically overdrafted basins in the Sacramento area. The nearest critically overdrafted basin to the Sacramento area is to the south in adjacent San Joaquin County; the Eastern San Joaquin Subbasin.

The law provides for financial and enforcement tools to carry out effective local sustainable groundwater management through the formation of groundwater sustainability agencies (GSAs). The law required GSAs to be formed for all high- and medium-priority basins by June 30, 2017. The remaining high- and medium-priority subbasins, or portions thereof, in the Sacramento area must have been claimed by a local agency(s) by June 30, 2017 or they may be considered probationary by the State Water Resources Control Board (SWRCB). If that occurs, the SWRCB may step in as the interim groundwater management entity, until such time that the local agencies can successfully assume groundwater management responsibilities. To assist GSAs in the development and implementation of GSPs, Proposition 1 (2014) authorized $100 million in DWR grant funding to support these efforts.

Alternatives to GSPs in Sacramento area

SGMA established a process for local agencies to develop an alternative to a GSP for evaluation by DWR. An alternative plan was required to be submitted to DWR for review no later than January 1, 2017, and every 5 years thereafter. Alternative plans shall provide information that demonstrates the basin has operated within its sustainable yield over a period of at least 10 years.

Two local agencies in the Sacramento and surrounding areas submitted alternatives to GSPs by the legislatively mandated deadline of January 1, 2017: Sacramento Central Groundwater Agency and Sutter County. DWR began to review these plans in early 2017. Per the Water Code, DWR has two years to review GSPs and determine adequacy. It is anticipated that these alternative plans would be reviewed and approved or denied by the end of 2018.

Figure 75. 2018 Draft CASGEM basin prioritization in the SM (Source: DWR SGMA Online Data Viewer).
Orange – high priority
Yellow – medium priority
Light green – very low priority

Groundwater Sustainability Agency Formation in the Sacramento area

As of May 11, 2018, 33 exclusive GSAs have been formed in the four subbasins that comprise the Sacramento Metropolitan Area including:

- North American Subbasin: 5 GSA's
    - Sacramento Groundwater Authority
    - West Placer Groundwater Sustainability Agency
    - Sutter County
    - South Sutter Water District
    - Reclamation District 1001
- South American Subbasin: 9 GSA's
    - Sacramento Central Groundwater Authority
    - County of Sacramento
    - Reclamation Districts 369, 551, 744, 755, 813, and 2110
    - Franklin Drainage District
- Solano Subbasin: 17 GSA's
    - Solano Subbasin Groundwater Sustainability Agency
    - Yolo Subbasin Groundwater Agency
    - County of Sacramento
    - City of Vacaville GSA
    - Solano Irrigation District
    - Reclamation Districts 3, 150, 307, 317, 349, 407, 501, 554, 556, 999, 2067, and 2111
- Yolo Subbasin: 2 GSA's
    - Yolo Subbasin Groundwater Agency
    - Reclamation District 999

These GSAs must now embark on the development and adoption of a GSP by the legislatively mandated deadline of January 31, 2022, or be subject to SWRCB intervention.

GSPs in the Sacramento area

- As of May 11, 2018, only one GSA has submitted a notice of intent to develop a GSP in the Sacramento Metropolitan Area; Yolo Subbasin Groundwater Agency.

Water Transfers in the Sacramento Region

Water transfers between willing sellers and willing buyers can help stretch California's water supplies in dry times and move water to places of critical need. Each year hundreds of water transfers occur in California. The majority of these transfers are between agricultural water users in the same basin. A water transfer is proposed and initiated by willing sellers who have legal rights to a supply of water of interest to a potential buyer. The seller must take specific actions within the seller's service area to make water available to the buyer that would not include water available in the watercourse, or in the best case, the transfer of "new water." Water transfers are one of the water management tools used to enhance flexibility in the allocation and use of water in California.

Since many Sacramento area water purveyors have the ability to conjunctively manage surface water and groundwater supplies, several area purveyors implemented groundwater substitution transfers during recent dry periods. Groundwater substitution transfers make surface water available for transfer by reducing surface water diversions and replacing that water with groundwater pumping. The rationale is that surface water demands are reduced because a like amount of groundwater is used to meet the demands. The resulting increase in available surface water supplies can be transferred to other users. Table 4 lists the groundwater substitution transfers that have occurred in the Sacramento area between 2009 and 2015.

Oil and Gas

primary author: Tom Barry

The Sacramento Basin is primarily a gas-producing region with over 70 gas fields (Figure 76) and only one small oil field (Brentwood). Fifty-two gas fields were active producers in 2016. Contour maps, cross sections and data sheets of all the Sacramento Basin oil and gas fields can be found in the California Division of Oil, Gas, and Geothermal Resources (DOGGR) publication, "California Oil and Gas Fields, Volume III – Northern California" (1983). Figure 77 shows the location of gas fields near the City of Sacramento. A generalized stratigraphic column of the Sacramento Basin is presented as Figure 78 (Magoon and Valin, 1995), and a reduced copy of a generalized cross section of the southern Sacramento Basin is presented as Figure 79 (DOGGR, 1982).

Geologic Setting and Hydrocarbon Traps

The Sacramento Basin is an elongate, northwesterly-trending structural trough that extends southeasterly as the San Joaquin Basin, together composing the Great Valley of California. The trough formed as a convergent margin forearc between the late Mesozoic and early Cenozoic eras, and is filled with as much as 12,192 meters of Jurassic to Holocene, marine and non-marine siliciclastic rocks (Magoon and Valin, 1995). Natural gas is produced from formations that range from Cretaceous to Pliocene in age.

Year	Seller(s)		Transfer Amount km^3 (AF)
2009	City of Sacramento	Sacramento Suburban Water District (SSWD)	0.0092537 (7,500)
2010	SSWD		0.003178 (2,576)
2013	SSWD	Conaway Preservation Group (CPG)	0.0097137 (7,857)
2014	CPG	Natomas Central Mutual Water Company (NCMWC)	0.023245 (18,845)
2015	CPG	NCMWC	0.02144 (17,382)
		2009-2015 Total Transfer Amount	**0.06683 (54,160)**

Table 4. Groundwater substitution transfers that occurred in the Sacramento area between 2009 and 2015.

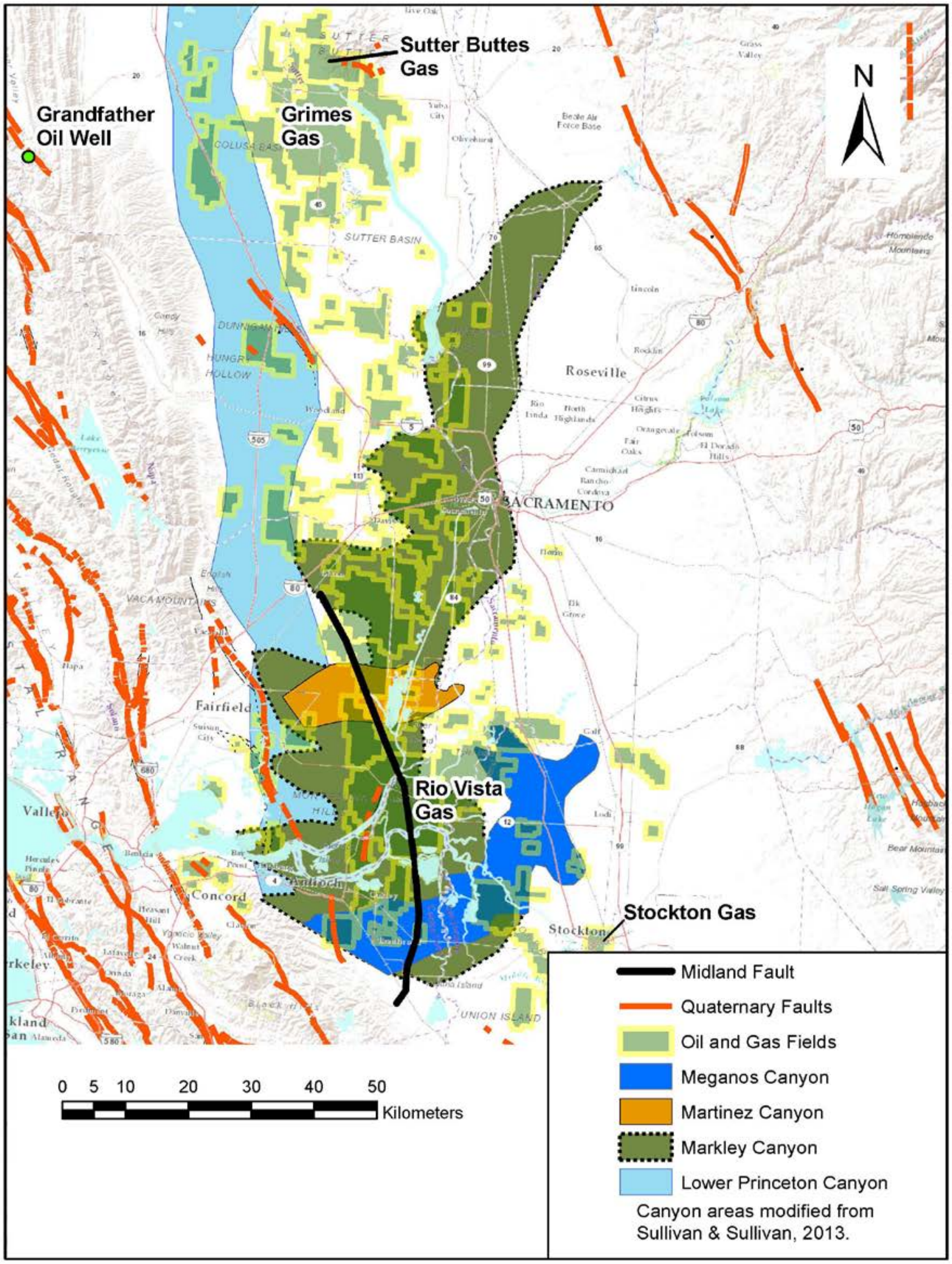


Figure 76. General location of gas fields in the Sacramento basin (DOGGR, 1983).

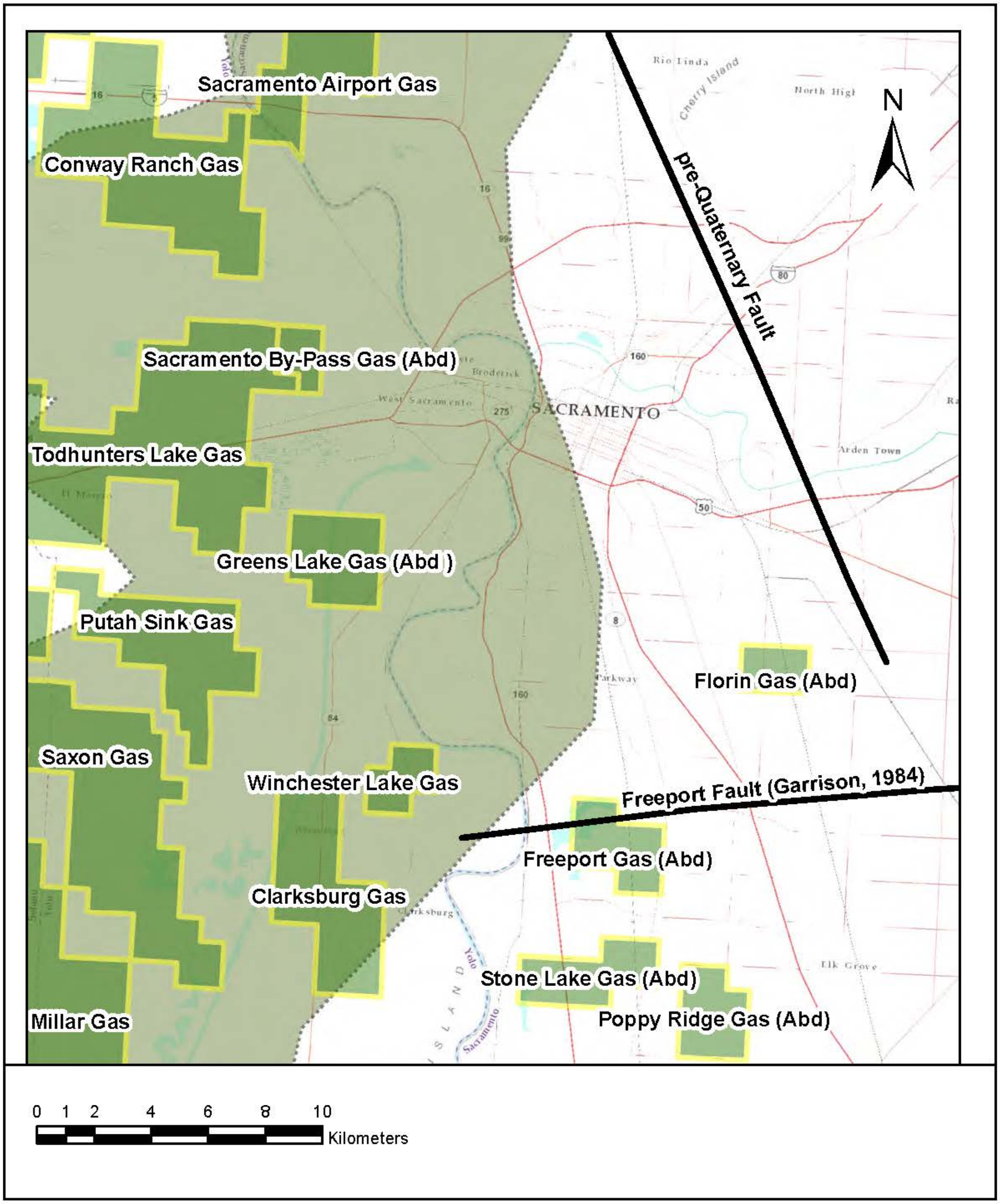


Figure 77. Location of gas fields near the City of Sacramento (DOGGR, 1983).

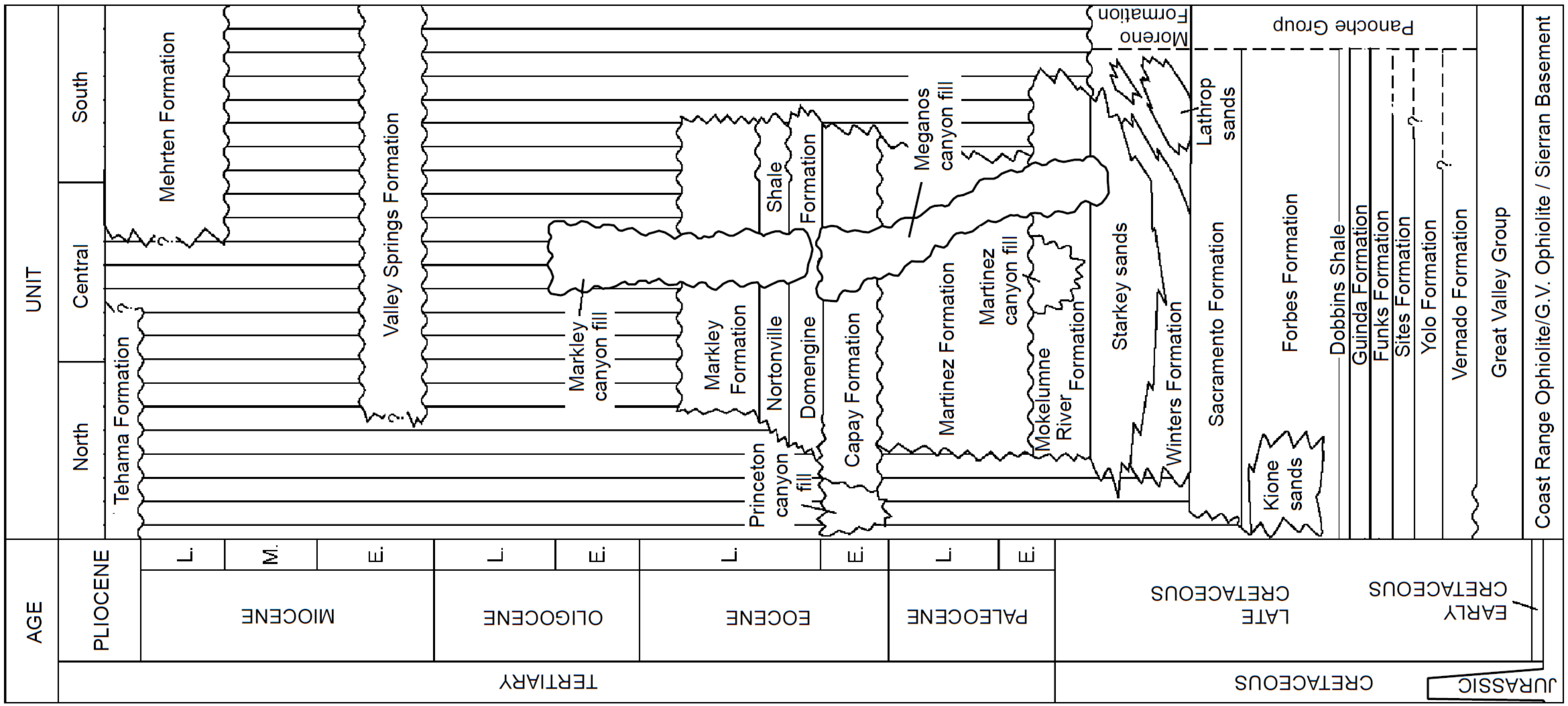


Figure 78. Stratigraphic chart of the Sacramento basin (from Magoon and Valin, 1995).

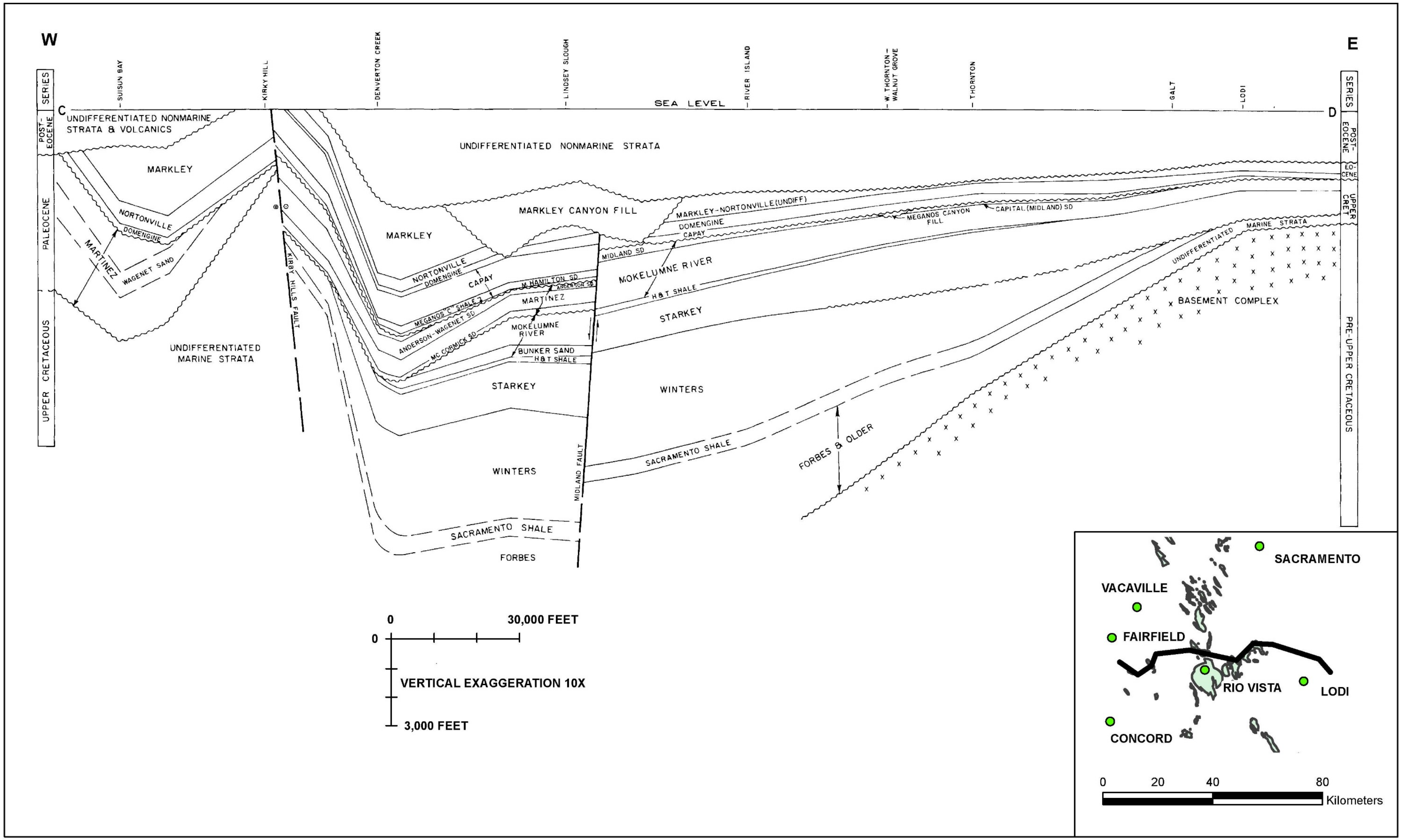


Figure 79. Generalized geologic cross section of the southern Sacramento basin (DOGGR, 1982).

There are two major gas-field systems generation commercial volumes of natural gas: the Cretaceous Dobbins-through-Forbes system and the Late Cretaceous-Eocene Winters-through-Domingene system (Figure 78). The hydrocarbons for both systems probably originated from gas-prone source rocks in the area of the "delta depocenter", which is suspected to be the Dobbins Shale and Forbes Formation for the Dobbins-Forbes system and the Winters Shale and Sacramento Shale for the Winters-Domingene system (Zieglar and Spotts, 1981). Within the northern Sacramento Basin, regional seal, or cap rocks, that partition the gas-field systems are the Princeton canyon fill and Capay Shale (Baker, 1975; Redwine 1984), and the Sacramento Shale and Markley canyon fill (and other canyon fills) in the southern Sacramento Basin (Magoon and Valin, 1995). The Capay, H & T and Sacramento shales are prominent Sacramento Valley stratigraphic markers. The base of the Capay Shale is a regional unconformity which truncates the other marker shales. The base of the Capay Shale and the unconformity at the base of the H & T Shale are marked by distinctive glauconite grits (Reynolds, 1978).

In the Dobbins-Forbes system, the Forbes Formation represents a submarine-fan/slope system that was deposited in the northern Great Valley forearc basin during late Cretaceous (lower Campanian) time. This unit is bounded by the Dobbins Shale below and the Sacramento Shale above. The mud-rich-fan system of the Forbes Formation is characterized by meandering channel-levee complexes that prograded southerly along the plunging axis of the forearc basin (Imperato and others, 1990; Moore, 1991). The Forbes Formation is overlain by the fluvial-dominated deltaic deposits of the Kione Formation in the northern and central Sacramento basin (Moore, 1991).

In the Winters-Domingene system, the Kione Sand represents a deltaic and lagoonal facies, and is an important reservoir unit in the northern Sacramento Valley (Reynolds, 1978). The Sacramento Shale separates the Kione system from the younger Starkey delta system (Graham, 1981). The Starkey Sands, Winters Shale and Winters Sands were deposited by a westwardly prograding delta complex.

The middle Eocene Domengine Formation is an important reservoir unit that can be regionally subdivided into two stratigraphic sequences. The base of each sequence consists of fluvial and estuarine sandstones that were deposited in northeasterly–southwesterly-trending incised-valley systems that are interpreted to have been formed by fluvial incision (Sullivan and Sullivan, 2012). Marine shales and shoreline sandstones overlay the incised-valley fills and reflect flooding of the shelf. The Nortonville Shale caps the upper sequence.

Controlling deposition, at least four mudstone-filled submarine canyons, are recognized in the Lower Tertiary section of the Sacramento basin (Figure 76). These submarine canyons successively fed sediments into a deep remnant of the Mesozoic forearc basin. The mudstone-filled submarine canyons and Eocene fluvial/estuarine incised valley systems are vertically stacked (Sullivan and Sullivan, 2012). The locations of these depositional systems are interpreted to have been controlled by tectonic subsidence due to their vertical stacking along the axis of the Sacramento Basin. However, the timing of the submarine canyons and fluvial/estuarine incised valley systems appear to have been controlled by eustasy based on correlation to worldwide sea level curves (Sullivan and Sullivan, 2013).

A significant amount of the trapped gas is attributable to fine-grained valley-fill sediments truncating and sealing older gas reservoirs at many Sacramento area gas fields including the Catlett, Conway Ranch, Fremont Landing, Karnak, Liberty Cut, Liberty Island, Maine Prairie, Millar, Rio Jesus, Sacramento Airport, Todhunters Lake, and Winchester Lake fields (Pepper-Kittredge and Wilson, 1984).

The upper Eocene Markley Canyon is the youngest of the submarine canyons, and the eastern edge of this canyon underlies a portion of the City of Sacramento (Figure 77). Two faults are shown on Figure 77. The east-west trending Freeport fault was mapped through the Freeport Gas Field, and it displaces the Late Cretaceous Sacramento Formation (shale) and Forbes Formation (Garrison, 1992). The USGS Quaternary Fold and Fault database shows a buried northwest trending pre-Quaternary fault east of the Markley Canyon.

Several of the formations cut by the Markley Canyon contain gas reservoirs. The Domengine, Martinez, Mokelumne, and Starkey formations contain reservoirs associated with canyon fill truncation (Pepper-Kittredge and Wilson, 1984). Truncated formations along the western margin of the Markley Canyon typically dip westerly and away from the canyon. Formations generally dip into the Markley Canyon on its eastern side (Pepper-Kittredge and Wilson, 1984).

Sedimentary rocks are deformed by folds and thrusts along the west side of the basin. This deformation caused by tectonic compression has also resulted in over-pressured fluids in the Mesozoic marine mudrocks and the occurrence of ridgetop perennial saline springs (Unruh and others, 1992; McPherson and Garven, 1999). A map of these perennial cold-water saline springs in Rumsey Hills and Dunnigan Hills was published in an issue of California Geology (Schaal and others 1994). These springs emerge either along west vergent thrust faults or the axis of an anticline. Oil seeps and historic shallow oil wells are also located in this area near Wilbur Springs. Exploratory wells in the hills west of the Sacramento Valley often encountered drilling problems due to the high pore pressures.

History of Oil and Gas Exploration and Development

Northern California and the Sacramento Valley are known for the vast quantities of natural gas. However, small amounts of oil have also been produced near the western edge of the valley. The Brentwood Oil Field, one well in the Winters Gas Field, and one well in the Bunker Gas Field have produced commercial amounts of oil. Numerous gas wells throughout the southern Sacramento Basin have produced commercial amounts of natural gas liquids (condensate).

Oil seeps are present in the hills west of the Sacramento Valley, where rocks of the Great Valley Group are in fault contact with rocks of the Franciscan Complex (Figure 33; McLaughlin and others 1990; Graham, 1981). The oldest drilled oil well in California is widely recognized to have been located in Humboldt County. However, an apparently older oil well was drilled in Colusa County along Bear Creek near Wilbur Springs (California Division of Oil and Gas, 1932). A Division of Oil and Gas (1932) telephone conversation log indicates that this well, the “Grandfather” well, was drilled in 1844 to a depth of either 21 or 32 meters. If this date is correct, then this well is older than the Drake well in Pennsylvania, which was drilled in 1859. The “Grandfather” well produced 1 barrel of oil per day which was originally used for medicinal purposes. The oil was later used during the Civil War as a lubricant on ships “going around the horn.” The 1932 memo states that a “gin pole” had been erected over the well and an attempt to clean out the hole with very crude equipment was being made (Figure 80).

The first natural gas well in California was likely the Court House well in Stockton, which was drilled around 1854-1855. In 1890 the Sacramento Natural Gas and Water Company was formed, and two gas wells were developed in the City of Sacramento near 5th and R streets. The Western States Gas and Electric Company had 11 operating wells in in the Stockton area by 1915. This company was acquired by Pacific Gas and Electric Company in the 1920s. The 1920 Division of Oil and Gas annual report noted that in 1919, natural gas from several counties, including San Joaquin and Sacramento counties was being produced and mixed with manufactured gas for domestic service (Division of Oil and Gas, 1920).

The Tracy Gas Field, discovered in 1935, is the first commercial gas field developed in northern California. The Rio Vista Gas Field, the largest gas field in California with almost 113 billion cubic meters of reserves (Hector, 2014), was discovered in June 1936. Rio Vista quickly became a boom town, and in August 1944 a group of “mudmen”, roughnecks, and geologists founded the Northern California Geological Society at Foster’s Bighorn bar (Kotick, 1976). Other significant gas field discoveries include: Sutter Buttes Gas Field in February of 1933, Willows-Beehive Bend Gas Field in August of 1938, Grimes Gas Field in November of 1959, and Malton-Black Butte Gas Field in October of 1964 (DOGGR, 1984).

The “McCune” 1 gas well was completed in sands of the Winters Formation in the Winters Gas Field during September 1959. The well initially produced 29-degree gravity oil at a maximum of 154 barrels per day in 1960. This well produced oil until 1963 and was the only producing oil well in the Sacramento Valley until December 1962, when oil was discovered in the Third Massive Sand in the Brentwood Oil Field (California Division of Oil and Gas, 1963).

Figure 80. Grandfather Oil Well on Bear Creek in Colusa County, probably 1932 (California Geological Survey Digital Archive).

Natural Gas Production

In 2015, approximately 710 Mm^3 of natural gas was produced from the Sacramento Valley. Production volumes from the five largest fields from 2011 to 2015 are presented in Table 5 (DOGGR, 2016). Forty different companies operated approximately 976 gas wells in 2016 that produced 570 Mm^3. California Resources Production Company operated approximately 701 or 72% of the Sacramento Valley wells with Pioneer Exploration with 42 wells (6%) and Royale Energy with 40 wells (6%). The natural gas industry in the Sacramento Valley is experiencing the lowest level of drilling activity since commercial gas was discovered in 1935. Current low well head gas prices and the often-misunderstood potential for significant new discoveries have led to this situation. In 2016, the number of idle wells in the Sacramento Valley were noted to number 992, as compared to the active 976 wells.

Natural Gas Storage

Natural gas storage enables utility and private companies to adjust for daily and seasonal fluctuations in demand throughout the year. Depleted oil and gas fields are the most common type of gas storage facilities in the United States, and conversion of an oil or gas field from production to storage takes advantage of existing infrastructure such as wells, gathering systems, and pipeline connections (API, AGA and INGSAA, 2016). A certain volume of cushion gas is required to remain in the reservoir for pressure maintenance so that injected gas volumes can be retrieved when needed. Seven depleted gas fields, located in or near the Sacramento Basin are used to store natural gas (Figure 81). The formations, zones, and capacities of these seven gas storage facilities are summarized in Table 6.

Underground Injection Control and Induced Seismicity related to Oil and Gas Operations

The US Environmental Protection Agency defines Class II injection wells as wells associated with oil and gas field operations that inject water, brine, gas, steam or air. All Class II injection wells are associated with a specific Underground Injection Control (UIC) project. The purpose of a UIC project may be water or gas disposal, enhanced oil recovery, or gas storage.

There are well documented examples of induced seismicity caused by the disposal of oil field brines and wastewater in other states such as Oklahoma and Ohio. However, in California, there are no known instances of induced seismicity that are caused by UIC projects. However, induced seismicity related to geothermal operations at the northern California Geysers is an everyday occurrence. There are also examples of probable induced seismicity related in former oil field practices in southern California (oil

	2015	2014	2013	2012	2011
Rio Vista Gas	192	241	277	303	292
Willows-Beehive Bend Gas	102	122	150	218	252
Grimes Gas	93	116	142	226	286
Sutter Buttes Gas	57	71	88	116	153
Malton-Black Butte Gas	20	20	23	28	40

Table 5. Five largest producing gas fields in the Sacramento Basin. Values represent net gas production by year (millions of cubic meters) (DOGGR, 2016).

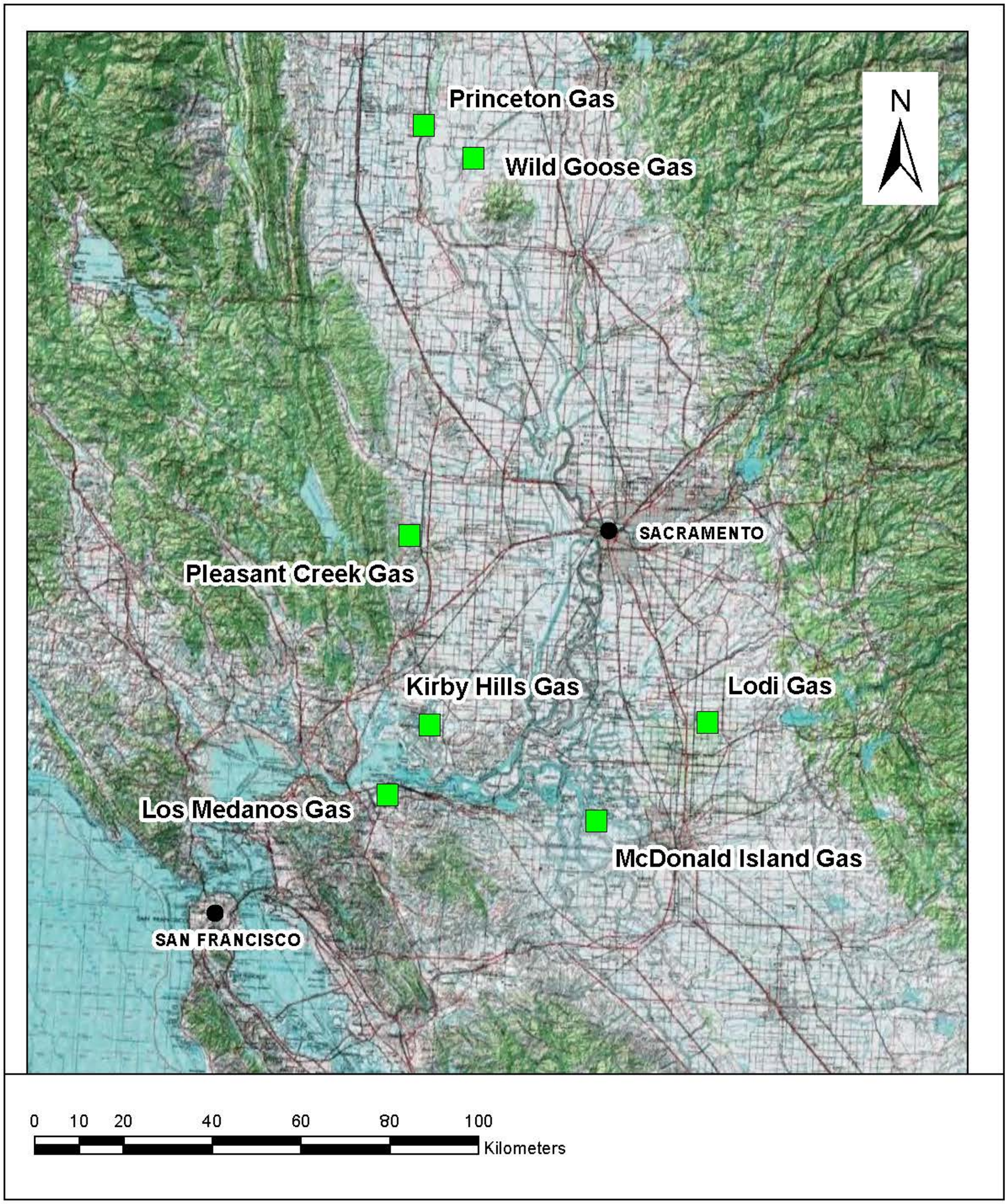


Figure 81. Location of gas storage facilities.

Gas Field	Formation	Zone	MCM
Kirby Hills Gas	Domengine	Domengine	538
	Martinez	Wagenet	
Lodi Gas	Domengine	Domengine	595
	Mokelumne River	Midland	
Los Medanos Gas	Domengine	Domengine	821
McDonald Island Gas	Mokelumne River	McDonald Island Sand	3,880
Pleasant Creek Gas	Winters	Peters	207
Princeton Gas	Kione	Kione	351
Wild Goose Gas	Kione	Kione	2,435

Table 6. Gas storage facilities in the Sacramento Basin. Values represent the storage zones and approximate total capacity in millions of cubic meters (DOGGR, 2016).

production without reinjection of produced water). In the early twentieth century, prior to the practice of reinjecting produced water, removal of oil field fluids in southern California caused land subsidence, earth fissures, and possibly induced seismicity. (Hough and Page, 2016).

Hydraulic fracturing and enhanced hydrocarbon recovery are rarely implicated in recent studies of induced seismicity outside of California. Hydraulic fracturing generally only causes micro-seismicity and does not typically induce felt earthquakes (Rubinstein and Mahhani, 2015). As of Spring 2018, there are no current or permitted hydraulic fracturing projects in northern California. Locations of hydraulic fracturing and well stimulations projects in southern California can be viewed on the California Division of Oil, Gas, and Geothermal Resources "Calstim'D" web application map viewer (DOGGR, 2018). Enhanced oil recovery does not generally cause induced seismicity because these types of UIC projects usually maintain reservoir pressures at levels that are typically lower than the original reservoir pressure.

Water disposal projects can cause induced seismicity if deep injection results in an increase in fluid pressure along pre-existing faults. Induced seismicity in Oklahoma is associated with UIC projects where large volumes of wastewater are reinjected into deeper zones that are close to underlying basement formations. In California, most Class II water disposal wells inject into depleted oil reservoirs and not into deeper basement zones. Increased fluid pressure only occurs if there is "net injection" in a zone, which would only occur if the injection volume exceeded the production volume. In most California oil fields, larger volumes of fluids (oil and water) are removed than reinjected (water or brine). Reservoir pressures tend to decrease over time as the field is developed.

Current oil and gas operations in California have not been clearly linked to induced seismicity. However, there have been several recent studies that attempted to link Class II injection projects to induced seismicity (Goebel, 2015, Goebel and others, 2015; Goebel and others, 2016; Foxall and others, 2018). Foxall and others (2018) concluded that, "there is no apparent relationship between periods of net injection in most of the oilfield areas and seismicity except possibly in the Valv pool of the Tejon Western area between 1984 and 1987."

Geology Based Parks and Recreation

California is rich in geologic history and there are numerous state park and recreation areas that focus on the diverse geology of the state. Brief summaries of the geology of many of California's state parks can be found on the California Department of Parks and Recreation website titled Geological Gems of State Parks (CDPR, 2018a). The prominent geology-based parks in the Sacramento region are discussed below.

Lower American River Parkway

primary author: Mike Conway

The Lower American River (LAR) extends from its headwaters at Folsom Lake to its confluence with the Sacramento River in downtown Sacramento. The LAR contains discharge from three branches of the American River (North, Middle, and South) that cascade through the Sierra Nevada, meeting in Folsom Lake. The LAR supports recreation, wildlife, and also has a unique geologic and hydrologic history. A levee-protected recreational river corridor, called the Lower American River Parkway (Parkway) was given its official protected status in 1959 when the County of Sacramento made it a public parkway in its General Plan. The 47 km Parkway extends across a mild slope following the LAR, also beginning beneath Folsom Dam and ending where the American River connects with the Sacramento River (Figure 82). The Parkway covers a swath averaging about 1 km in width but reaching 2 km in some areas. The Parkway contains a bike path which serves as the training ground for the region's cyclists and runners. The Parkway also provides commuters in the Sacramento region an alternative and scenic transportation network. The levee system that buffers the LAR also created the opportunity for this great recreational parkway to exist within and alongside a lush and woody floodplain habitat.

Setting

The LAR begins at the base of Folsom Dam, which is located at the transition from the plutonic rocks of the foothills and upland range of the Central Valley. The upper half of the LAR is flanked by a steep clay bank, generally on the north side of the river. The often vertical cut of the bank provides as much as 50 meters (m) of vertical relief above the river near the city of Folsom and 30 m in Fair Oaks.

A 37 km section of LAR, from its confluence with the Sacramento River to the Nimbus Dam, was granted state Wild and Scenic River designation in 1972 and federal Wild and Scenic River designation in 1981. The National Wild and Scenic Rivers System was created by Congress in 1968 to preserve certain rivers with outstanding natural, cultural, and recreational values in a free-flowing condition for the enjoyment of present and future generations (USDOI, 1980).

The environmental habitats along the LAR consist of oak savannas and woodlands. The dramatic and tough looking oak trees thrive in the dry low foothill soil. The Parkway has an abundance of deer, cougars, turkeys, beavers, snakes, and lizards. Figure 83 shows the transition between the lower foothill uplands (above 30 m) and the Central Valley lowlands (below 30 m), and also how close Sacramento is to the "Legal Delta" (Figure 83).

Figure 82. Map of the American River Parkway (not to scale). The shaded green zones indicate the limits of the Parkway (ARPF, 2009).

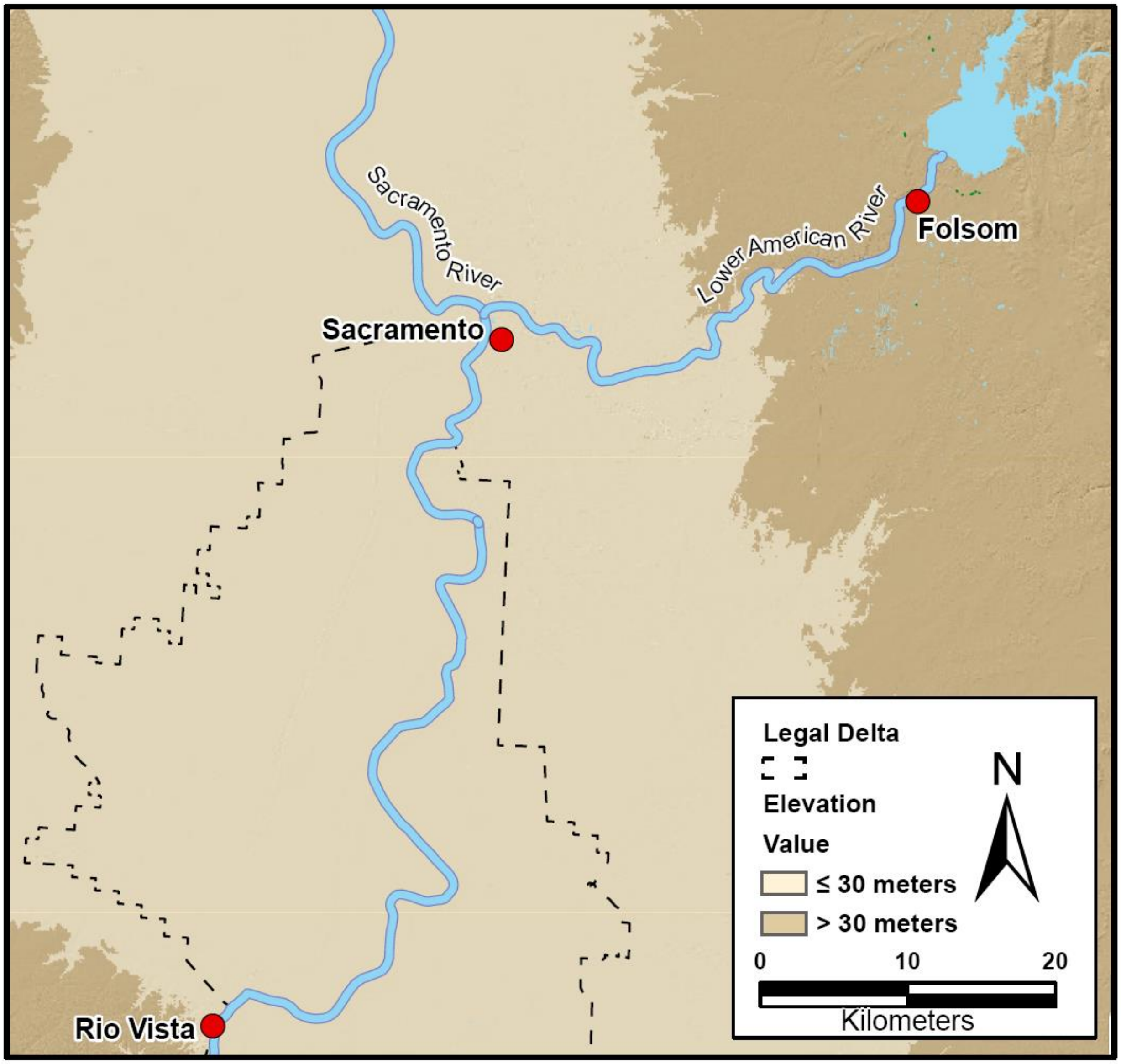


Figure 83. Map of the Lower American River and its intersection with the Sacramento Valley and the Legal Delta (Source: Mike Conway).

Though the modern LAR is confined by levees along the lower half, it's upper half is defined by a well-incised channel and doesn't require additional levees for flood protection. This conclusion is supported by the local Flood Insurance Rate Maps (FEMA, 2012). Neither the Valley lowlands, nor upper foothill or maintains can provide the same balance of flatland-like ease of access and flood protection to its inhabitants.

Hydraulic Mining, Gravel Mining, and Reclamation

Relative to the one billion cubic meters of sediment produced in the Sierras between the 1850s and the 1880s (James, 1999), the 196 $Mm^3$of sediment produced from the American River Basin (Fairman, 2007) was relatively small. A more detailed discussion of the environmental impacts of hydraulic mining on the Sacramento region is presented in "Chapter VIII – Environmental Concerns – [Hazards Related to Gold Mining]". After the California Supreme Court injunction was issued in 1884, another 24 million m^3 of sediment was produced in the basin prior to 1953 (James, 1999). Significant post-hydraulic mining production in 1907 and 1908 produced 300,000 m^3 of sediment in the river and likely resulted in raising the river stage in LAR for years to come. Even such a small relative volume of sediment could have been responsible for raising the river stage in Fair Oaks up to 30 cm between 1923 and 1937 (James, 1999). Sediment delivery to the LAR has decreased since North Fork Dam was completed in 1940 and Folsom Dam in 1955. The now reduced sediment supply has likely led to a net sediment removal from the bed and banks of the LAR (James, 1999; Fairman, 2007).

Recreation

The 1,862-hectare Parkway and the LAR that flows through it, provide extensive recreational opportunities. The Jedidiah Smith Memorial Bike Trail, locally referred to as The Bike Trail, is an extensive meandering network of trails extending 51 km between downtown Sacramento and Beale's Point at Folsom Lake, that parallels and often crosses the river.

The Parkway inspired the "World's Oldest Triathlon," Eppie's Great Race. The race has introduced many competitors to the Parkway, dating back to July 1974, and inspired countless other competitions.

Sport fishing is possible throughout the year along the LAR. Depending on the migration season, the river contains king salmon, steelhead, striped bass, shad, and catfish (USDOI, 1980). Additionally, the LAR provides the only fall migration pathway in an urban setting known to exist for king salmon (ARPF, 2009).

Landscape Evolution

Extensive dredge tailings cover most of the Parkway along the LAR. Vast piles of cobbles have come to support extensive vegetation. The alternating mound and depression landscape supports its own unique habitat, particularly cottonwood trees and reptiles that can bask in the warmth retained by the sun-drenched rocks (ARPF, 2009).

The most striking geological exposures of the LAR occur along the upper half of the LAR. A prominent cemented alluvial gravel face begins where Sunrise Boulevard crosses the river and continues along the north side of the river to Folsom Lake. The Fair Oaks Formation, also referred to as the Bluffs, is an exposed alluvial conglomerate face that contains a 30 m or more record of the American River evolution.

The Bluff is a distinctive exposure north of the river between Folsom and Fair Oaks (Figure 84). This represents the upper half of the LAR landscape and also marks the toe of the Sierran foothills and the transition to the Sacramento Valley lowlands. Land south of the river is covered in deep sequences of alluvial cobble and gravel deposits. The communities of Rancho Cordova and Gold River along with many industrial gravel mining operations have established themselves south of the river. Residents of the alluvial landscape benefit from rapid stormwater infiltration and a high suitability for the construction of building foundations, while other industries benefited from gravel and mineral recovery.

Gold Bug Mine Park

primary author: Garry Maurath

The Gold Bug Mine Park, located in Placerville, about 13 km from Sutter’s Mill in Coloma. The process of preserving and renovating the mine as part of a public park started in 1980 and on February 1, 1985, the park was approved for listing in the National Register of Historic Places and also as a State Point of Interest on the California registry (Gold Bug Park, 2018).

Opened in 1888 by William Craddock and John Dench, the mine was originally named The Hattie, after William Craddock’s eldest daughter, but played out shortly after it was opened. However, during the mining process, larger quartz vein structures were noted in the canyon walls near the mine and a new drift was started. These quartz vein structures were followed about a hundred meters into the side of the canyon wall. In 1926, John McKay took ownership of the mine and changed the name to the Gold Bug Mine, while also changing the direction of the workings to explore laterally for additional quartz veins. Eventually the last owner of the mine, William Meagher, stopped working

Figure 84. View from the Bluffs in Fair Oaks, looking east. Image courtesy of Jesse Bravo.

the claim and the Bureau of Land Management took over the land as public property (Gold Bug Park, 2018).

The Gold Bug Mine is approximately 305m east of the Melones fault zone. The Gold Bug and Priest Mine adits are in metamorphosed sandstone and shale of the Calaveras Formation. The quartz veins followed by the mine workings dip steeply to the east and parallel the metamorphosed sandstone and shale layers. The Melones fault zone seems to control the location of gold deposits and in this area. The surface of this fault can be seen in a near vertical roadcut behind a group of stores on Main Street across from Placerville's City Hall. Here, vertical layers of sheared talc schist and metamorphosed shale are well exposed (Burnett, 1993). Mine production records were lost due to fire so it is not known how much gold was extracted over the life of the mine (CDMG, 1993).

Today, a portion of the original mine has been restored, including lighting and the addition of a solid wooden floor, and is maintained as a public park, owned and operated by the City of Placerville. The City of Placerville is the only municipality in the state of California to own a gold mine. There are self-guided mine tours through a 107-m drift (Gold Bug Park, 2018).

Empire Mine State Park

primary author: Chris Dennis

The Empire Mine opened in 1850 and permanently closed in 1956. The Grass Valley district, which included the Empire Mine, was the richest and most famous gold-mining district in California (EMPA, 2018). The Empire Mine was one of the oldest, largest, deepest, longest and richest gold mines in California. It operated for more than 100 years and produced 5.6 million ounces of gold before it closed in 1956 (5.6 million ounces of gold is equivalent to a box two meters long, two meters high, and two meters deep filled with gold). The most productive period of the mine was during the early 1900s. A more detailed discussion of the geologic setting and production history of the mine are discussed above in “Chapter VII – Natural Resources [Empire Vein]”.

The Empire Mine state park was established in 1976 and the above ground facilities, including the Empire cottage, mine-yard, blacksmith shop, steam run machine shop (Figure 85), assayer’s office, and a portion of the main shaft (Figure 86), with a miner’s skip have been renovated and extensive museum displays created that depict mining activities and the mining lifestyle during the life of the mine. The Park welcomes around 100,000 visitors from all over the world each year. Empire Mine State Historic Park’s close to 344 ha include kilometers of scenic trails for hiking, biking, running, dog walking and horseback riding (EMPA, 2018).

Figure 85. View of steam powered machine shop as it would have appeared in the early 1900s before being electrified (Source: image courtesy of Chris Dennis).

Figure 86. View down the main drift at the Empire Mine. The vein was mined by stoping with inclined shafts following dip, with horizontal shafts every 300-400 feet along strike (Stephen Testa) (Source: image courtesy of Chris Dennis).

Malakoff Diggings State Historic Park

primary author: Garry Maurath

Established in 1965, Malakoff Diggins State Historic Park is the site of California's largest "hydraulic" mine. Located on the Yuba River the park contains extensive cliffs created by hydraulic mining operations that form a canyon about 2,100 m long and 910 m wide, and 160 m deep. The lower portion of the cliffs consists of white gold-bearing (auriferous) gravels. These gravels also contain an extensive array of plant and vertebrate fossils, including ancestors of horses, camels, and turtles. The geology and mining activities of Malakoff Mile are discussed in the *Lode Gold* section of this paper. The park also contains a 7,847-foot bedrock tunnel that served as a drain for mining operations. The visitor center offers a short video on hydraulic mining and exhibits on life in the old mining town of North Bloomfield. (CDPR, 2018b).

Discussion of the environmental impacts of hydraulic mining and the legal battle to end the practice are discussed in “Chapter VII – Natural Resources [How Mining Practices Shaped California Water Law]” of this paper.

VIII. ENVIRONMENTAL CONCERNS

primary author: Jeff Hess

Several key historical events drove major population and economic expansion in Sacramento: the 1849 Gold Rush; the advent of the railroad in the 1860s; and the coming of the military and aerospace industry in the 1900s. Each of these expansions brought not only opportunity, but resulted in a legacy of long-term environmental impacts.

Mining

The discovery of gold in nearby Coloma in 1848 unleashed a population explosion in, what would become, Sacramento. Mining initially consisted of placer mining (the mining of alluvial sediments for minerals, generally by hand) in the many streams and rivers coming out of the Sierra Nevada mountain range, but quickly expanded into hydraulic mining (using high-pressure water to mine alluvial sediments), hardrock mining (extracting minerals from veins, typically quartz, usually in metamorphic or igneous rock), and dredging (excavating alluvial sediments by mechanical means). All these methods resulted in significant environmental damage.

During the first few years of the Gold Rush most placer mining operations were small scale. Later, some operations became extremely large scale, diverting entire streams and rivers into flumes to get at the underlying streambeds. The need for lumber to build flumes, sluice boxes, and other equipment for these larger operations resulted in local deforestation, which in turn led to increased erosion and loss of habitat (Figures 87 and 88). An estimated 10-12 million ounces of gold was recovered during the period of 1848–1853 using placer mining methods.

Hydraulic mining was developed in 1853 around the same time as the larger placer mining operations and consisted of channeling water into smaller and smaller pipes while dropping in elevation, creating significant pressure (GreatMining .com, 2018). The water was then directed using a monitor to cut into ancient gravel beds. Many thousands of kilometers of waterways were constructed as part of the hydraulic mining operations. Runoff flows from these operations carried most of the displaced sand and gravel into natural drainages, which in turn carried most of the material to the eastern edge of the Central Valley, filling and choking channels. Litigation and conflict would culminate with *Woodruff v. North Bloomfield Gravel Mining Co.* (Kelley, 1959). For a more extensive explanation of the effect of mining on California water law, please refer to the "Chapter VII – Natural Resources [How Mining Practices Shaped California Water Law]" of this paper.

Though most of the hydraulic mining in the State took place outside of the Sacramento Region, some hydraulic mining did occur in the Michigan Bar-Sloughouse area on the Cosumnes River, and in the Folsom area (Carlson, 1955). The raised riverbeds restricted or eliminated riverboat access to much of the Feather River and Sacramento River (Hagwood, 1981), and led to a series of devastating floods in Sacramento in 1862 (Figure 89) and 1878. The flooding of valuable farmlands, ultimately litigation between landowners including farmers and miners would go on for more than a decade. The amount of damage was enormous and estimated at 15,782-ha of farmland ruined along with another 5,666-ha damaged. Silt was flushed all the way to San Francisco Bay and navigation of the Sacramento River was imperiled.

A landmark study by G.K. Gilbert (1917) addressing hydraulic mining debris from the Sierra Nevada attempted to quantify the amount of material that was moved downstream as a result of hydraulic mining operations. Figure 90 is a photograph that presents a view of the Yuba River near the Parks Bar Bridge, upstream of Smartsville, which was taken in 1908. This photograph shows that deposition of hydraulic mining spoils had filled much of the ancestral canyon of the Yuba River. When this photograph was taken, fifty years after the deposition of hydraulic mining spoils, most of the deposits had been removed. However, a considerable amount of material remained, and the channel of the Yuba River continued to incise its channel and form distinctive river terraces made of hydraulic mining spoils. Figure 91 is a Google Earth image of the area taken in 2017, where terrace deposits, formed from hydraulic mining spoils about 160-years ago, are clearly visible, particularly at the bend in the river visible at the right-hand side of the photograph, although the Yuba River is more deeply incised.

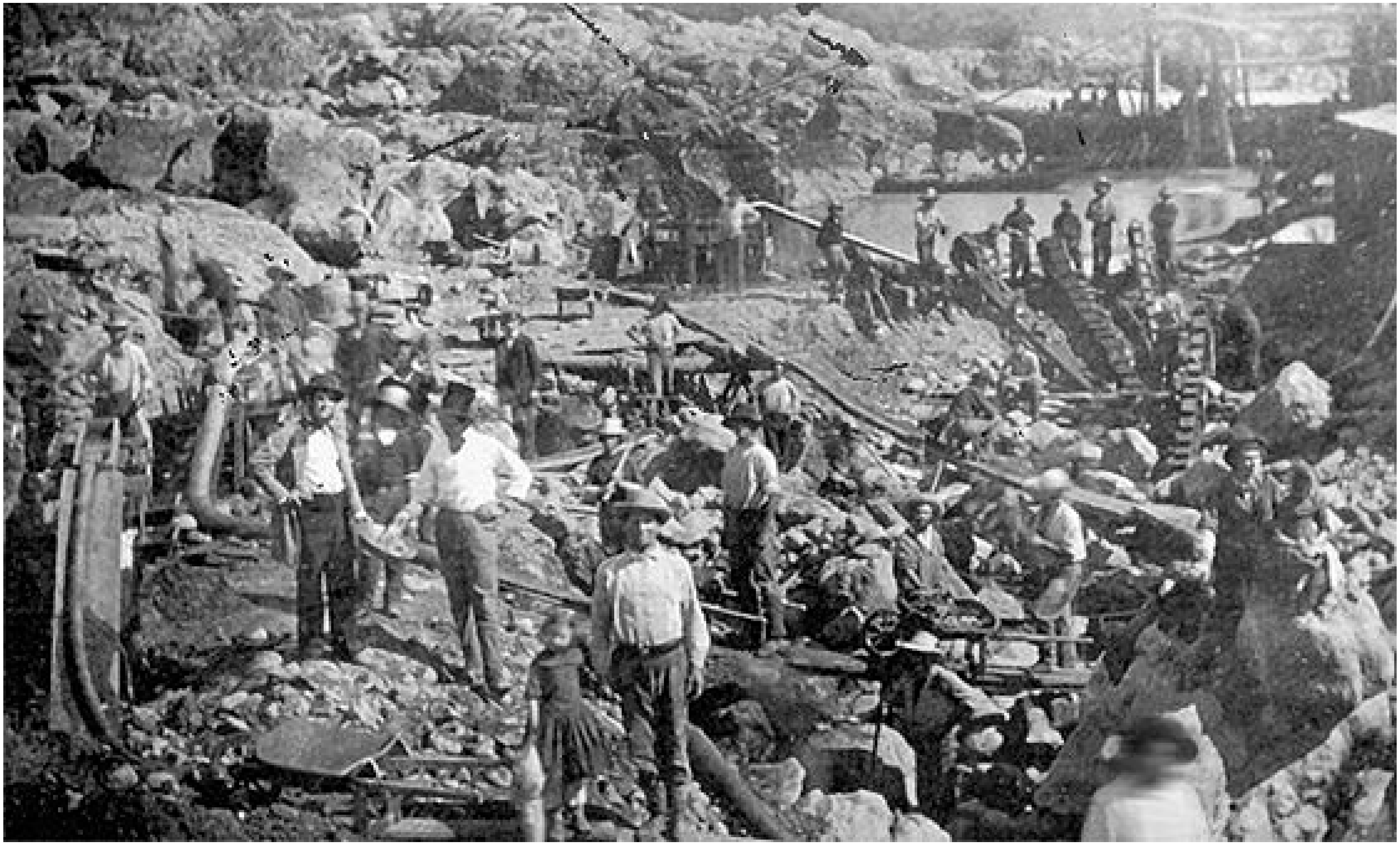


Figure 87. Placer mining on the American River (from http://www.miningartifacts.org/California-Mines.html).

Figure 88. Hydraulic mining in California (from http://www.miningartifacts.org/California-Mines.html).

Figure 89. Sacramento flood of 1862 (from NOAA Hydrometeorology Testbed, https://hmt.noaa.gov).

Figure 90. View of the Yuba River near the Parks Bar Bridge, upstream of Smartsville taken in 1908 showing that deposition of hydraulic mining spoils had filled much of the ancestral canyon of the Yuba River (Source: G.K. Gilbert, 1917, USGS Professional Paper 105, Plate V1).

Figure 91. View of the Yuba River upstream of Parks Bar Bridge, showing the area of the 1908 photograph presented in Figure 90. Scale is in the lower right-hand corner of the photograph. River terrace deposits can be seen along both banks of the river, particularly along the outside bend in the river shown in the right-hand side of the photograph. The Parks Bar Quarry can also be seen along the north bank of the Yuba River (top center of the photograph) (Source: GoogleEarth).

An estimated 11 million ounces of gold were recovered during the period of 1853–1884 using hydraulic mining. Also, mercury was used in sluice boxes to recover gold, leading to significant mercury in the resulting sediment-laden discharge and long-term mercury impacts to the rivers (see subsequent discussion on mercury).

Hazards Related to Gold Mining

Originally developed in California, dredges were used to excavate and process gravels and separate out gold. These floating dredges operated in Sacramento region from 1899 up until 1962. Photographs of various styles of dredges can be found in "Chapter VII – Natural Resources [Metal Mining], and Chapter X – major Engineering Structures [Levees and Levee Flood Control System]" of this paper. Over 6,880 ha of land along the American River between Sacramento and Folsom was dredged (CDMG, 1982), and more than 765 Mm^3 of gravel was dredged by the Natomas Company along the American River (CDMG, 1976). Dredging was very successful in recovering gold, with an estimate of more than 20 million ounces recovered using this method. However, the hydraulic dredging destroyed the agricultural potential for the land it dredged, with dredged land looking much the same today as it did when dredging ceased. Much of the land is now used for commercial and industrial use.

Of the estimated 47,000 abandoned lode gold mines, an estimated 84% have physical hazards and 11% have environmental hazards associated with them. Environmental hazards associated with hardrock mining are numerous, and can include: 1) acid mine drainage which leaches metals into mine-influenced waters and can result in streams devoid of life due to oxygen deprivation; 2) tailings ponds full of heavy metals, acidic water, mercury and cyanide; and 3) waste rock piles with potential acid rock drainage. The latter two pose not only an environmental hazard, but also a potential for catastrophic failure and the resulting damage the water and debris flow would pose.

One example of these hazards is at the Argonaut mine, discussed earlier in this paper under the lode gold mining section. Today, the Argonaut mine includes eight specific areas of environmental concern: Unprocessed and Semi-Processed Ore Storage Area (2 ha), Cyanide Plant Area (2.6 ha), Upper Earthen Tailings Dam, Grey Sands Tailings Pile Area, Lower Earthen Tailings Dam, Historic Impoundment and Concrete Dam Basin, Eastwood Multiple Arch Dam and Surface Water Drainage Areas, and a vacant Lot used for tailings disposal, and Mental Health Clinic soil contamination. The mine site has the distinction of being the number two site on the EPA Region 9 Abandoned Mine Site Prioritization List, and an assessment is ongoing to determine if the site should be listed on the National Priority List (NPL).

In the Unprocessed and Semi-Processed Ore Storage Area (2 ha) the area is barren and devoid of vegetation. Preliminary assessment by the EPA indicates high concentrations of arsenic (48,000 mg/kg), lead (4,000 mg/kg) and mercury (360 mg/kg) in residential soils which are also very acidic and corrosive. The Cyanide Plant area (approximately 2.6 ha) consists of various sized concrete cyanide processing tanks, vats, and a thickening basin. There are eight round concrete tanks measuring 7.6-m in diameter and 3-m deep that are partially buried, two of which were filled with a cyanide processing waste. Several other vertical concrete tanks contained some type of by-product. The sands were cyanided in leaching tanks and vats while the slimes were cyanided in an agitator, and then filtered. The gold bearing solution was then precipitated and roasted. Both sands and slimes were discarded in a large ravine adjacent to the plant.

At the most eastern part of the site is a concrete tailings dam known as the Eastwood Multiple Arch Dam (Figure 92). Constructed in 1916, it is approximately 14 m high and 128 m long. The dam impoundment is filled with sediment and water cascades over the top of the dam during storms. Runoff water from dam flows to Jackson Creek and Lake Amador. Considered structurally unsafe by the U.S. Army Corps of Engineers (Corps), there is a concern about the static and seismic stability of the dam which is only 365 m from downtown Jackson. A geotechnical investigation was conducted to determine the potential for liquefaction and mud/debris flow if the dam failed is in progress, and its extent and magnitude, and impacts to life and property. EPA is assisting the City and County officials in obtaining a FEMA Pre-Disaster Mitigation Grant or Flood Mitigation Assistance Grant to retrofit or reinforce the dam.

Mercury

Mercury was used in all types of gold mining in California, with hydraulic mining accounting for the greatest use and loss. An estimated 5,900 metric tons of mercury was lost into the environment from the various gold mining operations in California (USGS, 2000). It was later discovered that this mining also contaminated waterways with mercury (Churchill, 2000; Alpers and others, 2005). The presence of mercury in the sediments throughout the watersheds of both the American River and Sacramento River has led to fish advisories in both rivers. These fish advisories issued by the California Office of Environmental Health Hazard Assessment (OEHHA) provide fish consumption guidelines (OEHHA, 2018). For the lower American River in Sacramento, three species of fish are on the “do not eat” list for women 18 to 45 years of age and for children, due to the presence of elevated levels of mercury: black bass, striped bass, and pikeminnow.

Figure 92. Looking south towards the Eastwood Multiple Arch Dam (Source: image courtesy of Stephen Testa).

Railroads

The next expansion in Sacramento was the introduction of the railroad. In the 1850s, local rail service was set up between Sacramento and adjacent cities. In 1863, the railroad established a 97-ha railyard in downtown Sacramento, which eventually built and serviced locomotives and railcars starting in the mid-1870s. When the yard opened in the 1860s, the land was a swampy lake. Central Pacific Railroad was given the property under the condition that they fill in the swamp to make the land more suitable for industrial pursuits (Union Pacific, 2016).

In 1869, the Central Pacific Railroad linked up with the Union Pacific Railroad from the east, forming the first transcontinental railroad, with Sacramento serving as the western terminus. The Central Pacific Railroad later merged operations with the Southern Pacific Railroad in 1870.

The introduction of refrigerated railcars in the late 1800s led to a change in agricultural land use in Sacramento and the Central Valley. Wheat values declined, and fruit became a significant cash crop with the ability to ship fruit to the east coast without spoilage.

The Sacramento Railyard served as a key part of the Central Pacific Railroad and Southern Pacific Railroad for more than 100 years. The scope of industrial activities was extensive 100-years ago. Any work that needed to be done to run a railroad was done at the railyard, including forges and foundries where they made the silverware for the dining cars, lumber mills for the tracks, carpentry and upholstery shops to furnish the cars and repair shops for every kind of equipment. (Union Pacific, 2016) (Figures 93 and 94).

Rail operations at the Sacramento Railyard declined in the 1990s and eventually the buildings were demolished, and the property remediated. Sacramento was chosen for an early EPA Brownfields pilot program, with the railyard being one of the key projects. Soils throughout the yard were impacted by cleaning solvents and metals, and by polychlorinated biphenyl’s (PCBs) in portions of the site (DTSC, 2003). Environmental remediation activities were conducted during more than 10 years of cleanup at the site, with more than 611,650 cubic meters (m^3) of contaminated soil managed in a variety of ways, including offsite disposal, onsite treatment, and capping. Contaminated groundwater is also an issue at the site. A map of the plume, colored purple, is shown in Figure 95, which also shows the regional groundwater levels. Figure 95 also shows the relative locations of several other significant contaminant plumes in the Sacramento region, which are discussed in greater detail in the following sections. It is now the site of a newly planned mixed-use development for entertainment, retail, housing, office, theaters, parks, hotels, and museums.

Figure 93. Boiler Shop of the Sacramento Railyard, ca. 1968 (from Prints and Photographs Division, Library of Congress [HAER CA-303-B])

Figure 94. Plaining Mill and Machine Shop of the Sacramento Railyard, ca. 1968 (from Prints and Photographs Division, Library of Congress [HAER CA-303-B]).

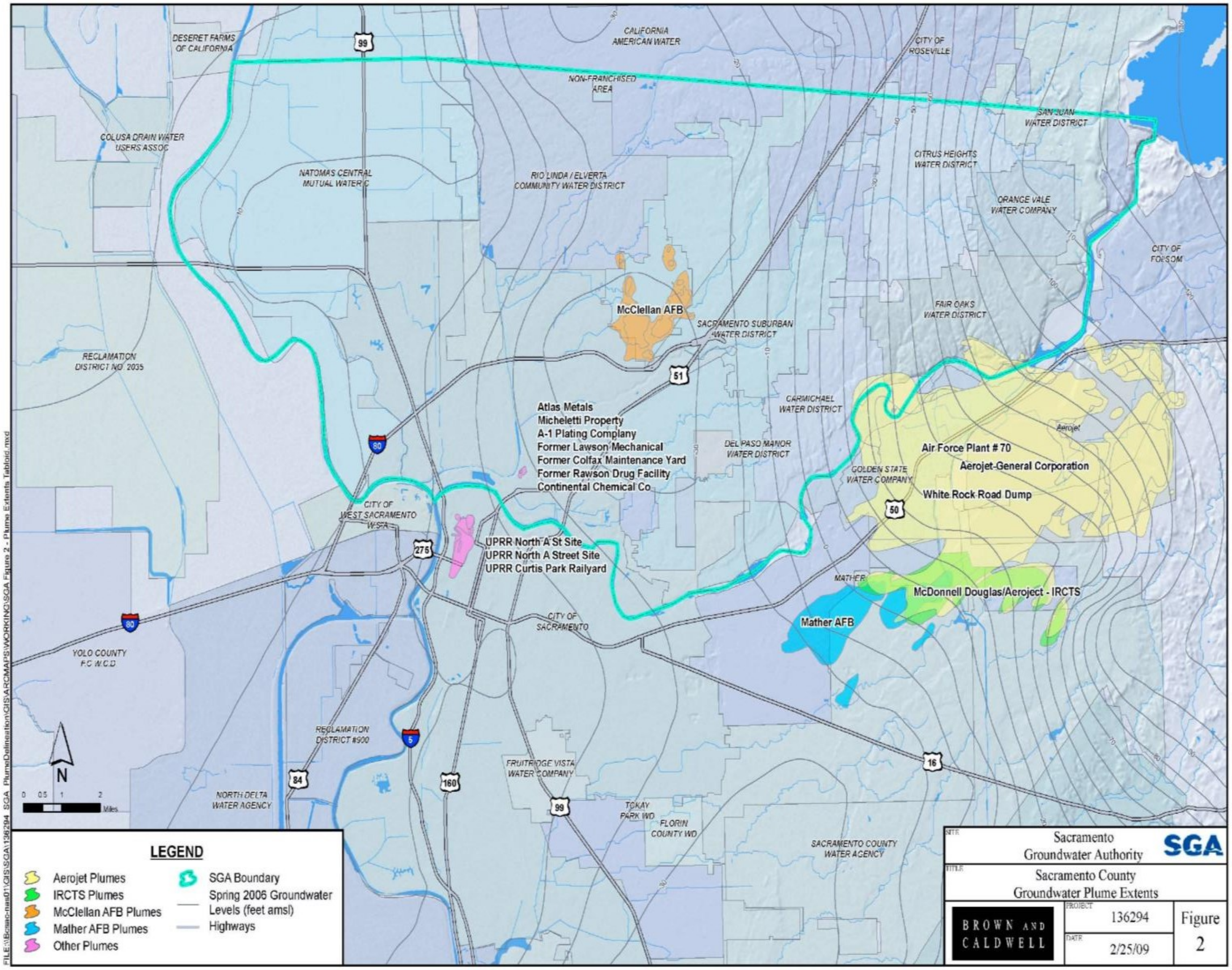


Figure 95. Contaminant plumes and regional groundwater elevations of the Sacramento region (Source: SGA, 2016).

Historic rail lines also pose an environmental concern. Contamination common along rail lines includes metals, pesticides (such as lead arsenate), and petroleum hydrocarbons. These chemicals have been associated with normal railroad operations. For example, arsenic is present in the soil along rail lines and right-of-ways from arsenic preserved rail ties, arsenic herbicides and pesticides, and arsenic-laced slag used as railroad ballast. Petroleum hydrocarbons include diesel and lubricating oil dripped from the trains, and creosote from preserved rail ties.

Military and Aerospace Industry

primary authors: Jeff Hess and Garry Maurath

The military and aerospace industry had a significant presence in the greater Sacramento region in the 1900s. Three current or former, Unites States Air Force and two United States Army instillations are in the Sacramento region. These bases are Beale Air Force Base (AFB), McClellan (former AFB), Mather (former AFB), Camp Kohler (former army base), and Sacramento Army Depot (former army depot). One of the factors that drew the Air Force and the Army to locate these bases in the area is the large expanse of flat terrain resulting from deposition of alluvial sediments in the Central Valley, and the ideal weather conditions associated with large mountain ranges paralleling both sides of the valley, thereby separating it from large bodies of water and the thermal disturbances associated with temperature differentials between land and water. The distance of the Central Valley from the ocean helps creates a weather pattern that results in a semi-aired environment. Additionally, the spatial extent of the Central Valley, 80-km by 650-km, is not conducive to the formation of stable inversion layers or thermal updrafts, thus the flying conditions within the Central Valley are typically excellent.

Mather Field (former AFB)

Mather Field, originally named Mills Field, is located 19 km east of Sacramento and opened on 30 April 1918. According to the US Air Force (personal communication, 2016), it was one of 32 Air Service training camps established after the United States entry into World War I in April 1917 to train pilots (Appendix A – Plate A). At the time primary flight training consisted of an eight-week course. In 1941, it became the site for advanced navigator training, an 18-week course, and then a twin-engine Advanced Flying School to training pilots of North American B-25 Mitchell medium range bombers. In 1944-45 it became the aerial port of embarkation to the Pacific in preparation for the expected transfer of large numbers of men and aircraft from the European theater to the Pacific theater of operations. A Strategic Air Command B-52 squadron was assigned to Mather from 1958-1989. During the cold war, Mather AFB was the sole aerial navigation school for the USAF and continued in the role of Interservice Navigator Training facility until the base was inactivated in September 1993 (wiki, 2016a). Mather was decommissioned in 1993 when operations transferred to Randolph AFB, Texas under the Base Realignment and Closure Act (BRAC). At this time, it was listed as a Superfund site in November 1989, with cleanup being overseen by the EPA. Soil and groundwater contain various volatile organic compounds (VOCs), gasoline, diesel fuel, metals, pesticides, and other contaminants (EPA, 2018a). Cleanup has been completed at most of the contaminated soil sites (69 of 82 sites), with cleanup efforts ongoing on nine sites. Groundwater contamination is significant, with four distinct plumes present related to Mather (see Figure 95 of the ground water plumes in the greater Sacramento region). Cleanup is ongoing for three of the four plumes.

The base was transferred to Sacramento County on 30 September 1993. There are several rare vernal pools on the former base with flora unique to California. The pools range from 50,000- to 200,000-years old and access to these pools is currently restricted. Sacramento County is in the process of establishing a vernal pool preserve at the former Mather Field. (Mather, 2016).

***McClellan (former AFB*)**

McClellan AFB, originally named the Pacific Air Depot (US Air Force personal communication, 2016) is located 11 km northeast of Sacramento in 1938 (Appendix A – Plate A). Named in honor of Major Hezekiah McClellan, a pioneer in arctic aeronautical testing, the location was selected to create a repair facility away from the coast, which would be better protected from potential attack. McClellan AFB is 1,180 ha in size and is the smallest of the four AFB's in the Sacramento region. The Sacramento Chamber of Commerce played an important role in urging the War Department to establish both the Mather and McClellan bases. McClellan AFB was closed in 2001 and the facility turned over to Sacramento County (wiki, 2016b).

For most of its operational lifetime, McClellan was a logistics and maintenance facility for a wide variety of military aircraft, equipment, and supplies, and was the garrison of the Air Force Material Command. The former AFB is now the McClellan Business Park and the airport operates as an uncontrolled airfield, designated Class E airspace by the FAA. McClellan Business Park is home to more than 240 businesses and the airport is home to the US Coast Guard Air Station Sacramento, Calstar, California Department of Forestry, Dassault Falcon, United States Forest Service, PODS, Surf Air, and the Sacramento Metropolitan Fire District (McClellan, 2016). In addition, CalFire has established their headquarters and training facility at the former base. During wildfire season C-130s are a common sight site as they use the former AFB as a staging area for air attacks against wildfires throughout northern California.

Figures 95 and 96 show the contaminant plume of McClellan. Contamination at McClellan was significant, with cleaning solvents, caustic cleansers, paints, metal plating wastes, low-level radioactive wastes and a variety of fuel oils and lubricants

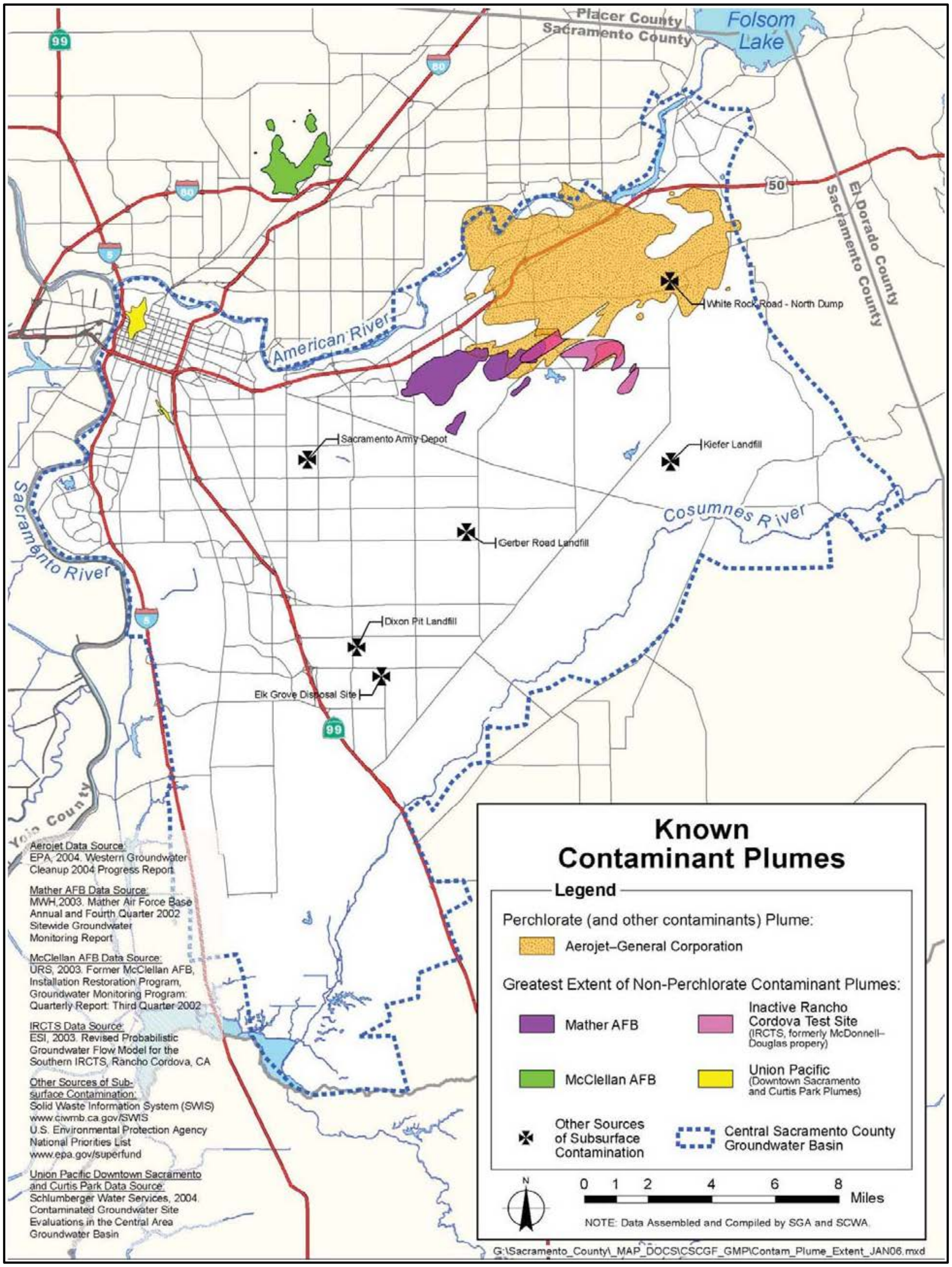


Figure 96. Contaminant plumes in the Sacramento region. First published as Figure 9 in the 2007-2008 SCGA Basin Management Report (Source: SCGA 2008).

released to the environment. While significant soil and groundwater cleanup efforts have been completed, the presence of radiological elements (e.g., radium, thorium and uranium) has hindered soil cleanup efforts at a few sites, and groundwater cleanup is ongoing. Over $500 million has been spent through 2016 on environmental cleanup efforts at McClellan (Air Force, 2016).

Aerojet Rocketdyne (1952-present)

Aerojet Rocketdyne relocated its test operations from Southern California to approximately 5,261 ha of gold-dredged land to support the Titan, Delta, and Polaris missile programs, the Apollo and Gemini rocket programs, and the space shuttle. Listed as a Superfund site in 1983, with cleanup being overseen by the EPA. Groundwater contains volatile organic compounds (VOCs) and rocket propulsion waste products such as perchlorate and N-Nitrosodimethylamine (NDMA) (EPA, 2018b). Groundwater plumes associated with Aerojet are shown on Figures 95 and 96. Some additional sources of subsurface contamination are also shown on Figure 96.

McDonnell Douglas/Boeing (1956-1969)

McDonnell Douglas/Boeing established the Rancho Cordova Test Site (RCTS) (now known as the inactive RCTS) on gold-dredged land to support the Thor missile system and the Saturn rocket program. It was issued an Imminent and Substantial Determination in 1991 by the State of California, and cleanup is overseen by the California Department of Toxic Substances Control (DTSC). Soil and groundwater at the site were impacted by chlorinated VOCs and perchlorate (DTSC, 2007). The groundwater plume associated with McDonnell Douglas/Boeing is shown in Figures 95 and 97.

Three of these sites: Mather AFB, Aerojet Rocketdyne, and McDonnell Douglas, are near each other east of downtown Sacramento. Together, these five sites, the Sacramento Railyard Mather AFB, McClellan AFB, Aerojet Rocketdyne, and McDonnel Douglas/Boeing have impacted groundwater quality in the Sacramento region, degrading a valuable source of drinking water (Figure 95).

Ground water beneath the Aerojet site has been impacted by contaminants to a depth greater than 152 meters. Groundwater treatment consists of pumping and treating the groundwater, and approximately 8,638 liters per minute were processed in the Aerojet groundwater treatment systems in 2015 (SGA, 2016). McClellan Air Park also employs “pump and treat” to treat the groundwater, and as of early 2016, is processing around 5,300 liters per minute from eight extraction wells.

Beal Air Force Base

Beale AFB, originally named Camp Beale after Edward Beale (1822-1893), a Brigadier General in the California Militia who was an explorer and frontiersman in California, is located approximately 64 km due north of Sacramento (Appendix A – Plate A). Established in 1942 by the War Department, Camp Beal's mission was to train the newly activated 13th Armored Division for the war in Europe (US Air Force personal communication, 2016). After World War II the War Department turned over the base to the USAF. Because of the initial mission of the base was for training both an armored division and an infantry division the U.S. government purchased 35,208 ha. In 1952 the government sold off 24,606 ha of land, including 4,538 ha that became the Spenceville Wildlife and Recreational Area. Although reduced in size, the current AFB is considerably larger than most AFB's, covering 9,308 ha (wiki, 2016c).

The base has a rich historic and cultural heritage as Native Americans lived on this land and numerous artifacts have been found, including mortar bowls carved into the bedrock along stream banks. The 19th century mining town of Spenceville was located on the base. German prisoners of war were held captive no the base during World War II and a block of prison cells, with drawings made by the POWs, still stands at the base. The base maintains 38 native American sites, 45 homestead sites, and 51 World War II sites.

The largest placer gold deposit in California, the Yuba River Goldfields, is located along the northern boundary of the base. Details of the discovery and mining of the Yuba Goldfields are discussed in the Mineral Resources section of this paper. Dredge tailings from the gold field were used to build streets and building foundations on base [reference economic minerals section]. (Beal, 2016a). In addition, the Spenceville mine was located on the eastern side of Beale during World War II. The area was eventually given to the State and the mine area was remediated. Today it is a part of the Spenceville Wilderness Area.

In 1964 Beal AFB became the home of the SR-71 Blackbird. As a result, Beal also became the home of reconnaissance missions during the Vietnam War. In 1990, the SR-71 mission was closed, and the aircraft remains retired. In 1976 the U-2 assets of the Air Force were relocated to Beal AFB. Currently, Beal AFB is home to the 9th Reconnaissance Wing of the Air Combat Command, which includes the nation's fleet of U-2 Dragon Lady, RQ-4 Global Hawk and the MC-12W Liberty reconnaissance aircraft (US Air Force personal communication, 2016b). The base supports several civilian needs including public safety and disaster relief in times of earthquakes, floods, forest fires, and search and rescue missions. The U-2 program also supports the state's agricultural industry by providing aerial reconnaissance of crops grown in the Central Valley. (Beal, 2016b)

Environmental cleanup objectives have been met at eight environmental sites across the Bas since 2015, and these sites have been closed. Beal AFB operates a wastewater treatment plant, which is in the southwest corner of the Base and uses the treated water for irrigation of areas across the base. The treatment plant was constructed during World War II and has been upgraded several times to meet water quality standards. The plant treats to secondary standards and processes about 946,300 liters per day of domestic sewage from the base housing area main base, and flight line. There are more than 64 km of sewer lines on base. The treated water is blended with approximately 1,635,300 liters per day of groundwater produced from the CG041-013 groundwater treatment system. The resulting blend of treated wastewater, classified as recycled water, is transferred to a 412,500 m^3 storage pond and is subsequently used to irrigate the Base golf course and landscaping surrounding the wastewater treatment plant. Plans are underway to demolish the existing plant and transfer the wastewater to an offsite public or private treatment facility by the end of 2018 (wiki, 2016c).

Camp Kohler

Camp Kohler, located adjacent to McClellan (Appendix A – Plate A), was dedicated on 1 December 1941 and closed December 1946. The buildings were scheduled to be sold off to veterans in September 1947, but the camp was destroyed by fire on 20 June 1947. Camp Kohler was originally designed as a transit depot for Army Air Forces personnel and equipment being transferred from Europe to the Pacific, and for a period of 52 days from 6 May through 26 June is was used as a temporary internment camp for Japanese migrant workers in transit to one of the War Relocation Centers in Utah, where they were detained for the remainder of the war. A large laundry facility operated at the camp and was transferred to McClellan AFB in August 1950. A sewage treatment plant located on the site was transferred to the County of Sacramento in June 1956 and demolished in 1972. The camp is commemorated by a historical marker and a small grove of cherry trees in Walerga Park. The only identifiable structures remaining are the foundation of the laundry facility, the back wall of the rifle range, the base swimming pool (Osbourne, 2011, Military Museum.org, 2018).

Sacramento Army Depot

The Sacramento Army Depot site, established in 1945, served as a repair facility for electronic equipment, such as night vision goggles, electronic circuit boards, and radium-dial-instrumentation (wiki, 2018) (Appendix A – Plate A), The 1.96 km^2 site is located about 11 km southeast of downtown near the intersection of Fruitridge and Florin-Perkins Roads. The depot was deactivated after the findings of the 1988 Base Realignment and Closure Commission and it was officially closed on March 3, 1995, and has been converted into a busines).

The Army burned, buried, or discharged wastes from metal-plating operations, spray booth operations and degreasing operations on the site. These improper waste disposal practices at the site contaminated soils and groundwater with volatile organic compounds (VOCs) and heavy metals (Figure 96). On July 22, 1987, the depot was added to the National Priorities List as a Superfund site (EPA, 2018c). Cleanup, operation and maintenance activities, and monitoring are ongoing.

The Sacramento Army Depot is participating in the Installation Restoration Program, a specially funded program established by the Department of Defense (DoD) in 1978. The EPA has conducted several five-year reviews of the site's remedy. The most recent review concluded that current mitigation, including institutional controls and maintenance of the existing soil cover, are enough to protect human health and the environment in the short term (EPA, 2018c).

Asbestos

primary author: Garry Maurath

Asbestos mining existed more than 4,000 years ago, but large-scale mining began at the end of the 19th century, when manufacturers and builders began using asbestos for its desirable physical properties (Alleman and Mossman, 1997). The amount of asbestos that is typically present in ultramafic rocks ranges from less than 1% up to about 25%, and sometimes more. Chrysotile and amphibole asbestos (such as tremolite) occur naturally in certain geologic settings in California, most commonly in association with ultramafic rocks and along associated faults (COS, 20168). Asbestos is released from ultramafic and serpentine rock when it is broken or crushed. This can happen when cars drive over unpaved roads or driveways, which are surfaced with these rocks, when land is graded for building purposes, or at quarrying operations. It is also released naturally through weathering and erosion. Once released from the rock, asbestos can become airborne and may stay in the air for long periods of time (California Air Resources Board [CARB], 2017).

Chrysotile is the most common type of asbestos found in California and it is associated with serpentine 9CARB, 2017). Although no known asbestos mines and historic prospects are in Sacramento County they are in areas of ultramafic rocks along the western slope of the Sierra Nevada mountain range and the mélange complex of the Cascades and Pacific Coast Range (Van Gosen and Clinkenbeard, 2011). Naturally occurring asbestos (NOA) is known to be present in Eastern Sacramento County. Figure 97 shows the distribution of metamorphosed mafic volcanic rocks in the Sierra foothills east of Sacramento, near Folsom, where NOA can be found (Higgins and Clinkenbeard, 2006, Churchill, 2000).

There have been numerous asbestos mines in California, including the Copperopolis chrysotile mine of the Jefferson Lake Asbestos Company, in Calaveras County, which

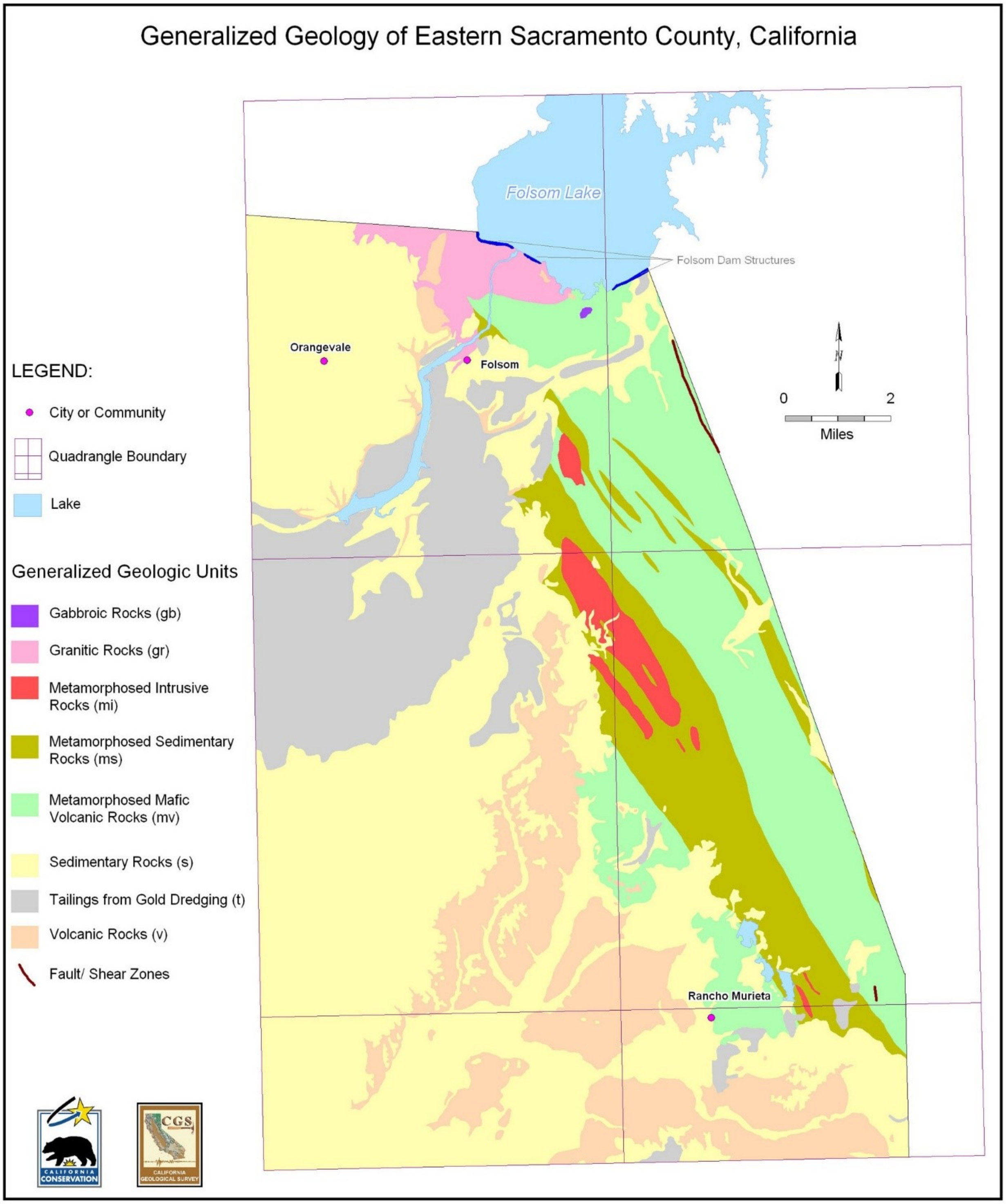


Figure 97. Generalized geologic map of eastern Sacramento County (Higgins and Clinkenbeard, 2006). The areas that are moderately likely to contain naturally occurring asbestos include Gabbroic Rocks (gb), Metamorphosed Intrusive Rocks (mi), and Metamorphosed Mafic Volcanic Rocks (mv).

closed in 1987. The former Copperopolis chrysotile mine is now used as an asbestos disposal site (Van Gosen and Clinkenbeard, 2011). All types of asbestos are hazardous and may cause lung disease and cancer. Health risks to people are dependent upon their exposure to asbestos. The longer a person is exposed to asbestos and the greater the intensity of the exposure, the greater the chances for a health problem (R.P. Nolan and others, 2001). The CARB adopted two statewide control measures to prohibit the use of serpentine or ultramafic rock for unpaved surfacing and controls dust emissions from construction, grading, and surface mining in areas with these rocks (CARB, 2017).

IX. NATURAL HAZARDS

Flooding in the Sacramento Region

primary author: Nicholas Pinter

Both the city of Sacramento and California have long histories of damaging floods. Many decades of investment in flood control have led to strengthened protections, but flood risk has not been reduced to zero, and will never be. Across the state, an estimated 7 million California residents and $575 billion in infrastructure are at risk of flooding (CA DWR, 2013). Of 85 Major Disaster Declarations in California since 1954, 47 of those have involved flooding.

Sacramento is located on the eastern edge of the California Central Valley, a sediment-filled tectonic trough separating the Sierra Nevada mountain range on the east and the Coast Ranges on the west and stretching more than 700 km from north of Redding to south of Bakersfield. The southern Central Valley is drained by the San Joaquin River, whereas the northern Central Valley is drained by the Sacramento River. Both rivers drain to the Sacramento-San Joaquin Delta, which is a large inland estuary and wetland that discharges to San Francisco Bay.

The City of Sacramento was founded near the confluence of the Sacramento and American Rivers. Other major tributaries of the Sacramento River include, roughly from south to north, the: Bear R., Yuba R., Feather R., Deer Creek, and the Pit River (Figure 98). The Sacramento River watershed encompasses an area of 68,600 km^2, with rain and snowfall within the basin providing 60% of the state's total water supply (CA DWR, 2013). Most of that precipitation falls during the winter months, most of that in the Sierra Nevada, and most of that as snow. The Sierras have been called the "water tower" of California, with snowmelt providing water supply during the dry summer months. Floods on most Central Valley rivers are typically caused by some combination of intense winter storms, snowmelt, and/or rain onto the Sierra snowpack. This also means that the temperature of water in the Sacramento and American rivers is generally very cold, and hypothermia during flooding is a more serious issue then might be expected given the climate of the area.

Figure 98. Watershed and major tributaries of the Sacramento River.

Understanding flooding in Sacramento requires an understanding of historical changes to the Sierra Nevada and Central Valley. At the time of first European arrival, the Central Valley was a vast wetland, densely vegetated and flooded basically wall-to-wall each year by seasonal runoff. This annual inundation was a boon to wildlife but a huge challenge to Western ambitions for settlement and agriculture (Figure 98). Through the latter half of the 19th century and into the 20th century, residents of Sacramento and the Valley strove to contain their rivers and carve dry land from the great swaths of Central Valley wetland. The second major transformation during the early history of the region followed the discovery of gold in the Sierra Nevada during the mid-19th century. The earliest placer mining was rapidly replaced by hydraulic mining, which used pressurized jets of water to blast loose entire hillsides of gold-bearing sedimentary deposits. Hydraulic mining for gold was extremely destructive and impacted all of the major Sierran rivers, filling the channels and burying floodplains to depths up to 5 meters (Figure 99) and locally more (Gilbert, 1917). Central Valley farms and towns constructed levees to try to keep these aggrading rivers within their banks, but this was a losing battle, and at the peak of hydraulic mining, the beds (bottoms) of many rivers including the Sacramento stood higher in elevation than the surrounding city streets (Kelley, 1989). Additional discussion on the impact of hydraulic mining can be found in “Chapter VIII – Environmental Concerns – [Hazards Related to Gold Mining]” of this paper.

Table 7 summarizes some of the major flood events that have impacted Sacramento and surrounding areas of the Sacramento River watershed and the Central Valley. Between conversion of wetlands and mining-driven aggradation, floods throughout the late 19th and early 20th centuries breached local levees time and time again. The most notable event in this early history of Central Valley flooding started in December of 1861, when a series of storms raked the Pacific margin, including all of California. Rain and snow fell for a month and a half, including snow accumulations of 2.5 to 3.5 m in the Sierra Nevada and rainfall that exceeded 400% of annual averages in parts of California (Porter and others, 2011; Ingram, 2013). River stages surged with each wave of storms, and in January of 1862, Sacramento was flooded and stayed under up to 3 m of water for more than three months. California's new Governor, Leland Stanford, rowed to his own inauguration. The State Legislature eventually fled the city for the safety of San Francisco. The 1861-62 flooding filled much of the Central Valley, turning it into an inland sea, up to about 500 km long and 30 km wide. During the peak of the storms runoff was so great that there was no low-tide inflow to San Francisco Bay; only a continuous discharge of floodwater into the Pacific Ocean (CA DWR, 2013). A quarter of California's cattle drowned in the flood, one in eight homes statewide were destroyed, and the state was driven into bankruptcy (Ingram, 2013). In the aftermath of the 1861-62 flooding, the ground level of most of downtown Sacramento was raised about 3 m, and the History Museum now runs "Underground Sacramento" tours of the first floors of many historic structures, now entombed below street level.

Figure 99. Lithograph of the 1861-62 flood in Sacramento.

Several floods have struck Sacramento and California since 1862 (Table 7), but none so devastating as this one. Through the 20th century, progress was made in providing flood protection to the region.

Floods along the Lower American River provide a smaller scale example, where peak annual river flows in the LAR, measured at Fair Oaks, have been between 54 to 3,794 m^3/s since the construction of Folsom Dam. Prior to its construction, both the annual base flow and annual peak discharge were higher. Records of peak flow prior to the construction of the dam were between 280 and 5,097 m^3/s (USGS, 2018; Fairman, 2007).

Folsom Dam and its downstream levees were originally designed to accommodate a storm with a recurrence interval of 250 years, but flood events in 1955, 1963, and 1965 proved that 120-year (recurrence interval) flood protection was a more reasonable value. Peak flow conditions caused by the 1986 storms further tested the integrity of the LAR conveyance system and showed that 120-year protection was also an overly optimistic estimate. The 1986 flood (3,794 m^3/s) was defined as a 70-year recurrence interval event (Mount, 1995). Based on the reassessment of the design flood following the 1986 flood of record, the discharge rate expected from 100-year event doubled from 3,260 to 6,520 m^3/s. The 1997 flood in Folsom had a 3-day volume identical to the 1986 flood of record, which resulted in reclassification of the dam's manageable return period event to about 70 years (James, 1999).

The USGS report that the estimated peak discharge in the LAR at the Fair Oaks gage 11446500, January 10, 1862 was 9,005 m^3/s (Matthai, 1951, Parrett, 2016, and USGS, 2018). Compared to peak discharges in the LAR for the other years of record, this be almost doubles anything observed since (Figure 100).

Hunsaker and Curran concluded the 1862 event was the type associated with a recurrence interval of a few hundred years or longer (Hunsaker and Curran, 2005). They also concluded that the rainstorms that caused widespread inundation in 1862 could happen again and create another "Lake Sacramento." In 2011, the USGS published a study titled "Overview of the ARkStorm Scenario," which also concludes that Sacramento and much of the Central Valley could be seriously inundated if the 1862 event were to happen today (Porter and others, 2011).

Sacramento is currently protected by a diverse array of flood-control measures, including levees, bypass channels, upstream dams. Today, the Sacramento River basin contains about 6000 km of levees and over 400 dams (CA DWR, 2013; Appendix C), including several dams that incorporate large volumes of flood storage (Figure 101).

Date	Location	Description
1805	Central Valley	Flood reportedly inundated the entire valley floor. The flood caused much loss of life and destruction in Indian villages.
1846	Sacramento	A New York Times article in 1862 noted that in Sacramento in 1846, the water was 2.1 m deep for 60 days.
1849-1850	Northern Central Valley	Flooding on the Sacramento and American Rivers, washing out bridges and flooding the city of Sacramento, resulting in much damage and lost lives. The city was navigated in whale ships. Significant areas of the Valley were inundated, with the Sacramento River kilometers wide for more than 161 km – “an unbroken sea of waters.”
Dec 1861 – Jan 1862 “The Great Flood”	Regional	Lower elevations experienced heavy rain, and upper elevations saw continuous snowfall. Flooding was widespread from Oregon and Idaho, throughout California, and to Arizona. Sacramento was a focus of the damage, as early-day levees failed. Exceptional stages on most streams and prolonged and widespread inundation throughout the Central Valley.
Nov 1950 – Jan 1951	Sacramento region	Heavy November rains caused extensive flooding in the Sacramento basin. In Sacramento, the American River inundated extensive areas on the north bank, including around four Avenue and fair Oaks Boulevard. Yuba River flooded the towns of Linda and Olivehurst in 1950.
Dec 1955 “Christmas day flood”	Butte Creek, Yuba City and Nicolaus	A levee breach on the Feather River killed 40 people, caused the mandatory evacuation of more than 30,000, and devastated the region’s economy. This was an all-time record flow, the worst flood in Northern California history. The flood brought large flows to many locations in the basin.
Dec 1962 – Feb 1963	Statewide	Numerous communities were flooded and damaged in the American and Yuba River basins. In the Delta, Prospect Island, Liberty Island Little Holland track flooded.
Dec 1982 – Mar 1983 Strong El Niño	Regional	Extremely wet conditions coupled with voluminous Sierra runoff led to a very high river stages and extensive damage in the Sacramento Valley. Heavy rains, high winds, flooding, and levee breaks caused damages of more than $500 million
Feb 1986 “St. Valentine’s day storm”	Northern California	Widespread flooding and weather-related damage. The floods of 1986 caused extensive damage to the flood management system of the Sacramento Valley.
Dec 1996 – Jan 1997	Northern California	Storms caused one of the worst floods of the century. There was widespread flooding and flood damage across the region from the major rivers and creeks in the Sierra Nevada
Jan – Apr 2017	Northern California	Near-record winter rain and snowmelt cause localized flooding, including several levee failures in the Delta. Near-failure of the Orville dam spillways caused evacuation of nearly 200,000 people

Table 7. Milestone floods that impacted Sacramento and the northern central Valley of California

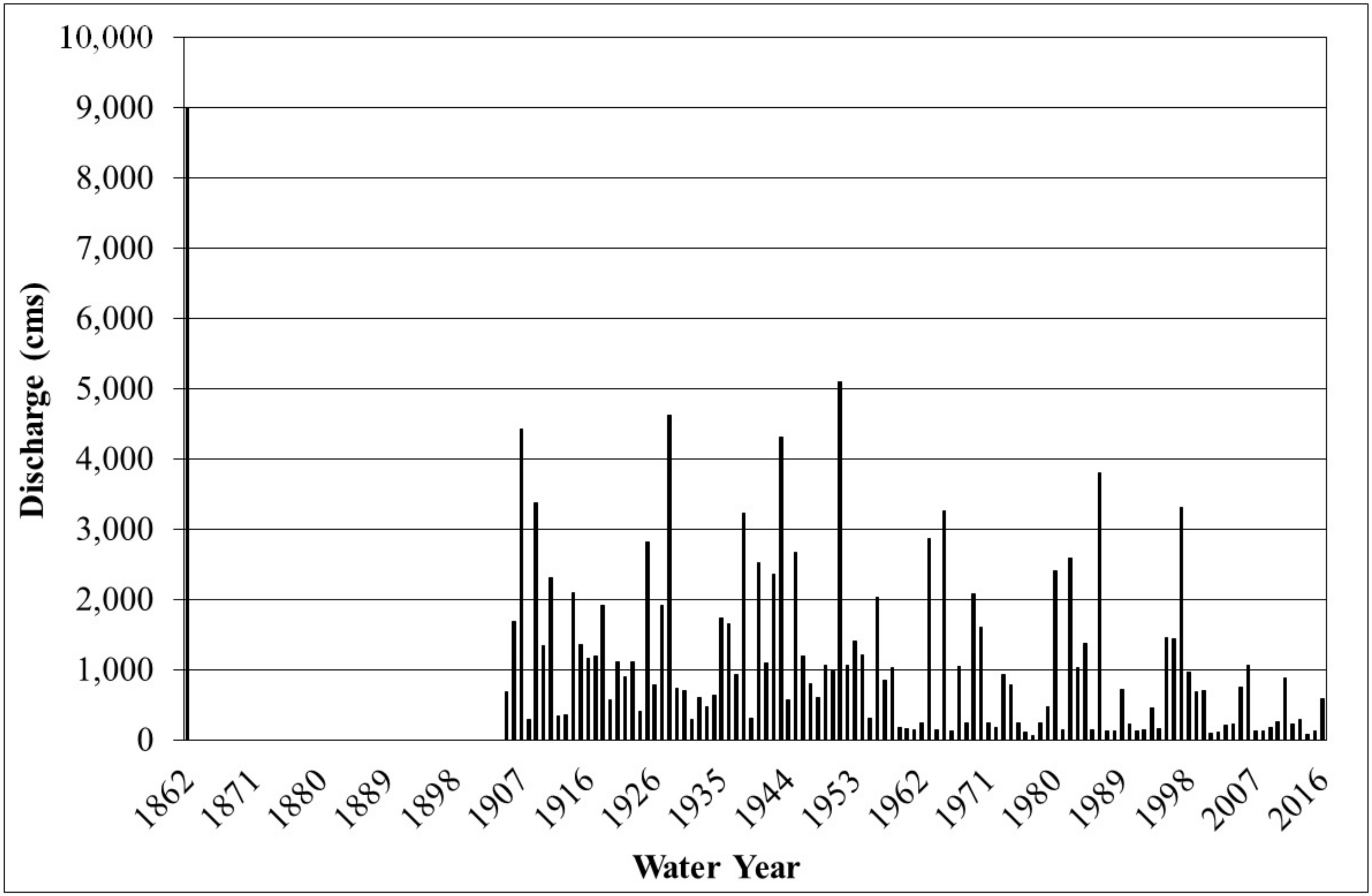


Figure 100. Peak annual discharge at the Lower American River, Fair Oaks gage 11446500, for water years 1862 through 2016 (USGS, 2018). Discharge in cubic meters per second (m^3/s).

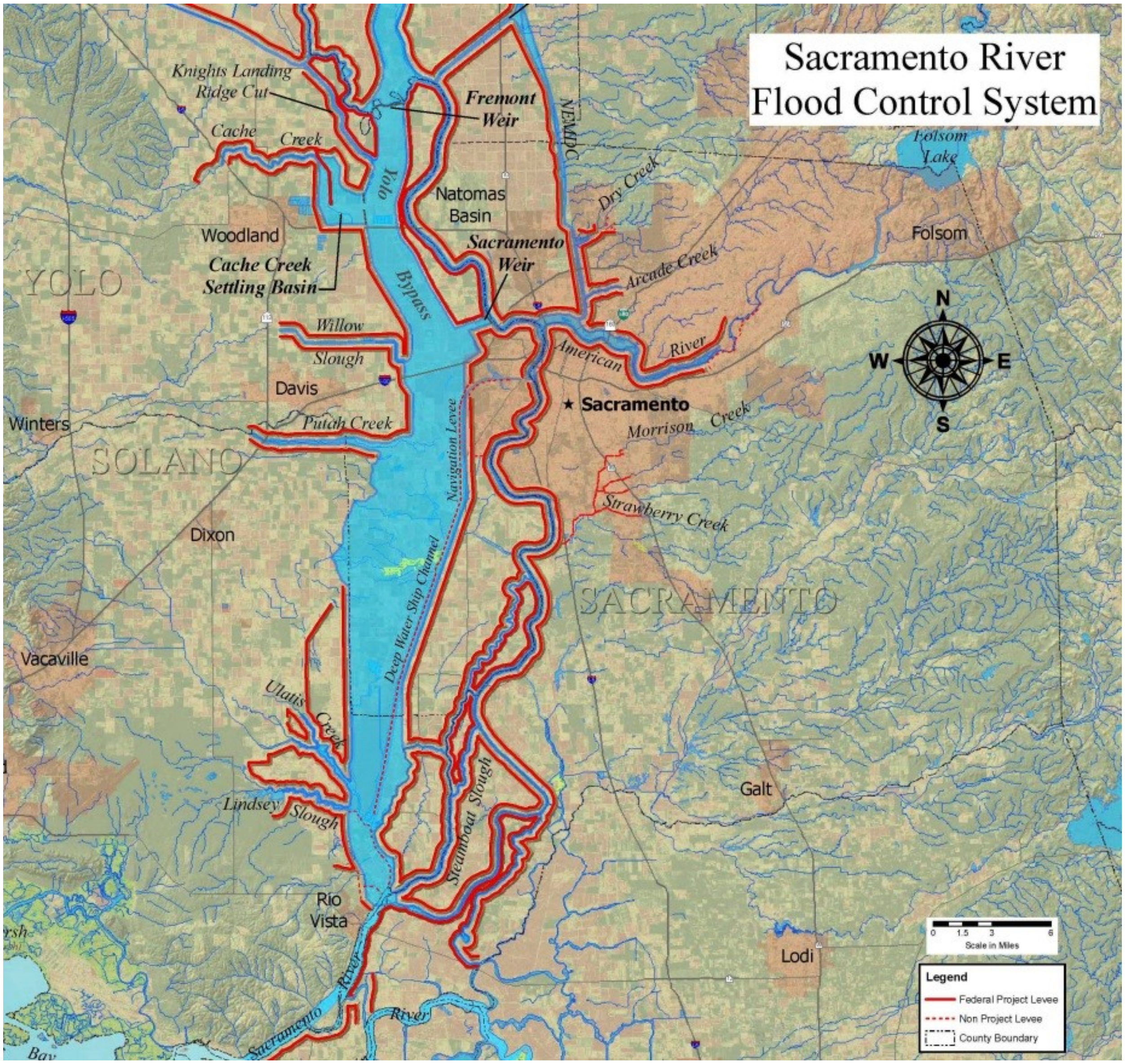


Figure 101. The Sacramento River flood control system in the vicinity of Sacramento. From the Sacramento Area Flood Control Agency.

The initial reliance on levees throughout the Central Valley was largely a failure (Kelley, 1989). Following major flooding in 1907, California finally abandoned the earlier paradigm of "levees only" and began planning a system of bypass channels that are now a mainstay for conveying flood flows past Sacramento and other areas (Figure 101; Lund, 2012; Hanak and others, 2011). During flood conditions, including recently in early 2017, weir structures on the Sacramento River are opened, and up to 80% of the river’s flow is sent down the 65-km long Yolo Bypass, significantly lowering flood stages through the Sacramento urban corridor. Most of the land in the Yolo Bypass is privately owned – deeded with inundation easements – and these bypasses are widely cited as great flood-management successes and examples of conjunctive uses and multiple benefits (flood control, wildlife habitat, agriculture, groundwater recharge, etc.). Plans are currently underway to expand the area within the Yolo and perhaps other bypasses, pending the delicate process of acquiring either private land or appropriate easements to that land.

The Yolo Bypass was last activated in 2017 for flood conveyance. Large flows during that winter on the Sacramento and other Central Valley rivers were largely conveyed without major damages. Flooding on smaller tributaries did cause local damage, and there were a couple of failures of small levees within the Sacramento-San Joaquin Delta, but overall, the system performed as designed. The real near-catastrophe in 2017 was the failure of the main spillway and near-failure of the emergency spillway on Oroville Dam, on the Feather River upstream of Sacramento. Although eventually controlled and now largely repaired, the events at Oroville resulted in the evacuation of nearly 200,000 people and came within hours of what could have resulted in a large loss-of-life failure. Since the Oroville event, massive (and massively expensive) repairs are underway at the site, and there is a renewed focus on the safety of aging dams and the "residual risk" downstream of those dams.

The other notable “residual risk” in the Sacramento region is the eventual risk of flooding behind even the largest levees. It would also be possible that Sacramento and the Central Valley may face catastrophic inundation because of an over-reliance on levee protection. For example, during high flows on the Sacramento and its tributary rivers in 1986, a levee protecting the town of Marysville failed, inundating the town and surrounding areas. Across the US, levees fail almost every year, but the 1986 failure and resulting flood damage were most noteworthy because they generated a legal case that ground through the courts until 2003, when a U.S. Federal judge ruled that the State of California was liable for almost $500 million in damages, interest, and legal fees (the "Paterno Decision"). California's levees had indeed been chronically underfunded and under-maintained for many years, but this ruling spurred California to raise its standards (to "200-year" protection levels for urban levees in the Central Valley) and invest more heavily in levee safety (nearly $5 billion in flood-related bonds approved). Thus, the condition of many California levees, urban levees in particular, has improved.

However, numerous experts have advised local leaders not to forget about residual risk. For example, Galloway (2005) stated: “Let no one believe that because you are behind a levee, you are safe.”

Indeed, the poster child of levee-related residual flood risk is the Natomas area on the northwest side of Sacramento (Figure 101), which is ringed by 68 km of levees. This land was sparsely populated until 1990. After levee improvements, Natomas is now home to over 90,000 people, 22,800 structures, and total infrastructure valued at about $10 billon. Some structures up to 7.6 m would be underwater should the levee fail. A more detailed discussion of the levee system constructed along the Sacramento / San Joaquin River system can be found in “Chapter X – Major Engineering Structures [Levees and Levee Flood Control System]” of this paper.

Land Subsidence

primary author: Robert Anderson

Land subsidence is a gradual settling or sudden sinking of the Earth’s surface that results from movement of subsurface geologic deposits. The principal causes are aquifer-system compaction, drainage and decompression of organic soils, oxidation of peaty soils, oil and gas extraction, hydrocompaction, natural compaction, sinkholes, and strong ground shaking (National Research Council, 1991). The effects of land subsidence include: damage to buildings and infrastructure such as roads and canals, increased flood risk in low-lying areas, and lasting damage to groundwater aquifers and aquatic ecosystems (USGS, 2017). “In general, if subsurface deposits are coarse sand and gravel, the compaction would be small and chiefly elastic and reversible, whereas if they contain fine-grained clays beds, the compaction would be much greater and chiefly inelastic and permanent” (Lofgren and Ireland, 1973).

Extensive groundwater withdrawal from unconsolidated deposits in the San Joaquin Valley has caused widespread land subsidence (locally exceeding 8 meters between 1926 and 1970 (Poland and others, 1975, Figure 2) and reaching 9 meters by 1981 (Ireland, 1986). More recently, groundwater level declines and land subsidence continued during the droughts of 2007-2010 and, most recently, 2013-2016. Groundwater pumping that results in renewed compaction and land subsidence in the Central Valley could cause serious operational, maintenance, and construction-design problems for the California Aqueduct, the San Luis and Delta-Mendota Canal, and other water-delivery and flood-control canals in the San Joaquin Valley. Subsidence has reduced the flow capacity of several canals that deliver irrigation water to farmers and transport floodwater out of the valley (Sneed and others, 2013).

Unlike the San Joaquin Valley to the south, groundwater levels in most of the Sacramento Valley remained generally higher since the 1920s. This was because much of the irrigation demands of the Sacramento Valley were supplied by surface water instead of groundwater. However, intensive pumping in some areas of the valley with no surface water supply, coupled with past drought cycles, caused significant groundwater declines, resulting in land subsidence in amounts up to about 1.6 meters in a broad swath from Zamora (Yolo County) to south of Davis, Solano County (Borchers, 2016). Because of the known historic land subsidence in this area, and in order to develop proactive mitigation, Yolo County and other local agencies initiated periodic local land subsidence surveys starting in 1999.

In the middle of California's latest record-breaking five-year drought (2012-2016), extensive groundwater pumping in Yolo County (Conaway Ranch) during 2013 and 2014 caused groundwater levels to drop about 12 meters below historic lows, resulting in significant localized land subsidence of about 23 cm (Borchers, 2016). In an effort to understand and abate the land subsidence, aquifer compaction modeling under several different groundwater management scenarios allowed Conaway Ranch managers to redistribute groundwater pumping to other areas of the ranch. As a result, the excessive groundwater level declines and land subsidence observed between 2013 and 2015 were mitigated (Borchers, 2016).

In 2008, DWR, in cooperation with federal, state, and local agencies, conducted a Sacramento Valley-wide land subsidence survey using a network of 330 monuments (Frame and D'Onofrio, 2008). In spring-summer 2017, DWR was coordinating a resurvey of the Sacramento Valley network to determine what, if any, land surface elevation decreases (possible land subsidence) have occurred since the baseline survey of 2008.

Faulting and Earthquakes

primary author: Robert Anderson

Sacramento is located on the Sierra Nevada microplate and relatively distant from faults with a high slip rate and comparatively frequent earthquake recurrence along its western and eastern boundaries (Figure 102) (Petersen and others, 2017). Although there are no known active faults in the city and county of Sacramento, there is some potential for damage from near or distant earthquakes.

During the last 500 my, the area that would become the Sacramento region has been on or near subduction zones, the Farallon Plate, the Pacific Plate and more recently, the San Andreas fault. A description of the subduction zones, and the Farallon Plate which the Sacramento region sat over are provided in "Chapter V – Bedrock Geology – [Present Day Plate Motions]" of this paper. The bedrock chapter also contains a discussion on regional faulting and its relationship to regional geology.

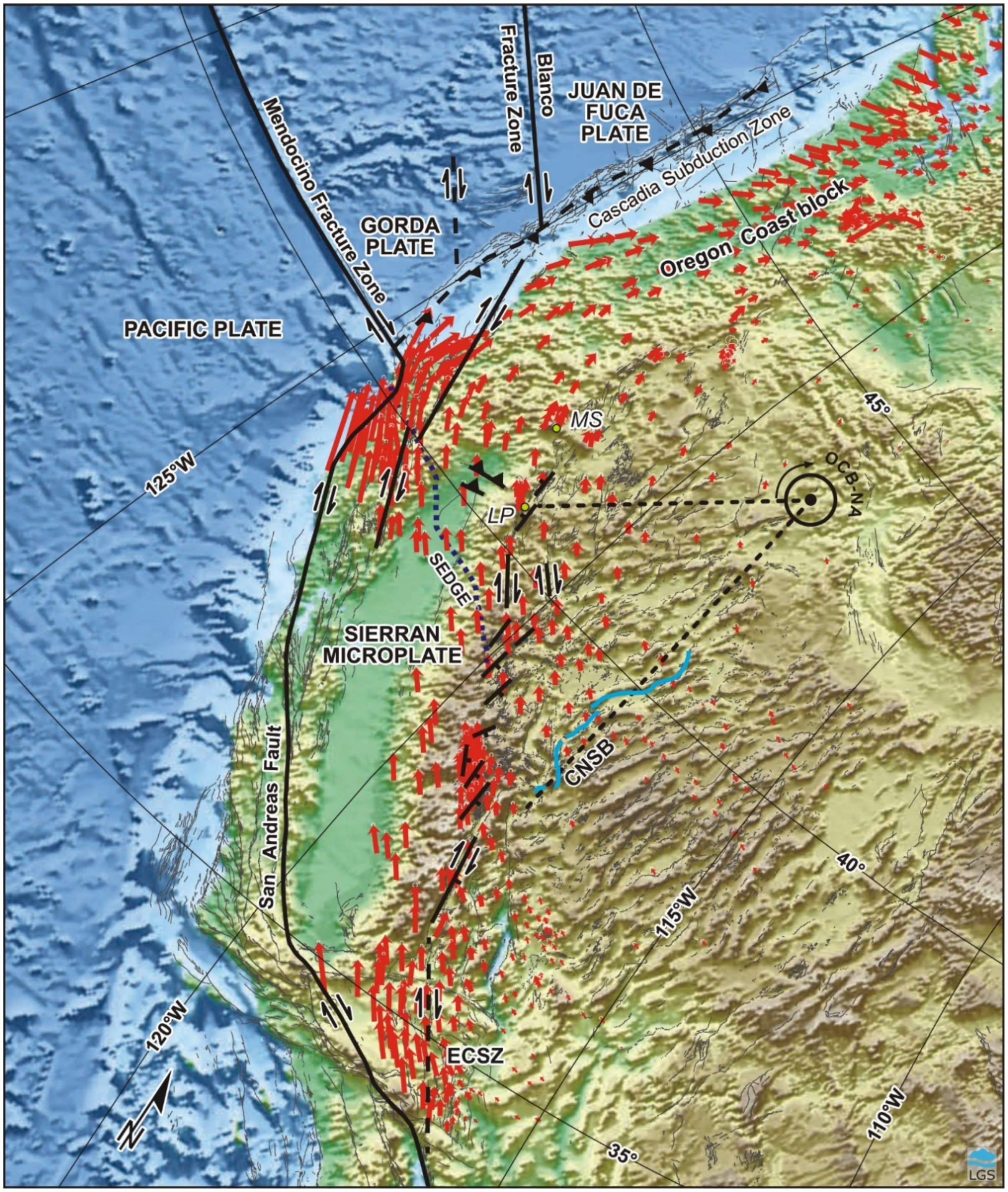


Figure 102: Graphic outlining the Sierran Nevadan micro plate and strain vectors showing movement. (Source: Unruh and others, 2017)

Fault	Distance from Sacramento	Style of Faulting	Comments
San Andreas fault	140 km	Right lateral strike slip (transform fault)	Principal fault in the San Francisco Bay Area
Hayward-Rodgers Creek fault	115 km	Right lateral strike slip	Branch of the San Andreas fault
Calaveras fault	100 km	Right lateral strike slip	Branch of the San Andreas fault
Dunnigan Hills fault	70 km	Thrust	Related to the Dunnigan Hills anticline
Hunting-Berryessa fault	80 km	Right lateral strike slip	Part of Concord-Green Valley fault zone-active fault
Concord-Green Valley fault	60 km	Right lateral strike slip	Active fault
Midland fault	40km	Reverse-oblique	Quaternary active blind fault
Willows fault	>15 km	Reverse	Projected from near the Sutter Buttes using gas well and geophysics information, activity unknown
Freeport fault	16 km	Normal	Blind fault, activity unknown
Mormon Island fault	35 km	Oblique	1 km southeast of Mormon Island Dam
East Branch of the Bear Mountains fault zone	45 km	Oblique (reverse strike slip)	Considered capable fault in Mormon Island Dam liquefaction assessment
Melones fault	55 km	Oblique (reverse strike slip)	Related to gold deposit emplacement in the northern part of the Mother Lode.
Foothills fault zone	55 km	Oblique	Associated in part with the Mother Lode
Stockton fault	90	Reverse	Blind fault marking the northern limit of the Stockton Arch, activity unknown

Table 8: Faults near Sacramento.

Table 8 lists many of the faults covered in this chapter as well as "Chapter VII – Natural Resources" of this paper. Most of the faults that may contribute to strong ground shaking in Sacramento are not close by (over 80 km) from the Sacramento CBD. As of June 2018, no active faults in the city or county of Sacramento have been identified by the California Geological Survey.

Several faults within or near the Sacramento region may be related to the formation of structural or stratigraphic traps for natural gas. These faults include but are not limited to the Willows fault, the Dunnigan Hills fault, the Midland fault, the Freeport fault and the Stockton fault. None of the faults are considered active by the California Geological Survey. Several of the faults are also mentioned in the chapter on oil and gas in this paper.

East of Sacramento there are several faults and fault zones associated with the development of zones of mineralization. Several local faults are only known from localized exposures in or near select mines, including faults in the Copperopolis, Auburn, Grass Valley, Nevada City, Spenceville and Sierra City areas. Locally, the region between the Melones fault and the Bear Mountains fault are related to some locations of lode gold deposits. The region near the Bear Mountains fault zone and related smaller faults is related to the location of copper deposits. Several of the faults and their relationship to the location of mineral deposits are mentioned in the chapter on mining.

In 1975 a M_w 5.7 earthquake occurred near the Oroville dam. An investigation of the earthquake by the CDMG indicated that the earthquake likely originated on the Cleveland Hills fault (Hart and Rapp, 1975) and a part of the Foothills fault zone. As a result of the determination, a number of fault studies were conducted to locate and evaluate a number of lineations and faults near the proposed Auburn dam site. The studies were focused in an area near the proposed Auburn dam site. The largest fault near the study area was the Bear Mountains fault zone. The fault studies were conducted to help determine the seismic hazard for the Auburn dam site.

Select Earthquakes Experienced in Sacramento

The Uniform California Earthquake Forecast model version three results indicate that the probability for strong ground shaking in Sacramento is low, but not zero (USGS, 2013). In addition, there are no known active faults in the city and county of Sacramento. Sacramento is not free of the potential for damage from seismic hazards from nearby or distant seismic sources.

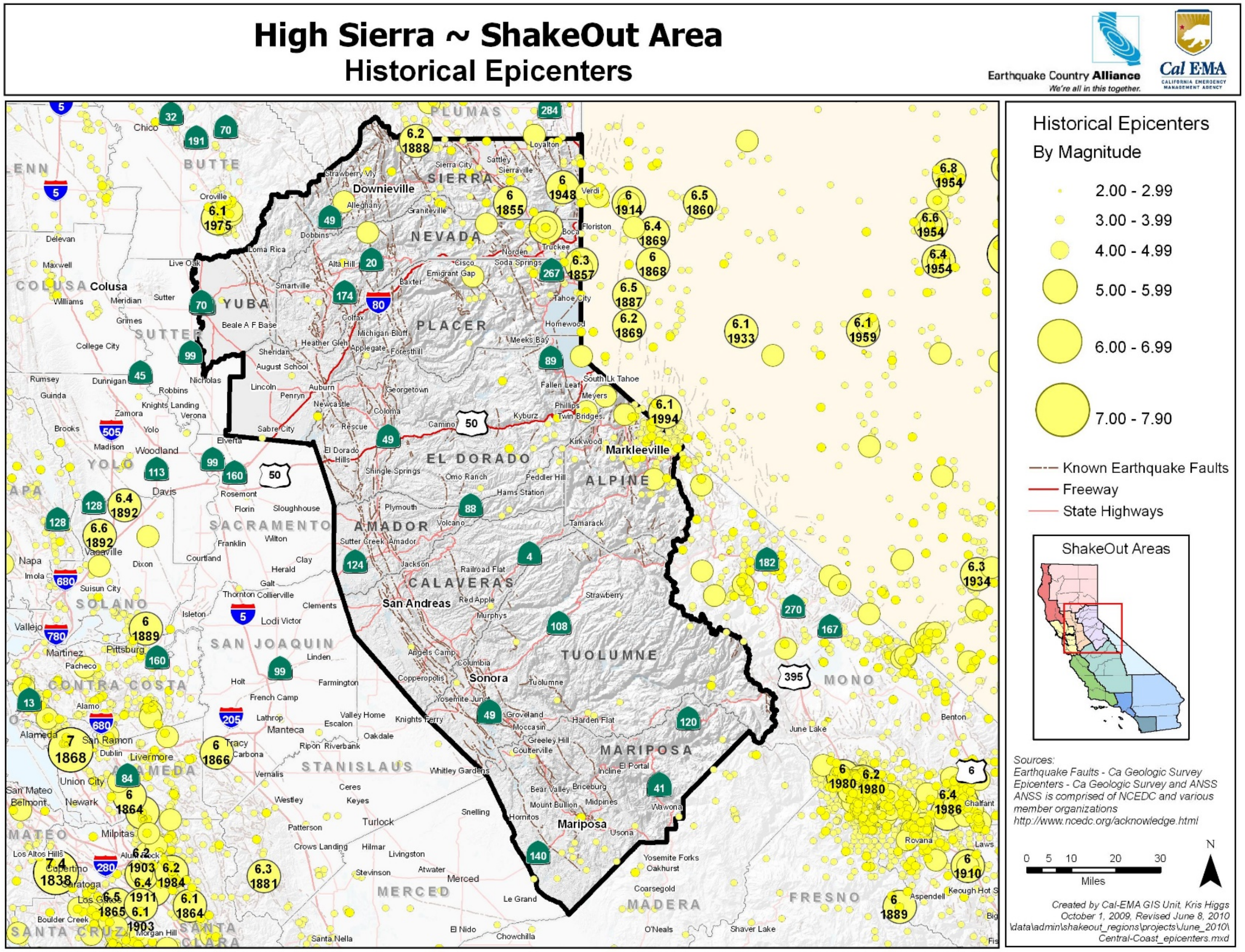


Figure 103. Map of earthquake epicenters near Sacramento with a magnitude greater than or equal to M 2.

There are number of areas where ground motion may originate from and affect Sacramento. Several of the areas include earthquakes in the San Francisco Bay Area, faults along the eastern edge of the Coast Range Mountains, faults along or within the Sierra Nevada foothills and mountains, distant source earthquakes such as the San Joaquin Valley, Northwestern California, western Nevada. Figure 103 indicates that there have been several earthquakes known to have occurred near Sacramento, but none have been very large or cause significant damage.

Sacramento has not experienced the frequency and severity of strong ground shaking on the level of the cities in the San Francisco Bay Area. This is due to the proximity of the San Francisco Bay Area cities to the faults of or related to the San Andreas fault system. The distance to large Quaternary and younger faults as well as other earthquake sources has also reduced the relative intensity of ground motion and other seismic hazards near Reno, Carson and Sparks Nevada as well as Truckee, Tahoe City and Markleeville, California.

However, Sacramento has experienced several earthquakes since it was founded. Figure 103 shows the estimated location of earthquakes near Sacramento from 1838 to 2010. Some of the most notable earthquakes felt in Sacramento were the 1892 Vacaville-Winters earthquakes, the 1906 San Francisco earthquake. Other notable earthquakes include the 1960 Dog Valley earthquake near Truckee, the Oroville earthquake in 1975, the 1989 Loma Prieta earthquake, the 1992 Petrolia earthquake, the 1994 Double Spring Flat, Nevada earthquake, and the Lake Almanor earthquake in 2015.

During the Dixie Valley earthquakes of 1954, several high-rise buildings in Sacramento swayed from long-period strong ground shaking. However, no significant damage was reported. The Dixie Valley earthquake sequence was located approximately 300 km east of Sacramento.

Minor damage to several high-rise buildings in Sacramento was reported after the 1992 Petrolia earthquake in northwestern California, including damage to a covered reservoir due to sloshing. No significant damage or significant secondary related effects such as liquefaction, lateral spreading or earthquake induced landslides have occurred in Sacramento.

Select Volcanic Hazard Sources

primary author: Robert Anderson

There are several volcanic sources within 500 kilometers of Sacramento (Figure 104). Although several have been identified as high- to very-high volcanic threats by the USGS, none pose a significant risk to Sacramento. A probabilistic volcano hazard

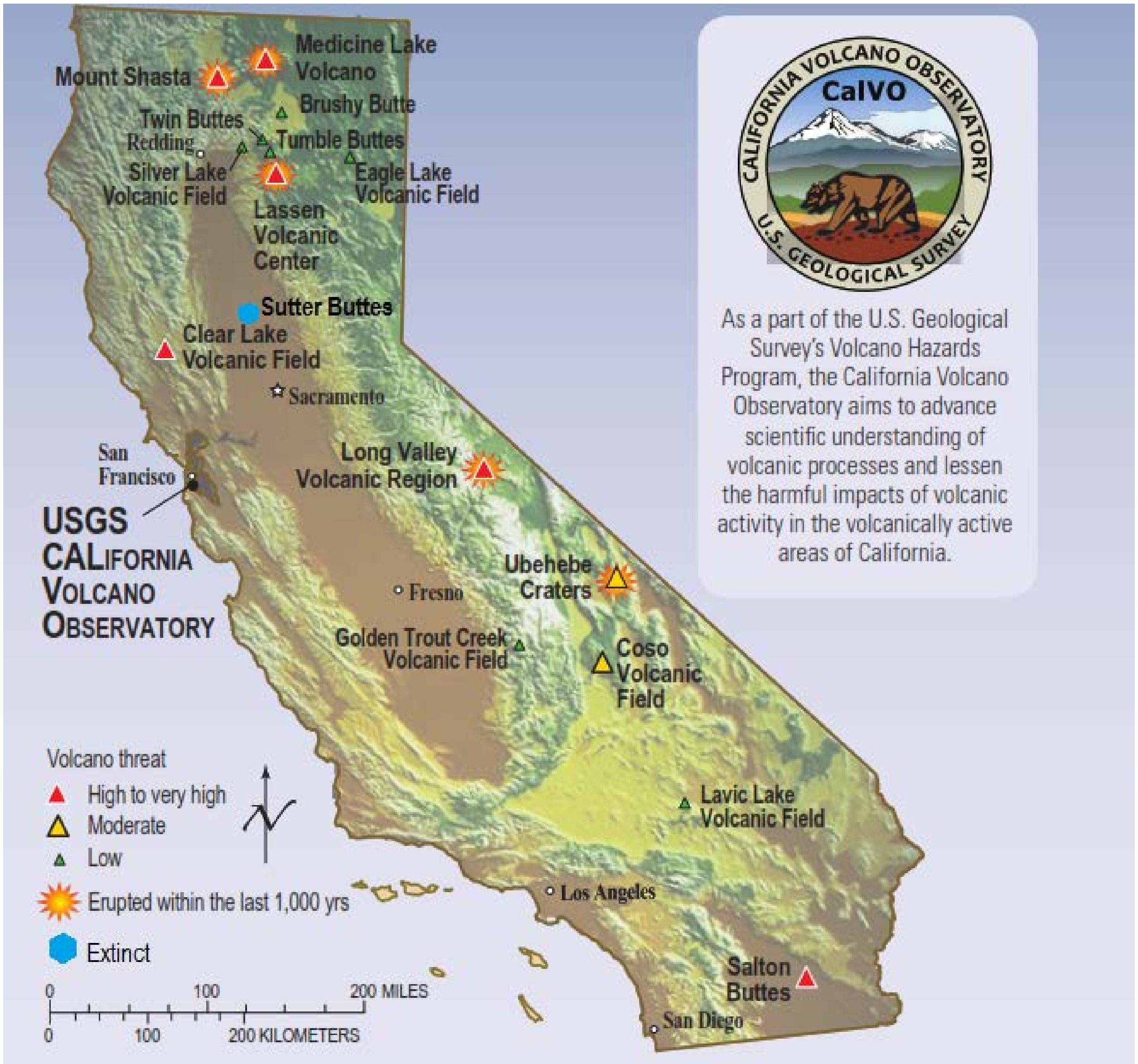


Figure 104. Modified map showing volcanos with a moderate to high volcanic threat. and the Sutter Buttes. (Source: USGS Fact Sheet 2014-3120)

Figure 105. Eruption of Lassen Peak, as seen from Red Bluff, California, May 22, 1915. The ash, rock and pumice cloud rose to a height of 9.2 km and drifted up to 440 km to the east.to Elko, Nevada (Source: USGS Fact Sheet 022-00 online version)

assessment has never been completed by the author for Sacramento. Should one of these volcanic sources erupt, volcanic hazards that could impact Sacramento include tephra (especially ash), sediments inundating major bodies of water, or a reduction in sunlight intensity and lowering average atmospheric temperature related to elevated concentrations of gasses and aerosols ejected into the atmosphere (Figure 105). However, the rock record indicates that volcanic activity has been prevalent in the past in the Sacramento region.

Formations that may cause problems for construction projects include the Mehrten, the Tuscan, and the Valley Springs formation. Some volcanic soils or rock retain water or may swell when hydrated causing construction problems. In addition, they are not easy to excavate, and may or may not very stable in large cuts or easily eroded.

A potential volcanic hazard for the Sacramento region is tephra (especially ash). Ash may be transported a long way from volcanic sources by either wind or water, blanketing large areas as well clogging or damaging water intakes or water treatment plants. Tephra may damage electrical component and systems, including power stations, as well as transmission and distribution systems by causing electrical shorts or physical damage to equipment. In addition, tephra, lahars, and lava can bury or burn crops and animals may be harmed by either inhalation or ingestion of tephra or ash.

Volcanic mudflows (lahars) can block drainages, leading to localized flooding. Lahars and pyroclastic flows, while locally destructive, are not considered to be a threat to Sacramento due to the large distance (over 100 km) to known active volcanic sources and the short range that these phenomena usually travel from their source. In the Sacramento region the Mehrten Formation contains a lahar. This unit of the Mehrten Formation is indurated and immobile Lahars and pyroclastic flows will not be further discussed in this section.

Volcanic eruptions are classified by a scale called the Volcanic Explosivity Index (VEI). The scale ranges from zero to eight. The VEI uses only whole numbers. A VEI of zero indicates that the eruption is non-explosive in nature, while a VEI value of eight would be a super eruption similar in magnitude to the Yellowstone eruption 600,000 years before present. Starting at a VEI value of one, an increase in VEI of one represents a logarithmic increase in ejecta. This means that a one-unit increase in the VEI represents a tenfold increase in the amount of ejecta ejected during an eruption (Newhall and Self, 1982). Table 9 summarizes the VEI and other elements of volcanoes that can be seen or are within 500 km of Sacramento. Table 9 includes information of select volcanic fields near Sacramento, including a VEI estimate of a Lassen Peak eruption in 1915. Figure 105 is an image of Lassen Peak erupting 1915 as seen from Red Bluff, California.

Source	Distance From Sacramento (km)	Most likely hazard	Most recent eruption	USGS Volcanic Threat Potential	VEI
Lassen Peak	340	Ash fall	1914-1917	Very high	3
Long Valley Caldera and Mono Craters	375	Atmospheric cooling, volcanic aerosols	600-years ago for Mono craters and 760,000-years ago	High to very high	7
Mt. Shasta	310	Ash fall	1796	Very high	Between 3 and 5
Clear Lake Volcanic Field	160	Ash fall	About 1,000-years ago	High	Undetermined
Medicine Lake Volcanic Field	450	Atmospheric cooling, volcanic aerosols	About 12,500-years ago	High	Undetermined
Sutter Buttes Volcanic Field	90	Seismic shaking, ash fall	About 1,400,000-years ago	extinct	Less than 1

Table 9. Summary of volcanic field within 500 km of Sacramento.

Approximately 600 Ka, Mt. Tehama, the predecessor of Lassen Peak, had an eruption that spread tephra over a region from Lassen Peak to Sacramento to the Sacramento-Joaquin Delta and to San Francisco, either via air or by streams and rivers (Source USGS Fact Sheet 022-00 online version accessed 11/21/17). Recently, Department of Water Resources geologists have found ash and tephra in the Sacramento-San Joaquin Delta sediments near Sacramento during geotechnical exploratory operations. (Scott Sochar, personal communication, DWR, 2016). Laterally extensive layers of volcanic ash, some as much as 3 m thick, were identified in Quaternary age sediments throughout the Sacramento-San Joaquin Delta, south of Sacramento. During the geotechnical exploration, more than one unit of tephra was encountered. Tephra deposits have also reported to have been identified and dated in Johnson and others, 2018 (in press). The sources of the ash/tephra are unknown, although it is likely that the bulk of the material was transported to the Sacramento, Sacramento-San Joaquin Delta and San Francisco area by water. Ash or tephra falls and is transported by streams and rivers. Today covering the same area would imperil infrastructure, interrupt air travel and contaminate surface water supplies and potentially damage or destroy buildings, crops as well as injure or kill livestock or people.

Sutter Buttes

The Sutter Buttes is a collection of partially eroded volcanic domes, flanked by an extensive debris skirt (Figure 106). It is isolated in the Sacramento Valley from other known volcanic features. This volcano is located approximately 90 km north of Sacramento near Yuba City, California and is a highly visible feature from Sacramento, as it is isolated in the flat expanse of the Great Valley (Figure 107). It is one of two volcanos easily visible from Sacramento on a clear day, the other being Mt. Konocti in the Coast Range.

The Sutter Buttes are mainly composed of andesite, dacite and rhyolites. However, a small but significant block of granite near its center has pierced and un-wrapped older sedimentary beds (Hausback and others, 2011) (Figure 108). Some of the sedimentary units have formed structural traps from which natural gas has been extracted.

The Sutter Buttes are flanked on the west side by the Willows fault. The Willows fault is linked to the Paskenta fault where it crosses the Corning fault northwest of the Sutter Buttes, and can be traced to the east side of the Coast Range Mountains. The Sutter Buttes petrology may be related to some of the Coast Range Volcanics (Hausback and others, 2011). However, the mode of emplacement, the presence of the granitic block and the reason why it is isolated in the Southern Sacramento Valley is unclear. The latest round of volcanism appears to have taken place between 1.6 to 1.4 million years

Figure 106. Lightning strike on Sutter Buttes. (Source: image courtesy of Jim Hafferty).

Figure 107. Aerial reconnaissance photograph showing Sutter Buttes, debris skirt, and surrounding valley (Source: image courtesy of Chad Coleman, Coleman Engineering).

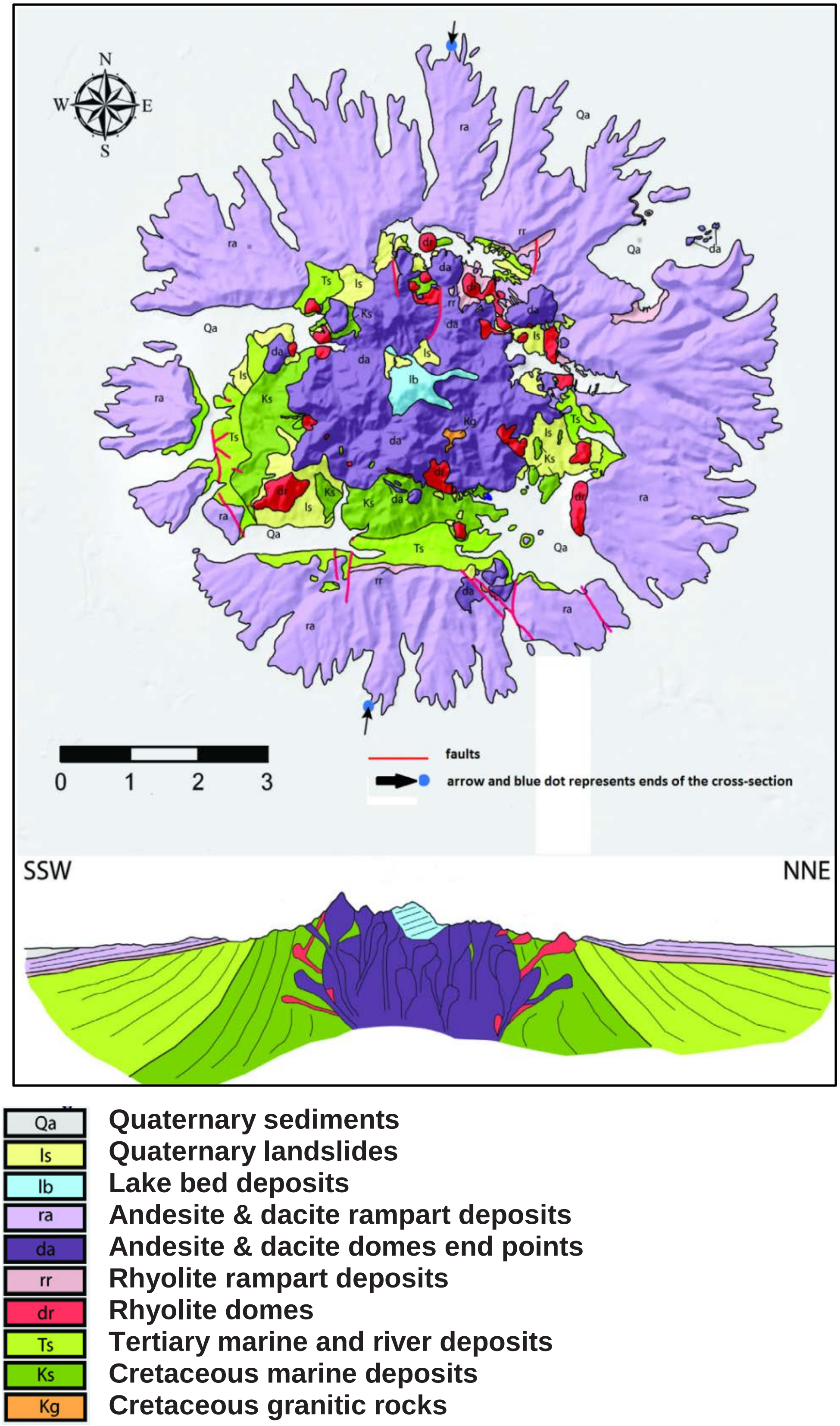


Figure 108. Geologic map and cross section through the Sutter Buttes (Source U.S.G.S. Fact Sheet 2011-3024, March 2011).

before present. No VEI has been established for this feature since the Sutter Buttes has not erupted within the last two hundred years. At present, the Sutter Buttes appear to be extinct.

X. MAJOR ENGINEERING STRUCTURES

Liquefaction, Landslides, and Lateral Spreading

primary author: Robert Anderson

There is no bedrock directly under the Sacramento Central Business District within the first 100 meters of the ground surface. To date, August 2018, no seismic hazard maps depicting landslides or liquefaction, or active faults had been prepared for the City and County of Sacramento by the California Geological Survey (CGS, 2018),

The levees may also be prone to long period strong ground shaking from earthquakes as far away as the greater San Francisco Bay Area, the Sacramento-San Joaquin Delta, the northwest coast of California, and the faults near Lake Tahoe or Carson City and Reno, Nevada. One should note that the older levees were constructed out of uncontrolled fill, for the most part, and locally may be underlain by sands and silts potentially prone to liquefaction. The suggested potential for liquefaction is, in part, based on the presence of sands and silts as well as uncontrolled fill in parts of Sacramento near the Sacramento River, the American River, the Cosumnes River, the San Joaquin River, the Yuba and Feather River, as well as other major streams or rivers that may have soils that are in part saturated, other than levees. No lateral spreading or earthquake induced land sliding has been observed in the levees near Sacramento. However, several levees have been breached over the years, in some cases resulting in the localized flooding of islands, including farms in the Sacramento-San Joaquin Delta.

In the Sacramento region, locations potentially prone to liquefaction include areas with a high groundwater table and young alluvial and fluvial soils. This includes the areas of the levee system and downtown Sacramento. The area potentially prone to liquefaction widens out towards Rio Vista in the area of the levees and islands in the northern part of the Sacramento-San Joaquin River Delta. In this area, there are local beds of peat that are also prone to settlement, oxidation, or loss of strength in the foundation of some levees and possibly other structures. A number of levees were reported damaged by earthquakes as far away as Coalinga (Finch, 1992). Table 1 of the Finch paper describes the mount of displacement experienced by the levees observed after several earthquakes. In no case were any of the levees breached. The levees were in the Sacramento-San Joaquin Delta, but were not in Sacramento. Finch did not report on any levee damage from the earthquakes mentioned in his paper in Sacramento.

A study released by the CALFED Bay-Delta Program in 2000, did not mention any damage to levees from the earthquakes mentioned in the Finch study of 1992. However, the CALFED study did produce an estimate of regions of the Delta with varying degrees of levee vulnerability.

However, there are several areas that may be prone to liquefaction and seismically induced ground failure including lateral spreading or slope failure of levees in the City of Sacramento and Sacramento County. These areas are in the young alluvium underlying a large portion of Sacramento/West Sacramento and the banks of the Sacramento, American Rivers and possibly major streams. Two other areas include the former China and Willow Lakes which were infilled at the old Sacramento Rail Yards north of the Sacramento central business district. The shallow lakes were infilled with uncontrolled fill and contains deposits of sand silt and clay in a young alluvium/fluvium.

Lateral spreading may be a problem for select unidentified levees in the Sacramento region since they may be prone to damage from long period, long duration strong ground motions and some have large slopes which are unsupported by engineered structures.

Landslides are rare in Sacramento since the city has relatively little relief. The primary location for small scale landslides would be along the levees in or near Sacramento. Limited landslide potential may be found in the bluffs overlooking the American River and Lake Natomas and in the bluff near Negro Bar. Another area near Sacramento that may be susceptible to landslides are along the perimeter of Folsom Lake. In western Placer and El Dorado Counties and southern Sacramento County, landslides may occur as small scale shallow slips related to slippage of colluvium.

Geotechnical Investigation Methods, Mitigation and Foundation Types

primary author: Jeremy Zorne

The greater Sacramento region includes diverse geology ranging from soft and loose recent alluvium near rivers, creeks, and drainages to outcropping and hard bedrock in the Sierra Nevada Foothills. From a geotechnical perspective, the general geologic conditions of the region can be broadly characterized into the following categories:

Artificial Fill / Dredge Tailings – includes levees, dikes, filled areas, and dredge tailings, typically near rivers and in basin areas.

- Alluvium (recent) – includes unconsolidated (soft, loose) recent alluvial and basin deposits, typically near creeks, rivers, drainages, and basins. Includes numerous mapped recent alluvial deposits – alluvium, basin, and fan deposits.
- Alluvium (older) – includes semi-consolidated to consolidated (stiff, dense) older alluvial deposits. Typically located in upland areas, on terraces, and dissected by creeks, rivers, and drainages. Includes numerous mapped older alluvial deposits – Riverbank, Laguna, Modesto, Turlock Lake Formations.
- Soft Rock – includes volcanic mudflow (Mehrten Formation, Ione Formation, Valley Springs Formation, etc.), and highly weathered metamorphic and intrusive rock. Typically located in the eastern valley and foothills regions.
- Hard Rock – includes less weathered and fresh metamorphic and intrusive rock. Typically located in the foothills region.

Surface water and groundwater is present throughout the region. Shallow groundwater is typically present within the central portion of the Sacramento Valley, near the major rivers. Shallow/perched groundwater is typically present near creeks/local drainages and near lakes and reservoirs. Seeps and springs are common with conglomerate and rock units. The selection of geotechnical exploration methods, equipment, and techniques varies with the geologic and groundwater conditions. Table 10 provides a general overview of the common geotechnical exploration methods used in the region.

The geologic categories in the region have unique and common geologic hazards and/or geotechnical constraints. Table 11 provides a general overview of common geologic hazards and geotechnical constraints. Table 12 provides a general summary of typical mitigation measures used in the region for the geologic hazards and geotechnical constraints.

Mitigation measures typically include (1) remedial grading (such as removal and replacement or re-compaction; (2) ground improvement such as chemical treatment, densification, soil strengthening; or (3) structural mitigation such as strengthened foundations, retaining structures, and other structural elements designed to suit the geotechnical conditions.

Table 13 provides a general summary of typical foundation types used for typical residential and commercial buildings in the region based on the geologic hazards and geotechnical conditions. Common foundation types presented in Table 13 include (1) Conventional - typical shallow foundations/slabs-on-grade; (2) Intermediate foundations, such as post-tensioned slabs, mat foundations, drilled piers, shallow foundations in conjunction with rammed aggregate piers; and (3) deep foundations (piles) the transfer structural loads through soft upper soils and bear within more competent soils below.

Geotechnical Case Summaries

The following case histories illustrate some of the mitigations and foundation types used in the region.

Case History No. 1 – Data Center Building Addition, Folsom, CA (Dredge Tailings) – Remedial Grading

This project consisted of a building addition for an existing single-story commercial building. The site is located near the American River (Lake Natoma) in an area that was previously dredged for gold recovery. Between approximately 1900 and 1962 placer gold was extracted from the area using various types of floating dredges. The dredges operated in artificial ponds filled by water from canals. As the dredges advanced

Typical Geotechnical Investigation Methods	Artificial Fill / Dredge Tailings	Alluvium		Rock	
		Recent	Older	Soft	Hard
Drilling - Hollow-Stem/Flight Auger	X	X	X	O	---
Drilling – Mud-Rotary	X	X	X	O	---
Drilling – Air-Track	---	---	---	O	X
Drilling – Rock Coring	---	---	---	O	X
Drilling – Air-Rotary/Sonic	X	O	X	X	X
In-Situ Testing (CPT, DMT, DCP)	X	X	X	O	---
Geophysical – Refraction Seismic	O	O	O	X	X
Backhoe/Excavator Test Pits	X	X	X	X	---

Key:
X = Common/Typically Used
O = Sometimes Used
--- = Not Typically Used

Table 10. Typical geotechnical exploration methods used in the Sacramento region based upon authors personal experience.

Common Geologic Hazards/Geotechnical Constraints	Artificial Fill / Dredge Tailings	Alluvium		Rock	
		Recent	Older	Soft	Hard
Expansive Soil	M	H	H	H	M
Compressible Soil	H	H	M	L	L
Liquefaction	H	H	M	L	L
Lateral Spreading	H	M	L	L	L
Slope Stability	H	H	M	H	M
Landslides / Rockfall	L	L	M	H	H
Differential Support Conditions	H	L	M	M	H

Key:
- H = High Potential/Occurrence
- M = Moderate Potential/Occurrence
- L = Low Potential/Occurrence

Table 11. Common geological hazards/geotechnical constraints of the Sacramento region based upon authors personal experience in the region.

Geologic Hazard/Geotechnical Condition	Remedial Grading[1]	Ground Improvement[2]	Structural[3]
No Significant Hazards/Constraints	---	---	---
Expansive Soil	X	X	X
Compressible Soil	X	X	X
Liquefaction	---	X	X
Uncontrolled/Undocumented Fill/Deposits	X	X	O
Differential Support Conditions	X	O	---
Lateral Spreading	---	X	X
Slope Stability	X	O	X
Landslides	X	O	X
Key: X = Common/Typically Used O = Sometimes Used --- = Not Typically Used	Legend: 1. Remedial Grading = typical site development earthwork 2. Ground Improvement = chemical treatment, densification, soil strengthening 3. Structural = Strengthened foundations, retaining structures		

Table 12. Typical mitigation measured employed in the Sacramento region based upon author's personal experience in the region.

Geologic Hazard/Geotechnical Condition	Conventional[1]	Intermediate[2]	Deep[3]
No Significant Hazards/Constraints	X	O	---
Expansive Soil	O	X	---
Compressible Soil	---	X	X
Uncontrolled/Undocumented Fill/Deposits	O	X	O
Liquefaction	O	X	X
Differential Support Conditions	O	X	O
Key: X = Common/Typically Used O = Sometimes Used --- = Not Typically Used	Legend: 1. Conventional = Typical shallow foundations/slabs-on-grade 2. Intermediate = Modified Foundations, Post-Tensioned Slabs, Mat Foundations, Drilled Piers, Rammed Aggregate Piers, etc. 3. Deep = deep foundations (piles)		

Table 13. Typical foundation types found in the Sacramento region based upon authors personal experience in the region.

operations, they “moved” the pond by excavating in the front and placing spoils in the rear. Photographs of dredges are presented in “Chapter VII – Natural Resources [Gold], and Chapter VIII – Environmental Concerns [Hazards Related to Gold Mining], and Chapter X – Major Engineering Structures [Historic Levee Construction and River Modification Methods]” of this paper. The movement of the dredges resulted in windrows of dredged material. Dredging depths were typically shallow, on the order of 4.6 to 7.6 m. During dredging operations, soil and aggregate picked up by the dredge buckets were screened into fine and coarse fractions using a rotating screen. The fine fraction was sluiced to remove the gold using water from the pond. The coarser sluiced fraction, consisting of medium and coarse sand and fine gravel, was returned to the rear of the dredge for disposal, where it was re-mixed with the screened gravel and cobble material using a sand wheel. The resulting mixture of sand, gravel and cobble was dumped off the end of the dredge using a pair of stackers. The process resulted in tailing windrows (piles) of loose gravel and cobble with some sand (uncontrolled fill). The proposed building expansion area was underlain by approximately 4.27 m of variably loose and open-graded dredge tailing materials.

Due to the variably-loose condition of the dredge tailings, remedial grading was conducted in the form of partial removal and re-compaction in order to provide uniform support for the planned building expansion. The remedial grading consisted of over-excavating the top 1.52 m of dredge tailing material, blending the tailings with import soil (to fill the voids) and re-compacting the blended material as engineered fill (Figure 109). After remedial grading, the new building expansion was supported on conventional shallow foundations.

Case History No. 2 – Natomas Meadows Clubhouse, North Natomas, Sacramento, CA (Expansive Soil) – Intermediate Foundations

The North Natomas area of Sacramento, north of the American River and east of the Sacramento River, is blanketed by moderately- to highly-expansive soil. Expansive soil can lead to significant post-construction building damage due to moisture-induced soil volume changes (shrinking and swelling). This project consisted of a Recreation Center and Community Clubhouse for the Natomas Meadows residential development. To mitigate the effects of expansive soil, the building foundation included a post-tensioned (PT) slab foundation designed to withstand the effects of expansive soil (Figure 110). PT slabs are used in the area extensively for both residential and commercial development in areas with expansive soil or differential support conditions.

Figure 109. Photograph of remedial grading in dredge tailings (Source: image courtesy of Jeremy Zorne).

Figure 110. Photograph of a typical post-tensioned slab foundation (Source: image courtesy of Jeremy Zorne).

Case History No. 3 – Camptonville CORE Academy, Marysville, CA (Uncontrolled/Undocumented Fill) – Ground Improvement

This project consists of a single-story classroom and administrative building for the Camptonville CORE academy. The site is located on the north side of Ellis Lake in Marysville, California. Geotechnical investigation revealed that the building area was underlain by rubble fill (predominantly concrete rubble) and debris (Figure 111). Due to the variably-loose condition, the rubble fill was not considered suitable for reliable support of the building. Due to the presence of shallow groundwater, removal and replacement with engineered fill was not economically feasible for the project. Therefore, displacement columns were used for ground improvement during this project (Figure 112). Drill Displacement Columns™ (DDC) are rotary displacement piles installed by inserting a specialized auger into the ground that displaces the soil laterally and allows concrete grout to be injected under pressure into the void space. This results in the creation of "composite ground" that improves compressible soil, fills voids, and increases the composite allowable bearing pressure for foundations. This method of ground improvement is comparable to large diameter compaction grouting. For this project, DDC elements were installed on a grid pattern below the building. After the DDCs were installed, the new building was supported on a conventional shallow foundation.

Case History No. 4 – Golden 1 Center, Downtown, Sacramento, CA (Compressible Soil, Liquefaction) – Deep Foundations

The Sacramento Entertainment and Sports Center (ESC), which is also known as The Golden 1 Center, is a multi-purpose arena, located in the heart of downtown Sacramento (Figure 113). The ESC encompasses four city blocks and is a major economic catalyst for the region. The state-of-the-art venue is an indoor-outdoor, multi-use facility which accommodates professional/collegiate sports, concerts, trade shows, and other entertainment.

The ESC site presented challenging subsurface conditions, including soft compressible soil, shallow groundwater (Figure 114), soil/groundwater contamination, and high seismic-induced liquefaction potential. The contamination plume consists of volatile organic compounds and is discussed in greater detail in "Chapter VIII – Environmental Concerns [Military and Aerospace Industry]" of this paper.

Figure 111. Photograph of typical rubble fill encountered in the Marysville, California area (Source: image courtesy of Jeremy Zorne).

Figure 112. Photograph of a DDC auger bit and grout injection line (being held by worker) (Source: image courtesy of Jeremy Zorne)

Figure 113. Photograph of Golden 1 Center during construction (Source: image courtesy of Jeremy Zorne).

Figure 114. Photograph of soft and wet ground conditions and stick up of a few driven piles that supported the former downtown plaza development (Source: image courtesy of Jeremy Zorne).

A deep foundation system was required to accommodate the high structural load of the ESC and the poor ground conditions. The elevation and consistency of the underlying dense sand and gravel bearing layer was highly variable across the site (Figure 115). Thus, fixed-length driven piles could not be used effectively as significant splicing or cut-offs would be necessary. In addition, the City would not allow driven piles due to noise and vibration concerns in this highly-developed and active downtown area. Therefore, displacement augercast piles of variable diameters and lengths were used to meet the project demands (Figure 116). In addition to flexibility in pile length and diameter, the displacement piles generated very little spoils, which significantly reduced off-haul of contaminated soil.

Case History No. 5 - Ground Improvement Project Downtown Sacramento

primary author: Jonathan Manke

One option for addressing the geology of Sacramento for site development is through ground improvement. Geopier Foundation Company, Inc. provided Rammed Aggregate Pier® (RAP) ground improvement for a 6-story parking structure at a site in downtown Sacramento (Figure 117).

The geotechnical investigation identified undocumented fill to depths of 2.1 m (Figure 118). The undocumented fill was placed during the late 1800s and early 1900s to raise the city above flood waters. The fill is underlain by alluvial, soft to medium silty clay and sandy silt to 9 m, then alluvial, dense sand and gravel to about 12.8 m, then medium to stiff clay to about 20 m and then dense gravels to the maximum depth explored of 24 m. Groundwater was observed between 2.4 and 3.65 m below the ground surface during RAP installations.

The geotechnical engineer determined that the fill and alluvial soils were too compressible to support the structure on typical spread footings without exceeding the tolerable settlement of the structure. Initial recommendations for 23-m long driven piles were provided to support the structure. However, RAP elements were also considered as a viable option to improve the existing soils to allow for support of the structure with conventional spread footings constructed over the RAP elements.

Typical Geopier® RAP installation is shown in Figure 119. RAPs are installed by drilling 45.7, 61, and 76 cm diameter holes (A.) and ramming 30.5 to 91 cm lifts of well-graded, crushed, aggregate in the holes (B.) to form very stiff, high-density aggregate piers (C.).

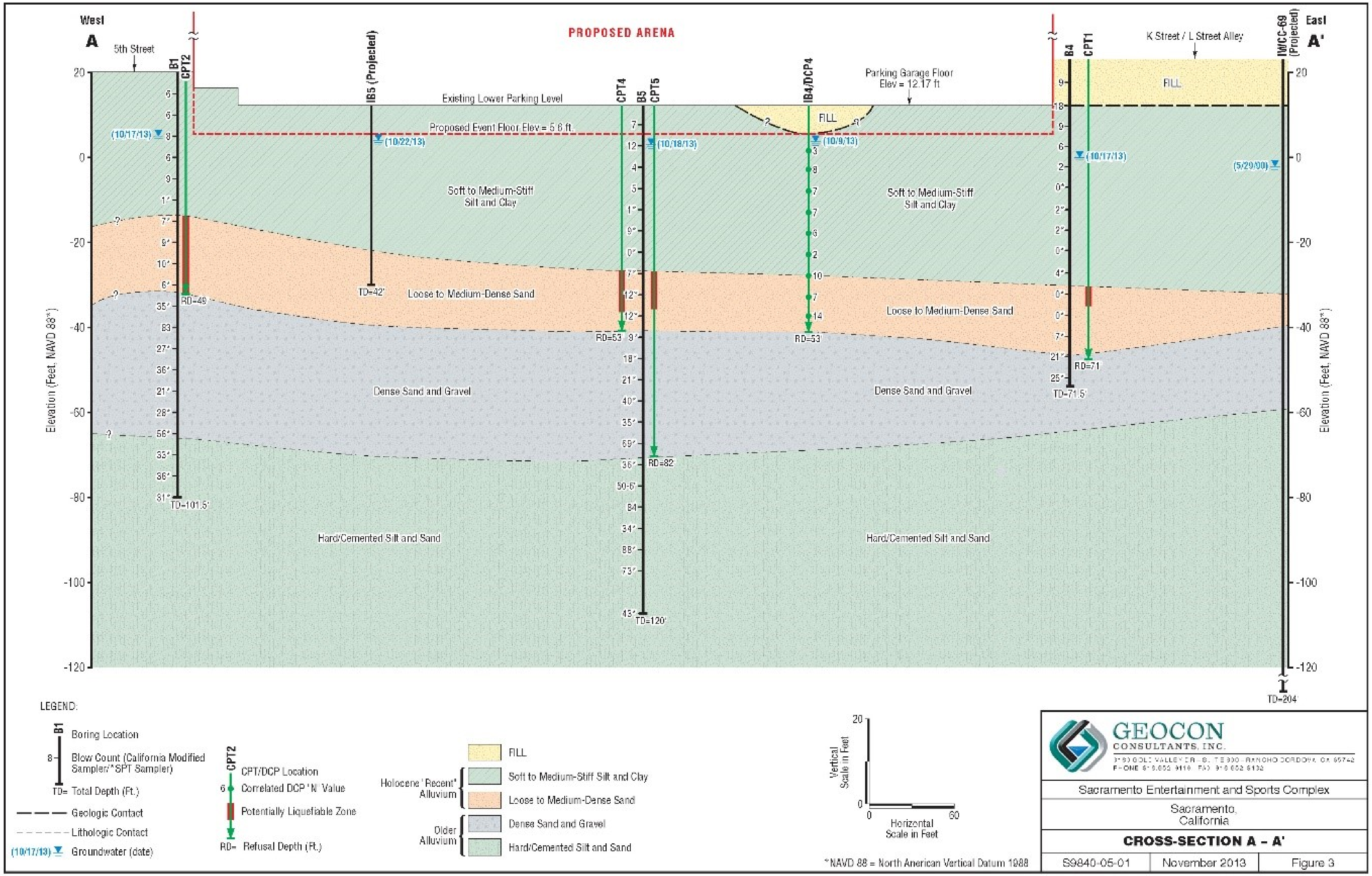


Figure 115. Generalized geologic cross section (West-East) beneath the Sacramento Enertainment and Sports Complex (Geocon, 2013).

Figure 116. Displacement pile installation equipment (Source: image courtesy of Jeremy Zorne).

Figure 117. Photo looking northwest towards downtown parking garage and construction diagram for the parking garage (Source: image courtesy of Jonathan Manke).

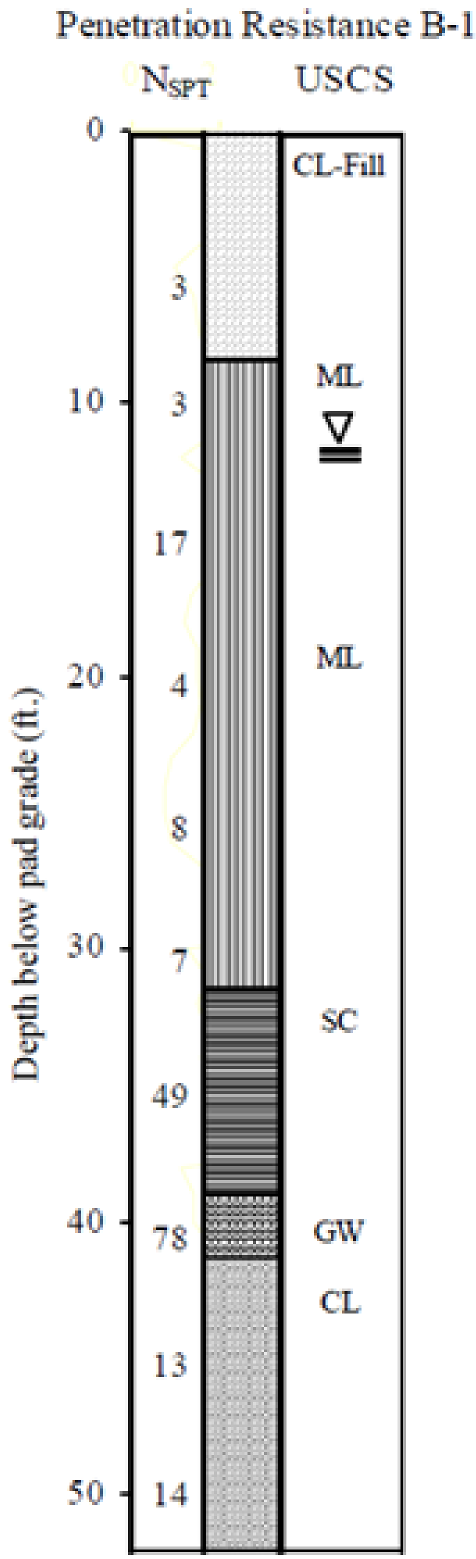


Figure 118. Geotechnical boring log for location B-1, downtown parking garage (Source: Jonathan Manke).

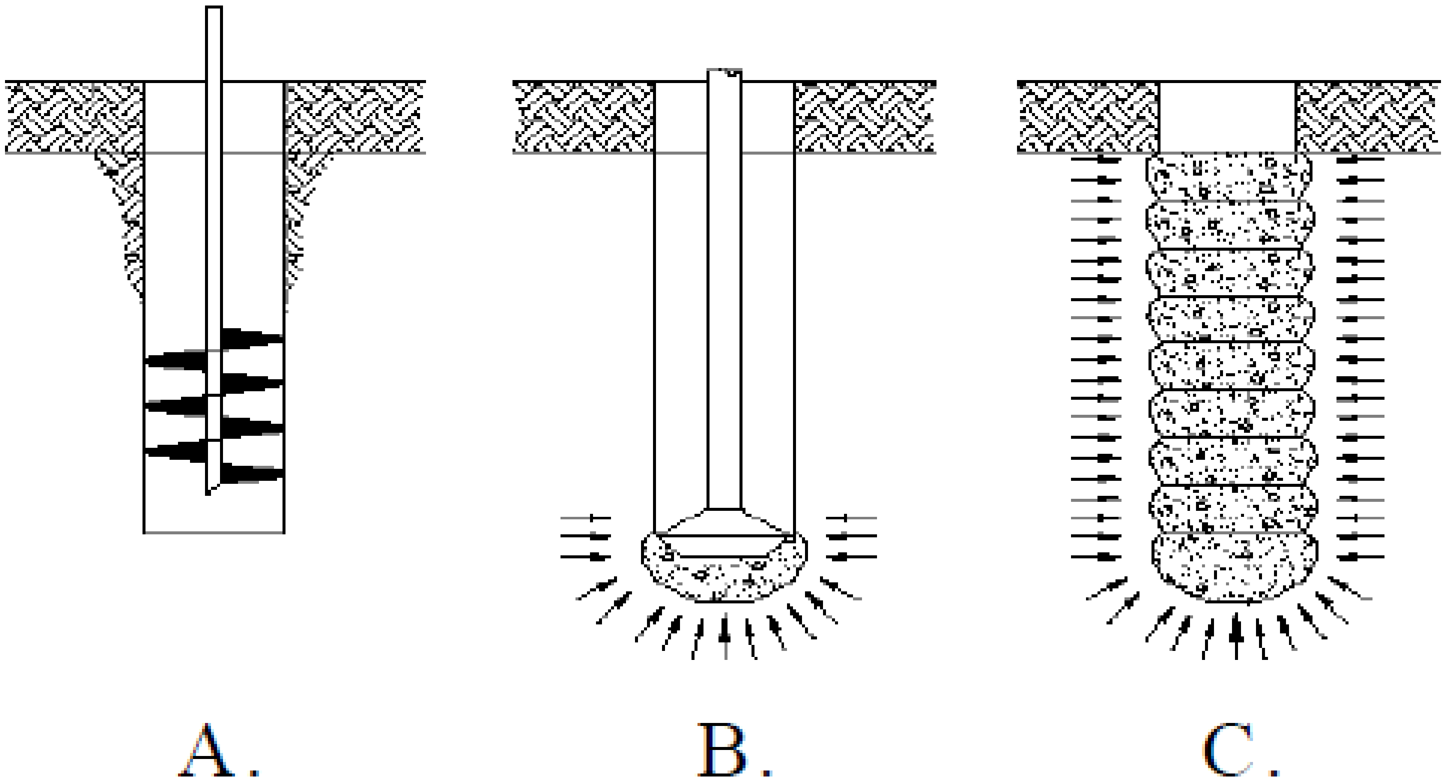


Figure 119. Geopier® RAP installation process (Source: Jonathan Manke).

The ramming equipment consists of 18-ton to 27-ton hydraulic excavators equipped with 2,000 to 4,000-pound hydraulic break hammers and specially modified tampers. The ramming action increases the lateral stress in the surrounding soil and increases the stiffness of the stabilized composite soil mass. The result of RAP installation is a significant strengthening and stiffening of subsurface soil, such that they are able to support high bearing capacity spread footings with minimal settlement.

The Sacramento parking garage utilized 76 cm diameter, drilled RAP elements only below the footings (Figure 119). The RAP elements extended to depths of 3.4 to 6.1 m below existing grade and reduced compressibility of the fill and alluvial soils such that a 335 kPa bearing pressure could be used and still achieve less than 3.8 cm of total settlement. Relative to the driven pile alternative, the Geopier method was more economical, faster, and minimized noise and vibrations to adjacent businesses.

Dams of the Sacramento Region

primary author: William A. (Bill) Fraser

Sacramento's location at the confluence of the American and Sacramento Rivers makes it a natural location for dam building, for consumptive water use, flood control, and power generation. In this section, several major dam projects in the immediate Sacramento region will be described from both an historic and engineering geology point of view.

Folsom Prison Dam

In 1867, the Natoma Water and Mining Company began construction on a dam along the American River 3.2 km upstream of the town of Folsom. The dam would divert a portion of the river flow into a conveyance channel, which would be used to float logs to a proposed sawmill in Folsom. As initial work began on the dam's foundation and a rail line along the channel alignment, the contractor entered into an agreement with the State to provide convict labor to construct the project in exchange for land to build a new State prison. After several disputes between the State and the Natoma Water and Mining Company, work on the dam and conveyance channel finally began in earnest in 1888 and was completed six years later in 1893. The revised labor agreement gave the prison the rights to some water from the project to generate power. As a result, a powerhouse was immediately constructed on prison grounds. Folsom Prison has the distinction of being the first prison in the nation to have electric lights.

Although the original intent of the project was logging, the project evolved to generate power in a new large powerhouse in Folsom. By 1895, the project water was used to generate 5000 kilowatts of electricity, which was transmitted to City of Sacramento some 35 km away. The distance made it one of the longest electrical transmissions of it time. The historic powerhouse itself has been completely restored as a State Park.

The dam was situated where the American River narrows between granitic outcrops on both sides of the river. It is constructed of granite block masonry, rises to 25 m high, and spans 260 m (Rice, 1910). An historic plan and cross sections can be viewed on page 183 of Rice (1910). The base width shown on that cross section appears to be approximately 18 m in length when measured horizontally along the rock line. The spillway is over the central portion of the dam. The 12 m wide by 2.4 m deep trapezoidal channel is located on the left side of the dam. The first 610 m of the conveyance channel is also made up of granite block walls, downstream to the prison powerhouse. The remaining 2,286 m leading to the Folsom Powerhouse is in rock-block-lined excavation, and further downstream, a cut and fill section, with riprap providing erosion protection between the channel and river.

Much of the Folsom Prison Dam across the American River was removed during construction of the Folsom Dam in the 1950s. Remnants of the left abutment and conveyance channel control structure and channel are still visible today (Figure 120).

North Fork Dam

The North Fork Dam (which retains Lake Clementine) lies along the North Fork of the American River near Auburn, CA. The dam was constructed in 1939 by the U.S. Army Corps of Engineers (USACE) primarily for sediment and debris control.

The story behind North Fork Dam truly begins 50 years earlier amongst a growing conflict between the hydraulic mining industry of the Sierra Nevada mountain range and the Sacramento Valley farming interests in the 1880s. Hydraulic mining was a major economic driver during this time, employing many Californians. However, the sediment generated by hydraulic mining was transported down river to the Sacramento Valley where it clogged river channels and resulted in widespread flooding and sediment deposition on farm land. California legislation was enacted in the 1880s that severely limited the hydraulic mining operations unless sediment from the operations could be controlled. The legislation also created the California Debris Commission to grant permits to those mining operations which could comply with the new law. The Commission also took a lead role in mitigating the damage done by the hydraulic mining industry.

In the years following the legislation, one proposal suggested the construction of large dams on major rivers to catch sediment and debris before it reached the valley. The wisdom and effectiveness of these debris control dams were debated for many years, but it took the hard-economic times of the Great Depression for the plan to finally gain approval. It was decided that the USACE would construct the dams and the hydraulic

Figure 120. Remnant of Folsom Prison Dam (Source: image courtesy of William A. Fraser).

mining industry would repay the government with a tax levied on the volume of debris collected (Hagwood, 1981).

Although the original vision included a system of dams, only two dams were ultimately constructed for this purpose: Englebright Dam east of Marysville and North Fork Dam near Auburn. North Fork Dam is a 42-m high thin concrete arch dam with a debris storage capacity of 19,880,000 m^3. The thin arch design had an economic advantage over a thicker concrete gravity section, but the arch dam needed to be carefully designed for the increased loads associated with the saturated debris. Because of its groundbreaking design within the 1930s, the dam was heavily instrumented with strain gages in order to monitor its performance under load.

Construction on the dam began in 1938 and completed in 1939. The initial work included a river diversion system with coffer dams both up and down stream. Removal of only 22,937 m^3 of weathered granitic rock was needed to prepare the foundation. Although the foundation rock was generally excellent, a zone of closer fracturing was encountered on the left abutment requiring an oversized foundation block as a result.

Ultimately, the dam never achieved its purpose. In 1940, mining activity was already on the decline in California and the California Debris Commission issued only a few permits for hydraulic mining. With the beginning of World War II in 1942, all mining was stopped nationwide to assist the war effort. After the war, the hydraulic industry never achieved its former importance due to changing economic and social culture. The North Fork Dam retains Lake Clementine a popular recreation lake today. In winter and spring, water spills over the top of North Fork Dam (Figure 121).

Folsom Dam

Unlike the San Francisco and Los Angeles areas, which established elaborate water systems very early on to augment their local water supplies, Sacramento could rely on abundant water supplies from the local rivers for consumptive use. However, the flood hazard presented by the American and Sacramento Rivers was a severe problem and in spite of significant early local efforts, a regional approach to flood control was ultimately needed. As the Sacramento region grew, the need for a large dam on the American River became apparent.

Folsom Dam was proposed by the USACE and was initially authorized as a 0.438 km^3 capacity flood control dam in 1944. The project was soon reauthorized in 1949 as a 1.233 km^3-capacity multipurpose dam to be part of the massive Central Valley Project

Figure 121. North Fork Dam (Source: image courtesy of William A. Fraser).

(CVP). The CVP services both the Sacramento and San Joaquin Valleys of California, and consists of 20 dams, 805 km of conveyance structures and 11 power plants. The CVP project provides not only flood control; but urban and agricultural water supply, power generation, recreation and environmental enhancement.

Folsom Dam was designed and constructed by the USACE. Construction began in 1948 and was completed in 1956. Upon completion, ownership of the dam was transferred to the U.S. Bureau of Reclamation (USBR). Three smaller dams were also constructed as part of the CVP locally: Nimbus Dam, an afterbay to Folsom Dam; Sly Park Dam in El Dorado County; and Sugar Pine Dam in Placer County.

Folsom Dam is on the American River about 32 km east of downtown Sacramento. The dam is situated in low granitic hills of the Sierra Nevada foothills, downstream of the confluence of all major forks of the American River. The main dam is a 104-m high concrete gravity dam with long earthfill wing dams either side. The reservoir is also retained by the Mormon Island Auxiliary Dam and a series of eight smaller dikes.

The concrete gravity section consists of twenty-eight 15 m long monoliths with a total crest length of 427 m (Figure 122). The crests of central monoliths 12 through 20 is the spillway section totaling 119.5 m long, controlled by eight approximately 15 m high radial gates. Monoliths 1 through 6 are imbedded within the Right-Wing Dam section and monoliths 22 through 28 are embedded within Left-Wing Dam section. The Right-Wing Dam is 2,043 m long and up to 59.4 m high. The Left-Wing Dam is 640 m long and up to 51 m high. The wing dams are zoned embankments founded on quartz diorite rock (Hall and others, 1989).

The concrete gravity section foundation is hard, fractured granodiorite to quartz diorite rock. Three roughly orthogonal joint sets, typical of granitic rock, were recognized which greatly control the patterns of weathering in the rock. Foundation excavations frequently encountered large, hard core stone underlain by weathered compressible rock (Kiersch, 1955). Four significant fault zones were recognized that were associated with breccia, gouge, clay and chlorite. Refer to Kiersch (1955) for a complete first-hand discussion of the site geology, subsurface investigations and construction geology aspects of the project during design and construction. Also, very comprehensive foundation conditions summary report was prepared by Sharp (1988) to support stability analysis.

Three significant dam safety-related issues have occurred during the operational life of the facility that merit discussion. In July of 1995, one of the eight radial gates failed suddenly as it was being opened, causing the uncontrolled reservoir release of 1,133 m^3/s through the spillway bay. The uncontrolled release was safely routed past the

Figure 122. Folsom Dam (Source: image courtesy of William A. Fraser).

Nimbus Dam and through the Lower American River without loss of life or property, however the incident resulted in the draining 40% of the capacity of the reservoir. The cause of the failure was found to be excessive friction on the gates trunnion rod and the incident is mentioned here because it underscores the need for better inspection and maintenance of spillway gates. While Folsom Dam is not under the jurisdiction of the California Division of Safety of Dams (DSOD), the incident caused the DSOD to train teams of climbers to access and inspect all radial gates statewide. Many similar programs have been initiated nationwide.

Mormon Island Auxiliary Dam

The Mormon Island Auxiliary Dam (MIAD) is a 32 m high, 1,470 m long zoned earthfill dam located on the southern side of the reservoir (Figure 123). The western portion of the dam, approximately 870 m in length, overlies metamorphic rocks consisting of weathered amphibolite schist. The eastern portion of the dam, approximately 600 feet in length, spans a topographic low which was once an ancient channel of the American River. Up to about 24 m of alluvium underlies the dam and much of it was mined for gold by dredges, essentially loosening and reworking the alluvium and often concentrating the finer grained fraction. To construct the dam, a narrow core trench was excavated down to the metamorphic bedrock.

The very thin core and inner filter zones were founded on bedrock, but the outer filters and shells zones of the dam were founded on dredge tailings. The dredge tailings are loose and fine enough to be liquefiable when saturated, and USBR concluded that the MIAD was seismically unstable in the early 1990s. Over the years, several *in-situ* methods were used at MIAD to densify the dredge tailings to resist liquefaction, including deep dynamic compaction, stone columns, and jet grouting. These attempts were largely unsuccessful. In 2009, USBR embarked a method of stabilization that they referred to as a “key-block” approach. This is a unique variation on a currently common method of embankment stabilization, which involves allowing foundation soils to liquefy but providing strong foundation elements to limit the resulting embankment deformation to acceptable levels. Secant pile walls arranged in a grid or cellular pattern is currently the most common method of providing the strong foundation elements for seismic stabilization.

As described by Malcolm Drilling Company (undated), USBR’s design called for the placement of a 274 m long by 16.7 m wide key-block at the downstream toe, to limit deformation of the downstream slope where underlain by dredge tailings. The key-block excavation would extend as deep as 24 m to a cleaned moderately weathered bedrock surface. The bottom of the key-block would be filled with several meters of lean

Figure 123. Left (eastern) portion of the Mormon Island Auxiliary Dam (Source: image courtesy of William A. Fraser).

concrete and the upper portion topped off with compacted granular fill. To avoid weakening the dam during construction, the 274 m long key-block would be constructed in 46 m cells allowing only two non-adjacent cells to be open at once. The cells needed to be entered by humans for foundation cleaning, mapping and other construction tasks, and so the temporary support system was elaborate. Essentially, a secant pile perimeter wall was constructed on all sides of the cell and five levels of shoring struts further braced the excavation. After placement of the key-block an additional buttress section designed to further limit deformation and improve post-earthquake performance was added to the dam.

Finally, even before Folsom Dam was fully completed, the dam was credited as saving Sacramento from severe flooding during the heavy rains of 1955. Ironically, this proved to be a bad omen as the dam originally thought to be designed to provide 250-year flood protection was determined to only offer 63-year flood protection after factoring in the heavy rains of 1964, 1986 and 1997. After this discovery the Sacramento region sought to improve its flood protection. Folsom Dam was designed with relatively small low-level outlets and large releases could not be made until the reservoir reached the spillway elevation or about 60% of capacity. One of the concepts evaluated to improve this situation was to enlarge the outlet capacity of the dam, but that solution was not favored.

The chosen remedy was a new spillway with a weir elevation 15 m lower than weir elevation of the main spillway (Figure 124). Work on the Auxiliary Spillway begun in 2008 and was completed in 2017. The site for the new spillway was just beyond the abutment of the Left-Wing Dam. The construction was phased so that the reservoir rim could be left in-place while construction of the control structure and downstream channel progressed, isolated from the reservoir. The control structure is essentially a concrete dam which provides the frame for six large submerged gates. The control structure foundation was built on slightly weathered to fresh granitic rock (Figure 125). The deeper portion of the foundation excavation was to remove poor rock associated with a wide shear zone which strikes up and downstream. A 914 m long downstream concrete lined channel with steep slopes was excavated and reinforced with rock bolts. An energy dissipation structure was provided where the new spillway channel meets the American River. The 335 m long approach channel upstream of the control structure would have required extensive underwater excavation. However, due to unusually low reservoir levels caused by a dry year, much of that work was able to be completed conventionally. At the end of construction, the remaining reservoir rim was removed,

Figure 124. Auxiliary spillway for Folsom Dam (Source: image courtesy of William A. Fraser).

Figure 125. Completed foundation excavation of the Folsom Auxiliary Spillway Control Structure looking downstream. The excavation achieved a slightly weathered to fresh granitic rock surface. The over-excavation in the center of the excavation was to remove poor rock associated with two parallel shear zones trending up and downstream. Workers are performing final cleanup prior to initial concrete placement. (Source: image courtesy of William A. Fraser).

allowing the reservoir to move against the completed control structure. The Auxiliary Spillway is now operational, and in conjunction with the existing facility, provides Sacramento with about 200-year flood protection.

Auburn Dam

A discussion of dams of the Sacramento region would not be complete without a discussion of the never-completed Auburn Dam. The 213 high and 1,219 m long double curvature thin arch dam was first authorized by Congress in 1964 and would have been located in the American River Canyon near the City of Auburn. The site was about 55 km northeast of Sacramento.

The multipurpose dam was designed and constructed by the USBR to be a part of the CVP. Construction begun in 1971, with work on the coffer dams, diversion tunnel, and foundation excavation, all progressing well through the early part of the decade. The foundation excavation was challenging, with talc zones in the metamorphic rock requiring excavation and replacement with concrete to depths approaching 30.5 m so that a uniform incompressible foundation could be achieved.

However, the construction effort soon ran into trouble through a string of unfortunate events. The first was the 1975 Magnitude M 5.7 Oroville Earthquake. Although the earthquake was some 72 km to the north, the discovery of surface rupture on a branch of the Foothills fault system suggested the entire fault system might not be inactive as previously believed.

In addition, it was suggested that the earthquake was triggered by the filling of Oroville Reservoir a few years earlier. Work slowed on the construction effort while the local and regional faulting were examined. Several consulting boards were convened by the major stakeholders to examine the emerging evidence and to provide advice on the implications to the thin arch dam. Although the evidence clearly indicated the Foothill fault system had generated earthquakes in the relatively recent geologic past, it was also clear the slip rate of these faults was low and therefore the time between earthquake events was very long.

The lack of young geologic deposits in the erosional terrain of the Sierra Nevada was a significant problem, and therefore displacements to paleo-B soil horizons and Late Tertiary volcanic units were used to recognize recent fault activity, due to the lack of younger geologic deposits in the erosional terrain of the Sierra Nevada. The practice of that day was to evaluate seismic hazards exclusively by deterministic methods, which does not consider slip rate or likelihood in the analysis. When presented with the same evidence, the consulting panels differed significantly in their expectation of future fault displacements. Estimates ranged from 0.025 m to 1 m depending on the methodology used. In the end, it was agreed that the design needed to accommodate 23 cm of displacement.

This displacement requirement would seem to be a fatal blow for the thin arch design, which was already breaking new ground because of its height and long crest length. By 1980, the USBR had developed a curved concrete gravity design which could use the prepared foundation and could accommodate the expected foundation displacement. However, the delay caused a shift in attitudes toward the wisdom of the already very expensive project, which was estimated to cost as much as 3 billion dollars in 1980. The project was scrutinized, but survived the Carter Administration of the late 1970s. With Ronald Reagan's presidential victory in 1981, new policies were enacted to reduce federal funding for water projects and increase cost sharing by local beneficiaries (Rogers, 2009). As a result, work beyond the foundation preparation would never occur.

Several attempts were made to restart the project throughout the 1980s without success. A very serious attempt was made in the 1990s when a flood control dam was proposed by the USACE at a new site downstream of the arch dam site. The proposal was for an "expandable flood control" dam, but Congressman John Doolittle, a local conservative supporter of multipurpose dams, would not support the flood control dam as it lessened the likelihood that a multipurpose dam would be built. The funding bill failed in the House due to the lack of support from the local congressman and other fiscally conservative congressmen.

The final blow occurred when, after many years of project inactivity, the California State Water Resources Control Board revoked the federal water right to the 3.08 km3 (2.5 MAF) of water per year from the American River at Auburn. As a result, work beyond the foundation preparation would never occur. The river has been restored across the dam site and the foundation preparation remains visible today, accessible by a three-mile hike from the Cool, CA (Figure 126).

Levees and Levee Flood Control System

primary author: Meredith Beswick

Ever since Sacramento was settled in 1848, the city and surrounding areas have battled to control the rivers and streams that flow through the Sacramento Valley. The Sacramento River is the principal river of the Sacramento Valley, and is the largest river in California. Starting in the Klamath Mountains north of Redding, the river flows south before reaching the Sacramento–San Joaquin River Delta and San Francisco Bay. The city of Sacramento is situated southeast of the confluence of the American and Sacramento Rivers. The American River flows from the eastern Sierra Nevada mountain range before joining the Sacramento River in the west. The Feather River is the other major river system that feeds into the Sacramento River north of Sacramento.

Figure 126. Auburn dam site viewed from the upper left abutment. The right abutment excavation for the arch dam and spillway channel is still visible in the landscape. The river has been restored across the dam site (Source: image courtesy of William A. Fraser).

and contributes significantly to flood risks within the Sacramento Valley. Figure 9 in "Chapter III – Quaternary Geology" of this paper shows the Central Valley with the major rivers described above

Formation of Sacramento Valley Flood Control Management

Hydraulic mining was very effective at recovering large amounts of gold, but it generated massive volumes of sediment that flowed into the rivers and streams, causing aggradation that in some areas raised the river beds more than 12 m. This exacerbated an already limited flood control situation by reducing the flow capacity of the rivers that marginally contained the high-water flow events before hydraulic gold mining began. Detailed discussions of the impact that hydraulic mining had on California are provided in "Chapter VII – Natural Resources [Metal Mining] and Chapter VIII – Environmental Concerns [Mining]" of this paper.

To encourage settlement and agricultural land development in Sacramento and the surrounding areas, the New Swamp and Overflowed Land Act was enacted in 1861. The purpose of this act was to take advantage of the federal Arkansans Swamp Lands Act of 1850, which allowed states to sell these lands to "provide for the reclamation of swamp and overflowed and salt marsh and tide lands." In order to obtain land, this act required the owners or buyers of swamp land to provide the appointed commissioners of the act with a survey of their land and to submit a plan of reclamation/drainage and development (Newspaper article, "The New Swamp and Overflowed Land Act", CA Farmer and Journal of Useful Sciences, Volume 15, No 13, dated 5/24/1861). The majority of the early levees in the areas surrounding Sacramento were built as a result of this act. This led to the development of reclamation districts, many of which exist today and are now the responsible entity for maintenance and inspection of their respective levee systems.

One of the major impacts of the Swampland Act was that it caused a fragmented approach to flood control and led to 'levee wars'. The reclamation districts and swampland owners built-up their levees or dammed-up natural levee breaks to protect their land, diverting the natural flow of the river into the adjacent low-lying basins. This increased the discharge downriver, causing flooding in adjacent communities. The most notable levee war was over the Parks Dam, which cutoff flow through Butte Slough into Sutter Basin. The communities located downstream in the diverted waterway were flooded after it was built, and a contingency from this community subsequently blew it up during a high-water event. The dam was rebuilt but failed during another high-water event. The owners attempted to rebuild the dam a third time in 1876 but was halted after a judicial inquiry. Judge Philip Keyser ruled to prohibit any dam that endangered others and any major project that would redirect major rivers. This ruling is credited with putting an end to the levee wars (Allen and Singer 2008).

An extensive engineering study of the Mississippi River was released in 1861 by Andrew Humphreys and Henry Abbot of the USACE. The study concluded that the Mississippi River could be contained within its levees by implementing improvements to encourage river scour to remove sedimentation naturally. This study heavily influenced early levee improvements in the Sacramento region as it was the first and most extensive of its kind. Around the same time this study was released, William Green, editor for the Colusa Sun newspaper and a previous State representative, recognized that the Sacramento Valley rivers could not contain all the floodwaters and advocated for a bypass system that would allow the levees to overtop in specific locations and drain into the adjacent basins. His idea did not gain traction with the state and federal governments until 1894 when the Manson-Grunsky Report was published proposing a plan for a bypass system for the Sacramento Valley. The report on flood control of the Sacramento River was authored by Marsden, Manson, and C.E. Grunsky, who were consulting engineers to the commissioner of public works at the time (House Report No. 616 1916) (Allan and Singer, 2008).

The Harbors and Rivers Act of 1907 includes a provision for a detailed study and survey of the Sacramento River from its mouth to the Feather River. An earlier version of this Act from 1824, stated that the federal government had power over navigable waters, rather than states, and led to the USACE performing surveys of various waterways. The 1907 survey, led by Captain Thomas Jackson, identified that a section of the Sacramento riverbed 14 miles south of the city of Sacramento had lowered approximately two feet since an 1885-1896 survey conducted in the era of unrestricted hydraulic gold mining. However, Captain Jackson estimated that over 382,277,429 m^3 of fine sediment in the American and Feather rivers would eventually pass through the Sacramento River. The study recommended dredging the river to remove the sediment and improve navigation of the channel.

While performing the survey, Jackson witnessed the damage from the flood of March 1907 and wrote in his report to the Harbors and Rivers Act Board in Washington DC:

> “The great problem of the Sacramento River is its flood control. Improvement for navigation is of secondary importance, and no project for such improvement should be considered that will decrease the present flood capacity of the river or will interfere in the execution of a flood project.” (60th Congress Letter to Secretary of War, 1908)

Approximately three years after Jackson’s survey of the Sacramento River, he released a flood control plan largely based on the Manson-Grusky report, which is known as the Jackson Plan. The plan proposed weir-bypass systems for large flows and included a plan for enlarging the systems. This was largely based on the 1907 surveys of the Sacramento Valley rivers that had an estimated flow capacity of 7,100 m^3 per second, but the 1906 in 1908 floods were estimated at over 17,000 m^3 per second. The

California State Legislature adopted the plan as the “Sacramento Flood Control Project” and formed The Reclamation Board, referred to today as the Central Valley Flood Protection Board. Under this Act, The Reclamation Board was “to regulate levees and other encroachments, and to review and approve flood control plans for the Sacramento River and its tributaries. The state’s adoption of a valley-wide flood management plan was intended to create a unified plan of flood control and to reclaim lands from overflow” (CA Legislative Information, Water Code Div. 6 Part 6, Ch. 2 Approved Projects, Article 2, 12645). The Reclamation Board united the reclamation districts and orchestrated their operation based upon a unified plan. Six years later, in 1917, the Sacramento Flood Control Project was implemented at the federal level, allowing federal funding. This was the start of an integrated approach of major flood control projects – dams, levees, weirs, and bypasses within the Sacramento region. Figure 101 shows the Greater Sacramento Flood control system as it stands today, and Figure 127 shows the levee areas that were investigated under the recent 5-year long Urban and Non-Urban levee evaluation program let by DWR (DWR, 2018),

Understanding Geologic Impact and High Water Event Occurrences on Sacramento Levees

Understanding local geomorphic processes is critical to proper characterization of levee subsurface stratigraphy and soil properties beneath levees and identification of appropriate levee improvement methods. Geomorphic processes in the vicinity of the Sacramento River, American River and their tributaries generates sediment from multiple depositional processes. A few of the key Recent and Holocene geomorphic features and deposits that are critical to levee improvement include:

- Overbank deposits: A deposit of typically fine-grained sediment from when water overtops the river and stream’s natural banks and/or levees
- Abandoned channels: A former river or stream channel that was cut off from the rest of the main active channel and typically lacks yearlong standing water. Abandoned channels commonly are filled in with fine grained flood deposits over time.
- Crevasse Splay: Forms when the natural levee breaks causing deposition of sediment similar to an alluvial fan deposit. These are generally graded with the coarser material at the bottom and nearest to the break and the finer sediment positioned near the top and furthest from the break.

The most recent geomorphology maps of the Sacramento region were created as part of the California Department of Water Resources Levee Evaluation Program by Fugro - William Lettis and Associates, Inc. (DWR-LEP). Within Sacramento County, these maps show alluvial deposits relative to the active river channels of the American and Sacramento Rivers, the Natomas Basin, the streams to the east of the Natomas Basin,

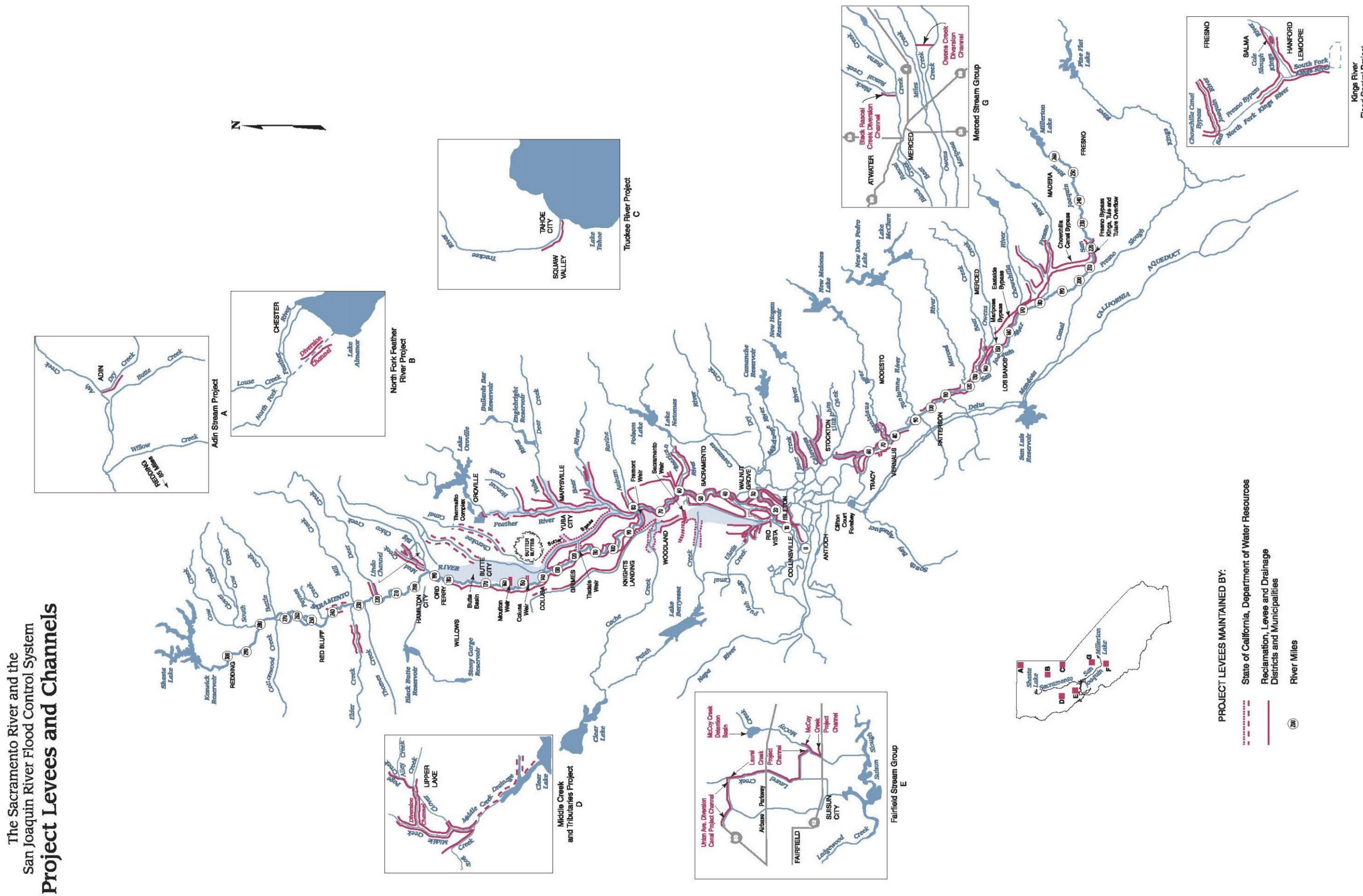


Figure 127. Map of levees investigated under the DWR Urban and Non-Urban Levee Evaluation Program (DWR 2018).

and streams in south Sacramento. Undifferentiated Holocene alluvial deposits, characterized as unconsolidated sand, silt, and minor lenses of gravel, are generally mapped to a distance of 0.8 to 3.2 km from both levees of the American River and the east levee of the Sacramento River that borders Sacramento County. These deposits are overlain by both Recent and Holocene crevasse splay deposits consisting of fine to coarse sand with silt, and overbank deposits consisting of sand, silt, and clay. Recognizing the potential for the presence of crevasse splay deposits is significant in understanding levee performance, as these deposits can form localized conduits for seepage beneath levees.

Intermittent exposures of the Pleistocene Riverbank Formation are mapped within these younger alluvial deposits. This formation becomes more continuous and laterally extensive with distance away from the active channels. The Riverbank Formation is characterized as semi- to consolidated gravel, sand, silt, and clay that tends to be indurated and strongly cemented and is referred to locally as hardpan. "Chapter III – Quaternary Geology" of this paper provides additional detail related to the historical channels of the American and Sacramento Rivers and their tributaries. Understanding the relative placement and extent of all the types of deposits discussed is critical to understanding the performance of Sacramento's levees and choosing compatible levee improvements where needed.

In addition to being situated in an alluvial basin, the Sacramento Valley watershed is subjected to cold and warm winter storms generally in the late and early part of the year (typically December through April). Cold storms can cause high rainfall in the valley and snow as low as 300 m elevation in the Sierra Nevada foothills with many meters of snow at higher elevations. Warm storms, referred to as the "Pineapple Express" or "atmospheric river" by the National Oceanic and Atmospheric Administration, bring warm rain to both low and high elevations and can be particularly devastating. These weather conditions are created by increasing moisture in the atmosphere from the tropical Pacific Ocean, combined with strong winds that blow the concentrated, warm moisture towards California along a relatively narrow area. The warm storms typically bring heavy rainfall in the valley as well as warm temperatures and rainfall on snow at high elevations, resulting in rapid snow melt. The intense rain compounded by intense snow melt runoff and aggraded rivers from historic hydraulic mining have led to many of the high flood water events throughout Sacramento's history. This was the case in December 1955, when California experienced 24-hour rainfall of approximately 0.4 m and Sacramento Valley rivers saw near-record flows. The toll on Sutter County was particularly severe. At 12:04 am on December 24, 1955, the levee broke at Shanghai Bend on the West Bank of the Feather River resulting in a wall of water approximately 6.4 m high surging through the area of Yuba City, flooding the city and farmlands to the south. The flood resulted in 38 deaths. Historic high water and flood events are discussed in more detail in “Chapter IX – Natural Hazards [Flooding in the Sacramento Region]” of this paper.

Historical Levee Construction and River Modification Methods

Prior to 1911, levees were built and maintained locally, and levees were constructed using whatever easily accessible soil was available, which was placed without proper compaction methods, typically along the existing banks of the waterway. Multiple techniques were used by USACE in the 1900s to improve the Sacramento and American river capacities. Levees were a key component of the USACE strategy that usually placed them close to the river bank to encourage the river to naturally scour the accumulated sediment. Three of the most common levee construction methods included (Allen and Singer 2008):

- Suction Dredging: A trench was excavated along the banks of the river with the removed material used to form low berms on either side of the trench. Sediment from the bottom of the river was vacuumed with a dredge and placed within the trenches to the top of the berms. After the soil had drained, the berms were pushed up against the dredged soil to form the levee. Figure 128 shows a photograph of a suction dredge operation.

- Clam-Shell Dredging: A crane on a barge would be used to dredge sediment from the river bottom a using a clam-shell bucket and place it on the banks of the river to the rough dimension of the levee. This technique led to the formation of waterside borrow trenches that could sometimes penetrate through fine-grained blanket layers and expose underlying shallow aquifer layers, which exposed the levee to under-seepage problems. Figure 129 shows a photograph of a clam-shell barge.

- Wing Dams: Pilings were driven into the sides of the riverbed and filled with rock, creating a wingwall on either side of the river channel. This narrowed the channel flow and increase scour downstream to move sediment.

Modern Levee Improvement Methods

Today, dredging is still used in parts of Northern California to maintain the depth of navigable channels. However, levee design and improvement methods have evolved as levee performance is studied after each high-water event. Local levee engineers have identified issues that have the potential to affect levee performance. These issues are defined in the USACE Engineering Manual for Design and Construction of Levees (Engineers Manual 1110-2-1913) as freeboard deficiency, through-seepage, under-seepage, slope stability, and erosion. Below are some techniques that are commonly implemented locally for each of these issues:

Figure 128. Suction dredge. Discharge is along right hand side of photograph. (Source – California Department of Water Resources).

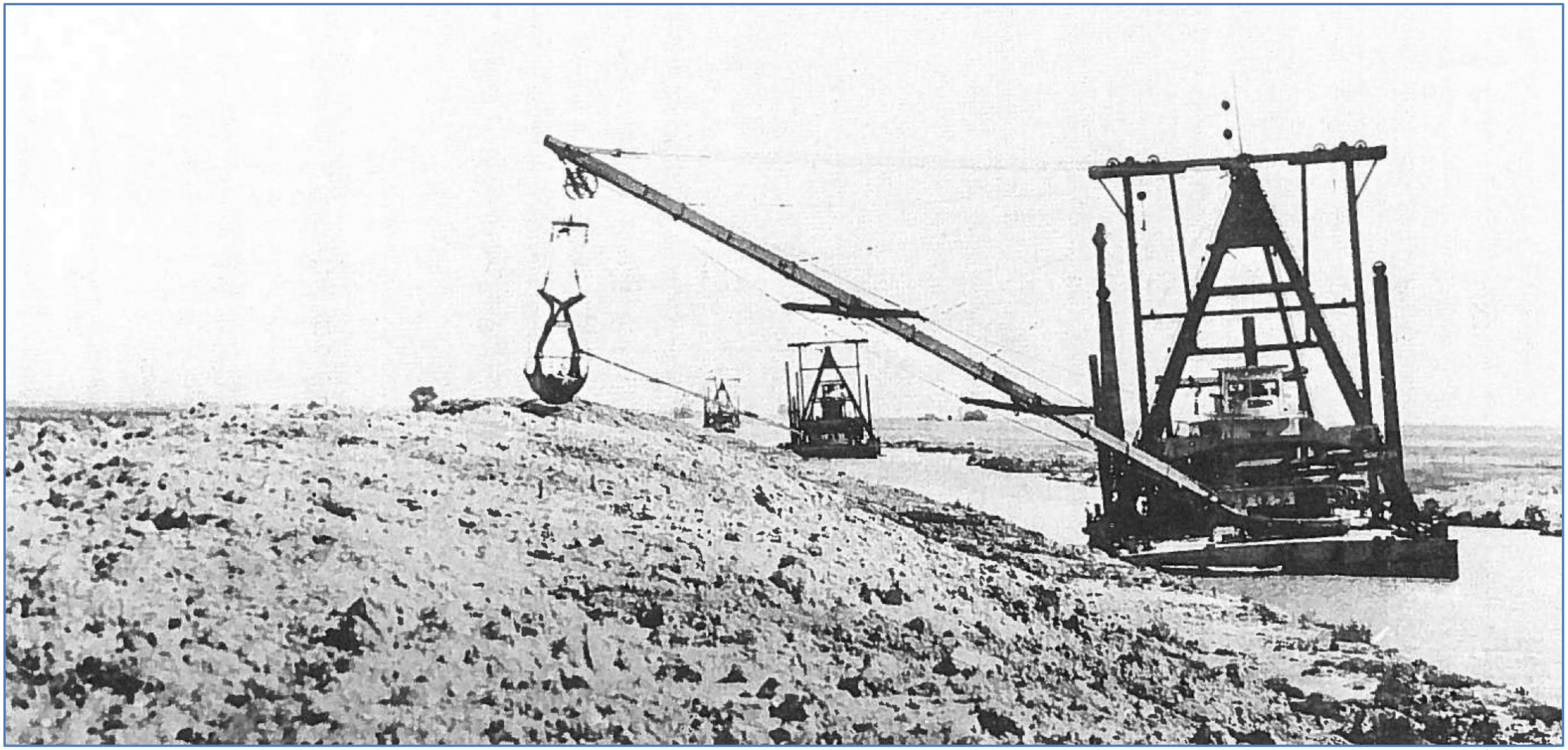


Figure 129. Clam shell dredge. Long-boom dredges constructing the east levee of the Sutter bypass (1920). The dredges progressed at a rate of about 27 m/day, ultimately emplacing 100 yd^3 of spoil per linear foot of levee. The view shows *Lisbon* (4.75 yd^3, 160-ft boom), *Gabilan* (3 yd^3, 182-ft boom), *Argyle* (4.75 yd^3, 158-ft boom), and an unidentified dredge in the rear. (Source – California Department of Water Resources).

1. Freeboard deficiency: water overtopping the levee

    a. Increase the levee height through raising with engineered fill or by adding a floodwall

2. Through-seepage: Water moving through a levee embankment that can cause internal erosion or piping of soils and lead to a levee breach.

    a. Stability Berm: Landside berm sized to enhance levee stability. A drain may be added at the interface between the berm and landside levee face at the base of the berm to improve drainage and stability. Such a berm is referred to as a drained stability berm.

    b. Seepage Cutoff Wall: Seepage cutoff walls are impermeable barriers installed through the center of the levee, typically, to prevent flow through the levee. In the Sacramento Valley, the impermeable barrier element is usually a soil bentonite cutoff wall 0.6 to 0.9 m wide and installed using conventional trench excavation techniques

       These seepage cutoff walls are typically constructed by soil excavated from the trench with bentonite to create a homogeneous, low permeability (hydraulic conductivity of 1 x 10^{-6} cm/sec or less) soil bentonite material. This material is used to backfill the trench to form the seepage barrier. Sometimes cement is also added to the soil bentonite mixture to give the material some nominal compressive strength. Cutoff walls are a common levee improvement method in the Sacramento region since the areas immediately adjacent to the levees are frequently developed and the room required to construct a stability berm may not be available.

3. Under-seepage: Water moving beneath a levee embankment that can cause erosion or piping of soils and lead to the collapse of the levee and a breach.

    a. Relief Wells: installed near the landside levee toe. These wells extend through the fine-grained blanket layer into an underlying permeable layer and relieve pressure beneath the blanket layer

    b. Seepage Cutoff Wall: As discussed above, a seepage cutoff wall can be used for through-seepage but can also be used for under-seepage as well. The cutoff wall is used to ‘cutoff’ more permeable layers such as sands, gravels, and cobbles, by passing through the permeable layers and keying into a fine-grained layer beneath. The cutoff wall creates a barrier to seepage beneath the levee reducing hydrostatic pressure at the levee toe. Cutoff walls can be installed to depths of approximately 24 m using conventional open trench excavation methods and to approximately 40 m using specialized equipment and in-place mixing techniques.

c. Seepage Berm: A seepage berm is typically a fine-grained layer of engineered soil, placed along the landside levee toe. Typically, local practice is that the berms have a minimum thickness of 5 feet at the landside levee toe and a width of four times the levee height with a maximum width of about 91 m. The seepage berm increases the thickness of the existing blanket layer which assists to counter the seepage uplift forces, and extends the length of the seepage path, which dissipates seepage pressure. A drainage layer may also be constructed at the base of the seepage berms.

4. Slope Stability

    a. Stability berms: As described in item 4 above, a berm is constructed on the landside of the levee to buttress and stabilize the slope.

    b. Slope flattening: The levee slope may also be flattened to increase stability.

5. Erosion

    a. Reinforced waterside slopes: vegetated mats, reinforced bank restoration, riprap, and similar erosion control systems are placed along the waterside slopes or riverbank to decrease the potential for erosion.

Major Levee Improvement Projects

It is important to note that the levees in the Sacramento region were not constructed to any engineering design standard and many kilometers of levees were built using uncontrolled fill by local landowners and farmers. No lateral spreading or earthquake induced land sliding has been observed in the levees near Sacramento. Although several levees have been breached due to heavy rainfall and resulted in localized flooding of islands, including farms in the Sacramento-San Joaquin Delta.

Natomas Levee Improvement Project

The Natomas Basin is located north of Sacramento and is bounded by 67 km of levees along the Sacramento River to the west, the Natomas Cross Canal to the north, the Pleasant Grove Creek Canal and Natomas East Main Drainage Canal to the east, and the Sacramento and American River confluence to the south. The basin is heavily developed, with 2,914 ha of the basin lying within the incorporated area of the city. The majority of that land has been developed for residential, commercial, and industrial purposes. The Sacramento International Airport, and portions of three major freeways, state highways, and rail lines also lie within the basin. In 2008, after an evaluation performed by USACE, it was determined the Natomas Basin levees did not meet Federal Emergency Management Agency (FEMA) 100-year flood certification criteria. As a result of this evaluation, FEMA decertified the levees, which led to a building moratorium within the basin and required all residents with federally backed loans to pay flood insurance.

The Sacramento Area Flood Control Agency (SAFCA) was formed in 1989 as a result, which expedited a levee rehabilitation investigation and construction of levee improvements for a 200-year level of flood protection It was imperative that 50 percent of the levees surrounding the basin were improved by 2010 to ensure that the basin could be remapped as an A99 zone by FEMA. In order to lift the building moratorium, SAFCA coordinated a multidisciplinary team of engineers, biologists, hydrologists, and geologists in collaboration with USACE, Reclamation District 1000, American River Flood Control District, City and County of Sacramento, and the Central Valley Flood Protection Board to achieve this goal. Constructed improvements included seepage cutoff walls, seepage berms, stability berms, and adjacent levees (SAFCA).

California Department of Water Resources Levee Evaluation Program (DWR Urban and Non-Urban Levee Evaluation Projects)

In 2006, the California Department of Water Resources (DWR) initiated a Levee Evaluation Program, which was a very intensive geotechnical investigation including over 3,058 km of levees. The program was divided into two projects, the Urban Levee Evaluation (ULE) Program and the Non-Urban Levee Evaluation (NULE) Program. ULE included approximately 531 km of State Plan of Flood Control (SPFC) levees and approximately 145 km of appurtenant (protecting the same basin) non-SPFC levees that protected areas with populations exceeding 10,000 people. NULE included 1,963 km of SPFC levees and approximately 452 km of appurtenant non-SPFC levees in the Central Valley in areas of populations of less than 10,000 (DWR, 2018). Both projects represented an unprecedented level of study in terms of the level of investigation, including extensive subsurface investigation and laboratory testing, geomorphic mapping, bathymetric studies, lidar surveys, helicopter electromagnetic surveys and geophysical surveys. The projects not only enriched our understanding of the potential performance of levees in the Central Valley, but has also been a major contribution to the profession of levee investigation and characterization. As part of the study, a Guidance Document for Geotechnical Analyses was developed under the direction of URS Corporation on behalf of DWR. The Guidance Document provides a set of protocols and criteria for performing geotechnical analysis for levees, including:

- Freeboard analysis
- Erosion evaluation
- Seepage analyses (under-seepage and through-seepage)
- Slope Stability analyses (landside steady-state, landside rapid loading and waterside rapid drawdown)
- Seismic vulnerability analyses (liquefaction potential and seismic slope stability)
- Remedial alternatives development and analyses and conceptual cost estimating.

All studies performed, and data collected for these projects are publicly available at the DWR levee evaluation program website (DWR, 2018).

Port of (West) Sacramento

primary author: Bob Anderson

West Sacramento is a separate city from Sacramento and is located to the west of Sacramento (Appendix A – Plate A). The port is connected to Suisun Bay via a 69 km long deep-water channel (the Sacramento River Deep Water Ship Channel) that has to be dredged to remain deep enough for shipping traffic. Some of the products shipped through the port include: rice, walnuts, almonds, corn, wood chips and timber, sand and gravel, cement, select minerals and oversized manufactured products. Construction on the port by the U.S. Army Corps of Engineers deep-water channel was started in 1949 and opened to traffic in 1963. The port is serviced by the Union Pacific and the Burlington Northern Santa Fe Railroads as well as by truck via Interstates 5 and 80 through connector roads. The port is one of two inland ports in California. The other is the Port of Stockton.

Ships at the port use lake Washington as a turning basin. The port is operated as a bulk commodity port and is not set up to take container traffic. Near West Sacramento, the port is flanked by levees. The levees may be prone to liquefaction as well as lateral spreading and landslides, although no such levee failures have been observed at the port. The reason for the potential problems is that the levees were not built to an engineering standard that accounted for seismic loading and that some of the soils beneath the levees may be a continuation of soils found underneath the Sacramento River as well as both Sacramento and West Sacramento (soils varying from young alluvium and fluvium as marsh deposits and peat). Here, the static factor of safety of the levees has not been determined. However, with changes in loading by the velocity of water and depth of waters the levees stability may be somewhat variable. So far, the levees have not been breached.

The main issue with the Sacramento River Deep Water Channel is that it must be periodically dredged to maintain it depth of 9 meters for deep draft sea traffic. The dredging causes problems with water clarity and siltation. This could result in a loss of Delta smelt critical habitat, and place additional stress on winter run salmon. The USACE started deepening the channel to -10.7 m below the mean lower low water level (MLLW) in 1990, but the project was suspended due to lack of funding. (USACE, 2011).

There is a current proposal to deepen the channel to a depth of 10.7 m MWWL, finishing up the work started in 1990. This would allow many more ships to come to the Port. The study has been underway for over five years and may be one of the next major developments for the channel.

XI. IN CLOSING

Sacramento has a unique geologic and geographic setting that drove growth of the region. The confluence of the American and Sacramento rivers was an ideal place in the mid-1800s to establish a bridge head for supporting gold mining in the Sierras and travel between the eastern United States and the west coast. Early in the history of the city, the San Pablo Bay, San Francisco Bay, Sacramento/San Joaquin Delta, in combination with the Sacramento River, provided access to the city from San Francisco. This access by ship allowed easy access to men and materials from around the world to Sacramento and the mines of the Mother Lode. It also served as the western terminus of the transcontinental railroad, the California Trail, and the Pony Express. Sacramento was also on the Siskiyou trail into Oregon. The city's association with so many transportation routes made the city a major transportation center in California. This association with transportation continues today with an in-land sea port, a large railyard, an international airport, as well as and four major highways crossing Sacramento.

Sacramento area regional geology varies quite a bit from West to East. Deep alluvial deposits are found to the west with scattered natural gas fields. The city of Sacramento partially over lies a buried canyon, making the depth of bedrock deeper than other portions of the surrounding valley. In the east, however, the Sierra Nevada mountain range starts, with an abrupt change in the depth to bedrock between Sacramento and Roseville, where the Rocklin Pluton is encountered at the surface. Further east, between Folsom and Auburn, lies the western portion of the Foothills fault system, The Melones fault, a major feature of the system is associated with the emplacement of gold in the Mother Lode. The Foothills fault system is comprised of two major faults, the Melones fault to the east and the Bear Mountains fault to the west, as well as a host of smaller faults in a shear zone. Together, these faults and the shear zone make up the Foothills Fault Zone. The Bear Mountains fault is also associated with gold, chromium, and copper deposits.

Erosion of the Sierra Nevada by surface runoff into the Central Valley has resulted in the formation of extensive aggregate and clay deposits. Mining of aggregate, clay, gold and other economic mineral deposits has generated billions of dollars in revenue and created thousands of jobs over the past 170 years, altering both the physical and economic landscape of Sacramento region.

One extraction method, hydraulic mining, used during the early years of gold mining in California had significant and far reaching environmental impacts that created major problems with river traffic and left Sacramento more prone to flooding due to the elevation of stream beds. Placer mining resulted in large fields of dredge tailings that had to be accounted for during planning and construction activities and 150 years after their creation they still impact construction projects in the Sacramento region. The principal material mined now is sand and gravel.

The Melones fault, the Bear Mountains fault and most related faults are not considered to be active by the state's definition, or their activity has not been determined. Nevertheless, the faults near Sacramento are still accounted for in local probabilistic seismic hazard assessments for structures in the area when appropriate.

The most prominent natural hazard is flooding. During the Quaternary and Tertiary periods Sacramento was periodically inundated as part of an inland sea. Sacramento had been flooded numerous times in the past. Much of Sacramento and its suburbs lie in the floodplains of the Sacramento and American Rivers, which periodically overflow their banks. Protection of these areas has led to the development of thousands of miles of levees and the installation of weirs that divert waters to designated flood areas northwest of the central business district. The flood designated areas are generally used for agriculture or wildlife refuges.

The construction of levees started shortly after Sacramento was founded, and the monitoring and maintenance of the levee system throughout the Sacramento/San Joaquin Delta is a large-scale infrastructure project that costs tens-of-millions of dollars per year. The levees range in age and make up. The original levees were not built to any engineering standards, and in some cases on soils with a high-water table. Soils in the region near the rivers or delta include peaty soils that may result in unstable foundations for levees. Maintenance of the levees was left up to either large organizations or to local levee districts with little or no funding for maintenance. Today, levees are maintained according to need and availability of funding. The establishment and, in some cases, the reevaluation of flood zones has helped control local development.

Environmental problems vary throughout the region and include legacy problems from several sites, such as closed and/or abandoned mining operations, closed military, manufacturing, and industrial facilities, and waste disposal sites. Many of these sites have been characterized and, in some cases, are undergoing remediation. Brownfield development is common and continues in several areas near the Central Business District where land is scarce and expensive. Two of the closed air force bases have been, in part, repurposed as manufacturing and business parks, and the airfields are being used for commercial air freight and tactical air support for wildfire operations.

It is not uncommon for residents to commute as far as the San Francisco Bay Area to work, since housing is much less expensive in the Sacramento region. This has led to major improvements in infrastructure, with the construction and redevelopment of several hospitals in the Central Business District and the Roseville/Rocklin Area, the expansion of the downtown wastewater treatment plant, and the improvement of several roads and interchanges. Initial funding has been partially secured for a major offsite reservoir (Sites reservoir) northeast of Sacramento. In addition, several high technology companies in the fields of robotics manufacturing, genetics, information technology, and computer development/manufacturing have established facilities, brining high paying jobs and expansion for the region’s tax base. Overall, the Sacramento Metropolitan Region has a bright future. The region has room to grow and expansion is still underway in the suburbs, especially to the north, east, and south.

XII. ACKNOWLEDGEMENTS

All the authors would like to acknowledge the following people for their assistance in the preparation of this paper. As with any large paper it is easy to omit someone and for that we are sorry. Any errors are owned by Robert Anderson and Garry Maurath.

Name	Affiliation
Julie Anderson	Family support
Greg Bartow	California State Parks
George Bromm	Collections manager, SCNHM
Tina Campbell	Paleontologist
Kerry Cato	AEG Foundation – President
John Clinkenbeard	California Geological Survey
Chad Coleman	Coleman Engineering
Dawn Collings	Shields librarian, UC Davis
Bruce C. Cooper	Central Pacific Railroad
Debbie Davidson	California Geological Survey – librarian
Travis David	California Energy Commission
Jean DeMouthe	Geology collections manager, CAS
AEG Foundation	AEG Foundation
Ricardo Goñi	Commercial photographer
Mark Goodwin	Assistant Director, UCMP
Jim Hafferty	Photographer

Brian Hausback	CSU Sacramento
Greg Hempen	AEG – President
Austin Hendy	Curator, LACMIP
Kristin Hilton	Editing
Stuart Hoffman	Starr Publishing
Don Hoirup	California Department of Water Resources
Pete Holland	California Geological Survey
Kathy Hollis	Collections Manager, USNM
Patricia Holroyd	Museum scientist (Vertebrate Collections), UCMP
Gene Hunt	Curator of Ostracoda, USNM
Kyle Johnson	Fugro
Amy Loseth	California Geological Survey – librarian
Paul Marshall	California Energy Commission
Lesa Maurath	Family support
Pam Maurath	Newleaf Strategies – President
Samuel A. McLeod	Collections manager, vertebrate collections, LACM
John Murphy	AEG - Chair - Sacramento Section
Claire Phillips	Park interpretative specialist, California State Railroad
Eilanna Price	USAF retired
Gabe Roark	California Energy Commission
Terry Rose	California Energy Commission
Abdul Shakoor	Editor of EG&E
Peter Spencer	Sierra College – librarian
Bob Sydnor	Consulting Geologist
Fui Thong	California Energy Commission
The Union	Newspaper serving western Nevada County
Hough Wagner	Paleontologist
Xiaoming Want	Curator of vertebrate paleontology, LACM
Chris Wills	California Geological Survey (retired)
Kyle K. Wyatt	Railroad history and museum consultant

Also, this publication would not have been possible without the assistance the following great group of talented individuals who volunteered their time as peer reviewers.

Karim Abulaban	California Energy Commission
Byron Anderson	Kleinfelder

Kartik Atyam	AECOM
Rich Boyd	Division of Oil, Gas, and Geothermal Resources
Rachael Cartwright	California State University, Chico
Lisa DeCarlo	California Energy Commission
Chris Dennis	California Energy Commission
Bob Dundas	California State University, Fresno
Horacio Ferriz	California State University, Stanislaus
Dan Gamon	California Department of Water Resources
Chris Higgins	California Geological Survey
Caryn Holmes	California Energy Commission
Sarah Hoover	Professor, Clackamas Community College
Mike Hughes	AECOM
Phil Kinney	Apex Companies, LLC
Joseph Krupansky	Former series editor
Michael Lohnash	Consultant, English grammar and style review
Dick McCarthy	California Seismic Safety Commission
Bill Motzer	Todd Groundwater
Eilanna Price	USAF retired
Rob Schumann	Kleinfelder
Tim Smith	California Energy Commission
Scott Sochar	California DWR
Eddy Teasdale	Luhdorff and Scalmanini Consulting
Ellie Townsend-Hough	California Energy Commission (retired)
Mike Turner	AECOM
Tim Williams	Kleinfelder
Kyle K. Wyatt	Railroad history and museum consultant

XIII. ABOUT THE AUTHORS

Robert Anderson is a Senior Engineering Geologist at the Alfred E. Alquist Seismic Safety Commission in Sacramento, California. Mr. Anderson is a Professional Geologist and a Certified Engineering Geologist in California. He holds a B.A. in Geology from California State University, Sacramento and an M.S. in Homeland Security from San Diego State University. He has investigated earthquakes in California, Nevada, Washington, and Virginia as well as in several countries. He is the co-editor along with Dr. Horacio Ferriz for the volumes *Applied Geology in California* and *Engineering Practice in Northern California.* Contact Bob at: Bobanderson816@gmail.com

Michael Anderson is the State Climatologist for California, a collaborative position between the State and the National Oceanographic and Atmospheric Administration to provide climate data services. He is a registered Civil Engineer working for the California Department of Water Resources. Michael began working in the Department of Water Resources Division of Flood Management (DWR-DFM) Forecasting Section in July 2005. He came to DWR after extensive graduate and post-graduate work at U.C. Davis in hydroclimate system modeling, monitoring, and evaluation. He received his Ph.D. in 1998 and M.S. in 1993 in Civil and Environmental Engineering from UC Davis. He received his Bachelor's degree in Civil Engineering from Colorado State University in 1991. Contact Mike at: Michael.L.Anderson@water.ca.gov.

Tom Barry is a licensed Professional Geologist, a Certified Hydrogeologist, and a Certified Engineering Geologist in California. Mr. Barry is employed at the Division of Oil, Gas, and Geothermal Resources Headquarters Underground Injection Control Unit in Sacramento. He holds a B.A. in Geology from San Francisco State University and an M.S. in Geology from San Jose State University. He is a former member of the California State Mining and Geology Board, a past chair of the San Francisco Section of AEG, and a past president of the Northern California Geological Society. Contact Tom at: thomas.barry@conservation.ca.gov

Meredith Beswick is a project level geological engineer for Kleinfelder in Sacramento, California. Ms. Beswick is a Professional Geologist and a Professional Engineer in California. She holds a B.S. in Geological Engineering from Colorado School of Mines in Golden, Colorado. She has been involved with the investigation, analysis, and construction of multiple Sacramento area levee projects including the Natomas Basin and the Department of Water Resources Urban and Non-Urban Levee Evaluation Projects. She was the Sacramento Association of Environmental and Engineering Geologist's (AEG) Chair from 2015-2018 and the current United States Society on Dams (USSD) Levee Committee Young Professional Vice-Chair. Contact Meredith at: Mbeswick@kleinfelder.com

Chris Bonds is a Senior Engineering Geologist with the California Department of Water Resources (DWR) in Sacramento. Since 2001, he has been involved in wide ranging DWR projects including exploration, monitoring, modeling, policy, research, and water transfers throughout the state. He has over 25 years of geology and groundwater experience with private consulting and public service in California, Alaska, and Hawaii and is a licensed Professional Geologist and Certified Hydrogeologist in California. Chris received a B.S. in Geology from California State University, Northridge and a M.S. in Geology from California State University, Los Angeles. Contact Chris at: Chris.Bonds@water.ca.gov

Mike Conway is an Engineering Geologist at the California Energy Commission. He holds a B.S. in Geology from University of California, Davis and a M.S. in Geology from California State University, Sacramento. He is a licensed Professional Geologist and a Certified Hydrogeologist in California. His career focus is water resource evaluation and analysis. Contact Mike at: mike.conway@energy.ca.gov

Christopher Dennis is a licensed Professional Geologist and Certified Hydrogeologist with the State of California, and a California Qualified Stormwater Developer. Mr. Dennis has over 26 years of professional technical and management experience. Fifteen of those years, he worked in private industry as a consultant and for the last 11 years, he has worked in the California Energy Commission as an Engineering Geologist. Mr. Dennis has been a consultant portfolio manager for several major oil companies and has been responsible for the evaluation and assessment of geologic, hydrogeologic, and environmental conditions at facilities throughout California. He holds a J.D. from Whittier Law School, Certificate in Dispute Resolution from Pepperdine Law School, and a B.S. in geological sciences. Contact Chris at: christopher.dennis@energy.ca.gov

William A. (Bill) Fraser has over 35 years of experience in the engineering geology related to dams. After initially working with the State Water Project, he retired in 2015 from the California Division of Safety of Dams after serving over 20 years as the Chief Geologist. In his career, he has been involved in over 200 dam projects in California. These projects include the new dams built in California over the past several decades, as well as numerous seismic reevaluations and subsequent seismic stabilizations. Most recently he temporarily came out of retirement to lead the geologic review of the Oroville Spillways Repair. He holds PG and CEG licenses in California. Contact Bill at: billf7281@comcast.net

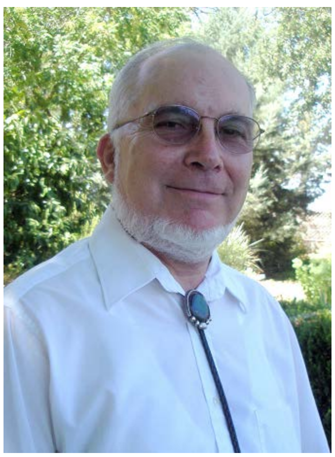
Fred Gius is a Senior Engineering Geologist with the California Geological Survey's Mineral Resources Program. He is a licensed Professional Geologist and a Certified Engineering Geologist in California. He holds a B.S. in Geology from California State University, Sacramento. He has experience evaluating mineral resources and mineral hazards; conducting geologic, geomorphic, and geotechnical investigations of flood control facilities; and participating on emergency response teams deployed on flood control, drought, and burn area response operations. Contact Fred at: fred.gius@conservation.ca.gov.

Jeffrey Hess, PG, CEM, is Chief Scientist with Gilbane Environmental. Mr. Hess is a Professional Geologist in Arizona, California, and Oregon, and a Certified Environmental Manager in Nevada. He holds a B.S. in Geology from California State University Sacramento, and a M.S. in Geology from Western Washington University. He has studied the origin, fate and transport, and remediation of metals and organic chemicals in the environment throughout his more than 30-year career. Among other publications, he is a contributing author to *Applied Geology in California* (2017) and *Mine Waste Management* (1992). Contact Jeff at: J.Hess@gilbaneco.com

Richard Hilton is a Professor of Geology and Paleontology at Sierra College in Rocklin California. He has taught geology at six other colleges and universities up and down California. His research emphasis is on the geology and paleontology of California and Nevada. He is a co-chair of the Sierra College Natural History Museum, and an emeritus board member of the Gateway Science Museum. He is on the geoscience board at California State University Chico. He has published numerous scientific articles in the field of vertebrate paleontology and a book entitled “Dinosaurs and Other Mesozoic Reptiles of California” published by the University of California Press. He has a Bachelor’s degree in Geology and a Master’s degree in Earth Science, both from CSU Chico. Contact Dick at: rhilton@sierracollege.edu

Jonathan Manke is the Area Manager of the Western United States for Geopier Foundation Company, Inc. in Davidson, North Carolina. Mr. Manke is a licensed civil and geotechnical engineer in California. He holds a B.S. degree in Civil Engineering from the University of Wisconsin-Milwaukee and a M.S. degree in Geotechnical Engineering from North Carolina State University. He has engineering licenses in 10 states and has evaluated ground improvement engineering solutions on hundreds of projects throughout the world. Contact John at: jmanke@geopier.com

Garry Maurath is an Engineering Geologist at the California Energy Commission. Dr. Maurath is a licensed Professional Geologist and a Certified Hydrogeologist in California. He holds a B.S. in Geology from Lehigh University, and an M.S. and Ph.D. in Geology from Kent State University. He spent more than 40 years in the private sector as a consultant before joining the Energy Commission in 2016, including 6 years in the US Army. He has been responsible for examining and evaluating geology, paleontology, hydrogeology, and environmental conditions for the planning, design, construction, maintenance, and/or clean-up of numerous facilities throughout the world. Contact Garry at: maurath.geol@gmail.com or garry.mauirath@energy.ca.gov



Eldridge M. Moores, B.S., Ph.D., D.Sc., is a Distinguished Professor Emeritus of Earth and Planetary Sciences, University of California, Davis, where he has been a faculty member since 1966. Moores's interests lie in tectonics of the Circumpacific and Alpine-Himalayan regions, structural geology, and primary-secondary education in and public awareness of Earth Science. His field experience has included work and/or geologic excursions in about 60 countries including all seven continents. Moores is relatively fluent, if rusty, in Modern Greek, German, and French, and can survive in Italian and Spanish. He is the author or co-author of over 130 publications, including two textbooks (with R. J. Twiss), entitled *Tectonics,* and *Structural Geology (2nd Ed),* and several monographs and popular books. Moores is prominently featured in *New* Yorker writer John McPhee's books *Assembling California* and *Annals of the Former World.* He was Editor of *Geology* from 1981-87, Science Editor of *GSA Today* from 1991-95, President of the Geological Society of America in 1996, and Vice President of the International Union of Geological Sciences from 2004-2008. He has received many awards for his professional work. Contact Eldridge at: emmoores@ucdavis.edu or eldridgemoores@gmail.com

Matt O’Neal is an Engineering Geologist at the California Geological Survey. He holds a B.S. in Geology from CSU Sacramento and is currently conducting thesis research to complete an M.S. in Geology from the same. In his six years at CGS, he has contributed to geologic mapping in the Sierra Nevada foothills and the Warner Range and surrounding areas, and to mineral resource and mineral hazard studies in the greater Sacramento region. His M.S. thesis fieldwork gets him up into the Sierra Nevada mountains to investigate two Oligocene age rhyolitic ignimbrites and to learn more about the Cenozoic development of the Sierra Nevada. Contact Matt at: matt.oneal@conservation.ca.gov

Kent E. Parrish is a Senior Associate Hydrogeologist at Wood Environment & Infrastructure Solutions, Inc. in Sacramento, California. He is a Professional Geologist in California and Arkansas and a Certified Hydrogeologist in California. Kent holds a B.S. in Geology from California State University, Sacramento (CSUS) and a M.S. in Geological Sciences from San Diego State University, California. Kent specializes in active mine reclamation, abandoned mine lands characterization and cleanup, groundwater and vadose zone modeling, aquifer testing analysis, and combining three-dimensional data visualization and geographical information systems with data interpretation. He has been a co-instructor at the graduate hydrogeology program at CSUS, is co-author of several environmental hydrogeology articles and abstracts, and is a Subject Matter Expert for the Board of Professional Engineers, Land Surveyors, and Geologists. Contact Kent at: kent.parrish@woodplc.com

Nicholas Pinter is a Professor and Roy J. Shlemon Chair in Applied Geosciences at the University of California at Davis. He holds a B.S. in Geology (and Archeology) from Cornell University, an M.S. from Penn State, and a Ph.D. from University of California at Santa Barbara. Prof. Pinter’s research focuses on river dynamics, flooding, floodplain management, and mitigation of flood risk and other natural hazards. He and his students study geomorphology applied to a range of problems, research that helps provide a scientific basis for sound public policy at local, national, and international levels. Contact Nick at: npinter@ucdavis.edu

Roy J. Shlemon received his doctorate from the University of California at Berkeley. Formerly on the faculty of the University of California at Davis and the Louisiana State University in Baton Rouge, Dr. Shlemon continues to teach seminars at various local universities. He resides in Newport Beach maintaining a consulting practice for the past 50+ years. His technical specialties are Quaternary geology, geomorphology and soil stratigraphy, particularly as applied to engineering practice. Projects are worldwide, focusing mainly on fault dating and slope stability assessments for siting nuclear power plants, waste facilities, dams and other large engineered structures. Dr. Shlemon is a member of many local, national and international professional societies, an Editor-in-Chief emeritus of the journal "Engineering Geology," a technical reviewer for various government agencies, and served as a "Neutral Referee" on behalf of the Orange County Superior Court. Contact Roy at: rshlemon@jps.net

Stephen M. Testa is President of Testa Environmental Corporation and former Executive Officer to the California State Mining and Geology Board. Mr. Testa is a Professional Geologist and a Certified Engineering Geologist in California. He holds a B.S. and M.S. in Geology from California State University, Northridge. He is the former President of the American Geosciences Institute, American Institute of Professional Geologists, Los Angeles Basin Geological Society and American Association of Petroleum Geologists Energy Mineral Division and Division of Environmental Geosciences. Mr. Testa is the author of over ten books and numerous articles pertaining to environmental and engineering geology, and history of geology. Contact Stephen at: stesta@goldrush.com

Jeffrey Unruh is a California-registered Professional Geologist with over 27 years of experience in applied neotectonics, structural geology and seismic hazard evaluation. Much of his professional work is focused on comprehensive, multidisciplinary studies for dams, water delivery systems, nuclear power plants and liquid natural gas facilities. Dr. Unruh also has extensive experience evaluating the structural geology of geothermal fields, and he has pioneered new methods (in collaboration with Dr. Robert Twiss of UC Davis) for using earthquake data to better understand how faults move in tectonically active areas. Dr. Unruh currently is President of Lettis Consultants International, Inc., a California-based earth science consulting firm. In addition to his professional consulting work, Dr. Unruh is an active member of the scientific and research community. He has published over 35 peer-reviewed technical papers, as well as numerous articles for popular books and field trip guides. Dr. Unruh held a courtesy position as a Research Geologist at the University of California, Davis from 1996 to 2015, and recently was named as a Fellow of the Geological Society of America. Contact Jeff at: unruh@lettisci.com or unruh.jeff@gmail.com

John Wakabayashi, Ph.D., P.G., is a Professor of Geology at California State University Fresno, where he has been a faculty member since 2005. Prior to his academic career he worked as a consultant in engineering and environmental geology for 16 years. His academic research interests focus on tectonics of convergent and transform plate margins from active tectonics to the rock record, integrating a range of disciplines including structural geology, petrology, sedimentary geology, and geomorphology. His applied geology interests include seismic hazard assessment, naturally-occurring asbestos and ambient levels of metals of environmental concern, and characterization of block-in-matrix geologic materials. He endeavors to blend his experience in applied geology into his teaching. In the same spirit, he applied research in basic geology to professional projects in engineering and environmental geology. In addition to his university teaching, he has led many field trips for a wide range of organizations. He is the author or co-author of over 80 peer-reviewed publications. He is the Richard H. Jahns Distinguished Lecturer in Applied Geology for 2017-2018 and a Fellow of the Geological Society of America (GSA). He is past chair of GSA's International Division (now GSA International), and was chair of the GSA Cordilleran Section Meeting held in Fresno in 2013. Contact John at: jwakabayashi@csufresno.edu

Jeremy Zorne is a Senior Geotechnical Engineer and Vice President of Geocon Consultants, Inc. in Sacramento, California. Jeremy is a Professional Civil and Geotechnical Engineer in California. He holds a B.S. and M.S. in Civil Engineering from California State University, Sacramento. Jeremy's diverse project experience includes geotechnical engineering and foundation engineering for transportation infrastructure (roadways, bridges, and retaining structures), water/wastewater treatment and distribution facilities, educational facilities, parks and recreation facilities, commercial/industrial development, and residential development. Jeremy serves on the *Civil Engineering Program Industry Advisory Committee* at Sacramento State, has served on the Boards of the Sacramento Section and Capital Branch of the American Society of Civil Engineers (ASCE), and was the founding Chair of the Sacramento Section Geo-Institute of ASCE. Contact Jeremy at: zorne@geoconinc.com

XIV. REFERENCES

Chapter I. Introduction

CGS, 2009, Preliminary 30x60-miunute Quadrangles - Lodi. Available at: http://www.conservation.ca.gov/cgs/rghm/rgm/Pages/preliminary_geologic_maps.aspx#30x60quads. Accessed on 29 July 2018

CGS, 2011, Preliminary 30x60-miunute Quadrangles - Sacramento. Available at: http://www.conservation.ca.gov/cgs/rghm/rgm/Pages/preliminary_geologic_maps.aspx#30x60quads. Accessed on 29 July 2018

CGS, 2018, Geospatial Data and Web Maps from the California Department of Conservation. Available at: https://maps.conservation.ca.gov/. Accessed on 29 July 2018

NPS, 2012, Map of National scenic and historic trails, National Park Service. Available at; https://en.wikipedia.org/wiki/Pony_Express. Accessed on: 14 Aug 2018

SCMHMP, 2004, Sacramento County Multi-Hazard Mitigation Plan. Available at: http://www.waterresources.saccounty.net/Drainage/Section%204-1%20Hazard%20ID3rdFinal.pdf. Accessed on: 14 August 2018.

Geodetic Datums

CGS, 2002, California Geologic Survey map of the geomorphic provinces of California, Note 36. Available at: http://www.conservation.ca.gov/cgs/Documents/Note_36.pdf. Accessed on: 9 Mar 2018

National Geodetic Survey, 2007. Datums, Heights and Geodesy, Presentation to the Central Chapter of the Professional Land Surveyors of Colorado, 2007 Annual Meeting. Presented by Daniel R. Roman, National Geodetic Survey, National Oceanic and Atmospheric Administration. Available at: https://www.ngs.noaa.gov/GEOID/PRESENTATIONS/2007_02_24_CCPS/Roman_A_PLSC2007notes.pdf. Accessed on: 3 May 2018

National Oceanic and Atmospheric Administration, 2018. Center for Operational Oceanic Products and Services, National Oceanic and Atmospheric Administration. Available at: https://tidesandcurrents.noaa.gov/. Accessed on May 3, 2018.

Zilkoski, D.B., Richards, J.H., and Young, G.M., 1992. Results of the General Adjustment of the North American Vertical Datum of 1988, Special Report. American Congress on Surveying and Mapping, Surveying and Land Information Systems, Vol. 52, No. 3, 1992, pp. 133-149. Available at: https://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm. Accessed on May 3, 2018.

Additional Resources

NOAA, 2016. 3D National Requirements and Benefits Study. Available at: https://communities.geoplatform.gov/ngda-elevation/3d-nation-study/. Accessed on: 10 April 2018

VERTCON, 2018. National Geodetic Survey. VERTCON vertical datum shift calculator. Available at: https://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl. Accessed on: 18 January 2018.

Chapter II. History and Founding

Blake, William P., 1855, Geologic map of a part of the state of California, explored in 1855 by Lieutenant R. S. Williamson, U.S. Topographic Engineer.

Galloway, John D., 1950, The first Transcontinental Railroad, Central Pacific – Union Pacific. Available at: http://penelope.uchicago.edu/Thayer/E/Gazetteer/Places/America/United_States/_Topics/history/_Texts/GALFTR/home.html. Accessed on: 14 August 2018.

Moulton, Candy, 2016, Building the Central Pacific Railroad, Truewest, 8 July 2016. Available at: https://truewestmagazine.com/building-the-central-pacific-railroad/. Accessed on 14 Aug 2018

Noble, Doug, 2010, the Sacramento Valley Railroad: The first railroad of the west. Mountain Democrat, 2 November 2010. Available at: https://www.mtdemocrat.com/uncategorized/the-sacramento-valley-railroad-the-first-railroad-of-the-west/. Accessed on: 14 Aug 2018.

Peper, Paula J., 2014. Sacramento's Sutter Park Neighborhood. StoneBridge Properties, LLC. First Edition, February 2014.

Wyatt, Kyle K., 2018, Railroad history and museum consultant, California Railroad Museum.

Additional Resources

AEG, 2018, AEG Geology of the Cities of the World series. Available at: http://www.aegweb.org/?page=GeologyCities. Accessed on 21 February 2018

Ambrose, S.E.,2000, Nothing like it in the world: the men who built the transcontinental railroad 1863-1869, Simon and Schuster publishers, New York, New York, 431 p.

Chapter III. Quaternary Geology

Arkley, R. J., 1954, Soils of eastern Merced County, California: University of California, College of Agriculture Soil Survey no. 11, 174 p., maps.

Arkley, R. J., 1959, Soils of eastern Stanislaus County, California: University of California, College of Agriculture Soil Survey no. 13, 197 p.

Arkley, R. J., 1962, The geology, geomorphology, and soils of the San Joaquin valley: in the vicinity of the Merced River, California: in Oakeshott, G. B. (ed.), California Division of Mines and Geology Bulletin 182, p. 25-32.

Atwater, B. F., 1982, Geologic maps of the Sacramento-San Joaquin Delta, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-1401, 20 map sheets, scale: 1: 24,000.

Atwater, B. F., Hedel, C. W., and Helley, E. J., 1977, Late Quaternary depositional history, Holocene sea-level changes, and vertical crust movement, southern San Francisco Bay, California: U. S. Geological Survey Professional 1014, 15 p., plate.

Atwater, B. F., Adam, D. P., and seven additional authors, 1986, A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada: Bulletin of the Geological Society of America, v. 97, p. 97-109.

Aune, Q. A., 1973, Geologic notes on the Folsom-Roseville area: in Hauge, C. (leader), Environmental Geology—A field trip to eastern Sacramento County and western El Dorado County, 1973 field trip guidebook, Geological Society of Sacramento, p. 59-65.

Averill, C. V., 1946, Placer mining for gold in California: California Division of Mines Bulletin 135, 320 p., plates.

Band, J. W., 1988, Neotectonics of the Sacramento-San Joaquin delta area, east-central Coast Ranges, California: Ph.D. Dissertation, University of California, Berkeley, 216 p.

Bartow, J. A., 1991, The Cenozoic evolution of the San Joaquin Valley, California: U. S. Geological Survey Professional Paper 1501, 40 p., plates.

Bartow, J. A., and Helley, E. J., 1979, Preliminary geologic map of Cenozoic deposits of the Folsom area, California: U. S. Geological Survey Open-File Report 79-550, scale 1: 62,500.

Bennett, J. H., 1987, Vacaville-Winters Earthquakes...1892, Solano and Yolo counties: California Geology, v. 40, no. 4, p. 75-83.

Benson, L. V., Burdett, J. W., Kashgarian, M., Lund, S. P., Phillips, F. M. and Rye, R. O., 1996, Climatic and hydrologic oscillations in Owens Lake basin and adjacent Sierra Nevada, California: Science v. 274, p. 746–751.

Benson, L. V., Lund, S. P., Burdett, J. W., Kashgarian, M., Rose, T. P., Smoot, J. P., and Schwartz, M., 1998, Correlation of Late-Pleistocene lake-level oscillations in Mono Lake, California with North Atlantic climate events: Quaternary Research, v. 49, p. 1–10. Available at: https://www.sciencedirect.com/science/article/pii/S0033589497919402. Accessed on: 8 Aug 2018

Birkeland, P. W., Burke, R. M., Walker, A. L., 1980, Soils and sub-surface weathering features of Sherwin and pre-Sherwin glacial deposits, eastern Sierra Nevada, California: Bulletin of the Geological Society of America, v. 91, p. 238–244.

Birkeland, P. W., and Burke, R. M., 1988, Soil catena chronosequences on eastern Sierra Nevada moraines, California, U. S. A: Arctic and Alpine Research, v. 20, p. 473-484.

Bischoff, J. L., Meisling, K. M., Fitts, J. P. and Fitzpatrick, J. A., 1997, Climatic oscillations 10,000-155,000 yr B.P. at Owens Lake, California reflected in glacial rock flour abundance and lake salinity in Core OL-92: Quaternary Research, v. 48, p. 313–325.

Bischoff, J. L. and Cummins, K., 2001, Wisconsin glaciation of the Sierra Nevada (79,000-15,000 yr B.P.) as recorded by rock flour in sediments of Owens Lake, California: Quaternary Research, v. 55, p. 14-24.

Blake, M. C., Harwood, D. S., Helley, E. J., Irwin, W. P., Jayko, A. S., and Jones, D. L., 1999, Geologic Map of the Red Bluff 30’ x 60’ Quadrangle, California: U. S. Geological Survey Miscellaneous Investigations Series Map I-2542, scale: 1: 100,000.

Bryant, W. B., 1982, Midland fault zone: California Division of Mines and Geology Fault Evaluation Report FER-133, 8 p., 3 figs.

Burke R. M., and Birkeland, P. W., 1977, Re-evaluation of multi-parameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California: Quaternary Research, v. 39, p. 24-35.

Burow, K. R., Weissmann, G. S., Miller, R. D., and Placzek, G., 1997, Hydrogeologic facies characterization of an alluvial fan near Fresno, California, using geophysical techniques: U. S. Geological Survey Open-File Report 97-46, 15 p., maps.

Burow, K. R., Shelton, J. L., Hevesi, J. A., and Weissmann, G. S., 2004, Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California: U. S. Geological Survey Scientific Investigations Report 2004-5232, 54 p.

Busacca, A., J., Singer, J., and Verosub, K. L., 1989, Late Cenozoic stratigraphy of the Feather and Yuba Rivers area, California, with a section on soil development in mixed alluvium at Honcut Creek: U. S. Geological Survey Bulletin 1590-G, 132 p.

Cherven, V. B., 1984, Early Pleistocene glacial outwash deposits in the eastern San Joaquin Valley California: a model for humid-region alluvial fans: Sedimentology, v. 31, no. 6, p. 823-836.

Clark, W. B., 1970, Gold districts of California: California Division of Mines and Geology Bulletin 193, 186 p., plates.

Cole, R. C., Stromberg, L. K., Bartholomew, O. F. and Retzer, J. L., 1954, Soil survey of the Sacramento area, California: U. S. Department of Agriculture, Soil Conservation Service, 101 p., maps.

Davis, S. N., and Hall, F. R., 1959, Water quality of eastern Stanislaus and northern Merced counties, California: Stanford University Publications in Geological Sciences, v. 6, no. 1, 112 p.

Drexler, J. Z., de Fontaine. C. S., and Brown, T. A., 2009, Peat accretion histories during the past 6,000 years in marshes of the Sacramento-San Joaquin Delta, CA, USA: Estuaries and Coasts, Springer US, v. 32, no. 5, p. 871-892.

Ehlers, J., and Gibbard, P. L. (eds.), 2004, Quaternary glaciations – extent and chronology, Part II (North America): Elsevier Science, Amsterdam, 450 p.

Environmental Protection Agency, 2004, Aerojet General Corporation Superfund site: “Edge of groundwater contamination plume appears in Carmichael:” EPA Region 9 status report (May 2004), Rancho Cordova, CA., 3 p.
Farina, R. J., and Carpenter, D. W., 1973, The bucket line gold dredge and tailings in the Folsom-Mather Field area: in Hauge, C. (leader), Environmental geology—a field trip to eastern Sacramento County and western El Dorado County, 1973 field trip guidebook, Geological Society of Sacramento, p. 41-48.
Florsheim, J. L., and Mount, J. F., 2003, Changes in lowland floodplain sedimentation processes: pre-disturbance to post-rehabilitation, Cosumnes, River, CA: Geomorphology, v. 56, p. 305-323.
Ford, R. S., Chee, L., and Cox. G. D., 1974, Evaluation of ground water resources: Sacramento County: Department of Water Resources Bulletin 118-8, 141 p., plates.
Franks, A., and Moss, G. (leaders), Geology of the Sacramento area, foothills, and the Sierra Nevada mountains: Association of Engineering Geologists Field Trip Guide, 1995 Annual Meeting of the Association of Engineering Geologists and Groundwater Resources Association, Sacramento, CA.
Fullerton, D. S., 1986, Chronology and correlation of glacial deposits in the Sierra Nevada, California: in Sibrava, V., Bowen, D. Q., and Richmond, G. M. (eds.), Quaternary glaciation of the Northern Hemisphere, Quaternary Science Reviews, v. 5, p. 161–169.
Gilbert, C. G., 1917, Hydraulic-mining debris in the Sierra Nevada: U S. Geological Survey Professional Paper 105, 154 p.
Gillespie, A. R., and Zehfuss, P. H., 2004, Glaciations of the Sierra Nevada, in Ehlers, J., and Gibbard, P.L. (eds.), Quaternary Glaciations—Extent and Chronology: Part II. North America: Elsevier, Amsterdam, p. 51–62.
Gillespie, A. R., and Clark, D. H., 2011, Glaciations of the Sierra Nevada, California, USA: Developments in Quaternary Science, v. 15, Chapter 34, Elsevier, Amsterdam, p. 447-462.
Hansen, R. O., and Begg, E. L., 1970, Age of Quaternary sediments and soils in the Sacramento area, California by uranium and actinium series dating of vertebrate fossils: Earth and Planetary Science Letters, v. 8, no. 6, p. 411-419.
Harden, J. W., 1987, Soils developed in granitic alluvium near Merced, California: Bulletin of the U.S. Geological Survey 1590-A, 65 p.
Harden, J. W., and Marchand, D. E., 1977, The soil chronosequence of the Merced River area: in Singer M. J. (ed.), Soil development, geomorphology and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Soil Science Society of America and Geological Society of America joint field session, 1977 Guidebook, p. 22-38.
Harwood, D. S., and Helley, E. J., 1987, Late Cenozoic tectonism of the Sacramento Valley, California: U.S. Geological Survey Prof. Paper 1359, 45 p.

Harwood, D. S., Helley, E. J., Barker, J. A., and Griffin, E. A., 1980: Preliminary geologic map of the Battle Creek fault zone, Shasta and Tehama counties, California: U. S. Geological Survey, Open-File Report OF-80474, scale 1: 24,000.

Hart, E. W., and Rapp, J. S., 1975, Ground rupture along the Cleveland Hill fault: in Sherburne, R.W., and Hauge, C.J. (eds.), Oroville, California earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 61-72.

Helley, E.J., 1966, Sediment transport in the Chowchilla river basin, Mariposa, Madera, and Merced counties, California. PhD Dissertation, University of California, Berkeley.

Helley, E. J., 1978, Geologic map of the alluvial of the Chowchilla River and adjacent foothill area, Mariposa, Merced, Madera counties, California: U.S. Geological Survey Miscellaneous Field Studies Map 927, scale: 1: 62,500.

Helley, E. J., and Harwood, D. S., 1985, Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California: U S. Geological Survey Misc. Field Studies Map, MF-1790, 17 p., 5 map sheets, scale 1:62,500.

Horner, T. C., and Giorgis, R. B., 1970, Cenozoic sedimentation in the Sacramento area: in Shlemon, R. J., Horner, T., and Florsheim, J. (leaders), Quaternary geology of the Sacramento area, Association of Engineering Geologists, Sacramento Section, Guidebook for Field Trip, 25 March 2000, p. 19-33. 2 plates, tables.

Hudson, F. S., 1960, Post-Pliocene uplift of the Sierra Nevada, California: Geological Society of America Bulletin, v. 71, p. 1547-1575.

Huntington, G. L., 1971, Soil survey, eastern Fresno area, California: U. S. Department of Agriculture, Soil Conservation Service, 323 p., tables, plates.

Huntington, G. L., Begg, E. L., Harden, J. W., and Marchand, D. E., 1977, Soil development, geomorphology and Cenozoic history of the northeastern San Joaquin Valley and adjacent area, California: guidebook, Joint Field Session of the American Society of Agronomy, Soil Science Society of America and the Geological Society of America: 344 p., plates, maps.

Ingebritsen, S. E., and Ikehara, M. E., 1999, Sacramento-San Joaquin delta: The sinking heart of the state: in Galloway, D. L., Jones, D. R, and Ingebritsen, S. E. (eds.), Land subsidence in the Unites States, U. S. Geological Survey Circular 1182, 177 p., maps.

Jaffe, B. E., Smith, R. E., and Foxgrover, A. C., 2007, Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856-1983: Estuarine Coastal and Shelf Science, Elsevier, v. 73, p. 175-187.

James, L. Allan, 1989, Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California: Annals of the Association of American Geographers, v. 79, no. 4, p. 570-592.

James, L. Allan, 1999, Time and persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California: Geomorphology, v. 31, p. 265-290.

Janda, R. J., 1965, Quaternary alluvium near Friant, California: in International Association for Quaternary Research Guidebook for Field Conference I, northern Great Basin and California: Lincoln, Nebraska Academy of Sciences, p. 128-133.

Janda, R. J., and Croft, M. G., 1967, The stratigraphic significance of a sequence of non-calcic brown soils formed on the Quaternary alluvium of the northeastern San Joaquin Valley, California: in Morrison, R. B., and Wright, H. E. (eds.), Quaternary soils: Proceedings of the International Association for Quaternary Research series, VII Congress: Reno, NV, University of Nevada, Desert Research Institute, Center for Water Resources Research, v. 9, p. 158–190.

Kelley, R. L., 1959, Gold vs. Grain: The Arthur H. Clark Company, Glendale, CA, 327 p.

Kiersch, G. A. and Treasher, R. C., 1955, Investigations, area and engineering geology; Folsom Dam Project, central California: Economic Geology, v. 56, no. 3, p. 271-310.

Kirshenbaum, N. W., 2000, The giant gold diggers: California's land-going fleet of dredges: The Mining History Journal, v. 7, p. 11-25.

Lindgren, W., 1911, Tertiary gravels of the Sierra Nevada, Folsom dredge fields: U. S. Geological Survey Professional Paper 73, 222 p., plates.

Lettis, W. R., 1982, Late Cenozoic stratigraphy of the western margin of the central San Joaquin Valley, California: U.S. Geological Survey Open-file report 82-526, 203 p.

Lettis, W. R., and Unruh, J. R., 1991, Quaternary geology of the Great Valley, California, in Morrison, R. B., ed., Quaternary Non-Glacial Geology of the Western United States: Decade of North American Geology, v. K-2, Geological Society of America, Boulder, CO, p. 164-176.

Lydon, P. A. (ed.), 1962, U. S. Highway 40, Sacramento to Reno, Dixie Valley and San Springs Range, Nevada: Guidebook, Annual Field Trip, Geological Society of Sacramento and Sacramento Section, California Association of Engineering Geologists, 89 p., maps.

Marchand, D. E., 1977, The Cenozoic history of the San Joaquin Valley and the adjacent Sierra Nevada as inferred from the geology and soils of the eastern San Joaquin Valley: in Singer, M. J. (ed.), Soil development, geomorphology and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Guidebook for Joint Field Sessions, Soil Science Society of America and Geological Society of America, p. 39-50.

Marchand, E., and Allwardt, A., 1981, Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1470, p. 1-70.

Miller, R. L., Fram, M. S., Fujii, R., and Wheeler, G., 2008, Subsidence reversal in a re-established wetland in the Sacramento-San Joaquin delta, California, USA: San Francisco Estuary and Watershed Science, v. 6, no. 3, article 1, p. 1-20. Available at: http://repositories.edlib.org/jmie/sfews/vol6/iss3/art1.

Moores, E., 1993, Geology and tectonics of the southwestern Sacramento Valley and adjacent Coast Ranges: Guidebook, Northern California Geological Society, 84 p.

Morrison, R. B., 1965, Means of time-stratigraphic division and long-distance correlation of Quaternary successions: in Morrison, R. B., and Wright, H. E. (eds.), International Association for Quaternary Research, Proceedings of the VII Congress, v. 8, University of Utah Press, Salt Lake City, p. 1-114.

Nikiforoff, C. C., 1941, Hardpan and microrelief in certain soil complexes of California: U. S. Department of Agriculture Technical Bulletin 745, p. 45.

Olmstead, F. H., and Davis, G. H., 1961, Geologic features and thousands of storage capacity of the Sacramento Valley, California: U. S. Geological Survey Water Supply Paper 1497, 249 p., plates, maps.

Phillips, F. M., Zreda, M. G., Benson, L. V., Plummer, M. A., Elmore, D. and Sharma, P., 1996, Chronology for fluctuations in late Pleistocene Sierra Nevada glaciers: Science, v. 274, p. 749–751.

Piper, A. M., Gale, H. S., and Thomas, H. E., 1939, Geology and ground-water hydrology of the Mokelumne area, California: U. S. Geological Survey Water-Supply Paper 780, 230 p., 10 plates.

Rapp, J. S., 1975, Sand and gravel resources of the Sacramento area, California: California Division of Mines and Geology, v. 121, 42 p.

Reynolds, S. N., and Reynolds, S. T., 1963, Midland fault, an Eocene subsurface fault, Delta area, California (abs.), American Association of Petroleum Geologists Bulletin, v. 47, no. 9, p. 1775.

Rogers, J. H., Davis, S. W., and Cook, T. D., 2009, Soil profile measurement and descriptions, San Joaquin and Redding soils: in Shlemon, R. J., Davis, S. W., Cook, T. D., and Rogers, J. H. (leaders), Guidebook: Soils and geomorphology of the northern Sacramento County, area, California, National Society of Consulting Soil Scientists, p. 10-13.

Rojstaczer, S., and Deverel, S. J., 1995, Land subsidence in drained histosols and highly organic mineral soils of California: Soil Science Society of America Journal, v. 59, p. 1162-1167.

Romanowitz, C, M., 1979, California's gold dredged: Mineral Information Service, p. 155-168.

Shlemon, R. J., 1967a, Landform-soil relationships in northern Sacramento County, California: Ph.D. dissertation, Univ. California Berkeley, Department of Geography, 295 p, map, cross sections.

Shlemon, R. J., 1967b, Quaternary geology of the northern Sacramento County, California: Annual Field Trip Guidebook of the Geological Society of Sacramento (May 1967), 60 p., plates.

Shlemon, R. J., 1971, The Quaternary deltaic and channel system in the central Great Valley, California: Annals of the Association of American Geographers, v. 61, p. 427-440.

Shlemon, R. J., 1972, The lower American River area, California: a model of Pleistocene landscape evolution, Yearbook, Assoc. of Pacific Coast Geographers, v. 34, p. 61-86.

Shlemon, R. J., 1998, Quaternary geology of the Sacramento area: in Shlemon, R., J., leader, Guidebook, Association of Engineering Geologists, Sacramento Section, 13 p., plates.

Shlemon, R. J., and Hansen, R. O., 1969, Radiometric and faunal dating of Quaternary alluvium in the Sacramento area, California (Abs.): Geological Society of America, Cordilleran Section, Part 3 (Eugene, OR), p. 61-62.

Shlemon, R. J., and Phelps, L. B., 1971, Dredge-tailing agriculture on the Rio Nechi, Colombia: Geographical Review, v. LXI, no. 3, p 196-414.

Shlemon, R. J., Begg, E. L., and Huntington, G. L., 1973, Fracture traces: Pacific Discovery, California Academy of Sciences, San Francisco, v. XXVI, no. 1, p. 31-32.

Shlemon, R. J., and Begg, E. L., 1975, Late Quaternary evolution of the Sacramento-San Joaquin delta, California: in Suggate, R. P., and Creswell, M. M. (eds.), Quaternary studies, p. 259-266, Cresswell, The Royal Society of New Zealand, Wellington, NZ.

Shlemon, R. J., Davis, S. W., Cook, T. D., and Rogers, J. H. (leaders), 2009, Soils and geomorphology of the northern Sacramento County area, California: Guidebook, National Society of Consulting Soil Scientists, 19 p.

Slemmons, D. B., 1966, Cenozoic volcanism of the central Sierra Nevada, California geology of northern California: California Division of Mines and Geology Bulletin 170, p. 199-208.

Smith, D. W., and Verrill, W. L., 1998, Vernal pool-soil-landform relationships in the Central Valley, California: in Witham, C. W., Bauder, E. T. Belk, D., Ferren, W. R. Jr., and Ornduff, R. (eds.), Ecology, conservation, and management of vernal pool ecosystems – Proceedings from a 1996 Conference, California Native Plant Society, Sacramento, CA, p. 15-23.

Soil Science Society of America, 2017, San Joaquin series, California state soil: 6 p. Available at: www.soils4teachers.org/state_soils. Accessed on: August 2017.

Staton, I., and Spangler, D., 2014, Geology of the northern Sacramento Valley, California: California Department of Water Resources, 77 p., appendices, plates.

Swanson, S. E., 1978, Petrology of the Rocklin pluton and associated rocks, western Sierra Nevada, California: Bulletin of the Geological Society of America, v. 89, no. 5, p. 679-686.

Tugel, A. J., 1993, Soil survey of Sacramento County, California: U. S. Department of Agriculture, Soil Conservation Service, 399 p., plates.

Ulrich, R., and Stromberg, L. K., 1962, Soil survey of the Madera area, California: U. S. Department of Agriculture Soil Survey Series 1951, no. 11, 155 p.

Unruh, J. R., and Moores, E. M., 1992, Quaternary blind thrusting in the southwestern Sacramento Valley, California: Tectonics, v. 11, p. 192-203.

Unruh, J. R., Loewen, B. A., and Moores, E. M., 1995, Progressive arcward contraction of a Mesozoic-Tertiary for-arc basin, southwestern Sacramento Valley, California: Geological Society America Bull., v. 107, no. 1, p. 38-53.

Verosub, K. L., Delusina, I., and Shlemon, R. J., 2005, Geologic subsidence in the Sacramento-San Joaquin Delta, California, and its implications for risk assessment: American Geophysical Union, Spring Meeting 2009, Abstract #C11A-05.
Wagner, D. L., Jennings, G. W., Bedrossian, T. L., and Bortugno, E. J., 1981, Geologic map of the Sacramento quadrangle: California Geological Survey, scale 1: 250,000.
Warhaftig, C., and Birman, J. H., 1965, The Quaternary of the Pacific mountain system in California: in Wright, H. E. and Frey, D. G. (eds.): The Quaternary of the United States, Princeton University Press, Princeton, p. 299–340.
Weir, W. W., 1950, Soils of Sacramento County, California: University of California, College of Agriculture, Division of Soils, 119 p., maps, scale 1:62,500.
Weissmann, G. S., Mount, J. F., and Fogg, G. E., 2002, Glacially driven cycles in accumulation space and sequence stratigraphy of a stream-dominated alluvial fan, San Joaquin Valley, California, U.S.A., Journal of Sedimentary Research, v. 72, p. 270-281.
Weissmann, G. S, Bennett, G. L., and Lansdale, A. L., 2005, Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA: in Harvey, A. M., Mather, A. E., and Stokes, M., eds., Alluvial fans: geomorphology, sedimentology, dynamics: Geological Society, London, Special Publications no. 251, p. 160-186.

Additional Resources

Arkley, R. J., 1964, Soil survey of the eastern Stanislaus area, California: U. S. Department of Agriculture, Soil Conservation Service, Series 1957, no. 20, 160 p., plates.
Arkley, R. J., Cole, R. C., Huntington, G. L., Carlton, A. B., and Smith, G. K., 1962, Soil survey of the Merced area, California: U. S. Department of Agriculture, Soil Conservation Service, Series 1950, no. 7, 131 p., plates.
California Office of Historical Preservation, State Park Commission, 1957, Historical Landmark 575, Sloughhouse, Highway 16 and Meiss Road, Sloughhouse. Available at: http://ohp.parks.ca.gov/?page_id=21387. Accessed on: August 2017.
Curtis, G. H., 1954, Mode of origin of pyroclastic debris in the Mehrten formation of the Sierra Nevada: University of California Publications in the Geological Sciences, v. 29, no. 9, University of California Press, Berkeley, p. 453-501.
Davis, S. W., 2009, Vernal pool construction: in Shlemon, R. J., Davis, S. W., Cook, T. D., and Rogers, J. H., Soils and Geomorphology of the Northern Sacramento County Area, California, Guidebook, National Society of Consulting Soil Scientists, Field Stop 3, p. 13-16.

Hauge, C. (ed.), 1973, Environmental geology-a field trip to eastern Sacramento County and western El Dorado County: 1973 Field Trip Guidebook, Geological Society of Sacramento, 140 p., maps.

Stromberg, L. K., Huntington, G. L., Begg, E. L., and Smith, G. K., 1962, Soil survey of the Madera area, California: U.S. Department of Agriculture, Soil Conservation Service, 155 p., tables, plates.

Lindgren, W., 1894, Sacramento folio, California: U. S. Geological Survey, Geological Atlas of the United States, folio 5, 3 p, plates.,

Harwood, D. S., and Helley, E. J., 1987, Late Cenozoic tectonism of the Sacramento Valley, California: U.S. Geological Survey Prof. Paper 1359, 45 p.

Shlemon, R. J., 1995, Pleistocene channels of the lower American River, Sacramento County, California: in Franks, A., and Moss, F. (leaders), Geology of the Sacramento area, foothills, and the Sierra Nevada mountains: Association of Engineering Geologists field trip guide, 1995 annual meeting of the Association of Engineering Geologists and Groundwater Resources Association, Sacramento, CA., p. 1-5.

Chapter IV. Paleontology

See references section of Appendix B. Paleontology

Chapter V. Bedrock Geology

Aalto, K.R., 2014, Examples of Franciscan Complex mélanges in northernmost California Coast Ranges, a retrospective: International Geology Review, v. 56, p. 555-570.

Amos, C. B., Audet, P., Hammond, W. C., Burgmann, R., Johanson, I. A., & Blewitt, G., 2014, Uplift and seismicity driven by groundwater depletion in central California: Nature, v. 509, p. 483–486.

Argus, D.F., and Gordon, R.G., 1991, Current Sierra Nevada–North America motion from very long baseline interferometry: Implications for the kinematics of the western United States: Geology, v. 19, p. 1085–1088.

Argus, D.F., and Gordon, R.G., 2001, Present tectonic motion across the Coast Ranges and San Andreas fault system in central California: Geological Society of America Bulletin, v. 113, p. 1580–1592.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States-an update: International Geological Review, v. 40, p. 375-402.

Bateman, P.C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, in Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 107-172.

Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E. M., and O'Day, M., 1972, What is Franciscan?: Bulletin of the American Association of Petroleum Geologists, v. 56, p. 2294-2302.

Bickford, M. E., and Day H. W., 2001, Tectonic setting of the Smartville and Slate Creek complexes, northern Sierra Nevada: evidence for zircon geochronology and common Pb studies: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A-208.

Blake, M.C., Jr., Jayko, A.S., McLaughlin, R.J., and Underwood, M.B., 1988, Metamorphic and tectonic evolution of the Franciscan Complex, northern California, in Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States: Englewood Cliffs, New Jersey, Prentice- Hall, Rubey Volume VII, p. 1035–1060.

Böhlke, J. K., 1999, Mother Lode gold, in Moores, E. M., Sloan, D., and Stout, D. L., eds., Classic Cordilleran Concepts: A View from California: Boulder, Colorado, Geological Society of America Special Paper 338. p. 55-67.

Busby, C.J., Hagan, J.C., Putirka, K., Pluhar, C.J., Gans, P., Rood, D., DeOreo, S.B., and Skilling, I., 2008, The ancestral Cascades arc: Implications for the development of the Sierran microplate and tectonic significance of high K2O volcanism, in Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: Geological Society of America Special Paper 438, p. 331-378

Cassel, E.J., Graham, S.A., Chamberlain, C.P., and Henry, C.D., 2012, Early Cenozoic topography, morphology, and tectonics of the northern Sierra Nevada and western Basin and Range: Geosphere, v. 8, p. 229-249; doi: 10.1130/GES00671.1

Chuber, S., 1962, Late Mesozoic stratigraphy of the Elk Creek-Fruto area, Glenn County, California: Ph.D. dissertation, Stanford University, 115 p.

Cloos, M., 1984, Flow mélanges and the structural evolution of accretionary wedges, in Raymond, L., ed., Mélanges: Their nature, origin, and significance: Geological Society of America Special Paper 198, p. 71–80.

Cloos, M., and Shreve, R.L., 1988a, Subduction channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description: Pure and Applied Geophysics, v. 128, p. 455-500.

Cowan, D.S., 1978, Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Geological Society of America Bulletin, v. 89, p. 1415-1423.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the Western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451–462, doi: 10.1130/0016-7606(1985)96<451:SSIMAC>2.0.CO;2

Day, H. W., Moores, E. M, and Tuminas, A. V., 1984, Structure and tectonics of the northern Sierra Nevada: Geological Society of America Bulletin, V. 96, no. 4, p. 436-450.

Dickinson, W. R., 1970, Relations of andesites, granites, and derivative sandstones to arc-trench tectonics: Reviews of Geophysics and Space Physics, v. 8, p. 813-860.

Dickinson, W. R., Ojakangas, R. W., and Stewart, R. J., 1969, Burial metamorphism of the late Mesozoic Great Valley Sequence, Cache Creek, California: Geological society of America Bulletin, v. 80, p 519-526.

Dickinson, W.R., and Rich, E.I., 1972, Petrologic intervals and petrofacies in the Great Valley Sequence, Sacramento Valley, California: Geological Society of America Bulletin, v. 83, no. 10, p. 3007-3024.

Dilek, Y., and Furnes, H., 2011, Ophiolite genesis and global tectonics: geochemical and tectonic fingerprinting of ancient oceanic lithosphere. Geological Society of America Bulletin, v. 123, p. 387-411. doi: 10.1130/B30446.1

Dilek, Y., Moores, E.M., and Erskine, M.C., 1988, Ophiolitic thrust nappes in western Nevada: Implications for the Cordilleran orogen: Journal of the Geological Society [London], v. 145, p. 969–975.Durrell, C., 1966, Tertiary and Quaternary geology of the northern Sierra Nevada, in Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 185-197.

Durrell, C., 1966, Tertiary and Quaternary geology of the northern Sierra Nevada, in Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 185-197

Edelman, S. H., and Sharp, W. D., 1989, Terranes, early faults, and pre-Late Jurassic amalgamation of the western Sierra Nevada metamorphic belt, California: Geological Society of America Bulletin, v. 101, no. 11, p. 1420-1433.

Ernst, W.G., 1970, Tectonic contact between the Franciscan mélange and the Great Valley Sequence, crustal expression of a Late Mesozoic Benioff Zone: Journal of Geophysical Research, v. 75, p. 886–902.

Ernst, W. G., 1993, Metamorphism of Franciscan tectonostratigraphic assemblage, Pacheco Pass area, east-central Diablo Range, California Coast Ranges: Geological Society of America Bulletin, v. 105, p. 618-636. doi:10.1130/00167605(1993)105<0618:MOFTAP>2.3.CO;2

Evarts, R. C., and Schiffman, P, 1983, Submarine hydrothermal metamorphism of the Del Puerto ophiolite, California American Journal of Science, v. 283, p. 289-340. doi:10.2475/ajs.283.4.289.

Fryer, P., Lockwood, J.P., Becker, N., Phipps, S., and Todd, C. S., 2000, Significance of serpentine mud volcanism in convergent margins: Geological Society of America Special Paper 349, p. 35-51.

Gabet, E.J., 2014, Late Cenozoic uplift of the Sierra Nevada, California? A critical analysis of the geomorphic evidence: American Journal of Science, v. 314, no. 8, p. 1224-1257, doi: 10.2475/08.2014.03.

Gerya, T.V., Stöckert, B., Perchuk, A.L., 2002, Exhumation of high-pressure metamorphic rocks in a subduction channel: a numerical simulation. Tectonics v. 21, no. 6, doi:10.1029/2002TC001406.

Godfrey, N.J., Beaudoin, B.C., Klemperer, S.L., and the Mendocino Working Group, 1997, Ophiolitic basement to the Great Valley forearc basin, northern California, from seismic and gravity data: Implications for crustal growth at the North American continental margin: Geological Society of America Bulletin, v. 109, p. 1536–1562, 10.1130/00167606 (1997)109<1536:OBTTGV>2.3.CO;2.

Godfrey, N.J., and Dilek, Y., 2000, Mesozoic assimilation of oceanic crust and island arc into the North American continental margin in California and Nevada:

Insights from geophysical data, in Dilek, Y., Moores, E. M., Elthon, D., and Nicolas., A., eds, Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 365-382.

Godfrey, N.J., and Klemperer, S.L., 1998, Ophiolitic basement to a forearc basin and implications for continental growth: The Coast Range–Great Valley ophiolite, California: Tectonics, v. 17, p. 558–570, doi: 10.1029/98TC01536.

Gutierrez, C. I., 2011. Preliminary geologic map of the Sacramento 30' x 60' quadrangle, California, California Geological Survey. Available at: http://www.conservation.ca.gov/cgs/rghm/rgm/Pages/preliminary_geologic_maps.aspx#30x60quads. Accessed on 29 July 2018

Hall, R., 1996, Reconstructing Cenozoic SE Asia, in Hall, R., and Blundell, D., eds., Tectonic evolution of Southeast Asia: Geological Society of London Special Publication, v. 106, p. 153-184.

Hamilton, W. B., 1969, Mesozoic California and underflow of the Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409-2430.

Hammond, W.C., Blewitt, G., Kreemer, C., 2016, GPS imaging of vertical land motion in California and Nevada; implications for Sierra Nevada uplift: Journal of Geophysical Research, v. 121, p. 7681-7703.

Harms, T.A., Jayko, A.S., and Blake, M.C., Jr., 1992, Kinematic evidence of extensional unroofing of the Franciscan complex along the Coast Range fault, northern Diablo Range, California: Tectonics, v. 11, p. 228-241.

Hart, E.W., and Rapp, J.S., 1975, Ground rupture along the Cleveland Hill fault: in Sherburne, R.W., and Hauge, C.J., eds., Oroville, California earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 61-72.

Henry, C.D., Hinz, N.H., Faulds, J.E., Colgan, J.P., John, D.A., Brooks, E.R., Cassel, E.J., Garside, L.J., Davis, D.A., and Castor, S.B. 2012, Eocene-early Miocene paleotopography of the Sierra Nevada-Great Basin-Nevadaplano based on widespread ash-flow tuffs and paleovalleys: Geosphere, v. 8, p. 1-27.

Hildebrand, R.S., 2009, Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera?: Geological Society of America Special Paper 457, 71 p., doi:10.1130/2009.2457.

Hopson, C.A., Mattinson, J.M., and Pessagno, E.A., Jr., 1981, The Coast Range ophiolite, western California, in Ernst, W.G., ed., The Geotectonic Development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 419–510.

Hopson, C. A., Mattinson, J. M., Pessagno, E. A. Jr., and Luyendyk, B. P., 2008, California Coast Range Ophiolite: Composite Middle and Late Jurassic oceanic lithosphere, in Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson, Geological Society of America Special Paper 483, p. 1-101.

House, M.A., Wernicke, B.P., Farley, K.A., and Dumitru, T.A. 1997, Cenozoic thermal evolution of the central Sierra Nevada, from (U-Th)/He thermochronometry: Earth and Planetary Science Letters, v. 151, p. 167-179.

House, M.A., Wernicke, B.P., and Farley, K.A., 1998, Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages: Nature, v.396, p. 66-69.

Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan- Knoxville paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074.
Jayko, A. S., 1988, Paleozoic and Mesozoic rocks of the Almanor 15' quadrangle, Plumas County: U.S. Geological Survey Open File Report 88-757, scale 1:48,000.
Jayko, A. S, 1990, Stratigraphy and tectonics of Paleozoic arc-related rocks of the northernmost Sierra Nevada, California; the eastern Klamath and northern Sierra terranes. Geological Society of America Special Paper 255, p. 307-323.
Jayko, A.S., Blake, M.C., Jr., and Harms, T., 1987, Attenuation of the Coast Range ophiolite by extensional faulting, and the nature of the Coast Range “thrust,” California: Tectonics, v. 6, p. 475–488.
Johnston, S.T., 2001, The Great Alaskan terrane wreck: Reconciliation of paleomagnetic and geological data in the northern Cordillera: Earth and Planetary Science Letters, v. 193, p. 259–272, doi:10.1016/S0012-821X (01)00516-7.
Johnston, S.T., 2008, The Cordilleran ribbon continent of North America: Annual Review of Earth and Planetary Sciences, v. 36, p. 495–530, doi: 10.1146/annurev.earth .36.031207.124331.
Kawamura, K., Sasaki, T., Kanamatsu, Y., Sakaguchi, A., and Ogawa, Y., 2012, Large submarine landslides in the Japan trench: A new scenario for additional tsunami generation: Geophysical Research Letters, v. 39, L05308, doi: 10.1029/2011GL050661.
Lallemand, S., Font, Y., Bijwaard, H., and Kao, Ho., 2001, New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications: Tectonopysics, v. 335, p. 229-253.
Lawton, J.E., 1956, Geology of the north half of the Morgan Valley quadrangle and the south half of the Wilbur Springs quadrangle, California: Ph.D. dissertation, Stanford University, California, 365 p.
Lockwood, J.P., 1971, Sedimentary and gravity-slide emplacement of serpentinite: Geological Society of America Bulletin, v. 82, p. 919-936.
MacPherson, G.J., Phipps, S. P.; and Grossman, J. N., 1990, Diverse sources for igneous blocks in Franciscan mélanges, California Coast Ranges: Journal of Geology, v. 98, p. 845-862.
Maxwell, J.C., 1974, Anatomy of an orogen: Geological Society of America Bulletin, v. 85, p. 1195–1204, doi:10.1130/0016-7606(1974)85<1195:AOAO>2.0.CO;2.
McLaughlin, R.J., Blake, M.C., Jr., Griscom, A., Blome, C.D., and Murchey, B., 1988, Tectonics of formation, translation and dispersal of the Coast Range ophiolite of California: Tectonics, v. 7, p. 1033–1056.
McQuarrie, N., and Wernicke, B.P., 2005, An animated tectonic reconstruction of southwestern North America since 36 Ma: Geosphere, v. 1, no. 3, p. 147-172, doi:10.1130/GES00016.1.
Medley, E.W., and Zekkos, D., 2011, Geopractitioner approaches to working with antisocial mélanges, in Wakabayashi, J., and Dilek, Y. eds., Mélanges: Processes of Formation and Societal Significance: Geological Society Paper 480, p. 261-277.

Moores, E. M., 1970, Ultramafics and orogeny, with models of the U.S. Cordillera and the Tethys: Nature, v. 228, p. 837-842, doi:10.1038/228837aO.
Moores, E. M., 1981, Ancient suture zones within continents: Science, v. 213, p. 41-46.
Moores, E. M., 2002, Pre-1Ga (pre-Rodinian) ophiolites: Their tectonic and environmental implications: Geological Society of America Bulletin 2002:114; p. 80-95. doi: 10.1130/0016-6706(2002)114<0080:PGPROT>2.0.CO;2
Moores, E. M., 2009, Western Pacific tectonics and the suggested Sierra seven suture saga: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 427.
Moores, E.M., Wakabayashi, J., and Unruh, J.R., 2002, Crustal-scale cross- section of the U.S. Cordillera, California and beyond, its tectonic significance, and speculations on the Andean Orogeny: International Geology Review, v. 44, p. 479–500.
Moores, E. M., Wakabayashi, J., Unruh, J. R., and Waechter, S. 2006, A transect spanning 00 million years of active plate margin history: Outline and field trip guide, in Prentice, C.S., Scothmoor, J.G., Moores, E. M., and Kiland, J.P., eds, 1906 San Francisco Earthquake Centennial Field Guides: Field trips associated with the 100th Anniversary Conference, 18-23 April 2006, San Francisco, California: Geological Society of America Field Guide 7, p. 373-413. doi:10.1130/2006.1906SF(20).
Moores, E. M., Yikilmaz, M.B., and Kellogg, L. H., 2013. Tectonics: 50 years after the revolution: Geological Society of America Special Paper 500, p. 321-369. doi:10.1130/2013.2500(10)
Mulch, A., Graham, S.A, and Chamberlain, P.C., 2006, Hydrogen isotopes in Eocene river gravels and paleoelevation of the Sierra Nevada: Science v. 313, p. 87-89.
Oskin, M., Stock, J., and Martin-Barajas, A., 2001, Rapid localization of Pacific-North American plate motion in the Gulf of California: Geology, v. 29, no. 5, p. 459-462, doi: 10.1130/0091-7613(2001)029<0459:RLOPNA>2.0.CO;2.
Pessagno, E.A., Jr., Hull, D.M., and Hopson, C.A., 2000, Tectonostratigraphic significance of sedimentary strata occurring within and above the Coast Range ophiolite (California Coast Ranges) and the Josephine ophiolite (Klamath Mountains), northwestern California: Geological Society of America Special Paper 349, p. 383–394.
Phipps, S.P., 1984, Ophiolitic olistostromes in the basal Great Valley sequence, Napa County, northern California Coast Ranges: in Raymond, L.A. (Ed.), Mélanges: Their Nature, Origin, and Significance. Boulder, Colorado, Geological Society of America Special Paper 198, p. 103-126.
Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037-1053.
Poage, M.A., and Chamberlain, C.P., 2002, Stable isotopic evidence for pre-Middle Miocene rain shadow in the western Basin and Range: implications for the paleotopography of the Sierra Nevada: Tectonics, v. 21, no. 4, 1034, doi: 10.1029/2001TC001303.
Raymond, L.A., 2015, Designating tectonostratigraphic terranes versus mapping rock units in subduction complexes: perspectives from the Franciscan Complex of California, USA: International Geology Review, v. 57, p. 801-823.

Roeder, D. H., 1973, Subduction and Orogeny: Journal of Geophysical Research, v. 78, p. 5005-5024.

Saleeby, J. B., Shaw, H.F., Niemeyer, S., Moores, E. M., and Edelman, S. H., 1989, U/Pb, Sm/Nd, and Rb/Sr, geochronological and isotopic study of northern Sierra Nevada ophiolitic assemblages, California, Contributions to Mineralogy and Petrology, v. 102, p. 205-220. doi:10.1007/BF00375341.

Schweickert, R. A., 1981, Tectonic evolution of the Sierra Nevada range, in Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 87-131.

Schweickert, R., and Cowan, D. S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geological Society of America Bulletin, v. 86, p. 1329-1336. doi: 10.1130/0016-6706(1975)86<<1329:EMTEOT>2.0.CO;2

Sharman, G.R. Graham, S.A., Grove, M., Kimbrough, D.L., and Wright, J.E., 2015, Detrital zircon provenance of the Late Cretaceous-Eocene California forearc: influence of Laramide low-angle subduction on sediment dispersal and paleogeography: Geological Society of America Bulletin, v. 127, p. 38-60, doi 10.1130/B31065.1

Shervais, J.W., Murchey, B.L., Kimbrough, D.L., Renne, P.R., and Hanan, B., 2005, Radioisotopic and biostratigraphic age relations in the Coast Range Ophiolite, northern California: Implications for the tectonic evolution of the Western Cordillera: Geological Society of America Bulletin, v. 117, p. 633–653, doi: 10.1130/B25443.1.

Sigloch, K., and Mihalynuk, M.G., 2013, Intra-oceanic subduction shaped the assembly of Cordilleran North America: Nature, v. 496, p. 50–56, doi:10.1038 /nature12019.

Sigloch, K., and Mihalynuk, M., 2017, Mantle and geological evidence for a late Jurassic-Cretaceous suture spanning North America, Geological Society of America Bulletin, June, 2017, doi: https://doi.org/10.1130/B31529.1

Slemmons, D.B., 1966, Cenozoic volcanism of the central Sierra Nevada, California, in Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 199-208.

Stock, G.M., Anderson, R.S., and Finkel, R.C., 2005, Rates of erosion and topographic evolution of the Sierra Nevada, California, inferred from cosmogenic ^{26}Al and ^{10}Be concentrations: Earth Surface Processes and Landforms, v. 30, p. 985-1006.

Suppe, J., 1973, Geology of the Leech Lake Mountain-Ball Mountain region, California: University of California Publications in the Geological Sciences, v. 107, p. 1-81.

Surpless, K.D., 2015, Geochemistry of the Great Valley Group; an integrated provenance record: International Geology Review, v. 57, p. 747-766.

Turner, H.W., 1896, Further contributions to the geology of the Sierra Nevada: United States Geological Survey, extract from 17th annual report the Survey, 1985-1896, Part 1-Director's report and other papers, p. 529-740.

Unruh, J.R., 1991, The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera: Geological Society of America Bulletin, v. 103, p. 1395-1404.

Unruh, J., and Humphrey, J., 2017, Seismogenic deformation between the Sierran microplate and Oregon Coast block, California, USA: Geology, published online March 2017, doi:10.1130/G38696.1

Unruh, J.R., and Moores, E.M., 1992, Quaternary blind thrusting in the southwestern Sacramento Valley, California: Tectonics, v. 11, p. 192-203.

Unruh, J. R., Ramirez, V. R., Phipps, S. P., and Moores, E. M., 1991, Tectonic wedging beneath fore-arc basins: ancient and modern examples from California and the Lesser Antilles: GSA Today, v. 1, p. 185-190.

Unruh, J.R., Loewen, B.A., and Moores, E.M., 1995, Progressive arcward contraction of a Mesozoic-Tertiary forearc basin, Sacramento Valley, California: Geological Society of America Bulletin, v. 107, p. 38-53.

Unruh, J., O'Connell, D., and Block, L.V., 2004, Crustal structure of the ancestral northwestern California forearc region from seismic reflection imaging: implications for convergent margin tectonics: Tectonophysics, v. 392, p. 219-240.

Unruh, J.R., Dumitru, T.A., and, Sawyer, T.L, 2007, Coupling of early Tertiary extension in the Great Valley forearc basin with blueschist exhumation in the underlying Franciscan accretionary wedge at Mount Diablo, California: Geological Society of America Bulletin, v. 119, p. 1347-1367.

Varga, R. J., and Moores, E. M., 1981, Age, Origin, and significance of an unconformity that predates island-arc volcanism in the northern Sierra Nevada, Geology 1981;9; p. 512-518. doi: 10.1130/0091-7613(1981)9<512:AOASOA>2.0.=0.CO;2

Wagner, D. L., Jennings, G. W., Bedrossian, T. L., and Bortugno, E. J., 1981, Geologic map of the Sacramento quadrangle: California Geological Survey, 1:250,000 scale.

Wahrhaftig, C.W., 1984, Structure of the Marin Headlands Block, California: A progress report: in Blake, M. C., Jr., ed., Franciscan Geology of Northern California: Pacific Section Society of Economic Paleontologists and Mineralogists (SEPM), v. 43, 31-50.

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: Journal of Geology, v. 100, p. 19–40.

Wakabayashi, J., 1999. Distribution of displacement on, and evolution of, a young transform fault system: The northern San Andreas fault system, California: Tectonics, v. 18, p. 1245-1274

Wakabayashi, J., 2013a, Paleochannels, stream incision, erosion, topographic evolution and alternative explanations of paleoaltimetry: Geosphere, v. 9, p. 192-215 doi: 10.1130/GES00814.1

Wakabayashi, J., 2013b, Subduction initiation, accretion and non-accretion, large-scale material movement, and localization of subduction megaslip, Franciscan Complex and related rocks, California: in Putirka, K., ed., Geological Excursions from Fresno, California, and the Central Valley: A Tour of California's Iconic Geology: Geological Society of America Field Guide 32, p. 129-162, doi: 10.1130/2013.0032(07)

Wakabayashi, J., 2015, Anatomy of a subduction complex: Architecture of the Franciscan Complex at multiple length and time scales: International Geology Review, v. 57, p. 669-746.

Wakabayashi, J., 2017a, Structural context and variation ocean plate stratigraphy, Franciscan Complex of California: Insight into mélange origins and subduction-accretion processes: Progress in Earth and Planetary Sciences 4: 18, 23p., doi: 10.1186/s40645-017-0132-y

Wakabayashi, J., 2017b, Sedimentary serpentinite and chaotic units of the lower Great Valley Group forearc basin deposits, California: Updates on distribution and characteristics: International Geology Review, v. 59, p. 599-620. doi.10.1080/00206814.2016.1219679

Wakabayashi, J., in press, Serpentinites and serpentinites: Variety of origins and emplacement mechanisms of serpentinite bodies in the California Cordillera: Island Arc. doi. 10.1111/iar.12205

Wakabayashi, J., and Unruh, J., 1995, Tectonic wedging, blueschist metamorphism and exposure of blueschists: are they compatible?: Geology, v. 23, p. 85-88.

Wakabayashi, J., and Sawyer, T.L., 2000, Neotectonics of the Sierra Nevada and Sierra Nevada-Basin and Range Transition, California, with field trip stop descriptions for the northeastern Sierra Nevada, in Brooks, E.R., and Dida, L.T. eds., Field guide to the geology and tectonics of the northern Sierra Nevada: California Division of Mines and Geology (now California Geological Survey) Special Publication 122, p. 173-212.

Wakabayashi, J., and Sawyer, T.L., 2001, Stream incision, tectonics, uplift, and evolution of topography of the Sierra Nevada, California: Journal of Geology, v. 109, p. 539–562, doi: 10.1086/321962.

Wakabayashi, J. and Rowe, C., 2015, Whither the megathrust? Localization of large-scale subduction slip along a contact of a mélange: International Geology Review. v. 57, p. 854-870. doi:10.1080/00206814.2015.1020453

Wentworth, C. M., Blake, M. C., Jr., Jones, D. L., Walter, A. W., and Zoback, M. D., 1984, Tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges, in M.C. Blake Jr., ed., Franciscan geology of northern California: Society of Economic Paleontologists and Mineralogists, v. 43, 163-173.

Additional Resources

Anczkiewicz, R., Platt, J.P., Thirlwall, M.F., and Wakabayashi, J., 2004, Franciscan subduction off to slow start: Evidence from high-precision Lu-Hf garnet ages on high-grade blocks: Earth and Planetary Science Letters, v. 225, p. 147–161, doi: 10.1016/j.epsl.2004.06.003.Anonymous, 1972, Ophiolites: Geotimes, v. 17, p. 24-25.

Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Zeng, Y., 2013, Uniform California earthquake rupture forecast, version 3

(UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792. Available at: http://pubs.usgs.gov/of/2013/1165/.

Grove, M., Gehrels, G.E., Cotkin, S.J., Wright, J.E., and Zou, H., 2008, Laurentian cratonal provenance of Late Ordovician eastern Klamath blueschists and a link to the Alexander terrane: in Wright, J.E., and Shervais, J.W., eds. Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper 438, p. 223-250.

Hildebrand, R.S., 2012, Mesozoic Assembly of the North American Cordillera: Geological Society of America Special Paper 495, 182 p., doi:10.1130 /9780813724959.

Hildebrand, R.S., 2015, Dismemberment and northward migration of the Cordilleran orogen: Baja-BC re-solved: GSA Today, v. 25, no. 11, p. 4–11, http://rock.geosociety.org/gsatoday/archive/25/11/article/i1052 -5173-25-11-4.htm.

Lahr, K.M., Lahr, J.C., Lindh, A.G., Bufe, C.G., and Lester, F.W., 1976, The August 1975 Oroville earthquakes: Bulletin of the Seismological Society of America, v. 66, no. 4., p. 1085-1099.

Lettis, W.R., and Unruh, J.R., 1991, Quaternary geology of the Great Valley, California, in Morrison, R.B., ed., Quaternary Non-Glacial Geology of the Western United States: Decade of North American Geology, v. K-2, Geological Society of America, p. 164-176.

Moores, E. M., 1998, Ophiolites, the Sierra Nevada, "Cordillera", and orogeny along the Pacific and Caribbean margins of North and South America: International Geology Review, v. 410, p. 40-54.

O'Connell, D. R. H., Unruh, J.R., and Block, L.V., 2001, Source Characterization and Ground Motion Modeling of the 1892 Vacaville-Winters Earthquake Sequence, California: Bulletin of the Seismological Society of America, v. 91, p. 1471-1497.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p., *https://dx.doi.org/10.3133/ofr20141091*.

Page, B.M., Thompson, G.A., and Coleman, R.G., 1998, Late Cenozoic tectonics of the central and southern Coast Ranges of California: Geological Society of America Bulletin, v. 110, p. 846-876, doi: 10.1130/0016-7606(1998)110<0846:OLCTOT>2.3.CO;2

Paterson, S.R., Tobisch, O.T., and Radloff, J.K., 1987, Post-Nevadan deformation along the Bear Mountains fault zone: Implications for the Foothills terrane, central Sierra Nevada, California: Geology, v. 15, p. 513 16,doi:10.1130/00917613 (1987)15<513:PDATBM>2.0.CO;2.

Peterson, G.L., 1967a, Upper Cretaceous stratigraphic discontinuity: Northern California and Oregon: American Association of Petroleum Geologists Bulletin, v. 51, p. 558–568.

Peterson, G.L., 1967b, Lower Cretaceous stratigraphic discontinuity in northern California and Oregon: American Association of Petroleum Geologists Bulletin, v. 51, p. 864–872.

Renne, P.R., Tobisch, O.T., and Saleeby, J.B., 1993, Thermochronologic record of pluton emplacement, deformation, and exhumation at Courtwright shear zone, central Sierra Nevada, California: Geology, v. 21, p. 331–334. doi:10.1130/00917613(1993)021<0331:TROPED>2.3.CO;2.

Saha, A., Basu, A.R., Wakabayashi, J., and Wortman, G.L., 2005, Geochemical evidence for subducted nascent arc from Franciscan high-grade tectonic blocks: Geological Society of America Bulletin, v. 117, no. 9/10, doi:10.1130/B25593.1

Schweickert, R. A., Armstrong, R. L., and Harakal, J. E., 1980, Lawsonite blueschist in the northern Sierra Nevada: Geology, v. 8, p. 27-31, doi:10.1130/0091-7613(1980_8<27:LBITNS.2.0.O;2.

Tobisch, O.T., Saleeby, J.B., Renne, P.R., McNulty, B., and Tong, W., 1995, Variations in deformation fields during the development of a large-volume magmatic arc, central Sierra Nevada, California: Geological Society of America Bulletin, v. 107, p. 148–166, doi: 10.1130/0016-7606(1995)107<0148:VIDFDD>2.3.CO;2.

Tobisch, O.T., Saleeby, J.B., Renne, P.R., McNulty, B., and Tong, W., 1995, Variations in deformation fields during the development of a large- volume magmatic arc, central Sierra Nevada, California: Geological Society of America Bulletin, v. 107, p. 148–166, doi: 10.1130/0016-7606(1995)107<0148:VIDFDD>2.3.CO;2.

Unruh, J.R., Humphrey, J., and Barron, A., 2003, Transtensional model for the Sierra Nevada frontal fault system, eastern California: Geology, v. 31, p. 327-330.

WCC (Woodward-Clyde Consultants), 1977, Earthquake evaluation study, Auburn Dam, Volume 3, Regional geology and tectonics: Report for the U.S. Bureau of Reclamation.

WCC (Woodward-Clyde Consultants), 1978, Stanislaus Nuclear Project, Site Suitability, Appendix C.4 of Volume 6: Foothills Fault system study: Report to Pacific Gas and Electric Company.

Wakabayashi, J., Ghatak, A., and Basu, A.R.,2010, Tectonic setting of supra subduction zone ophiolite generation and subduction initiation as revealed through geochemistry and regional field relationships: Geological Society of America Bulletin, v. 122, p. 1548-1568 doi: 10.1130/B30017.1

Wells, D., and Coppersmith, K., 1994, New empirical relationships among magnitude, rupture length, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1002.

Worrall, D.M., 1981, Imbricate low-angle faulting in uppermost Franciscan rocks, south Yolla Bolly area, northern California: Geological Society of America Bulletin, v. 92, p. 703–729, doi: 10.1130/0016-7606(1981)92 <703:ILFIUF>2.0.CO;2.

Chapter VI. Climate and Climate Change Impacts

Cal-Adapt website, 2018, Exploring California's Climate Change Research, Available at: http://cal-adapt.org/. Accessed on: 19 Jun 2018

Climate Action Team, 2013, Preparing California for Extreme Heat, Guidance and Recommendations, 30 pages. Available at: www.climate change.ca.gov. Accessed on 4 July 2018

Dettinger, Mike, Fred Martin Ralph, Tapash Das, Paul J Neiman, and Daniel R. Cayan. Cayan, 2011, Atmospheric rivers, floods and the water resources of California, Water 2011 V3, No. 2. P. 445-478

Dettinger, Mike, 2016, Historical and future relations between large storms and drought in California, San Francisco Estuary and Watershed Science, July 2016

Energy Commission, 2018, California Energy Commission website – research and development Reports and Publications. Available at: http://www.energy.ca.gov/research/reports_pubs.html. Accessed on: 19 Jun 2018

Gershunov, A., and Guirguis, K. "California heat waves in the present and future. Geophysical Research Letters, 39, L18710, doi: 10.1029/2012GL052979, 2012.

Hayhoe, K., Cayan, D., Field, CB, Frumhoff, PC, Maurer, E., Miller, N.L., Moser, S.C., Schneider, S.H., Cahill, K.N., Cleland, E.E., Dale, L., Dradek. R., Hanemann, R.N., Kalkstein, L.S., Lenishan, J., Lunch, C.K., Neilson, R. P., Sheridan, S.C., Verville, J. H., "Emissions Pathways, climate, change, and impacts on California. Proceedings of the National Academy of Sciences, August 24, 2004, Vol 101, no 34, 12422-13427.

Zhu, Y., and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric rivers. Monthly Water Review, v. 126, Issue 3pp. 725 – 735.

Chapter VII. Natural Resources

Non-metal Mining – (includes Placer Mining; does not include Dimension Stone)

Construction Aggregate

Allen, V.T., 1929, The Ione Formation of California: University of California, Berkeley Bulletin of the Department of Geological Sciences, v. 18, no. 14, p. 347-448.

Averill, C.V., 1946, Placer Mining for Gold in California: Division of Mines Bulletin 135, 377 p.

Bradley, W.W., 1917, The Counties of Colusa, Glenn, Lake, Marin, Napa, Solano, Sonoma, Yolo: California State Mining Bureau Report of the State Mineralogist, v. 15, p. 367-370.

Busby, C.J., Hagan, J.C. and Renne, P., 2013, Initiation of Sierra Nevada range-front Walker Lane faulting ca. 12 Ma in the Ancestral Cascades arc: Geosphere, v. 9, p. 1125-1146.

Busby, C.J., Andrews, G.D.M., Koerner, A.K., Brown, S.R., Melosh, B.L., and Hagan, J.C., 2016, Progressive derangement of ancient (Mesozoic) east-west Nevadaplano paleochannels into modern (Miocene-Holocene) north-northwest trends in the Walker Lane Belt, central Sierra Nevada: Geosphere, v. 12, p. 135-175.

Carlson, D.W., 1955, Mines and Mineral Resources of Sacramento County, California: California Journal of Mines and Geology, v. 51, no. 1, p. 117-199.

Christensen, O.D., Henry, C.D., and Wood, J., 2015, Origin of Gold in Placer Deposits of the Sierra Nevada Foothills, California: Geological Society of Nevada Symposium 2015, p. 833-859.

Clark, W.B., 2005, Gold Districts of California: California Geological Survey Bulletin 193, 199 p.

CNRA, 2009, California Natural Resources Agency Abandoned Mine Inventory. Available at: http://www.conservation.ca.gov/dmr/abandoned_mine_lands/. Accessed on: 8 July 2018

Creely, S., and Force, E.R., 2007, Type Region of the Ione Formation (Eocene, Central California: Stratigraphy, Paleogeography, and Relation to Auriferous Gravels, U. S. Geological Survey Open-File Report 2006-1378, 65 p.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.: American Journal of Science, v. 304, p. 105-168.

Dietrich, W.F., 1928, The Clay Resources and the Ceramic Industry of California, California Division of Mines and Mining, Bulletin 99, 388 p.

Doolittle, J.E., 1905, Gold Dredging in California: California State Mining Bureau Bulletin 36, 120 p.

Garside, L.J., Henry, C.D., Faulds, J.E. and Hinz, N.H., 2005, The upper reaches of the Sierra Nevada auriferous gold channels, California and Nevada, in Rhoden, H.N., Steininger, R.C., and Vikre, P.G., eds., Geological Society of Nevada Symposium 2005: Window to the World, Reno, Nevada, May 2005, 27 p.

Gutierrez, C. I., 2011. Preliminary geologic map of the Sacramento 30' x 60' quadrangle, California, California Geological Survey. Available at: http://www.conservation.ca.gov/cgs/rghm/rgm/Pages/preliminary_geologic_maps.aspx#30x60quads. Accessed on 29 July 2018

Hammond, J.H., 1889, The Auriferous Gravels of California: California State Mining Bureau Report of the State Mineralogist v9, p. 105-138.

Henry, C.D., Hinz, N.H., Faulds, J.E., Colgan, J.P., John, D.A., Brooks, E.R., Cassel, E.J., Garside, L.J., Davis, D.A., and Castor, S.B., 2012, Eocene-Early Miocene paleotopography of the Sierra Nevada-Great Basin-Nevadaplano based on widespread ash-flow tuffs and paleovalleys: Geosphere, v. 8, p. 1-27.

Jenkins, O.P., 1954, California Journal of Mines and Geology: California Division of Mines, Volume 50, 780 p.

Jenkins, O.P., 1955, California Journal of Mines and Geology: California Department of Natural Resources Division of Mines, Volume 51, 465 p.

Logan, C.A., 1925, Sacramento County: California State Mining Bureau Report of the State Mineralogist, v. 21, no. 1, p. 1-22.

Long, K.R., DeYoung, J., Jr., and Ludington, S.D., 1998, Database of Significant Deposits of Gold, Silver, Copper, Lead, and Zinc in the United States: U.S. Geological Survey Open-File Report 98-206.

Mosier, D.L., 2003, History of Brickmaking in California, http://calbricks.netfirms.com/brickhistory.html (accessed 4/20/2017).

O'Brien, J.C., 1950, Mines and Mineral Resources of Yolo County: California Journal of Mines and Geology, v. 46, no. 3, p. 421-436.

Pask, J.A., and Turner, M.T., 1952: Geology and Ceramic Properties of the Ione Formation, Buena Vista Area, Amador County, California, California Division of Mines, Special Report 19, 38 p.

Severson, T., 1973, Sacramento: An Illustrated History 1839 to 1874 From Sutter's Fort to Capital City, California Historical Society, 207 p.

Southam, G., Lengke, M.F., Fairbrother, L. and Reith, F., 2009, The Biogeochemistry of Gold: Elements, v. 5, pp. 303-307.

Testa, S. M. and Arcand, W. J., 2016, An Overview of Surface Mining in the Yuba Goldfields, California, Association of Engineering and Environmental Geologists Special Publication on Applied Geology in California, pp.369-377.

Tucker, W.B. and Waring, C.A., 1917, Part III: The Counties of El Dorado, Placer, Sacramento, Yuba: California State Mining Bureau Report of the State Mineralogist, v. 15, p. 400-416.

Wakabayashi, J., 2013, Paleochannels, stream incision, erosion, topographic evolution, and alternative explanations of paleoaltimetry, Sierra Nevada, California: Geosphere, v. 9, p. 191-215.

Watts, W.L., 1890, Sacramento County: California State Mining Bureau Report of the State Mineralogist, v. 10, p. 496-514.

Wheeler, S.M., and Beebe, C.W., 2011, The Rise of the Postmodern Metropolis: Spatial Evolution of the Sacramento Metropolitan Region: Journal of Urban Design, v. 16, p. 307-332.

Whitney, J.D., 1880, The Auriferous Gravels of the Sierra Nevada: Contributions to American Geology, Volume 1, Cambridge University Press, John Wilson and Sons

Winston, W.B. and Janin, C., 1910, Gold Dredging in California: California State Mining Bureau Bulletin 57, 312 p.

Wood, J., 1994, A Re-Evaluation of the Origin of Kaolinite in the Ione Depositional System (Eocene), Sierra Foothills, California: Los Angeles, California State University, M.S. Dissertation, 86 p.

Yeend, W.E., 1974, Gold-Bearing Gravel of the Ancestral Yuba River, Sierra Nevada, California: U.S. Geological Survey Professional Paper 772, 44 p.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001, Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present: Science, v. 292, p. 686-693.

Additional Resources

Alpers, C.N., Hunerlach, M.P., May, J.T., Hothem, R.L., 2005, Mercury Contamination from Historical Gold Mining in California: U.S. Geological Survey Fact Sheet 2005-3014, 6 p.

Churchill, R.K., 2000, Contributions of mercury to California's environment from mercury and gold mining activities; Insights from the historical record, *in* Extended abstracts for the U.S. EPA sponsored meeting, Assessing and Managing Mercury from Historic and Current Mining Activities, November 28-30, 2000, San Francisco, Calif., p. 33-36 and S35-S48.

Clark, W. B., 1965, Tertiary channels: California Division of Mines and Geology, Mineral Information Service, v. 18, no. 3, pp. 39-44.

Clinkenbeard, John P., 2012, Aggregate Sustainability in California, California Geologic Survey Map Sheet 52 (updated 2012). Available at: http://www.conservation.ca.gov/cgs/information/publications/ms/Documents/MS_52.pdf. Accessed on: 19 March 2018

Gilbert, Grove Karl, 1917, Hydraulic Mining Debris in the Sierra Nevada: U.S.G.S. Professional Paper No. 105, 155 p., photographs from paper are available from library of congress HAER, CAL, 58-SMAV1.V1, 1991)

Irelan, W., 1888, Eight Annual Report of the State Mineralogist, California State Mining Bureau, 948 p.

Ross, Philip R., 1970, Origins of Hydraulic Mining: The Holmes Book Company, Oakland, California, 88 p.

Ross, Philip R., 1970, Origins of Hydraulic Mining: The Holmes Book Company, Oakland, California, 88 p.

Wagner, D.L., Jennings, C.W., Bedrossian, T.L., and Bortugno, E.J., 1981, Geologic map of the Sacramento quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series Sacramento Quadrangle – Map No. 1A, scale 1:250,000.

Dimension Stone

CSMB, 2011, California quarries from the American Era through 1914, California State Mining Board. Available at: https://quarriesandbeyond.org/articles_and_books/pdf/ca-quarrying_amer_era_to_1914_full_version.pdf. Accessed on: 14 Aug 2018

Day, Gary, 2014, Looking back: Rocklin's legacy was founded in Granite, Placer Herald December 2014. Available at: http://www.placerherald.com/article/12/30/14/looking-back-rocklin%E2%80%99s-legacy-was-founded-granite. Accessed on: 4 April 2018

Swanson, Samuel E., 1978, Petrology of the Rocklin pluton and associated rocks, western Sierra Nevada, California. GSA Bulletin: 89 (5): 679–686. May 1978.

Lode Gold

Busbya and Putirka, 2009. Miocene Evolution of the Western Edge of the Nevadaplano in the Central and Northern Sierra Nevada: Palaeocanyons, Magmatism, and Structure, Cathy J. Busbya and Keith Putirkab, International Geology Review Vol. 51, Nos. 7–8, July–August 2009, 670–701

Clark, W. B., 1952, Argonaut Mine Tailings, Amador County: Unpublished preliminary report no. 24, California Division of Mines, 4p.

Clark, W.B., 1970, Gold districts of California: Division of Mines and Geology Bulletin 193, 186 p. Available at: http://www.westernmininghistory.com/articles/284/page1. Accessed on 23 February 2018. Courtesy of Western mining history.

Clark, 1976. Stratigraphy of the North Half of the Western Sierra Nevada Metamorphic Belt, California, U.S. Geological Survey Professional Paper 923, Loren Clark, 1976.

Dodge, F.W. and R.C. Loyd, 1984, gold deposits of the western Sierra Nevada. Field Trip Guide, U.S. Geological Survey, Open file Report 84-169, 25 p.

Edelman and Sharp, 1989. Terranes, Early Faults, and Pre-Later Jurassic Amalgamation of the Western Sierra Metamorphic Belt, California, Steven Edelman and Warren Sharp, Geological Society of America Bulletin, v. 101, p. 1420-1433, November 1989.

Green Energy, 2018: Pelton Turbine. Available at: https://www.gerenewableenergy.com/hydro-power/large-hydropower-solutions/hydro-turbines/pelton-turbine.html. Accessed on: 23 February 2018

Knopf, A., 1929, The Mother Lode System of California: USGS Professional Paper 157, 88p.

Logan, C. A., 1934, Mother Lode Gold Belt of California: California Division of Mines Bulletin 108, 298p.

Original Sixteen to One Mine, 2018, website of the Original Sixteen to one Mine, Inc. Available at: http://www.origsix.com/tmarticle.asp?id=123. Accessed on 23 Feb 2018

Snow and Scherer, 2006. Terranes of the Western Sierra Nevada Foothills Metamorphic Belt, California: A Critical Review, Cameron A. Snow and Hannah Scherer, International Geology Review, Vol. 48, 2006, p. 46–62.

Snow, Bird, Metcalf, and McWilliams, 2010. Chronology of Gold Mineralization in the Sierra Nevada Foothills from $^{40}Ar/^{39}Ar$ Dating of Mariposite, Cameron Snow, Dennis Bird, James Metcalf, and Michael McWilliams, International Geology Review, 50:6, 503-518, August 2010.

Testa, S. M. and Arcand, W. J., 2016, An Overview of Surface Mining in the Yuba Goldfields, California, Association of Engineering and Environmental Geologists Special Publication on Applied Geology in California, pp.369-377.

Wittkopp, R.W. and Babros, W.C., 2015. The Gold Mines of the Allegany-Forest City Mining District, Sierra County, California, Comstock Bonanza Press.

Wagner, Jack R., 1980, Gold Mines of California, An Illustrated History of the Most Productive Mines with Descriptions of the Interesting People Who Owned and Operated Them, Howell-North Books, San Diego California

Zimmerman, J. E., 1983, The geology and Structural Evolution of a Portion of the Mother Lode Belt, Amador County, California: Unpublished M.S. Thesis, University of Arizona, 138p.

Additional Resources

Averill, C. V., 1942. Mine and mineral resources of Sierra County; California Div. Mine. Rept. 38, pp. 17-48.

Carlsson, C., 2017. San Francisco, Yerba Buena Cove, 1851, Courtesy, Wind Powered Transportation…Back Then Historical Essay. Available at: http://www.foundsf.org/index.php?title=Wing_Powered_Transportation...Back_Then.

Carlson, D. W., and Clark, W. B., 1956. Lode gold mines of the Alleghany-Downieville area, Sierra County: California Journal of Mines and Geology, vol. 52, no. 3, pp. 237-272.

Clark, W. B., and Fuller, W. P., Jr., 1968. The Original Sixteen-to-One Mine, California Div. Mine. and Geology Mineral Information Service. vol. 21, no. 5, pp. 71-75 and 78.

Clark, W. B. and Lydon, P. A., 1962, Mines and Mineral Resources of Calaveras County, California: California Division of Mines & Geology County Report 2.

Clark, W. B., 1970, Gold districts of California: California Division of Mines and Geology Bulletin 193, 186 p., plates.

Clark, J., 2005. Gold in Quartz, The Legendary Idaho Maryland Mine, Comstock Bonanza Press.

Cooke. H. R., Jr., 1947. The Original Sixteen-to-One gold quartz vein, Alleghany, California: Econ. Geology, vol. 42, no. 3, pp. 211-250.

Crawford, J. J., 1894. Gold-Nevada County: California Min. Bur. Rept. 12, pp. 185-203.

Crawford, J. J., 1896. Gold-Nevada County: California Min. Bur. Rept. 13, pp. 234-271.

Farmin, R., 1938. Dislocated inclusions in gold quartz veins at Grass Valley, California: Econ. Geology, vol. 33, pp. 579-599.

Farmin, R., 1941. Occurrence of scheelite in Idaho-Maryland Mines at Grass Valley, California: California Div. Mines Rept. 37, p. 224.

Ferguson, H. G., 1915. Lode deposits of the Alleghany district, California, U. S. Geol. Survey, Bull. 580, pp. 153-182.

Ferguson, H. G., and Gannett, R. W., 1932. Gold-quartz veins of the Alleghany district, California, U. S. Geol. Survey Prof. Paper 172, 139 pp.

Gilbert, Grove Karl, 1917, Hydraulic Mining Debris in the Sierra Nevada: U.S.G.S. Professional Paper No. 105, 155 p.

Hanks, H. G., 1886. Nevada County: California Min. Bur. Rept. 6, pp. 44-49.

Hobson, J. B., 1890. Grass Valley district: California Min. Bur. Rept. 10, pp. 370-384.

Hobson, J. B., and Wiltsee, E. A., 1893. Grass Valley mining district: California Min. Bur. Rept. 11, pp. 267-285.
Hoover, H. c., 1896. Some notes on crossings: Min. and Sci. Press, vol. 72, pp. 166-167.
Howe, Ernest, 1924. The gold ores of Grass Valley, California: Econ. Geology, vol. 19, pp. 595-621.
Irelan, William, 1888. Grass Valley district: California Min. Bur. Rept. 8, pp. 425-435.
Isenberg, Andrew C., 2005, Mining California – An Ecological History: Hill and Wang, New York, 242 p.
Johnston, W. D., Jr., 1932. Geothermal gradient at Grass Valley, Calif.: Washington Acad. Sci. Jour., vol. 22, pp. 267-271.
Johnston, W. D., Jr., 1940. The gold-quartz veins at Grass Valley, California: U. S. Geol. Survey Prof. Paper 194, 101 pp.
Johnston, W. D., Jr., and Closs, Ernst, 1934. structural history of the fracture systems at Grass Valley, Calif.: Econ. Geology, vol. 29, pp. 39-54.
Knaebel, J. B., 1931. The veins and crossings of the Grass Valley district: Econ. Geology, vol. 26, pp. 375-398.
Lindgren, W., 1895. Smartsville folio, California: U. S. Geol. Survey Geol. Atlas of the U. S., folio 18, 6 pp.
Lindgren, W., 1896. Nevada City special folio, California: U.S. Geol. Survey Geol. Atlas of the U. S., folio 29, pp.
Lindgren, W., 1896. Gold-quartz veins of Nevada City and Grass Valley districts: U. S. Geol. Survey, 17th Ann. Rept. pt. 2, pp. 1-262.
Lindgren, W., 1900. U. S. Geol. Survey Geol. Atlas of the U.S., Colfax folio 66.
Lindgren, W., 1911. The Tertiary gravels of the Sierra Nevada of California, U. S. Geol. Survey Prof. Paper 73, p. 142.
Logan, C. A., 1923. Quartz mining in the Alleghany district, California Mining Bureau, Report 18, pp. 499-519.
Logan, C. A., 1929. Alleghany District, California Mining Bureau Report 25, pp. 156-159.
Logan, C. A., 1930. Nevada County, Grass Valley district: California Div. Mines Rept. 26, pp. 96-99.
Logan, C. A., 1941. Mineral resources of Nevada County-gold quartz mining: California Div. Mines Rept. 37, pp. 380-431.
MacBoyle, E., 1919. Nevada County, Grass Valley district: California Min. Bur. Rept. 16, pp. 14-30.
MacBoyle, E., 1920. Sierra County, Alleghany mining district: California Mining Bureau, Report 16, pp. 1-5.
Simkin., W. A., 1923. The Alleghany district of California: Pacific Mining News of Eng. and Min. Journal, vol. 2, pp. 288-291.
Turner, H. W., 1897. Downieville folio, U. S. Geol. Survey Geological Atlas of the U. S., folio 37, 8 pp.
Vanderburg, W. O., 1930, Mining Methods and Costs at the Argonaut Mine, Amador County: California Bureau of Mines Information Circular 6311, 15p.

Foothill Copper-Zinc Belt

Heyl, G. R., 1948, Ore Deposits of Copperopolis, Calaveras County, California: California Division Mines Bulletin 144, 425p.

Reynolds, S.D., 2008, Spenceville Abandoned Copper Mine, Nevada County, California. Draft Final Closure Report: California Geological Survey, Sacramento, CA.

Reynolds, S.D., 2012, Reclamation of Spenceville Copper Mine: In *Reclaiming the Sierra: Green Solutions to Abandoned Mines*, Sierra Fund, Nevada City, CA, May 3–5, Abstracts, p. 17.

Russell, Daniel E., 2008, The Spenceville Copper Mine, Nevada County, California, mindat.org. Available at: https://www.mindat.org/article.php/320/Spenceville+Copper+Mine%2C+Nevada+Co.%2C++CA. Accessed on: 7 Aug 20189

Chromium

CDMG, 1951. Cater, F.W., Jr., Rynearson, G.A., and Dow, D.H., 1951, Chromite Deposits of El Dorado County, California, Geological Investigations of Chromite in California, Part 3: California Division of Mines and Geology Bulletin 134.

GSA, 1980. Springer, R.K., 1980, Geology of the Pine Hill Intrusive Complex, a Layered Gabbroic Body in the Western Sierra Nevada Foothills, California: Summary, GSA Bulletin (1980) 91 (7): pp. 381-385.

Loyd, R.C., 1984, California Division of Mines and Geology Open File Report 84-50, Mineral Land Classification of the Folsom 15-Minute Quadrangle, Sacramento, El Dorado, Placer, and Amador Counties, California.

USGS, 1940. Wells, F.G., Page, L.R., and James, H.L., 1940, U.S. Geological Survey, Bulletin 922-O, Chromite Deposits of the Pilliken Area, El Dorado County, California, Strategic Minerals Investigations.

Additional Resources

USBM, 1958. McInnis, Wilmer; Heidrich, Hilda, 1958, U.S. Bureau of Mines, Minerals Yearbook Metals and Minerals (except fuels) Year 1957, Volume I (1958).

How Mining Practices Shaped California Law

Atchison v. Peterson, 20 Wall 507 (1874)

Dorrity, 1992, Will Federal Environmental Regulation be Permitted to Infringe on State Vested Water

Rights? 11 UCLA Journal of Environmental Law and Policy, Dorrity K. (1992)

Freyfogle, 1985, Lux v. Haggen and the Common Law Burdens of Modern Water Law, Columbia Law Review, Eric T. Freyfogle (1985)
Gilbert, 1917, Hydraulic-mining debris in the Sierra Nevada, USGS Professional Paper 105, G.K. Gilbert (1917)
Irwin v. Phillips, 5 Cal. 140 (1855)
Katz v. Walkinshaw, 141 Cal. 116 (1902)
Kelly, 1998, Battling the Inland Sea Floods, Public Policy, and the Sacramento Valley, Robert Kelley
Kinney, 1912, Kinney, Law of Irrigation & Water Rights
Los Ángeles v. Glendale, 23 Cal. 2d 68 (1943)
Los Ángeles v. San Fernando, 14 Cal. 3d 199 (1975)
Lux v. Haggen, 69 Cal. 255 (1886)
National Audubon Society v. Department of Water and Power, 33 Cal. 3d 419 (1983)
Poland, 1988, Subsidence Due to Groundwater Withdrawal, in Perspectives on Water, Oxford Press Review, J. Poland (1988)
Reich, 1994, Mission Revival Jurisprudence: State Courts and Hispanic Water Law Since 1850, Washington Law Review, Peter L Reich (1994)
Shaw, 1922, Development of the Law of Waters in the West, California Law Review, Lucien Shaw
Tarlock, 1994, From Natural Scarcity to Artificial Abundance: The Legacy of California, Water Law and Politics (inaugural issue), Hastings Journal of Environmental Law and Policy, A. D. Tarlock (1994)
Vernon Irrigation Co. v. Los Angeles, 106 Cal. 237 (1895)
Wiel, 1912, Public Policy in Western Water Decisions, California Law Review, Samuel C. Wiel
Woodruff v. North Bloomfield Gravel Mining Co., 18 F. 753 (9^{th} Cir. 1884).

Additional Resources

Governor's Commission to Review California Water Rights, Groundwater Rights in California, Back ground and Issues, by Anne J. Schneider, Staff Paper No. 2, July 1977.

Water Resources

Belitz, K., Fram, M.S., and Johnson, T.D. 2015. Metrics for Assessing the Quality of Groundwater Used for Public Supply, CA, USA: Equivalent-Population and Area. Environmental Science & Technology. v. 49. p. 8330-8338.
Bennett, G.L., V, Fram, M.S., and Belitz, Kenneth, 2011, Status of groundwater quality in the Southern, Middle, and Northern Sacramento Valley study units, 2005–08—California GAMA Priority Basin Project. USGS Scientific Investigations Report 2011–5002.

Berkstresser, C.F., Jr., 1973, Base of Fresh Ground-Water – Approximately 3,000 micromhos - in the Sacramento Valley and Sacramento-San Joaquin Delta, California. U.S. Geological Survey Water-Resources (USGS) Investigation 40-73.

Brown and Caldwell, 2016, Public draft 2015 Urban Water Management Plan, Davis, California. Available at: http://cityofdavis.org/Home/ShowDocument?id=5586. Accessed on: 13 August 2018

Borchers, 2016, Land Subsidence from Groundwater Use in California, Chapter 6 (Jim Borchers) in Applied Geology in California, Special Publication 26. Association of Environmental and Engineering Geologists.

Burt, 2011, Characteristics of Irrigation Pump Performance in Major Irrigated Areas of California. ITRC Report No. R 11-004. Irrigation Training and Research Center. May.

CalWater, 2016, 2015 Urban Water Management Plan. Dixon District. California Water Service. June. Central Sacramento County Groundwater Management Plan Task Force (CSCGMPTF)

Central Sacramento County Groundwater Management Plan. February, Davis 2016, Final 2015 Urban Water Management Plan. City of Davis. June.

Department of Water Resources – California (DWR), 1970, Groundwater Geology of Northern Sacramento County. Field Trip Guidebook. May 9. California Department of Water Resources. Central District.

DWR, 1974, Evaluation of Ground Water Resources: Sacramento County. Bulletin 118-3. California Department of Water Resources. July.

DWR, 1978, Evaluation of Ground Water Resources: Sacramento Valley. Bulletin 118-6. California Department of Water Resources. August.

DWR, 1980, Bulletin 118-80. Ground Water Basins in California, A Report to the Legislature in Response to Water Code Section 12924.

DWR, 2003, California's Groundwater. Bulletin 118-03. Online Basin Summaries for the North American, South American, Solano, and Yolo Subbasins. California Department of Water Resources. Available at: http://www.water.ca.gov/groundwater/bulletin118/sacramentoriver.cfm

DWR, 2015a, Management of the California State Water Project. California Department of Water Resources. Bulletin 132-15. July. Available at: http://www.water.ca.gov/swpao/docs/bulletins/bulletin132/Bulletin132-15.pdf

DWR, 2015b, California's Groundwater Update 2013. A Compilation of Enhanced Content for California Water Plan Update 2013. California Department of Water Resources. April.

DWR, 2015c, Sustainable Groundwater Management Program. Draft Strategic Plan. California Department of Water Resources. March 9.

DWR, 2016, Unpublished Well Completion Report data for counties in the Sacramento Region, including Sacramento, Placer, Solano, and Yolo.

DWR, 2017a, California Department of Water Resources; California State Water Project. Available at: http://www.water.ca.gov/swp/

Fogg, G. and others, 2000, Connected-network paradigm for the alluvial aquifer system. Geological Society of America. Special Paper 348.

Fogg, G., 2008, My View: California water storage: Underworld and body. Special to the Bee. Opinion. Graham E. Fogg. Sacramento Bee. November 28.

Freeport Regional Water Authority (FRWA), 2017a. Freeport Regional Water Project. Available at: http://www.freeportproject.org/nodes/explore/

Freeport Regional Water Authority (FRWA), 2017b. Vineyard Surface Water Treatment Plant. Available at: http://www.freeportproject.org/nodes/explore/watertreatment.php

Hackell, 1966, Summary of the Geology of the Great Valley, Chapter 5. Geology of Northern California. Bulletin 190. California Department of Mines and Geology.

Ireland, R.L., 1986, Land subsidence in the San Joaquin Valley, California, as of 1983: U.S. Geological Survey Water Resources Investigations Report 85–4196, 50 p.

Lofgren, B.E. and Ireland, R.L., 1973, Preliminary Investigation of Land Subsidence in the Sacramento Valley, California. USGS Open File Report 74-1064.

Metropolitan Water District of Southern California (MWD), 2012, Available at: http://www.mwdh2o.com/Who%20We%20Are%20%20Fact%20Sheets/6.4.2_Maps_Major_Water_Conveyance.pdf

National Research Council, 1991, Panel on Land Subsidence, Committee on Ground Failure Hazards Mitigation, Commission on Engineering and Technical Systems, National Research Council. National Academy Press. Washington, D.C.

PBS, 2001, John Augustus Sutter 1803-1880. Available at: http://www.pbs.org/weta/thewest/people/s_z/sutter.htm. Accessed on: 8 July 2018

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, A.G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437-H, 78 p.

PCWA, 2005, West Placer County Groundwater Storage Study-Final Report. Placer County Water Agency. December.

RD2035, 2016, Agricultural Water Management Plan 2016. Reclamation District 2035. June 30.

Rio Vista, 2016, City of Rio Vista 2015 Urban Water Management Plan. City of Rio Vista Public Works Department. June 6.

Regional Water Authority (RWA), 2017, Regional Water Authority Drought Projects. Available at: http://rwah2o.org/9-7-million-for-water-projects-recommended-for-sacramento-region/

RWA Drought Projects Factsheet 2016.

SCGA, 2016, South American Subbasin Alternative Submittal. Sacramento Central Groundwater Authority. December.

SGA, 2014, Groundwater Management Plan, Sacramento County – North Basin. Sacramento Groundwater Authority. December.

SGA, 2011, Groundwater Quality Vulnerability Assessment. Prepared by Kennedy/Jenks Consultants, October 2011.

SID, 2016, 2015 Agricultural Water Management Plan. Solano Irrigation District. January.

Sneed, Michelle, Brandt, Justin, and Solt, Mike, 2013, Land subsidence along the Delta-Mendota Canal in the northern part of the San Joaquin Valley, California, 2003–10: U.S. Geological Survey Scientific Investigations Report 2013–5142, 87 p. Available at: http://dx.doi.org/10.3133/sir20135142

SSWD, 2016, Agricultural Water Management Plan. South Sutter Water District. March.

U.S. Bureau of Reclamation (USBR), 2017a. Reclamation; Managing Water in the West; Central Valley Project Water Supply. Available at: https://www.usbr.gov/mp/cvp-water/

USBR, 2017b, Mid-Pacific Region; Central Valley Project (CVP). Available at: https://www.usbr.gov/mp/cvp/

USGS, 2005, Estimated Withdrawals from Principal Aquifers in the United States, 2000. Department of the Interior. United States Geologic Survey. Circular 1279.

USGS, 2017, Land Subsidence in California. March 1. Available at: https://ca.water.usgs.gov/land_subsidence/index.html

Vacaville, 2016, Urban Water Management Plan. City of Vacaville Utilities Department. July.

Water Education Foundation, 2002, The Water Forum Agreement: A Model for Collaborative Problem Solving.

Water Forum (Sacramento Water Forum), 2015, Water Purveyor Overview. Available at: http://www.waterforum.org/water-supply/water-purveyor-overview/. Accessed on: 8 July 2018

Water Forum, 2012, 2011 & 2012 Water Conservation Report: Water Conservation Element of the Water Forum Agreement. July. Available at: http://www.waterforum.org/wp-content/uploads/2015/09/WC-Annual-Report-Year-11-and-12-2015.pdf

Water Forum Agreement (WFA), 2000, Water Forum Agreement.

Wikipedia, 2017, Central Valley Project. Available at: https://en.wikipedia.org/wiki/Central_Valley_Project

Woodland, 2016, 2015 Urban Water Management Plan-Final. City of Woodland. June.

WPCGMP, 2007, Western Placer County Groundwater Management Plan. Montgomery-Watson-Harza. November.

Yolo County, 1976, Investigation of Groundwater Resources. Yolo County. Clendenen & Associates-Consultants. May.

Additional Resources

DWR, 2017b, Base of Fresh Groundwater in the Central Valley. California Department of Water Resources. Map.

Frame and D'Onofrio, 2008, DWR/USBR Sacramento Valley Subsidence Project Report.
Freeze, R.A. and J.A. Cherry, 1979, Groundwater. Prentice Hall.

Oil and Gas

American Petroleum Institute, American Gas Association, and Interstate Natural Gas Association of America (API, AGA and INGS), 2016, Underground Natural Gas Storage, Integrity and Safe Operations, July 6.
Baker, P., 1975, A Re-Interpretation of the Eocene Capay Formation, Yolo County, California, Stanford University M.S. Thesis, August.
California Division of Oil and Gas, 1920, Summary of Operations, Forty-Ninth Annual Report of the State Oil and Gas Supervisor, Vol. 5, No. 12.
California Division of Oil and Gas, 1932, Memorandum of Telephone or Personal Conversation between F. Leslie Meeker and Deputy Supervisor H.V. Dodd, November, 19, 1932, in well files 01100254 and 01100255. Available at: ftp://ftp.consrv.ca.gov/pub/oil/WellRecord/011/01100254/01100254_DATA_04-17-2006.pdf. Accessed on: 20 March 2018
California Division of Oil and Gas, 1963, Summary of Operations, Forty-Ninth Annual Report of the State Oil and Gas Supervisor, Vol. 49, No. 2.
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 1982, California Oil and Gas Fields, Volume III – Northern California, Contour maps, cross sections, and data sheets for California's oil and gas fields. Available at: ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtasheet_vol_3.pdf
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2016, 2015 Report of California Oil and Gas Production Statistics, PR03, April.
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2018, Calstim'D web application map viewer. Available at: https://maps.conservation.ca.gov/doggr/calstimd/#openModal. Accessed on: 8 July 2018
Foxall, W., Layland-Bachmann, C., Jordan, P., T. Goebel, and E. Brodsky, 2018, Regional and Site-Specific Analysis of Spatio-temporal Relationships between Fluid Injection Associated with Oil Production and Induced Seismicity in California, Final report prepared for the California Department of Conservation, Division of Oil, Gas and Geothermal Resources, Department of Conservation Agreement No. 2016-026, February 12.
Garrison, R. D., 1992, Transverse Faulting and Gas Prospects in Basement of the Freeport Area, Southeast Sacramento Basin, in V.C. Chevren and W.F. Edmondson (eds.) Structural Geology of the Sacramento Basin: Pacific Section, American Association of Petroleum Geologists, p. 109-118.
Goebel, T., 2015, A comparison of seismicity rates and fluid injection operations in Oklahoma and California: Implications for crustal stresses. The Leading Edge, June 2015, 640-648.

Goebel, T., E. Hauksson, F. Aminzadeh, and J-P Ampuero, 2015, An objective method for the assessment of fluid-induced seismicity and application to tectonically active regions in central California. J. Geophys. Res., 120, 7013-7032.

Goebel, T., S. Hosseini, F. Cappa, E. Hauksson, F. Aminzadeh, J-P Ampuero and J. Saleeby, 2016, Wastewater disposal activity and earthquake swarm activity at the southern end of the Central Valley, California. Geophys. Res. Lett. 43, doi:10.1002/2015GL066948

Graham, S.A., 1981, Stratigraphic and Depositional and Hydrocarbon Occurrence, Sacramento Valley, California, in Field Guide to the Mesozoic-Cenozoic Convergent Margin of Northern California, Pacific Section AAPG Vol. 50, P. 43-58

Kotick, O.F., 1976, Short History of Northern California Geological Society, AAPG Bulletin Vol. 60, No. 6, p. 988-992.

Hector, S.C., 2014, Rio Vista Gas Field: History of Development, Pacific Section AAPG, SPE and SEPM Joint Technical Conference, Bakersfield, California, April 27-30.

Hough S.E., and M. Page, 2016, Potentially Induced Earthquakes during the Early Twentieth Century in the Los Angeles Basin, Bulletin of the Seismological Society of America, Vol. 106, No. 6, December, doi: 10.1785/0120160157

Imperato, D.P., Nilsen, T.H., and Moore, D.W., 1990, Regional stratigraphy of the mud-rich turbidite system of the Forbes Formation, Sacramento Basin, California, in Ingersoll, R.V., and Nilsen, T.H., eds., Sacramento Valley Symposium and Guidebook: Society of Economic Paleontologists and Mineralogists Book 65, p. 69-79.

Magoon L.B., and Z.C. Valin, 1995. Sacramento basin province (009), US Geological Survey National Oil and Gas Assessment, U. S. Geological Survey, Central Energy Resources Team

McLaughlin, R.J., Ohlin, H.N., and Thormahlen, D.J., 1990, Geologic Map and Structure Sections of the Little Indian Valley, Wilbur Springs Geothermal Area, Northern Coast Ranges, California, Scale 1:24,000, U.S. Geological Survey, Map I-1706.

McPherson, B.J. and G. Graves, Hydrodynamics and Overpressure Mechanisms in the Sacramento Basin, California, American Journal of Science, Vol. 299, p. 429-466.

Moore, D.W, 1991, Stratigraphy, sedimentology, and provenance of the lower Campanian Forbes and Marsh Creek formations, southern Sacramento and northern San Joaquin Basins, California, San Jose State University M.S. Thesis, May.

Pepper-Kittredge, O. and M.L. Wilson, 1984, The Markley Submarine Valley and its Stratigraphic Relationships Sacramento Valley, California in A.A. Almgren and P.D. Hacker (eds.), Paleogene submarine canyons of the Sacramento Valley, California: Pacific section, American Association of Petroleum Geologists, p. 81-99.

Redwine, L.E., 1984, The Tertiary Princeton Submarine Valley System beneath the Sacramento Valley, California, in A.A. Almgren and P.D. Hacker (eds.),

Paleogene submarine canyons of the Sacramento Valley, California: Pacific section, American Association of Petroleum Geologists, p. 53-80.
Reynolds, S.T., 1978, Basic Subsurface Geology of the South-Central Sacramento Valley, in Fieldtrip Guidebook: Castle Steam Field, Great Valley Sequence, April 29, 1978, Guidebook 45, Pacific Sections AAPG SEPM SEG, P. 4-8.
Rubinstein, J. and A.B., Mahani, Myths and Facts on Waste Water Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity, Seismological Research Letters, Volume 86, Number 4 July/August, doi: 10.1785/022015006.
Schaal, R.B., R.E. Criss, and M.L. Davisson, 1994, Saltwater Springs Atop the Rumsey Hills, California, California Geology, Vol. 47, no. 4. P. 67-75.
Sullivan, R. and M.D. Sullivan, 2012, Sequence Stratigraphy and Incised Valley Architecture of the Domengine Formation, Black Diamond Mines Regional Preserve and the Southern Sacramento Basin, California, U.S.A., Journal of Sedimentary Research, Vol. 82, P. 781-800.
Sullivan, R. and M.D. Sullivan, 2013, Markley Submarine Canyon or Something Different? A New Eocene Canyon in the Sacramento Basin, Northern California, Search and Discovery Article #30275, July 22.
Unruh, J.R., Davisson, M.L., Criss, R.E., and E.M. Moores, 1992, Implications of perennial saline springs for abnormally high fluid pressures and active thrusting in western California, Geology, Vol. 20, P. 431-434.
Zieglar and Spotts, 1981, Reservoir and Source-bed History of Great Valley, California: American Association of Petroleum Geologists Bulletin, Vol. 62, P. 813-826.

Geology Based Parks and Recreation

ARNHA, 2005, The Lower American River: Prehistory to the Parkway. Edited by Peter J. Hayes. The American River Natural History Association. Third Edition, 2005.
ARPF, 2009, Jedidiah Smith Memorial Trail Map. American River Parkway Foundation. Available at: http://arpf.org/pdf_files/ARPmap.pdf. Accessed on: 14 February 2018.
Burnett, John L., 1993, The Gold Bug Mine, California Geology, May-June 1993. Available at: ftp://ftp.consrv.ca.gov/pub/dmg/pubs/cg/1993/46_03.pdf. Accessed on: 22 February 2018
CDPR, 2018a, California Department of Parks and Recreation, Website Geological Gems of State Parks. Available at: https://www.parks.ca.gov/?page_id=29631. Accessed on: 12 April 2018
CDPR, 2018b, California Department of Parks and Recreation, Website Geological Gems of State Parks. Available at: https://www.parks.ca.gov/?page_id=494. Accessed on: 12 April 2018
CDMG, 1993, Gold – California State Mineral, California Geology, May-June 1993. Available at: ftp://ftp.consrv.ca.gov/pub/dmg/pubs/cg/1993/46_03.pdf. Accessed on: 22 February 2018

EMPA, 2018, Empire Mine Park Association website. Available at: http://www.empiremine.org/. Accessed on: 23 February 2018

Gold Bug Park, 2018, Available at: https://www.goldbugpark.org/visitor-info/history/. Accessed on: 22 February 2018

Fairman, David, 2007 A Gravel Budget for the Lower American River. MS Thesis, Spring 2007. California State University, Sacramento.

FEMA, 2012. Flood Insurance Rate Map. Panel 06067C0205H, Federal Emergency Management Agency, effective August 16, 2012.

James, L. Allan, 1999, Time and persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California: Geomorphology, v. 31, p. 265-290.

USDOI, 1980. Final Environmental Impact Statement, Proposed Designation of Five California Rivers in the National Wild and Scenic Rivers System. Prepared by the Heritage Conservation and Recreation Service, United States Department of the Interior, December 1980. Accessed at: https://www.rivers.gov/documents/studies/american-eel-klamath-smith-trinity-eis.pdf. Accessed on: 15 February 2018.

Additional Resources

Clark, W.B., 1970, Gold districts of California: Division of Mines and Geology Bulletin 193, 186 p. Available at: http://www.westernmininghistory.com/articles/284/page1. Accessed on 23 February 2018. Courtesy of Western mining history.

Dodge, F.W., and Loyd, R.C., 1984, Gold deposits of the western Sierra Nevada; Field Trip Guide: U.S. Geological Survey Open File Report 84-169, 25 p.

Hunsaker, L. and Curran, C., 2005. “Lake Sacramento” – Can It Happen Again? Printed by Copy Quik & Academy Printing, Grants Pass, Oregon. Copyright November, 2005.

Matthai, Howard F., 1951. Revision of Peak Discharge of American River at Fair Oaks, California, March 25, 1928. United States Geological Survey internal paper, unpublished paper, prepared December 14, 1951. Available at: https://cepsym.org/history/1951-Matthai-USGS.pdf. Accessed on: 15 February 2018.

Mount, Jeffrey F., 1995. California Rivers and Streams: The Conflict Between Fluvial Process and Land use. University of California Press, Berkeley and Los Angeles, California, 1995.

Peper, Paula J., 2014. Sacramento’s Sutter Park Neighborhood. StoneBridge Properties, LLC. First Edition, February 2014.

Porter, K., A. Wein, C. Alpers, A. Baez, P. Patrick, and others, 2011. Overview of the ARkStorm Scenario. United States Geological Survey Open File Report 2010-1312. Available at: https://pubs.usgs.gov/of/2010/1312/. Accessed on: 15 February 2018.

Shlemon, R. J., 1972. The Lower American River Area, California: A Model of Pleistocene Landscape Evolution. Yearbook of the Association of Pacific Coast Geographers. January, 1972.

Shlemon, R. J., 1995. Pleistocene channels of the lower American River, Sacramento County, California: (appended, five-page article) in Franks, A., and Moss, G. (leaders), Geology of the Sacramento area, foothills, and the Sierra Nevada mountains: Association of Engineering Geologists Field Trip Guide, 1995 Annual Meeting of the Association of Engineering Geologists and Groundwater Resources Association, Sacramento, CA.

Chapter VIII. Environmental Concerns

Mining, Railroads, Military, and Aerospace Industry

Alpers, C.N., Hunerlach, M.P., May, J.T., Hothem, R.L., 2005, Mercury Contamination from Historical Gold Mining in California: U.S. Geological Survey Fact Sheet 2005-3014, 6 p.

Beal AFB, 2016a, Beal Air Force Base Environmental Cleanup Program, Issue 70, August 2016. Available at: http://www.beale.af.mil/Portals/110/Docs/Environmental%20Docs/RAB_Newsletter_August_2016.pdf?ver=2016-09-07-174558-287. Accessed on: 22 January 2018

Beal AFB, 2016b, Beal Air Force Base Environmental Cleanup Program, Issue 67, October 2015. Available at: http://www.beal.af.mil/Portals/110/Docs/Environmental%20Docs/AFC-151109-027.pdf?ver=2016-02-22-155414-733. Accessed on: 22 January 2018

Carlson, D.W., 1955, Mines and Mineral Resources of Sacramento County, California: California Journal of Mines and Geology, v. 51, no. 1, p. 117-199.

CDMG, 1976, Gold Districts of California, Bulletin 193, California Division of Mines and Geology. Available at: http://www.westernmininghistory.com/articles/270/page1. Accessed on: 7 Aug 2018

California Department of Toxic Substances Control, 2007. DTSC proposes groundwater cleanup at the Inactive Rancho Cordova Test Site, Fact Sheet

Churchill, R.K., 2000, Contributions of mercury to California's environment from mercury and gold mining activities; Insights from the historical record, *in* Extended abstracts for the U.S. EPA sponsored meeting, Assessing and Managing Mercury from Historic and Current Mining Activities, November 28-30, 2000, San Francisco, Calif., p. 33-36 and S35-S48.

EPA, 2018a, U.S. Environmental Protection Agency Superfund Website. Available at: https://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/vwsoalphabetic/Mather+Air+Force+Base. Accessed on: 21 march 2018

EPA, 2018b, U. S. Environmental Protection Agency Superfund Website. Available at: https://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/3dec8ba3252368428825742600

43733/60508b9cae7346f088257007005e9436!OpenDocument. Accessed on: 21 March 2018

EPA, 2018c, U. S. Environmental Protection Agency Superfund Website. Available at: https://cumulis.epa.gov/supercpad/cursites/csitinfo.cfm?id=0902715. Accessed on: 21 March 2018

Gilbert, Grove Karl, 1917, Hydraulic Mining Debris in the Sierra Nevada: U.S.G.S. Professional Paper No. 105, 155 p.

Google Earth, 2017, Ortho-photo of Yuba River upstream of Parks Bar Bridge

GreatMining.com, 2018, Available at: http://www.greatmining.com/hydraulic-mining.html. Accessed on: 7 Aug 2018

Hagwood, Joseph J., 1981, *California Debris Commission*: U.S. Army Corps of Engineers Sacramento District, 102 p.

Kelley, R. L., 1959, Gold vs. Grain: The Arthur H. Clark Company, Glendale, CA, 327 p.

Mather, 2016. Available at: http://www.sacsplash.org/vernal-pools. Accessed on: 10 Oct 2016

Military Museum dot org. Available at: http://www.militarymuseum.org/CpKohler.html. Accessed on: 18 January 2018

OEHHA, 2018, California Office of Environmental Health Hazard Assessment. Available at: https://oehha.ca.gov/advisories. Accessed on: 8 July 2018

Osborne, Richard, 2011, World War II Sites in the United States: A Directory and Tour Guide

Personal communication, 2016a, US Air Force, Pentagon – Historical Support Division, Wright Patterson AFB

SCGA, 2008, Sacramento Central Groundwater Authority Basin Management Report 2007-2008. Available at: http://www.scgah2o.org/Documents/2007-2008%20Basin%20Management%20Report.pdf. Accessed on: 8 Aug 2018

Union Pacific, 2016. Sacramento Rail Yard Cleanup Clears Way for Economic Revitalization, Inside Track, January 07. Available at: https://www.up.com/aboutup/community/inside_track/sac-yard-1-07-2016.htm

wiki, 2016a, Wikipedia web page for Mather Air Force Base. Available at: https://en.wikipedia.org/wiki/Mather_Air_Force_Base. Accessed on: 10 Oct 2016

wiki, 2016b, Wikipedia web page for McClellan Air Force Base. Available at: https://en.wikipedia.org/wiki/McClellan_Air_Force_Base. Accessed on: 10 Oct 2016

wiki, 2016c, Wikipedia web page for Beal Air Force Base. Available at: https://en.wikipedia/org/wiki/Beal_Air_Force_Base. Accessed on: 11 October 2016

wiki, 2018, Wikipedia web page for Sacramento Army Depot. Available at: https://en.wikipedia.org/wiki/Sacramento_Army_Depot. Accessed on: 23 January 2018

Additional Resources

Goldfields, 2016. Available at: http://richmedia.onset.freedom.com/marysville/I21dj8-goldfields.pdf. Accessed on: 11 October 2016

Isenberg, Andrew C., 2005, Mining California – An Ecological History: Hill and Wang, New York, 242 p.

SGA, 2015, Sacramento Groundwater Authority, Figure 15 of the Sacramento Groundwater Authority Basin Management Report – 2016 Update. Available at: http://www.sgah2o.org/basin-conditions/groundwater-quality/. Accessed on: 8 Aug 2018

SGA, 2014, Sacramento Groundwater Authority, 2014 Groundwater Management Plan, Sacramento County – North Basin. Available at: http://www.sgah2o.org/wp-content/uploads/2016/06/GMP_SGA_2014_Final.pdf. Accessed on: 7 Aug 2018

Travis, 2016. Available at: https://travisheritagecenter.org/html/1-history.html. Accessed on: 11 October 2015

U.S. Geological Survey (USGS), 2000. Mercury Contamination from Historic Gold Mining in California, Fact Sheet FS-061-00

Asbestos

Alleman, James E. and Brooke Mossman, 1997, Asbestos Revisited, Scientific American, v. 277, pp. 54-57, doi:10.1038/scientificamerican0797-70

CARB, 2017, California Air Resources Board fact sheet. Available at: https://www.arb.ca.gov/toxics/asbestos/general.html. Accessed on 25 February 2018

CGS, 2018, California geological survey mineral resources webpage. Available at: http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/asbestos. Accessed on 25 February 2018

Churchill, Ronald K., Chris T. Higgins, and Bob Hill, 2000. California Geological Survey, Open-File Report 2000-02, Areas More Likely to Contain Natural Occurrences of Asbestos in Western El Dorado County, California, May 2000. Available at: http://www.capcoa.org/Docs/noa/%5B2%5D%20El%20Dorado%20County%20-%20CA%20Dept%20of%20Cons.pdf. Accessed on: 5 April 2018.

Higgins, Chris T. And John P. Clinkenbeard, 2006, Relative likelihood for the presence of naturally occurring asbestos in Eastern Sacramento County, California, California geological survey special report 192. Available at: http://www.conservation.ca.gov/cgs/information/publications/sr/Documents/east_sac_county_sr192.pdf accessed on 25 February 2018

Nolan, R.P., A.M. Langer, M. Ross, F.J. Wicks, and R.F. Martin, 2001, Health effects of chrysotile asbestos: contribution of science to risk-management decisions: The Canadian Mineralogist, Special Publication 5. Montreal, Quebec, Canada, 312 p.

Van Gosen, Bradley S. and John P. Clinkenbeard, 2011, Reported historic asbestos mines, historic asbestos prospects, and other natural occurrences of asbestos in

California, CGS Map Sheet 59, and USGS Open-File Report 1188. Available at: https://pubs.er.usgs.gov/publication/ofr20111188. Accessed on 25 February 2018

Additional Resources

CDMG, 2000, A general location guide for ultramafic rocks in California – areas more likely to contain naturally occurring asbestos, California Division of Mines and Geology, Open-File Report 19. Available at: ftp://ftp.consrv.ca.gov/pub/dmg/pubs/ofr/ofr_2000-019.pdf, Accessed on: 25 Feb 2018

Chapter IX. Natural Hazards

Flooding in the Sacramento Region

California Department of Water Resources, 2013. California's Flood Future: Recommendations for Managing the State's Flood Risk. Available at: http://www.water.ca.gov/SFMP/. Accessed on: 17 January 2018.

Dettinger, M., 2011. Climate Change, Atmospheric Rivers, and Floods in California – Multimodal Analysis of Storm Frequency and Magnitude Changes. *Journal of the American Water Resources Association*, Vol. 47, No. 3. June 2011.

Galloway, G., 2005, cited in Armah, J., H. Ayan, C. Bernard, A. Blumenhal, L. Fortmann, L.R. Garretson, C. Goodwin, W.D. Runolfson, T.B. Davis, J. Vano, and R.O. Zerbe Jr, 2009. Principles and guidelines for evaluating federal water projects: U.S. Army Corps of Engineers planning and the use of benefit cost analysis: A report for the Congressional Research Service. Evans School of Public Affairs, Univ. of Washington. Available at: http://fas.org/irp/agency/dhs/fema/evans.pdf. Accessed on: 17 January 2018.

Gilbert, G.K., 1917. Hydraulic-Mining Debris in the Sierra Nevada, U.S. Geological Survey Professional Paper 105.

Holms, R. 2011 Ten U.S. Historic Floods accessed September 17, 2011. Accessed at http://www.time.com/time/specials/packages/article/0,28840,2070796_2070791,00.html Accessed on: September 18, 2011

Hunsaker, L. and Curran, C., 2005. “Lake Sacramento” – Can It Happen Again? Printed by Copy Quik & Academy Printing, Grants Pass, Oregon. Copyright November, 2005.

Ingram, L., 2013. California megaflood: Lessons from a forgotten catastrophe. Scientific American, January 2013.

Kelley, R., 1989. Battling the Inland Sea: Floods, Public Policy, and the Sacramento Valley. Berkeley: The University of California Press.

Lund, J.R., 2012. Flood management in California. Water, 4: 57-169.

Matthai, Howard F., 1951. Revision of Peak Discharge of American River at Fair Oaks, California, March 25, 1928. United States Geological Survey internal paper, unpublished paper, prepared December 14, 1951. Available at: https://cepsym.org/history/1951-Matthai-USGS.pdf. Accessed on: 15 February 2018Ingram, L., 2013. California megaflood: Lessons from a forgotten catastrophe. Scientific American, January 2013.

Ohara, N., Kavvas, M.L., Anderson, M. L., Chen, Z.Q., and Ishida, K., 2017. Characterization of Extreme Storm Events Using a Numerical Model-Based Precipitation Maximization Procedure in the Feather, Yuba, and American River Watersheds in California. *Journal of Hydrometeorology*. May 2017

Parrett, Charles, 2016. Revision to the official USGS estimate of the 1862 American River peak discharge. Emails dated December 31, 2009 and August 31, 2016. Available at https://cepsym.org/history/1951-Matthai-USGS.pdf. Accessed February 15, 2018.

Porter, K., A. Wein, C. Alpers, A. Baez, P. Patrick, and others, 2011, Overview of the ARkStorm scenario: U.S. Geological Survey Open-File Report 2010-1312.

United States Geological Survey, 2018. National Water Information System, Peak Streamflow for the Nation, United States Geological Survey gage 11446500, American River at Fair Oaks, California. Accessed at: http://nwis.waterdata.usgs.gov/nwis/peak?site_no-11446.500&_agency_cd=USGS&format=html. Accessed on: 15 February 2008.

Additional Resources

Multimodal Analysis of Storm Frequency and Magnitude Changes. *Journal of the American Water Resources Association*, Vol. 47, No. 3. June 2011.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson, 2011. Managing California's Water: From Conflict to Resolution. San Francisco: Public Policy Institute of California.

Holms, R. 2011 Ten U.S. Historic Floods accessed September 17, 2011. Accessed at http://www.time.com/time/specials/packages/article/0,28840,2070796_2070791,00.html Accessed on: September 18, 2011

Ohara, N., Kavvas, M.L., Anderson, M. L., Chen, Z.Q., and Ishida, K., 2017. Characterization of Extreme Storm Events Using a Numerical Model-Based Precipitation Maximization Procedure in the Feather, Yuba, and American River Watersheds in California. *Journal of Hydrometeorology*. May 2017

Faulting and Earthquakes

Hart, E.W., and Rapp, J.S., 1975, Ground rupture along the Cleveland Hill fault: in Sherburne, R.W., and Hauge, C.J., eds., Oroville, California earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 61-72.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p., http://dx.doi.org/10.3133/ofr20141091.

Unruh, J., and Humphrey, J., 2017, Seismogenic deformation between the Sierran microplate and Oregon Coast block, California, USA: Geology, 45 (5): 415-418, published online March 2017, doi: https://doi.org/10.1130/G38696.1

Additional Resources

Anonymous, 2016, Earthquake Shaking Potential Map (revised), California Geological Survey, Map Sheet 48.

Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Zeng, Y., 2013, Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, http://pubs.usgs.gov/of/2013/1165/.

Garrison, L. E., 1992, Transverse Faulting and Gas Prospects in Basement of the Freeport Area, Southeast Sacramento Basin, in Structural Geology of the Sacramento Basin, Cherven, V.B. and Edmonson W.F., eds., Annual Meeting of the American Association of Petroleum Geologists, Pacific Section, April 27 - May 2, 1992, American Association of Petroleum Geologists, Bakersfield, California, pp 109-118.

Higgs, K., 2010, High Sierra-Shake Out Area Historical Epicenters. https://www.shakeout.org/highsierra/. Accessed on: 15 August 2018.

Hart, E.W., and Rapp, J.S., 1975, Ground rupture along the Cleveland Hill fault: in Sherburne, R.W., and Hauge, C.J., eds., Oroville, California earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 61-72.

Paterson, S.R., Tobisch, O.T., and Radloff, J.K., 1987, Post-Nevadan deformation along the Bear Mountains fault zone: Implications for the Foothills terrane, central Sierra Nevada, California: Geology, v. 15, p. 513 16, doi:10.1130/00917613 (1987)15<513:PDATBM>2.0.CO;2.

Peterson, G.L., 1967a, Upper Cretaceous stratigraphic discontinuity: Northern California and Oregon: American Association of Petroleum Geologists Bulletin, v. 51, p. 558–568.

Peterson, G.L., 1967b, Lower Cretaceous stratigraphic discontinuity in northern California and Oregon: American Association of Petroleum Geologists Bulletin, v. 51, p. 864–872.

Powers, P.M. and Field, E.H., 2013, Appendix “O” Gridded Seismicity Sources in Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Zeng, Y., 2013, Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, http://pubs.usgs.gov/of/2013/1165/

Select Volcanic Hazard Sources

Hausback, B.P., Muffler, L.J.P., and Clynne, M.A., 2011, Sutter Buttes—the Lone Volcano in California’s Great Valley: U.S. Geological Survey Fact Sheet 2011-3024, 4 p.

Newhall, C.G. and Self, S., 1982, The Volcanic Explosivity Index (VEI): An Estimate of Explosive Magnitude for Historical Volcanism: Journal of Geophysical Research, v. 87, p. 1231-1238.

USGS, 2018a, U.S. Geologic Survey Open Fact Sheet 022-00. Available at: https://pubs.usgs.gov/fs/2000/fs022-00/. Accessed on 02/27/2018.

Additional Resources

Clynne, M.A., Christiansen, R.L., Miller, Miller, C.D., Stauffer, P.H., and Hendley, J.W. (II), 2001 (revised 2005), Volcano Hazards of the Lassen Volcanic National Park Area, California, U.S. Geological Survey Fact Sheet 022-004, Available at: https://pubs.usgs.gov/fs/2000/fs022-00. Accessed on: Nov.28, 2017.

Hearn, B. Jr., Donnelly-Nolan, J. M. and Goff, F.E.,1981, The Clear Lake Volcanics: Tectonic Setting and Magma Sources in Research in The Geysers-Clear Lake Geothermal Area, Northern California, Geological Survey Professional Paper 1141, 270 p.

Hill, D.P., Bailey, R.A., Hendley, J.W., II, Stauffer, P.H., Marcaida, M., 2014, United States Geological Survey-Reducing the Risks from Volcano Hazards California’s Restless Giant-the Long Valley Caldera, USGS Fact Sheet 2014-3056.

Jarosinski, J., 2010, The Volcanic History of the Long Valley Caldera, 16 p. Available at: http://www.indiana.edu/~sierra/papers/2010/jarosinski.pdf.

Stovall, W.K., Marcaida, M., and Mangan, M.T., 2014, The California Volcano Observatory—Monitoring the State's Restless Volcanoes: U.S. Geological Survey Fact Sheet 2014–3120, 4 p., Available at: https://dx.doi.org/10.3133/fs20143120. ISSN 2327-6932. Accessed on: Nov. 28, 2017

Chapter X. Major Engineering Structures

Dams of the Sacramento Region

Rice, A., 1910, The story of the Folsom Power Plant: *Journal of Electricity, Power, and Gas*, Vol. 24, No. 9, pp.179-184.

Hagwood, Joseph J., 1981, *California Debris Commission*: U.S. Army Corps of Engineers Sacramento District, 102 p.

Hall, R.L., Woodson, S.C., and Nau, J.M., 1989, *Seismic Stability Evaluation of the Folsom Dam and Reservoir Project, Report 3, Concrete Gravity Dam*: US Army Corps of Engineers Technical Report GL-87-14.

Sharp, Michael K., 1988, *Foundation Conditions Report, Folsom Dam Project*: Appendix A in US Army Corps of Engineers Technical Report GL-87-14.

Kiersch, G. A., and Treasher, R. C., 1955, Investigations, Areal and Engineering Geology-Folsom Dam Project, Central California: *Economic Geology*, vol.50, pp. 271-310.

Rogers, J.S., 2009, *Auburn Dam, Auburn Folsom Unit, American River Division, Central Valley Project*. Bureau of Reclamation, Historic Reclamation Projects 39 p.

Additional Resources

California Department of Corrections and Rehabilitation, Inside CDCR Newsletter, 2015, *Unlocking History: Go behind the granite of Folsom Prison*: Electronic Document available at https://www.insidecdcr.ca.gov/2015/01/unlocking-history-folsom-prison/

CGS, 2018, California Geological Survey mapping program website. Available at: http://maps.conservation.ca.gov/cgs/informationwarehouse/. Accessed on: 30 Jul 2018

Malcom Drilling Company, undated, *A collaborative Success-Construction of the Mormon Island Auxiliary Dam Key-Block for Seismic Rehabilitation by Harris, M.J., Lindquist, E.S., Jameson, R., and Porter, T., Available* at: https://www.google.com/search?q=malcolm+drilling+harris+mormon+island&spell=1&sa=X&ved=0ahUKEwia4ZzP563aAhUsgK0KHa6EDeMQBQgmKAA&biw=1408&bih=680&dpr=1.82

Levees and Levee Flood Control System

DWR, 2018, California Department of Water Resources Levee Evaluation Program Website. Available at: http://dwr-lep.com/auth. Accessed on: 13 July 2018

Allan, James, L. and Michael B. Singer, 2008, Development of the Lower Sacramento Valley Flood-Control System: Historical Perspective., Natural Hazards Review, American Society of Civil Engineers, vol. 9, no. 3, Aug. 2008, pp. 125–135. Available at: doi:10.1061/(asce)1527-6988(2008)9:3(125).

Sacramento Area Flood Control Agency website: SAFCA.org. Accessed 05/2018.
United States Engineers Manual 1110-2-1913 Engineering and Design, Design and Construction of Levees. Dated April 30, 2000.
US Secretary of War, 1908, Letter from the Secretary of War, transmitting with a Letter from the Chief of Engineers, Reports of Examination and Survey of Sacramento River, California, from Its Mouth to Feather River, 60th Congress, Second Session, December 7, 1908 – March 4, 1909, House Documents Vol 24 of 151, Washington Government Printing Office 1908.

Additional Resources

California Farmer, 1861, The New Swamp and Overland Land Act, The California Farmer Journal of Useful Sciences, vol. 15, no. 13, 5 May 1861, pp. 89–89., California Digital Newspaper Collection, Center for Bibliographic Studies and Research, University of California, Riverside. Available at:, https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=CF18610524.2.11&e=-------en--20--1--txt-txIN--------1. Accessed on: 3 April 2018
Curry, 1916, Extract from House Report No. 616, Control on Floods on the Mississippi and Sacramento Rivers, Supplemental Report on Control of the Sacramento River Submitted by Mr. Curry of the Committee on Flood Control (to Accompany H.R. 14777), Committed to the Committee of the Whole House on the state of the Union and ordered to be printed, Washington Government Printing Office, dated April 29, 1916.
Friends of North Bloomfield & Malakoff Diggins Website, 2018, the Sawyer Decision Legal Action Taken to Stop Hydraulic Mining! Malakoff Diggins Historic Park, California State Parks. Available at: http://malakoffdigginsstatepark.org/history/north-bloomfield-gravel-mining-company/sawyer-decision/. Accessed on 3 April 2018

Port of West Sacramento

USACE, 2011, U.S. Army Corps of Engineers Draft Supplemental Environmental Impact Statement/ Subsequent Environmental Impact Report. Available at: https://www.spn.usace.army.mil/Portals/68/docs/SRDWSC/01_Executive_Summary.pdf. Accessed on: 7 Aug 2018

APPENDIX A – OVERSIZE DRAWINGS

Plate A. Location Map for the Sacramento Region.

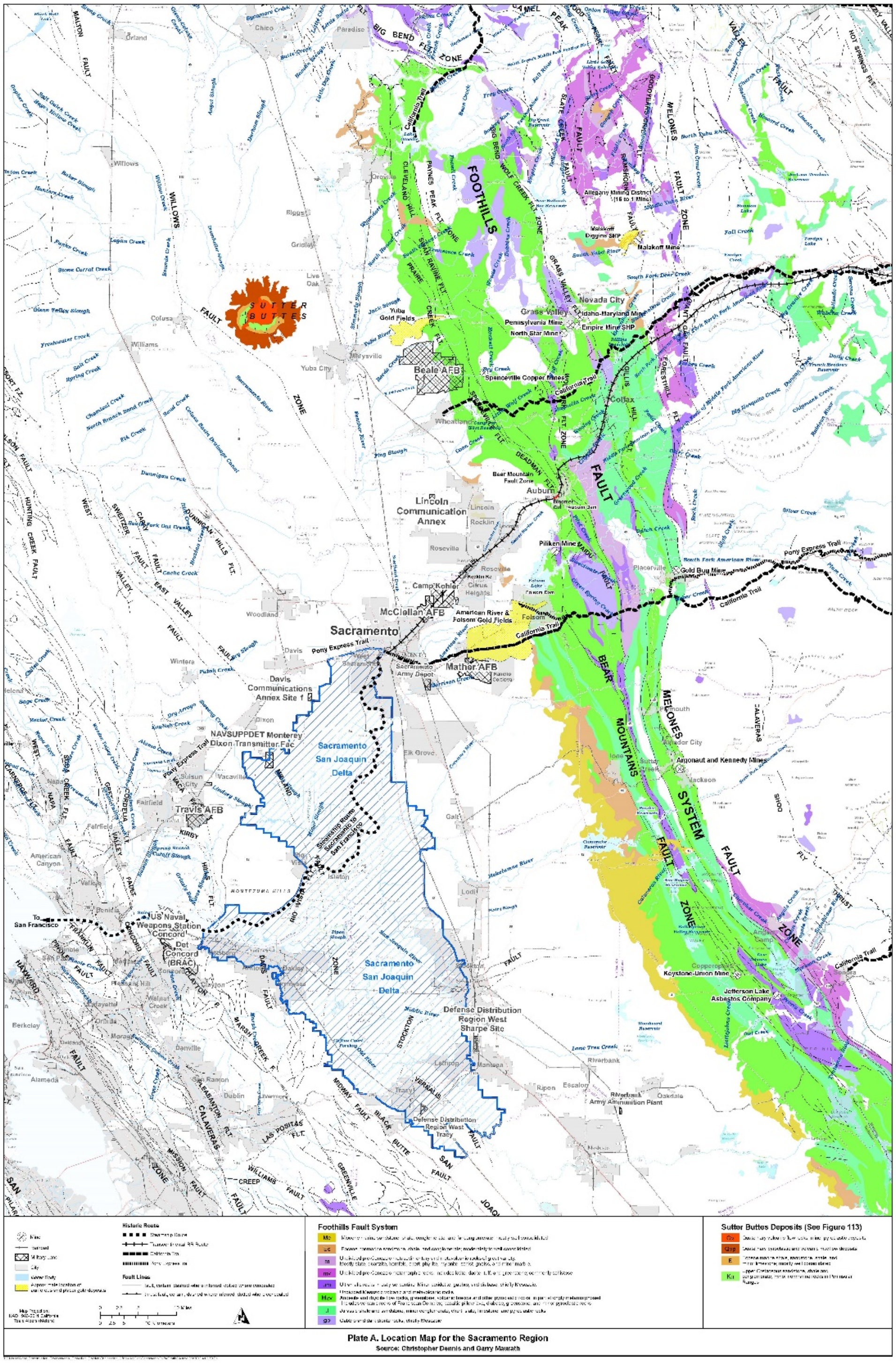


Plate B. Informal Summary of Geologic History of the Sacramento Region.

Plate B: Informal Summary of the Geologic History of the Sacramento Region

Geologic Time			Geologic Events in the Middle California Area	Depositions and Formations: California Department of Mines & Geology	Depositions and Formations: California Department of Water Resources	Depositions and Formations: North of American River	Depositions and Formations: South of American River	Description and Location of Resulting Deposit	Activity Relevant to Sacramento Fan Structure
Cenozoic	Quaternary	Holocene	After the last deglaciation, stream flows drop and streams become undersized compared to their valleys.	Alluvium				Unconsolidated gravel, sand, silt, and clay are deposited along stream channels	The Sacramento Fan is no longer fed at the apex. All branches of the American River use the current Channel. The Fan drains inward from the Fair Oaks cliffs. The American River continues to cut southward into the south bank of fan.
		Pleistocene	Continued uplift and tilting of the Sierra Nevada during Pleistocene time causes entrenchment of the Arroyo Seco and underlying units. Sediments fans alluvial fans on the lower Sacramento Valley floor. A depositional plain, (the Victor Alluvial Plain), develops as fans coalesce. Glacial periods are associated with sea levels changes. Volcanic activity at mount Konocti near Clear Lake.	Victor	Modesto	Modesto	Modesto	Modesto: Unconsolidated gravel, sand, silt, and clay from a granitic source is deposited, largely near stream channels	
			The Sierra Nevada are subjected to cycles of glaciation and deglaciation. Sea level cycles in a corresponding manner. Deglaciation results in results in floods of clasts that spread into the Sacramento Valley. A direct river outlet to the ocean develops in the Bay Area. Former openings in the Southern Coast Ranges are closed due to increased elevation of the Coast Ranges. Volcanic activity is increasingly evident at Clear Lake.	South Fork Gravels Arroyo Seco	Riverbank Turlock Lake (equivalent to Fair Oaks	Riverbank	Riverbank Upper Fair Oaks	Upper Fair Oaks: Rounded pebble to cobble gravels with granitic red matrix. Clasts largely of metamorphic with less component andesitic clasts. Largely equivalent to South Fork Gravels of DWR (1974). Riverbank: Gray unconsolidated gravel, sand, silt, and clay from a granitic source. Victor: Unconsolidated gravel, sand, silt, and clay derived from a granitic source.	Deposition of the Riverbank Formation continues. Initiation of Riverbank fan deposits may extend back into late Pliocene time. Clast composition of well cores indicates Riverbank deposits extend 210 feet below and surface under the California State University Sacramento campus. Increased competence of the American River allows it to cut incrementally northward into the dead fan.
		Pliocene/Pleistocene	Continued uplift and tilting of the Sierra Nevada causes trenching of Laguna Alluvial Plain, making it an erosional surface. The Arroyo Seco pediment (not the Arroyo Seco Gravels), which is found on alluvial fans south of the Sacramento Area, forms from the weathered top of the remaining Laguna erosional surface. Streams from the Sierra Nevada begin to downcut due to an increase in slope caused by uplift of the Sierra Nevada. Beginning of Pleistocene Ice Age. Uplift and tilting of the Sierra Nevada continues, causing heavy sediment flow into the Sacramento Valley, with sedimentary deposits forming alluvial fans. As the fans increase in size, they merge and form the Laguna Alluvial Plain. Outlets to the ocean are cut off from the Northern Coast Ranges to the Sacramento Valley and south to the current Bay Area. This accelerates sediment accumulation in the valley. Sutter Buttes begin to emerge.	Fair Oaks Laguna	North Merced Gravel (equivalent to Arroyo Seco Gravels)	Lower Fair Oaks	Arroyo Seco Gravels	North Merced Gravel. A thin sediment veneer forms on top of the Laguna Formation. This is generally absent in the Sacramento area. Fair Oaks Formation or Turlock Lake: Light brown, granitic sands rich in quartz and biotite are deposited. This unit also includes some silt and clay. Arroyo Seco Gravels: Rounded gravels with red matrix derived from granite. Clasts are largely metamorphic and andesitic pebbles and cobbles. The unit forms a caprock where found in the Sacramento area.	The Fair Oaks Formation continues to be deposited on the fan. The drainage shadow of the Pine Hill Complex allows the fan to expand southward. The American River (south Fork?) swings southward and begins flow over southern portion of the fan. Initial deposits are Arroyo Seco Gravels that later cap ridge summits between the current American and Cosumnes River Channels.
	Tertiary	Pliocene	Uplift and tilting of the Sierra Nevada causes heavy sediment influx into the Sacramento Valley, and sediments spread onto alluvial fans. As fans increase in size, they merge onto the old Laguna alluvial plain. There were no low and water passages from the Sacramento Valley to the ocean through the Northern Coast Ranges, but there may have been an outlet through the San Joaquin Valley south of the Bay Area. This accentuates sediment accumulation in the valley.	The Laguna Formation is deposited according CDMG (1981), DWR (1974), and Shlemon (1967)				Laguna sedimentary deposits are tan to brown and volcanic-rich, with grain sizes ranging from clay to silt and sand; minor granitic and metamorphic input.	Sediments of derived from the Rocklin /Penryn Plutons are deposited on the fan as the lower Fair Oaks Formation
		Miocene	Intense volcanic activity that began in Oligocene time continues intermittently with ash falls contributing to deposition in the Sacramento Valley. This activity terminates at 16 ma and deep erosion of Sierra Nevada begins	Rhyolitic Valley Springs Formation deposited as volcanic sediment blanket on Sierra Nevada north of Merced River. (Howard, 1979)				Valley Springs: Mostly tuffaceous rhyolitic beds of light colored sand and ash.	Little evidence of Valley Springs significantly contributing to fan. American River system may have begun fan deposition from Auburn apex during latter Miocene
			Earlier volcanic activity is followed by another intense period of volcanism, burying the Sierra Nevada with the rhyolitic ash flow Valley Springs Formation and andesitic Mehrten volcanics. Volcanic deposition is less intense in the Sierran foothills. A westward drainage system is initiated again from the Sierran slopes. Volcanism stops, and deep valleys are eroded through both Mehrten and Valley Springs volcanic sediments. Lava flows pour down Sierran valleys starting at 9 ma. Beginning about 15 ma to 18 ma, the Lovejoy Basalt lava flows through deep stream cut channels in the Ione Formation and across the valley floor. The west slope of the Sierra Nevada remains a smooth, sloping plane. Late Miocene uplift starts at 9 ma. The inland sea regresses from the Sacramento Valley and the Sierra Nevada are uplifted and tilted westward, causing increased streamflow and rates of erosion. Sea level rises, but the Sacramento Valley stays above water with the exception of some minor transgressions into the southwestern portion of the valley. Coast Ranges are deformed by imbricate faults associated with the San Andreas Fault system. Subduction of the Fallon Plate is completed near San Francisco at 5 ma.	Eruption associated with Mehrten and Lovejoy Basalt volcanism bury the Sierra Nevada with a blanket of volcanic debris, former drainages fill, producing a mountain range with less local relief. Stream paths tend to straighten down-gradient toward the valley. Again, the southern boundary of the volcanic deposition is the Merced River. (Howard, 1979) Deposition of the Mehrten Formation in the Great Valley begins in late Miocene and continues through early Pliocene time. Shlemon (1967) notes that the Mehrten-Laguna transition is evident south of the American River in early Pliocene time.				Mehrten: Near the fan Apex: gravelly andesitic deposits that include lahars and earthflows give rise lahars and earthflows give rise to andesitic tuff breccias; some are welded, dark colored conglomerates with generally well rounded clasts. Tuffaceous matrix of tuff breccias is often pinkish tan. Distal from the Fan Apex: Later deposits tend to be dark andesitic sands with noticeable magnetite content, occasional conglomerate lenses and reworked ash beds	Overburden appears to have been unroofed from much of the Penryn Pluton. Mehrten deposits form the first sedimentary apron near the apex of the fan (see 1981 CDMG map). Evidence indicates that all three branches of the American River are flowing into Auburn/Roseville area. This appears to be the beginning of the Sacramento fan.
		Oligocene	Rhyolitic volcanic eruptions begin on a large scale north of the Merced River at 33 ma. The Sierra Nevada are covered with a volcanic blanket of light colored lavas, ash, and lahars. Volcanic-rich alluvium flows westward into the Sacramento Valley, and is no longer channeled by the previous trellis-type drainage system. Climatic cooling that began at end of Eocene time continues, resulting in polar glaciation and lowering of sea level. There is a resulting increase in erosion, which may explain the lack of marine sediments except for deposits in some isolated valley gorges, which were still underwater. Terrestrial sediments become more common. At 29 ma, the westward moving North American continent begins to override the East Pacific Rise, and the Fallon Plate undergoes complete subduction. The edge of the North American continent creeps westward onto the northwest-moving Pacific Plate. A shear zone develops in Southern California and gradually shifts eastward, reaching Middle California at 21 ma.	No remnants of any Sacramento area (surface) units.					
		Eocene	Deep valleys are eroded in the Sierra Nevada foothills and later widened. Foothill valleys are filled with coarse gravel. Fine placer gold is eroded into streams and remains a lag deposit while clastic sediment is flushed to the edge of the foothills.	Ione Formation is deposited at the edge of an inland sea that occupies the Great Valley.				The Ione Formation has various phases that include quartzose sands with flakes of white anauxite, and occasionally abundant quartzite pebbles. A clay member is also common.	California Division of Mines and Geology (CDMG) 1981 map shows Ione Formation remnants near Citrus Heights and Lincoln. These deposits lie disconformably over small areas of the Rocklin/Penryn pluton. The Ione Formation is also frequently preserved south of the Cosumnes River.
		Paleocene	Wide fluctuations in early Tertiary sea level affect deposition in the Great Valley. Large gorges and submarine canyons develop on the Sacramento Valley floor (Meganos, Markley, and Princeton Gorges). An inland sea in the Sacramento Valley is connected to the Pacific Ocean through the Markley Strait (near the current San Francisco Bay area). Stockton Arch emerges and becomes prominent.	No deposition of any preserved units on the valley floor (Sacramento Area).					
Mesozoic	Cretaceous		By Late Cretaceous time the volcanic cap of the Sierra is uplifted and eroded, exposing older metamorphic rocks and Cretaceous granitic plutons. West side of the Great Valley and Coast Ranges is underplated by accretionary wedges. Stockton Arch appears between two valleys, but is still submarine. Subduction of the Kula Plate may have resulted in an ancient San Andreas Fault system (strike-slip motion) until subduction of the Fallon Plate was initiated.	Considerable granitic debris was added to sediments in the offshore basin. In the trench, the accumulating sediments were crumpled, sheared, and in some cases forced under the Coast Range Thrust. Extended period of erosion at close of Cretaceous time.				Chico. Exposure of the Chico Formation along the American River near Folsom and resting on the Rocklin Pluton. (Durrell, 1987). The Chico Formation consists of mostly marine sandstones, with lesser amounts of clay, silt and gravel	Removal of some of the country rock covering the Rocklin/Penryn Pluton. Chico Formation is deposited in late Cretaceous time (Durrell, 1987). It appears to have been unconformably deposited onto parts of the exposed pluton and in the Sacramento area prior to initiation of deposition on the fan.
	Late Jurassic to Early Cretaceous		Nevadan Orogeny: subduction resumes and accentuates mountain-building forces and additional granitic magmas invade the crust. Deformation reaches a climax in late Jurassic. Igneous precursors of serpentine are implanted into the metamorphic complex. Older subduction zone and associated trench shift 80 miles seaward to the present site of Coast Ranges, and a new trench forms offshore. Buckling at the edge of the new continent creates a forearc basin. The Coast Ranges begin to form as a submarine range. By early Cretaceous time, the descending oceanic plate reaches sufficient depth to cause melting. Sierra Nevada become a volcanic arc.	Triassic and Jurassic sea floor sediments (and volcanic rocks from the offshore island arc) are accreted onto the ancient coast. A second series of metamorphic rocks is compressed against the older Calaveras rocks to the east. A widespread product of this deformation is the Mariposa Slate. The submerged forearc basin begins to fill with volcanic debris from the Sierra Nevada. Deposition of the Great Valley Sequence begins.				Highway 50 crosses the eastern boundary of these formations west of Placerville. Remains of metamorphic units can be observed on foothill slopes as tilted tombstones. (Howard, 1979)	Rocklin/Penryn Pluton is implaced approximately 129 ma
	Close of Paleozoic to early Mesozoic		Subduction begins and compression causes crumpling and metamorphism of sea floor sediments. Ancestral Sierra form.	Sediments are metamorphosed to slate, phyllite, quartzite, marble, schist, and gneiss, then invaded by granitic magmas during Triassic time (ending at 205 with the Calaveras Formation).				Metamorphic rocks, including highly folded quartzite and chert are prominently exposed in Sierra Nevada foothills along California 140 near Briceburg and Merced Rivers. (Howard, 1979).	
	Middle to Late Paleozoic		Time of Pangea. California lies beneath the sea.	Thick assemblage of marine shale, siltstone, limestone, and volcanic rocks are deposited over the location of modern Sierra Nevada.					

Source: Quaternary Geology of the Sacramento Area, Association of Engineering Geologists, Sacramento Section Guidebook for Field Trip, 25 March 2000, Dr. Roy J. Shlemon, Consultant, Dr. Tim Horner, California State University, Sacramento Dr. Joan Fryxell, University of California, Davis (modified by Christopher Dennis)

References:

CDMG, 1981, Geologic map of the Sacramento quadrangle, ed. by Wagner, D. L., Jennings, C. W., Bedrossian, T. L., and Bortugno, E. J.: Division of Mines and Geology, California Department of Conservation, Regional geologic map series, map no. 1A, scale 1:250,000, 4 sheets.

Durrell, C., 1987, Geologic History of the Feather River Country, California. Berkeley, University of California Press, 337 p.

DWR, 1974, Evaluation of Ground Water Resources: Sacramento County: California Department of Water Resources Bulletin No. 118-3, 141 p.

Giorgis, R. B., 1987, A provenance study of Cenozoic Formations in the Sacramento Area, unpublished Senior thesis, Geology Department, CSU, Sacramento, 22 p.

Howard, A. D., 1979, Geologic History of Middle California, Berkeley, University of California Press, 113 p.

Shlemon, R. J., 1967, Quaternary geology of northern Sacramento County, California: Annual Field Trip Guidebook of the Geological Society of Sacramento, 67 p.

APPENDIX B – AN OVERVIEW OF THE PALEONTOLOGICAL RESOURCES OF THE GREATER SACRAMENTO REGION

primary author: Richard Hilton

Introduction

The largest collections of fossils from the greater Sacramento area are in the collections of the University of California, Museum of Paleontology in Berkeley, the California Academy of Sciences in San Francisco, and the Sierra College Natural History Museum in Rocklin (where many interesting fossils from the greater Sacramento area are on display).

Institutional acronyms and websites

It should be noted that the information in the reported collections below is only as accurate as the data that was originally recorded (or modified) for each specimen. As geological and paleontological work progresses that information is subject to change and as such all collections should be thought of as being in a state of flux.

- CAS = California Academy of Sciences http://researcharchive.calacademy.org/research/izg/fossil/index.asp
- LACM = Natural History Museum of Los Angeles County, Los Angeles, CA https://collections.nhm.org/vertebrate-paleontology/
- LACMIP = Natural History Museum of Los Angeles County – Invertebrate Paleontology Department, Los Angeles, CA https://collections.nhm.org/vertebrate-paleontology/
- Invertebrate Database http://ip.nhm.org/ipdatabase/lot_show
- NMNH = National Museum of Natural History, Smithsonian (see USNM) https://naturalhistory.si.edu
- SCNHM = Sierra College Natural History Museum https://www.sierracollege.edu/about-us/beyond-the-classroom/nat-hist-museum/index.php
- SDSNH = San Diego Natural History Museum http://www.sdnhm.org/science/paleontology/resources/collection-database/
- UCLA = University of California Los Angeles. Most fossils are located at the University of California Museum of Paleontology http://ucmpdb.berkeley.edu
- UCMP = University of California Museum of Paleontology at Berkeley
- Data for UCMP collections is based on searches conducted at http://ucmpdb.berkeley.edu, accessed in December 2016, made available with the following disclaimer <http://ucmpdb.berkeley.edu/disclaimer.shtml>. These data have not been personally verified, but are used with permission. On request of UCMP, locality numbers are provided for UCMP specimens listed.

- USNM = United States National Museum, Washington, DC http://www.nmnh.si.edu/ Information provided with the permission of the National Museum of Natural History, Smithsonian Institution, 10th St and Constitution Ave NW, Washington, DC 20560-0193. http://collections.nmnh.si.edu/search/paleo/

The following compilation is incomplete because of the inaccessibility of some of the records, the possibility that the author missed published records, and the restriction that some locations not be available to unauthorized persons. Some fossils listed in the literature have been lost, misplaced, or destroyed in earthquakes and fires. According to Curator Austin Hendy, LACM, LACMIP fossils are currently being digitized and so far, only a fraction of about 7 million specimens have been recorded. It is therefore likely that not all the fossils in the collections of LACMIP from the greater Sacramento area are represented here.

When discussing the history of fossil collections in each section it is important to note that, when fossils are listed by authors, they may be repeating fossils collected previously by others. No attempt has been made to adjust ages and dates to the present geologic calendar. Most fossils are listed as found and recorded. Unless described in a quote, specific English measurements have been converted to the metric system.

Fossils are an important resource and should never be removed from either private or public lands without permission and/or a permit to do so, and then only by a professional. It is important that fossils be removed in such a way as to preserve them as undamaged as possible. Records should be maintained of the details of the location, formation, rock types, stratigraphy, taphonomy, associations, and context.

Common microfossils

Diatoms = one-celled phytoplankton that make their skeletons of silicon dioxide.
Foraminifera = one-celled, amoeboid protists that make their skeletons out of calcium carbonate.
Radiolaria = one-celled protozoa that make their skeletons of silicon dioxide.

Common invertebrates

Ammonoid = group of extinct, coiled and chambered mollusks related to chambered nautilus, squid, and octopus
Ammonite = group of extinct, coiled and complexly chambered Ammonoids
Baculites = group of extinct, straight and complexly chambered Ammonoids
Bivalve = such as clams, oysters, mussels
Brachiopod = group of clam-like organisms, totally unrelated to bivalves, usually bilaterally symmetrical
Cnidaria = such as coral and jellyfish
Gastropod = such as snails

Limpet = gastropod with a shallow conical, hat-like shell
Nautiloid = group of coiled, chambered cephalopod mollusks related to squid and octopus
Ostracoda, Ostracod = group of crustaceans, sometimes known as seed shrimp
Schaphopod = tusk shell

Common vertebrates

Aves = bird
Camelidae, *Camelops* = camel
Cervidae = deer
Cervus = *elk or wapiti*
Equidae, *Equus* = horse
Mammalia = mammal
Mammut = mastodon
Mammuthus = mammoth
Odocoileus = genus of deer including white-tail and mule deer

Fossils from the indurated bedrock of the Western Sierra Nevada

Fossil-bearing allochthonous limestone blocks of late Paleozoic age in the Sierra foothills

Among the first and oldest fossils found in the region covered by this publication are marine fossils found in allochthonous limestone blocks in the foothills of the Sierra. In discussing the Sacramento Folio, Lindgren (1894) first reports crinoid stems south of Clipper Gap in lenticular masses of limestone. Lindgren (1900) reports fossils found in a large block of crystalline limestone on the east bank of the Bear River Canyon due west of Colfax. Fossils here include crinoid stems, brachiopod fragments of various species, and the horn corals *Clisiophyllum gabbi* Meek and *Lithostrotion whitneyi*. Lindgren (1900) remarks that these are unhesitatingly referred to the lower Carboniferous. The author has collected fossil corals and brachiopods from the site. This may be the same locale mentioned by Lindgren (1911), who found "Carboniferous" fossil-bearing limestone in the same general area. These outcrops have been cited by Edelman and Sharp (1989) as having produced the only known Permian Tethyan fossils in the Western Metamorphic Belt of the Sierra.

Lindgren (1900) cites 3 other localities in the Colfax/Auburn area. The first is a small limestone outcrop on the south side of the canyon of the Middle Fork of the American River above Mammoth Bar, where crinoid stems and sections of shells were found. mLindgren and Turner (1894) report coral from this location. The second locality is southeast of the southwestern corner of the Colfax quadrangle. The formation here contains a small lenticular mass of limestone in which a coral *(Phillipastrea)* and a gastropod *(Pleurotomarid)* were found. The third locality is a limestone outcrop in the "Cape Horn slates" below Cape Horn on the trail from Colfax to Iowa Hill. "The fossils consist of round crinoid stems, probably indicating a Paleozoic age." Lindgren and Turner (1895b), in discussing the Smartsville Folio, list foraminifera and *Spirifera* (a brachiopod) in lenses of Carboniferous limestone. Lindgren and Turner (1894) report several well-defined Carboniferous fossils, principally corals, in two places on the Placerville sheet. One of these locations is listed as being southeast of Applegate's Ranch (now the town of Applegate) near the Central Pacific Railroad. Clark (1976) reports that one of the limestone outcrops south of Highway I-80 has yielded possible Devonian corals and bryozoans.

Fossils below all Permian, Calaveras Formation, Placer County

NMNH, 1 foraminifera.
SCNHM**,** 2 Cnidaria, upper Paleozoic**,** 1 bryozoan (moss animal), Bear River**.**

Radiolarian cherts

Radiolarian cherts are found in many locations in the Sierra foothills (Graymer and Jones, 1994). Radiolaria are excellent microfossils useful for age determinations, especially when macrofossils or datable rocks are not available.

Fossils from the Jurassic "Slates" of the Sierra foothills

The first mention of fossils from the indurated bedrock of the Sierra (in the area covered in this paper) was by Blake (1864), who reports an ammonite found at Oregon Bar on the Middle Fork of the American River (east of Clipper Gap). Geologist Fielding B. Meek, upon receiving a photograph of the specimen, said it was not possible to determine whether the ammonite belonged to the genus *Ammonites* or *Ceratites*. Whitney (1865) reports that John Conness, US Senator from California 1863-1869, gave John B. Trask, California's first State Geologist (Gabb, 1864, 1869), what appeared to be a goniatite (ammonoid) found near Coloma. Whitney concluded that it was perhaps of Triassic age.

Several fossils have been reported from the Jurassic "slates" in the Colfax sequence of the Mariposa Formation, and from the Mariposa Formation. Smith (1910) restricted the name "Mariposa Formation" to the lower part of the Mariposa slate and applied the name Colfax Formation to the upper portion. Later, Tuminas and Moores (1982), Tuminas (1983), and Day and others (1985), used the term Colfax sequence to describe these rocks. The earliest fossils recorded from the Colfax Formation are from Gabb (1870), who records *Ammonites (Perisphinetes) colfaxii* from a railroad cut west of Colfax. Turner (1894) commented that the specimen was sent to Cambridge. Lindgren and Turner (1894) report 3 ammonite species and 1 bivalve from the Gold Belt mentioned in the Placerville Sheet. Lindgren (1900) reports another locality at Irving's Ranch, southwest of Colfax, where specimens of the ammonite *Olcosteplianus lindgreni* Hyatt occur in a rusty-brown sandy slate.

Other fossils from the Jurassic slates (Mariposa Formation) are reported by Turner (in Lindgren, the Sacramento Folio, 1894). He reports an ammonite found on Wilkerson’s Ranch near White Rock Station in El Dorado County, and that Dr. Cooper Curtice and geologist Waldemar Lindgren obtained ammonites and belemnites from the same slates in Placer and El Dorado Counties. The author reports 2 ammonites as well as a bivalve from the Colfax sequence of the Mariposa Formation in the Weimar area. Recently a new genus and species of urchin (CASG 72939), *Sierradiadema kristini* (Figure B-1), was found at Cherokee Bar on the Middle Fork of the American River, and described from the Colfax sequence (Mooi and Hilton, 2014).

Fossils below all SCNHM, upper Jurassic, Mariposa Formation (Colfax sequence)

Weimar, Placer County:
1 bivalve and 2 ammonites.

Pre-Pliocene fossils from the eastern border of the Sacramento Valley and the Sierra Foothills

The upper Cretaceous Chico Formation intermittently exposed from Folsom to the Lincoln area

In the Sacramento region, the Upper Cretaceous Chico Formation outcrops along the western Sierran edge sporadically from Folsom to Lincoln. Lindgren (1894, 1911) identified these marine sedimentary rocks as late Coniacian to middle Campanian. Hilton and Antuzzi (1997) report that some of the fossils here are late Campanian. By the Late Cretaceous, erosion had stripped away kilometers of overlying rock from the original Sierra and exposed the granitic rock and subjacent metamorphic rock along the western foothills. Based on rock material in turbidites (Mariposa Formation clasts), the sea flooded this area perhaps as far east as Clipper Gap or even Weimar. The marine deposits of the Chico Formation sit nonconformably upon the granitic rock and metamorphic country rock along the base of the Sierra east of Sacramento. The type section of the Chico is located along Chico Creek near the town of Chico (Taff and others, 1940). Trask was the first to collect fossils from the Chico Formation in the Sacramento area (Hilton and Antuzzi, 1997). They were described by Gabb (1864, 1869).

Figure B-1. The urchin *Sierradiadema kristini,* (CAS) Colfax Sequence.

Gabb (1864, vol. I) lists 3 bivalves and 1 ammonite found in outcrops of the Chico Formation near Folsom. These outcrops are on the north side of the river including the area of Negro Bar. He also lists 1 ammonite, 1 brachiopod, 15 bivalves, and 12 gastropods including 3 limpets from the (Rock Corral) locale. This locale is north of the American River near the Sacramento/Placer county line.

Whitney (1865) comments on Cretaceous deposits on the north side of the American River near Folsom a little below the Railroad Bridge. He reports several *Exogyra parasitica* (an oyster), and a single ammonite (*A. complexus*?). These fossils were deposited into the collection of CAS. He also describes a site between Beal's Bar and the Halfway House near the county line of Sacramento and Placer "not far from Texas Flat." The Texas Flat fossil locale was discovered by Trask about 4 km northwest of Folsom in a mining shaft, about 12 m below the surface. His notes mention shark teeth in a blue clay both above and below a fossiliferous sandstone layer. He collected many Cretaceous fossils, including 10 bivalves, 1 brachiopod, and 7 gastropods, one of which is a limpet. These were deposited in CAS. Trask notes outcrops of the fossiliferous beds near Texas Flat, Halfway House, Volcano Ridge, and Mississippi Flat. Gabb (1869, vol. II) lists 1 ammonite from near Rock Corral in Placer County, plus 3 gastropods, 13 bivalves, and 2 ammonites from Texas Flat.

Turner (1894) reports 2 ammonites and 4 bivalves found on the north side of the American River near Folsom. He also reports that Trask collected 12 gastropods plus 3 limpets and 21 bivalves at Texas Flat (later designated as Rock Corral). Anderson (1902) lists 13 gastropods, plus 1 limpet, 20 bivalves, and 1 brachiopod from Texas Flat. Schenck and Keen (1940) report *Inoceramus whitneyi* (a Cretaceous bivalve) from Sacramento County.

A substantial collection of Chico Formation fossils was made by Hilton and Antuzzi (1997) during housing construction in the Granite Bay area and curated at SCNHM. Here the Chico Formation consists of a basal conglomerate of unknown thickness, overlain by 40 m of offshore marine fine-grained siliciclastics containing, in the upper part, a bouldery turbidite layer. The fossils were collected near the site that roughly coincides with Gabb's (1864,1869) Texas Flat locale. Evidence from the ammonites *Hoplitoplacenticeras* and *Metaplacenticeras* collected by Hilton and Antuzzi (1997) indicates that the Chico Formation ranges from late early to late Campanian for the Granite Bay outcrops. Fossils originally came from three environments: offshore, nearshore, and terrestrial. The area of deposition for all three was offshore. The nearshore fossils were largely deposited offshore by turbidity currents and debris flows, while the terrestrial fossils were deposited offshore by turbidity currents and as flotsam from fluvial systems flowing into the marine environment.

Numerous marine invertebrate fossils were collected at this Granite Bay locale (Figure B-2). These included gastropods, scaphopods, bivalves, ammonites, *Baculite*s, nautiloids, crinoids, urchins, and shrimp burrows (Hilton and Antuzzi, 1997). Marine vertebrates include several bones and teeth of fish including shark teeth. The partial remains of the mosasaur *Clidastes* were collected (Hilton and Antuzzi, 1997). This is the first of the genus found on the west coast and the first mosasaur found in the Chico Formation. A life-size model was fabricated and now hangs in the SCNHM (Figure B-3). Parham and Stidham (1999) report two types of marine turtles from the Chico Formation at Granite Bay, a dermochelyid and a toxochelyid. A third type of turtle (Protostegidae), preliminarily identified by J.F. Parham (personal communication, 1997) and reported by Hilton and Antuzzi (1997) and Hilton (2003), is reported here by Parham and Stidham (1999) to be more likely a dermochelyid.

The woody portions of plants and seeds, as well as some leaves and fronds, washed into the marine environment as flotsam from streams and rivers, and were sometimes further transported to the site from the nearshore by turbidity currents. The leaves include both monocots and dicots, and fronds from ferns and cycads (Hilton and Antuzzi, 1997). An entire trunk of a moderate-sized tree fern (Hilton and others, 1997) was also discovered (Figure B-4). Gymnosperms are represented by foliage from Araucariaceae (monkey puzzle tree) and Taxodiaceae (conifer). Seeds of numerous unidentified cycads and Araucariaceae were found.

There is also some evidence of terrestrial fauna at the Granite Bay site. Two species of terrestrial gastropods were discovered; one of these was described as a new species (*Polygyroidea hiltoni*) by Roth (2000). The most surprising of the finds was a bone from a theropod dinosaur, the first (and as to date the only) evidence of a meat-eating dinosaur from California (Hilton and Antuzzi, 1997, Hilton, 2003). The fossils above give us a window into the Late Cretaceous Sierran terrestrial environment. Turbidite petrology and clast size indicate a rugged cliffy coast below a lush forest complete with leafy angiosperms plus cycads, ferns, and conifers. The conifers include the Araucariaceae (monkey puzzle trees), one resembling the Norfolk Island pine found growing today in the Southern Hemisphere.

Fossils below all CAS, Cretaceous

loc. 33552, 2 bivalves, 2 gastropods, Folsom, Sacramento County.
loc. 33709, about 18 bivalves, 2 gastropods, 1 ammonite, 8 *Baculites*, Rock Corral, border of Sacramento and Placer Counties.
loc. 33732, 4 bivalves, Folsom Bridge, Sacramento County.
loc. 34439, 5 bivalves, 3 urchin spines, Folsom, Sacramento County.
loc. 60958, various bivalves, gastropods, *Baculites*, Folsom, Sacramento County.
Numerous unlabeled, uncatalogued, Cretaceous bivalves and *Baculites* from the Folsom/Roseville area of Sacramento and Placer Counties.

Figure B-2. Ammonite and nautiloid, (SCNHM) Chico Formation, Granite Bay.

Figure B-3. Life-sized model (SCNHM) of the mosasaur *Clidastes,* by Rick Campbell, Chico Formation, Granite Bay.

Figure B-4. Tree fern, (SCNHM) Chico Formation, Granite Bay.

Fossils below all LACMIP, Chico Formation

loc. 17871, 1 bivalve, early Campanian, Treelake, Granite Bay, Placer County.
loc. 28764, 1 gastropod, early Campanian, Granite Bay (Rock Corral) near Folsom, Sacramento County, Sta. 89, UCLA collection labels.
loc. 28765, 5 bivalves, 1 ammonite, 1 *Baculites*, Campanian, near Folsom, Sacramento County, Sta. 88, UCLA collection labels.
loc. 26463, UCLA locality # 6463, a horribly preserved gravel shell hash, with recognizable specimens of the bivalve Glycymerididae (probably *Glycymeris*), Cretaceous, north bank of the American River at Negro Bar near Folsom, Sacramento County
loc. 29632, 1 ammonite sp., Cretaceous, Chico Formation? American River, Folsom, Sacramento County, UCLA collection label.

Fossils below all SCNHM, upper Cretaceous, Chico Formation, Granite Bay, Placer County (border of Sacramento and Placer Counties)

Invertebrates

1 crustacean burrow, 2 shrimp burrows, 1 crustacean (crab? claw), 1 coral, 1 crinoid stem (sea lily), 4 Echinoidea (sea urchin), 1 *Phyllacanthus*? sp. (sea urchin), 1 Goniasteridae (sea star), 65 bivalves, 45 ammonites, 7 *Baculites*, 6 nautiloids, 58 gastropods, plus 11 limpets, 4 scaphopoda, 1 brachiopod.

Vertebrates

26 Chondrichthyes (shark teeth), 2 *Enchodus* (fish) teeth, 1 *Enchodus* (fish) skull fragment, 1 *Protosphyraena* (fish) tooth, 4 unidentified fish teeth, 2 unidentified fish bones, Reptiles: 4 unidentified reptiles, 3 reptilia?, 6 unidentified Chelonoidea (turtle), 1 protostegid (turtle), 1 unidentified mosasaur (sea-going lizard), 1 *Clidastes propython* (Cope) (mosasaur), 1 theropod dinosaur, 1 Aves, 1 Aves?

Plants

30 unidentified seeds, 2 dicot seeds, 1 dicot? seed, 2 unidentified seeds?, 2 Icacinaceae seed (flowering plant), 1 Araucariaceae seed (monkey puzzle tree), 2 Araucariaceae needles, 2 Araucariaceae wood, 1 cycad seed (sago palm), 1 fern leaf, 3 cone fragments, 1 wood fragment, 1 wood fragment (burned?, petrified), 1 plant stem, 16 unidentified leaves or leaf fragments, 29 leaves or fragments (dicots), 1 flower?, 2 ribbed plant bark, 1 *Chamaceyparis* (false cypress), 2 conifer wood, 1 plant wood, 1 conifer needles, 1 conifer “leaf”, 2 plant needles, 11 fern frond fragments, 1 fern seed mold, 1 fern seed, 1 fern stem

mold, 1 tree fern, 2 unidentified fern, 1 *Ctenis cycadoidea* (fern),1 *Equisetum* (horsetail) impression.

Fossils below all SCNHM, upper Cretaceous

1 Echinoidea (sea urchin), 1 bivalve, 4 ammonites, Rocklin, Placer County.
1 ammonite, 1 unidentified coprolite (fossil dung), 2 unidentified fish teeth, Roseville, Placer County.
1 *Baculites*, Bear River, Placer County.
1 scaphopod, 1 Pinaceae (fir) cone, Folsom (Negro Bar), Sacramento County.
1 shark tooth, Lake Natomas, Folsom, Sacramento County.

Fossils below all UCMP, Placer County

loc. IP11369, IP12667, IP11368, IP12690, 4 bivalves, no formation or age given.
loc. IP11333, IP11334, 3 gastropods no formation or age given.
loc. IP12802, 2 gastropods, Late Cretaceous.
loc. V91215, fish (Condrichthyes), Late Cretaceous, Treelake, Granite Bay.

The "Eocene" Walkup Clay in Lincoln

According to Allen (1929), the Walkup Clay outcrops east of the Gladding, McBean Company clay pit in Lincoln. Here it appears at the surface at the Walkup pit where it rests on fossiliferous Cretaceous sandstone containing concretions. No contact with the overlying Ione Formation is exposed. Allen reports that the Walkup clays are crudely bedded but in some places, they become shaley and contain thin lenses of limestone. The color is gray, but where weathered it may be buff or yellowish. Allen collected poorly preserved casts of a coral that resemble *Stephanophyllia* (?) *vacavillensis* previously described from the Meganos Eocene near Vacaville. He mentions some of the other forms might be doubtfully referred to that horizon. Allen reports that limited evidence points to an Eocene age for the Walkup clays.

The Eocene-Oligocene Wheatland Formation northeast of Wheatland

The Wheatland Formation of Clark and Anderson (1938) briefly outcrops as sandstone, shale, and conglomerate northeast of Wheatland along Dry Creek, at the juncture of the Sierra and Great Valley Provinces. According to Clark and Anderson (1938), the beds here are about 91 m thick and dip 3˚-5˚to the southwest. The conglomerate contains a marine invertebrate molluscan fauna. Clark and Anderson (1938) consider the Formation to be upper Eocene to Oligocene. Kleinpell (1938) reported a Refugian age (Refugian Californian Stage from 35-33.5 Ma) for benthic foraminifers in the Wheatland Formation. Weaver and others (1944) concluded the Formation was lowest Oligocene. Dalrymple (1964) produced a radiometric date on andesitic pebbles in the Wheatland Formation at 53.5 m.y.o. This date however is on a clast and consequently only provides the maximum date for the Formation. Dalrymple (1964) cites a date of 33 Ma as the onset of volcanism in the Sierra Nevada. Addicot (1981) then uses this date as a lower limit on the Wheatland Formation as it contains volcanic clasts.

Fossil below CAS, Eocene, Wheatland Formation, Yuba County, Clark and Anderson (1938)

loc. 31904, 1 gastropod.

Fossils below LACMIP, Eocene, east bank of Dry Creek, Yuba County

loc. 20460 = UCLA loc. 460, fossils not listed.

Fossils below all UCMP, Eocene, Dry Creek, (Wheatland), Nevada County ([sic] Yuba County)

loc. A1889, 27 gastropods and 10 bivalves.

Eocene marine fossils from Yuba County

Primary author: Chris Bonds

Bonds (2007) reports Lower to Middle Eocene marine macrofossils, (46 to 50 m.y.o.) from an exploratory drill hole located 4.5 km northeast of Marysville in Yuba County. The fossils were recovered from drill cuttings between 232-262 m in-depth and their interpreted ages correlate with the Capay Formation in the area. The variety and type of fossils observed, combined with the presence of the clay mineral glauconite, strongly indicate a shallow-marine shelf depositional environment.

These fossils have not been formally reported, but only preliminarily summarized in a 2007 memorandum report with limited circulation outside DWR. They are tentatively curated by DWR.

The fossils include 86 gastropods (snails), 21 scaphopods (tusk shells), 19 bivalves (clams), 13 solitary corals, and 1 shark tooth.

Fossils identified down to the species level include:

1	*Tornatellaea vacavillensis* (snail)	(Figure B-5)
6	*Glyptoactis domenginica* (clam)	(Figure B-6)
1	*Glycymeris (Glycymerita) sagittata* (clam)	(Figure B-7)
11	T*urbinolia dickersoni* (solitary coral)	(Figure B-8)

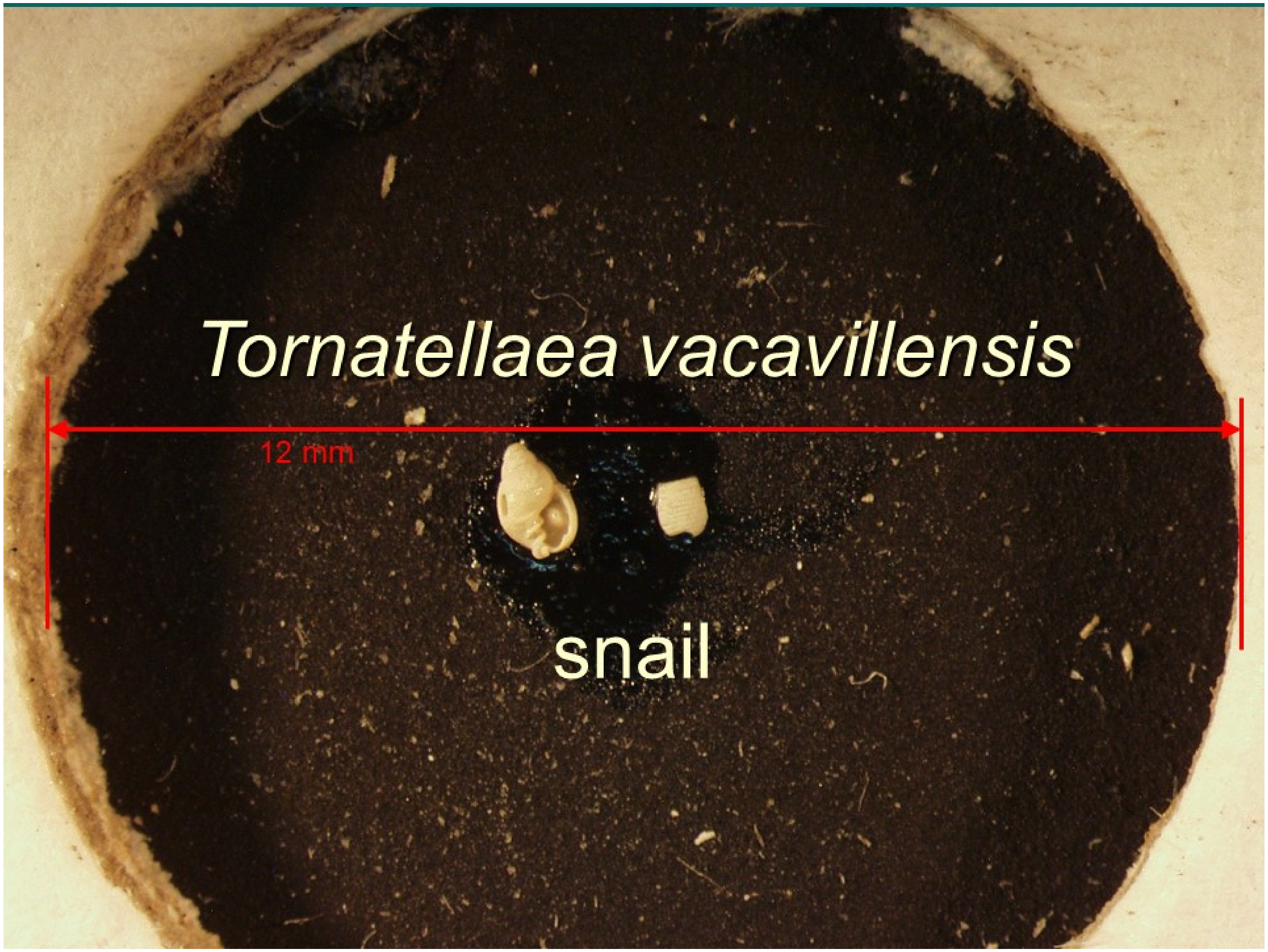


Figure B-5. *Tornatellaeua vacavillensis* (Source: image courtesy of Chris Bonds)

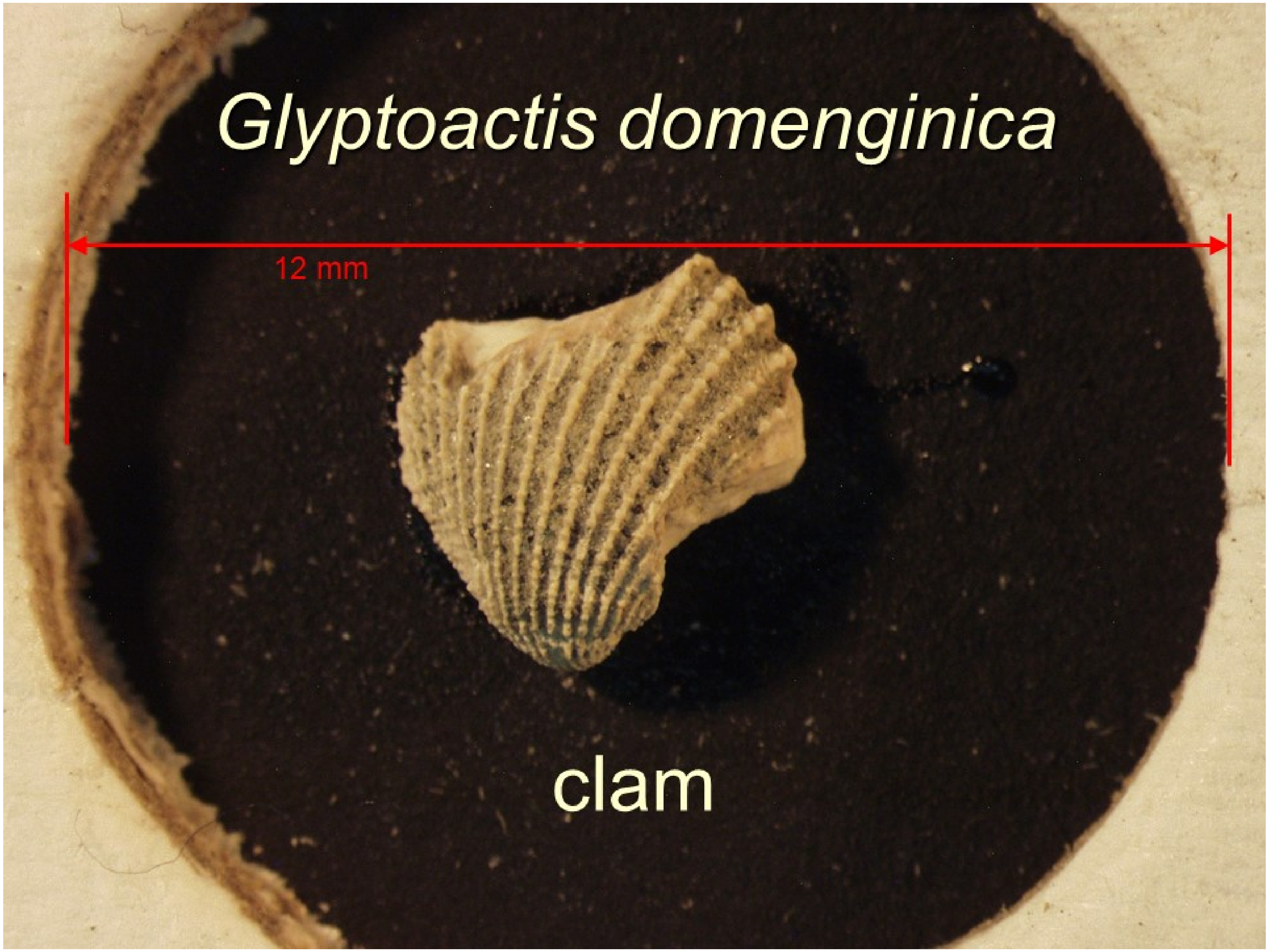


Figure B-6. *Glyptoactis domenginica* (Source: image courtesy of Chris Bonds)

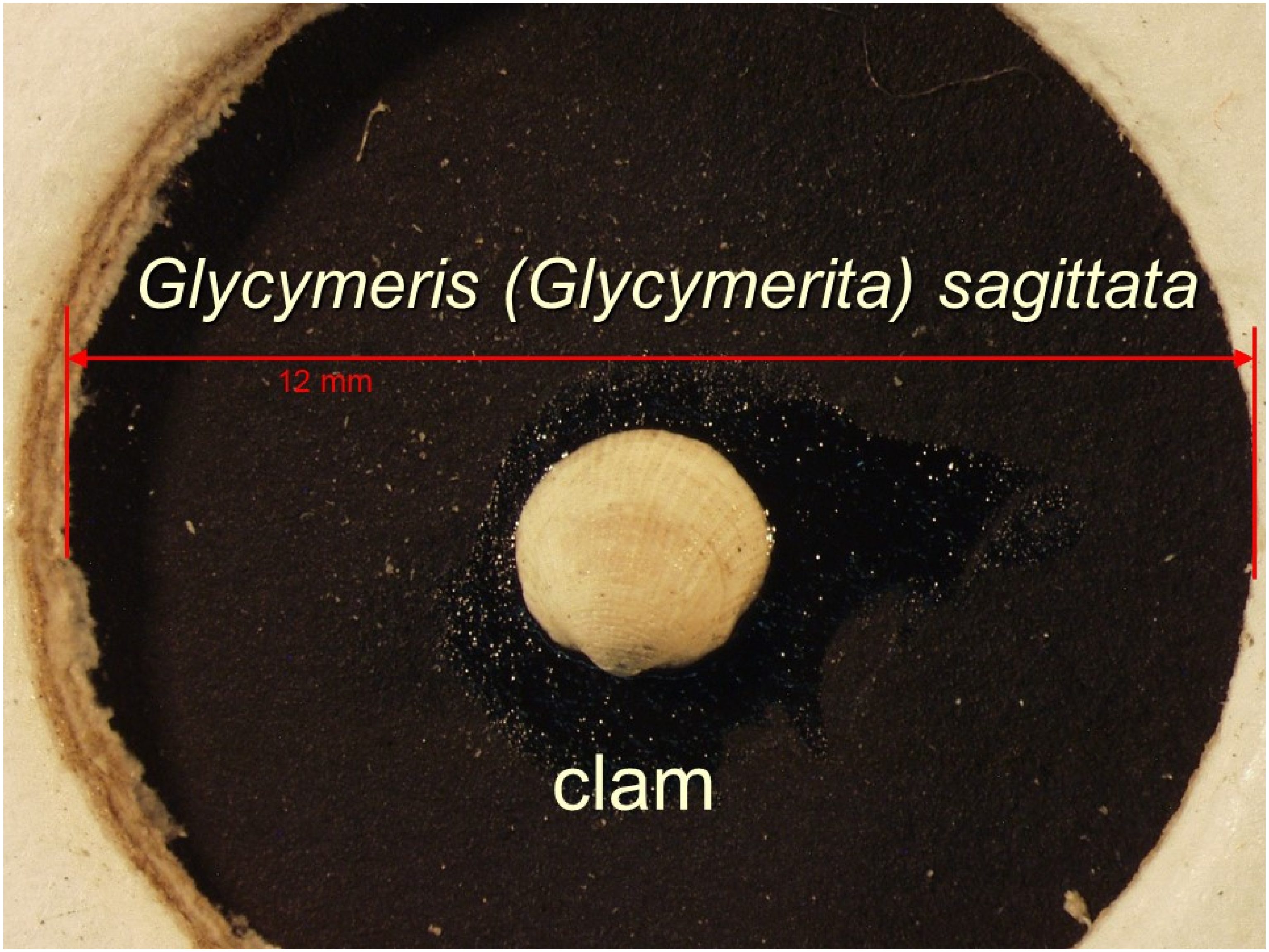


Figure B-7. *Glycymeris (Glycymerita) sagittalta* (Source: image courtesy of Chris Bonds)

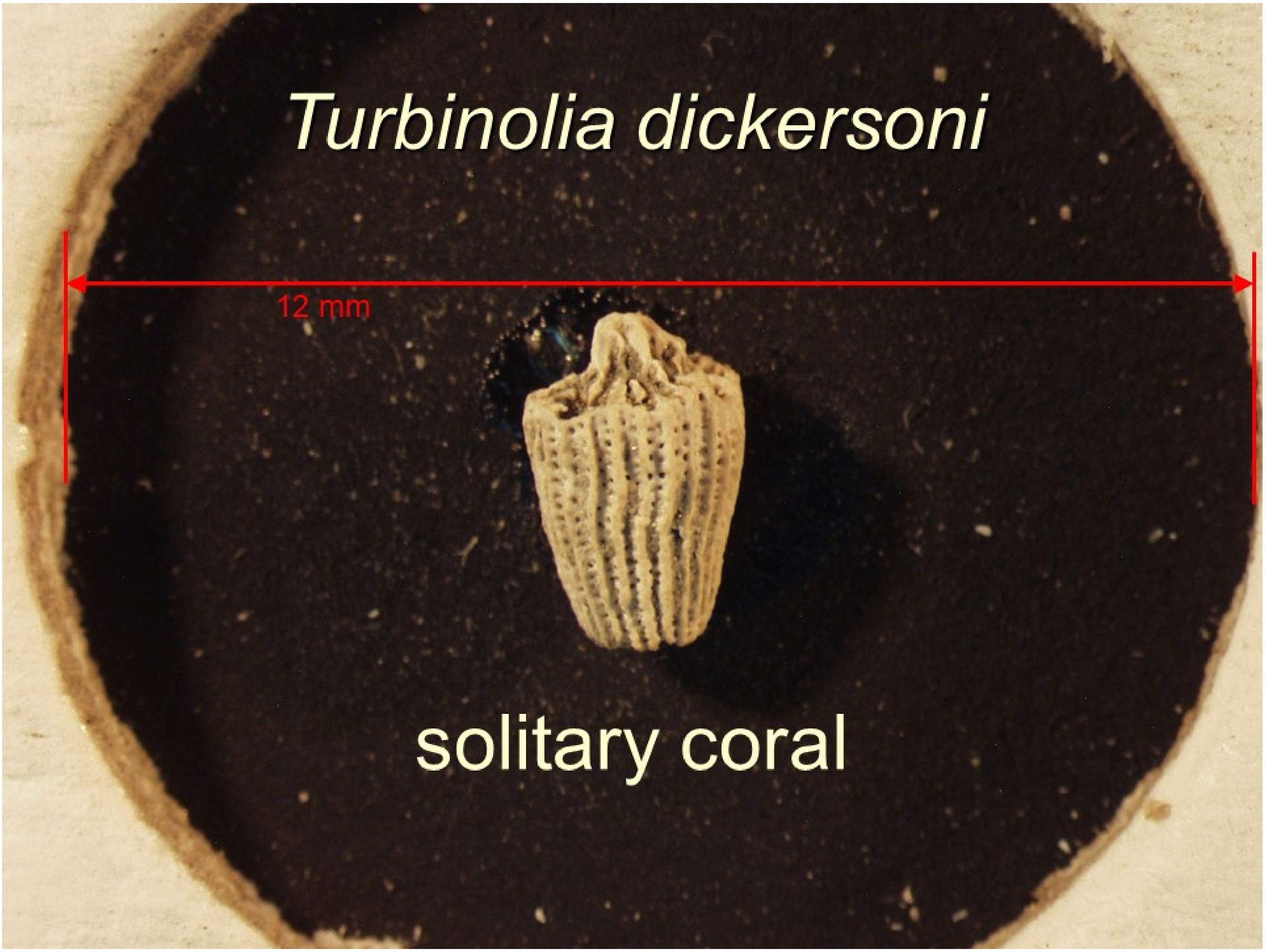


Figure B-8. *Turbinolia dickersoni) sagittalta* (Source: image courtesy of Chris Bonds)

These four species are identified as age-diagnostic index fossils for the Lower to Middle Eocene Epoch, "Domengine" and "Transition" West Coast Eocene Molluscan Stages which span a 2- to 4-million-year time frame between 46 and 50 Ma.

Tentative Genus designations :

- 47 *Turitella* (snail)
- 4 *Crepidula* (snail)
- 1 *Ectinochilus* (snail)
- 2 *Cirsotremas* (snail)
- 3 *Siphonalia* (snail)
- 21 *Dentalium* (tusk shell)
- 2 Turbinolia (coral)
- 1 Odontaspis (shark)

The Eocene-early Oligocene Ione Formation in the Lincoln, Rocklin, and Granite Bay areas

primary author: Richard Hilton

The first time the term Ione Formation was used was by Lindgren (1894) in the text of the Sacramento Folio. In 1894 Turner mapped and described the lone Formation at the type locality, near the town of Ione, making the following divisions in ascending order: 1) white clay and sand beds which contain coal seams; and 2) sandstone, usually white in color, but sometimes red and occasionally passing over into a quartz conglomerate. Over this he describes clay rock or tuff (Valley Springs Formation). Paske and Turner (1952) report a lower and upper section separated by an unconformity. Fossils from the Ione Formation only come from the upper smectitic unit referred to as the Bench Gravels (Lindgren, 1911; Christensen and others, 2015). Both units appear to be deposited in fluvial, lagoonal and deltaic environments with episodic ocean incursion in the western areas (Bateman and Wahrhaftig, 1966). Creely and Force (2007) report that one hallmark of the Ione Formation is its characteristic light color. Local precipitation of iron oxides renders it various hues of red, brown, and orange. Some of the mud rocks, including shales, tend towards brown while the lignites are black.

Uphill from the Ione, the Auriferous Gravels (Lindgren, 1911) are found as fluvial deposits on the ridges of the Sierra Nevada and are laterally equivalent to the Ione Formation (Allen, 1929). MacGinitie (1941) used paleobotanical evidence to help establish that the Ione Formation and the Auriferous Gravels were once continuous. Most of the paleobotanical evidence comes from fluvial deposits well above the valley floor in places like Chalk Bluff (MacGinitie, 1941) and out of the physical boundaries of this paper.

The Ione Formation outcrops discontinuously for 320 km along the western foothills of the Sierra Nevada from Friant near Fresno, north to Oroville Table Mountain (Creely and Force, 2007; Wood and others, 1995). It is found in two major areas of the foothills in the Sacramento area. One is in the Lincoln area and the other in the Rocklin-Granite Bay area. Both areas contain deltaic deposits, while one small linear topographic high in Granite Bay (Prior Ridge) is a ridge-forming inverted topographic fluvial deposit. The Rocklin-Granite Bay deposits are associated with the terminus of an Auriferous Gravel paleochannel (Lindgren, 1911; Lawler, 1995) traced to as far east as the Hope Valley area on the east side of the Sierra crest (Garside and others, 2005; Christensen and others, 2015). The clays deposited at Lincoln, on the other hand, may be an interfluve deposit not associated with a major Auriferous Gravel channel (Creely and Force, 2007).

Allan (1929) describes the outcrop at the Gladding, McBean Company in Lincoln as follows: Below the clay pit, drilling has revealed from the surface, blue clay that passes downward containing lignitic streaks. At 43 m from the surface they encounter the "Walkup Clays" (see Walkup clay section). Above these beds starting at the surface of the pit is 10.6 meters of massive white Ione clay followed by 3 m of bedded white and brown Ione clays. Here he marks a disconformity. Above the disconformity are 6.1 m of biotite sands and sandy clays of the "Rhyolite period" (Valley Springs Formation). Here he marks a second disconformity separating the Valley Springs Formation from 2-4.5 m of andesitic lithic tuff and boulders (Mehrten Formation). The white clays of the Ione Formation are frequently well suited to the manufacture of pottery. A bed of pure quartz sand is also found at Lincoln. Helley and Harwood (1985) describe the Ione Formation as "Light-colored, commonly white conglomerate, sandstone, and claystone. Argillaceous sandstone and claystone comprise about 75% of the Ione along the southeast side of the Sacramento Valley. Ione sandstones are characterized by fine grains of angular quartz and thin stringers of weathered anauxite."

There are no radiometric dates for the Lincoln-Granite Bay areas and almost nothing written about the age of the material, so dates are inferred from other areas of the Ione and Auriferous Gravels. According to Garside and others (2005), "The paucity of modern age determinations on the Auriferous Gravels limits our present understanding of this unit." Christensen and others (2015) report the upper or Bench Gravel to be >31.5 - < 38 m.y.o., making them late Eocene-early Oligocene, substantially younger than previously believed. For example, Allen (1929) reported an early to middle Eocene (Domengine) age, while MacGinitie (1941) reported an Eocene 52-49 m. y. o. estimate.

The younger dates place the age of fossil paleobotanical specimens in a cooler climate than was previously believed, as the climate underwent a long-term and mostly gradual cooling of about 12˚ C from the Eocene Climatic Optimum about 52-50 Ma to the beginning of the Oligocene (Zachos and others, 2001, 2008; Hyland and Sheldon, 2013; Mudlesee and others, 2014). Millar (1996) summarizes the climate history of the Sierra Nevada saying that the early Tertiary was subtropical to tropical, but by the end of the Eocene (about 34 Ma) global climates changed rapidly from consistently warm to cool-seasonal temperate conditions. Lindgren (1911) commented that paleobotanical specimens from various sites in the auriferous bench gravels and Ione showed that the climate was like that of the southern temperate zone of the Atlantic coast region today, with heavy rainfall and warmer temperatures.

The first coal mined in the Lincoln area was in 1864 (Hausback and Hilton, 1994). Merrill (1984) reports a non-marine trace fossil *Ophiomorpha* found east of Sacramento in the Ione Formation. They are found as clay-lined burrows with knobby walls in sandstone units. Hausback and Hilton (1994) report petrified wood and plant leaf impressions collected while doing EIR preliminary work in the proposed Lincoln Quarry by Teichert Corporation north of Lincoln (Gust, 2008) and are in the collection of the SCNHM. Fossil leaf, seed, and tree trunk impressions have been found in the deposits of the inverted topography at Prior Ridge and are curated in the SCNHM. They come from coarse-grained, cross-bedded channel deposits. The leaf impressions are mostly magnolia, while the seeds are of lily and palm nut. The deltaic deposits in the Rocklin-Granite Bay area contain opalized wood, some of the most beautiful petrified wood to be found anywhere (Figure B-9). One large specimen is on display at the SCNHM.

The author and James Wood collected a humerus from a bird in the uppermost tufaceous deposits of the upper Ione in the Twelve Bridges area of Lincoln. The specimen resides in the SCNHM. James Wood (personal communication, 2016) comments that the petrified wood and humerus from both the Lincoln and Rocklin-Granite Bay areas are from the younger smectitic unit equivalent to the Chalk Bluff flora (MacGinitie, 1941) and are lowest Oligocene about 30 Ma. The petrified wood was deposited by fluvial and deltaic activities while the bone was in lacustrine tuffs.

Fossils below all SCNHM, Placer County

1 *Sequoia* (redwood) cone, 1 root cast, 12 leaf impressions, 1 magnolia? flower, 2 opalized wood, 2 petrified wood, 3 petrified wood sections, Roseville.
2 petrified wood thin sections, 1 *Acer* (pre-maple) petrified wood, 1 *Juglan* (walnut) petrified wood, 1 *Katsura* (a dicot) seed pod, 1 lily seed, 3 seeds, 3 dicot seeds, 4 monocot impressions, 3 palm seeds, 1 dicot impression, 1 *Cinnamomum* (camphor) leaf and stem? (Figure B-10), 1 grass stem impression, near Eureka Road.
4 unidentified seed pods, Roseville (Wexford).
1 *Umbelluaria*? (laurel) petrified wood, Roseville (east).
1 unidentified seed, Granite Bay.

Figure B-9. Opalized wood, (SCNHM) Ione Formation, Granite Bay.

Figure B-10. *Cinnamomum* (Camphor) leaf, (SCNHM) Ione Formation, Granite Bay.

1 rhizome,1 large leaf fragment, Lincoln Teichert Quarry (proposed, north of Lincoln).
2 seeds, Lincoln.
1 carbonized wood, Lincoln clay pit.
1 Aves, 1 *Quercus* (oak) leaf, Twelve Bridges, Lincoln.

Fossils below all UCMP, Eocene, no formation given, Placer County

loc. 22, 7 plant specimens (magnolia), Voy's Rock Corral. (Voy was a geologist who made several collections in California; Rock Corral is probably the same Rock Corral referred to by Gabb (1869) near Folsom on the Placer-Sacramento County line).

The Miocene-Pliocene andesitic fluvial and lahar deposits of the Mehrten Formation (and Lincoln Clay) in the Lincoln, Rocklin, Folsom, and American River areas

The Mehrten Formation is named for exposures in the bluffs along the Mokelumne River near the Mehrten Dam site. The type section is along Clements-Comanche road about 2 km east of the Comanche Dam site (Piper and others, 1939). Lindgren (1911) proposed a Miocene age for the andesitic materials that blanket the Sierra (Mehrten Formation); however, based on fossil flora and vertebrate remains, Chaney and Axlerod (1944) restricted the age to upper Miocene to lower Pliocene. According to Savage and Russell (1983), the Mehrten Formation is Clarendonian and Hemphillian. The youngest dated flows or debris deposits of the Mehrten Formation are as young as about 3 Ma while the oldest date from 16 to 18 Ma (Wagner and Saucedo, 1990; Saucedo and Wagner, 1992; Cousens and others, 2008). Garside and others (2005) report that the Mehrten ranges from 14-4 Ma in the northern and central Sierra. O'Brient (1978) cites a K/Ar date (obtained by the US Bureau of Reclamation) on a tuff in the Mehrten Formation near Auburn on Maidu Hill at 8.7± 0.4 m.y.o.

The only outcrops of the Mehrten Formation near Sacramento are in the area between Lincoln, Granite Bay (Livingstone, 1974) and the American River (Shlemon and others, 2000). According to Moses (1985), the US Bureau of Reclamation personnel doing studies on the proposed Auburn Dam Site divided the Mehrten Formation into: 1) conglomerate; 2) indurated conglomerate; 3) tuffaceous sandstone; and 4) laharic mudflow deposits. O'Brient (1978) combined the conglomerate units into a single unit. Moses (1985) did a detailed analysis of the lithologic and stratigraphic nature of these deposits and divided the Mehrten Formation here into four lithostratigraphic units: 1) fluvial deposits, composed of clast supported, sub-rounded to rounded, coarse, predominately andesitic gravel; 2) cobble tuff breccia deposits, consisting of matrix supported, andesitic cobbles and boulders; 3) tuff deposits, composed of thin-bedded lithic fragments, pumice fragments, and broken crystal grains; and 4) tuff breccia deposits, consisting of angular to sub-rounded centimeter- to several meter-diameter andesitic clasts. Unit four forms the capping uppermost very resistant portion of the Mehrten Formation east of Sacramento. Turner (1894) commented that, “The andesite-breccia and tuff masses appear to have, in some cases at least, reached their present position in the form of mud flows.” These deposits are known today as lahars. Google Earth and SRTM images of the area between Rocklin and Folsom provide us with unprecedented views of the shape of the Mehrten Formation deposits. These images show us that the fluvial deposits and lahars were deposited in distributaries of the ancestral American River. The distributaries converge at Auburn and do not cross the American River Canyon. The distributaries diverge into lower elevations at the Sacramento Valley floor. The northernmost branch shows clearly that the deposits formed natural levees as they spilled toward the edges of the channel and as the remaining material in the center drained further downstream, spreading out on the open space of the valley floor. The levees were left as a pair of long linear ridges. Clover Valley lies between them.

Curtis (1954) comments that the clay beds within the Mehrten Formation contain fossil leaves. The author has seen similar beds containing fossil leaves at mid-elevations in the Sierra but outside the boundaries of this paper.

Moses (1985) found no fossils in the Mehrten Formation in the Auburn-Folsom area other than a few unidentifiable root casts in the capping breccia (lahars).
Over the years during construction in the area of Rocklin and Roseville the author and volunteers at Sierra College have picked up several plant fossils in the finer mudrock between the coarse breccia of the lahars of the Mehrten Formation (Figure B-11).

Fossils below all SCNHM, Mio-Pliocene, Mehrten Formation, Placer County

> 1 unidentified leaf, 2 *Quercus* leaves (oak), 2 live oak leaves, 1 oak leaf, 1 acorn cup, 1 limb mold, Rocklin.
> 10 unidentified leaves**,** 2 oak leaves**,** 1 bay leaf, 2 pine needles**,** 1 pinecone, Roseville.

Fossils below all UCMP, “Miocene,” Hemphillian, Lincoln Clay Pit, Placer County

loc. V67103, 1 Hipparioni (horse), 1 Reptilia, 1 Osteichthyes (fish), no record of formation but possibly Mehrten Formation.

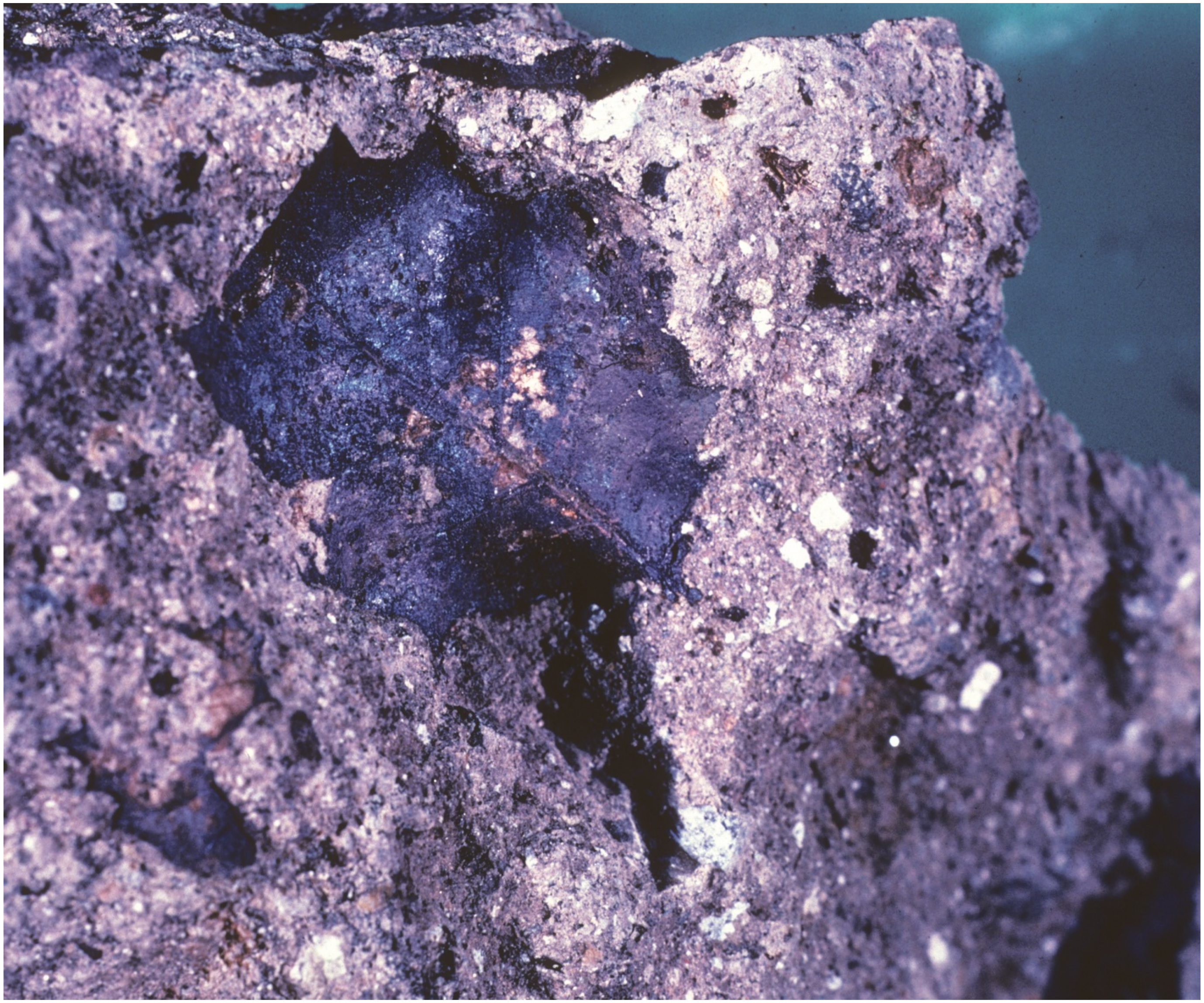


Figure B-11. *Quercus*, Live Oak leaf, 5 cm long, (SCNHM) Mehrten Formation, Roseville.

Pre-Pliocene fossils from the Western Border of the Lower Sacramento Valley

The Great Valley Group (Sequence) from beneath the Sacramento Valley

The Great Valley Sequence (Bailey and others, 1964), now referred to as the Great Valley Group, is exposed in the upturned edges of thousands of meters of marine Cretaceous beds west of the area covered by this paper. Well logs below provide a couple of fossils in the area.

Dunnigan Hills, Yolo County, Standard Oil Company of California Peter Cook #1 Well number 28 of Stewart (1949), are fossils from core samples: Stewart reports *Baculites* from Cretaceous marine? from near the bottom of the well. No formation name given.

Fairfield Knolls, Yolo County, well number 23 of Stewart (1949), 13 km west of Davis and 5 km north of Putah Creek are fossils from core samples: Cretaceous marine? bivalve *Inoceramus* (Figure B-12) near the bottom of the well.

The Late-Paleocene Meganos Formation

Fischer (1979) reports that the late Paleocene Meganos Formation was deposited in a submarine canyon and fan system. According to Stewart (1949), the Meganos Formation type section is at Mount Diablo. Fischer (1979) describes Meganos Formation in the area of Mount Diablo and delta areas as having a lower section of a submarine fan facies of coarse-grained clastic materials and an upper section composed of a claystone canyon-fill sequence. The Marysville claystone member of the Maganos Formation was proposed by Williams (1929), with the type locality on the west side of Sutter Buttes. Stewart (1949) reports that the Marysville claystone and lower portion of the Ione sands (Allen's Dry Creek Formation) form the Capay Stage. For the "Eocene" Meganos, *see also* the Sutter Buttes section.

Fairfield Knolls, Well number 23 of Stewart (1949), about 13 km west of Davis and about 5 km north of Putah Creek, fossils from core samples.

Maganos Formation, Marysville Claystone member, Lower Eocene: 1 foraminifera, 28 gastropods, 11 bivalves, 2 starfish, 2 worms?, 1 fish otolith (ear bone), fish scales, and 1 fish vertebra.

Figure B-12. *Inoceramus* (giant clam) (SCNHM), Great Valley Group.

The Eocene Capay Formation and related units of Solano County

Baker (1975) reports that the marine Capay Formation is early Eocene and composed of clastic sedimentary rocks that range from mudstones to conglomerates. These were deposited in water deeper than 1000 m as submarine canyon fill and were derived primarily from Sierran sources (including the Klamath Mountains). The Capay "Shale" is also referred to as Meganos "E" Shale by Sullivan and Sullivan (2007). The type locality of the Capay fauna described by Merriam and Turner (1937) is in Smith Canyon in the Rumsey Hills on the west side of the Sacramento Valley (Bentson, 1941). Stewart (1949) reports fossils from core samples in the Dunnigan Hills, Yolo County, Standard Oil Company of California Peter Cook #1 Well number 28, Lower Eocene (no formation listed): 8 gastropods, 1 bivalve, 1 worm?, 2 starfish, and 1 fish otolith. Below these fossils is listed one undated radiolarian.

Fossils below all CAS, Eocene, Capay or Domengine Formation, Solano County, Hanna and Hertlein (1941)

Acc. # 70384.00, hyracodontid sp. (rhinoceros).
Acc. # 7767.00, 1 foraminifera (see Domengine Formation below).

The Capay Formation also outcrops in the Sutter Buttes (see Sutter Buttes section). *See also* the Eocene Domengine Formation section below.

The Eocene Domengine Formation

Graymer and others (2002) describe the Domengine Sandstone (Eocene) as white fine- to coarse-grained quartz and quartz-lithic sandstone and very light brown siltstone. Locally it includes conglomerate with pebbles of quartz, chert, and andesite, as well as thin beds of gray shale. Scheirer and Magoon (2007) comment that the Eocene Domengine Formation and its equivalent southeast of the Jacalitos oil field (the Avenal Sandstone) blanket much of the northern and central San Joaquin Basin. Scheirer and Magoon (2007) pinpoint the upper age of the Domengine Formation at 48.5 to 47.5 million years and assign an age for the base at 49 m.y.o. Bodden (1983) reports an "analysis of calcareous nannofossils indicates an early middle Eocene age for the Domengine on the north side of Mt. Diablo. Strata previously mapped as 'Domengine' on the south side of Mt. Diablo range in age from early Eocene to late middle Eocene. Differences in Domengine age-equivalent strata reflect separation of the two areas at time of deposition."

Bodden (1983) comments on the Domengine Formation that outcrops in the northern foothills of Mt. Diablo. Here it represents the initial phase of a major transgression that affected the southern Sacramento Basin during the middle Eocene. Here he cites an array of shallow marine and paralic (marine and continental sediments) deposits. The

Domengine here is 230 m thick, and rests unconformably on older rocks. He recognizes six distinct units within the Domengine: "(1) A basal unit, consisting of shale, sandstone, and poorly sorted conglomerate, representing alluvial deposition. (2) The Black Diamond Coal Seam, deposited as a lagoonal swamp. (3) The lower 'White Sand,' made up of white quartz sandstone, shale, and coal, deposited in lagoonal, marsh, and fluvial environments. (4) The upper 'White Sand,' consisting of massive white sandstone, and thin shale and coal, representing deposition in environments associated with a barrier-beach complex. (5) A unit of shale, with thin, cross-laminated sandstone and siltstone interbeds, deposited in a nearshore marine muddy bottom setting. (6) The 'Brown Sand,' consisting of mostly fine-grained, glauconitic sandstone, with marine fossils, deposited as a series of near-shore marine sand bars."

Stewart (1949) at Fairfield Knolls, Yolo County, Well number 23, about 13 km west of Davis and about 5 km north of Putah Creek cites fossils from core samples recovered from the Domengine Formation (Eocene): 3 gastropods, 2 bivalves, 1 foraminifera, and 2 fish otoliths.

Fossils below all CAS, Eocene, Stevens Well, Woodland, Yolo County

loc.1355, microfossils.

See also previous Capay Formation, Solano County section.

The Late Miocene Neroly Sandstone

The Neroly Sandstone outcrops sporadically along the western edge of the Montezuma Hills. Graymer and others (2002) describe the formation as a "Dark-red-brown or brown-gray weathering, blue to dark-blue-gray, volcanic-rich, cross-bedded sandstone, conglomerate, and minor siltstone." They report that in places it contains non-marine fossils. It contains the Black Diamond Park Tuff with K/Ar ages of about 9.8 million years and the Alves Tuff at about 11.1 million years, as reported by Sarna-Wojcicki and Walker (1999).

Plio-Pleistocent Fossils

The Pliocene-Pleistocene Tehama and Wolfskill Formations along the western border of the lower Sacramento Valley

The Tehama Formation was named by Diller (1894) for exposures in Tehama County in the northern Sacramento Valley. Russell and Vander-Hoof (1931) describe the Tehama Formation as follows: "The Tehama Formation is composed of about 2000 feet of massive, pale greenish gray to pale buff sandy clays which are usually tuffaceous; intercalations of sand and gravel, often strongly cross-bedded, are present throughout.

A massive coarse-grained pumice tuff member occurs near the base." This is the Nomlaki Tuff member named from its type locality on the Nomlaki Indian Reservation in Tehama County by Anderson and Russell, in Russell and Vander-Hoof (1931). This tuff was assigned to the upper Pliocene based on vertebrate fossils obtained from fine-grained sediments of the Tehama Formation, 3 m stratigraphically above the tuff at a locality west-northwest of Corning (Vander-Hoof, 1933b). Olmstead and Davis (1961) and Page and Bertoldi (1983) agree that the Tehama Formation be assigned to the upper Pliocene and possibly the lower Pleistocene. Evernden and others (1964) dated the Nomlaki Tuff at 3.4 million years, confirming the Pliocene age for the base of the Tehama. In some areas in the southwestern Sacramento Valley the Putah Tuff also lies near the base of the Tehama Formation. This unit has yielded a radiometric age of 3.3 ± 0.1 million years (K/Ar) (Miller, 1966).

In the southwestern part of the Sacramento Valley, north of Mount Diablo, Hackel (1966) reports continental beds equivalent to the Laguna Formation have been called the Wolfskill Formation. It lies above the lower Pliocene Pinole or Lawlor Tuff. Cohee and Wright (1973) report a formal proposal for the abandonment of Wolfskill Formation, with its rocks reassigned to the Tehama Formation now geographically extended into central California.

Starting along the northwest portion of the area covered in this paper is the area of the Dunnigan Hills. The Tehama Formation is exposed in the Dunnigan Hills anticline (Bryan, 1923). A horse jaw found at the southern end of the Dunnigan Hills, west of Woodland, was said by Vander-Hoof to be either upper Pliocene or Pleistocene (in Anderson and Russell, 1939). The bone occurred in light greenish-gray sandy clay a few meters below a gravel cap of the Red Bluff Formation. Anderson and Russell (1939) stated that the bone-bearing sediments probably are correlative with the Tehama Formation. Vertebrate fossils have been collected from the northwestern part of the Montezuma Hills west of the Sacramento-San Joaquin Delta. These are dated as probably early middle Pliocene (Stirton in Weaver, 1949) and described from the Wolfskill Formation (now Tehama Formation). Olmstead and Davis (1961) report that stratigraphically at least several hundred feet above the bone-bearing beds is a bed of diatomaceous clay of Pliocene or Pliocene and Pleistocene age, which occurs beneath alluvial fan deposits with sediments probably referable to the Tehama Formation. They report, "The clay was penetrated at a depth of 5.5 to 6.5 meters below the land about 3 km north of the Montezuma Hills in a test boring made by the US Army Corps of Engineers and at similar depths in two other test holes several hundred feet away. Samples of the clay were examined by K. E. Lohman of the Paleontology and Stratigraphy Branch of the US Geological Survey who identified 20 species and varieties of diatoms."

Fairfield Knolls, well number 23 of Stewart (1949), about 13 km west of Davis and about 5 km north of Putah Creek are fossils from core samples, Tehama Formation, Plio-Pleistocene: 6 gastropods, 9 bivalves and 1 fish otolith.

Fossils below all UCMP

loc. V96016, 38 Osteichthyes (fish),1 Osteichthyes, teleost (fish), 1 Reptilia, 1 Mammalia, Pliocene, Blancan, Tehama Formation, Corcoran Ranch 1, SMUD Cogeneration Pipeline, north of Davis, Yolo County.

loc. V6342, 1 *Mammuthus*, Gallup Ranch (near Woodland), Yolo County.

loc. V72240, 1 Nannohippus (horse), Pliocene, Blancan, Tehama Formation, Colusa 2, Chamisal Creek (near Arbuckle), Colusa County.

loc. V3824, 4 "Miocene", Tehama Formation, Denverton, near Rio Vista, Solano County.

loc. V3824, 2 *Mammut*, Hemphillian, Wolfskill, "Miocene," Tehama Formation, Denverton, near Rio Vista, Solano County.

loc. V3824, 4 *Pliohippus* (horse), Hemphillian, Wolfskill, "Miocene," Tehama Formation, Denverton, near Rio Vista, Solano County.

loc. V3824, 3 Hipparionini (horse), Hemphillian, Wolfskill, "Miocene," Tehama Formation, Denverton, near Rio Vista, Solano County.

loc. V5704, 1 Mammalia, Denverton 2. Hemphillian, Wolfskill, "Pleistocene," Tehama Formation, Denverton, near Rio Vista, Solano County.

loc. V5510, 1 Camelidae, Blancan, Wolfskill Formation (Tehama), Rio Vista 1, Solano County.

loc. V5913, 1 *Haplomastodon* (mastodon) and 1 Mammalia, Blancan, Wolfskill (Tehama), Rio Vista 1, Solano County.

loc. V81123, 1 *Equus*, Dunnigan Hills, Pliocene, Blancan, Tehama Formation, Yolo County.

loc. V92032, 1 *Pliohippus*, Dunnigan Hills North, Blancan, Tehama Formation, Yolo County.

loc. V5129, 4 Mammalia, 12 *Equus*, 1 Hipparionini (horse), Dunnigan 1, Blancan, Tehama Formation, Yolo County.

loc. V81040, 1 *Equus*, Blancan, Tehama Formation, Dunnigan Creek, west of Dunnigan?, Yolo County.

loc. V81042, 1 *Equus*, Pliocene, Blancan, Tehama Formation, Cache Creek Aggregates, between Highways 5 and 505 west of Woodland on Cache Creek, Yolo County.

loc. V2906, 1 *Equus*, Pliocene, Blancan, Tehama Formation, Cache Creek, Cache Creek Aggregates, between Highways 5 and 505 west of Woodland on Cache Creek, Yolo County.

loc. V6302, 1 *Mammuthus,* Pliocene, Blancan, Tehama Formation, Gallup Ranch, near Woodland, Yolo County.

loc. V72187, no fossil listed, Pliocene, Blancan, Tehama Formation, Dunnigan Hills, Smith Creek, at Junction of 5 and 505, Yolo County, also reported by Jefferson (1991b).

Plio-Pleistocene Montezuma Formation west of the Delta.

The Montezuma Formation is an older alluvial unit of late Pliocene (Bell and Hanson, 1995) to early Pleistocene age (Graymer and others, 1994). Weaver (1949) named the Montezuma Formation for the Montezuma Hills at the southwestern end of the Sacramento Valley, and mapped this unit as far north as Putah Creek. The lower part of his Montezuma Formation apparently includes some of the Tehama Formation as mapped by Kirby (1943b) farther north. The Montezuma Formation is a poorly consolidated unit consisting of orange-weathering, brown, poorly sorted quartz-lithic sand, silt, and pebble gravel (Guitierrez and others, 2010).

Bell and Hanson (1995) report that the Montezuma Formation yielded a *Haplomastodon (?)* in Rio Vista that suggests that the Formation is probably late Pliocene (Blancan) age. The Formation overlies with angular unconformity a unit that contains the Lawlor Tuff. Graymer and others (2002) provides a date for the tuff in this area at Ar/Ar age of 4.83 ± 0.04 million years (Sarna-Wojcicki, written communication, 2002).

Fossils below all UCMP, Montezuma Formation, "Pleistocene," Rancholabrean, Solano County

loc. V3719, 1 *Mammuthus*, 1 *Equus*, Collinsville.
loc. V79073, 1 *Sigmodon lindsayi* (rat), Collinsville.
loc. V79073, 1 Mammalia, Stratton Lane, Collinsville.
loc. V5510, 7 *Equus*, 2 *Cervus*, Montezuma Hills.
loc. V5510, 1 Mammalia,1 Eutheria (placental mammal), 1 *Camelops*, Montezuma Hills 1.
loc. V69182, 1 *Mammuthus*, Putah Creek 2.
loc. V69184, 1 *Glossotherium harlani* (ground sloth), Putah Creek 4.

Fossils below all UCMP, "Pleistocene," all Rancholabrean, Montezuma Formation, Yolo County

loc. V6911, 1 *Mammuthus*, Putah Creek nursery [*sic*].
loc. V69182, 1 *Mammuthus*, Putah Creek 2.
loc. V69183, 1 *Mammuthus*, Putah Creek 3.
loc. V69183, 1 *Glossotherium harlani* (ground sloth), Putah Creek 3.
loc. V54030 = V5430, 1 *Smilodon* (saber-toothed cat), Putah Creek 1, no record of formation. Jefferson (1991b) reports UCMP V54030, Montezuma Formation.

loc. V69182 and V69183 probably represent part of the same bone assemblage. The Yolo/Solano county line runs along Putah Creek in this area, thus localities directly across the stream from one another are in different counties.

The Plio-Pleistocene Laguna Formation in the Sacramento area

The Laguna Formation (also referred to as the Arroyo Seco Gravel by Olmsted and Davis,1961) was named by Gale and others (1939) for arkosic alluvial deposits in the vicinity of Laguna Creek, San Joaquin County. Piper and others (1939) describe the Laguna Formation as overlying with apparent conformity the (Late Miocene through middle [?] Pliocene) Mehrten Formation below and the Arroyo Seco Gravel (Pleistocene) above (Wagner and Saucedo, 1990; Saucedo and Wagner, 1992; Cousens and others, 2008; Garside and others, 2005). Marchand and Allwardt (1981) report that the presence of andesitic detritus, reworked from the Mehrten in the base of the Laguna and of arkosic or biotite-bearing deposits in the upper Mehrten, may have led to the erroneous impression of a transitional or conformable Mehrten-Laguna contact.

The Laguna Formation type section is on the north bank of Hadselville Creek in the Mokelumne area, a short distance upstream from Laguna Creek (Piper and others, 1939). Olmsted and Davis (1961) report that at the type section the Laguna is a compilation of Laguna Formation, Arroyo Seco Gravel, and gravel deposits of uncertain age. Olmstead and Davis (1961) report that the Laguna Formation contains an abundance of somewhat clayey silt to silty fine sand, with scarce, poorly sorted gravel beds.

According to Piper and others (1939), the Laguna Formation is probably Pliocene and continued without interruption into the earliest Pleistocene. Marchand and Allwardt (1981) also provide a Pliocene age for the Laguna Formation. Hanson and Schorn (2005), report that the base of the Laguna Formation is marked by the 3.3 m.y.o. Nomlaki Tuff.

In a quote from Shlemon and others (2000), “Shlemon (1967a, 1967b, 1974, 1998) provides a very accurate description of the terraces and channels that formed during this northward migration (American River). A potential source of confusion with these younger deposits is the variety of names that have been used by geologists who mapped the Sacramento area. Equivalent names include ‘Gravels underlying Arroyo Seco surface’ and ‘upper Fair Oaks’ (Shlemon, 1967), ‘Gravel of uncertain age’ (Piper and others, 1939), ‘fanglomerate’ and ‘Red Bluff Formation’ (Olmsted and Davis, 1961), ‘Arroyo Seco Gravels,’ ‘Gravels of uncertain age’ and ‘South Fork Gravels’ (Ford, 1972; DWR, 1974) and ‘Laguna Formation’ (CDMG, 1984 [*sic*]).’ All of these names have been used to refer to essentially the same material, although the usage is not always consistent between authors or even within studies.”

A single horse tooth was collected from a well about 6.5 km north of Galt from a clayey silt, inferred to be the Laguna Formation, 18 m below the surface and identified as *Neohipparion* cf. *N. gidleyi.* It was determined by Stirton (1939) to be early late Pliocene in age.

Pleistocene fossils from in and around the Southern Sacramento Valley

Introduction

Pleistocene sedimentary rocks are common in and around the southern Sacramento Valley. Whenever erosion or development occurs in the area there is a fair chance that Pleistocene fossils may be exposed. Piper and others (1939) were the first to publish detailed geologic maps in the southern Sacramento and northern San Joaquin Valley areas. Locally, the first important differentiation of late Cenozoic units was in the northeastern San Joaquin Valley by Piper and others (1939), who distinguished three major deposits from oldest to youngest as the Laguna Formation, the Arroyo Seco Gravel, and the Victor Formation. Davis and Hall (1959) proposed to subdivide the Victor Formation into the Turlock Lake (oldest), Riverbank (middle), and Modesto (youngest) Formations. Marchand and Allwardt (1981) proposed that this division be formalized. Locally, late Cenozoic deposits have been studied and described by Shlemon (1967a, 1967b, 1971, 1972) along the American River. See Shlemon and others (2000) for use of terms and a history of term usage for the region.

Based on his survey of vertebrate fauna from the late Cenozoic nonmarine deposits of the San Francisco Bay region, Savage (1951) proposed two major divisions of Pleistocene-age fossils: the Irvingtonian (older Pleistocene fauna) and the Rancholabrean (younger Pleistocene and Holocene fauna). The Irvingtonian fauna is represented by *Borophagus* (bone-crushing dogs), hyenas, saber-toothed cats, rabbits, giant marmots, horses, mammoths, and mastodons. The age of the Rancholabrean fauna was based on the presence of bison and on the many mammalian fossil species still living. Other Rancholabrean fauna include mammoths, mastodons, camels, horses, and ground sloths.

Many museum records do not designate a formation name for Pleistocene fossils as formation designations came about relatively late in the history of collecting. Below we start with Pleistocene fossils with no formation designation.

Pleistocene fossils found in the Sacramento area that do not have formations assigned to them in the literature or in collections

Western edge of the lower Sacramento Valley from north to south: Dunnigan Hills/ Zamora, Woodland/Cache Creek area

Page and Bertoldi (1983) report 23 species of Pleistocene diatoms from a diatomaceous clay 163-166 m beneath the valley floor about 8 km NE of Zamora. The clay lies about 3 m above a volcanic ash considered to be < 450,000-years old.

Fossil below UCMP, Rancholabrean, Cache Creek, Yolo County

loc. V91204, 1 *Mammuthus*.

Fossil below USNM, Rancholabrean, Bird Hollow near Blacks Station (Zamora), Yolo County, Hay (1927)

cat. # 2099, *Mammuthus columbi.*

Putah Creek, Davis, and Dixon

Dundas and Cunningham (1993) report the recovery of skeletal remains of (UCMP, loc. V76199) *Glossotherium harlani* and *Mammuthus columbi* from fluvial sediments of Putah Creek near Davis. U/Th radiometric age determination of 2 mammoth bones suggests a possible late Sangamonian (Late Pleistocene) age. Nearby localities contain ground sloth and mammoth remains with one locality V5430 (also referred to by Jefferson (1991b) as V54030 featuring a *Smilodon* canine, UCMP specimen 44932).

Fossil below SCNHM, Putah Creek, Woodland, Yolo County

1 *Mammuthus*.

Fossils below all UCMP, Rancholabrean

loc. V76199, 1 *Mammuthus*, 2 *Glossotherium harlani* (ground sloth). Specimens 116084, 139027, Yolo County.
loc. V5430 and 54030, 1 *Smilodon* (saber-toothed cat), Putah Creek 1, border of Solano and Yolo Counties.
Jefferson (1991b) reports UCMP V54030, Montezuma Formation.
loc. V65241, 1 *Cervus* sp., Tule Canal, Dixon, Solano County.
loc. D9049, 107 bivalves, north side of Davis, Yolo County. Absolute age U/Th 54,805 ± 202,000 B.P., also listed as LACMIP loc. and UCLA loc. 6560, freshwater mollusks.

Rio Vista and Montezuma Hills

A small vertebrate fauna was collected from a terrace deposit that overlies with unconformity the Montezuma Formation in its type area along the south flank of the Montezuma Hills (Bell and Hanson, 1995). This locale has yielded an undetermined species of ground sloth, 2 murid (mouse), 1 leporid (rabbit or hare), and 1 *Sigmodon* (cotton rat). Another locale in the same deposit .8 km away yielded *Mammuthus* and *Equus* remains. In Rio Vista, Solano County, a nearly complete skeleton *of Elephas americanus* was excavated by amateurs and largely destroyed. A cast of one of its teeth, USNM (old Mus. # 13995), is in the National Museum, later catalogued as USNM #11328 *Mammuthus columbi* in the Department of Paleontology.

Fossils below UCMP, listed by Savage (1951), Pleistocene, Rancholabrean, Collinsville, Montezuma Hills, Solano County

loc. V3719, *Mammuthus cf. columbi* and *Equus*.

Fossils below UCMP, listed by Jefferson (1991b), Rancholabrean, Rio Vista, Solano County

loc. V65617, *Mammuthus columbi*, Pleistocene, Hay (1927).
loc. V65617, 1 *Elephas* (mammoth or mastodon).

Fossil below SCNHM, Rio Vista (golf course), Solano County

1 mastodon (Figure B-13).

Central southern Sacramento Valley and Sacramento proper

Fossils below all SDNHM, listed by Jefferson (1991b), Rancholabrean, Sacramento, Sacramento County

loc. O663, 1 *Equus* sp. (small size), 1 *Equus* sp., 1 cf. *Camelops* sp., 1 Cervidae (deer).

Fossils below all SCNHM, Pleistocene, Sacramento County

1 bovid, Sacramento MUD vault, 9th St. between I and J Streets, Sacramento.
1 camel, 1 camel?, 1 *Bison,* Lost Lake, near Laguna Creek.
1 camel, bank of Cosumnes River.

Fossils below all UCMP, Pleistocene

loc. V6747, 3 *Equus*, 1 *Camelops*, 1 *Camelops hesterus*, 1 mammal, Davis Gravel Pit, Sacramento County.

Figure B-13. Mastodon tooth and tusk fragment, (SCNHM) Pleistocene, Rio Vista

loc. V3915, 1, *Bison latifrons*, Rancholabrean, near Oswald Road, Sutter County.
loc. V6426, 1 Mammalia, Irvingtonian, Gilsizer Slough, appears in drill tailings at the 140-foot level.
The two specimens above were found respectively about 5 and 8 km west of the Feather River about halfway between the Sutter Buttes and Sacramento.

Sierra foothills

Fossils below all SCNHM

1 *Bison latifrons*, Rancholabrean, Penn Valley, Nevada County.
2 mammoth, Roseville, Placer County.
2 *Bison*?, Sloughhouse off Jackson Highway 16, Sacramento County.

Fossils below all UCMP, Rancholabrean

loc. V6951, 1 *Mammut americanum,* Shingle Springs, El Dorado County.
loc. V6952, 1 *Mammut americanum*, Rocklin, Placer County (found in southeastern corner of the western end of Placer County in the "auriferous gravel"), Hay (1927).
loc. V69051, 1 *Bison* sp., Shingle Springs, El Dorado County, listed by Jefferson (1991b) source Hay (1927).

Also listed by Jefferson (1991b):
1 *Mammut*, Gold Hill, near Placerville, Hay (1927).
1 *Mammut*, Grey's Flat, placer and lode gold mine located 1.5 km south of Rescue, Rancholabrean.

The Red Bluff Formation

In the northern Sacramento Valley, the Red Bluff Formation unconformably overlies the Tehama and Tuscan Formations of Late Pliocene age (Olmstead and Davis, 1961). It, in turn, is overlain unconformably by alluvial-fan deposits of Late Pleistocene and Recent age. Hershey (1902) proposed that the Formation was deposited in the Late Pleistocene. Helley and Harwood (1985) give the Red Bluff Formation a maximum age of 1.08 m.y.o. The Colusa Basin Watershed Assessment, Final (2008) interprets the Red Bluff Formation as a sedimentary cover on a pediment surface. The Assessment authors report that the "Red Bluff pediment is overlain by the Rocklin ash bed (0.45 m.y.o.) (Meyer and others, 1980) and in turn overlies the basalt of Deer Creek (1.08 ± 0.16 m.y.o.). Therefore, the pediment must have formed sometime within that 630,000-yr interval."

The Red Bluff Formation was named for its type locality at Red Bluff (Diller, 1894). According to Olmstead and Davis (1961), in its type area it consists of an ill-sorted pebble and small-cobble gravel having a distinctly reddish silty or sandy matrix. Locally abundant clay probably is of residual origin. According to Helley and Harwood (1985), the Red Bluff Formation is a thin veneer of distinctive, highly weathered bright-red gravels locally beveling and overlying the Tehama and Laguna Formations. It appears to have undergone considerable weathering after its deposition. Olmstead and Davis (1961) report that in most places it is less than 15 m thick, and it rests in a belt of exposures that extends southward discontinuously for about 210 km along the western margin of the Sacramento Valley to the vicinity of Cache Creek. Kirby (1943b) mapped the Red Bluff Formation in the Dunnigan Hills where it is deformed by the doubly plunging anticline of the Dunnigan Hills (Helley and Harwood, 1985). Here, and in scattered patches south to Cache Creek and perhaps to Putah Creek, it unconformably overlies the Tehama Formation (Helley and Harwood,1985; Piper, 1939; Shlemons,1967).

Fossils below both UCMP, Rancholabrean, Red Bluff Formation, Woodland, Yolo County

loc. V3402, 2 *Equus*.

The Turlock Lake/Fair Oaks Formations

The Turlock Lake Formation

According to Marchand and Allwardt (1981), “The members of the Quaternary alluvium sequence (Turlock Lake, Riverbank and Modesto Formations) are relatively undeformed, lithologically indistinguishable (with some minor exceptions), and appear to have been deposited in response to climatic events. All three units take the form of a series of terraces opening westward into alluvial fans, each terrace-fan system appearing successively west of the previous one filling an incision into it.”

First recognized in the San Joaquin Valley by Arkley (1954), the Turlock Lake Formation was named by Davis and Hall (1959) for arkosic silt, sand and gravel overlying the Mehrten Formation and underlying the Riverbank Formation along the eastern edge of the northern San Joaquin Valley. Here it is composed of two distinct units in the subsurface: 1) the Corcoran Clay Member, a diatomaceous lacustrine unit located in the middle of the Formation (Frink and Kues, 1954; Davis and Hall, 1959; Marchand and Allwardt, 1981; Page, 1986; Burow and others, 2004), and 2) the Friant Pumice Member, located near the top. Marchand and Allwardt (1981) describe the Turlock Lake Formation as consisting primarily of arkosic alluvium, mostly fine sand, silt, and in places clay at the base grading upward into coarse sand and occasional coarse pebbly sand and gravel. According to Marchand and Allwardt (1981), the type section is exposed in road cuts along hillsides within Turlock Lake State Park between the Lake and the Tuolumne River.

Helley and Harwood (1985) mapped the Turlock Lake Formation along the east and south margins of the Sacramento Valley. According to Springhorn (2008), the age of the Turlock Lake Formation is constrained at the base by the presence of the Bishop Ash Bed at 758 ± 2,000 years (Sarna-Wojcicki, 1995) established in the San Joaquin Valley. The upper age is constrained by the Friant Pumice Member, located near the top of the Turlock Lake Formation, that has a date (K/Ar) of 0.62 ± 0.02 million years (Janda, 1965), and the Lava Creek B ash bed (about 665 ± 5 thousand years; Sarna-Wojcicki, 1995). In the Sacramento Valley, the top of the Turlock Lake Formation is established by the presence of the Rocklin tephra, 565 to 610 thousands of years (Lanphere and others, 2004) overlying diatomaceous clay (Helley and Jaworoski, 1985).

Fair Oaks Unit (Formation)

Horner and Springhorn (2014) report that the Turlock Lake Formation is also referred to as the Fair Oaks unit. Florsheim (2000) reports that "Fair Oaks Formation" is "an informal name applied to sediments north of the American River that occur stratigraphically below the Riverbank Formation and above the Arroyo Seco Gravel and Mehrten andesitic sediments." Marchand and Allwardt (1981) believe most of the Fair Oaks Formation of Shlemon (1967a, b) exposed along the north bluff of the American River east of Sacramento, to be correlative with the Turlock Lake Formation. Marchand and Allwardt (1981) report that the term "Fair Oaks" was useful when the correlation with the Turlock Lake was uncertain but now the entire area between the type Turlock Lake and the American River area has been mapped and the Turlock Lake has been traced northward to the American River. They suggest abandonment of the Fair Oaks as mapped by Shlemon (1967a).

The type locality of the Fair Oaks Formation is the bluff exposures on the north bank of the American River adjacent to the Sunrise Bridge (Shlemon (1967). Shlemon (1995) comments that the Fair Oaks Formation is probably equivalent in part to the Laguna Formation mapped in southern Sacramento County (Gale and others, 1939) and to the Turlock Lake Formation in Stanislaus County (Davis and Hall, 1959). Quoting Florsheim (2000), "At the type locality at the base of the bluffs and observable only when river level is extremely low, are remnants of two other buried paleosols. A paleomagnetic reversal occurs in sediments between the two soils (unpublished data). This is assumed to mark the Brunhes/Matuyama boundary, a magnetic reversal occurring about 760 Ka. Accordingly, the Fair Oaks Formation, with its four buried paleosols, may well record up to five discrete glacial events in the Sierra Nevada; these giving rise to the Fair Oaks-age channel gravel south of the American River, and to extensive overbank sedimentation now preserved in the bluffs at Fair Oaks."

Shlemon and others (2000) comment that the Fair Oaks-age channels southeast of Sacramento are estimated to be 400- to 700-thousand years old based on stratigraphic position, on inferred correlation to buried paleosols, and magneto-stratigraphic dating of overbank deposits exposed at the type locality on the north bank of the American River. Horner and Springhorn (2014) report that recent work done by Springhorn and Brian Hausback (CSU Sacramento) traced an ash layer laterally for several kilometers along the Sacramento River. Elmira Wan of the US Geological Survey analyzed and found it to be equivalent to the Bishop Tuff that dates to 770,000 years before present (B.P.), pushing back the estimated age of the Fair Oaks.

Hausback and Hilton (1994) report a portion of a fossil horse foot in the Turlock Lake Formation from a railroad cut north of Roseville.

Fossils below all SCNHM, Pleistocene, Turlock Lake Formation, Placer County
1 *Equus*, 37 *Salix* (willow) (Figure B-14), 5 *Populus* (cottonwood).
1 *Equus*, Roseville.
Pine branch with needles, Turlock Lake Formation?, Roseville (Twelve Bridges).

The Rancholabrean Riverbank Formation

The Riverbank Formation was first recognized by Arkley (1954) in the Merced River area. It was later named by Davis and Hall (1959) with the type section located on the south bluff of the Stanislaus River near the town of Riverbank. Marchand and Alwardt (1981) re-described the type section because the upper few meters are actually Modesto Formation. The term Riverbank Formation has been extended into deposits in the American River drainage (Shlemon, 1967a, 1967b, 1971, 1972). Marchand and Allwardt (1981) subdivided the Riverbank into three informally designated units that all appear to coarsen upward and consist of arkosic sediment derived mainly from the interior of the Sierra Nevada. Helley and Harwood (1985) report that the “Riverbank Formation consists of reddish gravel, sand and silt forming clearly recognizable terraces and fans. The upper member is made of unconsolidated but compact dark-brown to red alluvium composed of gravel, sand, silt and with minor clay. The lower member consists of red semi-consolidated gravel, sand, and silt. The upper member is absent along the west side of the southern Sacramento Valley but both members of the Riverbank Formation are found along the east edge of the lower Sacramento Valley.”

According to Wagner and others (1987), the Riverbank Formation is Pleistocene. Marchand and Allwardt (1981) place the Riverbank in the San Joaquin Valley between 130,000 and 450,000 years B.P. In the Sacramento Valley, CBWA (2008) divided the Riverbank into two informal members in contrast to Marchand and Allwardt (1981) who recognized three members in the northeastern San Joaquin Valley. CBWA tentatively correlates the two members with the upper two members in the San Joaquin Valley of Marchand and Allwardt (1981), with the lithology being the main distinction between the two areas. Both members form a dominant part of the landscape from Oroville south to the delta along the east side of the valley.

Figure B-14. Willow, *Salix,* (SCNHM) Turlock Lake Formation, Roseville

CBWA (2008) reports that the Riverbank alluvium is older than the Modesto alluvium but younger than the Red Bluff Formation. The Red Bluff is overlain by the Rockland ash bed (0.45 m.y.o.), and the Riverbank, which is cut and filled below the Red Bluff, can be no older than the ash bed and is probably much younger. With the degree of erosional dissection of the Riverbank and strong soil-profile development, CBWA (2008) concludes that it must be at least twice as old as the older Modesto age of about 50,000 B.P. According to CBWA (2008), "The Riverbank in the San Joaquin Valley occupies the stratigraphic interval between the Modesto Formation above and Turlock Lake Formation below. The upper part of the Turlock Lake contains the Friant Pumice Member (600,000 yr old). The Riverbank in the San Joaquin Valley must be considerably younger since a period of erosion and soil formation occurred between its deposition and that of the Turlock Lake."

Shlemons (1995) recognizes two distinct Riverbank-age channels both whose gravels attain a thickness of 15 m in the Sacramento area. The older gravel, identified in the subsurface, can be traced all the way to the town of Franklin. The younger of the two, a terrace gravel, can be traced from Folsom to Perkins and on to the Sacramento Municipal Airport. The gravels date from 250,000- and 150,000-years old respectively with a minimum age of about 100,000 years deduced from uranium series dates of (Hansen and Begg, 1970) on vertebrate fossils from quarries near Perkins.

Paleontological remains have been found at several localities in alluvial deposits referable to the Rancholabrean Riverbank Formation in the Sacramento area. Mammoth remains were found during the excavation of a Sacramento Municipal Utility District trench in Elk Grove. These are on display at the SCNHM (Figure B-15).

Fossils below all SCNHM, Pleistocene, Rancholabrean, Riverbank Formation, Sacramento County

1 *Mammuthus columbi*, south of Bilby Road, Elk Grove.
1 Equidae, Sacramento Wastewater Treatment Plant, Elk Grove.
1 Megalonychidae (*Megalonyx*) *jeffersonii*? (ground sloth), Lost Lake, near Laguna Creek.

Fossils below all UCMP, Rancholabrean, Riverbank Formation, Sacramento County

loc. V74086, 1 *Mammut columbi*, Ehrhardt Ave (near Cosumnes River College), Sacramento.
loc. V6846, 1 *Mammut columbi*, Chicken Ranch Slough 1, Sacramento.
loc. V68141, 2 *Equus*, Chicken Ranch Slough 1-2. Site crosses Eastern Avenue between Whitney and Marconi Avenues in Sacramento? (or) enters the American River 1.6 km north of the H Street Bridge, Sacramento.

Figure 15. *Mammuthus columbi* (Mammoth), palette, Pleistocene, Rancholabrean, Riverbank Formation, Elk Grove

Fossils from ARCO Arena

During construction of a ground-recessed stadium at ARCO Arena (now Sleep Train Arena) north of I-80 and east of I-5, fossils were excavated and then curated at the SCNHM (Hilton and others, 2000). These fossils were recovered from overbank strata in the Riverbank Formation from 3.5 to 9 m below the valley floor. The fossils include: *Paramylodon harlani* (Harlan's ground sloth), *Bison antiquus*, *Canis latrans* (coyote), *Equus* sp., *Camelops hesterus*, cf. *Sciurus* sp. (squirrel), Antilocapridae (antelope or deer), Cervidae, and *Mammuthus* sp. Plant fossils include an unidentified leaf and *Prunus* cf. *ilicifolia* (holly leaf cherry seed).

Fossils below all SCNHM, Pleistocene, Rancholabrean, Riverbank Formation, ARCO Arena (Sleep Train Arena), Sacramento County

> 1 bivalve, 1 Aves, 40 Mammalia, 4 Pilosa (ground sloth),1 Megalonychidae (ground sloth), 1 Antilocapridae (deer or antelope), 1 Carnivora (coyote?), 1 Artiodactyla, 35 Bovidae (bison), 4 Bovidae (bison?), 5 Camelidae (Figure B-16), 1 Equidae, 6 *Mammuthus*, 1 Elephantidae, 2 Rodentia, 1 squirrel, 1 seed, 1 leaf, 1 limb cast.

Fossils from the Teichert Quarry

Shlemon and others (2000) comment that immediately west of Jackson Road where the power lines cross, numerous vertebrate fossils have been found in overbank sediments stratigraphically above the channel gravel but below the San Joaquin soil in the Teichert Gravel Quarry. A minimum age of 100,000 years was deduced from uranium series dates of Hansen and Begg (1970). Hansen and Begg (1970) comment that Douglas fir, sycamore and willow tree remains were found in the Teichert Quarry. These yielded radiocarbon dates in excess of about 35,000 years (Shlemon, 1972). Jefferson (1991a) reports radiometric dates: uranium series, 112,000 to 67,000 years B.P., Hansen and Begg (1970) list fossils from the Teichert Quarry: *Perognathus (*pocket mouse), *Odocoileu*s (deer), Anatidae (duck), *Clemmys marmorata* (pond turtle), and 1 *Colubridae* (snake).

Fossils below all UCMP, from Teichert Gravel Pit E 1, Sacramento County:
loc. V69129, 1 Osteichthyes *Orthodon* (blackfish),1 Osteichthyes (fish),1 Osteichthyes *Archoplites* (sunfish), 2 Amphibia *Scaphiopus* (spadefoot),1 *Rana* (frog), 2 *Scaphiopus* (spadefoot toad), 1 Aves (Neornithes), 2 Aves, 3 Mammalia,1 *Equus*, 2 *Canis latrans* (coyote), 1 *Canis dirus* (dire wolf), 1 *Bison*, 24 *Thomomys* (pocket gopher), 4 *Scapanus latimanus* (broad-footed mole), 12 *Microtus* (vole), 3 *Sorex* (shrew), 15 *Neotoma (*wood

Figure B-16. Camel calcaneum (heel) and metatarsal (canon bone), (SCNHM) Pleistocene, Riverbank Formation, Sports Arena, North Natomas rat), 9 *Spermophilus* (ground squirrel), 20 *Reithrodontomys* (harvest mouse), 2 S*ylvilagus (*rabbit), 3 *Mammuthus*.

Fossils below all UCMP, from Teichert Gravel Pit E 2, Sacramento County
loc. V75126, 1 *Glossotherium harlani* (ground sloth),1 *Camelops hesternus*.

See also Riverbank Formation in the Sutter Buttes section.

The Rancholabrean Modesto Formation

The Modesto Formation was first recognized by Arkley (1954) and the term first used by Davis and Hall (1959). The type section is along the Tuolumne River in Stanislaus County (Davis and Hall, 1959). Marchand and Allwardt (1981) report that the sediments of the Modesto Formation are virtually identical to the Laguna, Turlock Lake, and Riverbank Formations and that "the Modesto Formation is composed of arkosic sediments and associated deposits of local derivation. Gravel, sand, and silt were deposited as a series of coalescing alluvial fans extending continuously from the eastern San Joaquin Valley north to the tributaries of the Sacramento (River) in the north." According to CBWA (2008), the Modesto Formation was deposited by still-existing rivers and streams. It consists of distinct alluvial terraces and some alluvial fans and abandoned channel ridges, and forms the lowest deposits lying topographically above the Holocene deposits along streams and in valleys. The Modesto Formation consists of tan and light gray gravely sand, silt, and clay.

According to CBWA (2008), the Modesto Formation has two members. The upper member is composed of unconsolidated, unweathered gravel, sand, silt, and clay and forms terraces that are topographically the lowest of the two Modesto terraces. They are only a few meters thick and generally form a thin veneer deposited on older alluvial deposits. Janda and Croft (1967) and Croft (1972) provide dates on the younger Modesto that range to as little as 9,000 years. Marchand and Allwardt (1981) provide an age of the upper member that is probably bracketed by carbon-14 ages of approximately 27,000 and 9,000 years B.P. Helley and Harwood (1985) report the age of this member has been placed at approximately 12,000–26,000 years B.P. Helley and Harwood (1985) mention that alluvium of the lower member of the Modesto Formation surrounds the Dunnigan Hills.

According to CBWA (2008), the lower member is composed of unconsolidated, slightly weathered gravel, sand, silt, and clay and forms terraces that are topographically a few meters higher than those of the upper member. It forms alluvial fans along the main channels of both the Sacramento and Feather Rivers. It forms large natural levees bordering the Sacramento River from Stony Creek to the Sutter Buttes. Age estimates for the lower member range from 29,000 to 42,000 years B.P. (Marchand and Allwardt, 1981). DWR Bulletin 118 (2004) reports that the Modesto Formation was deposited between 14,000 to 42,000 years B.P. Shlemon and others (2000) comments that based on correlation of soil profile development with similar deposits numerically dated elsewhere in the Central Valley, the Modesto-age channels are judged to be about 15-20 Ka and 60-70 Ka respectively.

Helley and Harwood (1985) report that in the Sacramento region the Modesto Formation consists of tan and light-gray gravely sand, silt, and clay.

Fossils below all UCMP, Pleistocene, Rancholabrean, Modesto Formation, Willow Slough (north of Davis), Yolo County

loc. V96015, 1 reptile, 6 Mammalia, 1 Microtinae (vole).

Rancholabrean Fossils from Hawver Cave, its Entrance, and Cool Quarry in El Dorado County Near Auburn

Hawver Cave, Hawver Cave Entrance, Cool Quarry, and Crystal Cavern 1 (in El Dorado County) have provided a wealth of Pleistocene fossils from the foothills east of Sacramento. Crystal Cavern 1 lies outside the mapped parameters of this paper and will not be discussed here.

Hawver Cave and Cool Quarry are found in a single limestone outcrop. Hawver Cave was first discovered in the early 1880s when limestone was first quarried in the area. The original site of Hawver Cave is located about 5 km due east of Auburn where Highway 49 passes the limestone quarry. Fossils from Hawver Cave were brought to the attention of UCMP scientist Chester Stock by Dr. J.C. Hawver (a dentist working in Auburn) (Stock, 1918). This early collection of fossils was done by Hawver, Eustace L. Furlong, and Chester Stock between 1906 and 1909, and curated at UCMP (Stock, 1918) (Figure B-17). Some of the fossils appear to have washed into the cave but a significant number were deposited in the rubble at the bottom of a collapsed sinkhole. Stock (1918) describes this material as a cave-breccia. Most of the original cave has been quarried for use as limestone products and much of the remainder of the "cave" today is actually an underground mine that was used to extract limestone. Lundelius and others (1983) considered the faunal assemblage to be Wisconsin (85,000-11,000 years B.P.).

In "Avifauna of the Pleistocene Cave Deposits of California," Miller (1911d) discusses bird fossils found at Hawver Cave. Miller (1911d) lists 10 bird species with 69 specimens from Hawver Cave. Stock (1918) lists the following mammals: *Scapanus* possible n. sp. (mole), *Canis* near *dirus* Leidy (dire wolf), *Canis ochropus* Eschscholtz

Figure B-17. *Megalonyx jeffersonii,* ground sloth claw (UCMP cast in SCNHM), Rancholabrean, Hawver Cave.

(coyote), *Smilodon* (?) sp. (saber-toothed cat), *Felis hawveri* n. sp. (mountain lion), *Felis* (cat), *Ursus* (bear), *Procyon psora* Gray (raccoon), *Mephitis occidentalis* Baird (striped skunk), *Neotoma fuscipes* Baird (packrat), *Microtus* sp. (vole), *Peromyscus boylii* Baird (brush mouse), *Thomomys* sp. (pocket gopher), *Aplodontia* sp. (mountain beaver), *Citellus beecheyi* Richardson (ground squirrel), *Lepus* probably n. sp. (rabbit and hare), *Mylodon harlani* Owen (ground sloth), *Megalonyx* (?) sp. (ground sloth), *Nothrotherium shastense hawveri* n. ssp. (ground sloth), *Euceratherium collinum* (?) Sinclair and Furlong, Bovidae (*Bison* sp.), *Odocoileus* sp., *Equus* sp., *Mammut*.

Miller and DeMay (1942) list 8 bird species plus two questionable from Hawver Cave.

UCMP shows the following Pleistocene, Rancholabrean localities:
loc. -1069, Hawver Cave.
loc. -1073, Hawver Cave, S entrance.
loc. V4805, Cool Quarry.

The author has modified the list below to reflect additional fossils listed by Jefferson (1991a, b) and to provide common names. Listed by Jefferson (1991a, b), Rancholabrean, Wisconsinan, in part early Holocene. Sources for Jefferson (1991a, b) include: Miller (1911b), Stock (1918), Miller and DeMay (1942), Brattstrom (1954), Kurten and Anderson (1980), Lundelius and others (1983).

Fossils below all UCMP, loc. -1069, Hawver Cave, Rancholabrean

11 unidentified vertebrates
1 Osteichthyes (fish)

Amphibians

40 *Bufo* (toad)
1 *Rana* (frog)

Reptiles

2 *Sceloporus graciosus* (sagebrush lizard)
2 *Sceloporus occidentalis* (western fence lizard)
1 *Clemmys* (turtle)
1 *Clemmys marmorata* (pond turtle)
1 *Crotalus horridus* (timber rattlesnake)
1 *Crotalus viridis* (western rattlesnake)
1 *Gerrhonotus multicarnatus* (alligator lizard)

Birds

40 unidentified Aves
18 *Callipepla californica* (California quail)

1 *Oreortyx picta (pictus)* (mountain quail)
1 *Buteo* (large hawk)
1 *Buteo* f*erruginus* (ferruginus hawk)
listed as *Archaeobuteo ferruginus* by Jefferson (1991a)
1 *Buteogallus* (hawk)
1 *Buteogallus milleri* (hawk)
1 *Urbitinga milleri* (hawk)
1 *Coragyps occidentalis* (black vulture)
1 *Catharista shastensis* (condor-like vulture)
1 *Cathartes aura* (turkey vulture)
1 *Corvus carax* (common raven)
1 *Euphagus cyanocephalus* (Brewer's blackbird)
1 *Colaptes auratus* (northern flicker)
1 *Anas crecca Carolinensis* (green-winged teal)
Jefferson (1991a) lists *Hypomorphinus milleri* an Accipitriformes (hawk) and *Cyanocitta stelleri* (Steller's jay)

Mammals

127 unidentified Mammalia (mammals)
37 *Lepus* (rabbit and hare)
2 *Lepus californicus* (black-tailed jackrabbit)
12 *Sylvilagus* (cottontail rabbit)
18 *Thomomys* (gopher)
8 Scapanus latimanus (broad-footed mole)
3 *Scapanus latimanus* occultos (broad-footed mole)
27 *Neotoma* (woodrat)
7 *Neotoma fuscipes* (dusky-footed woodrat)
1 *Dipodomys* (kangaroo rat)
2 Peromyscus (deer mouse)
2 *Peromyscus boylii* (brush mouse)
15 *Spermophilus* (ground squirrel)
1 *Spermophilus citellus* (European ground squirrel)
2 *Spermophilus citellus beecheyi* (California ground squirrel)
2 *Microtus* (vole)
2 Odocoileus hemionus (mule deer)
22 *Odocoileu*s (deer)
3 *Euceratherium collinum* (shrub ox)
7 *Bison* (bison)
1 *Homo sapiens* (human)

Edentates

6 *Pilosa* (anteater and sloth)
12 *Nothrotheriops shastensis* (ground sloth)

28 *Nothrotheriops shastensis* hawveri (ground sloth)
3 *Glossotherium harlani* (ground sloth)
4 *Megalonyx* (ground sloth)
1 *Glyptotherium floridanum* (giant armadillo)

Carnivores and Omnivores

1 *Smilodon* (saber-toothed cat)
15 *Felis* (cat)
32 *Felis concolor* (mountain lion)
1 *Martes* (martin)
1 *Mustela* (weasel)
1 *Mustela frenata* (long-tailed weasel)
1 Mephitinae (skunk)
1 *Canis dirus* (dire wolf)
1 *Canis latrans* (coyote)
1 *Procyon* (raccoon)

Bats

1 *Eptesicus fuscus* (big brown bat)
1 *Antrozous pallidus* (pallid bat)
1 *Tadarida brasilliensus* (Mexican free-tailed bat)
1 *Pipistrellus hesperus* merriami (canyon bat)

Jefferson (1991b) lists: 1 *Ursus* sp. (bear), 1 *Aplodonta rufa* (mountain beaver), 3 *Equus* and proboscidians *Mammut* sp. and *Mammuthus* sp.

<u>Fossils below all UCMP, loc. -1073, Hawver Cave, S Entrance, Pleistocene, Rancholabrean, Placer County</u>

1 Mammalia (mammal)
5 *Thomomys* (gopher)
1 *Spermophilus* (ground squirrel)
2 *Spermophilus beecheyi* (California ground squirrel)
2 *Lepus* (rabbit and hare)
1 *Mephitis* (skunk)
1 *Mephitis (<u>mephitis</u>) occidentalis* [*sic*] *occidentalis* (striped skunk)
1 *Canis latrans* (coyote)
8 *Homo sapiens* (human)

<u>Fossils below all UCMP, loc. V4805, Cool Quarry, Pleistocene, Rancholabrean, Placer County</u>

Amphibians

1 *Bufo* (toad)

1 *Rana* (frog)

Reptiles

1 *Crotalus* (rattlesnake)
2 *Gerrhonotus multicarinatus* (alligator lizard)

Birds

1 unidentified Aves (bird)

Mammals

4 Mammalia (mammal)
2 *Lepus* (rabbit and hare)
2 *Sylvilagus idahoensis* (cottontail rabbit)
2 *Thomomys* (gopher)
1 *Neotoma fuscipes* (dusky-footed woodrat)
2 *Neotoma* (woodrat)
1 *Peromyscus* (brush mouse)
2 *Spermophilis* (ground squirrel)
1 *Spermophilis beecheyi* (California ground squirrel)
1 *Eutamias* (chipmunk)
1 *Microtus mephitis* (vole)
1 *Odocoileu*s (deer)
3 *Odocoileus hemionus* (mule deer)
1 *Bison* (bison)
2 *Bison antiquus* (bison)
2 *Nothrotheriops shastensis* (ground sloth)
2 *Felis* (cat)
3 *Felis concolor* (mountain lion)
1 *Canis dirus* (dire wolf)
1 *Mephitis* (striped skunk)
2 *Antrozous pallidus* (pallid bat)
Jefferson (1991b) lists *Brachylagus idahoensis* (pygmy rabbit)
Jefferson (1991b) lists *Tamias* (chipmunk)

Holocene Fossils

The Holocene begins as the Pleistocene ends about 9,700 years B.P. If one defines a fossil as “any evidence of prehistoric life” then Holocene fossils end with the discovery of California by Cabrillo in1842 and the beginning of written history for the State. Sometimes it is difficult to tell if a specimen is modern or truly a Holocene fossil without an accurate date. The only Holocene fossils listed include those below.

Fossils below all UCMP, Recent (Holocene), Lower Sacramento River, Solano County

loc. 2445 bivalves.

Fossils from the Sutter Buttes

The Sutter Buttes is an extinct volcano whose magma rose up through several hundreds of meters of sedimentary layers to erupt in the middle of the Sacramento Valley about 1.6 Ma (Hausback and Nilsen, 1999). Historically, the Sutter Buttes have also been called the Marysville Buttes by various authors and on various maps but will be referred to as the Sutter Buttes throughout this discussion. According to Hausback and others (2011), the sedimentary rocks of the Sutter Buttes range in age from Late Cretaceous, about 83.5 Ma (Almgren, 1986; Williams, 1997) to 1.6 Ma when the volcanic events at the Sutter Buttes commenced. Younger fossiliferous beds of the Riverbank Formation are superimposed on these older units.

The geomorphology of the volcano was described by Williams and Curtis (1977) in terms of the structure of a castle and its defenses. Working out from the center of the volcano they describe the center area of intrusive and extrusive domes as the "castellated interior." On the edge of the domes are uplifted and steeply tilted or overturned sedimentary beds that today surround the castellated interior. This area is eroded to low rolling hills and termed the "moat." It lies between the castellated interior and the surrounding skirt of topographically higher volcanic debris originally shed from the castellated interior and termed the "ramparts." The ramparts lie in a circle like the skirt surrounding a crouching young girl.

The thickest, most complete, and most easily viewed section of the sedimentary rocks of the moat can be seen along Pass Road dissecting the volcano as one goes north and then west out of the town of Sutter. **Do not trespass** as most of this land is privately owned.

Note: The age designations at the Sutter Buttes are listed as recorded in the literature.

Upper Cretaceous Forbes Formation

The Forbes Formation of Kirby (1943b) contains benthic foraminifers in well logs in the northern San Joaquin Valley (Almgren, 1986; Williams, 1997), indicating deposition from about 83.5 to 78 Ma. The oldest fossil-bearing sedimentary unit exposed by the uplifting and tilting of beds in the Sutter Buttes is the upper Cretaceous Forbes Formation "Forbes Shale." The earliest reference of Cretaceous beds in the Sutter Buttes comes from Watts (1894) who reported fossils found at South and West Buttes areas and identified by Cooper (1894) as being Cretaceous in age. Cooper (1894) reports 58 specimens with 7 new species from the Cretaceous at the Sutter Buttes. Later, Dickerson (1916) referred to the “Chico” Cretaceous beds. Williams (1929) mentions 7 bivalves and 2 gastropods from the uppermost Cretaceous beds on the western side of the Buttes. Northwest of Sutter in the southern moat area, in the topmost sandstone of the Cretaceous beds, Williams mentions 6 bivalves, a *Dentalium* (tusk shell), 1 shark tooth, and plant remains. Johnson (1943) describes a thick section of Forbes Shale with no base exposed, and with thicknesses exposed between 838 and 1325 m, while Garrison (1962a) proposed a similar thickness between 823 and 1219 m.

According to Hausback and Hilton (1994), shale of the Forbes Formation underlies much of the smooth grassy hills of the moat area, but contrary to most published descriptions there are also prominent conglomerates and sandstones within the upper part. Within these coarser units Hausback describes abraded molluscan fragments but comments there are no *in situ* molluscan fossils indicating a shallow water environment. Toward the upper Forbes, he comments that this portion of the Formation was probably deposited in shoaling conditions by redeposition of sands from storm waves. Here it is interbedded with bioturbated fine-grained sandstone and mudstone containing molluscan fossils. From the east side of the South Butte, Dickerson (1916) describes upper Cretaceous marine fossils from the 30.5 m of impure, gray limestone with thin strata of hard gray, medium-grained sandstone above about 183 m of non-fossiliferous sandstone at the base that is in contact with the andesitic castellated core. These fossils come from what at the time was called the upper Cretaceous Chico Formation. They are listed as 2 bivalves, *Spisula ashburneri* Gabb, *Trigonia evansana* Meek, and 1 gastropod, *Gyrodes expansa* Gabb. Stewart (1949) comments on a shale below the lower Eocene of the Sutter Buttes containing 3 gastropods and 2 bivalves (these may be Cretaceous). Below this, collected from a concretionary shale, he mentions 1 *Baculites*.

Fossils below all CAS online data, Sutter Buttes, Sutter County

4 gastropods, Cretaceous, Cooper (1894).
CAS loc. 442, 1 bivalve.

Fossils below all CAS Collection data, Cretaceous, Sutter Buttes, Sutter County

loc. 13093, 1 bivalve.
loc. 31371, 8 bivalves, 3 gastropods, 1 *Baculites*, 1 Cnidarian, South Butte.
loc. 53342, 1 gastropod.
loc. 61072, 1 bivalve.

Fossils below all UCMP, Cretaceous, Sutter Buttes, Sutter County

loc1 Plantae, Pinopsida, *Margeriella cretacea*, “Chico Conifer.”
loc. P3847, 1 Plantae, Pinopsida, *Margeriella*, South Butte.

Upper Cretaceous Kione Formation

Most of the Marysville "beds" of Williams (1929) are Cretaceous in age (Johnson, 1943). Johnson named the Cretaceous sandstone that is similar to the Ione Formation the Kione Formation. The Kione conformably overlies the Forbes Formation. Garrison (1962a) comments that the Kione Formation was named for its likeness to the Ione Formation but is Cretaceous in age (hence the K). According to Williams and Curtis (1977), the Kione consists of white quartz-anauxite sands, though some beds are tinted in shades of pink, purple, and brown by oxidation of small amounts of iron. Hausback and Hilton (1994) comment that the Kione Formation has features characteristic of deposition in a complex of deltaic, fluvial, and shallow-marine environments. They report that locally it contains abundant molluscan fossils (particularly oyster fragments) as well as plants. Williams and Curtis (1977) report the bivalve *Trigonias* and other Cretaceous fossils in the Kione Formation.

Upper Cretaceous Sacramento Shale

According to Hausback and others (2011), the Sacramento Shale overlies the Kione Formation at the Sutter Buttes. There is no mention of fossils from the Sacramento Shale in the Sutter Buttes in present literature. The Sacramento Shale of Callaway (1964) contains benthic foraminifers in well logs from the San Joaquin Valley (Almgren, 1986; Williams, 1997), indicating deposition from about 78 to 77 Ma.

Eocene Capay Formation "Capay Shale"

According to Hausback and others (2011), the Capay Formation overlies the Sacramento Shale. The type locality of the Capay fauna described by Merriam and Turner (1937) is in Smith Canyon in the Rumsey Hills on the west side of the Sacramento Valley (Bentson, 1941). Hausback and Nilsen (1999) comment that the Capay ranges from 76 to as much as 122 m on the western flank of the Buttes. They report that the Capay Formation consists chiefly of greenish-gray shale and claystone. It contains interbedded buff-colored sandstone locally rich in ferruginous concretions. Carboniferous mudstones are occasionally present as are thin seams of low-grade coal especially on the north and east sides of the Buttes (Williams and Curtis, 1977). According to Hausback and Nilsen (1999), the Capay contains abundant benthic foraminifers and ostrocods that indicate a shallow-marine environment and a Penution (early Eocene) to Ulatisian (early middle Eocene) age (Stipp, 1926; Merriam and Turner, 1937; Israelsky, 1940; Marianos and Valentine, 1958; Olson, 1961).

Watts (1894) was the first to describe the general geologic relationships of the Eocene at the Sutter Buttes and referred its age to the "Cretaceous B" of Gabb (1864). Cooper (1894) reports 3 gastropod specimens comprising 3 new species from the Cretaceous B (Eocene). Lindgren and Turner (1895a) report abundant marine fossils from the "Tejon" (Eocene) of the Sutter Buttes including a coral and a bivalve. Dickerson (1913) lists and describes fossils found in the “Eocene” strata of the Sutter Buttes to date (1913) including the fossils of Gabb (1864) and Lindgren and Turner (1895a). Dickerson (1914) describes fossils from the Sutter Buttes as from the *Siphonalia sutterensis* zone, which is the uppermost “Tejon.” He later modifies the list (1916) with the following for the Eocene “Tejon:” 1 foraminifera, 5 corals, 1 urchin, 25 bivalves, 2 scaphopods, 45 gastropods plus 1 limpet, 1 crab, and 1 shark. East of Noyesburg School, Dickerson (1917) reports that the fauna from this horizon contains many tropical forms and that the climate during the deposition of this portion of the Eocene was tropical or subtropical. Clark (1921) reports 2 corals, 1 urchin, 10 bivalves, and 38 gastropods from the Eocene “Meganos” at Sutter Buttes.

The Marysville claystone member of the Maganos Formation was proposed by Williams (1929), with the type locality on the west side of Sutter Buttes. Stewart (1949) reports that the Marysville claystone and lower portion of the Ione sands (Allen’s Dry Creek Formation) form the Capay Stage. The locality from which Dickerson originally collected the portion of the foraminifera studied by Stipp (1926) is in the western moat area. Stipp (1926) agrees with Dickerson (1916) that both the molluscan fauna and the foraminifera support the conclusion that these fossils were deposited in an open-sea condition in relatively warm water at approximately 100 fathoms. Stipp (1926) made a collection, part of which was from a locality 46 m lower than those collected by Dickerson. These beds (locality 248) also contained numerous mollusca, bryozoan, corals, ostracods and foraminifera. Stipp (1926) records 22 genera of foraminifera from the Sutter Buttes, 21 of which are present in the glauconitic shales and at least 3 in the underlying buff-colored shales. Williams (1929) reports 3 (possibly 4) species of Bryozoans (moss animals). Merriam and Turner (1937) report 2 bivalves, 7 gastropods and 1 coral from the middle Eocene. Israelsky (1940) described foraminifera from the western moat area at the same location where Dickerson’s molluscan fauna were obtained. Hanna and Hertlein (1941) report 3 gastropods from the middle Eocene from two locations: from the western moat area and Well #4, 2.5 km north of Sutter. Bentson (1941) noted that the total number of Eocene species in the fauna is 77. The total number of genera is 69. These include 17 bivalves, 63 gastropods, 8 scaphopods and 4 corals**.** Stewart (1949) reports 1 gastropod from site #30, south of the South Butte site, lower Eocene (UCMP A1405), fine silty sandstone, 914 m east along strike. Below this are other lower Eocene fossil species: 24 gastropods, 10 bivalves, 1 worm?, and 2 corals. A shale below the lower Eocene contained 3 gastropods and 2 bivalves (these may be Cretaceous). Schenck and Keen (1940) report a gastropod from the Marysville Formation (Capay). Marianos and Valentine (1958) report 11 species of ostracods from the Capay Formation in the western moat area.

Fossils below all UCMP, Sutter County

loc. 1853, A4335, MF3901,15 foraminifera, Eocene, Capay Formation, western moat area.

loc.1853, 4 Anthozoa, Wasatchian**,** Capay Formation, Marysville (Sutter) Buttes.
loc. 692-, 1 *Alaria*, 2 gastropods, Eocene, Capay Formation.
loc.1853, 36 gastropods, Wasatchian, Capay Formation, Marysville (Sutter) Buttes.
loc. 1855, 2 gastropods, Eocene, Capay Formation, probably from the Sutter Buttes.
loc. A1405, 2 gastropods, Eocene, Capay Formation, Marysville (Sutter) Buttes.
loc.1853, 5 bivalves, Wasatchian**,** Capay Formation. Marysville (Sutter) Buttes.
loc.1853, 1 Synecodus (fish), Wasatchian, Capay Formation, Marysville (Sutter) Buttes.
loc. MF7626, foraminifera, Eocene, "Tejon" Formation, Marysville (Sutter) Buttes.

Fossils below all USNM, Eocene, western moat area, Sutter Buttes, Sutter County

PAL 594024, 1 Ostracoda, no formation given, Marianos and Valentine, 1958.
PAL 326333, 1 Ostracoda, Capay Formation, Marianos and Valentine. PAL 306377, 2 Ostracoda, Capay Formation, Marianos and Valentine, 1958.

"middle Eocene" Ione Formation

The age of the depositional strata of the Ione Formation is currently in a state of flux (see Ione section of paper). According to Thamer (1961) and Garrison (1962a), the Ione Formation is approximately 45 m thick in the Sutter Buttes and consists of friable, white-weathering, quartzose sandstone. Turner (1894) reports that Lindgren, working at the Sutter Buttes, found a series of beds of clay and sandstone with layers of lignite he considered to be Ione. He collected some marine shells, said to be "Miocene" age by Dr. W.H. Dall. Lindgren and Turner (1895a) comment about the Ione Formation at the Sutter Buttes, that in the clays of very disturbed beds are carbonaceous strata with impressions of leaves. Stewart (1949) reports: 4 gastropods, plus 2 limpets, 8 bivalves and 1 barnacle from site #29 in the western moat area site, Ione Formation, Dry Creek Sandstone member, middle Eocene. In the glauconitic sandstone unit: 1 gastropod, 2 bivalves and 1 urchin. In the western moat area, Ione Formation, lower Eocene**:** 31 gastropods, 12 bivalves, 1 ostracod, 1 starfish, and 1 fish otolith.

Fossils below all CAS online database, "Eocene," Sutter Buttes, Sutter County

1 gastropod (Eocene), Schenk and Keen (1940), 5 gastropods, Cooper (1894), 3 gastropods, Hanna and Hertlein (1941), 1 urchin, Reed (1933), 48 foraminifera, Israelsky (1939), 21 ostracods, Marianos and Valentine (1958).

Fossils below all CAS collections, Sutter County

loc. 192, several gastropods, Eocene, western moat area.
loc. 193, 1 gastropod, Eocene, western moat area.
loc. 194, 2 gastropods, Eocene, western moat area.

loc. 195, 1 gastropod, Eocene, western moat area.
loc. 196, 2 gastropods, Eocene, western moat area.
loc. 248, numerous bivalves, Eocene, Sutter Buttes.
loc. 248, numerous gastropods, Eocene, Sutter Buttes.
loc. 248, 5 gastropods, Eocene, western moat area, UC loc. 1853.
loc. 248, 2 gastropods, Eocene, western moat area, UC loc. 1853.
loc. 248.01,1 gastropod, Eocene, western moat area.
loc. 248, numerous Cnidaria, Eocene, Sutter Buttes.
loc. 248, 1 urchin, Eocene, Sutter Buttes.
loc. 248, numerous foraminifera, Eocene, Sutter Buttes.
loc. 311, 1 bivalve, Eocene, western moat area.
loc. 406, bivalves, gastropods, Cnidarian, urchin, Eocene, Tejon Group, southeast (moat) side of Buttes.
loc. 407, 1 bivalve, 1 echinoid, no age or formation given.
loc. 409, various bivalves, 1 gastropod, no age or formation given, west side of Buttes.
loc. 566, various bivalves and gastropods, Eocene, no formation given, Sutter Buttes.
loc. 30295, 1 gastropod, no age or formation given.
loc. 30300, 1 gastropod, no age or formation given.
loc. 30301, 1 gastropod, Eocene, western moat area.
loc. 53728, 3 bivalves, Eocene, West Buttes.
loc. 53729, 3 gastropods, Eocene, Sutter Buttes.
loc. 53752, 2 gastropods, Eocene, Meganos, Sutter Buttes.
loc. 53753, 2 gastropods, Eocene, Sutter Buttes.
loc. 53754, 1 gastropod, Eocene, Sutter Buttes.
loc. 53755, 2 bivalves, Eocene, Sutter Buttes.
loc. 53756, 5 bivalves, Eocene, Sutter Buttes.
loc. 53757, 2 gastropods, Eocene, Sutter Buttes.
loc. 53758, 5 gastropods, Eocene, Sutter Buttes.
loc. 53759, 10 gastropods, Eocene, Sutter Buttes.
loc. 53760, 1 gastropod, Eocene, Sutter Buttes.
loc. 53761, 1 bivalve, Eocene, Sutter Buttes.
loc. 53762, 1 gastropod, Eocene, Sutter Buttes.
loc. 53763, 12 bivalves, Eocene, Sutter Buttes.
loc. 69348, 1 bivalve (rudist), Eocene, western moat area.

Fossils below all LACMIP, Eocene, Sutter Buttes, Sutter County

loc. 21377, no specimens listed. Also listed as UCLA loc. 1377, 4 km NW of Sutter City.
loc. 21378, 1 Echinoida (urchin). Also listed as UCLA (loc. 1378), east of West Butte.

Fossil below UCMP, Eocene, Sutter Buttes, Sutter County

loc. A4153, 1 foraminifera, Eocene, Ione Formation, Buttes Well #4.

Butte Gravels

Williams and Curtis (1977) noted numerous conglomeritic layers within and above the Ione Formation that they assign to the Butte Gravels. They noted the presence of a richly fossiliferous sandstone on the south flank of the Buttes, about 220 m above the Kione, dominated by the early Eocene gastropod *Turritella merriami* Dickerson. Williams (1929) notes 7 bivalves, 5 gastropods, plus 1 limpet, worm tubes, and plant remains from the "Butte Gravels."

Pliocene non-marine Sutter Formation "Sutter Beds"

According to Springhorn (2008), based on dated volcanics near the base, in the body, and on top of the unit, he finds that the Sutter Formation is early Pliocene to Late Pliocene. The Sutter Formation overlies the Ione and Butte Gravels. According to Hausback and Hilton (1994), a prominent conglomerate forms the base of the Formation, but the rest consists chiefly of fine-grained sandstone, siltstone, tuff and minor amounts of gravel. Williams and Curtis (1977) give it a thickness of 182-305 m in the Sutter Buttes. Springhorn (2008) reports a thickness of 421 m. According to Hausback and Hilton (1994), other researchers provide a thickness of as much as 550 m. Fragmentary teeth from the Pliocene horse *Dinohippus mexicanus* were found about 76 m from the top of the Sutter Beds south of Pass Road (Williams and Curtis, 1977).

Fossil below UCMP, Miocene, Hemphillian, Sutter Formation, Sutter Buttes 2, Sutter County

loc. V6402, 1 *Pliohippus coalingus* (horse).

Pleistocene Riverbank Formation

According to Helley and Harwood (1985), the upper member of the Riverbank Formation occurs (with angular unconformity) on the western side of the Sutter Buttes.

Fossil below UCMP, Pleistocene, Riverbank Formation, Sutter Buttes, Sutter County

loc. V4043, *Hipparionini* (horse).

Note: CAS collections yield one crude oil sample from a depth of 1767 m, Sutter Buttes, no age or formation listed.

References

Addicot, W. O., 1981, *A brief history of Cenozoic marine Biostratigraphy of the Pacific Northwest,* Geological Society of America Special Paper 184, pp. 3-47.

Allen, V. T., 1929, *The Ione Formation of California*: University of California Press, Berkeley, CA, *Bulletin of the Department of Geological Sciences*, Vol. 18, No. 14, pp. 347–448.

Almgren, A. A., 1986, *Benthic foraminiferal zonation and correlations of Upper Cretaceous strata of the Great Valley of California—a modification.* In Abbott, P. L., Editor, Cretaceous Stratigraphy, Western North America: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, pp. 137-152.

Anderson, F. M., 1902, Cretaceous Deposits of the Pacific Coast, California Academy of Science, Proceedings, 3d Series, Vol. 2 (1902a), 126 p.

Anderson, C. A. and Russell, R. D., 1939, Tertiary formations of northern Sacramento Valley, California: *California Journal of Mines and Geology,* Vol. 35, No. 3, pp. 219-253, Geologic Map, scale approx. 1:63,360.

Arkley, R. J., 1954, Soils of eastern Merced County: California University of Agriculture Experimental Station, Soil Survey, No. 11, 174 p.

Bailey E. H., Irwin W. P., and Jones D. L., 1964, Franciscan and related rocks and their significance in the geology of the western California: *California Division of Mines and Geology Bulletin* 183,177 p.

Baker, P., 1975, *A reinterpretation of the Eocene Capay formation, Yolo County, California*: MS Thesis, Stanford University, Stanford, CA, 112 p.

Bell, C. J. and Hanson, C. B., 1995, A Fossil *Sigmodon* (Mammalia: Rodentia) from the San Francisco Bay Area, Solano County, California, with Comments on Additional Fossil Material from Kern County, California, *PaleoBios* 16(4), pp. 9-12.

Bentson, H., 1941, *The Stratigraphy and faunas of the Capay Eocene of the Sacramento Valley*: Ph.D. Thesis, University of California, Berkeley, CA, 633 p.

Blake, W. P., 1864, Proceedings of California Academy of Sciences, Vol. III, 167 p.

Bodden, R. W., III, 1983, Depositional environments of the Eocene Domengine Formation outcrop on the north side of Mt. Diablo, California. In Cherven, V. B. and Graham, S. A. (Editors), Geology and sedimentology of the southwestern Sacramento Basin and East Bay Hills: Pacific Section, Society of Economic Paleontologists and Mineralogists, Vol. 29., pp. 43-57.

Bonds, C. L., 2007, State of California Department of Water Resources (DWR), Division of Planning and Local Assistance, Central District, Yuba River Well Installation and Monitoring Project Groundwater Substitution Water Transfer Monitoring Program, Yuba County, California, 18 p.

Brattstrom, B. H., 1954, The fossil pit-vipers (Reptilia: Crotalidae) of North America.

Transactions of the San Diego Society of Natural History, 12(3): 31-46.

Bryan, K., 1923, Geology and ground water-resources of Sacramento Valley, California: .S. Geological Survey Water-Supply Paper 495, 285 p.

Burow, K. R., Shelton, J. L., Hevesi, J. A., and Weissmann, G. S., 2004, Hydrogeologic Characterization of the Modesto Area, San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2004-5232, 62 p.

Callaway, D. C., 1964, Distribution of uppermost Cretaceous sands in the Sacramento-Northern San Joaquin Basin of California: Selected Papers Presented to San Joaquin Geological Society, Vol. 2, pp. 5-18.

CAS, California Academy of Sciences, 55 Music Concourse Drive, San Francisco, CA 94118, http://researcharchive.calacademy.org/research/izg/fossil/index.asp

Christensen, O. D., Henry, C. D., and Wood, J., 2015, *Origin of gold in placer deposits of the Sierra Nevada Foothills, California:* Geological Society of Nevada Symposium.

Chaney, R. W. and Axelrod, D. I., 1944, Pliocene floras of California and Oregon: Carnegie Institution of Washington, Publication 553, 407 p.

Clark, B. L., 1921, The stratigraphy and faunal relationships of the Meganos group Middle Eocene of California, *Journal of Geology*, Vol. 29, 125 p.

Clark, B. L. and Anderson, C. A., 1938, Wheatland Formation and its relation to early Tertiary andesites in the Sierra Nevada: *Geological Society of America Bulletin*, Vol. 49, pp. 931-956.

Clark, L. D., 1976, Stratigraphy of the north half of the western Sierra Nevada metamorphic belt, California, Geological Survey Professional Paper 923, pp. 1-26.

Cohee, G. V. and Wright, W. B., 1973, Changes in Stratigraphic Nomenclature by the U.S. Geological Survey, p. A68.

Colusa Basin Watershed Assessment. Final. 2008, H. T. Harvey & Associates. Prepared for: Colusa County Resource Conservation District, 100 Sunrise Boulevard, Suite B, Colusa, CA 95932

Cooper, J. G., 1894, Catalogue of California Fossils, Bulletin No. 4, California State Mining Bureau, September, pp. 36-45.

Cousens, B. L., Prytulak, J., Henry, C. D., Alcazar, A., and Brownrigg, T., 2008, Geology and geochronology, and geochemistry of the Miocene-Pliocene ancestral Cascades arc, northern Sierra Nevada, California and Nevada--The roles of the upper mantle, subducting slab, and the Sierra Nevada lithosphere, *Geosphere*, Vol. 4, pp. 814-828.

Creely, S. and Force, E. R., 2007, Type region of the Ione Formation (Eocene) Central California: Stratigraphy, Paleogeography, and relation to Auriferous gravels: USGS Open File Report 2006-1378, 65 p.

Croft, M. G., 1972, Subsurface geology of the late Tertiary and Quaternary water-bearing deposits of the southern part of the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1999-H, 29 p.

Curtis, G. H., 1954, Mode of origin of pyroclastic debris in the Mehrten Formation of the

Sierra Nevada: University of California Publications. In *Geological Sciences* 29: 453-501.

Dalrymple, G. B., 1964, Cenozoic Geochronology of the Sierra Nevada, California: University of California Publications, *Bulletin of the Department of Geological Sciences*, Vol. 47, 41 p.

Davis, S. N. and Hall, F. R., 1959, Water quality of eastern Stanislaus and northern Merced Counties, California: Stanford University Publications, Stanford, CA, Geological Sciences, Vol. 6, no. 1, 112 p.

Day, H. W., Moores, E. M., and Tuminas, A. C.,1985, Structure and tectonics of the northern Sierra Nevada: *Geological Society of America Bulletin*, 96:436–450.

Dickerson, R. E., 1913, Fauna of the Eocene at Marysville Buttes, California: University of California Publications, *Bulletin of the Department of Geology*, Vol. 7, No. 12, pp. 257-298.

Dickerson, R. E., 1914, Note on the faunal zones of the Tejon group: University of California Publications, *Bulletin of the Department of Geology*, Vol. 8, No. 2, pp. 17-25.

Dickerson, R. E., 1916, Stratigraphy and fauna of the Tejon Eocene of California: University of California Publications, *Bulletin of the Department of Geology*, Vol. 9, No. 17, pp. 363-524.

Dickerson, R. E., 1917, Climatic Zones of Martinez Eocene Time: *Proceedings of the California Academy of Sciences*, Vol. 7, Issue 6, 7, & 8, pp. 193-196.

Diller, J. S., 1894, Tertiary revolution in the topography of the Pacific coast: *U.S. Geological Survey 14th Annual Report*, Part 2, pp. 397-434.

Dundas, R. G. and Cunningham, L. M., 1993, Harlan's Ground Sloth *(Glossotherium harlani)* and a Columbian Mammoth *(Mammuthus columbi)* from Stevenson Bridge, Yolo County, California: *PaleoBios* No. 3, pp. 47-62.

DWR Bulletin 118-3, 1974, Evaluation of Groundwater Resources, Sacramento County: Department of Water Resources, Sacramento, 139 p., with map**.**

Edelman, S. H. and Sharp, W. D., 1989, Terranes, early faults, and pre-late Jurassic amalgamation of the western Sierra Nevada metamorphic belt, California: *Geological Society of America Bulletin*, Vol. 101, No. 11, pp. 1420-1433.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: *American Journal of Science* 262:145-198.

Fischer, P. J., 1979, The Evolution of a Late Paleocene Submarine Canyon and Fan System: The Meganos Formation, Southern Sacramento Basin, California: *Field Trip Guide Book for the Geological Society of America*, Cordilleran Section Meeting at San Jose, CA, April 9-11, 10 p.

Florsheim, J., 2000, Late Quaternary Geology of the Lower Cosumnes River and Floodplain. In Quaternary Geology of the Sacramento Area: Association of Engineering Geologists, Sacramento Section, Guidebook for Field Trip, March 25, 4 p.

Ford, R. S., 1972, Groundwater Geology of Northern Sacramento County: *University of*

Pacific Spring Conference Far Western Section, National Association of Geology Teachers (NAGT), April 23, 1972, 23 p.

Frink, J. W. and Kues, H. A., 1954, Corcoran Clay, A Pleistocene lacustrine deposit in the San Joaquin Valley, California: *American Association of Petroleum Geologists Bulletin*, Vol. 38, pp. 2353-2371.

Gabb, W. M., 1864, Paleontology of California, Triassic and Cretaceous fossils: *Geological Survey of California*, Vol. 1, 243 p.

Gabb, W. M., 1869, Paleontology of California, Cretaceous and Tertiary fossils: *Geological Survey of California*, Vol. II, 299 p.

Gabb, W. M., 1870, Descriptions of some secondary fossils from the Pacific States: *American Journal of Conchology*, 5:5–18.

Gale, *in* Piper, A. M., Gale, H. S., and Thomas, H. E., 1939, Geology and Ground-Water Hydrology of the Mokelumne Area, California: U.S. Geological Survey Water-Supply Paper 780, 230 pp. with 10 plates (maps and hydrographs of the Mokelumne River).

Garrison, L. E., 1962a, The Marysville (Sutter) Buttes, Sutter County, California. In Geologic Guide to the Gas and Oil Fields of Northern California, Bowen, O. E. Jr. (Editor), *California Division of Mines and Geology Bulletin* 181, pp. 69-72.

Garside, L. J., Henry, C. D., Faulds, J. E., and Hinz, N. H., 2005, The upper reaches of the Sierra Nevada auriferous gold channels, California and Nevada. In Rhoden, H. N., Steininger, R. C., and Vikre, P. G. (Editors), *Geological Society of Nevada Symposium: Window to the World*, Reno, Nevada, May, pp. 1-27.

Graymer, R. W. and Jones, D. L., 1994, Tectonic implications of radiolarian cherts from the Placerville belt, Sierra Nevada foothills, California: *Geological Society of America Bulletin*, Vol. 106, pp. 531-540.

Graymer, R. W., Jones, D. L., and Brabb, E. E. (Compilers), 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California. In U.S. Geological Survey, Denver, CO.

Graymer, R. W., Jones, D. L., and Brabb, E. E., 2002, *Geologic Map and Map Database of Northeastern San Francisco Bay Region, California.* U.S. Geological Survey Miscellaneous Field Studies Map MF-2403, U.S. Geological Survey, Menlo Park, CA. August 8, 2002.

Guitierrez, C., Bryant, W., Saucedo, G., and Wills, C., 2010, Geologic Map of California: *California Department of Conservation.* May 27. Web <http://www.quake.ca.gov/gmaps/GMC/stategeologicmap.html>

Gust, S., 2008, Paleontological resources mitigation plan for the Lincoln Quarry, Placer County, California, Prepared for Geology Division, Teichert Aggregates, Sacramento, Cogstone Project #1589, 28 p.

Hackel, O., 1966, Summary of the Geology of the Great Valley. In Geology of Northern California, *California Division of Mines and Geology Bulletin* 190, pp. 217-238.

Hanna, G. D. and Hertlein, L. G., 1941, Characteristic fossils of California: *California Division of Mines Bulletin* 118, pp. 165-182.

Hansen, R. O. and Begg, E. L., 1970, Age of Quaternary sediments and soils in the

Sacramento area, California, by uranium and actinium series dating of Vertebrate Fossils: Earth and Planetary Science Letters 8, 411-419 North Holland Publishing Company.

Hanson, B. C. and Schorn, H., 2005, Paleontological resources in the vicinity of FERC Project 2100 (Oroville Reservoir and lower Feather River): Literature-based inventory and significant assessment, Prepared for Montgomery Watson Harza.

Hausback, B. P. and Hilton, R. P., 1994, “Geology in the Sutter Buttes Volcano” Field Trip B. In *Guidebook to Selected Field Trips in Northern California, National Association of Geology Teachers Far Western Section*, Fall meeting, pp. 66-82.

Hausback, B. P. and Nilsen, T. H., 1999, Sutter Buttes. In Wagner, D. L. and Graham, S. A. (Editors), Geologic Field Trips in Northern California; centennial meeting of the Cordilleran Section of the Geological Society of America: California Department of Conservation, *Division of Mines and Geology Special Publication*, 119, pp. 246-254.

Hausback, B. P., Muffler, L. J. P., and Clynne, M. A., 2011, Sutter Buttes—the lone volcano in California’s Great Valley: U.S. Geological Survey Fact Sheet 2011-3024, 4 p.

Hay, O. P., 1927, *The Pleistocene of the Western Region of North America and its Vertebrated Animals,* Carnegie Institute, Washington, DC, Publication 322B.

Helley, E. J. and Harwood, D. S., 1985, Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California: USGS Miscellaneous Field Studies Map MF-1790, 24 p. with 5 plates (maps).

Helley, E. J. and Jaworoski, C., 1985, The Red Bluff Pediment; a datum plane for locating Quaternary structures in the Sacramento Valley, California: *U.S. Geological Survey Bulletin* 1628, 13 p.

Hershey, O. H, 1902, The Quaternary of southern California: California University, *Bulletin of the Department of Geological Sciences* 3, pp. 1-29.

Hilton, R. P., 2003, *Dinosaurs and Other Mesozoic Reptiles of California*, University of California Press, Berkeley, California, 318 p.

Hilton, R. P. and Antuzzi P., 1997 “Chico Formation Yields Clues to Late Cretaceous Paleoenvironment in California”. In *California Geology*, published by California Department of Conservation, Division of Mines and Geology, September/October.

Hilton, R. P., Antuzzi P., Arens, N. C., and Erwin, D., “A Tree Fern from the Late Cretaceous Chico Formation of Northern California.” In *Abstracts with Program*, Geological Society of America, 1997, p. A-97.

Hilton, R. P., Dailey, D. C., and McDonald, H. G., A Late Pleistocene Biota from the Arco Arena site, Sacramento, California. In *PaleoBios*, Vol. 20, No. 1, April 15, 2000, pp. 7-12.

Horner, T. C. and Springhorn, S., 2014, Field Trip #4: Miocene and Pleistocene Stratigraphy near Sacramento, CA. In *Selected Geology Field Trips in the Sacramento Region, the San Joaquin Delta, and Sierra Nevada, National Association of Geoscience Teachers Far Western Section*, Fall Conference-

October 10-12, p. TH1- TH18.
Hyland, E. G. and Sheldon, N. D, 2013, Coupled CO2-climate response during the Early Eocene climatic optimum: Paleogeography, Paleoclimatology, Paleoecology, Vol. 369, pp. 125-135.
Israelsky, M. C., 1940, Notes on some Foraminifera from Marysville Buttes, California: *Sixth Pacific Science Congress*, Vol. 2, pp. 569-580.
Janda, R. J., 1965, Quaternary alluvium near Friant, California: *International Association of Quaternary Research Guidebook for Field Conference I*, northern Great Basin and California, pp. 128-133.
Janda, R. J. and Croft, M. G., 1967, The Stratigraphic significance of a sequence of non-calcic brown soils formed in the northwestern San Joaquin Valley, California. In *International Association of Quaternary Research*, VII Congress, Reno Nevada Proceedings Vol. 9, pp. 158-190.
Jefferson, G. T., 1991a, A Catalogue of Late Quaternary Vertebrates from California: Part One, Non-marine Lower Vertebrate and Avian Taxa: Natural History Museum of Los Angeles County, Technical Report No. 5.
Jefferson, G. T., 1991b, A Catalogue of Late Quaternary Vertebrates from California: Part Two: Mammals: Natural History Museum of Los Angeles County, Technical Report No. 7.
Jennings, C. W., 1994, Fault Activity Map of California and Adjacent Areas: California Division of Mines and Geology, Sacramento, CA Geologic Data Map No. 6.
Kirby, J. M., 1943b, Rumsey Hills area: *California Division of Mines Bulletin* 118, pp. 601-605.
Kleinpell, R. M., 1938, Miocene Stratigraphy of California: Tulsa, OK, American Association of Petroleum Geologists, 450 p.
Kurten, B. and Anderson, E., 1980, Pleistocene mammals of North America: Columbia University Press, New York, NY, 443 p.
LACM = Natural History Museum of Los Angeles County, Los Angeles, CA https://collections.nhm.org/vertebrate-paleontology/
LACMIP = Natural History Museum of Los Angeles County – Invertebrate Paleontology Department, Los Angeles, CA https://collections.nhm.org/vertebrate-paleontology/
Paleontology Department, 900 Exposition Blvd, Los Angeles, CA 90007, invertebrate database, ip.nhm.org/ipdatabase/lot_show
Lanphere, M. A., Champion, D. E., Clynne, M. A., Lowenstern, J. B., Sarno-Wojcicki, A. M., and Wooden, J. L., 2004, Age of the Rockland tephra, western USA: Quaternary Research 62, pp. 94-104.
Lawler, D. A., 1995, Ancestral Yuba River Gold Map, Northern California: California Gold, 48 Shattuck Square, Suite 108, Berkeley, California, 94704.
Lindgren, W., 1894, Sacramento Folio: U.S. Geological Survey Atlas, No. 5.
Lindgren, W., 1900, Description of the Colfax quadrangle: U.S. Geological Survey Geological Atlas, Colfax Folio 66,10 p.
Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada of California: U. S.

Geological Survey Professional Paper 73, 226 pgs.
Lindgren, W., and Turner, H. W., 1894, Placerville Folio: U.S. Geological Survey Folio 3.
Lindgren, W., and Turner, H. W., 1895a, Marysville Folio: U.S. Geological Survey Folio 17.
Lindgren, W., and Turner, H. W., 1895b, Smartsville Folio: U.S. Geological Survey, Folio 18, 6 p.
Livingston, J. G.,1974, Engineering Geologic Map of the Rocklin Quadrangle, Placer County, California: Map prepared for Placer County Planning Department.
Lundelius, E. L., Jr., Graham, R. W., Anderson, E., Guilday, J., Holman, J. A., Steadman, D. W., and Webb, S. D., 1983, Terrestrial vertebrate faunas. In Wright, H. E., Jr. and Porter, S. C. (Editors), Late-Quaternary environments of the United States, The late Pleistocene, Vol. 1, University of Minnesota Press. pp. 311-353.
MacGinitie, H. D., 1941, *A Middle Eocene Flora from the Central Sierra Nevada*: Carnegie Institution of Washington, Washington, DC, Publication 534.
Marchand, D. E. and Allwardt, A., 1981, Late Cenozoic Stratigraphic Units, Northeastern San Joaquin Valley, California: *U.S. Geological Survey Bulletin* 1470.
Marianos, A. W. and Valentine, J. W., 1958, Eocene ostracod fauna from the Marysville Buttes, CA: *Micropaleontology*, Vol. 4, pp. 363-372.
Merriam, C. W. and Turner, F. E., 1937, The Capay middle Eocene of northern California: University of California Publications, *Bulletin of the Department of Geological Sciences*, Vol. 24, pp. 91-114.
Merrill, R. D., 1984, Ophiomorpha and other nonmarine trace fossils from the Eocene Ione Formation, CA, *Journal of Paleontology*, 58(2): 542-549.
Meyer, C. E., Woodward, M. J., Sarna-Wojcicki, A. M., and Naeser, C. W., 1980, Zircon fission-track age of 0.45 million years of ash in the type section of the Merced Formation west-central California: U.S. Geological Survey Open-file Report 80-1071, 6 p.
Millar, C. I., 1996, Tertiary vegetational history in Sierra Nevada: ecosystem project final report to congress, Vol. 2, pp. 71-122.
Miller, L. and Holmes, 1911d, Avifauna of the Pleistocene Cave Deposits of California: University of California Publications, *Department of Geology Bulletin*, Vol. 6, No. 16, pp. 385-400.
Miller, L. and Holmes, 1911b, Additions to the avifauna of the Pleistocene deposits at Fossil Lake Oregon: University of California Publications, *Department of Geology Bulletin*, 6:305-316.
Miller, W. L., 1966, *Petrology of the Putah Tuff Member of the Tehama Formation, Yolo and Solano Counties, California*: MS Thesis, University of California, Davis, CA.
Miller, L. and DeMay, I. S., 1942, The fossil birds of California: University of California, *Publications in Zoology*, 47(4): 47-142.
Mooi, R. and Hilton, R. P., 2014, First record and phylogenetic significance of a Jurassic diadematacean sea urchin from California: *Journal of Paleontology* 88(3): 421-

433.
Moses, L. J., 1985, *A Study of the Neogene Mehrten Formation: stratigraphy, petrology, paleomagnetism, Southwestern Placer County, CA*: MS Thesis, University of California, Davis, CA, 97 p.
Mudlesee, M., Bickert, T., Lear, C. H., and Lohmann, G., 2014, Cenozoic climate changes: A review based on time series analysis of marine benthic Oz18O records: Reviews of Geophysics, pp. 333-374.
O'brient, J. D., 1978, An evaluation of Tertiary volcanism along the Maidu East Shear Zone, Auburn Damsite: Seismic evaluation of Auburn Damsite, Vol. 5, 115 p.
Olmstead, F. H., 1971, Pre-Cenozoic geology of the south half of the Auburn 15" Quadrangle, California: *U.S. Geologic Survey Bulletin* 1341, 30 p.
Olmstead, F. H. and Davis, G. H., 1961, Geologic Features and Ground-water Storage Capacity of the Sacramento Valley California: U.S. Geological Survey Water Supply Paper 1497, Washington, DC, 249 pp. with 5 plates (maps and cross section).
Olson, R. E., 1961, Correlation of Eocene strata exposed in Fig Tree Gulch, Sutter County, California: *Report of the Annual Field Trip of the Geological Society of Sacramento*, pp. 32-35.
Page, R. W., 1986, Geology of the fresh ground-water basin of the Central Valley, California (Regional aquifer-system analysis): U.S. Geological Survey Professional Paper: 1401-C).
Page, R. W. and Bertoldi, G. L., 1983, A Pleistocene diatomaceous clay and pumiceous ash: *California Geology*, Vol. 36, pp.14-20.
Parham, J. F. and Stidham, T. A., 1999, Late Cretaceous sea turtles from the Chico Formation of California: *PaleoBios* 19(3).
Pask, J. A. and Turner, M. D., 1952, *Geology and Ceramic Properties of the Ione Formation, Buena Vista Area, Amador County, California*: Division of Mines, California Department of Natural Resources, San Francisco, CA, Special Report 19.
Piper, A. M., Gale, H. S., and Thomas, H. E., 1939, Geology and Ground-Water Hydrology of the Mokelumne Area, California: U.S. Geological Survey Water-Supply Paper 780, 230 p. with 10 plates (maps and hydrographs of the Mokelumne River).
Roth, B., 2000, Upper Cretaceous (Campanian) Land Snails (Gastropoda: Stylommatophora) from Washington and California: Journal of Molluscan Studies, The Malacological Society of London, 66, pp. 373-381.
Russell, R. D. and VanderHoff, V. L.,1931, A Vertebrate fauna from a new Pliocene Formation in Northern California: University of California Publications, *Bulletin of the Department of Geological Sciences*, Vol. 20, pp.11-21.
Sarna-Wojcicki, A. M., 1995**,** Age, areal extent, and paleoclimatic effects of "Lake Clyde," a mid-Pleistocene lake that formed the Corcoran Clay, Great Valley, California: Glacial History of the Sierra Nevada, California: Symposium in Memorial to Clyde Wahrhaftig.

Sarna-Wojcicki, A. M. and Walker, J. P., 1999**,** Use of tephrachronology in correlation and dating of some late Neogene sedimentary sections, east San Francisco Bay Area, and sediment provenance in the Shell Ridge and Los Medanos Hills areas, east of Mount Diablo: *Northern California Geological Society Field Trip Guide*, 35 p.

Saucedo, G. J. and Wagner, D. L, 1992, a, California Geological Survey - Geologic Map of the Chico Quadrangle, California Geological Survey, Regional Geologic Map No. 7A, scale 1:250,000.

Savage, D. E., 1951, Late Cenozoic vertebrates of the San Francisco Bay region: University of California Publications, *Bulletin of the Department of Geological Sciences* 28(10): 215-314.

Savage, D. E. and Russell, D. E., 1983, Mammalian paleofaunas of the world: Addison-Wesley Publishing Company, Reading, MA, vii + 432 p.

SDSNH, San Diego Natural History Museum, 1788 El Prado, Balboa Park, San Diego, CA, 92101, http://www.sdnhm.org/science/paleontology/resources/collection-database/

Schenck, H. G. and Keen, A. M., 1940, California fossils for the field geologist (preliminary edition): Stanford University Press, Stanford, CA, 88 p.

Scheirer, A. H. and Magoon, L. B., 2007, Age, Distribution, and Stratigraphic Relationship of Rock Units in the San Joaquin Basin Province, California, Chapter 5, in Scheirer, A. H. (Editor), Petroleum Systems and Geologic Assessment of Oil and Gas in the San Joaquin Basin, California: U.S. Geological Survey Professional Paper 1713, 107 p.

Shlemon, R. J., 1967, Pleistocene channels of the lower American River, Sacramento County, California: Yearbook - Association of Pacific Coast Geographers 29, 158 p.

Shlemon, R. J., 1967a, Landform-soil Relationships in Northern Sacramento County, California: Ph.D. Dissertation, University of California, Berkeley, CA, Department of Geography, 295 p. plus map and cross sections.

Shlemon, R. J., 1967b, Quaternary Geology of the Northern Sacramento County, California: *Annual Field Trip Guidebook of the Geological Society of Sacramento*, May, 60 p.

Shlemon, R. J., 1971, The Quaternary Deltaic and Channel System in the Central Great Valley, California: *Annals of the Association of American Geographers*, Vol. 61, pp. 427- 440**.**

Shlemon, R. J., 1974, The lower American River area, California: a model of Pleistocene landscape evolution: *Yearbook of the Association of Pacific Coast Geographers*, Vol. 34, pp. 61- 86.

Shlemon R. J., 1995, Pleistocene channels of the lower American River, Sacramento County, California: (appended five-page article). In Franks A., and Moss, G. (Leaders), Geology of the Sacramento area, foothills, and Sierra Nevada mountains: *Association of Engineering Geologists Fieldtrip Guidebook*, Annual Meeting of the Association of Engineering Geologists and Groundwater

Resources Association, Sacramento, CA.
Shlemon, R. J., 1998, Quaternary Geology of the Sacramento Area: Association of Engineering Geologists, *Sacramento Section Fieldtrip Guidebook,* March, 162 p.
Shlemon, R. J., Horner, T. C., and Florsheim, J., 2000, Quaternary Geology of the Sacramento Area: Association of Engineering Geologists, *Sacramento Section Fieldtrip Guidebook*, March 25, 38 p. with references as attachments.
SCNHM, Sierra College Natural History Museum, 5000 Rocklin Road, Rocklin, CA, 95677, www.**sierracollege**.edu/about-us/beyond-the-classroom/nat-hist-**museum**/
Smith, J. P., 1910, Geologic record of California: *Journal of Geology*, 18:216– 227.
Springhorn, S. T., 2008, Stratigraphic analysis and hydrogeologic characterization of Cenozoic strata in the Sacramento Valley near the Sutter Buttes. MS Thesis, California State University, Sacramento, CA, 246 p.
Stewart, R., 1949, Lower Tertiary stratigraphy of Mount Diablo, Marysville Buttes, and west border of lower Central Valley of California: U.S. Geological Survey Oil and Gas Investigations Preliminary Chart, OC-34.
Stipp, T. F., 1926, The Eocene Foraminifera of the Marysville Buttes: MA Thesis, Stanford University, Stanford, CA, 70 p.
Stirton, R. A., 1939, Cenozoic Mammal Remains from the San Francisco Bay Region: University of California, *Bulletin of the Department of Geological Sciences* 24(13).
Stock, C., 1918, The Pleistocene Fauna of Hawver Cave, University of California Publications, *Bulletin of the Department of Geology*, Vol. 10, No. 24, pp. 461-515.
Sullivan, R. and Sullivan, M., 2007, Origin of Eocene Depositional Sequences in the Sacramento Basin, California: The Interplay of Tectonics and Eustasy, Search and Discovery Article #50054, *Adapted from extended abstract prepared for presentation at AAPG Annual Convention, Long Beach, CA, April 1- 4.
Taliaferro, N. L., 1951, Geology of the San Francisco Bay Counties: *California Division of Mines Bulletin* 154.
Taff, J. A., Hanna, G. D., and Cross, C. M., 1940, Type locality of the Chico Formation: *Geological Society of America Bulletin*, Vol. 51, pp. 1311-1328.
Thamer, D. H., 1961, Report of the Annual Field Trip of Geological Society, Sacramento, CA, pp. 36- 40.
Tuminas, A. C., 1983, Structural and stratigraphic relations in the Grass Valley-Colfax area of the northern Sierra Nevada foothills, California: unpublished Ph.D. Dissertation, University of California, Davis, CA, 415 p.
Tuminas, A. C., and Moores, E. M., 1982, Sedimentology and possible paleotectonic setting of a Late Jurassic flysch sequence in the western foothills of the northern Sierra Nevada, California: *Geological Society of America Abstracts with Program*, 14:241.
Turner, H. W., 1894, The Rocks of the Sierra Nevada: U.S. Geological Survey, Fourteenth Annual Report, Part II, pp. 435-495.
UCMP, University of California Museum of Paleontology, http://ucmpdb.berkeley.edu

USNM, Smithsonian Institution, 10th and Constitution Ave. N.W., Washington, DC 20560-0193. http://www.nmnh.si.edu/

VanderHoff, V. l., 1933b, A skull of *Pliohippus tantalus* from the later Tertiary of the Sierran foothills of California: University of California, *Bulletin of the Geological Society*, Vol. 23, pp. 183- 193.

Wagner, D. L., Jennings, C. W., Bedrossian, T. L., and Bortugno, E. J., 1981, *Geologic Map of the Sacramento Quadrangle:* California Division of Mines and Geology, California Geological Survey, Regional Geologic Map Series No. 1A, scale 1:250,000.

Wagner, D. L. and Saucedo, G. J., 1990, Age and Stratigraphic relationships of Miocene volcanic rocks along the eastern margins of the Sacramento Valley, California. In Ingersall, R. V., and Nilsen, T. H. (Editors), *Sacramento Valley Symposium and Guidebook*, Pacific Section S.E.P.M., Vol. 65, pp. 143-151.

University of California Museum of Paleontology. Paleontology Collections Database. University of California, Berkeley, CA. <http://bscit.berkeley.edu/ucmp/loc.shtml>

Watts, W. L., 1894, The gas and petroleum yielding formations of the central valley of California: *California State Mining Bureau Bulletin* No. 3. August, pp. 9-10.

Weaver, C. E., and others, 1944, Correlation of the marine Cenozoic formations of western North America [chart 11]: *Geological Society of America Bulletin*, Vol. 55, No. 5, pp. 569-598.

Weaver, C. E., 1949, Geology of the Coast Ranges immediately north of the San Francisco Bay region, California: *Geological Society of America Memoirs,* 35, 242 p.

Whitney, J. D., 1865, Geology, Volume I: Report of Progress and Synopsis of the field-work, from 1860 to 1864, Geological Survey of California, 498 p.

Williams, H., 1929, Geology of the Marysville Buttes, California: *University of California Publications in Geological Sciences*, Vol. 18, No. 5, pp. 103-220.

Williams, H. and Curtis, G. H., 1977, The Sutter Buttes of California, A Study of Plio-Pleistocene Volcanism: *University of California Publications in Geological Sciences*, Vol. 116, pp. 1-67.

Williams, T. A., 1997, Basin-fill architecture and forearc tectonics, Cretaceous Great Valley Group, Sacramento Basin, Northern California: Ph.D. Dissertation, Stanford University, Stanford, CA, 412 p.

Wood, J. L., Glasmann, J. R., and Stout, S., 1995, *Geology of the Ione Formation in the Ione Area,* 1995, Association of Environmental and Engineering Geologists, Field Trip Guidebook: *Geology and Geotechnical Aspects of the Ione Formation.*

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to Present: *Science*, Vol. 292, pp. 686-693.

Zachos, J., Dickens, G. R., and Zeebe, R. E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: *Nature*, Vol. 451, pp. 279-283.