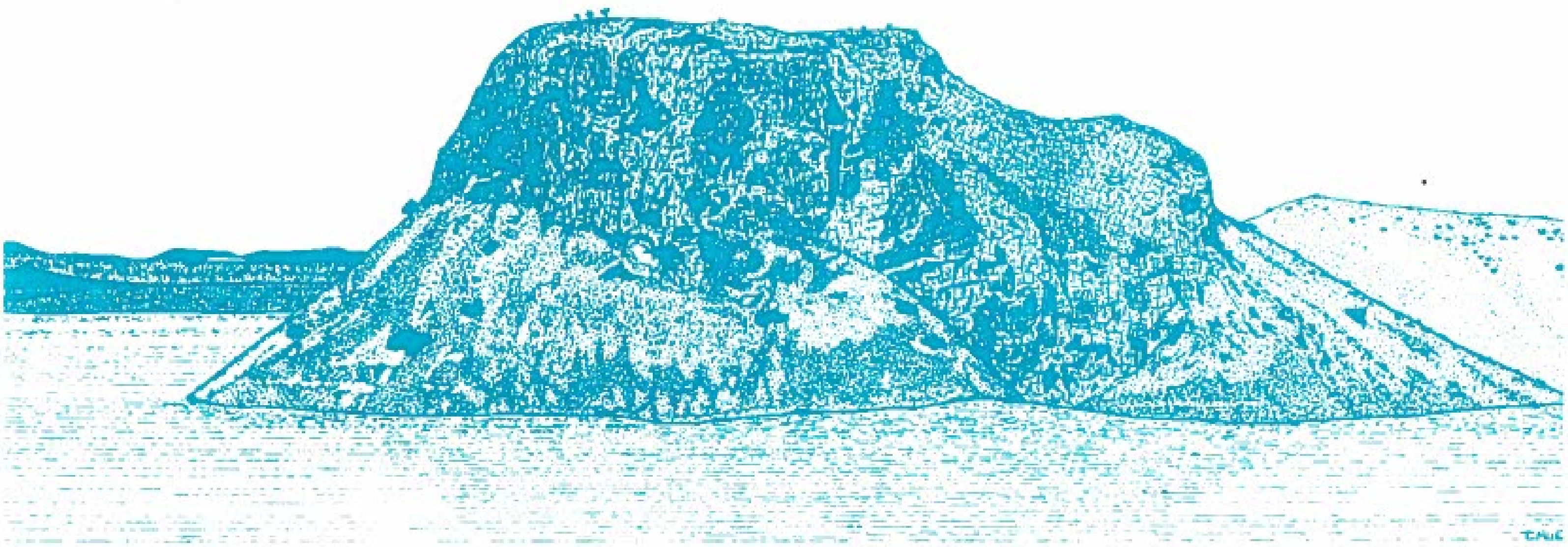
Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico

by Richard P. Lozinsky



CIRCULAR 187 New Mexico Bureau of Mines & Mineral Resources 1985

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

COVER—Elephant Butte, the landform after which the area is named, is a volcanic plug that intrudes through the Hall Lake Member of the McRae Formation. Can you see the elephant? Sketch by Teresa A. Mueller.

The text of NMBMMR Circular 187 was printed and bound in June 1985, but numerous problems encountered in drafting of the map sheets (in pocket) held up its release until September 1986. Please correct the year and month of release on the cover, title page, and authority page.

Circular 187

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico

by Richard P. Lozinsky
New Mexico Bureau of Mines and Mineral Resources,
Socorro, New Mexico 87801

SOCORRO 1985

Original Printing 1985

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63–1–4
Printed by University of New Mexico Printing Plant, June 1985

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

Preface

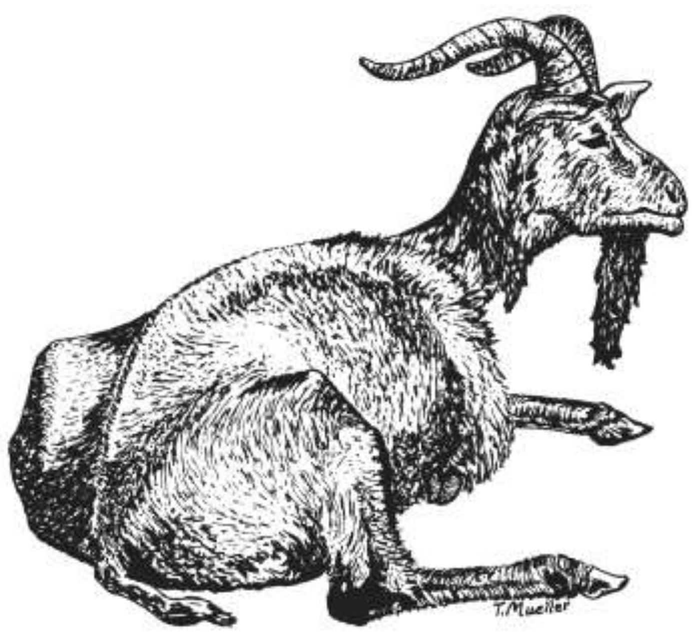
The work on the Elephant Butte area was done in 1981-82 as a M.S. thesis project at the University of New Mexico. The major emphasis of this report is on the late Cenozoic geology; however, all stratigraphic units and structures exposed within the area were mapped (Sheet 1) in order to better interpret the origin of the younger deposits. The area is a critical one for studies of the Rio Grande rift and evolution of the Rio Grande fluvial system for three reasons: 1) the location is at the junction between two intrarift basins and includes parts of three uplifts; 2) there are excellent exposures of upper Cenozoic basin fill, including deposits of the ancestral Rio Grande; and 3) this is one of the few places along the rift where the Rio Grande has migrated outside a basin to cut a channel within bedrock of an adjacent uplift. Included in this report is a seven-stage evolutionary history of the Elephant Butte area that covers the last 4-5 million years (Sheet 2). This study ties in with other work done on the Rio Grande rift between Hatch and Las Cruces, New Mexico (e.g., Seager and others, 1971, 1975; Seager and Hawley, 1973).

This publication is intended not only for persons involved with geological investigations, but will also be of value to all persons who enjoy the Elephant Butte area and wish to gain a better understanding of how it developed throughout geologic time. The landforms and rock types are quite diverse, and there is a variety of fossils including large dinosaur and mammal bones. The submerged channel of the Rio Grande shown on Sheet 1 should be of interest to boating and fishing enthusiasts.

ACKNOWLEDGMENTS -I am grateful to the Tenneco Oil Co. for granting me access to the Pedro Armendaris land grant. I would like to thank my thesis committee members, Drs. Stephen G. Wells, Albert M. Kudo, Vincent C. Kelley, and John W. Hawley for their supervision and guidance. In addition, special thanks go to: Teresa A. Mueller for drafting; Dr. Donald L. Wolberg and Adrian P. Hunt for identification and recovery of fossils; and Earle and Jean George and Ival and Helen Kennedy for their hospitality during field work. Finally, I want to express my appreciation to the following people of the New Mexico Bureau of Mines and Mineral Resources for their support in the publication of this study: Jiri Zidek (Editor), Frank E. Kottlowski (Director), and especially John W. Hawley (Environmental Geologist).

Socorro, New Mexico
April 14, 1984

Richard P. Lozinsky
Research Assistant
New Mexico Bureau of Mines and Mineral Resources



Drawing of one of the goats that live on Elephant Butte Island.

Contents

Figures

Tables

Appendices

Sheets

Abstract

A 256-km^2 area surrounding the Elephant Butte Reservoir, Sierra County, New Mexico, was mapped to interpret the late Cenozoic (Pliocene to Holocene) history. The interpretation is based on examining faults, geomorphic features, and upper Cenozoic sedimentary and volcanic units.

Less than 10% of the study area is covered by Precambrian and Paleozoic units, approximately 40% is covered by upper Cretaceous units, and more than 50% is covered by Cenozoic units. The major Cenozoic sedimentary deposits are mapped as the Palomas Formation of the upper Santa Fe Group, which is divided into the piedmont and the axial facies. Other Cenozoic units include pediment, alluvial-fan, terrace, and eolian deposits.

Regional geomorphic surfaces include the erosional Cutter surface, located along the rift margin, and the constructional Cuchillo surface located within the rift. Five terrace levels occurring along the Rio Grande and Cuchillo Negro Creek and three pediment levels occurring along the Mud Springs Mountains are recognized and postdate the Palomas Formation. The Rio Grande is interpreted to have left the basin where it cut bedrock in the marginal uplifts by laterally cutting meanders at Long Point and Rattlesnake Islands and by stream piracy around Long Ridge. Most structural features resulted from Laramide and Rio Grande rift tectonic activity.

Palomas Formation deposition occurred from early Pliocene to middle Pleistocene. The Rio Grande became a through-flowing drainage system flowing within the basin by 3.8 m.y. B.P. Initial incision of the Rio Grande during middle Pleistocene ended Palomas Formation deposition, formed the Cuchillo surface, and marked the end of major episodic movement on the Hot Springs fault. Since the initial incision, the Rio Grande has undergone several incision episodes and has partly migrated out of the basin. Presently, the Rio Grande has the potential to reestablish its course within the basin.

Introduction

The main objectives of this investigation were to produce a geologic map of the Elephant Butte area (Sheet 1, in pocket) and to interpret the late Cenozoic (Pliocene to Holocene) history of the Rio Grande in the vicinity of Elephant Butte Reservoir. The interpretation is based on an examination of the following: 1) faults, in order to establish the types and timing of faulting events; 2) upper Cenozoic volcanic deposits, in order to determine types and timing of eruptions; 3) upper Cenozoic sedimentary deposits, in order to determine provenance, mode of deposition, and ages; and 4) geomorphic features, in order to determine ages and processes that formed them.

The study area is located near the junction between two structural and physiographic basins of the Rio Grande rift, the Engle and the Palomas. Only limited work has been done on the upper Cenozoic stratigraphy in this portion of the rift. In addition, a significant part of this investigation involved the study of the present course of the Rio Grande as it meanders across the basin-bounding fault. This is one of the few places along the Rio Grande rift where the Rio Grande has crossed a basin-bounding fault to cut into bedrock of the marginal uplifts, rather than continuing to cut into basin-fill sediments within the basin. This study includes mapping of all bedrock within the study area, but the upper Cenozoic deposits and structures are emphasized. All original measurements were made in metric units, and, to be consistent, metric units are used throughout this book. A conversion chart is provided on page 39.

Geographic setting

The approximately 256-km^2 study area includes the region surrounding the southern portion of Elephant Butte Reservoir, Sierra County, New Mexico (Fig. 1). The area is in the northern portion of the Mexican Highland section of the Basin and Range physiographic Province (Fenneman, 1931; Thornbury, 1965). Truth or Consequences (hereafter referred to as T or C), the county seat, lies within the southwest corner of the study area. Specifically, the study area includes the Elephant Butte 7 1/2-min topographic quadrangle and portions of the Cuchillo, Huerfano Hill, and Black Bluffs 7 1/2-min topographic quadrangles (Fig. 1).

The topography of the area ranges from low rolling hills to rugged canyonlands. Elevations vary from 1,290 m along the Rio Grande to more than 1,650 m on ridge crests. Paved and dirt roads provide excellent access to the western portions of the study area. Private ranch roads, extending north and south of NM-52, allow good access to the eastern portions. Remote regions along the reservoir shore are most accessible by boat. Except for the Rio Grande, all drainages in the area are ephemeral.

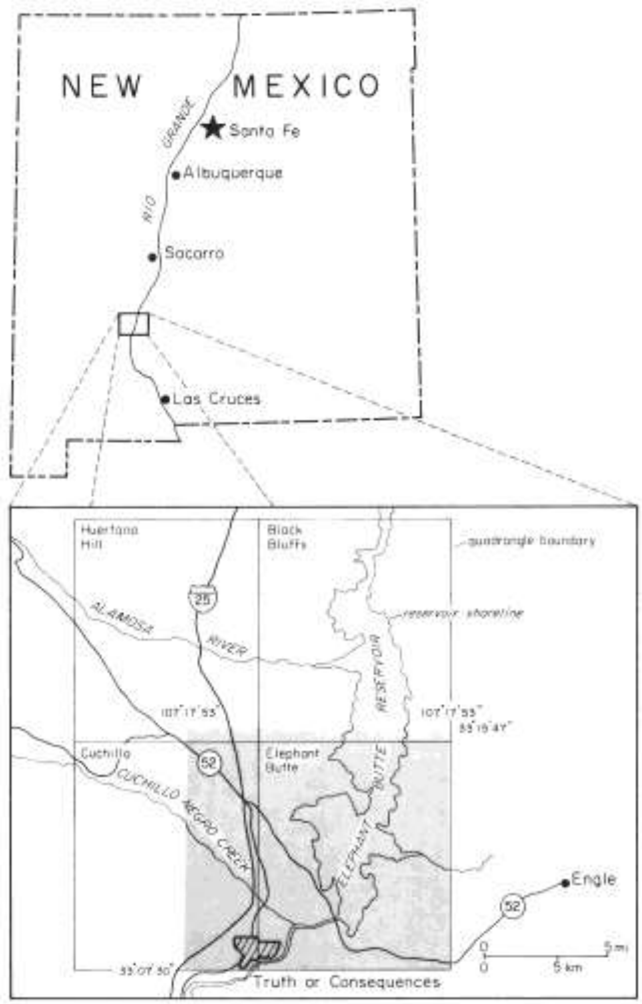


FIGURE 1—Location map of study area (shaded region). Latitude and longitude coordinates shown along corners of study area.

depression (Bryan, 1938; Kelley, 1956) from central Colorado to at least southern New Mexico, a distance of about 800 km. The rift is generally characterized by distinct gravity anomalies (Ramberg, 1978), high heat flow, and crustal thinning (Cordell, 1978). Faulting began as early as 27-32 m.y. B.P. in some portions of the rift (Chapin, 1979) and has continued to the present (Seager, 1975). The presence of the Basin and Range Province makes the southern Rio Grande rift less well defined than the northern Rio Grande rift (Seager and Morgan, 1979). However, based on high heat flow, exceptionally deep basins, recently active volcanoes, and late Quaternary faulting, Seager and Morgan (1979) were able to trace the rift south from Socorro, New Mexico, to El Paso, Texas. In this study, the Rio Grande rift will be defined as that determined by Seager and Morgan (1979).

The study area lies on the eastern margin of the Rio Grande rift at the constriction between the Engle and the Palomas Basins (Fig. 2). The two basins cover an area of about 1,200 km^2 and 1,400 km^2, respectively, and they are filled with at least 2,000 m of upper Tertiary—Quaternary Santa Fe Group sediments (Hawley, 1978). The northeastward-tilted Mud Springs uplift separates the two eastward-tilted, structural basins. As seen in Figure 2, the eastern portion of the study area includes the Cutter sag and the northern Caballo uplift. The Cutter sag is an uplifted structural high (relative to the Engle Basin) separating the eastward-tilted fault blocks of the Caballo and Fra Cristobal uplifts. These uplifts (including Mud Springs uplift) contain Precambrian igneous and metamorphic rocks overlain by Paleozoic sedimentary rocks. Mesozoic sedimentary rocks are exposed in the Cutter sag and are capped by late Cenozoic basalt flows. The Hot Springs fault extends through the study area and forms the boundary between the Rio Grande rift and

Climate and vegetation

The climate is arid, typical of areas in the southwestern U.S. Summer temperatures often exceed 32°C and winter temperatures usually range between 10 and 16°C. Precipitation averages 23.9 cm/yr (Kelley and Silver, 1952), of which more than half usually occurs in the late summer months in the form of intense, localized thunderstorms.

Vegetation is sparse, with creosote bush *(Larrea tridentata)*, mesquite *(Prosopis juliflora)*, and yucca *(Yucca baccata* and *Yucca elata)* dominating in most areas. Juniper *(Juniperus monosperma)* and cottonwood *(Populus fremontii)* trees can be found scattered along drainages.

Geologic setting

The study area lies in the southern portion of the Rio Grande rift. The rift consists of a series of deep, roughly north—south-trending structural basins that are bordered by uplifts (Bryan, 1938). These basins are connected by structural and physiographic constrictions that form a rather continuous structural

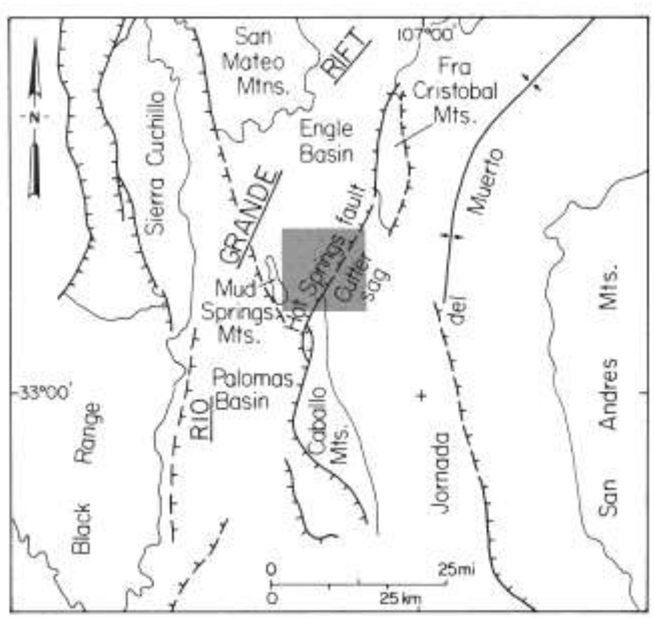


FIGURE 2—Regional tectonic-setting map. Shaded region is study area. Hatched lines are normal faults; hatchures on downthrown side; dashed where buried or inferred. Solid lines delineate major uplifts. Adapted from Woodward and others (1978).

the marginal uplifts. The broad, shallow Jornada del Muerto syncline borders the uplifts to the east. The extensive volcanic complex of the Sierra Cuchillo and the Black Range lies about 30 km to the west.

Previous work

The earliest work in the study area was limited to general descriptions and mapping of the stratigraphy and structure. In a water-resource survey of the Rio Grande, Lee (1907a) described the geology and constructed a very generalized geologic map while investigating favorable dam sites. He speculated on the entrenchment history of the Rio Grande and noted that the river had left the basin-fill to cut bedrock in Elephant Butte Canyon. Geologic reports pertaining to the construction of Elephant Butte. Dam (1906-1916) could not be obtained. Other early reports concerned with the region include Shumard (1858), Keyes (1905), Lee (1905, 1907b), Darton (1922, 1928), Harley (1934), and Bryan (1938).

Work in the 1950's and 1960's focused on studies of the surrounding uplifts. Kelley and Silver (1952) investigated the stratigraphy and structure of the Caballo Mountains including the Elephant Butte area. Bushnell (1953) undertook a detailed stratigraphic examination of the Mesaverde and McRae Formations. Thompson (1955, 1961) mapped the stratigraphy and structure of the southern Fra Cristobal Mountains. Doyle (1951) and Melvin (1963) provided descriptions and maps of the Paleozoic and Cretaceous units in the northern Caballo Mountains. The Mud Springs Mountains were mapped by Hill (1956), who described the Paleozoic units with emphasis on fossil assemblages. The New Mexico Geological Society's sixth conference guidebook (Fitzsimmons, 1955) contains many articles, maps, and road logs pertinent to the study area.

Recent work in the area addressed more specific problems. Warren (1978) mapped the region immediately north of the study area in an attempt to investigate the petrogenesis of the volcanic units and found that the Hot Springs fault ended in his study area. In an uncompleted study, Loeber (1976) examined the volcano—tectonic evolution of this portion of the rift, which includes part of the present study area. His descriptions of the volcanic deposits aided in this study. Mason (1976) mapped the quadrangle immediately to the south of the Elephant Butte quadrangle, which includes a large part of the Caballo Mountains. His descriptions and thicknesses of the Paleozoic units were useful in this study.

As part of a regional geothermal study, Zimmerman and Kudo (1980) remapped the Mud Springs Mountains. Cenozoic sedimentary deposits exposed between T or C and the Mud Springs Mountains were mapped by Wells and Granzow (1980) as part of the same geothermal study. They correlated the Santa Fe sediments with the Camp Rice Formation (Hawley, 1978) and concluded that only minor faulting has occurred around T or C since middle to late Pleistocene. Little has been published on the Quaternary stratigraphy between the Mud Springs Mountains and the Elephant Butte Reservoir.

Methods and techniques

Mapping

Geologic mapping was done on a 1:24,000 topographic base compiled from the Elephant Butte 7 1/2-min quadrangle and portions of the Cuchillo, Black Bluffs, and Huerfano Hill 7 1/2-min topographic quadrangles. Vertical, color, aerial photographs at 1:24,000 scale and vertical, black and white, aerial photographs at 1:29,000 scale were utilized in mapping the eastern and western areas, respectively. For mapping purposes, the reservoir level was placed at 1,341 m.

Stratigraphic sections and paleocurrent readings

Four stratigraphic sections of the Palomas Formation and terrace deposits were measured. Two of the measured sections involved both the Palomas Formation and terrace deposits, and two involved only the Palomas Formation (*see* Appendix I). The measured section locations are marked on Sheet 1 (in pocket). A Munsell color chart aided in distinguishing sediment colors for descriptions.

Paleocurrent readings were conducted on imbricated clasts in undeformed sediments of the Palomas Formation and terrace deposits in order to interpret transport direction. In a well exposed outcrop, 50 clast-imbrication measurements were made on the largest clasts (15 to 25 cm in diameter) in about a 1 m^2 area. These data were processed by a Hewlett—Packard 9830A computer to construct a rose diagram. Imbrication measurements were made at four localities, three in the Palomas Formation and one in the Rio Grande terrace deposits in the wing dam area. These locations are marked with a f on Sheet 1 (in pocket).

Clast counts of pediment and terrace deposits

Clast counts were used to distinguish differences in the clast composition of the pediment and terrace deposits (e.g., clast differences between Rio Grande terrace and Cuchillo Negro terrace deposits). The procedure for clast counting was to lay out two 7.6 m lines on the deposit; the first line was placed parallel with flow or dip direction of the deposits, and the second line was placed perpendicular to the first line. Observations were made every 30 cm on each line, and rock type and roundness (based on roundness chart in Compton, 1962, p. 215) of the largest clast were noted within a 30-cm circle. Fifty observations were conducted at each location.

One count was made on each of the deposits on the five Cuchillo Negro terrace levels, two on the deposits of the Rio Grande terrace levels 3 and 4, and two on the deposits of Mud Springs pediment levels 2 and 3. In addition, three counts were made on the present Cuchillo Negro channel bed, one within the study area, one near the Black Range, and one approximately midway between the Black Range and the study area. This was done to check on possible changes in clast composition upstream. Within the study area, each clast-count locality is marked with an X on Sheet 1 (in pocket).

Fitting regression curves to profiles of geomorphic surfaces

Least-square (linear regression) fits of longitudinal profiles of geomorphic surfaces were used to 1) extrapolate Mud Springs pediment levels for possible correlation with Cuchillo Negro terrace levels, 2) test Cuchillo Negro terrace gradients to see if a significant change in gradients has occurred over time, and 3) extrapolate the Cuchillo surface eastward to approximate its former elevation near the Hot Springs fault. Elevations and distances for fitting the regression curves to the longitudinal profiles were taken from the topographic base maps and entered into a Texas Instruments 58 programmable calculator using the program in Appendix **II.** The best curve fit for the profile was obtained using either a linear curve for terrace levels or an exponential curve for pediment levels and the Cuchillo surface. Care was taken to select surfaces that were continuous and least dissected.

Absolute- and relative-dating procedures

Most age estimates in this study are based on relative-dating techniques. These techniques include crosscutting relationships between geologic features that have known or inferred ages and those that do not and correlations with ages from other studies (e.g., Gile and others, 1981). No radiometric dating was done in this study, but fossils aided in establishing approximate ages of the Santa Fe Group sediments.

Stratigraphy

The study area includes an incomplete sequence of stratigraphic units ranging in age from Precambrian to Holocene. Silurian, Mississippian, Triassic, Jurassic, and Lower Cretaceous units are absent. Outcrops are usually good to excellent. Because of the scope of this study, descriptions of rocks other than late Cenozoic units are general. More detailed descriptions are included in Hill's (1956) study of the Mud Springs Mountains, Kelley and Silver's (1952) study of the Caballo Mountains, and Bushnell's (1953) study of the Cutter sag region.

Precambrian

A very small outcrop of Precambrian granite (peb) occurs at the southwest base of the Mud Springs Mountains. The medium- to coarse-grained granite is light pink on fresh surfaces and weathers to a reddish pink. The contact with the overlying Bliss Formation is sharp. Just outside of the study area Precambrian metamorphic units crop out in the Mud Springs and Caballo Mountains.

Paleozoic

The Bliss Formation, El Paso Group, Montoya Group, Percha Shale, Magdalena Group, and Manzano Group compose the Paleozoic units in the study area. The El Paso, Montoya, and Magdalena Groups were mapped as undifferentiated units, whereas the Manzano Group (Herrick, 1900) was divided into the Abo, Yeso, and San Andres Formations. The sequence from the Bliss Formation to the Magdalena Group is exposed both in the Mud Springs Mountains and in isolated outcrops in and around the T or C city limits. The Magdalena and Manzano Groups crop out in the Caballo Mountains. The Abo Formation also can be found along the Cuchillo Negro Creek. These Paleozoic units cover less than 10% of the study area.

Cambrian and Ordovician

Bliss Formation

The Bliss Formation (Oeb) of Late Cambrian to Early Ordovician age was initially named "Bliss Sandstone" by Richardson (1904); however, Kelley and Silver (1952) changed the terminology to Bliss Formation. The 44m-thick formation is characterized by mostly 30-60cm-thick, medium- to coarse-grained, dark-brown hematitic sandstone with minor interbeds of limestone, siltstone, and oolitic hematite (Hill, 1956). The Bliss Formation rests nonconformably on Precambrian granite in the Mud Springs Mountains. In outcrop, the ledgy slope-former creates a distinctive dark-brown band along the southwest base of the mountain.

El Paso Group

Conformably overlying the Bliss Formation is the El Paso Group (Oe; Richardson, 1904). Kelley and Silver (1952) divided the group into two formations that were recognized by Hill (1956) in the Mud Springs Mountains. These are the Sierrite Limestone and the Bat Cave Formation. The Sierrite Limestone consists of alternating beds of medium-grained, gray limestone and tan chert that are relatively barren of fossils.

The Bat Cave Formation conformably overlies the Sierrite Limestone and is composed of fine- to medium-grained, medium-gray limestone with nodules and lenses of brownish chert. Stromatolites in massive reef-like bodies flanked by brecciated limestone were noted by Hill (1956). Other fossils include fragmentary gastropods, trilobites, and cephalopods. The cliff-forming El Paso Group is about 140 m thick (Hill, 1956).

Montoya Group

The Montoya Group (Om; Richardson, 1909) is 110 m thick (Hill, 1956) and rests disconformably on the El Paso Group. The contact is marked by a sharp color contrast between the gray limestone of the El Paso Group and the dark brown of the lower Montoya Group. Hill (1956), following the mapping of Kelley and Silver (1952), divided the group into four formations (in ascending order): the Cable Canyon Sandstone, the Upham Dolomite, the Aleman Formation, and the Cutter Formation. The Cable Canyon is a massive, medium- to coarse-grained, dark-brown sandstone overlain by massive, dark-gray dolomite with scattered chert nodules of the Upham Dolomite. The Aleman Formation consists of 30-60-m-thick beds of fine-grained, gray dolomite interspersed with brown chert lenses. Medium-gray, fine-grained dolomite with scattered brown chert nodules characterizes the Cutter Formation. *Zygospira, Rasfinesquina*, and *Endoceras* are found in the Aleman and Cutter Formations (Hill, 1956). The lower formations are cliff-formers, but the upper two formations tend to form steep slopes with distinctive ledges.

Devonian

Percha Shale

Devonian strata are represented in the study area by the 30-m-thick (Hill, 1956) Percha Shale (Dp; Gordon and Graton, 1907). The Percha Shale disconformably overlies the Cutter Formation and consists predominantly of olive-green to gray-brown shale interbedded with thin gray limestone and siltstone. The Percha Shale forms a smooth erosional slope, which is in marked contrast to the surrounding ledge-formers and the steeper slope-formers.

Pennsylvanian

Magdalena Group

The Magdalena Group (Pm) was named by Gordon (1907) for Pennsylvanian units in the Magdalena mining district, Socorro County, New Mexico. He divided the group into the Sandia (Herrick and Bendrat, 1900) and Madera (Keyes, 1903) Formations. In mapping the Caballo Mountains, Kelley and Silver (1952) divided the Magdalena Group into three formations (in ascending order): the Red House Formation, the Nakaye Formation, and the Bar B Formation. Gordon's (1907) nomenclature is used here.

The Magdalena Group attains a thickness of 495 m (Hill, 1956) in the Mud Springs Mountains and about 244 m (Mason, 1976) in the northern Caballo Mountains. The Sandia Formation rests unconformably on the Montoya Group and consists of 30-150-cm-thick beds of fine-grained, gray limestone with dark shale interbeds. At the base, a few beds of coarse-grained, light-gray sandstone can be found. Thin (30-60 cm thick) to massive beds of fine-grained, dark-gray to gray limestone with dark shale intervals characterize the Madera Formation. Nodules and lenses of dark and light brown chert are present in both formations. Fossils include brachiopods, fussilinids, and corals (Mason, 1976). The Sandia Formation is generally a steep slope-former, whereas the Madera Formation is a ridge-former comprising the highest peaks and ridges in the study area.

Permian

Abo Formation

The Abo Formation (Pa; Lee and Girty, 1909) conformably overlies the Madera Formation with perhaps a local unconformity (Kelley and Silver, 1952). Mason (1976) measured the thickness of the Abo Formation just south of the study area in the Caballo Mountains to be 171 m. Thin- to medium-bedded (30-120 cm thick) dark-red shale and siltstone with scattered, thin interbeds of gray limestone and fine-grained sandstone characterize the Abo Formation. Beds can be lenticular and contain mudcracks, ripple marks, and crossbedding. The Abo Formation is a resistant unit that forms the prominent red ridge in the northern Caballo Mountains. The darker red and more resistant nature of the well bedded Abo Formation distinguishes it from the overlying Yeso Formation.

Yeso Formation

The contact between the Yeso Formation (Py; Lee and Girty, 1909) and the Abo Formation is gradational. The contact was mapped at the top of the highest resistant sandstone. The Yeso Formation primarily consists of orange to pale-red, 30-140-cm-thick beds of sandstone that have thin interbeds of greenish-gray mudstone, siltstone, and limestone. Gypsum beds that are less than 30 cm thick occur in the upper section. Because of drag folding within the Yeso Formation, thicknesses are difficult to measure; Mason (1976) estimated a thickness of about 180 m. The Yeso Formation forms a distinct strike valley between the Abo and San Andres ridges in the Caballo Mountains.

San Andres Formation

The Yeso Formation grades into the overlying San Andres Formation (Ps; Lee and Girty, 1909). The contact was mapped where the limestone became the dominant lithology. The 232-m-thick (Mason, 1976) San Andres Formation is composed principally of 30-150-cm-thick, evenly bedded, fine-grained, light- to dark-gray limestone. Dark shale and lenticular sandstone are thinly interbedded. Chert nodules and lenses are rare. The very resistant San Andres Formation forms the prominent ridge on the eastern side of the Caballo Mountains.

Mesozoic

Mesozoic units cover approximately 40% of the study area, but they include only rocks of Late Cretaceous age. The Late Cretaceous units are generally exposed east and south of the Elephant Butte Reservoir and include (in ascending order): the Dakota Sandstone, the Mancos Shale, the Mesaverde Formation, and the McRae Formation. The upper McRae Formation may be early Tertiary in age (Kelley and Silver, 1952; Bushnell, 1953), but it is discussed in this section.

Cretaceous

Dakota Sandstone

The Dakota Sandstone (Kd; Meek and Hayden, 1862) rests on an erosional surface of considerable relief on the San Andres Formation (Mason, 1976). Within a short distance along Mescal Creek, thicknesses range from 24 m (Melvin, 1963) to 57 m (Mason, 1976) to 75 m (Kelley and Silver, 1952). White to buff, medium-to coarse-grained sandstone is the dominant lithology. Beds range in thickness from about 60 to 120 cm. A few interbedded, thin, gray shales and occasional lenses of pebbly conglomerate and carbonaceous materials are also present. The Dakota Sandstone is a resistant ridge-former, and, when included with the San Andres Formation, the two units generally define the eastern margin of the Caballo Mountains.

Mancos Shale

The Mancos Shale (Km; Cross, 1899) appears to conformably overlie the Dakota Sandstone within the study area, but Kottlowski and others (1956) have observed an unconformable contact in other areas of southern New Mexico. The easily erodable and poorly exposed Mancos Shale is 81 m thick (Doyle, 1951) at the mouth of Mescal Creek. The lower section is composed of medium to dark gray, thin bedded (less than 60 cm thick), fetid limestone, shale, and siltstone. The upper section primarily consists of brownish gray to black calcareous shale with a few scattered, thin limestone and siltstone beds. The Mancos Shale forms the strike-valley on the eastern side of the Caballo Mountains.

Mesaverde Formation

Upper Cretaceous sandstones and shales exposed in Mesaverde National Park were named the Mesaverde Group by Holmes (1877); however, in the Caballo Mountains—Jornada del Muerto area, most workers have considered the Mesaverde a formation (Doyle, 1951; Kelley and Silver, 1952; Bushnell, 1953). The Mesaverde is considered a formation in this study. Extensive outcrops of the Mesaverde Formation occur throughout the eastern and southeastern portions of the study area. Total thickness ranges from 1,006 m (Bushnell, 1953) to 1,051 m (Melvin, 1963) within the study area. Bushnell (1953) divided the formation into two members: the lower main body (Kmm) and the upper Ash Canyon Member (Kma).

The contact between the main body and the Mancos Shale is conformable and is excellently exposed along Mescal Creek. Alternating beds of sandstone, siltstone, shale, and mudstone that attain a thickness of about 975 m (Bushnell, 1953) characterize the main body. Buff to brown sandstone is the dominant lithology and is commonly fine- to medium-grained and crossbedded. The sandstone beds, ranging in thickness from 30 cm to 6 m, are lenticular with lateral continuity usually less than 1.5 km. The olive-gray to brown siltstones, shales, and mudstones are generally more continuous than the sandstone beds, but thicknesses are seldom greater than 2 m. Less than 30 cm thick, dark-brown to black bituminous beds occur near the base of the main body. Although the main body is dominantly sandstone, the sandstone to shale ratio tends to decrease down section. Pebbly conglomerate lenses may also be found near the top.

Bivalves occurring in the basal sandstone beds of the main body were identified as *Inoceramus, Gryphaea,* and *Ostrea* (Melvin, 1963; Mason, 1976). During this study, well preserved leaf fossils were located in the upper part of the main body near the wing dam area. The collection (identified by C. Robinson, Bureau of Land Management, pers. comm. 1982) included *Sequoia montana, Ficus planicostata,* cf. *Dryophyllum* sp., cf. *Laurophyllum wardiana,* cf. *Dillenites cleburni, Cercidiphyllum* sp., and cf. *Quercus viburnifolia.* Petrified wood is also common in the upper sandstone units.

The Ash Canyon Member intertongues with the underlying main body. Because of this intertonguing relationship, the contact between the main body and the Ash Canyon Member can be mapped only approximately. Bushnell (1953) measured the Ash Canyon Member to be 34 m thick at the type locality near Kettle Top; however, in other areas, thickness varies by perhaps as much as 10 m. The Ash Canyon Member is composed of conglomerate and medium- to coarse-grained sandstone. The conglomerate beds contain subangular to subrounded pebbles of chert, quartz, and petrified wood. The beds tend to be massive and crossbedded, and they weather to red and brown hues. Fragments of petrified wood and nearly complete logs were reported by Bushnell (1953) and they also were observed in this study.

Because of the abundance of sandstone, the Mesaverde Formation is a resistant unit. However, because of steepness of dips, two distinct erosion patterns exist. Hogbacks tend to form in exposures west of the dam where dips are steep, whereas mesas predominate east of the dam where dips are shallow.

McRae Formation

Kelley and Silver (1952) named the "red beds" exposed near Elephant Butte the McRae Formation after an army fort that existed in the area in the late 1800's. The McRae Formation is a thick sequence of nonmarine strata that is primarily exposed from Long Ridge east into the Jornada del Muerto. The total thickness is believed to approach 975 m (Bushnell, 1953); however, this thickness is speculative because part of the section lies submerged beneath the waters of Elephant Butte Reservoir. The McRae Formation has been divided into two members (Bushnell, 1953): the Jose Creek (Kmj) and the Hall Lake (Kmh). It is generally accepted, based on fossil evidence, that the Jose Creek Member is Upper Cretaceous; however, the upper Hall Lake Member may be, in part, lower Tertiary.

The Jose Creek Member rests unconformably on the Mesaverde Formation. A sequence of sandstone, shale, conglomerate, and a unique breccia conglomerate compose the Jose Creek Member. At the type locality, occurring southeast of Kettle Top, the thickness has been measured at 120 m (Bushnell, 1953).

The breccia conglomerate that crops out along NM-52, just south of Elephant Butte, is a matrix-supported breccia. The matrix is composed of green to gray, fine-to medium-grained, angular crystal and lithic fragments. The cobble- to boulder-size clasts of differing angularity range compositionally from basalt to latite and exhibit porphyritic texture. In the breccia conglomerate, large xenoliths of Mesaverde sandstone also occur as clasts. The breccia conglomerate appears to grade laterally into the conglomerate beds.

The conglomerate beds are massive and consist of subangular to subrounded, porphyritic basalt to latite cobbles and pebbles that are surrounded by a sandy andesitic matrix. Northward, in the vicinity of the type locality, the Jose Creek Member consists of dark-brown to green sandstone interbedded with olive to purple shales, siltstones, and conglomerates. The primarily coarse-grained sandstone beds are 30-150 cm thick, while the more lenticular shale and siltstone beds are 30-90 cm thick. The conglomerate beds are compositionally similar to those exposed near the breccia conglomerate. Cream to tan, 30-60-cm-thick chert beds occur near the top of the unit. The Jose Creek Member generally erodes to form low hills or, where interbedded with shales, ridges.

The Hall Lake Member composes the greater thickness of the McRae Formation. Bushnell (1953) estimated the total thickness to be 884 m. Because of the abundance of nonresistant shales, the Hall Lake Member is a valley-former.

The Hall Lake Member conformably overlies the Jose Creek Member. Basal conglomerate, consisting of quartzite, gneiss, and granite cobbles, that is up to 3 m thick marks the boundary; however, where the conglomerate is absent the first purple or maroon shale is used for the boundary. The Hall Lake Member is composed principally of maroon, purple, and brown shale beds up to 120 cm thick. Alternating with the shale beds are green to purple, lenticular, medium-to coarse-grained sandstone beds and widely scattered, 30-90-cm-thick, purplish conglomerate beds consisting of intermediate volcanic clasts. A few, 3060-cm-thick, nodular limestone and ridge-forming chert beds can also be found. These chert beds vary in color from white to pinkish-white and are recrystallized ash deposits as evidenced by the presence of shard structures in thin section.

Numerous plant fossils have been found in the Jose Creek Member. Bushnell's (1953) floral assemblage included *Geinitzia* cf. *formosa, Canna magnifolia, Phyllites* cf. *ratonensis, Salix* sp., and *Cinnamonum* sp. During this study *Sabalites montana, Araucarites longifolia, Ficus planicostata*, and *Sequoia* sp. (identified by C. Robinson, Bureau of Land Management, pers. comm.

FIGURE 3—Possible femur of a sauropod occurring in Jose Creek Member of McRae Formation. Site located in extreme northeast corner of study area just south of Cottonwood Canyon.

1982) were collected. In addition, petrified logs and trunks, some appearing in place, are common.

Lee (1905) found remains of a ceratopsian dinosaur near Elephant Butte. Six new localities that produced fossil bones were discovered during this study. The fossils were found both in the Jose Creek and Hall Lake Members. It appears that bones exist just above and just below the Jose Creek—Hall Lake contact. Identifiable remains include ceratopsian frill and jaw fragments. However, the most interesting find is a 168-cm-long femur (Fig. 3) that may be of sauropodian affinity (bones identified by D. Wolberg, New Mexico Bureau of Mines and Mineral Resources, 1981). For more detailed descriptions of the dinosaur fossils, see Lozinsky and others (1984).

Cenozoic

Cenozoic units cover more than 50% of the study area and consist of a variety of sedimentary and igneous rocks. Features produced by igneous activity include dikes, basalt flows, maars, and a sill. A major component of the sedimentary rocks consists of the Santa Fe Group sediments, which are exposed extensively west of the Hot Springs fault. Other sedimentary rocks include pediment, fan, fluvial, and eolian deposits.

Tertiary

Intrusive sill

A 15-18-m-thick latite sill (T1) intrudes the lower section of the Magdalena Group in the Mud Springs Mountains. The sill is generally a cliff-former that weathers into blocky fragments. The age is tentatively placed at 30-35 m.y. B.P. based on the similarity with other rocks occurring in the San Mateo Mountains to the north (A. Kudo, pers. comm. 1982). Contacts with the Magdalena Group limestone are sharp, with 3060-cm-thick bake zones.

Megascopically, the intrusive is light gray to buff on fresh surfaces and weathers to a light to yellowish brown. The texture is porphyritic, with mainly hornblende and minor augite phenocrysts. The hornblende occurs as small, dark euhedral laths. The dark phenocrysts constitute about 7 to 10% of the rock. A few anhedral quartz phenocrysts are present. The light-colored, aphanitic groundmass probably consists mostly of feldspar.

Andesite dikes

A group of predominantly northwest-trending andesite dikes (Ta) intrudes Mesaverde and McRae strata in the eastern portions of the study area *(see* Sheet 1, in pocket). The dikes are mostly vertical and can extend up to 10 km in length; however, most average about 1.5 km. Thickness ranges from about 60 cm to a rare maximum of 8 m. The dikes are gray, fine- to medium-grained, and can be porphyritic with plagioclase phenocrysts. Weathered surfaces vary in color from reddish brown to dark gray. Bake zones in Mesaverde and McRae bedrock are commonly thin (less than 30 cm thick) and cause increased induration and redness. Although previous workers (Kelley and Silver, 1952; Bushnell, 1953) classified the dikes as basalt, Loeber (1976) did petrologic studies and determined that the composition was andesitic. North of Jose Creek the dikes form prominent linear ridges cutting across topography; south of Jose Creek they do not form prominent ridges (mapping was aided by aerial photographs). This difference in outcrop pattern may be due to the erodability of the country rock in which the dikes intrude. Dikes in the north primarily intrude the less resistant McRae Formation while dikes in the south intrude the more resistant Mesaverde Formation. Because no formational contacts are offset by the dike traces, the dikes are believed to have been intruded along joints rather than faults.

The age of the dikes is not clearly defined. Most previous workers (Kelley and Silver, 1952; Loeber, 1976) have suggested a Pliocene to Pleistocene age. The dikes intrude the McRae Formation, but were not affected severely by the last major faulting event that occurred during the Miocene and Pliocene (Seager, 1975). They are truncated by the Cutter surface (discussed in the geomorphology section), which is covered by the basalt flows. The basalt flows have been dated as late Pliocene, 2.1 ± 0.4 m.y. B.P. (Bachman and Mehnert, 1978). Therefore, the above cross-cutting relationships suggest an early to middle Pliocene age for the andesite dikes.

Santa Fe Group

Hayden (1873) first proposed the term Santa Fe for late Tertiary basin-fill deposits located in the Rio Grande rift just north of Santa Fe, New Mexico. Cope (1883) suggested that equivalent deposits were present in the Caballo area (Kelley and Silver, 1952). These deposits were later referred to as the Palomas Gravel by

TABLE 1—Comparison of Camp Rice, Sierra Ladrones, and Palomas Formations. General references: Hawley (1978), Hawley and others (1976), and Gile and others (1981).

Unit	Lithology	Geographic position	Age
Camp Rice Formation (Seager and Hawley, 1973)	Fluvial facies—light-gray to brown sand, gravel, sandstone, and conglomerate that are internally cross-stratified. Sand is fine- to coarse-grained and is moderately well sorted. Laterally intertongues with and overlain by piedmont facies.	basin-floor deposit	Ranges from late Pliocene to middle Pleistocene. Contains late Blancan and Irvingtonian vertebrate faunas and volcanic ashes dated at 0.6 m.y., 0.7 m.y., and 2 m.y.
	Piedmont facies—gravelly fan and coalescent-fan deposits that are derived from adjacent uplifts.	valley-margin deposit	
Sierra Ladrones Formation (Machette, 1978)	Axial stream deposits—light-gray to light-yellow-brown, fine- to medium-grained, crossbedded sand and sandstone. Contains green clay beds, reworked clay balls, and sparse pebbly to gravelly channels. Laterally intertongues with and overlain by piedmont deposits.	basin-floor deposit	Ranges from early Pliocene to middle Pleistocene. Contains Blancan invertebrate fauna and volcanic ashes dated at 1.45 m.y. and a basalt flow occurring near base dated at 4.5 ± 0.1 m.y.
	Piedmont deposits—light-brown to light-red-brown sandstone and fanglomerate; medium- to massively bedded containing clasts derived from adjacent uplifts.	valley-margin deposit	
Palomas Formation (this study)	Axial facies—light-gray to buff, moderately well sorted, fine- to coarse-grained sand that is crossbedded and contains gravel lenses. Green and red clay lenses and mudballs also occur. Overlies, laterally intertongues with, and is overlain by piedmont facies.	basin-floor deposit	Ranges from early Pliocene to middle Pleistocene. Contains Blancan fauna, a basalt flow dated at 2.9 ± 0.3 m.y., and a volcanic ash dated at 1.45 m.y.
	Piedmont facies—light-brown to reddish-brown sandy silt, conglomerate, and fanglomerate derived from local uplifts.	valley-margin deposit	

Gordon and Graton (1907) and Harley (1934). The Santa Fe was assigned formation status by Darton (1922), and eventually it was raised to group status by Kottlowski (1953). Speigel and Baldwin (1963), following Bryan's (1938) usage, formally defined the Santa Fe Group to include all Middle Miocene(?) to Pleistocene(?) sedimentary and volcanic rocks in the Rio Grande rift. Galusha and Blick (1971) attempted to restrict the Santa Fe Group to a small geographic area near Santa Fe; however, this concept has not been accepted. The Santa Fe Group in south-central New Mexico has been described in detail by Hawley and others (1969, 1976), Seager and Hawley (1973), and Seager and others (1971, 1975).

Within the study area, the Santa Fe Group is exposed extensively west of the Hot Springs fault filling the Engle Basin. These deposits belong to the upper Santa Fe Group and are here named the Palomas Formation after the Palomas Gravel of Gordon and Graton (1907) who described this unit in the Sierra County area (Gordon, 1910, p. 237, plate XII). The unit is designated a formation rather than a gravel because of its varied lithologic character. The Palomas Formation, based on rough age correlations, lithologic similarities, and geographic position (Table 1), is broadly equivalent to the Sierra Ladrones Formation to the north (Machette, 1978) and the Camp Rice Formation to the south (Strain, 1966; Hawley and others, 1976). Wells and Granzow (1980) also correlated the Palomas Formation (then an unnamed unit) with the Camp Rice Formation. Ages for the Palomas Formation are not known precisely. The lower age limit is believed to be early Pliocene based on a faunal assemblage from near T or C, which is described later in this section. The upper age limit is not defined within the study area, but when correlated with the Camp Rice and Sierra Ladrones Formations, it would be approximately 400,000 to 500,000 years old (Hawley, 1978; Machette, 1978). Limited data exists on the thickness of the Palomas Formation. About 3 km northwest of Long Point Island, Loeber (1976) suggested a thickness of about 1,070 to 1,220 m, which includes both the upper and the lower Santa Fe Group. Information from a drill hole located just north of the study area, in SE 1/4 sec. 8, T. 12 S., R. 4 W., showed a total thickness of 440 m, of which 180 m belongs to the upper Santa Fe Group (Hawley, 1978); however, it is not known how the upper Santa Fe Group was defined. Generally, the Palomas Formation tends to thicken basinward towards the Hot Springs fault. In this study, the Palomas Formation is divided into two facies, the piedmont (QTpp) and axial (QTpa). Measured sections of the Palomas Formation are presented in Appendix I.

PIEDMONT FACIES—The piedmont facies rests with an angular unconformity on Precambrian, Paleozoic, and Cretaceous rocks along the flanks of the Mud Springs and Caballo Mountains (*see* Sheet 1, in pocket). Away from the mountains, no lower contact of the piedmont facies could be recognized. A dark-red, silty clay unit exposed at the bottom of a cliff on the south side of the Rio Grande, in secs. 3 and 4, T. 14 S., R. 4 W., may be equivalent to the Rincon Valley Formation (Seager and others, 1971) of the lower Santa

FIGURE 4—Fanglomerate of proximal subfacies. Clasts derived from Caballo Mountains to the east. Outcrop occurs just east of the Rio Grande near T or C.

Fe Group because it is dark red and silty (J. Hawley, pers. comm. 1982); however, due to limited exposures this could not be ascertained, and, therefore, the unit is included in the piedmont facies. Two subfacies, proximal and distal, can be recognized in the piedmont facies, but they have not been mapped individually due to their complex intertonguing contact.

The term proximal refers to the local provenance and short transport of the sediments. The proximal subfacies primarily consists of light-brown to reddish-brown, poorly sorted, lenticular to weakly stratified fanglomerates (Fig. 4). Total thickness of the proximal subfacies is unknown, but ranges from a minimum of about 3 m in the Cuchillo Negro Creek to more than 30 m along the Caballo Mountains. Slightly imbricated clasts are mostly subangular to angular and can be up to 60 cm in size, but are commonly in the pebble to cobble range. Paleocurrent readings on imbricated lasts indicate a transport direction away from local uplifts (*see* Appendix III). Clast composition of the proximal subfacies reflects the lithologies of the nearby uplifts. Near the Mud Springs Mountains, clasts of the proximal facies are composed predominantly of limestone and chert from the Magdalena Group, with minor amounts of sandstone from the Abo Formation. At the flanks of the Caballo Mountains, the clasts range compositionally from primarily sandstone and shale from the Mesaverde and McRae Formations in the wing dam area to mixtures of limestone from the San Andres Formation and Magdalena Group to sandstone from the Abo Formation near the southern border of the study area. Bed thickness can be from 30 cm to more than 2 m. Beds tend to become coarser and more massive near the uplifts and can exhibit some cross-stratification. Deposits of the proximal subfacies can be both matrix-supported and clastsupported, but the former is more common. In outcrop, clast-supported beds often grade up into matrix-supported beds. Pebbly sandstone to silty sand generally compose the matrix. Occasional red clay interbeds that are 30-120 cm thick are paleosols, as evidenced by increased reddening and clay content. The proximal subfacies is moderately to very well

FIGURE 5—Distal subfacies showing alternating sequence of sandy silt and conglomerate beds. Outcrop occurs on the north side of Cuchillo Negro Creek in the NW1/4SW1/4 sec. 8, T. 13 S., R. 4 W.

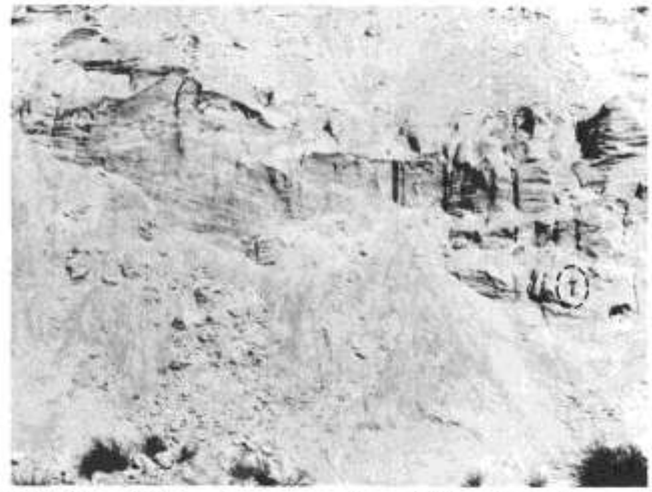


FIGURE 6—Thick sand exposure of axial facies. Note the cross-bedded and well-sorted nature. Outcrop occurs on west side of NM-85 at the north end of T or C (hammer for scale).

indurated with calcium carbonate cement, which causes the unit to be a resistant cliff-former.

The term distal refers to a distant source area and long transport. Alternating beds of light-pink to dark-reddish-brown sandy silt, conglomerate, and clay compose the distal subfacies (Fig. 5). Along the Cuchillo Negro Creek, the distal subfacies is 49 m thick, but thickness increases northward (basinward). The distal subfacies rests with a slight angular unconformity at the base and intertongues laterally with the proximal subfacies. Individual beds generally are poorly expressed and can be lenticular, especially the conglomerate beds. Bed thickness ranges from less than 30 cm up to 2.5 m, but is usually 60 to 120 cm. Overall, the subfacies coarsens upward because the lower beds primarily consist of the sandy silt beds, whereas higher up in the section the conglomerate beds become more numerous. The sandy silt beds commonly can be distinguished by tonal changes. The poorly to moderately sorted conglomerate beds consist of subangular to subrounded (most being subrounded) clasts that range in size from pebbles to small boulders up to 30 cm in diameter. The cobble-size clasts are imbricated and compositionally include porphyritic volcanics (rhyolites, latites, and andesites), tuffs, basalts, quartzite, and sandstone with minor chert and limestone. Similar to the proximal facies, the conglomerates are primarily matrix-supported and commonly grade down into a clast-supported bed. The matrix consists of sandy silt. Paleocurrent measurements on imbricated clasts indicate an eastward transport direction for the distal subfacies (Appendix III). Scattered throughout the unit are 30-90-cm-thick beds and lenses of green and red clay. Many of the red clay zones exhibit a downward decrease in reddening and clay content, and they are believed to be paleosols. Near the Mud Springs Mountains in NE 1/4 NE 1/4 sec. 30, T. 13 S., R. 4 W., a 90-120-cm-thick, white diatomaceous bed is exposed. The abundant and well-preserved diatoms (including *Denticular elegans* var.) are perhaps early Blancan age and could be associated with hot spring activity (sample identified by J. Bradbury, U.S. Geological Survey, written comm. 1982).

Deposits of the distal subfacies are poorly indurated and weather to form the badland topography occurring in the western portion of the study area.

AXIAL FACIES—Overlying and laterally intertonguing with the piedmont facies is a thick accumulation of internally cross-stratified sands with scattered lenses of gravel and clay, here termed the axial facies. The axial facies crops out in a broad zone up to 3 km wide that extends through the length of the study area and roughly parallels the Hot Springs fault. Light-gray to buff, moderately well sorted, fine- to coarse-grained sand composes the bulk of the unit (Fig. 6). The sand is generally arkosic and occurs in poorly exposed beds up to 2 m thick that are trough cross-bedded. The sand is poorly indurated, but locally coarser sand beds and conglomerates can be indurated and form resistant ledges. The cement is predominantly calcium carbonate; however, silica- and iron-manganese-oxide-cemented sands occur locally, which may be indicative of hot spring activity. The conglomerate clasts are subrounded to rounded and generally pebble-sized, but cobble-size clasts can also be found. Clasts include quartz, chert, granite, sandstone, and a variety of volcanic lithologies. Green to red clay lenses and mudballs can be found throughout the unit, but not in great abundance. The total thickness of the axial facies is estimated to be at least 30 m. Occurring just west of T or C, along NM-85, is a coarse gravel unit that may be a younger terrace deposit; however, no inset contact could be located and so it was included with the axial facies. Because of the weak to moderate induration, the deposits of the axial facies form the low, rolling topography immediately west of the reservoir.

The age of the axial facies (and of the proximal facies due to the intertonguing contact) can be defined approximately on the basis of dates on faunal and volcanic material found both within and near the study area. A faunal assemblage dated at about 3.8 m.y. B.P. was located by C. Repenning, U.S. Geological Survey (written comm. to J. Hawley, 1981) just northwest of T or C in a roadcut along 1-25. Fossils identified include aff. *Oryzomys* (rice rat), *Prosigmodon intermedium* (cotton rat), and *Paraneotoma fossilis* (pack rat). This approximately establishes a lower age limit for the axial facies because the green clay lens in which the fossils were found occurs in the lower portion of the unit. In addition, mastodon, *Equus simplicidens* (horse), *Gigantocamelus* (camel), and *Tapirus* (tapir) bones were found in the axial facies along the western shore of the reservoir (Tedford, 1981). These fossils were assigned a medial Blancan age on the basis of stratigraphic correlation with a basalt flow dated by Bachman and Mehnert (1978) at 2.9 m.y. B.P., which is interbedded in the axial facies. The basalt flow is located north of the study area at Mitchell Point. As mentioned earlier, an upper age limit is less well defined. Machette (preliminary tephrochronologic determination by G. Izett, U.S. Geological Survey, 1981; M. Machette, written comm. 1982) found a 1.4 m.y. B.P. (correlated with Cerro Toledo volcanic ash) volcanic ash deposit located a few km south of the study area. The ash was deposited on top of an axial sand inter-tongue in the piedmont facies along the western side of the Caballo Mountains, and it probably lies in the upper part of the piedmont facies. Younger ages have not been found within or near the study area, but again, when correlated with the Camp Rice Formation, the upper age limit may be 400,000 to 500,000 years (Hawley, 1978). These dates indicate that the axial facies (and portions of the piedmont facies) were deposited over a span of 3 million years or more.

INTERPRETATION—The coarsening of the proximal subfacies toward the nearby mountains, the similarity of clasts to the lithologies of the nearby mountains, the angularity of clasts, and the transport direction of the clasts away from the uplifts all indicate that the proximal deposits were derived from local mountains. These deposits are believed to have formed mainly by debris flows due to the poorly sorted, massive, and lenticular nature of the beds, which is typical of debris flows (Bull, 1972; Reading, 1978). In studying alluvial fans, Bull (1972) established a set of criteria for recognizing alluvial-fan deposits in the stratigraphic record, which included:

1) deposit rarely contains well-preserved organic material;
2) deposit commonly consists of mudflow and debris-flow deposits and/or water-laid deposits;
3) beds within deposit vary in particle size, sorting, and thickness;
4) deposit has intertonguing relation with deposits of other depositional environments (e.g., axial facies);
5) deposit contains multiple soil profiles;
6) beds within deposit are much longer than wide;
7) particle size decreases away from source area.

The proximal subfacies exhibit these characteristics (as discussed earlier) and, therefore, are interpreted to represent alluvial fans that formed at the flanks of the local mountains and extended basinward. The fans coalesced along the mountain fronts to form a bajada.

The more rounded, finer grained, and less massive distal subfacies suggest a more complex mode of deposition. The finer sediments and rounded clasts indicate a longer transport distance. The porphyritic volcanic clasts found within the distal subfacies were derived from the Mogollon-Datil volcanic complex that comprises the Black Range and Sierra Cuchillos some 30 km to the west. The poorly sorted and lenticular beds within the unit are again indicative of deposition by debris and mud flows (Bull, 1972). However, the better sorted beds and rounded clasts are an indication of longer transport than the proximal facies.

Several of Bull's (1972) criteria for recognizing alluvial fans are present in the distal subfacies. These include aspects 1-6 listed above. However, because of the widespread existence of the distal subfacies, this fan system would have been much larger and more complex than the fan system that deposited the proximal subfacies. Thus, the distal subfacies was perhaps deposited by an extensive piedmont-fan system that originated at the lower slopes of the Black Range and Sierra Cuchillos and extended into the Engle Basin. This system could have had many shifting channels prograding out into the Engle Basin, possibly similar to the unconfined humid fans and braided systems described by Reading (1978). Channels on this piedmont fan may have been ancestral Cuchillo Negro and Alamosa tributaries. (The Alamosa is a large ephemeral tributary to the Rio Grande that lies about 5 km north of the study area; *see* Fig. 1.) As the piedmont-fan system prograded, bringing coarser material from the west, a general upward-coarsening sequence resembling the one observed in the distal subfacies may have resulted.

The moderately well sorted, trough crossbedded sand of the axial facies is believed to have been deposited by an aggrading through-flowing fluvial system, the ancestral Rio Grande. Fluvial sand deposits can be traced north and south of the study area (Hawley, 1978), which lends support for a through-flowing drainage. This fluvial system flowed south and occupied an area about 3 km wide in the study area, much wider than the present-day Rio Grande. Recent studies of braided rivers by Cant and Walker (1978) and Campbell (1976) found trough crossbedding, nondefined channels, and large amounts of sand with very small amounts of silt and clay to be important characteristics in recognizing deposits of braided systems. The axial facies show these characteristics and thus suggest that the ancient river was a braided system.

Based on contact relationships, deposition of the piedmont facies was occurring in the study area before deposition of the axial facies began. However, later deposition occurred penecontemporaneously, as evidenced by the lateral intertonguing contacts between deposits of the axial facies, proximal subfacies, and distal subfacies. Several paleosols found within the piedmont facies suggest deposition was not continuous everywhere; rather specific areas were free of deposition to allow for soil formation. Deposition of the Palomas Formation ended with the formation of the constructional Cuchillo surface about 400,000 to 500,000 years ago (Hawley, 1978). The Cuchillo surface is discussed in the geomorphology section.

SUMMARY—The Palomas Formation may be up to 180 m thick, and it ranges in age from about 3.8 m.y. (early Pliocene) to 400,000 to 500,000 yrs B.P. (middle

Lake Member of the McRae Formation by up to 2 m. The valley-fill sediments contain light-brown to buff, poorly sorted, loosely consolidated clay, silt, and sand with scattered angular to subrounded pebbles and cobbles. The scattered clasts are derived from Mesaverde and McRae strata and the basalt flows. Secondary gypsum crystals can be found locally in the deposits. Capping the valley-fill sediments is a desert pavement primarily consisting of basalt clasts. These sediments perhaps represent a back-filling episode during development of the Rio Grande. The undifferentiated alluvium in the northeast portion of the study area includes pediment gravels developed on the southern flanks of the Fra Cristobal Mountains.

A thin veneer of reworked distal subfacies sediments that have been deposited on the axial facies sediments make up a smaller portion of the undifferentiated alluvium. These deposits occur along the western shore of the reservoir *(see* Sheet 1, in pocket) and are distinguished because of the color contrast between the reddish, reworked distal subfacies and the light-colored axial facies. The reworked sediments are less than 2 m thick and consist mainly of poorly sorted, weakly stratified, poorly to moderately cemented silty sand with scattered, subrounded, porphyritic volcanic clasts. In aerial photographs, the sediments appear to have been deposited by channels that carried debris from the distal subfacies across the axial facies and into the Rio Grande. However, with later incision the channels may have been abandoned, and, because they are better indurated than the axial fades, they became a positive topographic feature (i.e., reverse topography).

Eolian deposits

Eolian deposits (Qes) are restricted primarily to areas east of the Rio Grande floodplain and are usually developed at localities protected by ridges or hills *(see* Sheet 1, in pocket). They are thought to be of Holocene age because they overlie the terrace deposits. These deposits occur mainly as large featureless sheets with minor coppice dunes developed on the sheet. Weakly consolidated, white to tan, well-sorted, fine-grained sand and some silt compose the eolian deposits. Because the prevailing winds come out of the south and southwest (Kelley and Silver, 1952) and because the deposits occur east of the Rio Grande floodplain, the major source of the sand is probably the floodplain itself. A minor portion may also be derived from the axial facies of the Palomas Formation. Thicknesses are generally less than 4 m.

Valley-fill alluvium

Valley-fill alluvium consists of 1) floodplain deposits of the Rio Grande and the Cuchillo Negro Creek (Qv_1) and 2) ephemeral tributary deposits that grade to the Rio Grande and the Cuchillo Negro Creek (Qv_2). The valley-fill alluvium is considered latest Pleistocene to Holocene in age. Excavations during the construction of the Elephant Butte Dam showed the floodplain deposits to be about 30 m thick (construction blueprints of Elephant Butte Dam, U.S. Bureau of Reclamation). Thickness for the tributary deposits is inferred to be 30 m or less.

The floodplain deposits are composed mostly of unconsolidated, moderately sorted, fine- to coarse-grained sand with gravel lenses in channels and mainly silt and clay in floodplains. The gravel contains angular to rounded clasts of quartz, sandstone, and a variety of porphyritic volcanic clasts. Clast composition and roundness of the Cuchillo Negro Creek bedload is presented in Appendix IV. Comparison of these data with data obtained on the Cuchillo Negro terrace levels shows no major change in clast composition or roundness, which suggests that no major shift in source area has occurred. In addition, data were collected at two localities on the Cuchillo Negro Creek upstream from the study area. One is located in the Black Range near the town of Chloride and the other is located about halfway between the Black Range and the study area, near the town of Cuchillo (Appendix IV). As the data indicate, clasts are predictably more angular near the Black Range, but no significant change in clast composition is apparent. Also included in the floodplain deposits is an approximately 2-m-high terrace.

The tributary deposits are composed of a poorly sorted mixture of unconsolidated clay, silt, and sand with gravel lenses, which are derived primarily from the Palomas Formation. Clast size and composition are similar to those described in the distal facies. The tributary deposits are restricted to the western portion of the study area. In the Cutter sag, drainages have very little fill and are developed mainly on bedrock, perhaps because drainages in the Cutter sag have smaller drainage basins and have to cut through more resistant bedrock. At arroyo mouths, the tributary deposits intertongue with and overlap the floodplain deposits.

Summary of Cenozoic units

The latite sill occurring in the Mud Springs Mountains is thought to be 30-35 m.y. old (A. Kudo, pers. comm. 1982). Crosscutting relationships suggest that the andesite dikes are early to middle Pliocene in age. The Palomas Formation is interpreted to have been deposited as alluvial fans (piedmont facies) and by the ancestral Rio Grande (axial facies), and it ranges in age from Pliocene (3.8 m.y. B.P.) to middle Pleistocene (400,000 to 500,000 yrs B.P.; Hawley, 1978). The Jornada deposits are perhaps early to late Pliocene in age. Bachman and Mehnert (1978) dated the basalt flows that overlie the Jornada deposits in the Cutter sag at 2.1 ± 0.4 m.y. old. Rock Canyon maar erupted during the later stages of Palomas Formation deposition, whereas Rattlesnake and Reservoir maars erupted after the deposition of the Palomas Formation. Stratigraphic relationships between the Palomas Formation, the Mud Springs pediment deposits, the Cuchillo Negro terrace deposits, and the valley-fill deposits are shown in Figure 8. Undifferentiated alluvium includes valley-fill and pediment deposits occurring in the Cutter sag and reworked piedmont fades sediments of the Palomas Formation deposited along the western shore of the reservoir. Eolian sand-sheet deposits can be found mainly east of the Rio Grande and are probably Holocene in age.

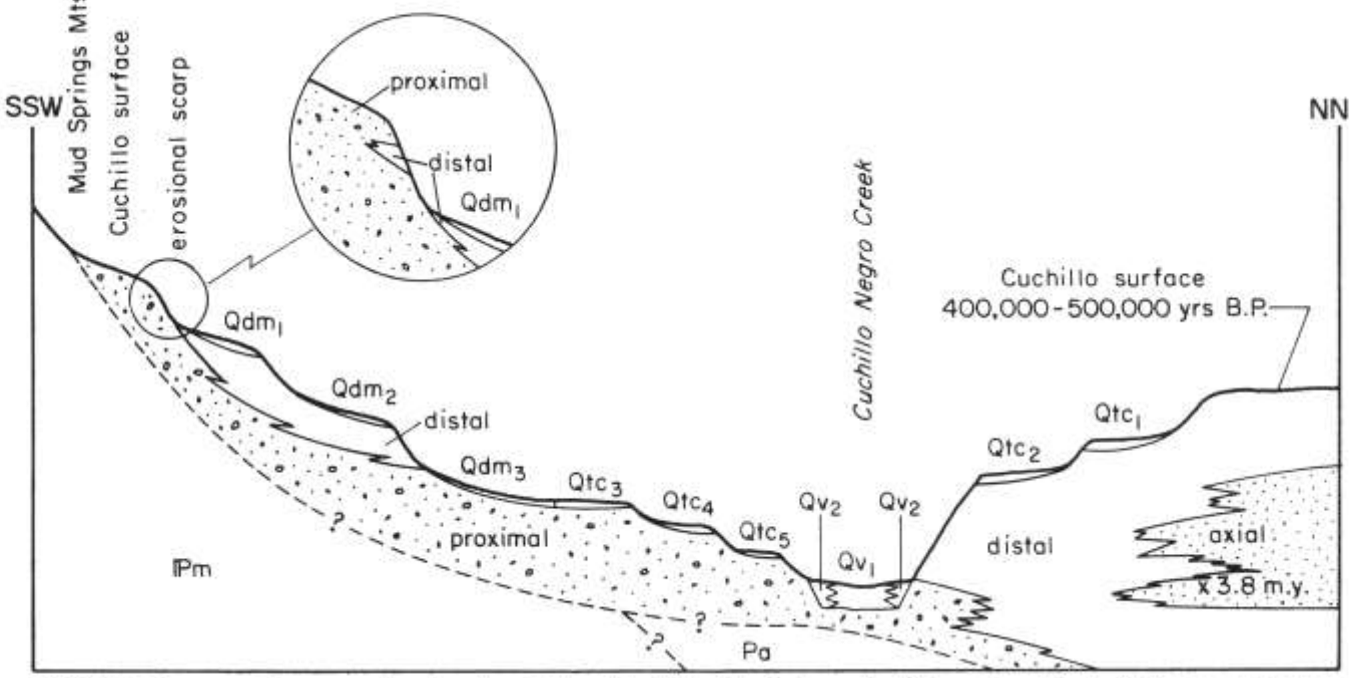


FIGURE 8—Diagrammatic cross section showing stratigraphic relationships between the Palomas Formation (axial facies, proximal and distal subfacies), Mud Springs pediment deposits (**Qdm**), Cuchillo Negro terrace deposits (**Qtc**), and valley-fill alluvium (**Qv**). Note enlargement of erosional scarp formed by differential erosion of proximal and distal subfacies; Pennsylvanian Magdalena Group (**IPm**); Permian Abo Formation (**Pa**).

Geomorphology

Major geomorphic features in the study area consist of terraces, pediments, and two regional geomorphic surfaces, the Cutter and the Cuchillo. The geomorphic features were formed by either erosional or depositional processes. A discussion on the present course of the Rio Grande is also included in this section.

Cutter surface

The Cutter is a regional surface and is hereby defined as that erosional surface in the Cutter sag that has beveled Mesaverde and McRae bedrock within the study area. It is commonly covered by the Jornada deposits and, in places, capped by the basalt flows. Kelley and Silver (1952) originally named the surface Jornada; however, Hawley and Kottlowski (1969) used the same term for a much younger surface in the southern Jornada del Muerto. So, to avoid confusion, the name Cutter has been adopted for this area.

Within the study area, the Cutter surface generally slopes to the west as indicated by the westward flow direction of the basalt. In the past, the Cutter surface may have covered most of the Cutter sag and perhaps graded to the former level of the Engle Basin. Later incision caused by uplift along the Hot Springs fault probably resulted in the removal of much of the Cutter surface. Remnants of the Cutter surface remain only in the southeastern corner of the study area and beneath the basalt flows. Presently, at its lowest point, the Cutter surface stands about 150 m above the present base level.

The Cutter surface is believed to have formed during a period of little or no movement along the Hot Springs fault. A quiescent period would have allowed the ancestral drainages in the Cutter sag (e.g., McRae and Jose Creeks) to gradually erode the bedrock to a common base level rather than having the drainages deeply incise the bedrock. The gradual wearing down of the bedrock by erosion would have tended to produce a relatively flat, undulating surface. The age of the Cutter surface is probably early to late Pliocene because the surface cuts the andesite dikes, but it is covered by the 2.1 ± 0.4 m.y. old basalt flows. In addition, the Cutter surface may be correlative with the angular unconformity between the Abo Formation and the piedmont facies exposed along Cuchillo Negro Creek.

Cuchillo surface

The Cuchillo surface is a constructional surface of regional extent that marks the end of deposition of the Palomas Formation. It occurs as a dissected, slightly undulating surface that gently slopes to the southeast in the northwestern corner of the study area and as isolated remnants along the flanks of the Mud Springs Mountains (diagonally ruled area on Sheet 1). To the west, outside the study area, the Cuchillo surface becomes an almost continuous surface merging with the Palomas surface around the Mud Springs Mountains and extends westward to the Black Range and the Sierra Cuchillos. Within the study area, the original Cuchillo surface would have graded eastward to the former level of the ancestral Rio Grande. Subsequent erosion and dissection have resulted in the present remnant surface, which is now at its lowest point, about 140 m above the present base level. A thick, pedogenic calcium carbonate horizon (Appendix I, section 2) occurs near the surface, and scattered patches of desert pavement occur on the surface. The Cuchillo surface formed when aggrading of the Palomas Formation by alluvial-fan deposition ceased due to the initial incision of the Rio Grande. The surface is constructional within the study area because no erosion of the beds has occurred since the sediments were initially deposited. Outside the study area and towards the mountains to the west, the Cuchillo surface may be erosional.

The absolute age of the Cuchillo surface is not well defined within the study area; however, based on the volcanic ash discussed in the stratigraphy section, it is believed to be younger than 1.45 m. y. because about 30 m of Palomas Formation sediments overlie the ash. Hawley (1978, p. 103) has correlated the Cuchillo surface with Jornada I and La Mesa surfaces of the Las Cruces area. This correlation places the age of the Cuchillo surface between 250,000 and 1,500,000 years (Gile and others, 1981, p. 38). However, the Cuchillo surface predates the initial incision of the Rio Grande, which occurred about 400,000 years ago (Gile and others, 1981, p. 47). Moreover, the upper basin-floor deposits of the Camp Rice Formation contain ashes dated at 700,000 and 600,000 years (Gile and others, 1981, p. 47), and these basin-floor deposits are broadly equivalent with the axial facies of the Palomas Formation (*see* Table 1). Therefore, based on the above discussion, the age of the Cuchillo surface can be bracketed between 400,000 and 500,000 years (middle Pleistocene) within the study area. Kelley and Silver (1952) thought the Cutter and the Cuchillo surfaces were once continuous, but the age differences presented here do not support that interpretation.

Pediments associated with local mountain ranges

Localized pediment surfaces include a series along the eastern and southern flanks of the Mud Springs Mountains and a few small remnants along the western base of the northern Caballo Mountains (Sheet 1, in pocket). The pediments have developed on the piedmont facies of the Palomas Formation and are covered by gravels of the Mud Springs and Caballo deposits.

Three pediment levels, including their associated deposits, have been recognized along the Mud Springs Mountains (Fig. 9). The highest pediment level is assumed to be the oldest based on height and preservation (most dissected), and so is designated as pediment level 1. Level 2 is of intermediate age, and level 3 is the youngest because it is the lowest and best preserved. Pediment level 3 was traced to grade into terrace level 3 (terrace levels are discussed in the next section), implying that the higher pediment levels may be broadly equivalent to terrace levels 1 and 2.

Only one pediment level and associated deposits have been recognized along the northern Caballo Mountains. The distal regions of this pediment level have been removed by lateral erosion by the Rio Grande. Possibly, the Caballo pediment originally may have graded to Rio Grande terrace level 3. The Mud Springs and Caballo pediment levels are interpreted to have formed during stable base-level periods as the Rio Grande underwent incision episodes. Ages for the Mud Springs and Caballo pediments are discussed in the next section.

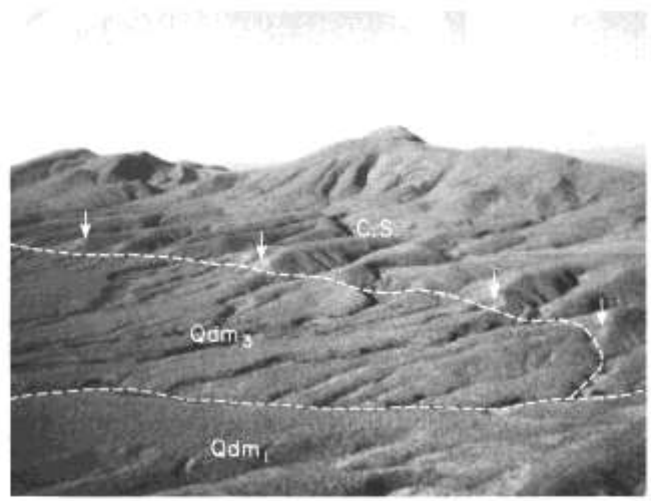


FIGURE 9—Aerial view of pediment levels 1 and 3 along Mud Springs Mountains including remnant Cuchillo surface (C.S.). Note erosional scarp (arrows).

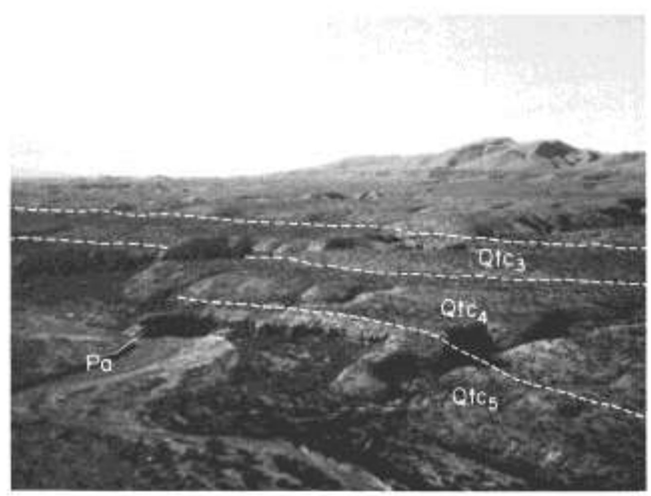


FIGURE 10—Aerial view, looking southwest, of Cuchillo Negro terrace levels 3, 4, and 5 and present Cuchillo Negro Creek, which is flowing east (left). Mud Springs Mountains are in near distance and Caballo Mountains are in far distance; the Abo Formation is exposed along the floodplain margin.

Terraces

Five terrace levels have been recognized along the Rio Grande and Cuchillo Negro Creek. They are inset, erosional (strath) terraces cut into the Palomas Formation and some Mesaverde strata. The terrace levels have been designated by numbers based on elevations above the floodplain (Fig. 10). Therefore, terrace level 1 would represent the oldest and highest level above the floodplain, while level 5 would represent the youngest and lowest terrace level. Table 2 shows the terrace levels and associated elevations. Gradients for a rather continuous portion of the three lower Cuchillo Negro terraces and for the present Cuchillo Negro Creek are also shown in Table 2. A difference is apparent in the gradients of levels 3 and 4 (both 0.012) when compared with the gradients of terrace level 5 (0.009) and the present gradient (0.010). Terrace levels 1 and 2 have not been found in Elephant Butte Canyon.

TABLE 2—Terrace-level data including both Rio Grande and Cuchillo Negro terraces. Elevations based on present base level. Gradients shown are from Cuchillo Negro terraces only. Present gradient of Cuchillo Negro Creek is 0.010. Gradient data are shown in Appendix V.

Terrace	Height above floodplain terrace occurs between: (m)	(ft)	Gradients for Cuchillo terraces only (ft/ft)	Type
1	36–42	120–140	—	strath
2	30–36	100–120	—	strath
3	24–30	80–100	0.012	strath
4	18–24	60–80	0.012	strath
5	6–12	20–40	0.009	strath

Absolute ages for the terrace level) (and pediment levels) are unknown because no datable material has been found. Ages generally are believed to range from middle to late Pleistocene because the terraces must be younger than the Cuchillo surface, but terrace level 5 may be early Holocene. Hawley and Kottlowski (1969) have recognized and established approximate ages for geomorphic surfaces in the Las Cruces area, and these levels have been recognized by Hawley (1965) as far north as the Rincon area, located about 30 km south of the study area. The terrace and the pediment levels in the study area may correlate with the surfaces found farther south; however, it must be stressed that this correlation is based solely on similarities in height above the present base level, and that the terraces have not been traced physically southward. Table 3 shows the possible correlations. The Tortugas and Picacho deposits have not been precisely dated, but they are known to be older than the C" dated fills (Leasburg and Fillmore alluviums) and younger than the middle Pleistocene basalt flows capping La Mesa surface (Gile and others, 1981).

TABLE 3—Possible correlations with Hawley and Kottlowski's (1969) geomorphic surfaces. Includes both Rio Grande and Cuchillo Negro terrace levels (based on Gile and others, 1981, p. 40).

Terrace levels in this study	Heights above base level in this study (m)	Hawley and Kottlowski's surfaces	Heights above base level (m)	Range of ages in yrs B.P.
1 and 2	30–42	Tortugas	32 or more	150,000–250,000
3 and 4	18–30	Picacho	18–24	50,000–150,000
5	6–12	Leasburg	Slightly above present base level	8,000–25,000
2 m terrace in Qv_1	2	Fillmore	Near present base level	7,500–prehistoric

Present course of Rio Grande

Part of this investigation involved the study of the past and present course of the Rio Grande as it meanders across the Hot Springs fault. This section briefly describe s the present coursethe Rio Grande including, the portion that lies submerged beneath the water, of Elephant Butte Reservoir. The description of the submerged portion is based on a topographic map (1:24,000) surveyed in 1908 by the U.S. Bureau of heclamation. In addition, this section addresses the question of why the Rio Grande crosses the Hot Sr rings fault to cut into more resistant bedrock rather than continuing to cut into the basin-fill sediments Palomas Formation).

The Rio Grande generally follows a meandering course through the study area *(see* Sheet 1, in pocket) with its floodplain width controlled by bedrock lithology. The floodplain broadens on the west side of the fault in the less resistant Palomas Formation and narrows on the east side of the fault in the more resistant McRae and Mesaverde strata. On the east side of the fault the river is superposed as it cuts across the structural grain of the Mesaverde strata. The Rio Grande crosses the Hot Springs fault a total of six times in the vicinities (from north to south) of Long Point Island, Rattlesnake Island, and Long Ridge. In only a few places along the Rio Grande rift does the river cross the rift-bounding fault to cut into the marginal uplifts.

The crossings near Long Point and Rattlesnake Islands appear as meander loops that have cut laterally into the McRae Formation at the maximum distance of about 1.0 and 0.5 km, respectively. The crossings near Long Ridge seem more complex than a simple lateral cutting of a meander because the river follows a more complicated course around Long Ridge and lies much farther east of the fault (2.1 km at its maximum distance).

Few workers have offered explanations about why the river crosses the Hot Springs fault. It has been suggested by Kelley and Silver (1952) that in the past the Rio Grande flowed over a higher surface, perhaps the Cutter, and became entrenched due to uplift on the east side of the fault. However, there are some inconsistencies in this theory. If the Cutter surface was the higher surface on which the river once flowed, it would be very difficult to explain the deposition of the axial facies of the Palomas Formation on the west side of the fault from 3.8 m.y. ago to perhaps 400,000

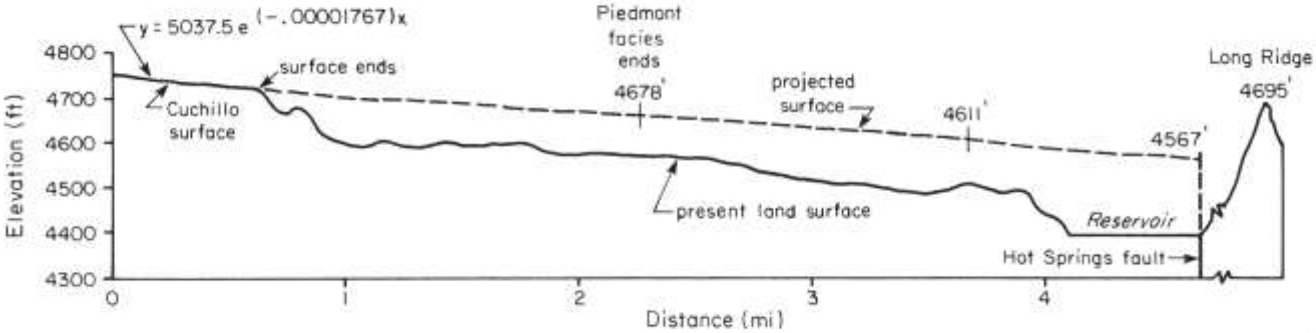


FIGURE 11—Projection of Cuchillo surface profile towards Long Ridge; constructed from data presented in Appendix VI; vertical exaggeration is 10X.

yrs ago because the Cutter surface is thought to be older than 2.1 m.y. If the Rio Grande shifted after 400,000 yrs ago, there was not enough uplift along the Hot Springs fault to aid in entrenchment. Movement on the Hot Springs fault is interpreted to have ended after the initial incision of the Rio Grande, which occurred about 400,000 yrs ago (Gile and others, 1981). Also, no terrace deposits were found on Long Ridge that would have recorded an eastward shift of the ancestral river (however, terrace deposits on Long Ridge could have been removed by erosion).

Possibly the strongest argument against the river flowing over any surface on the east side of the Hot Springs fault has to do with the Cuchillo surface. As stated earlier, the Cuchillo surface represents the highest aggradation of the Rio Grande. Projection of the Cuchillo surface profile eastward does not clear Long Ridge, but intersects it at least 8-14 m below the crest (Fig. 11). The height difference probably was not caused by movement along the Hot Springs fault because little to no movement is interpreted to have occurred since the initial incision of the Rio Grande. Hence the Rio Grande has never aggraded high enough to have migrated over Long Ridge.

At Long Point and Rattlesnake Islands, the crossings of the Rio Grande are believed to have resulted from lateral cutting by meanders because they occur only a short distance east of the fault, they have cut into only the less resistant McRae Formation, and they have no major obstacles such as ridges in their migration paths. The migration must have occurred before Rattlesnake maar eruptions because if the migration had occurred after the maar eruption, the maar probably would have been eroded by the migrating river. The Long Ridge crossing is believed to have a different interpretation.

The Long Ridge interpretation begins with the Rio Grande flowing on the west side of the Hot Springs fault through the wing dam area (*see* Sheet 1, in pocket). A tributary of the Ash Canyon—Jose Creek system, headwardly eroding northward between Long Ridge and Elephant Butte, is hypothesized to have captured the river just south of Rattlesnake Island and pirated it around Long Ridge. The tributary originally would have flowed on the Cutter surface and subsequently would have been aided by uplift that occurred before 400,000 yrs ago. The uplift enabled the tributary to cut through any structural controls. Field evidence indicates that piracy may have occurred during or just after terrace level 2 time. Cuchillo Negro terrace levels 1 and 2, occurring north of Mim's Lake, appear to be entering the Rio Grande at that point. Paleocurrent measurements at this locality indicate a southwest flow direction that would support the hypothesis that a river flowed through the wing dam area (Appendix III). Rio Grande terrace levels 1 and 2 have not been found in Elephant Butte Canyon, which may indicate that the Rio Grande did not flow through the canyon at that time to form those terrace levels. Consequently, the absence of terrace levels 1 and 2 in Elephant Butte Canyon establishes the timing of the piracy because terrace levels 3, 4, and 5 are found in the canyon. Finally, the interpretation is consistent with the historical interpretation that the Cuchillo surface does not extend over Long Ridge.

This interpretation is not without problems. In Elephant Butte Canyon, Rio Grande terrace levels 1 and 2 may have been deposited and later removed by erosion. A more important problem is the absence of terrace deposits in the wing dam area. However, scattered granite, chert, and clasts of McRae Formation are found in the wing dam area, which could only have been derived from farther upstream and may represent reworked terrace deposits. In addition, a tectonic slice of Mesaverde strata occurring west of the main branch of the Hot Springs fault suspiciously appears to have been beveled at about 35 m above base level (or terrace level 2 height), perhaps by the Rio Grande. Therefore, based on the above discussion, the most feasible interpretation appears to be that the Long Ridge crossing of the Rio Grande is the result of stream piracy and capture.

Summary

Two regional surfaces occur in the mapped area, the erosional Cutter and the constructional Cuchillo. The age of the Cutter surface ranges from early to late Pliocene, whereas the age of the Cuchillo surface is interpreted to be middle Pleistocene (400,000 to 500,000 yrs ago). The pediment and terrace levels are interpreted to have formed during stable periods in the history of the Rio Grande. Their ages range from middle Pleistocene to early Holocene. Crossings of the Hot Springs fault by the Rio Grande at Long Point and Rattlesnake Islands resulted from laterally cutting meanders. The Long Ridge crossing is thought to have resulted from stream piracy and capture.

Structure

Structures within the study area primarily occur east of the Hot Springs fault (*see* Sheet 1, in pocket). No deformation has been observed in the Santa Fe Group sediments, except near the Hot Springs and the T or C faults where the beds become tilted and warped. Kelley and Silver (1952) recognized several episodes of deformation in the region; however, most of the present topography and prominent structures are the result of Laramide and Rio Grande rift tectonic activity. Descriptions of the folds and faults are limited to a general discussion on trends and dynamics because most of these structures formed before the Pliocene and, therefore, are not a part of the late Cenozoic history. Because of the importance of the Hot Springs fault to the late Cenozoic history, it will be discussed separately. For summarized information on individual structures, see Figure 12 and Appendix VII.

Folds

The larger folds in the study area (those exceeding 100 m in length) are characteristically open and upright. Trends on folds range from N. 75° W. to N. 55° E., with plunges usually less than 30° to the west and south. Fold-limb dips seldom exceed 20°. Most larger folds are symmetrical, except for a few located in the southeast corner of the study area, just north of NM-52. Many of the large folds are either nearly parallel or normal to the major fault trends. Trends with shallow oblique angles to faults are rare.

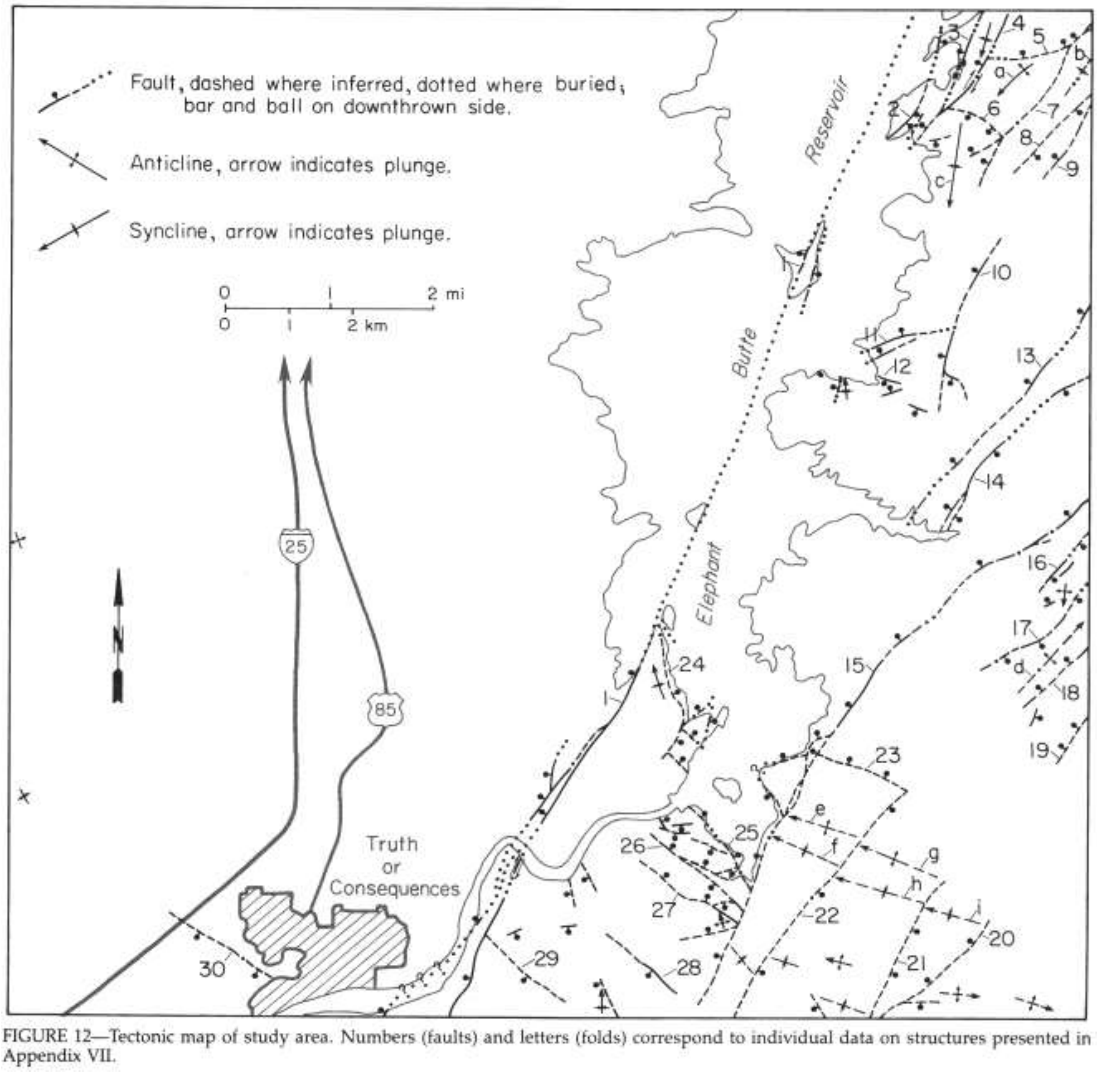


FIGURE 12—Tectonic map of study area. Numbers (faults) and letters (folds) correspond to individual data on structures presented in Appendix VII.

Kelley and Silver (1952) recognized an overturned syncline located in the vicinity of T or C. Because most of the bedrock involved in the folding lies buried beneath the Palomas Formation, this is an inferred structure and therefore has not been mapped. In T or C, dips in isolated outcrops of Magdalena Group limestone are overturned about 70° to the southwest. When approaching the Mud Springs Mountains, however, the beds steepen along strike and eventually become right-side-up, dipping at 26° to the northeast in the Mud Springs Mountains. The syncline is interpreted as plunging to the south and its axial plane may be nearly horizontal. In addition, a few minor, overturned folds are present in the northern Caballo Mountains, but they have not been mapped because of their small size.

Scattered throughout the Cutter sag, northern Caballo, and Mud Springs Mountains are numerous small folds that rarely exceed 100 m in length. Trends vary greatly, but most seem to be north—northwest-trending folds. The small folds are primarily open, symmetrical, and upright and seldom occur in sets. A fold along Long Ridge has a curved axial trace, perhaps due to drag along the Hot Springs fault.

Faults

Faults outnumber folds in the study area and form many of the contacts between formations observed in the Cutter sag. Based on fault trends and linear extent, the faults can be grouped into two types: 1) northnortheast-trending faults with traces generally longer than 1.5 km and 2) randomly trending faults with traces generally shorter than 1.5 km.

The type 1 faults show primarily normal movement with a very minor strike-slip component. Exceptions are the Hot Springs fault and a pair of faults located north of Kettle Top, which do show some strike-slip motion. In the latter case, a syncline has apparently been offset horizontally by about 3 km. No type 1 faults show reverse motion. Fault-plane dips are typically steep, ranging from about 40° to nearly vertical, with most faults downthrown to the west. Strati-graphic throw ranges from about 3 m to more than 300 m, but most are in the 30-m range. Tectonic slices occur in a few of the fault planes. Notably, the fault located just east of Elephant Butte has slices of Mesaverde and McRae strata caught within the fault plane. Because many type 1 faults juxtapose resistant units with less resistant units (i.e., Mesaverde with McRae), the topographic expression of the faults can be very prominent.

As stated earlier, type 2 faults have several trends, but most are about normal to the type 1 faults. They also show primarily normal motion, with fault-plane dips ranging from 60° to 80°. Stratigraphic throw on type 2 faults is generally less than 30 m. Included in this fault group is a reverse fault located in T or C, which offsets Palomas and Magdalena strata. At about the same location, a much larger fault may exist. Here, the contact between the axial facies and the piedmont facies drops about 6 m across the arroyo, but no fault trace has been found. Kelley and Silver (1952) speculated that a large, normal fault separating the Mud Springs uplift from the Palomas Basin exists in the area. It is this inferred fault or a branch of it that may be responsible for the drop in the facies contact.

Hot Springs fault

The Hot Springs fault is the most prominent structural feature in the study area. It extends the entire length of the study area (Fig. 13), a distance of more than 15 km, trending N. 20°-30° E. Much of its trace lies submerged beneath the waters of Elephant Butte Reservoir, but before the reservoir was filled the fault was mapped at about the same position (Lee, 1907a). The fault splays into several branches in the south. This splaying also may occur where the trace is hidden beneath the reservoir. The pair of faults that displace the syncline in the northern part of the study area could be branches of the Hot Springs fault. North of the study area, Warren (1978) mapped the Hot Springs fault as two splay segments, with the western segment ending in the Santa Fe Group sediments and the eastern segment, which he calls the Walnut Creek fault, continuing to form the range-bounding fault for the Fra Cristobal Mountains. To the south, the Hot Springs fault merges with the Caballo fault to become the range-bounding fault for the Caballo Mountains (Mason, 1976).

The Hot Springs fault is a normal fault downthrown to the west and dipping about 70°-80° to the west. In addition, strike-slip motion also has occurred as evidenced by the apparent 460-m right-lateral offset of the San Andres Formation east of T or C. Kelley and Silver (1952) suggested that the westward bend of the units in the northern Caballo Mountains is the result of left-lateral drag. However, Mesaverde Formation beds in the Long Ridge area do not show this bend, and, therefore, it is thought that the bend may represent a fold that has been truncated by the fault. In fact, the Mesaverde Formation beds exhibit a slight right-lateral drag as does a fold axis near Long Ridge. The stratigraphic throw on the Hot Springs fault is variable. Based on gravity data, Loeber (1976) calcu-

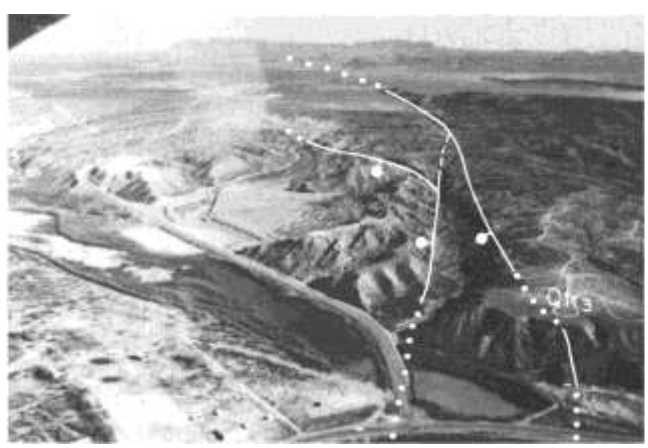


FIGURE 13—Aerial view, looking north, of the Hot Springs fault and associated splays in the wing dam area. Mim's Lake (cutoff meander) is in the foreground and Fra Cristobal Mountains are in the far distance. Note that Hot Springs fault does not offset the Qtr, terrace.

lated a displacement of at least 1,070 m near Long Point Island. Mason (1976) estimated displacements between 610 and 2,740 m in the northern Caballo Mountains. Near the wing dam, the displacement must be at least 1,220 m because lower Mesaverde strata abut Palomas sediments.

Age of structures

The overturned folds in the study area formed during the Laramide orogeny (Kelley and Silver, 1952). The open and upright folds are thought to be younger. The folds are cut by the faults occurring in the Cutter sag. Movement on these faults must have ended before the formation of the Cutter surface because no offset is seen in the Cutter surface. Because the Cutter surface is interpreted to have formed during early to late Pliocene, the open folds would have formed before early Pliocene. Kelley and Silver (1952) suggested that these folds are of Miocene age and formed during the early stages of Rio Grande rifting.

Most of the faulting in the study area occurred before the emplacement of the andesite dikes. Little to no displacement is seen on dikes that are cut by faults, even though the faults have had more than 100 m of stratigraphic offset. Moreover, because the Cutter surface was not offset, faulting in the Cutter sag must have ceased before formation of that surface. Activity along the Hot Springs and related faults appears to have continued because these faults involve the Palomas Formation. Movement on the Hot Springs fault has been episodic, as indicated by lower beds along the fault plane that are more deformed than higher beds (Fig. 14). The episodic movement implies that sufficient time existed between faulting events to allow sediment accumulation along the fault scarp. The horizontal movement of the Hot Springs fault is thought to have occurred early in its history, before Palomas Formation deposition. This is supported by the following observations: 1) Palomas fanglomerates (proximal subfacies) consisting of clast types derived from the adjacent formations in the Caballo Mountains do not appear to be displaced horizontally and 2) no landforms generated by horizontal movement are seen in the present topography (e.g., offset drainages). Despite the apparent 460-m horizontal movement early in its history, vertical movement has been the dominant motion of the Hot Springs fault before, during, and after Palomas Formation time, as indicated by the 1,070 m of vertical separation.

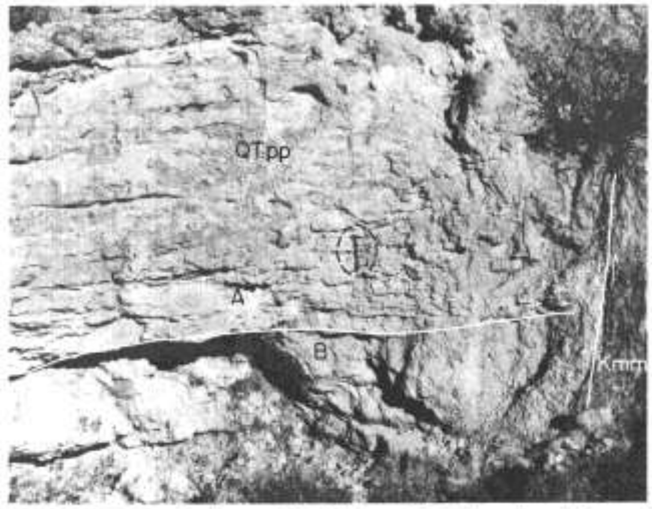


FIGURE 14—Fault plane of Hot Springs fault showing deformed beds of proximal subfacies (left) faulted against Mesaverde Formation (right). Note bed **A** is less deformed than bed **B** in proximal subfacies. Exposure occurs in wing dam area (hammer for scale).

Episodic movement probably continued on the Hot Springs fault until the Cuchillo surface formed. How long movement continued following Cuchillo surface formation is unclear. Loeber (1976) noted the Hot Springs fault did not offset Rattlesnake maar deposits, but due to high water level during the present study this could not be substantiated. Rattlesnake maar is interpreted as having been deposited in the initial incised valley of the Rio Grande, which suggests that activity had ceased before its deposition. Also, Rio Grande terrace level 3 deposits, which overlie the Hot Springs fault near Mim's Lake, are not offset by the fault (Fig. 13). Based on the data above, it can be concluded that little to no movement has occurred on the Hot Springs fault since the time of initial incision of the Rio Grande.

The significance of the structural data to the late Cenozoic history is that faulting in the Cutter sag ended before the formation of the Cutter surface, but episodic movement along the Hot Springs fault continued until the time of initial incision of the Rio Grande. These conclusions are in general agreement with the findings of Chapin and Seager (1975) in the Socorro and Las Cruces areas of the Rio Grande rift. They determined faulting activity was greatest during late Miocene and Pliocene, with activity decreasing during the Quaternary. Currently, the Elephant Butte area is seismically inactive (Sanford and others, 1981).

Late Cenozoic history of the Elephant Butte area

The late Cenozoic history of the study area is based on the interpretations discussed in the previous chapters. To more clearly present these interpretations, the late Cenozoic history has been divided into seven stages. The stages range in age from Pliocene to the present. Schematic maps and cross sections depicting the position of important features through time have been constructed for each stage and are presented on Sheet 2 (in pocket). These maps and cross sections represent episodes in time and show how the study area may have evolved.

The maps and cross sections are based on a reduction of Sheet 1 so that accurate placement of important features is maintained. In the explanation of the stages, the numbers or letters in parentheses (e.g., 1 or L.R.) correspond to the location of important features on the maps and cross sections *(See* Sheet 2, in pocket).

Stage I

The interpretation begins with the early phases of deposition of the Palomas Formation, before the ancestral Rio Grande flowed through the study area. The age is believed to be early Pliocene. At that time, the major uplifts (1) were almost at their present elevations (Seager and Chapin, 1975), and the Engle Basin was probably an internally drained bolson with a playa (2). Along the major uplifts, sediments of the proximal subfacies were being deposited as alluvial fans (3). The coalescing of the local fans formed a bajada. Sediments of the distal subfacies (4) were being deposited by the shifting braided channels of the piedmont-fan system, which has its origins in the Black Range and Sierra Cuchillos to the west. The Hot Springs fault (5) was inactive, which allowed for the development of the Cutter surface (6) by the ancestral drainages in the Cutter sag. The Cutter surface probably graded to the surface level of the Engle Basin across the Hot Springs fault.

Stage II

By 3.8 m.y. ago, the ancestral Rio Grande established itself on the west side of the Hot Springs fault. The braided river system (7a) flowed south and was perhaps as much as 3 km wide. Renewed activity along the Hot Springs fault (5) uplifted the Cutter sag and caused the Engle Basin to subside. Movement on the Hot Springs fault was episodic. The subsidence increased aggradation in the Engle Basin. Sediments of the proximal subfacies (3) continued to be deposited as alluvial fans along the major uplifts (1) and also along the scarp of the now active Hot Springs fault. However, deposition of the distal subfacies sediments increased. The piedmont fan, depositing sediments of the distal subfacies (4), formed a complex braided-fan system with many shifting channels. One of these channels may have been the ancestral Cuchillo Negro Creek. Soils formed on the inactive areas of the fan. With aggrading and prograding of the piedmont fan towards the ancestral Rio Grande, sediments of the piedmont facies intertongued with sediments of the axial facies. During aggradation of the Palomas Formation, the Mud Springs uplift became partially buried, especially in the vicinity of T or C.

About 2.1 ± 0.4 m.y. B.P. basalts erupted along fissures onto the Cutter surface (including a possible flow over Elephant Butte) and flowed westward (8). The eruption culminated with the formation of cinder cones. The renewed uplift of the Cutter sag caused dissection and initiated the retreat of the Cutter surface (6) by erosion. With uplift, the drainages in the Cutter sag incised and superposed themselves on structural features. The drainage near Elephant Butte is the ancestral Ash Canyon—Jose Creek system (9), which is headwardly eroding northeastward.

Eastward tilting of the Engle Basin by the Hot Springs fault probably forced the ancestral Rio Grande to flow along the fault throughout Stage II time. During the final phases of aggradation, the Rock Canyon maar (10) erupted through the axial facies and was subsequently buried. The aggregation of the Palomas Formation ended with the formation of the Cuchillo surface.

Stage III

The initial incision of the Rio Grande (7) is thought to have occurred about 400,000 yrs ago (Gile and others, 1981, p. 47). The incision downcut to level 1, reduced river size, and isolated the Cuchillo surface (11) from further deposition. Following the end of Palomas Formation deposition, erosion became the dominant process in the study area, and the Hot Springs fault (5) became relatively inactive. The Cuchillo Negro Creek (12) also incised and, at its confluence with the Rio Grande, formed a wide mouth perhaps because of a sudden gradient drop upon entering the Rio Grande. (Presently, the Rio Grande gradient is about 1 m/km, whereas the Cuchillo Negro gradient is about 10 m/ km.) When base level 1 became stable, pediment level 1 (13) began development along the Mud Springs Mountains, isolating portions of the Cuchillo surface against the mountain front. During pedimentation, differential erosion between the better cemented sediments of the proximal subfacies and the poorly cemented sediments of the distal subfacies formed an erosional scarp (14) along the Mud Springs Mountains.

East of the Hot Springs fault, incision of the Cutter surface (6) continued and the basalt flows (8) began to be eroded. At that time, a tributary of the Ash Canyon—Jose Creek system (9) expanded northward. The expansion of the tributary may have been aided by capturing and incorporating a north-flowing creek (9a). This region is primarily underlain by the less resistant Hall Lake Member (Kmh) of the McRae Formation *(see* cross section on Sheet 2). A tributary would be aided greatly in its expansion when encountering the Hall Lake shales as opposed to the more resistant Jose Creek Member (Kmj) and Mesaverde Formation (Kma, Kmm). Stage III ended when the Rio Grande incised for the second time.

Stage IV

Stage IV began with the Rio Grande incising to base level 2. The incision formed terrace level 1 (15) and began the removal of the Cuchillo surface (11) by erosion. Removal of the Cuchillo surface may have partially exhumed the buried Rock Canyon maar (10). During the second incision, the Cuchillo Negro Creek (12) shifted slightly south. When level 2 was stabilized, the Rio Grande (7) started to meander and, where the Hot Springs fault (5) has juxtaposed the McRae Formation with the Palomas Formation, the river laterally cut across the Hot Springs fault at Long Point (L.P.) and Rattlesnake Island (R.I.). Level 2 stability enabled pediment level 2 (16) to begin development along the Mud Springs Mountains.

In the Cutter sag, the Cutter surface (6) and the basalt flows (8) continued to be eroded. Also, the basalt flow associated with Elephant Butte may have been eroded away by that time. Meanwhile, the tributary just west of the Elephant Butte (9) continued to incorporate the north-flowing creek, and, with increased lateral cutting by the Rio Grande, the two drainages intersected (17). This intersection may not have been sufficient to capture the Rio Grande because the gradient difference may not have been great enough. However, aided perhaps by plugging or partial plugging of the channel in the wing dam area by debris from Cuchillo Negro Creek, the river was forced to use the new course east of Long Ridge (L.R.). Modern tributaries of the Rio Grande can occasionally deposit large amounts of sediment that can partially block the channel during flood events (J. Hawley, pers. comm. 1982). The capture, coupled with renewed incision, ended Stage IV and fixed the new course of the Rio Grande at Long Point and Rattlesnake Island and around Long Ridge.

Stage V

The third incision of the Rio Grande formed terrace level 2 (18). During this incision, the Rio Grande (7) probably cut a larger channel through Elephant Butte Canyon. The Cuchillo Negro Creek (12) and its confluence with the Rio Grande shifted south as a result of the stream piracy. Note that terrace level 2 (18) also is present in the wing dam area where the river flowed before capture.

Eventually, incision ended and base level 3 became stable. Base-level stability enabled pediment level 3 (19) to begin formation along the Mud Springs and northern Caballo Mountains (on the proximal subfacies). Portions of pediment levels 1 and 2 (13 and 16) were removed by the development of pediment level 3. Erosion continued to remove the Cuchillo surface (11) and began to erode portions of terrace levels 1 and 2 (15 and 18). In the Cutter sag, the Cutter surface (6) and the basalt flows (8) continued to be eroded. During the same period, Kettle Top (K.T.) may have become an isolated remnant due to removal of the basalt flows. Rattlesnake and Reservoir maars (20) may have erupted at this time, forming a crater and spraying pyroclastic debris along the Rio Grande. Rock Canyon maar (10) has probably become totally exhumed. The fourth incision of the Rio Grande ended Stage V.

Stage VI

Terrace level 3 (21) formed when the Rio Grande incised. During this stage, the study area underwent a fourth incision to stabilize at base level 4 and a fifth incision to stabilize at base level 5. In the process, terrace level 4 (22) was formed. Further pedimentation along the Mud Springs Mountains during the stable periods may have been hampered by encountering the well-cemented sediments of the proximal subfacies and by insufficient time between incisions for pedimentation. Based on the work of Gile and others (1981), the age differences between the older terrace deposits and the younger terrace deposits lend support to this idea (*see* Table 3 for ages). The Cuchillo Negro Creek (12) shifted northward during the two incision episodes. Dissection of the pediment and terrace levels continued. Terrace level 2 (18), which was present in the wing dam area, may have been removed by this time.

The Rio Grande is at base level 5 in this stage. Meanders of the Rio Grande (7) became enlarged in the Palomas Formation. The Rio Grande also shifted south in the vicinity of present-day T or C, leaving behind terrace levels 3 (21) and 4 (22). The Cutter surface (6), the basalt flows (8), and the Cuchillo surface (11) have been removed by erosion to just about their present position. Finally, perhaps during Stage VI time, sand (23) derived from the floodplain and axial facies was beginning to be carried by wind and deposited in the Cutter sag region. Stage VI ended with the sixth incision episode.

Stage VII

During the sixth incision episode, the Rio Grande cut down to a depth of about 30 m below the present base level and then backfilled its channel (depth is based on thickness of valley-fill deposits). The incision also resulted in the formation of terrace level 5 (24). Stage VII represents the study area as it appears today (Sheet 2, in pocket). The Cuchillo surface, the basalt flows, and the Cutter surface had been eroded back to their present areal extent. The various terrace and pediment levels that were formed during the previous stages now remain as remnants along the major drainages and uplifts. Major processes at this time primarily involve 1) lateral channel shifts and some aggradation of river floodplain areas, 2) aggradation of arroyo-valley floors and deposition on arroyo-mouth fans, and 3) local arroyo incision. However, during the twentieth century, human activity has begun to influence the course of the Rio Grande.

Elephant Butte Dam was constructed from 1909-1916, which caused a large portion of the river's course within the study area to be submerged. The damming of the Rio Grande has temporarily hindered further development of the river and has resulted in the formation of a huge sediment trap behind the dam. This has greatly affected sedimentation downstream, because large floods no longer occur below the dam. Also, the Mim's Lake meander was cut off and established in its present course by the Bureau of Reclamation in the 1940's.

One can speculate about developments that might have occurred if the Rio Grande had been left unhampered by human activity. At Long Point and Long Ridge, opposing meanders can be seen cutting laterally into the Palomas Formation on the west side of the Hot Springs fault (Sheet 2, in pocket). If the meanders had been allowed to continue to cut towards one another, and barring possible meander cutoffs, the Rio Grande would have had the potential to reestablish itself on the west side of the Hot Springs fault and the course through Elephant Butte Canyon would have been abandoned.

Conclusions

1. Palomas Formation ranges in age from 3.8 m.y. (early Pliocene) to 400,000 to 500,000 yrs B.P. (middle Pleistocene).
2. Piedmont-facies sediments were deposited by 1) alluvial fans deriving detritus from the local uplifts and 2) a large piedmont-fan system deriving detritus from the Black Range and the Sierra Cuchillos.
3. Axial-facies sediments were deposited by the ancestral Rio Grande that flowed through the study area by 3.8 m.y. B.P.
4. Pediment and terrace deposits, inferred to range in age from middle Pleistocene to early Holocene, formed during stable base-level episodes.
5. Cutter surface ranges in age from early to late Pliocene, and the Cuchillo surface is interpreted to be middle Pleistocene.
6. Crossings of the Hot Springs fault by the Rio Grande at Long Point and Rattlesnake Islands resulted from laterally cutting meanders, whereas the Long Ridge crossing is interpreted to be the result of stream piracy.
7. Crossings occurred either during or just after terrace level 2 time.
8. Faulting in the Cutter sag ended before the formation of the Cutter surface.
9. Movement along the Hot Springs fault was episodic and continued until the initial incision of the Rio Grande.
10. Potential exists for the Rio Grande to reestablish its course west of the Hot Springs fault.

References

Aubele, J. C., Crumpler, L. S., Loeber, K. N., and Kudo, A. M., 1976, Maar and tuff rings of New Mexico; *in* Woodward, L. A., and Northrup, S. A. (eds.), Tectonics and mineral resources of southwestern North America: New Mexico Geological Society, Special Publication no. 6, pp. 109-114.

Bachman, G. 0., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America, Bulletin, v. 89, no. 2, pp. 283-292.

Bryan, K., 1938, Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico; *in* Natural Resources Planning Board (U.S.), The Rio Grande joint investigations in the upper Rio Grande Basin: U.S. Government Printing Office, Washington, D.C., v. 1, pt. 2, pp. 197-225.

Bull, W. B., 1972, Recognition of alluvial-fan deposits in the stratigraphic record; *in* Rigby, K., and Hamblin, W. K. (eds.), Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists, Special Publication 16, pp. 63-83.

Bushnell, H. P., 1953, Geology of the McRae Canyon area, Sierra County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 106 pp.

Campbell, C. V., 1976, Reservoir geometry of a fluvial sheet sandstone: American Association of Petroleum Geologists, Bulletin, v. 60, pp. 1009-1020.

Cant, D. J., and Walker, R. G., 1978, Fluvial processes and fades sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, pp. 625-648.

Chapin, C. E., 1979, Evolution of the Rio Grande rift-a summary; *in* Riecker, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 1-5.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas; *in* Seager, W. R., Clemons, R. E., and Callender, J. F. (eds.), Las Cruces country: New Mexico Geological Society, Guidebook to 26th Field Conference, pp. 297-321.

Compton, R. R., 1962, Manual of field geology: John Wiley and Sons, Inc., New York, 378 pp.

Cope, E. D., 1883, On distribution of the Loup Fork formation in New Mexico: American Philosophical Society, Proceedings, v. 21, pp. 308-309.

Cordell, Lindrith, 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America, Bulletin, v. 89, pp. 1073-1090.

Cross, W., 1899, Description of the Telluride quadrangle, Colorado: U.S. Geological Survey, Atlas, folio 57.

Darton, N. E., 1922, Geologic structure of parts of New Mexico: U.S. Geological Survey, Bulletin 726-E, pp. 173-275.

, 1928, "Red beds" and associated formations in New Mexico, with an outline of the geology of the state: U.S. Geological Survey, Bulletin 794, 356 pp. (Published in 1929).

Doyle, J. C., 1951, Geology of the northern Caballo Mountains, Sierra County, New Mexico: Unpublished M.S. thesis, New Mex ico Institute of Mining and Technology, Socorro, 51 pp.

Fenneman, M. N., 1931, Physiography of western United States: McGraw-Hill, New York, 534 pp.

Fitzsimmons, J. P. (ed.), 1955, South-central New Mexico: New Mexico Geological Society, Guidebook to 6th Field Conference, 193 pp.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History, Bulletin, v. 144, pp. 1-127.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico-guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.

Gordon, C. H., 1907, Notes on the Pennsylvanian formations in the Rio Grande Valley, New Mexico: Journal of Geology, v. 15, pp. 805-816.

, 1910, Sierra and central Socorro Counties; *in* Lindgren, W., Graton, L. C., and Gordon, C. H. (eds.), The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, pp. 213-285.

Gordon, C. H., and Graton, L. C., 1907, Lower Paleozoic formations in New Mexico: Journal of Geology, v. 15, pp. 91-92.

Harley, G. T., 1934, The geology and ore deposits of Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 10, 220 pp.

Hawley, J. W., 1965, Geomorphic surfaces along the Rio Grande valley from El Paso, Texas, to Caballo Reservoir, New Mexico; *in* Fitzsimmons, J. P., and Lochman-Balk, C. (eds.), Southwestern New Mexico II: New Mexico Geological Society, Guidebook to 16th Field Conference, pp. 188-198.

, (compiler), 1978, Guidebook to the Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 pp.

Hawley, J. W., Bachman, G. 0., and Manley, K., 1976, Quaternary stratigraphy in the Basin and Range and Great Plains provinces, New Mexico and western Texas; *in* Mahaney, W. C. (ed.), Quaternary stratigraphy of North America: Dowden, Hutchison, and Ross, Inc., Stroudsburg, Pennsylvania, pp. 235-274.

Hawley, J. W., and Kottlowski, F. E., 1969, Quaternary geology of the south-central New Mexico border region; *in* Kottlowski, F. E., and LeMone, D. V. (eds.), Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, pp. 89-104.

Hawley, J. W., Kottlowski, F. E., Seager, W.R., King, W. E., Strain, W. S., and LeMone, D. V., 1969, The Santa Fe Group in the south-central New Mexico border region; *in* Kottlowski, F. E., and LeMone, D. V. (eds.), Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, pp. 52-76.

Hayden, F. V., 1873, First, second, and third annual reports of the U.S. Geological Survey of the territories for years 1867, 1868, 1869 (reprint): U.S. Government Printing Office, Washington, D.C., 261 pp.

Herrick, C. L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, pp. 112-128.

Herrick, C. L., and Bendrat, T. A., 1900, Identification of an Ohio coal measures horizon in New Mexico: American Geologist, v. 25, pp. 234-242.

Hill, J. D., 1956, Paleozoic stratigraphy of the Mud Springs Mountains, Sierra County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 72 pp.

Holmes, W. H., 1877, Geological report on the San Juan district, Colorado: U.S. Geological and Geographical Survey of the Territories, 9th Annual Report, pp. 237-276.

Kelley, V. C., 1956, The Rio Grande depression from Taos to Santa Fe; *in* Rosenzweig, A., and Hayes, P. T. (eds.), Southwestern Sangre de Cristo Mountains: New Mexico Geological Society, Guidebook to 7th Field Conference, pp. 109-114.

Kelley, V. C., and Silver, C., 1952, Geology of the Caballo Mountains, with special reference to regional stratigraphy and structure and to mineral resources, including oil and gas: University of New Mexico, Publications in Geology, no. 4, p. 286.

Keyes, C. R., 1903, Geological sketches of New Mexico: Ores and Metals, v. 12, p. 48.

, 1905, Geological structure of the Jornada del Muerto and adjoining bolson plains: Iowa Academy of Science Proceedings, v. 12, pp. 167-169.

Kottlowski, F. E., 1953, Tertiary-Quaternary sediments of the Rio Grande Valley, in southern New Mexico; *in* Kottlowski, F. E., Callaghan, E., and Jones, W. R. (eds.), Southwestern New Mexico: New Mexico Geological Society, Guidebook to 4th Field Conference, pp. 144-148.

Kottlowski, F. E., Flower, R. H., Thompson, M. L., and Foster, R. W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 1, 132 pp.

Lee, W. T., 1905, The Engle coal field, New Mexico: U.S. Geological Survey, Bulletin 285, p. 240.

, 1907a, Water resources of the Rio Grande valley in New Mexico and their development: U.S. Geological Survey, Water-Supply Paper 188, 59 pp.

,1907b, Notes on red beds of the Rio Grande region in central New Mexico: Journal of Geology, v. 15, pp. 52-58.

Lee, W. T., and Girty, G. H., 1909, The Manzano Group of the Rio Grande valley, New Mexico: U.S. Geological Survey, Bulletin 389, 141 pp.

Loeber, K. N., 1976, Geology and igneous petrology of the Truth or Consequences-Engle area, Sierra County, New Mexico: Unpublished report, University of New Mexico, 119 pp.

Lorenz, V., McBirney, A. R., and Williams, H., 1970, An investigation of volcanic depressions, part III-Maars, tuff-rings, tuff-cones, and diatremes: National Aeronautics and Space Administration, Progress Report NGR-38-003-012, 113 pp.

Lozinsky, R. P., Hunt, A. P., Wolberg, D. L., and Lucas, S. G., 1984, Late Cretaceous (Lancian) dinosaurs from the McRae Formation, Sierra County, New Mexico: New Mexico Geology, v. 6, no. 4, pp. 72-77.

Machette, M. N., 1978, Geological map of the San Acacia quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map 1415, scale 1:24,000.

Mason, J. T., 1976, The geology of the Caballo Peak quadrangle, Sierra County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 131 pp.

Meek, F. B., and Hayden, F. V., 1862, Description of new lower Silurian (primodel), Jurassic, Cretaceous and Tertiary fossils collected in Nebraska territory . . . with some remarks on the rocks from which they were obtained: Academy of Natural Sciences of Philadelphia, Proceedings, v. 13, pp. 419-420.

Melvin, J. W., 1963, Cretaceous stratigraphy in the Jornada del Muerto region, including the geology of the Mescal Creek area, Sierra County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 121 pp.

Ramberg, I. B., 1978, Comparison of the Oslo graben with the Rio Grande rift; *in* Olsen, K. H., and Chapin, C. E. (eds.), International symposium on the Rio Grande rift, programs and abstracts: Los Alamos Scientific Laboratory, Publication LA-7487C, pp. 68-71.

Reading, R. H. (ed.), 1978, Sedimentary environments and facies: Blackwell Scientific Publications, Oxford, 557 pp.

Richardson, G. B., 1904, Report of a reconnaissance in Trans-Pecos Texas, north of the Texas and Pacific Railway: University of Texas Mineralogical Survey, Bulletin 9, 119 pp.

, 1909, Description of the El Paso district: U.S. Geological Survey, Texas Geological Atlas, El Paso Folio, no. 166, 11 pp.

Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1981, Earthquakes in New Mexico, 1849-1977: New Mexico Bureau of Mines and Mineral Resources, Circular 171, 20 pp.

Seager, W. R., 1975, Cenozoic tectonic evolution of the Las Cruces area, New Mexico; *in* Seager, W. R., Clemons, R. E., and Callender, J. F. (eds.), Las Cruces country: New Mexico Geological Society, Guidebook to 26th Field Conference, pp. 241-250.

Seager, W. R., Clemons, R. E., and Hawley, J. W., 1975, Geology of Sierra Alta quadrangle, Dona Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 102, 56 pp.

Seager, W. R., and Hawley, J. W., 1973, Geology of the Rincon quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 101, 42 pp.

Seager, W. R., Hawley, J. W., and Clemons, R. E., 1971, Geology of the San Diego Mountain area, Dona Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 97, 38 pp.

Seager, W. R., and Morgan, P., 1979, Rio Grande rift in southern New Mexico, west Texas and northern Chihuahua; *in* Riecker, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 87-106.

Shumard, G. G., 1858, Observations on the geological formations of the country between the Rio Pecos and the Rio Grande, in New Mexico near the 32nd parallel: St. Louis Academy of Science, Transactions (1857), v. 1, pp. 273-289.

Speigel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, 258 pp.

Strain, W. S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: University of Texas (Austin), Texas Memorial Museum, Bulletin 10, 55 pp.

Tedford, R. H., 1981, Mammalian biochronology of the late Cenozoic basins of New Mexico: Geological Society of America, Bulletin, Part I, v. 92, pp. 1008-1022.

Thompson, S., III, 1955, Geology of the southern part of the Fra Cristobal Range, Sierra County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 67 pp.

, 1961, Geology of the southern part of the Fra Cristobal Range, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, thesis file (revision of Thompson, 1955), 89 pp.

Thornbury, W. D., 1965, Regional geomorphology of the United States: John Wiley and Sons, Inc., New York, 609 pp.

Warren, R. G., 1978, Characterization of the lower crust-upper mantle of the Engle Basin, Rio Grande rift, from a petrochemical and field geologic study of basalts and their inclusions: Unpublished M.S. thesis, University of New Mexico, 156 pp.

Wells, S. G.,and Granzow, H., 1980, Hydrogeology of the thermal aquifers near Truth or Consequences, New Mexico: New Mexico Energy Institute/Department of Energy Subcontract, final report, part II, no. 314-150178-00493-D, 40 pp.

Woodward, L. A., Callender, J. F., Seager, W. R., Gries, J. C., Shaffer, W. L., and Zilinski, R. E., 1978, Tectonic map of the Rio Grande rift region in New Mexico, Chihuahua, and Texas; *in* Hawley, J. W. (compiler), Guidebook to the Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, Sheet 2, scale 1:1,000,000.

Zimmerman, C. J., and Kudo, A. M., 1980, Geological mapping of the Mud Springs Mountains, near Truth or Consequences, New Mexico: New Mexico Energy Institute/Department of Energy Subcontract, final report, part I, no. 314-150178-00493-D, 3 pp.

Appendix I—Measured sections

Section 1—Lower Palomas Formation

This section includes the lower part of the distal subfacies, the proximal subfacies, and the unconformable contact with the underlying Abo Formation. It is located along the north side of Cuchillo Negro Creek in the NW1/4SW1/4 sec. 8, T. 13 S., R. 4 W. The section begins on top of a hill.

Lithology	Thickness ft	m
Conglomerate, matrix white (5YR 8/1 to 7.5YR N8/), intensely calcium carbonate impregnated, especially top 45 cm. Very poorly sorted, rounded to subangular clasts of mostly volcanic clasts and Abo sandstone. Clasts average about 10 cm in size but can be up to 30 cm. Prominent ridge-former. Grades down into noncalcium carbonate impregnated unit.	4.3	1.3
Conglomerate, light gray (5YR 7/1) to light reddish brown (5YR 6/4), poorly indurated, poorly sorted, and thin- to medium-bedded with subangular to subrounded clasts in a silty sand matrix. Clasts are primarily volcanic with minor Abo sandstone and average about 15–20 cm in size. Clasts are slightly imbricated to the southeast. Cliff-former. Grades down into sandy silt unit.	27.2	8.3
Sandy silt, pink (7.5YR 7/4) to light brown (7.5YR 6/4), poorly indurated. Beds poorly expressed. Slope-former. Conformable basal contact.	23.9	7.3
Conglomerate with sandy silt lenses, reddish brown (2.5YR 5/4) to light reddish brown (5YR 6/4). Sandy silt lenses, pinkish white (5YR 8/2). Grades down from a matrix-supported pebbly conglomerate into a clast-supported cobble and boulder conglomerate. Conglomerate is poorly sorted, poorly indurated, and weakly bedded. Clasts are subrounded to subangular and include volcanic clasts and minor Abo sandstone. Clast size averages 20–30 cm. Clasts are slightly imbricated to the southeast. Sandy silt matrix. Sandy silt lenses range from 15–30 cm thick and extend laterally up to 2 m. A 15-cm-thick, medium- to coarse-grained, slightly crossbedded, well cemented (calcium carbonate) sandstone with scattered subrounded to subangular pebbles forms a prominent ledge at the base. Unit is generally a cliff-former. Sharp basal contact.	41.6	12.7
Sandy silt with clay interbeds, light red (2.5YR 6/8) to light reddish brown (5YR 6/4). Clay interbeds, red (2.5YR 5/8) to light brown (7.5YR 6/4). Sandy silt beds are poorly expressed and form badland topography. Clay interbeds range from 15–30 cm thick and form color bands in exposures. Unit is generally poorly indurated and friable. Sharp conformable contact at base.	30.5	9.3
Conglomerate, reddish brown (2.5YR 5/4) to light reddish brown (5YR 6/3). Poorly sorted, lenticular, weakly bedded, clast-supported conglomerate with a sandy silt matrix. Clasts are subangular to subrounded and consist of mostly volcanic clasts and minor Abo sandstone. Unit is moderately indurated and pinches out about 2 m on either side. Cliff-former. Sharp basal contact.	9.2	2.8
Fanglomerate (proximal subfacies intertongue), pinkish gray (5YR 6/2) to light pink (5YR 8/3). Massive, matrix-supported, poorly sorted fanglomerate with a sandy silt matrix. Clasts are angular to subrounded and include mostly limestone and Abo sandstone with minor chert. Clasts average 15–30 cm in size. Unit moderately well-indurated with calcium carbonate cement and is a cliff-former. Unit grades down into sandy silt.	8.5	2.6
Sandy silt, light red (2.5YR 6/6) to pinkish white (7.5YR 8/2). Poorly indurated and weakly bedded with well indurated silt concretions. A 30-cm-thick, pebbly lense occurs about 150 cm from base. Pebbles include angular to subrounded limestone and Abo sandstone. Unit is generally a slope-former. Sharp basal contact.	15.1	4.6
Fanglomerate (proximal subfacies), reddish brown (2.5YR 4/4) to light reddish brown (2.5YR 6/4). Well indurated, poorly sorted, massive, matrix-supported fanglomerate with a sandy silt matrix. Clasts are angular to subrounded and include mostly limestone and Abo sandstone with minor chert. Clasts average 20–30 cm in size, but can be up to 60 cm and are slightly imbricated to the north. Top 60 cm is very well indurated. Prominent ledge-former. Rests with angular unconformity on Abo Formation.	12.1	3.7
Total thickness:	172.4	52.6

Section 2—Upper Palomas Formation

This section includes the Cuchillo surface and the upper part of the distal subfacies. It is located in the SE1/4NW1/4 sec. 5, T. 13 S., R. 4 W. The section begins on the Cuchillo surface.

Lithology	Thickness ft	m
Conglomerate, matrix white (5YR 8/1 to 7.5YR N8/). Plugged, pedogenic, calcium carbonate horizon for top 1 m. Conglomerate is poorly sorted, clast-supported and exhibits faint cross-bedding. Clasts are subangular to rounded and include mostly volcanic clasts with minor quartz clasts and Abo sandstone. Clast size averages 8 cm, but can be up to 30 cm. Sandy silt matrix. Unit is a cliff-former and has sharp conformable basal contact.	6.9	2.1
Sandy silt, reddish brown (5YR 5/4) to brown (7.5YR 5/4). Bedding poorly expressed. Unit poorly indurated and has calcium carbonate coatings on top 30 cm. Slope-former. Conformable contact at base.	4.9	1.5
Alternating beds of conglomerate and sandy silt. Conglomerate matrix, reddish brown (2.5YR 5/4) to light reddish brown (5YR 6/4). Conglomerate beds are poorly sorted, moderately indurated, clast-supported and massive. Clasts are subangular to subrounded and include mostly volcanic clasts with minor quartz clasts and Abo sandstone. Clast size averages 6–10 cm, but can be up to 30 cm, and clasts are slightly imbricated to the southeast. Bed thickness ranges from 30 cm to 2 m. Thinner beds tend to be lenticular,		

Lithology	Thickness ft	m
matrix-supported and contain smaller clasts. Sandy silt beds are reddish brown (5YR 5/4) to light brown (7.5YR 6/4), poorly indurated with poorly expressed bedding. Bed thickness ranges from 1 to 3 m. Contacts between the conglomerate and the sandy silt beds are conformable. About halfway down in the section scattered, 30-cm-thick, red (10R 4/6) clay beds occur. Conglomerate beds tend to be cliff-formers while the sandy silt beds are slope-formers. Grades down into sandy silt.	61.7	18.8
Sandy silt, reddish brown (5YR 5/4) to brown (7.5YR 5/4) with alternating 30-cm-thick, weak red (10 R 4/4) to brown (2.5YR 4/4) clay beds. Sandy silt beds are poorly indurated with poorly expressed beds up to 1 m thick. Lenticular, pinkish white (5YR 8/2) to light brown (5YR 6/4), calcareous zones are possible paleosols. Unit is very erodable and forms badland topography. Section ends where buried by arroyo.	25.9	7.9
Total thickness:	99.4	30.3

Section 3—Terrace deposit and partial Palomas Formation

This section includes the Rio Grande terrace level 2 deposit, axial facies, and some proximal subfacies. It is located in a road cut northeast of Mim's Lake in NW$^1/_4$SE$^1/_4$ sec. 23, T. 13 S., R. 4 W. The section begins on top of the terrace.

Lithology	Thickness ft	m
Fine-grained sand and silt, very pale brown (10YR 8/3) to brownish yellow (10YR 6/6). Weathers to pinkish white (7.5YR 8/2). Loosely consolidated, bedding poorly expressed with fine-grained sand concretions occurring near the base. Unit is a slope-former, pinches out 6 m laterally, and may be eolian in origin. Sand grains have limonite stains. Sharp basal contact.	6.6	2.0
Conglomerate, pale brown (10YR 6/3) to light brown (8YR 6/4). Moderately to poorly sorted, massive to weakly stratified, clast-supported conglomerate with a fine-grained sand to silty matrix. Clasts are subangular to subrounded and include mostly porphyritic volcanic clasts, basalt, Abo sandstone, and quartz with some chert, granite, and schist. Most clasts are coated with limonite. Clast size averages 6–10 cm, but can be up to 30 cm. Unit thickens to 3.4 m south where overlying unit pinches out. A pedogenic horizon caps unit where overlying unit is absent. Rests disconformably on medium- to coarse-grained sand.	6.9	2.1
Medium to coarse-grained sand (axial facies), white (10YR 8/1) to light gray (10YR 7/1). Trough and longitudinal crossbedded, well sorted, loosely consolidated sand with scattered pebbly and coarse-grained sand lenses. Limonite staining occurs within unit and on the subangular to subrounded pebbles. Clasts include quartz, chert, and Mesaverde sandstone. Scattered within unit are dark-reddish-brown (5YR 3/2) to dark-brown (7.5YR 4/2) clay balls up to 10 cm in size. Unit rests with a slight angular unconformity on the fanglomerate. Axial facies pinch out about 30 m south and the conglomerate rests on the proximal subfacies.	11.5	3.5
Fanglomerate (proximal subfacies), light olive-brown (2.5Y 5/4) to light yellowish-brown (2.5Y 6/4). Poorly sorted, lenticular to weakly stratified, moderately indurated (with calcium carbonate cement) fanglomerate with a sandy matrix. Clasts are angular to subangular and include Mesaverde sandstone and McRae Formation conglomerates. Clast size averages about 15–20 cm, but can be up to 30 cm. Section ends at road level, but unit continues to an undetermined depth.	7.9	2.4
Total thickness:	32.9	10.0

Section 4—Terrace deposit and Palomas Formation

This section includes Rio Grande terrace level 4 deposit and some proximal subfacies. Section located in roadcut along NM–51 in the SW$^1/_4$NW$^1/_4$ sec. 35, T. 13 S., R. 4 W. The section begins on top of the terrace.

Lithology	Thickness ft	m
Fine-grained sand, very pale brown (10YR 8/4 to brownish yellow (10YR 6/6). Very loosely consolidated and lacks stratification. Thickens westward. Scattered, subrounded to subangular clasts with calcium carbonate coatings occur throughout unit. Clasts are similar to conglomerate below. Perhaps overbank deposit. Unit rests conformably on conglomerate.	2.3	0.7
Conglomerate, light brownish gray (10YR 6/2) to light yellowish brown (10YR 6/4). Poorly sorted, poorly stratified, matrix supported, moderately indurated conglomerate with a silty sand matrix. Clasts are subrounded to subangular and include porphyritic volcanic clasts, basalt, Abo and Mesaverde sandstone, granite, quartz, and chert. Clast size averages 6–10 cm, but can be up to 30 cm. Unit generally fines upward into primarily pebbles with larger clasts restricted to the basal 1 m. Scattered, fine-grained sand and silt lenses occur throughout unit. Rests with angular unconformity on fanglomerate.	11.8	3.6
Fanglomerate (proximal subfacies), pale brown (10YR 6/3) to light yellowish brown (10YR 6/4), weathers to very pale brown (10YR 7/3). Poorly sorted, lenticular to weakly stratified, well indurated (with calcium carbonate cement), matrix-supported fanglomerate with a sandy matrix. Clasts are angular to subrounded and include Abo and Mesaverde sandstone and San Andres and Magdalena limestone. Clast size averages about 8 cm, but can be up to 30 cm. Larger clasts generally occur in lenses. Section ends at road level but unit continues to an undetermined depth.	10.8	3.3
Total thickness:	24.9	7.6

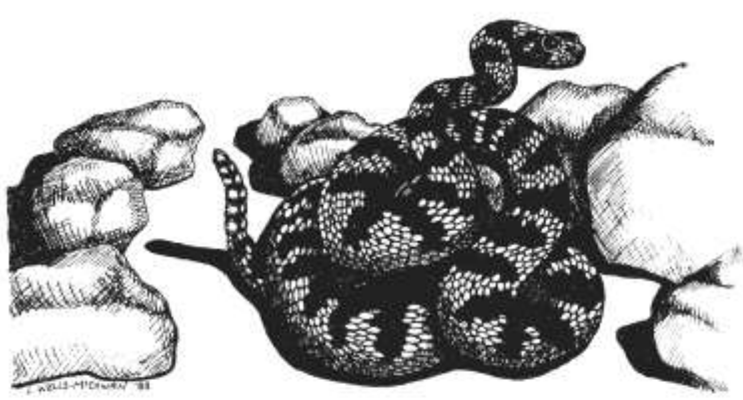
Appendix II—Linear regression programs

Pediment levels and Cuchillo surface program

Step	Procedure	Press
1	Select program	[2nd] [Pgm] 12
2	Initialize	[2nd] [E′]
3	Repartition if desired	[2nd] [Op] 17
4	Choose curve:	
	exponential,	[2nd] [A′]
	power,	[2nd] [B′]
	logarithmic	[2nd] [C′]
5a	Enter x_i^2	[A]
5b	Enter y_i^2	[B]
	Repeat step 5 for each data pair	
6a	Calculate y-intercept and slope of line fitted to data points	[C]
6b	Display slope	[x ≷ t]
7	Calculate y′ given x	[D]
8	Calculate x′ given y	[E]
9	Calculate correlation coefficient	[2nd] Op 13

Terrace levels program

Step	Procedure	Press
1	Select program	[2nd] [Pgm] 01
2	Initialize	[SBR] [CLR]
3		[RST]
4a	Enter X_i	[x ≷ t]
4b	Enter Y_i	[2nd] [Σt]
	Repeat step 4 for each data pair	
5		[2nd] [Op] 14
6	Calculate y-intercept and slope of line fitted to data points	[2nd] [Op] 12
7	Display slope	[x ≷ t]
8	Calculate correlation coefficient	[2nd] [Op] 13



Drawing of one of the snakes that live on Rattlesnake Island.

Appendix III—Paleocurrent readings

The following are rose diagrams and associated data tables for paleocurrent measurements on imbricated clasts that were based on 50 measurements per lo cality. the counting localities (f) are shown on Sheet 1 (in pocket). The direction on the Azimuth scale is in degrees.

A) Proximal subfacies derived from Caballo Mountains located in the NW1/4NE1/4 sec. 27, T. 13 S., R. 4 W.

Count number	Flow direction	Count number	Flow direction	Count number	Flow direction
1	311	18	169	35	329
2	322	19	317	36	78
3	245	20	294	37	239
4	314	21	306	38	231
5	334	22	351	39	68
6	331	23	346	40	264
7	327	24	56	41	79
8	94	25	327	42	56
9	346	26	348	43	100
10	206	27	234	44	260
11	355	28	18	45	299
12	351	29	252	46	258
13	341	30	224	47	279
14	312	31	248	48	263
15	321	32	224	49	247
16	317	33	326	50	56
17	344	34	201		

B) Proximal subfacies derived from Mud Springs Mountains located in the NE1/4SW1/4 sec. 17, T. 13 S., R. 4 W.

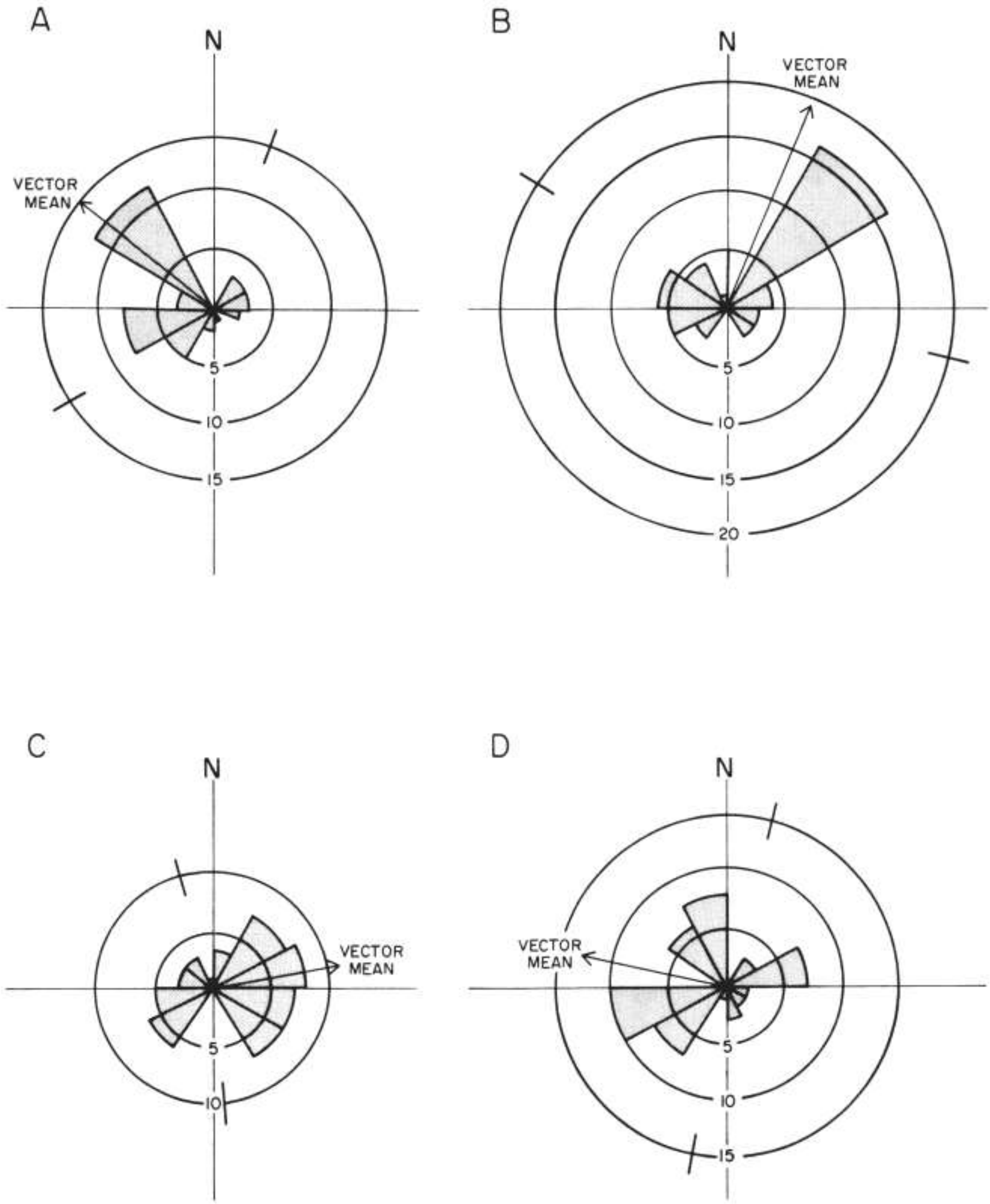
Count number	Flow direction	Count number	Flow direction	Count number	Flow direction
1	290	18	59	35	289
2	255	19	132	36	260
3	59	20	37	37	291
4	25	21	49	38	77
5	247	22	29	39	51
6	86	23	303	40	137
7	18	24	105	41	69
8	287	25	29	42	217
9	122	26	218	43	95
10	47	27	46	44	217
11	6	28	57	45	43
12	249	29	39	46	36
13	39	30	297	47	38
14	104	31	54	48	304
15	341	32	321	49	49
16	73	33	312	50	288
17	33	34	252		

C) Distal subfacies located in the NW1/4SW1/4 sec. 8, T. 13 S., R. 4 W.

Count number	Flow direction	Count number	Flow direction	Count number	Flow direction
1	127	18	334	35	26
2	146	19	43	36	54
3	75	20	104	37	105
4	106	21	39	38	39
5	250	22	122	39	131
6	63	23	26	40	224
7	292	24	227	41	267
8	34	25	106	42	234
9	104	26	286	43	106
10	301	27	59	44	66
11	217	28	72	45	254
12	131	29	63	46	237
13	74	30	317	47	301
14	76	31	247	48	52
15	121	32	83	49	26
16	217	33	255	50	98
17	288	34	121		

D) Cuchillo Negro terrace level 2 deposits located in the NW1/4SE1/4 sec. 23, T. 13 S., R. 4 W.

Count number	Flow direction	Count number	Flow direction	Count number	Flow direction
1	307	18	85	35	331
2	106	19	75	36	338
3	53	20	63	37	327
4	285	21	233	38	233
5	233	22	252	39	265
6	32	23	236	40	260
7	73	24	231	41	315
8	87	25	332	42	246
9	161	26	305	43	311
10	122	27	196	44	249
11	86	28	308	45	337
12	229	29	165	46	244
13	36	30	175	47	252
14	234	31	346	48	334
15	69	32	148	49	253
16	93	33	341	50	244
17	260	34	339		


A
N
VECTOR MEAN
5
10
15
B
N
VECTOR MEAN
5
10
15
20
C
N
VECTOR MEAN
5
10
D
N
VECTOR MEAN
5
10
15

Appendix IV—Clast count data

These data are based on 50 counts per locality and they are presented as percentages.

	Mud Springs deposit 2	Mud Springs Deposit 3	Rio Grande terrace 3	Rio Grande terrace 4	Cuchillo Negro terrace 2	Cuchillo Negro terrace 3	Cuchillo Negro terrace 4	Cuchillo Negro terrace 5	Cuchillo Negro within area	Cuchillo Negro near Chloride	Cuchillo Negro near Cuchillo
Clast roundness											
Round	—	—	26	22	12	14	12	18	14	8	8
Subround	12	8	62	64	48	50	58	52	58	34	64
Subangular	40	38	12	10	38	36	24	30	24	40	28
Angular	48	54	—	4	2	—	6	—	4	18	—
Clast type											
Basalt	—	—	6	12	6	8	12	14	6	4	4
Porphyritic volcanic	6	2	32	30	32	18	38	20	30	26	60
Rhyolite	2	2	26	14	46	64	40	54	54	38	26
Quartz	—	—	14	10	4	2	2	—	2	—	2
Granite	—	—	8	8	—	—	—	—	—	—	—
Metamorphic	—	—	2	4	—	—	—	—	—	—	—
Limestone	82	62	2	—	—	4	—	6	—	4	—
Abo Sandstone	—	2	2	4	10	2	2	4	6	28	6
Mesaverde and McRae	—	—	6	14	—	—	—	—	—	—	—
Chert	10	32	2	4	2	2	6	2	2	—	—

Appendix V—Cuchillo Negro gradient data

The gradients were calculated using the program in Appendix II.

Present level		Terrace level 5	
Distance	Height (ft)	Distance	Height (ft)
0	4540	2800	4520
2000	4520	5000	4500
4100	4500	7600	4480
5200	4480	9600	4460
7400	4460	15,400	4420
9200	4440	Calculated gradient: .008	
11,200	4420		
13,600	4400		
15,400	4380		
17,600	4360		
Calculated gradient: .010			

Terrace level 4		Terrace level 3	
Distance	Height (ft)	Distance	Height (ft)
0	4600	0	4620
3200	4550	1300	4620
5100	4540	2900	4580
6500	4530	4200	4570
9400	4480	5600	4560
Calculated gradient: .012		8100	4540
		9900	4520
		10,800	4500
		12,600	4480
		14,300	4440
		14,900	4440
		16,300	4440
		Calculated gradient: .012	

Appendix VI—Cuchillo surface projection data

Data from topographic quadrangles from airport to Long Ridge

Distance (X) from point northwest of airport (ft)	Height (Y) (elevation; ft)
0	5040
2240	5020
3740	5000
7380	4980
8840	4960
10,240	4940
13,160	4920
15,440	4900
17,860	4880
20,660	4860
23,060	4840
25,300	4820
27,500	4800
29,600	4780

Using the data to the left in the program for exponential curve fitting (found in Appendix II), the following formula was calculated for the best curve estimate:

$$Y = 5037.5\, e^{(-.000001767)X}$$

where Y = height and X = distance
regression coefficient (r) = .9990

Using the above formula, projected heights can be determined by entering known distances (X).

Projected heights:

End of piedmont facies .... 4678 ft
Midway between piedmont facies and Hot Springs fault .... 4611 ft
Near Hot Springs fault .... 4567 ft

Appendix VII—Fault and fold data

Fault data on major faults

(See Figure 12 for locations)

Fault	Stratigraphic separation (m)	Dip	Drag	Slickensides	Remarks
1	900–2400	65°–80° W	Appears norm	Shear zone	Splays in south. Fault plane silicified along Caballo Mtns. Shows right lateral component in south.
2	<120	78° SE	Norm	70° NE	Dike partly follows trace. Dike may be slightly offset.
3	<120	Almost vertical	None seen	None seen	Very steep (80–90°). May have left lateral component. Merges with fault no. 4.
4	<120	78° NE	None seen	None seen	May have up to 3 km right lateral movement. Offsets syncline. May merge with Hot Springs fault to south.
5	<120	?	None seen	None seen	Inferred fault. Separates Kmj and Kmh. Change in dips across zone.
6	75–100?	?	None seen	None seen	Inferred fault. Perhaps buried in slope debris.
7	≈180	50°–70° NW	Norm	None seen	Fault forms escarpment with Kma. Fault difficult to locate.
8	<60	78° SE	Norm	None seen	Poorly exposed.
9	<120	40°–76° W	Norm	Vertical	Fairly well exposed. May continue under basalt and connect with fault no. 10.
10	<200	50°–70° W	Norm	Vertical	Forms prominent scarp. Suddenly untraceable to south.
11	<120	76° NW	Norm	75° SW	Fairly well exposed. Loose under Qes.
12	<6	Steep	None seen	Vertical to horizontal	Cluster of small faults that offset Kmh–Kmj contact.
13	75–120	60°–70° NW	Norm	80° NE	Cut by dike. Untraceable south of McRae Creek.
14	<120	40°–60° SE	Norm	70° NE	Cut by dikes. Localized travertine occurs along trace.
15	<120	50°–80° W	Both norm & reversed	Appear vertical	Numerous tectonic slices caught in fault plane.
16	<120	Steeply to east	None seen	None seen	Loose trace under basalt
17	<75	50°–70° E	None seen	Vertical	Poorly exposed.
18	<75	67° W	None seen	Vertical	Poorly exposed. May connect with fault no. 22.
19	<120	To west	None seen	None seen	Poorly exposed. May connect with fault no. 20.
20	<120	To west	None seen	None seen	Fault plane not seen. Trace seen on air photos.
21	<120	To east	None seen	None seen	Fault plane not seen. Spring where crosses Jose Creek.
22	<120	To east	None seen	None seen	Fault plane not seen. Trace seen on air photos.
23	<50	To north	None seen	None seen	
24	<120	Steeply to east	None seen	None seen	May continue south and somehow connect with fault no. 25.

Fault	Stratigraphic separation (m)	Dip	Drag	Slickensides	Remarks
25	<120	Steeply to north	None seen	None seen	
26	<30	Steeply to north	None seen	None seen	Faults in this area difficult to recognize and trace.
27	<30	65° N	None seen	None seen	
28	<75	To southwest	None seen	None seen	
29	45?	To southwest	None seen	None seen	Poorly exposed. Seen on air photos.
30	<3	60°–70° NE	None seen	None seen	Small reverse fault offsets Palomas and Magdalena strata

Fold data on major folds
(*See* Figure 12 for locations)

A = anticline; **S** = syncline

Fold	Type	Dip of limbs	Plunge	Remarks
a	A	22° 19°	SW	Unique fold with a very broad crest.
b	S	12° 7°	—	Broad syncline occurring in Mesaverde.
c	S	15° 22°	S	West limb of syncline faulted to the northeast between faults 3 and 4.
d	A	6° 8°	NE	Apex lies in graben between two faults.
e	A	12° 60°	NW	Axial trace inferred.
f	S	4° 12°	NW	Axial trace inferred.
g	A	18° 7°	NW	Axial trace inferred.
h	S	14° 18°	NW	Inferred to plunge based on outcrop pattern of Jose Creek Member.
i	S	9° 21°	NW	Axial trace inferred.

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

Editors: Jiri Zidek and Deborah Shaw
Drafter: Teresa A. Mueller

Type face: Palatino

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Saddlestitched with softbound cover

Paper: Cover on 12-pt. Kivar
Text on 70-lb white matte

Ink: Cover—PMS 320
Text—Black

Quantity: 900

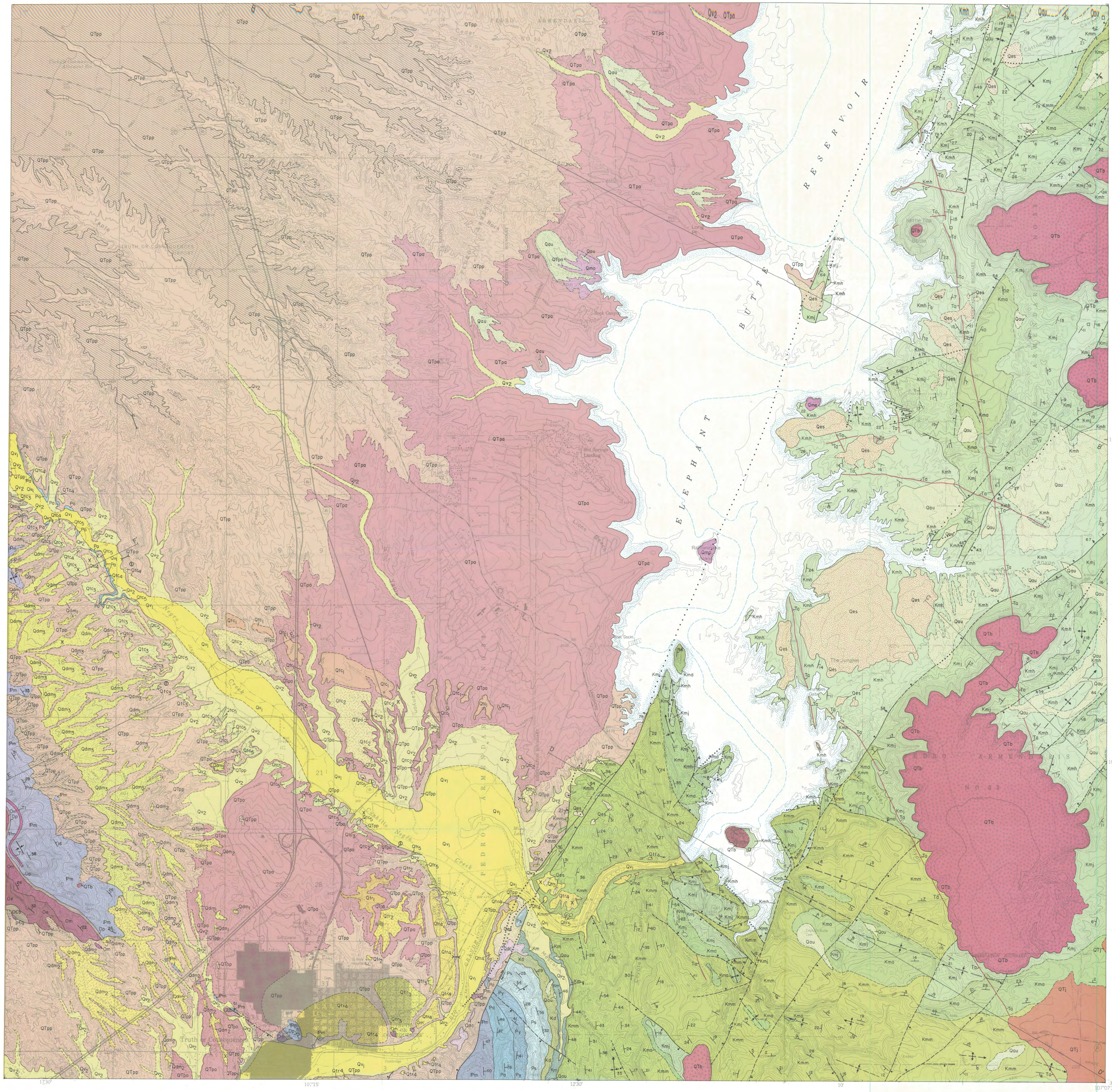
Contents of pocket

SHEET 1—Geology of the Elephant Butte area, Sierra County, New Mexico

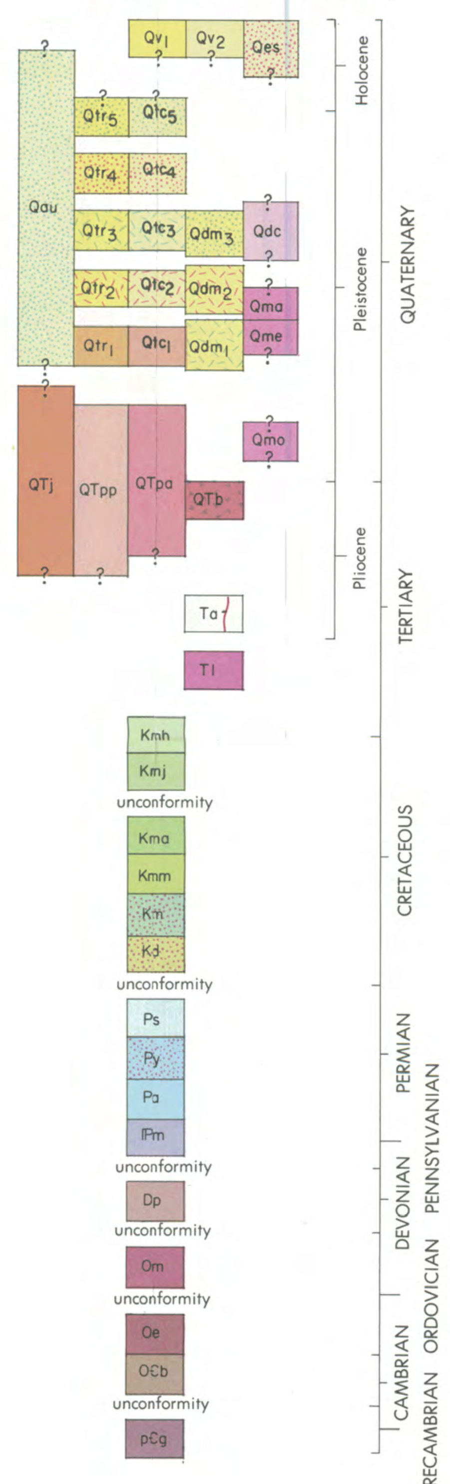
SHEET 2—Cross sections and evolutionary stages of the Elephant Butte area, Sierra County, New Mexico

Elephant Butte during the 1920's showing construction buildings and railway station at the dam site. Photo courtesy of Anne Olsen, New Mexico Bureau of Mines and Mineral Resources collection.

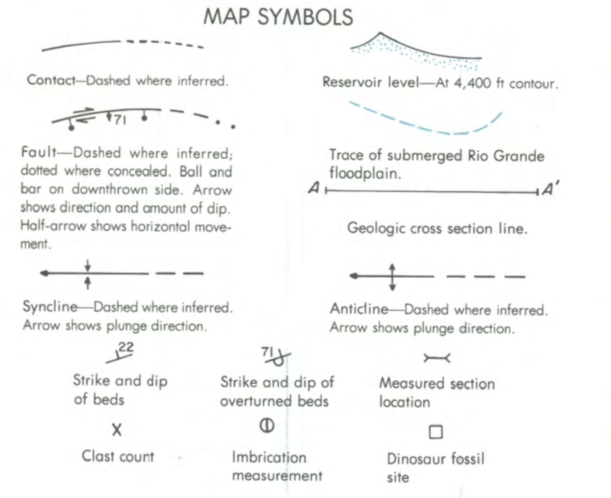
NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES
A DIVISION OF NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

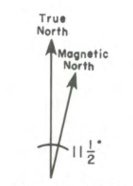


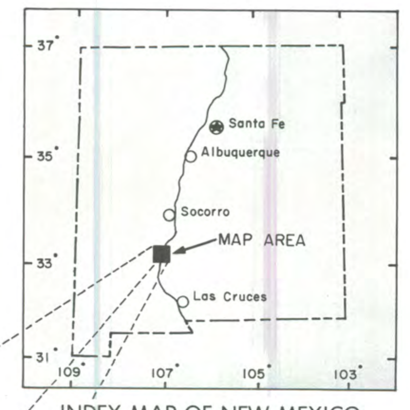
CORRELATION OF ROCK UNITS



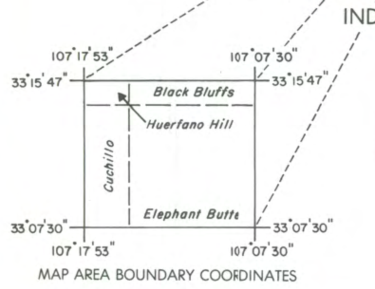
MAP SYMBOLS







INDEX MAP OF NEW MEXICO



MAP AREA BOUNDARY COORDINATES

Geology by Richard P. Lozinsky, 1982
Base by U.S. Geological Survey
Geology and color separations prepared by Michael W. Wooldridge, Cindie A Salisbury, Teresa A. Mueller, and Irean L. Rae

DESCRIPTION OF ROCK UNITS

Qv1, Qv2 — **Valley-fill alluvium**—Divided into two deposits:
Floodplain deposits of Rio Grande and Cuchillo Negro Creek (Qv_1)—Unconsolidated, moderately sorted, fine- to coarse-grained sand with gravel lenses in active channels and mainly silt and clay in floodplains. Gravel consists of angular to rounded quartz, sandstone, and a variety of porphyritic volcanic clasts. Up to 30 m thick.
Tributary deposits of ephemeral nature that grade to Rio Grande and Cuchillo Negro Creek (Qv_2)—Poorly sorted mixture of unconsolidated clay, silt, and fine- to medium-grained sand with gravel lenses. Gravel consists of angular to rounded quartz, chert, sandstone, and a variety of porphyritic volcanic clasts. Estimated to be up to 30 m thick.

Qes — **Eolian sand sheets**—Loosely consolidated white to tan, well sorted fine-grained sand and some silt. Mainly a sheet deposit with some coppice dunes. Generally less than 4 m thick.

Qau — **Alluvium undifferentiated**—Alluvial-fan, pediment, and valley-fill deposits in Cutter sag and reworked piedmont-facies sediment of the Palomas Formation along the western shore of the reservoir. Minimum thickness about 1 m.

Qtr5, Qtr4, Qtr3, Qtr2, Qtr1 — **Terrace deposits of Rio Grande**—Loosely consolidated, poorly to moderately sorted, weakly to moderately stratified sand and gravel with silt lenses. Gravel clasts (sometimes up to 30 cm in diameter) include subrounded to rounded volcanic clasts, quartz, granite, sandstone, and metamorphic clasts. Locally capped by a pedogenic calcium-carbonate horizon. Terraces occur at five levels above the present base level, with one (1) denoting the oldest. Generally less than 6 m thick at each level.

Qtc5, Qtc4, Qtc3, Qtc2, Qtc1 — **Terrace deposits of Cuchillo Negro Creek**—Loosely consolidated, poorly to moderately sorted, weakly to moderately stratified sand and gravel with silt lenses. Gravel clasts (sometimes up to 30 cm in diameter) are angular to rounded and consist of volcanic clasts, sandstone, quartz, chert, and minor amounts of limestone. Locally capped by a pedogenic calcium-carbonate horizon. Terraces occur at five levels above the present base level, with one (1) denoting the oldest. Generally less than 6 m thick at each level.

Qdm3, Qdm2, Qdm1 — **Mud Springs pediment deposits**—Mainly poorly sorted, angular to subangular limestone and chert with minor amounts of subrounded volcanic clasts. Capped by pedogenic calcium-carbonate horizon. Unit thickens into weakly bedded fanglomerate. Deposits occur at three levels above the present base level, with one (1) denoting the oldest. Generally less than 1 m thick at each level, but can be up to 9 m thick.

Qdc — **Caballo pediment deposits**—Pale-red to light-brown, poorly sorted, silt, sand, and fanglomerate of reworked San Andres, Yeso, Abo, and Magdalena detritus. Clasts are angular to subangular. Estimated thickness less than 6 m.

Qma, Qme, Qmo — **Maar deposits**—Scoriaceous basalt and thin-bedded ash and lapilli breccia. Breccia contains fragments of basalt and pumice with scattered pieces of Palomas and McRae detritus. Qma – Rattlesnake maar; Qme – Reservoir maar; Qmo – Rock Canyon maar. Thickness unknown.

QTb — **Basalt flows**—Dark-gray to black, scoriaceous porphyritic basalt containing olivine and plagioclase phenocrysts. Mostly aa flow with minor pahoehoe. Locally may include up to three flow units. Ranges from 3 m to 23 m in thickness.

QTj — **Jornada deposits**—Loosely consolidated, poorly sorted, pale-red to buff silt and sand with pebble and cobble interbeds. Clasts are angular to rounded and include sandstone, quartzite, granite, limestone, and a variety of volcanic lithologies. In places capped by a pedogenic calcium-carbonate horizon. Generally less than 6 m thick.

QTpa, QTpp — **Palomas Formation**—Upper Santa Fe Group basin fill divided into two major facies:
Axial facies (QTpa)—Moderately to well sorted, cemented and uncemented, fine- to coarse-grained, crossbedded, light-gray to buff sand containing lenses of subrounded to rounded quartz, chert, granite, and volcanic clasts. Minor red and green clay interbeds also occur. Intertongues with and overlies QTpp. Estimated to be 30 m thick.
Piedmont facies (QTpp)—Includes two subfacies:
1) Proximal subfacies containing light- to reddish-brown, well indurated, poorly sorted, weakly bedded fanglomerates with clasts derived from local uplifts; and 2) distal subfacies composed of alternating beds of light-pink to dark-reddish-brown sandy silt, conglomerate, and clay. Beds are moderately to poorly indurated and poorly sorted. Clasts (up to 30 cm in diameter) include quartz, sandstone, chert, and a variety of volcanic lithologies. Intertongues with and overlies the proximal subfacies. May be up to 180 m thick. Diagonally ruled area is the constructional Cuchillo surface, which represents the highest level of aggradation of the Palomas Formation.

Ta — **Andesite dikes**—Gray, fine- to medium-grained, porphyritic andesite containing plagioclase phenocrysts. Weathers brown or dark gray. Up to 8 m thick.

Tl — **Latite sill**—Light-gray to buff porphyritic latite containing hornblende, augite, and minor quartz phenocrysts. Weathers to yellowish brown. Ranges from 15 to 18 m in thickness.

Kmh, Kmj — **McRae Formation**—divided into two members:
Upper Hall Lake Member (Kmh)—Mostly maroon to brown shales interbedded with purple to green, medium-grained sandstone and minor conglomerate. Dinosaur bones occur near base. Estimated to be 884 m thick.
Lower Jose Creek Member (Kmj)—Mainly dark-brown to olive-green, medium- to coarse-grained sandstone interbedded with conglomerates composed of porphyritic volcanic clasts and minor thin-bedded, olive-green to purple shales. Also includes a breccia conglomerate consisting of cobble- to boulder-size clasts, ranging compositionally from basalt to latite, surrounded by a matrix of crystal and lithic fragments. Petrified wood is common. 120 m thick.

Kma, Kmm — **Mesaverde Formation**—Divided into two members:
Ash Canyon Member (Kma)—Medium- to coarse-grained, buff to brown sandstone and pebbly conglomerate. Pebbles are subrounded and include chert and quartz. Petrified wood is common. 34 m thick.
Main body (Kmm)—Mostly buff to brown, fine- to medium-grained, lenticular sandstone alternating with olive-green to brown siltstone, shale, and mudstone. 975 m thick.

Km — **Mancos Shale**—Upper half contains black, calcareous shale with minor limestone and siltstone interbeds. Lower half composed of dark-gray, thin-bedded, fetid limestone. 81 m thick.

Kd — **Dakota Sandstone**—Mostly medium-bedded, white to buff, medium- to coarse-grained sandstone with minor gray-shale interbeds and pebbly conglomerate lenses. Ranges from 24 m to 75 m in thickness.

Ps — **San Andres Formation**—Thin- to medium-bedded, gray limestone with minor thin-bedded, dark-gray shale and lenticular sandstone. Chert nodules and lenses are rare. 232 m thick.

Py — **Yeso Formation**—Mostly orange to pale-red, thin- to medium-bedded sandstone with greenish-gray mudstone, siltstone, and limestone interbeds. Upper section contains thin-bedded gypsum. Estimated to be 180 m thick.

Pa — **Abo Formation**—Mostly thin- to medium-bedded, dark-red shale and siltstone with scattered thin limestone and sandstone interbeds. 171 m thick.

IPm — **Magdalena Group**—Upper two-thirds contain thin- to massive-bedded, gray limestone. Lower third consists of thin- to medium-bedded, gray limestone with dark-gray shale and coarse-grained sandstone interbeds. Light- and dark-brown chert lenses and nodules occur throughout. 244 m thick in Caballo Mountains and 495 m thick in Mud Springs Mountains.

Dp — **Percha Shale**—Olive-green to grayish-brown shale with thin, gray limestone and siltstone interbeds. 30 m thick.

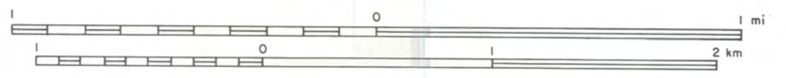
Om — **Montoya Group**—Dark-brown, medium- to coarse-grained basal sandstone overlain by thin- to massive-bedded, gray dolomite with scattered brown chert nodules and lenses. 110 m thick.

Oe — **El Paso Group**—Upper half consists of medium-bedded, gray limestone with brown chert lenses and nodules. Lower half composed of interbedded gray limestone and tan chert. 140 m thick.

O€b — **Bliss Formation**—Thin-bedded, medium- to coarse-grained, dark-brown hematitic sandstone with minor siltstone, limestone, and oolitic hematite interbeds. 44 m thick.

p€g — **Granite**—Coarse-grained, pink orthoclase-rich granite.

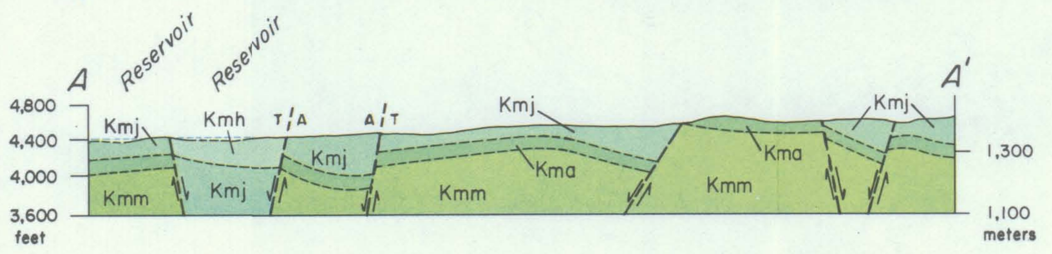
scale 1:25,000

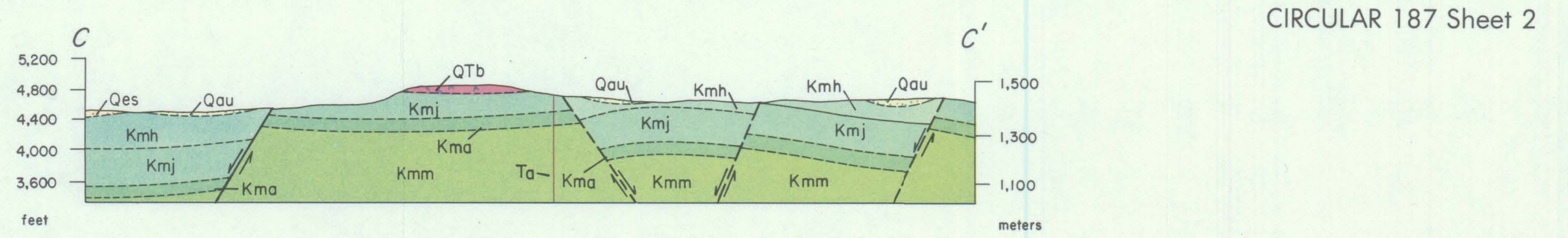


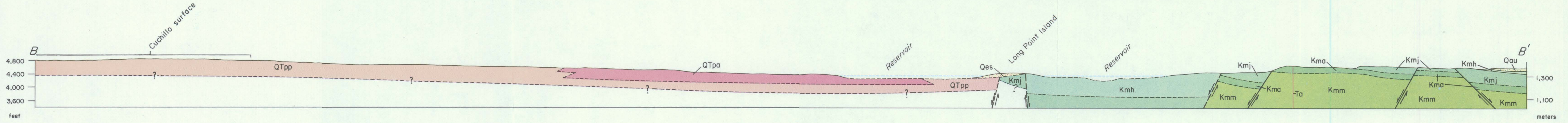
contour interval 20 feet
datum is mean sea level

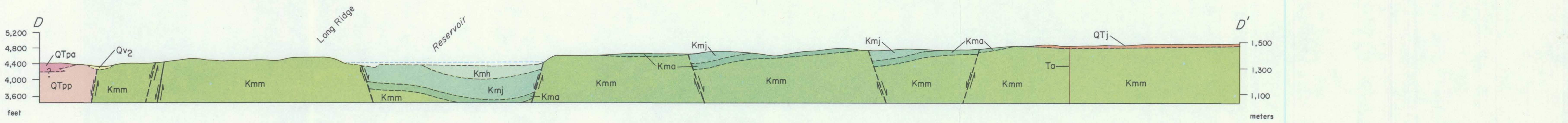
Geology of the Elephant Butte area, Sierra County, New Mexico

by Richard P. Lozinsky, 1986

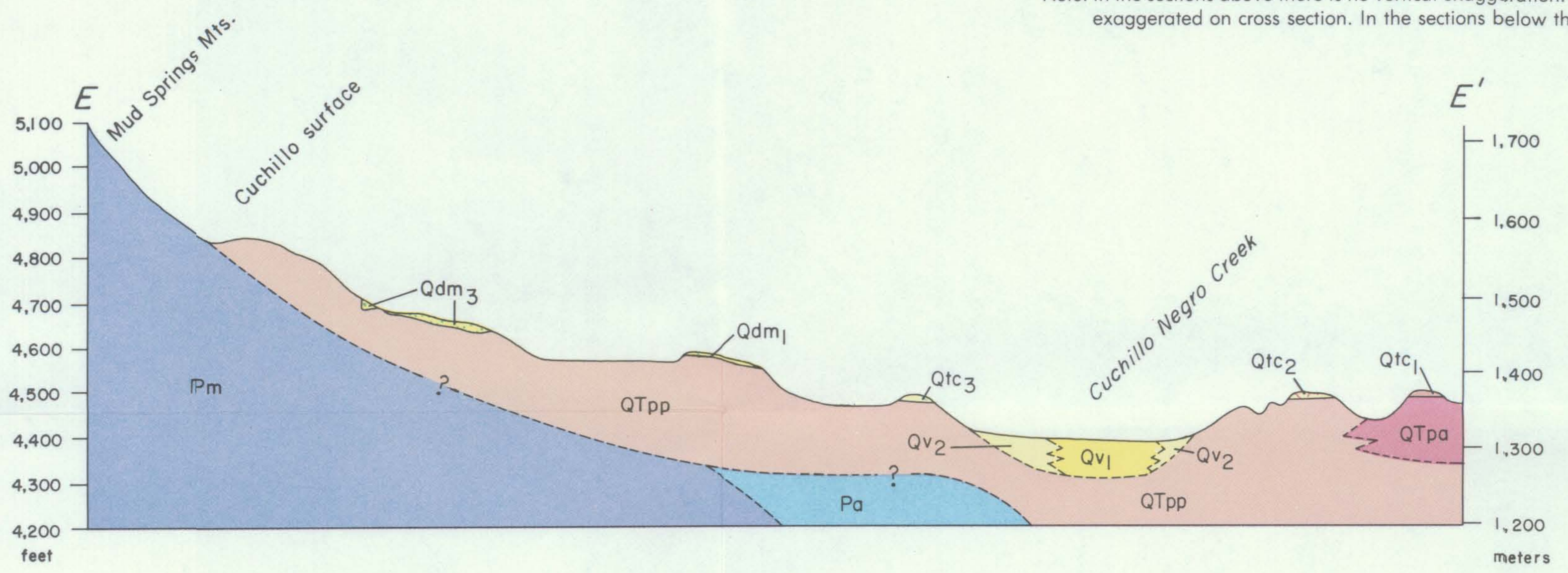


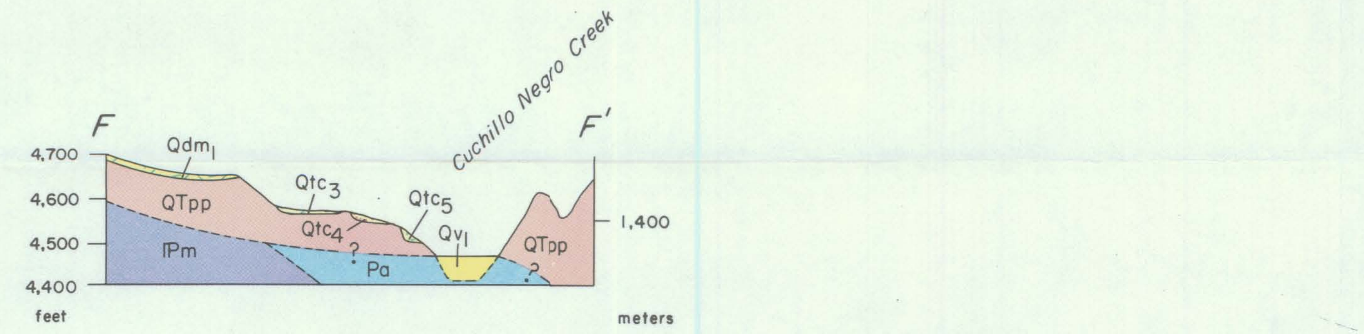


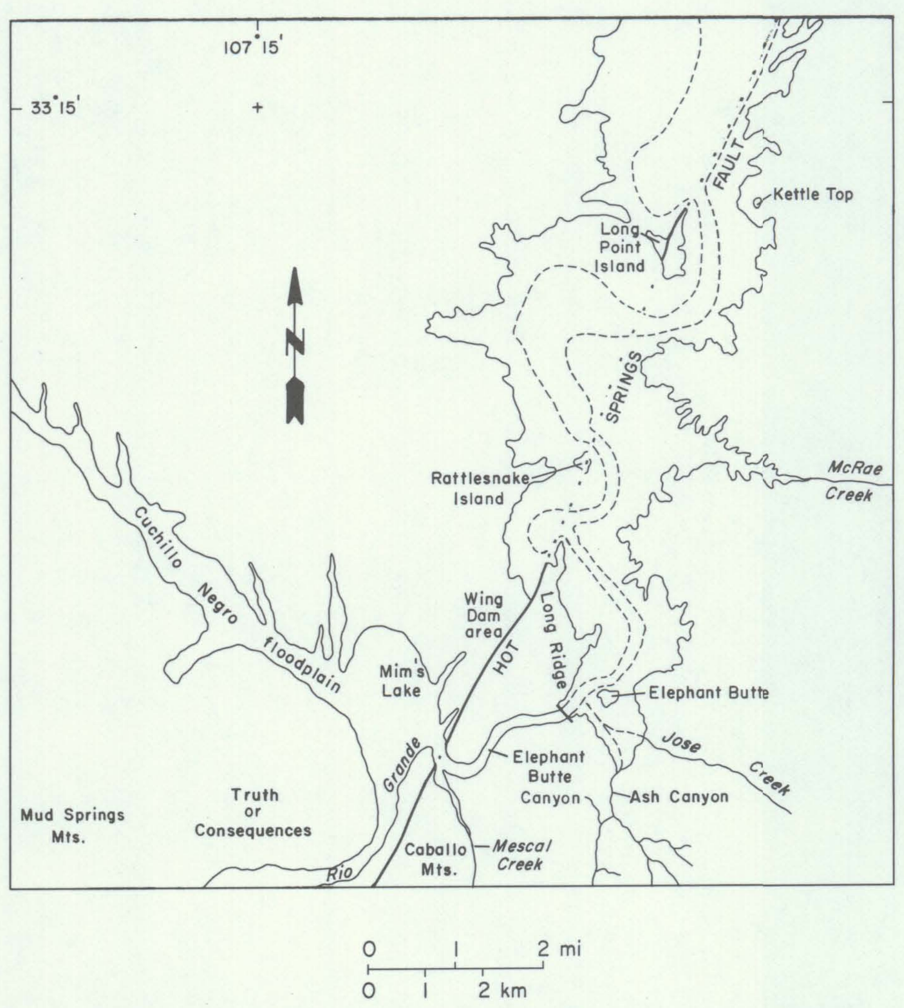




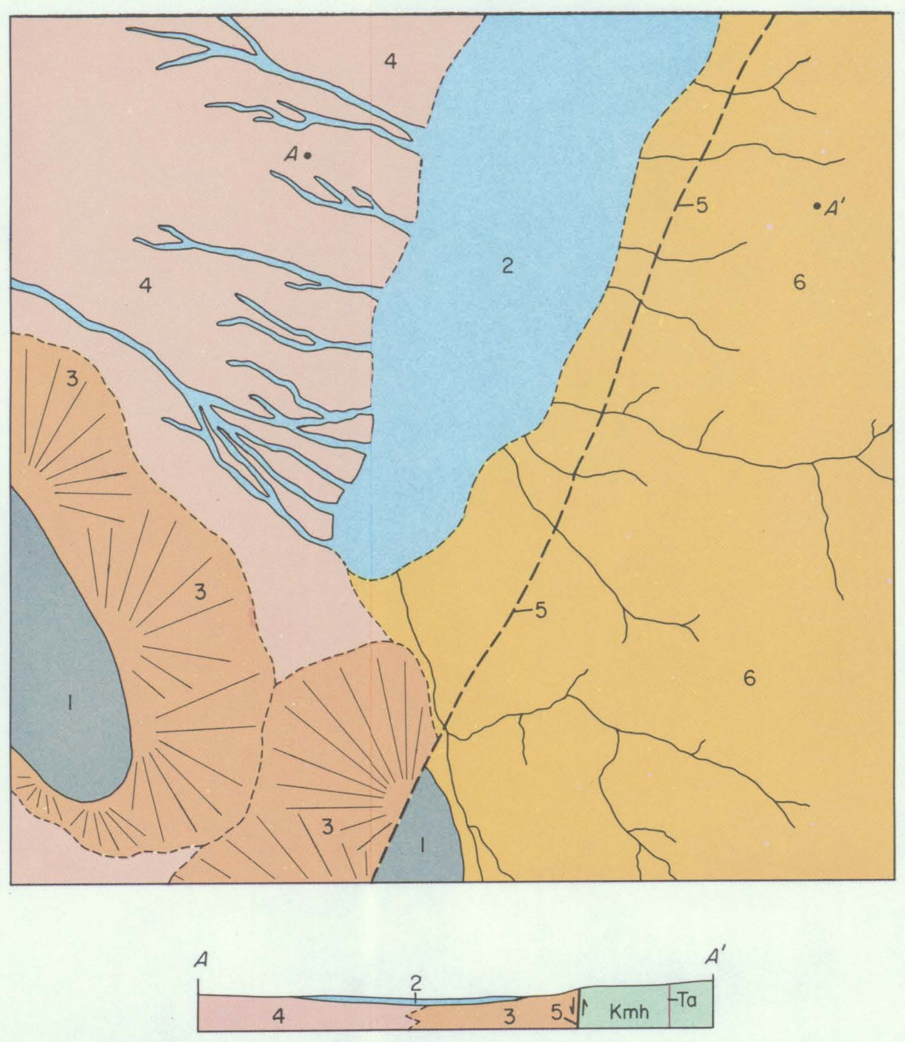
Note: In the sections above there is no vertical exaggeration. The thickness of surficial deposits is exaggerated on cross section. In the sections below the vertical exaggeration is 5X.



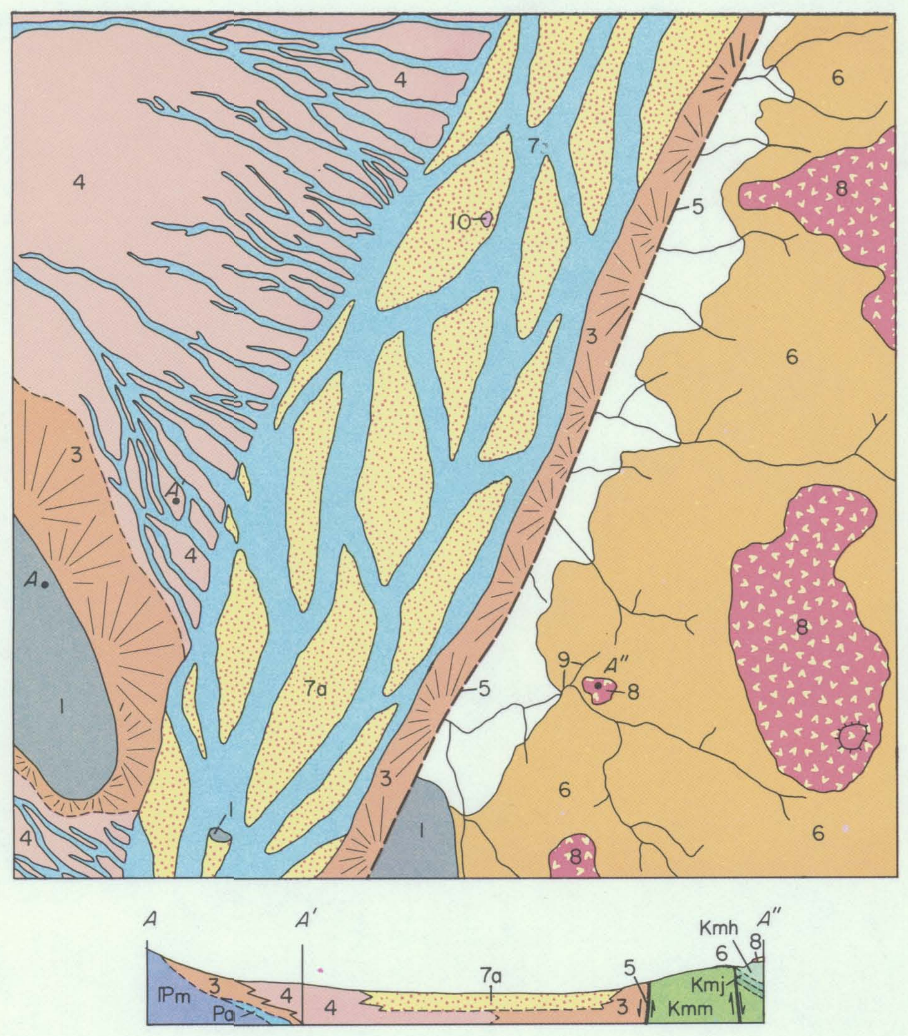




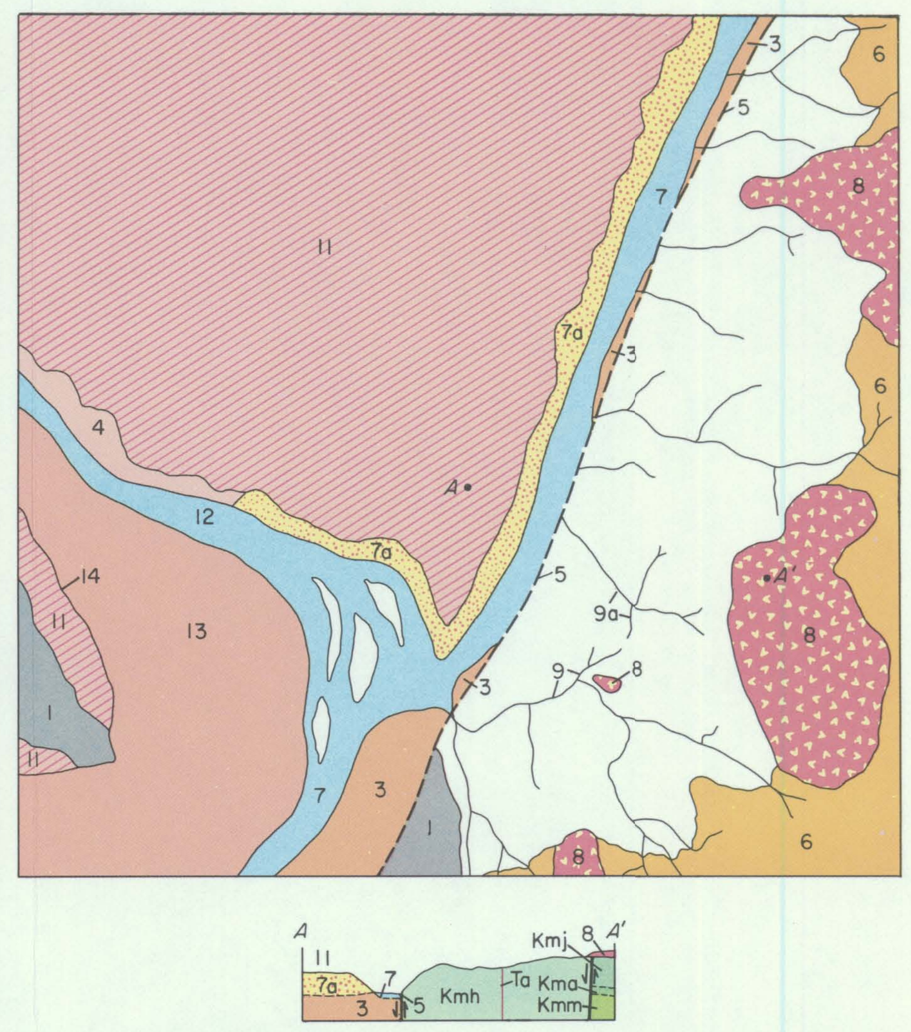
Index map for stages



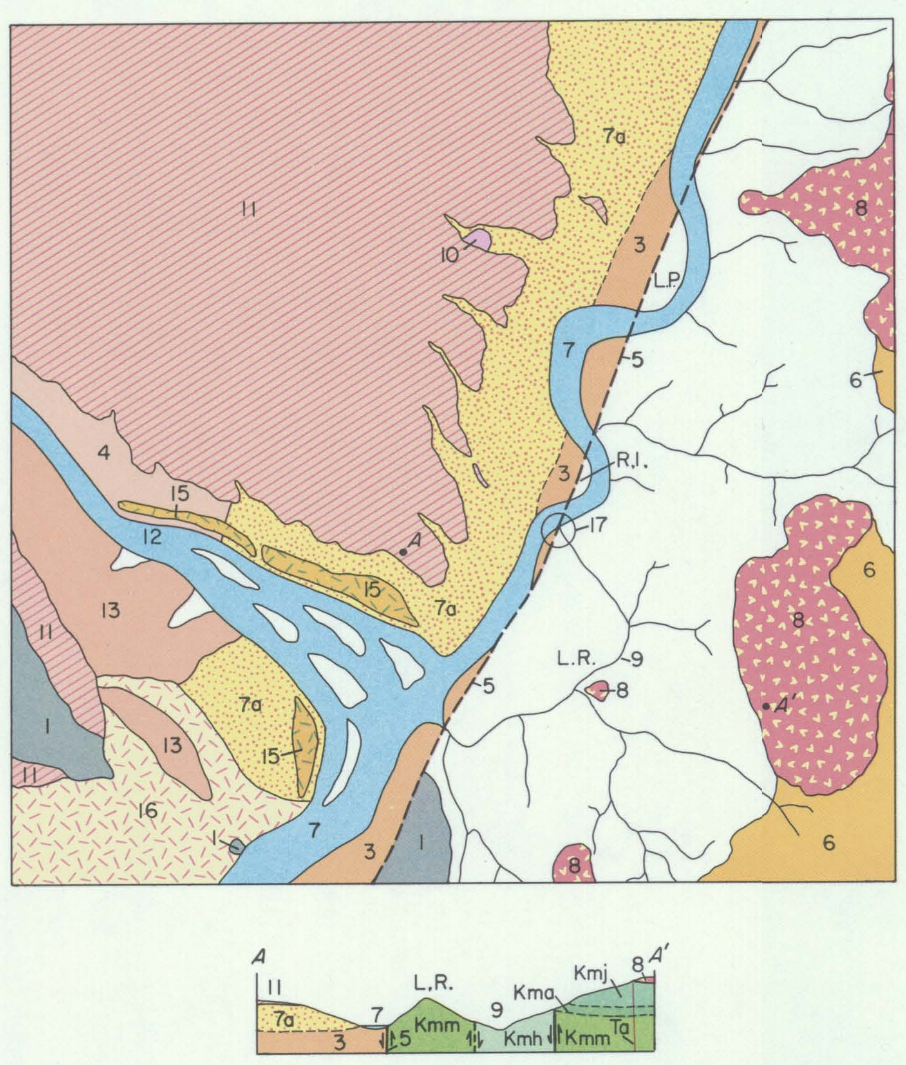
Stage I—Early Pliocene, Engle Basin as a bolson



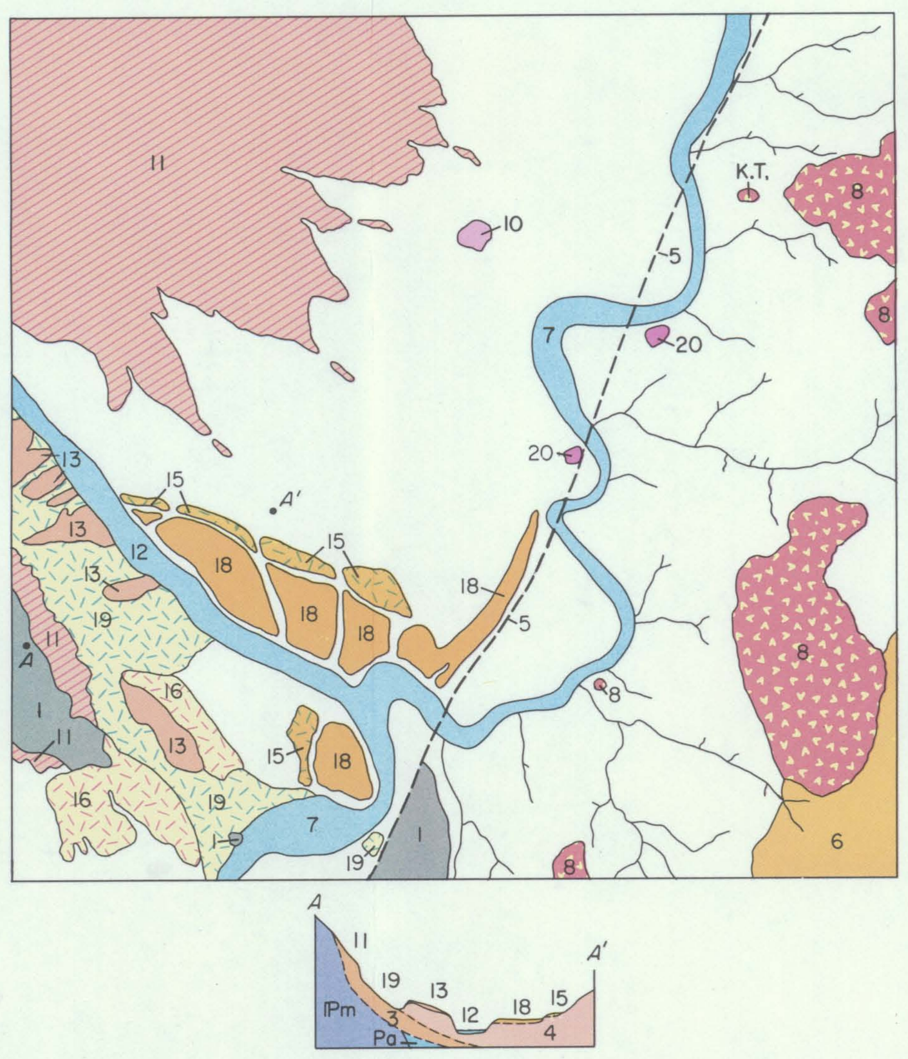
Stage II—Middle Pliocene—early Pleistocene, ancestral Rio Grande



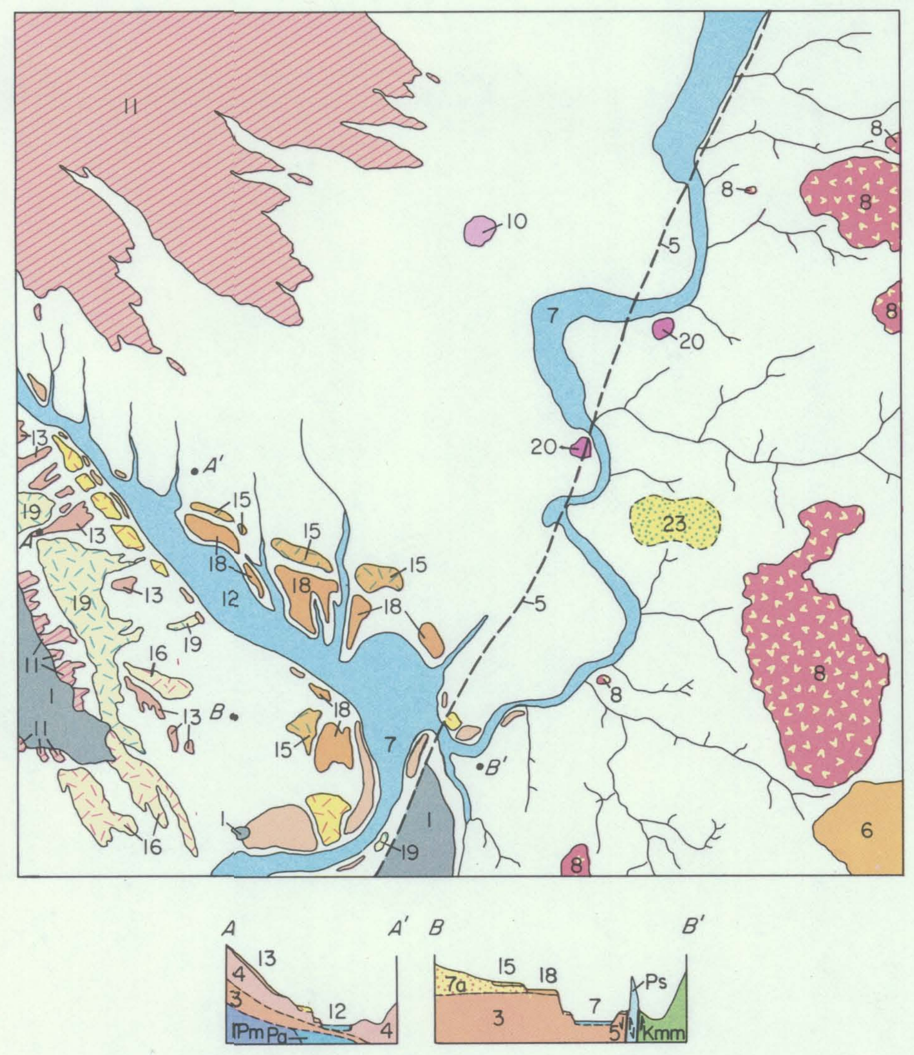
Stage III—Middle Pleistocene, base level 1 development



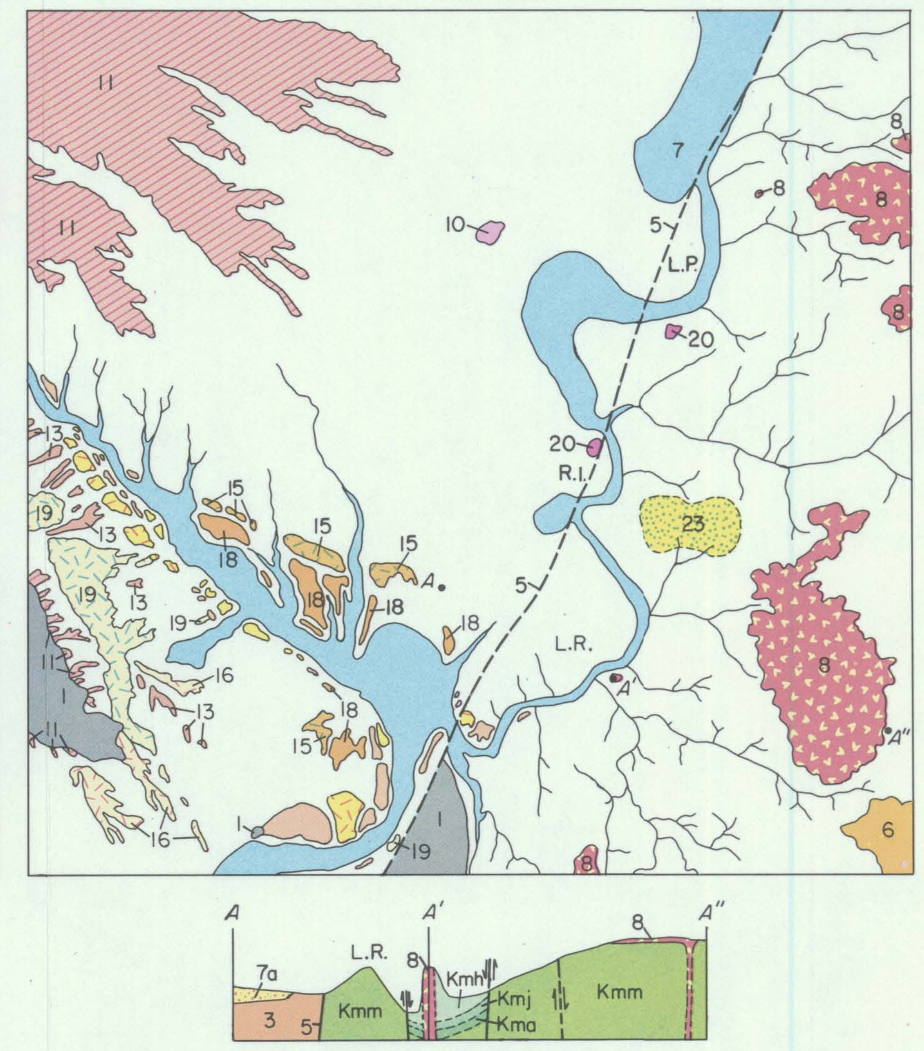
Stage IV—Middle to late Pleistocene, capture of Rio Grande



Stage V—Late Pleistocene, base level 3 development



Stage VI—Late Pleistocene, base level 5 development



Stage VII—Latest Pleistocene to Holocene, final development to present configuration

EXPLANATION*

1 major uplifts
2 playa
3 proximal subfacies
4 distal subfacies
5 Hot Springs fault
6 Cutter surface
7 Rio Grande
7a axial facies
8 basalt flows
9 Ash Canyon - Jose Creek
9a north-flowing creek
10 Rock Canyon maar
11 Cuchillo surface
12 Cuchillo Negro Creek
13 pediment level 1
14 Mud Springs erosional scarp
15 terrace level 1
16 pediment level 2
17 point of capture
18 terrace level 2
19 pediment level 3
20 Rattlesnake and Reservoir maars
21 terrace level 3
22 terrace level 4
23 eolian sand
24 terrace level 5
K.T. Kettle Top
R.I. Rattlesnake Island
L.P. Long Point
L.R. Long Ridge

*The colors used in these stages do not correspond with the unit colors shown on Sheet 1 because they are used to emphasize progression only. However, formal units in the cross sections beneath the stages do correspond with the unit colors shown on Sheet 1.

Cross sections and evolutionary stages of the Elephant Butte area, Sierra County, New Mexico

by Richard P. Lozinsky, 1986

Geology by Richard P. Lozinsky, 1982
Drafted by Teresa A. Mueller

Lozinsky ELEPHANT BUTTE AREA New Mexico Bureau of Mines & Mineral Resources Circular 187