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Cover Photo: Elaine Mustoe viewing a small portion of a siltstone outcrop on northern Slide Mountain. These shallow impressions appear to represent the tracks of a large, short-legged animal. The outcrop also contains many similar depressions that suggest these creatures were traveling in a herd. See article p. 3, especially Figure 11. (Photo by George Mustoe.)

Ten-Year Direction for Federal and State Earth Science

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To meet the challenges facing Washington State in the next millennium, Washington's Department of Natural Resources has developed a set of goals for its natural resources programs during the coming decade that focuses on:

- completing the transition to understanding, managing, and protecting whole ecosystems;
- enhancing the value of our legacy of public lands and natural resources and the income they produce for trust beneficiaries, both now and in the future;
- preparing for catastrophic events like earthquakes, major wildfires, windstorms, and floods;
- accommodating public access and recreational opportunities for a rapidly growing population;
- providing the Legislature and the public with information they need to be full participants in the stewardship of our lands and resources;
- operating an efficient business and delivering excellent service.

Within this framework, the Geology and Earth Resources Division's 10-year direction is to:

- assure that a core program exists and is effectively funded;
- provide strong leadership to gain the attention of the public and decision makers on issues such as disaster preparedness, wise use of nonrenewable resources, and protection of valuable mineral resources;
- develop a strong education and information program that fosters the concept of shared responsibility for disaster preparedness among individuals, businesses, and government.

The major elements of the division's core geologic program consist of producing a comprehensive geologic database for the state both in standard (paper) and GIS format, services and products aimed at reducing risk from geologic hazards, assistance in the wise use of our nonrenewable resources by providing scientific geologic data, and service to the public by being the state's source for geologic information.

To essentially the same end, our federal counterparts in the Geologic Division of the U.S. Geological Survey have formed a 10-person Scientific Strategy Team (SST) chaired by Steve Bohlen, Acting Associate Chief Geologist for Science. The goal for the team is to identify critical earth and biological science issues facing the nation in the next 10 to 20 years and to articulate 10-year goals for the Geologic Division to address these issues. The SST held roundtable discussions with invited panelists in Reston, Denver, and Menlo Park during July. State Geologist Raymond Lasmanis participated in the Menlo Park discussion on "Spatial Data Issues and Geologic Mapping".

Continued on page 32

Paleogeography and Paleontology of the Early Tertiary Chuckanut Formation, Northwest Washington

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INTRODUCTION

Residents of northwest Washington feel at home in a landscape where majestic forests provide a foreground for rugged mountain vistas—except on the many days when the panorama is obscured by fog and drizzle. Fossils in the Chuckanut Formation tell us that the area's environment was once much different—50 million years ago, the region was a swampy subtropical flood plain.

This paper describes a scientific odyssey that began in 1841 when sailing vessels of the U.S. Exploring Expedition arrived at Bellingham Bay under the command of Lieutenant Charles Wilkes. Expedition geologist James Dwight Dana is now remembered for his landmark *System of Mineralogy* published in 1837. Nearly forgotten is his small collection of plant fossils from the Bellingham area, specimens that marked the beginning of paleontologic research in the Pacific Northwest.

The 1852 discovery of extensive coal deposits at Bellingham Bay sparked further interest in the Tertiary sedimentary rocks. A century and a half later, geologists are studying these strata to trace the complex tectonic history of the region and to better understand the early Tertiary landscape and the plants and animals that once inhabited Washington's northwest corner.

GEOLOGIC SETTING

The Chuckanut Formation consists of thick sequences of arkosic sandstone, siltstone, conglomerate, and coal that unconformably overlie Paleozoic and Mesozoic metamorphic basement rock. McLellan (1927) named the Chuckanut Formation during his investigation of outcrops of sedimentary rock on northern Lummi Island, but he did not describe a type section. Stratigraphic sections were later mapped on the mainland near Lake Whatcom and Chuckanut Drive, just east and south of Bellingham, respectively (Glover, 1935; Weaver, 1937). Correlative rocks extend from southwestern British Columbia to central Washington (Fig. 1).

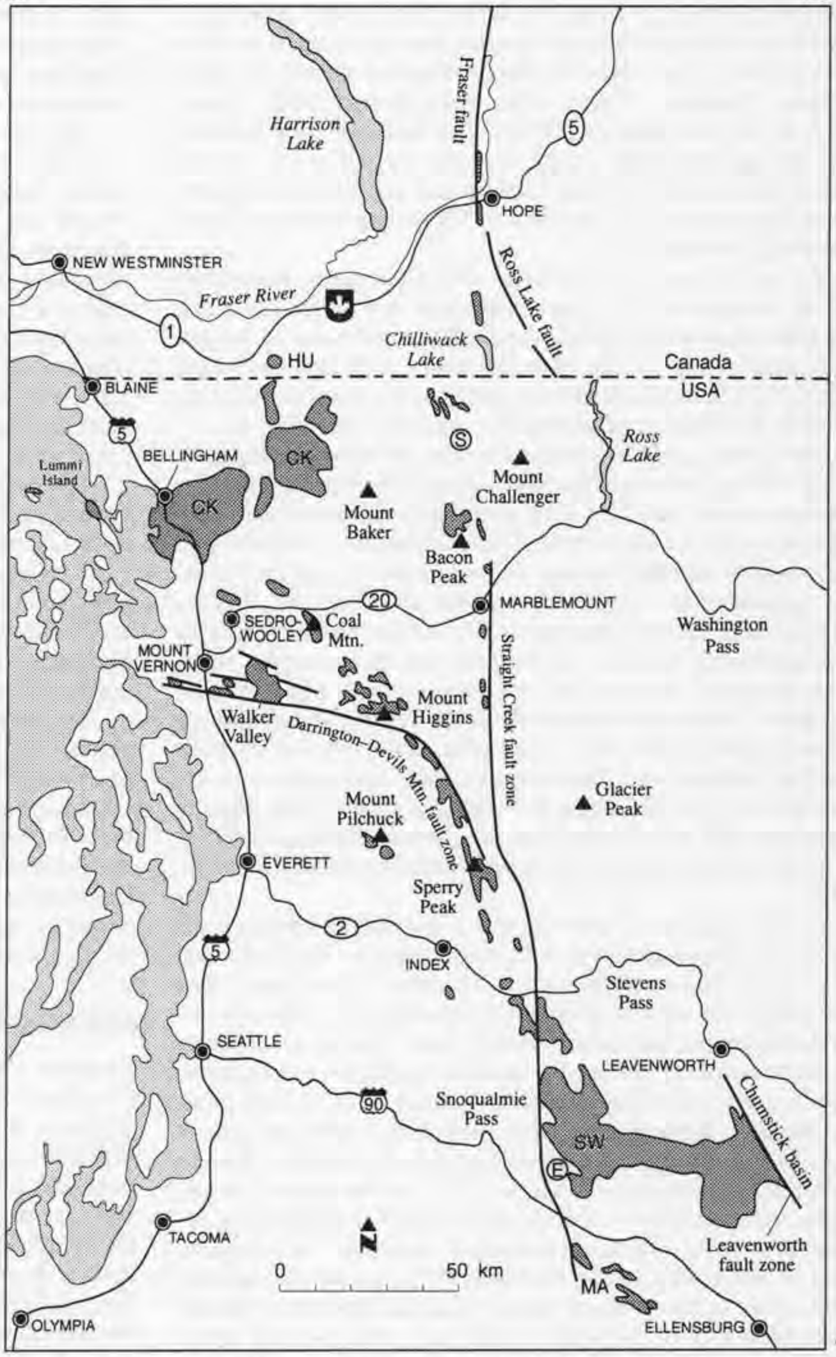


Figure 1. Outcrop map of Chuckanut (CK), Swauk (SW), Manastash (MA), and Huntingdon (HU) Formations. Circled letters: E, Easton Schist; S, Shuksan Metamorphic Suite. Compiled from Johnson (1984a), Lewellen and others (1985), Whetten and others (1988), Monger (1989), Tabor and others (1993, in progress), and Tabor (1994).

Weaver (1937) suggested that these early Tertiary strata were deposited on a coastal plain that extended over much of Washington prior to the uplift of the Cascade Range. Pabst (1968) also believed that the Chuckanut Formation originated as part of a very large and relatively undisturbed basin, but she erroneously assumed that the Chuckanut sediments were the landward extension of marine Nanaimo Group strata of the San Juan Islands and Vancouver Island. We now know that the Chuckanut is early Tertiary and Nanaimo rocks are Cretaceous and that the two formations are separated by faults.

Some researchers continue to believe that the Chuckanut Formation and other nonmarine arkosic sedimentary rocks formed as large sheet-like deposits (for example, Cheney, 1994). Other investigators have proposed that early Tertiary sediments were deposited in a series of relatively small pull-apart basins produced by oblique northward subduction of the Kula oceanic plate beneath North America during the early Tertiary (Johnson, 1985; Evans and Johnson, 1989; Evans, 1994; Evans and Ristow, 1994). This interpretation assumes that oblique strike-slip faults initially created several neighboring basins and that later folding and dip-slip faulting produced low areas where portions of the sedimentary rock were protected from erosion.

We prefer another scenario—the Chuckanut Formation and its correlatives may have originated in a single basin that was later dissected by strike-slip faulting, and many of the present outcrops are slivers of sedimentary rock that have been tectonically transported. This hypothesis is consistent with the regional distribution of nonmarine arkosic rocks (Fig. 1).

The Swauk and Chuckanut Formations have similar ages, compositions, and fossils, and division of these strata into two formations was based on their geographic locations on opposite sides of the Cascade crest. These formations owe their present positions to mid-Tertiary tectonic activity, and they probably originated as a single depositional unit. The northwestern outcrop belt of the Chuckanut Formation is underlain by greenschist and phyllite of the Shuksan metamorphic suite. These basement rocks are correlatives of the Easton metamorphic suite, which unconformably underlies the Swauk Formation near Snoqualmie Pass. This structural evidence suggests that the Shuksan and Easton rocks have been separated approximately 190 km along the Straight Creek fault zone, a separation that closely matches the present distance between the main outcrop zones of the Swauk and Chuckanut (Johnson, 1985).

Smaller bodies of arkosic rocks distributed between the Swauk and Chuckanut type localities appear to be blocks that were transported north along the Straight Creek–Fraser fault zone and northwest in a radial splay along the Darrington–Devils Mountain fault zone. Both of these fault zones initially had predominantly strike-slip motion, which later changed to oblique high-angle displacement (Cheney, 1987). This complex tectonic history must have played an important role in controlling early Tertiary depositional environments, but the evidence remains hazy. Tabor (1994) believes that stratigraphic relationships at the southern end of the fault zone indicate that strike-slip movement had ceased by late Eocene, about 44 Ma. Coleman and Parrish (1991) concluded that most of the offset in the northern region occurred after 46.6 Ma. At its southern end, the Straight Creek fault zone does not offset the Snoqualmie batholith, and the Chilliwack batholith lies across the fault zone near the U.S.–Canadian border. Radiometric dates from these plutons show that faulting had ceased by the Miocene (Engels and others, 1976; Tabor and others, in progress).

The mechanics and timing of the Darrington–Devils Mountain fault zone are not well understood. The fault zone offsets rhyolitic dikes that have fission-track ages of 41.5 ±3.4 and 52.7 ±2.5 Ma (Cheney, 1987), and the magnitude of tectonic activity is illustrated by the south face of Mount Higgins, a scarp nearly 10 km in length with a maximum height of 1,600 m, truncating Chuckanut strata (Jones, 1959).

Sediment compositions and southwesterly paleocurrent directions indicate that much of the Swauk and Chuckanut Formations was derived from a distant eastern source, perhaps the Omineca Crystalline Complex near the present Washington–Idaho–British Columbia border. The younger strata of both formations contain increased proportions of sediment from local sources; the diverse paleocurrent directions may represent complex stream drainages that originated when local uplands were created by mid-Eocene faulting.

The fault-bounded Manastash Formation west of Ellensburg may also have originated within the Swauk/Chuckanut basin. Early collections of plant fossils suggested that the Swauk and Manastash had no taxa in common (Smith, 1904). However, the Manastash fossils consisted of only six genera identified from 25 specimens collected at a single site. In recent years, roadcuts in the upper South Fork Manastash watershed have yielded numerous plant fossils, including *Sabalites* (fan palms), *Taxodium* and *Glyptostrobus* (subtropical conifers), and other distinctive taxa that also occur in the Swauk and Chuckanut Formations. Newman (1981) noted that similar fossil pollen is present in all three formations.

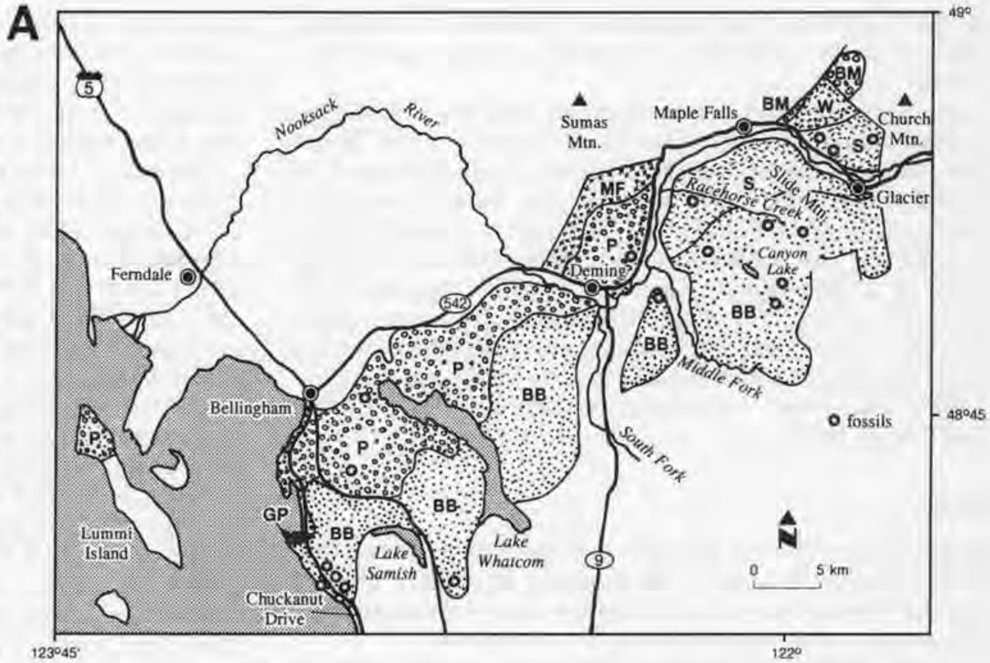
The basal part of the Chumstick Formation appears to have been deposited in the same basin as the nearby Swauk Formation. Eocene displacement along the Leavenworth fault zone partitioned the basin, and most of the Chumstick strata accumulated in this new graben (Evans, 1994). Oligocene orogeny ended fluvial deposition, and layers of Chuckanut, Swauk, and Manastash sediment were eventually uplifted and folded into northwest-trending anticlines and synclines.

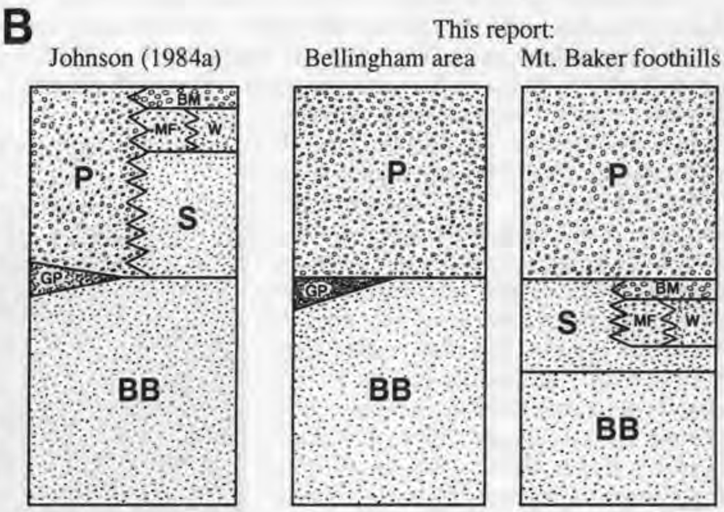
The present location of the seaward portion of the fluvial system that produced these rocks remains a mystery. Marine sedimentary rocks of the Crescent Formation on the northern Olympic Peninsula are possible Chuckanut correlatives on the basis of results of isotopic studies (Heller and others, 1992). An alternate explanation is that deltaic and marine facies were transported northward by a major strike-slip fault zone believed to underlie Puget Sound (Johnson, 1984a). If so, the missing strata may be slip-sliding away to the Gulf of Alaska.

STRATIGRAPHY

Johnson (1984a) estimated a total thickness of 6,000 m for the Chuckanut Formation near Bellingham, but oil and gas wells drilled in the lowlands near the U.S–Canada border penetrated sedimentary rocks that span the entire Eocene Epoch in a thickness of only 2,500 m (Mustard and Rouse, 1994). These stratigraphic disparities have geologists puzzled. Outcrops near Bellingham may have been affected by thrust faults that locally duplicated strata, or differences in thickness may reflect widely varied sedimentation rates. Equally perplexing, our paleobotanical data suggest that the Chuckanut Formation consists of two units that were deposited under different climatic conditions. Current mapping efforts by geologists from the U.S. Geological Survey, the Washington State Division of

Figure 2. A. Northern outcrop zone of the Chuckanut Formation as mapped by Johnson (1984a). Abbreviations for members: BB, Bellingham Bay; BM, Bald Mountain; GP, Governors Point; MF, Maple Falls; P, Padden; S, Slide; W, Warnick. **B.** We have modified Johnson's original stratigraphy in accordance with our hypotheses that the Slide and Padden Members were separated by an episode of climatic change, rather than representing interfingering sedimentary facies. The stratigraphic positions of the Bald Mountain, Warnick, and Maple Falls members are uncertain; they lack plant fossils and do not show clear depositional contacts. We have tentatively placed these units as correlatives of the Slide Member on the basis of their geographic proximity to Slide strata on Church Mountain and the petrographic similarity of the Warnick Member to the Slide and Bellingham Bay Members, but this interpretation is only a guess.





Geology and Earth Resources (DGER), and Simon Fraser University should resolve some of these uncertainties.

Johnson (1984a) divided the northwestern Chuckanut outcrop belt into seven stratigraphic members that were deposited in different fluviatile environments (Fig. 2). The 3,300-m-thick Bellingham Bay Member and the 1,960-m Slide Member represent the early deposition. They consist of alternating beds of arkose and siltstone with minor amounts of conglomerate and coal.

The Governor's Point Member is a wedge-shaped body of arkose and conglomerate having a maximum thickness of only 365 m at the Chuckanut Bay type section. This coarse sediment was deposited along a braided river in a watershed bordered by local uplifts. The 3,000-m-thick Padden Member includes beds of massive arkose and conglomerate alternating with mudstone. Abundant lithic fragments and chert clasts suggest that the Coast Plutonic Complex of British Columbia was an important sediment source.

Three younger stratigraphic members are exposed in the Mount Baker foothills. These relatively small deposits were laid down after the initial meandering river environment had been disrupted by uplifts that created steep-gradient tributaries that carried sediment from local sources. The Maple Falls and Warnick Members each consist of approximately 1,000 m of conglomerate-rich arkose alternating with siltstone and mudstone and probably formed as adjacent interfingering deposits that were later pulled apart by the Boulder Creek fault. Conglomerate and coarse-grained arkose of the 450-m-thick Bald Mountain Member were deposited as an alluvial fan adjacent to an uplift block.

East of Mount Vernon in Skagit County, Chuckanut strata have been juxtaposed between the pre-Tertiary metamorphic Haystack terrane and Oligocene marine deposits of the Bulson Creek unit by motion along the Darrington–Devils Mountain fault zone (Whetten and others, 1988; Marcus, 1991). The stratigraphy of all these deposits needs further study.

Evans and Ristow (1994) identified three stratigraphic units in the southeastern outcrop belt. The Coal Mountain unit consists of 1,700 m of strata in the foothills southeast of Sedro-Woolley (Robertson, 1981). The slightly younger Higgins Mountain unit is exposed in the Finney Peak–Mount Higgins area. Both units are composed of massive arkose overlain by thinly bedded arkose and shale (Tabor and others, 1993). The Big Four–Sperry Peak unit in Snohomish County contains 1,900 m of strata that may be correlative to the Higgins Mountain unit on the basis of lithologic similarity.

Big Four–Sperry strata contain abundant clasts of chert and metamorphic rocks derived from local mélange assemblages, and paleocurrent directions are highly varied, in contrast to the dominantly southwestern current directions in the older parts of the Swauk and Chuckanut Formations. These characteristics suggest that the Big Four–Sperry strata were deposited after the original basin was fragmented by strike-slip faulting.

The stratigraphic relationships of Chuckanut Formation outcrops along the western margin of the Straight Creek fault zone are uncertain. Evans and Ristow (1994) described the Grade Creek unit, which consists of several elongate bodies of arkosic rock in the Suiattle River area south of Marblemount. Haugerud (1980) mapped about 1 km^2 of Chuckanut strata near the summit of Bacon Peak, east of Baker Lake.

Chuckanut outcrops near the U.S.–Canada border have been mapped by Monger (1989) and Tabor and others (1994). Near Vancouver, early Tertiary rocks of the Burrard and Kitsilano Formations have recently been redefined as stratigraphic members of the Huntingdon Formation, a northern extension of the Chuckanut Formation (Mustard and Rouse, 1994).

Arkosic rocks on Sumas Mountain near the U.S.–Canada border contain an angular unconformity between the Chuckanut Formation and younger sedimentary rocks. Mustard and Rouse (1994) noted that these upper strata were not correlative to the Huntingdon Formation type locality, as had been proposed by Miller and Misch (1963). Sumas Mountain geology is being studied by Joe Dragovich of DGER. (See Dragovich and others, 1997.) The alleged Chuckanut–Huntingdon unconformity is not evident farther south in the Bellingham area, and analyses of fossil pollen indicate that the Chuckanut and Huntingdon Formations are correlative (Reiswig, 1982; Mustard and Rouse, 1994).

AGE

Radiometric evidence suggests that the Swauk, Manastash, and Chuckanut Formations were mostly deposited during the Eocene Epoch, but we lack definitive dates for deposition of the youngest and oldest stratigraphic members.

The age of the Chuckanut Formation was considered to be Late Cretaceous and Paleocene, but recent evidence suggests a late Paleocene to early Oligocene age range. The Late Cretaceous age was linked to the mistaken view that the Chuckanut Formation could be correlated with the Nanaimo Group on Sucia Island (McLellan, 1927; Miller and Misch 1963; Pabst, 1968). The Paleocene age estimate was based on similarities between Chuckanut and Swauk Formation plant fossils and leaf impressions from the ancient floras of the Rocky Mountain regions. We now realize that Swauk and Chuckanut fossils more closely resemble Eocene and early Oligocene floras such as those of Washington's Puget Group (Wolfe, 1968), the Clarno Formation of central Oregon (Manchester, 1981, 1994), the Goshen and Comstock floras of western Oregon (Sanborn, 1937; Chaney and Sanborn, 1933), the LaPorte, Weaverville, and Chalk Bluffs floras of California (Potbury, 1937; MacGinitie, 1937, 1941), and fossils from southeast Alaska (Wolfe, 1977). These paleofloras all represent warm, humid, low-elevation forests.

Studies of fossil spores and pollen have yielded age estimates that range from Late Cretaceous to Oligocene (Hopkins, 1966; Griggs, 1970; Reiswig, 1982), but more recent palynology research indicates that Chuckanut strata near the Canadian border are of late Paleocene to early Oligocene age (Mustard and Rouse, 1994). Small arkosic outcrops along the Ross Lake and Fraser fault zones in British Columbia contain middle Eocene pollen (Monger, 1989).

Fission-track ages obtained from detrital zircons suggest a maximum age of approximately 55 Ma for Chuckanut strata in the northwest outcrop belt. A 49.9 ±1.2 Ma tuff interbed from the lower part of the formation indicates a predominately Eocene age (Johnson, 1984a). Evans and Ristow (1994) reported an age of 44.5 ±4.5 Ma for a bentonite bed in the upper part of Chuckanut strata at Mount Higgins in Skagit County, and Chuckanut outcrops near Barlow Pass in eastern Snohomish County are overlain by volcanic rocks that have K-Ar ages from 40.5 ±5 to 36.8 ±9.2 Ma and zircon fission-track ages of 45–32 Ma (Tabor and others, 1984). Whetten and others (1988) obtained a fission-track age of 52.7 ±2.5 Ma from an interbedded rhyolite flow in Chuckanut outcrops in western

Figure 3. Depositional environments characteristic of modern meandering rivers. **A.** When flow is normal, sedimentation is limited to deposition of point bars at the inside bends of the channel, where the current is retarded. Higher velocities at the outside of the bend erode the bank, gradually causing the channel to migrate laterally. Modern rivers have been known to shift their channel by as much as several hundred meters per year (Wolman and Leopold, 1957). Although each point bar occupies only a small area, channel migration eventually distributes bar deposits over the entire flood plain, causing them to be the dominant type of sediment. Napo River, an Amazon tributary. Photo by Peter Frey. **B.** During floods, meandering rivers distribute silt and fine sand over adjacent lowlands in ribbon-like deposits that may be many kilometers in length, but only a few centimeters in thickness. Nooksack River during the December 1995 flood. Photo by Philip A. Dwyer/Bellingham Herald. Used with permission.

Skagit County, and a tuff layer in the nearby Coal Mountain unit has been fission-track dated at 52.5 ±4.8 Ma (Evans and Ristow, 1994). Sedimentary rocks exposed on the west side of the Straight Creek fault zone near Marblemount have a maximum age of about 45 Ma, also on the basis of fission-track ages of detrital zircons (Evans and Ristow, 1994).

The Padden, Maple Falls, Warnick, and Bald Mountain Members have not been radiometrically dated. Older Chuckanut strata appear to have been deposited contemporaneously with the Swauk and Manastash Formations. Tabor and others (1982) described dacitic to andesitic Silver Pass Volcanics as interbeds within the upper Swauk Formation and reported fission-track ages of 54.1 ±2.1, 52.2 ±1.9, and 49.1 ±5.2 Ma. Cheney (1994) considered the Silver Pass rocks to be a younger unit that unconformably overlies the Swauk Formation. This interpretation, however, conflicts with fission-track dates of 50.5 ±1.2, 48.6 ±2.3, and 43.6 ±1.1 Ma recorded from other volcanic beds within the Swauk. Cheney assumed that these ages have been reset, since it would not be possible for the Silver Pass Volcanics to unconformably overlie younger rocks. The Swauk is locally overlain by the Teanaway Basalt, which originated from feeder dikes that cross-cut folded sedimentary strata. K-Ar ages of these igneous rocks range from 39.7 ±0.8 to 48.3 ±1 (Cheney, 1994). Manastash strata have not been radiometrically dated, but the formation is overlain by Taneum Andesite, fission-track dated at 51.8 ±1.0 and 46.2 ±1.1 Ma (Tabor and others, 1982).

PALEOGEOGRAPHY

The origin of ancient fluvial sediments can best be understood by examining the depositional environments associated with modern meandering rivers. Figure 3 shows two examples. The ribbon or lens shape of most fluviatile deposits explains the Chuckanut Formation's lack of stratigraphic continuity. Figure 4 depicts the various types of sediment accumulation, each associated with characteristic types of fossils.

Figure 4. A. Depositional environments that produced sediment types found in the Chuckanut Formation. Most sandstones in the Chuckanut Formation were deposited as point bars at bends in a meandering channel. Point bar deposits are typically cross-bedded and may contain imprints of leaves transported from upstream habitats. Casts of driftwood logs are common (Fig. 5A). Channel migration can create oxbow lakes that favor the slow accumulation of silt and clays and offer ideal conditions for the preservation of fossils.

B. Although lowlands adjacent to the channel occupied most of the land area, they received sediment only during floods. These high-water events produced several types of deposits. Levees accumulated when the river reached the crest of its banks, causing silt and sand to be deposited bordering the main channel. Many trees and shrubs can tolerate periodic immersion of their roots, and levees provided habitat for abundant vegetation. Bank-dwelling plants were an important source of leaves and driftwood that were transported to downstream sites, but levees themselves offered unfavorable conditions for the preservation of fossils. Levees remained above the water table during most of the year, and exposure to the atmosphere caused rapid aerobic decomposition of leaf litter, producing compost rather than fossils.

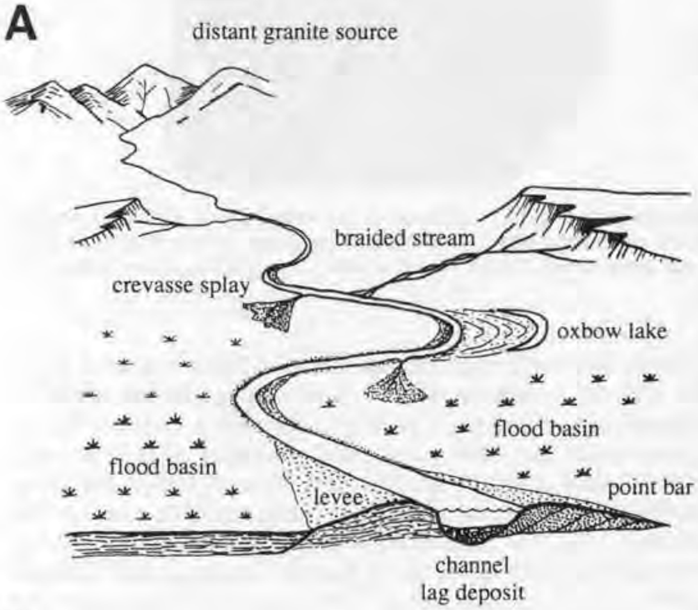
In the flood plains adjacent to these levees, low topography created swampy conditions favorable to plant growth, and perpetual soil saturation led to anaerobic conditions that inhibited microbial decomposition. Occasional floods contributed layers of fine sediment that helped preserve organic remains.

In places, accumulation of organic matter produced peat deposits that were later altered to form bituminous coal. At flood-prone sites, these carbonaceous layers contain interbeds of siltstone and fine sandstone. Plant fossils are abundant in all of these flood-basin deposits; some specimens consist of scores of overlapping leaves that completely cover the bedding surface.

Crevasse splays formed when the levee was breached, depositing a fan of sediment on the adjacent flood plain. These deposits were created during episodes that may have lasted only a few hours. Ancient crevasse splays can be recognized as sandy interbeds enclosed within finer grained flood-basin deposits. Although fossils in flood-basin deposits provide a record of plants that grew in the immediate area, organic material contained in crevasse-splay deposits was transported from upstream sites. Fossils in crevasse splays often show the effects of hydraulic sorting. Although seeds (Fig. 5B,C) are relatively common, their natural buoyancy can cause them to be transported far from the plants that produced them.

Coarse-grained sandstones with interbedded conglomerates originated in braided streams and alluvial fans where tributary streams carried sediment derived from local uplifts. Examples include massive conglomerate beds of the Governor's Point Member exposed at Teddy Bear Cove, south of Bellingham. Conglomerate layers also originated as lag gravel left behind in the river channel when currents swept away finer sediment. These channel lag deposits account for most of the conglomerate interbeds in the Bellingham Bay and Slide Members.

A



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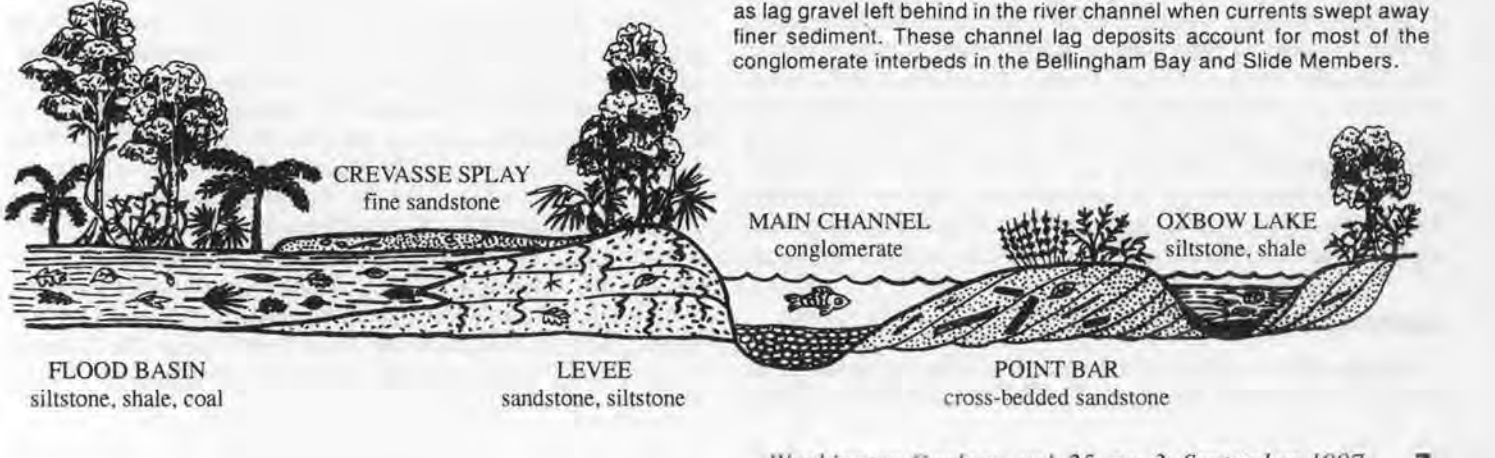


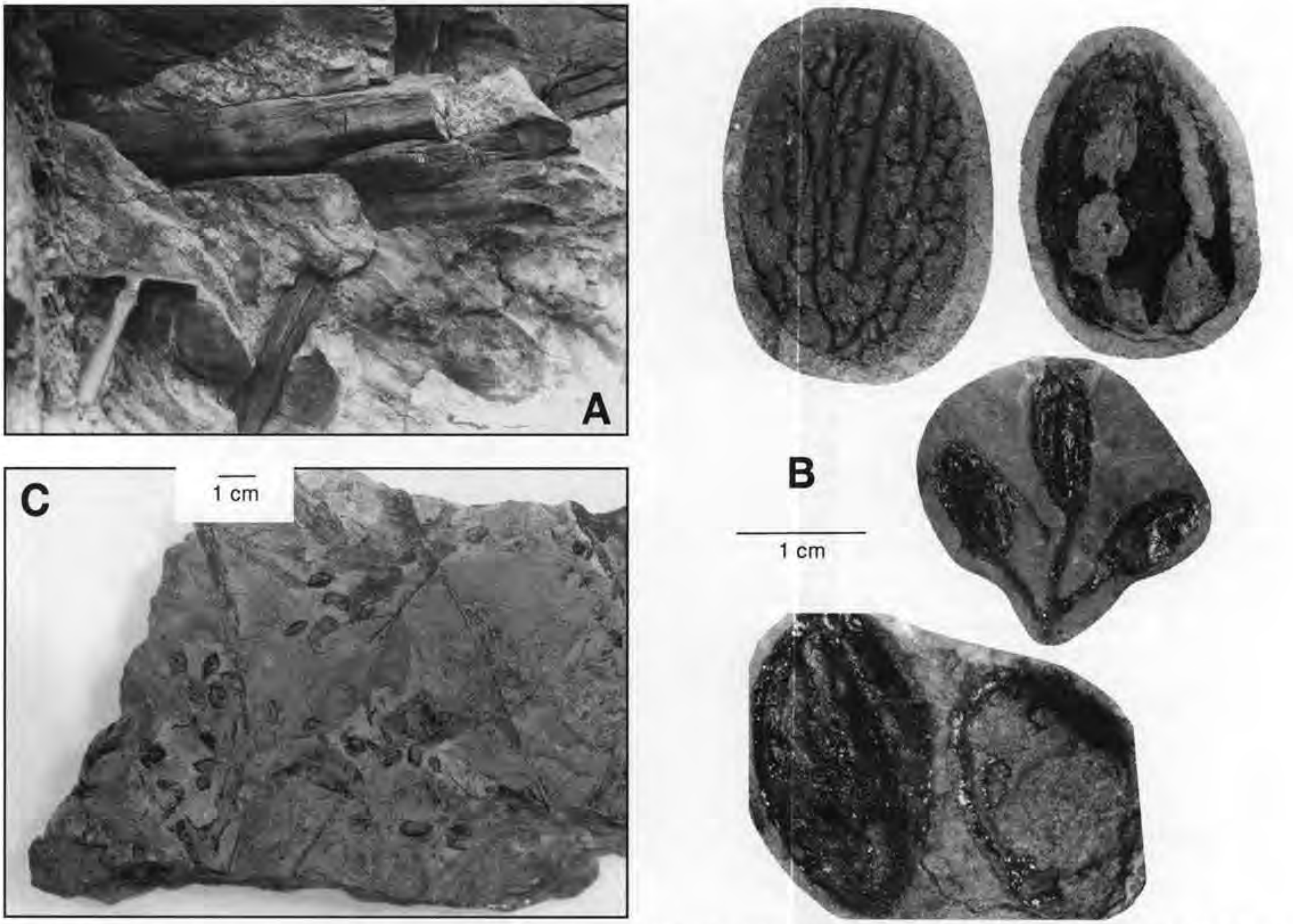


Figure 5. A. Driftwood casts in point bar deposits of the Bellingham Bay Member exposed in a roadcut along Chuckanut Drive, south of Larrabee State Park. **B.** Seeds are commonly transported because of their buoyancy, eventually being preserved in crevasse splays and sand bars. **C.** Some crevasse splay deposits contain fragments of streamside plants that were swept away by flood waters. This slab from the Bellingham Bay Member contains twigs, leaves, and about two dozen seeds.

In the field, interpretation of ancient depositional environments is complicated by limited outcrops and confusing structural complexities, and depositional sequences may not be well defined. Sigafoos (1964) observed that flood-basin sediments may be affected by localized erosion and deposition during flood events, producing complex stratigraphic sequences. Meandering rivers migrate laterally, which produces abrupt changes in the depositional record. These channel migrations are evidenced by the "fining-upward" cycles present in many Chuckanut outcrops, where conglomerate is overlain by sandstone, which is in turn overlain by siltstone. Johnson (1984b) described various depositional environments represented by rocks of the Chuckanut Formation, although he did not consider evidence from fossils. Burnham (1990, 1994) provided excellent examples of stratigraphic interpretation in her studies of plant fossils from the Puget Group in King County, and Evans (1991a,b) has reported on the relationships between sedimentology and paleobotany for the Chumstick Formation. These studies are examples of the kind of interdisciplinary research that is needed for the Chuckanut Formation.

ANIMAL FOSSILS

Contemporaries of Marie Pabst recall hearing her speak of an alleged ichthyosaur skeleton exposed at Clark Point, southwest of Bellingham on the north end of Guemes Island (Hopkins 1966), an interpretation that was compatible with her erroneous belief that the Chuckanut Formation included Cretaceous strata. Her 1968 monograph, however, makes no mention of such a fossil. Mustoe and Pevear (1981) described segmented cylindrical concretions that probably explain this mystery (Fig. 6). Similar pseudofossils occur in outcrops at Pleasant Bay and at the north end of Lummi Island (Calkin, 1959). A turtle carapace (Fig. 7) was found in Padden Member sandstone near Bellingham, along with a bone fragment from an unidentified larger animal (Mustoe and Pevear, 1981).

Slide Member siltstones exposed in Racehorse Creek gorge have yielded specimens of a large freshwater mussel, probably *Anodonta* (Fig. 8), and nearby roadcuts contain poorly preserved specimens of *Viviparus*, an aquatic gastropod. Both mollusks occur in the Eocene rocks of the Cowlitz Formation in Lewis County (Henderson 1935), the Puget Group in King County, and the Roslyn Formation in Kittitas County (D. Q. Hopkins, Burke Museum, Univ. of Wash., written commun., 1996). *Viviparus* is found in sedimentary interbeds of the Eocene Teanaway Basalt, which unconformably overlies the Swauk Formation in Kittitas County (Foster, 1960), and in leaf-bearing beds containing the Eocene Weaverville flora of northern California (MacGinitie, 1941).

Figure 6. These vertebra-like pseudofossils in Padden Member strata at Clark Point appear to have formed when an elongate zone of sediment became cemented with calcium carbonate. Later deformation caused this concretion to fracture at regular intervals, while the enclosing sandstone was plastically deformed.

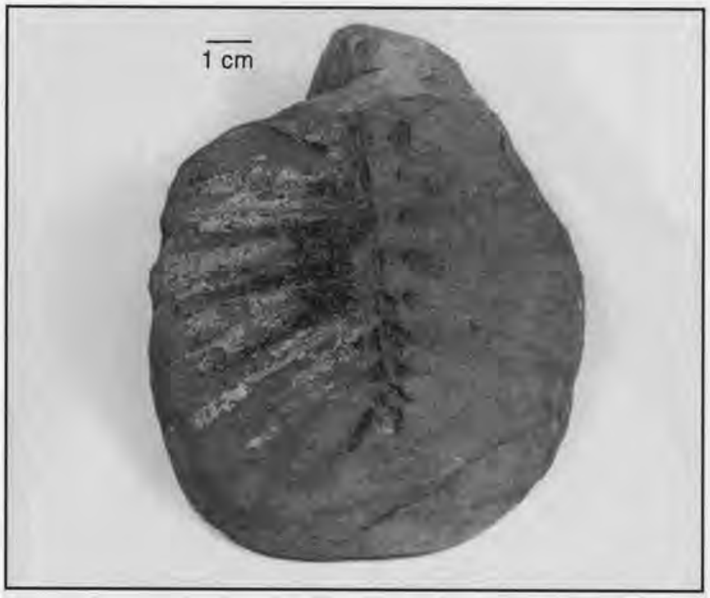


Figure 7. Cast of the underside of the carapace of a turtle found at Clark Point.

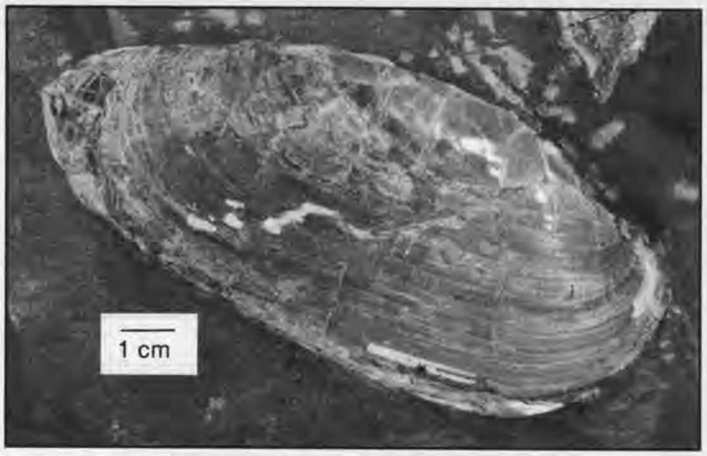


Figure 8. Fresh-water mussel (genus *Anodonta*) preserved in Slide Member siltstone at Racehorse Creek. Specimen provided by Joe Kelly.

Planktonic larvae of *Anodonta* attach to the gills of fish, and the presence of this mussel in the Chuckanut Formation provides proof that fish inhabited the ancient river. *Anodonta* now has worldwide distribution, including two species in lakes and rivers of Washington. *Viviparus* lives in the Mississippi River system and in the eastern states from New York to Florida. These gastropods prefer warm climates, and *Viviparus* is common in rice paddies of Southeast Asia (Prashad, 1928; Webb, 1942).

Fossilized insect wings have been found in siltstone at Chuckanut Drive (Mike Sternberg, oral commun., 1996), and plant fossils at other sites show evidence of damage by lepidopteran (butterfly and moth) leaf miners and other insects (Wes Wehr, Burke Museum, oral commun., 1996).

TRACE FOSSILS

In 1993, logging road construction in the Mount Baker foothills near Canyon Lake exposed a bedding plane that contained nine tracks from a heron-like bird (Fig. 9; Mustoe, 1993), and spectacular palm frond impressions (Fig. 10; Mustoe and Gannaway, 1995). Siltstones on the northern slopes of Slide Mountain contain tracks of small shorebirds.

In the spring of 1996, Wes Gannaway found an outcrop on Slide Mountain that contains about 200 large mammal tracks, roughly circular depressions 12–18 cm in diameter and 4–6 cm deep. The tracks are dispersed over a single bedding plane of badly weathered siltstone. The stratum contains abundant fragments of a small, delicate variety of *Equisetum* (horsetail), indicative of a shallow-water environment. The general form of the foot imprints suggests that they are "squelch tracks" left by a herd traveling in saturated sediment. In a few places, the tracks represent a single animal (cover photo).

Animals that might have produced the large, round Chuckanut tracks include members of the Pantodonta and Dinocerata, two extinct orders of herbivores that somewhat resembled dwarfed rhinoceroses (Fig. 11). The best known pantodont is *Coryphodon*, one of the most common early Eocene land mammals of Europe and North America (Cailleux, 1945). The discovery of a cluster of skeletons in New Mexico suggests that these swamp-dwelling animals traveled in herds (Lucas, 1984). Dinocerata included titanotheres (bronto-

Figure 9. Slide Member bedding plane near Canyon Lake containing nine tracks from a heron-like bird (highlighted with chalk).

theres) and uintatheres, which were abundant in North America and Asia during the middle and late Eocene. Titanothere fossils from the Clarno Formation of central Oregon (Retallack and others, 1996) and Quesnel, British Columbia (McAnally, 1996), establish their presence in the Northwest approximately when Chuckanut sediments were being deposited.

Indistinct tracks of smaller mammals at another Slide Mountain site cannot be reliably identified (Fig. 12). Mollusk and small arthropod trails, however, are quite common, locally producing intense bioturbation of the sediment.

PLANT FOSSILS

Leaf impressions are abundant in many of the fine-grained beds of the Chuckanut Formation. Floristic diversity is so great that almost every collecting site yields new taxa—not surprising when we remember that modern New World tropical forests contain approximately 3,660 plant genera (Takhtadzhian, 1986). Large Chuckanut collections at the University of California at Berkeley, the Burke Museum of Natural History and Culture at the University of Washington (Seattle), Western Washington University (Bellingham), and the Denver Museum of Natural History probably contain only a fraction of the taxa that inhabited the ancient forest.

When Chuckanut leaf fossils are collected from a single bed, these assemblages tend to be dominated by only a few taxa. This distribution is comparable to modern tropical and subtropical forests where at any given site, leaf litter is composed of material from nearby trees and shrubs (Burnham, 1989, 1993). Wolfe (1968) reported an analogous situation in the Puget Group in King County: of 72 species of fossil plants collected from 35 sites in the Green River Gorge, 28 percent of the species were found at only a single site and 48 percent occurred at one or two sites.

The fossil record is likely to be dominated by decay-resistant species and by plants that produced many leaves. As a result, fossils often give fairly good representation of trees, moderate evidence of shrubs, and hardly any indication of herbaceous plants. In addition, leaves are selectively sorted by hydraulic processes prior to burial (Spicer, 1980, 1981, 1989; Ferguson, 1985; Greenwood, 1991).

Figure 10. Palm frond imprints in a Slide Member outcrop, Mount Baker foothills east of Deming, Wash.

Most Chuckanut fossil sites are in steeply tilted beds that make it difficult to collect large numbers of specimens from a single bed. Instead, a single exposure may span a stratigraphic range of several meters and contain fossils from several different plant communities. The Chuckanut Formation lacks distinctive marker beds, so that stratigraphic relationships among different collecting sites cannot be determined. Most fossils are found in fine-grained strata, but these shale and siltstone beds are very susceptible to weathering, and the best Chuckanut Formation collecting sites occur where road construction or landslides have created fresh exposures.

Our knowledge of the ancient Chuckanut forest is still expanding. Newberry (1863, 1898), Lesquereux (1859), Knowlton (1902), and LaMotte (1938) described Chuckanut leaf fossils, but few of these identifications meet modern standards of botanical nomenclature. Fossil pollen grains can be of limited value for understanding ancient plant communities because many early Tertiary palynomorphs are recognized on the basis of physical form rather than genetic relationships. For example, Griggs (1970) reported 79 palynomorph genera from the Chuckanut, but only 30 taxa could be taxonomically correlated with modern plants, and 18 of these identifications were tentative. Marie Pabst's Ph.D. research at the University of California at Berkeley was originally intended to be a compre-

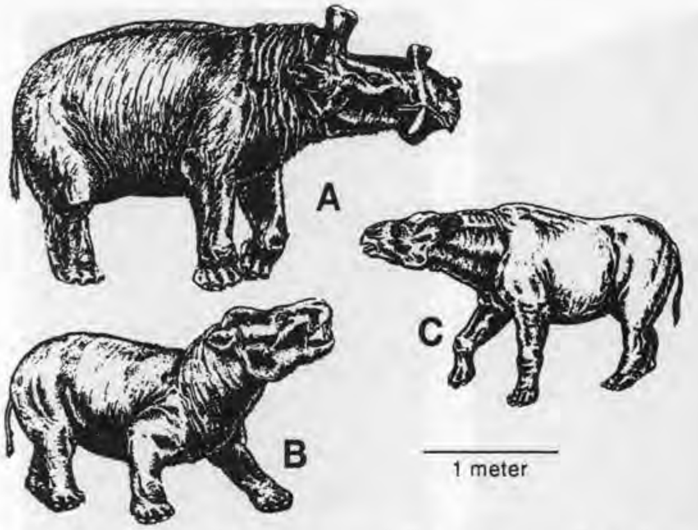


Figure 11. Selected Eocene members of the Pantodonta and Dinocerata. **A**, *Eobasileus* (Dinocerata, middle to late Eocene); **B**, *Coryphodon* (Pantodonta, early Eocene); **C**, *Palaeosyops* (Dinocerata, middle Eocene). Drawings from Rich and others, 1996, by permission.

Figure 12. Wes Gannaway examining small mammal tracks exposed during logging road construction on Slide Mountain.

hensive study of fossil plants from the Chuckanut Formation, but her completed dissertation included only the ferns, conifers, and horsetails (Pabst, 1968). Unpublished manuscripts[1] record her attempts to identify ancient flowering plants by comparing them to modern herbarium specimens and to other early Tertiary plant fossils. Many Chuckanut Formation leaf impressions have simple oval or elongate shapes and smooth margins and lack distinguishing characteristics. Pabst's identifications of these specimens contain many uncertainties.

Name-giving does not necessarily mean that we know very much about an ancient plant. The inexact nature of paleobotany is exemplified by *Republica*, a plant fossil that occurs in the middle Eocene Klondike Mountain Formation at Republic, Washington (Wolfe and Wehr, 1987). Similar leaf imprints occur in the Chuckanut Formation. *Republica* is possibly an ancient relative of the Hamamelididae (witch hazel family), but earlier reports (MacGinitie, 1941; Wolfe, 1968) placed this genus in the Lauraceae (laurel family) and the Moraceae (mulberry family). Pabst considered Chuckanut specimens that she identified as *Tetracera* to be from a tropical vine, but Wolfe (1977) reclassified these leaf types as members of the Fagaceae (oak/beech family), implying that the fossils came from a deciduous tree.

Instead of making a concentrated effort to identify plant taxa from the Chuckanut Formation, we examined the morphology of dicotyledonous leaves from different stratigraphic members. Statistical analysis of the data indicates that Chuckanut Formation strata were deposited during two different climatic regimes.

PALEOCLIMATE

Pabst (1968) used floristic analysis to interpret ferns and conifers from the Chuckanut Formation. The method attempts to understand an ancient plant community by comparing fossil species to their nearest living relatives. Floristic analysis allows botanists to study the patterns of evolution within a particular family or genus, and paleoenvironmental conditions are determined by assuming that modern species have the same habitat requirements as their ancestors. This method is of limited value for studying leaf fossils from hard-to-identify flowering plants because taxonomic errors may cause invalid results.

In contrast, we used vegetational analysis, which considers leaf morphology without regard to taxonomy. Vegetational analysis is based on the principle that plant foliage provides an indication of habitat conditions. Bailey and Sinnot (1915, 1916) realized that the sizes and shapes of leaves are related to environmental factors. Competition for sunlight in tropical and subtropical forests favors large leaves, and smooth margins and elongate tips are features that help leaves shed rain. Plants from cool, dry climates are likely to have small leaves with blunt tips and toothed margins. These characteristics are found even among taxa that are not closely related; all plants within the community are exposed to the same set of environmental conditions and use similar evolutionary strategies.

Paleobotanists analyze leaf shapes to study ancient climates. Wolfe and Upchurch (1987) observed that Late Cretaceous leaf fossils shared many morphological characteristics with living plants in Fiji and New Guinea, but the relationships between leaf morphology and environmental conditions are complex. Wolfe (1993, 1995) developed the Climate–Leaf Analysis Multivariate Program (CLAMP), a computerized mathematical model that can be used to determine climate parameters from vegetational characteristics. Mean annual temperature can be estimated to within 1°C for sites that contain 20 or more dicot species. Other climate characteristics can be determined with lesser degrees of accuracy.

Leaf imprints from the Bellingham Bay and Slide Members are typical of subtropical low-elevation rain forests

[1] Pabst, M. B., A report on some fossil plants from the Chuckanut Formation of northwestern Washington, 41 p. Further notes on the flora of the Chuckanut Formation, 63 p. Unpublished manuscripts (1952) as part of the Wes Wehr papers, Manuscripts & Archives Division, University of Washington Allen Library.

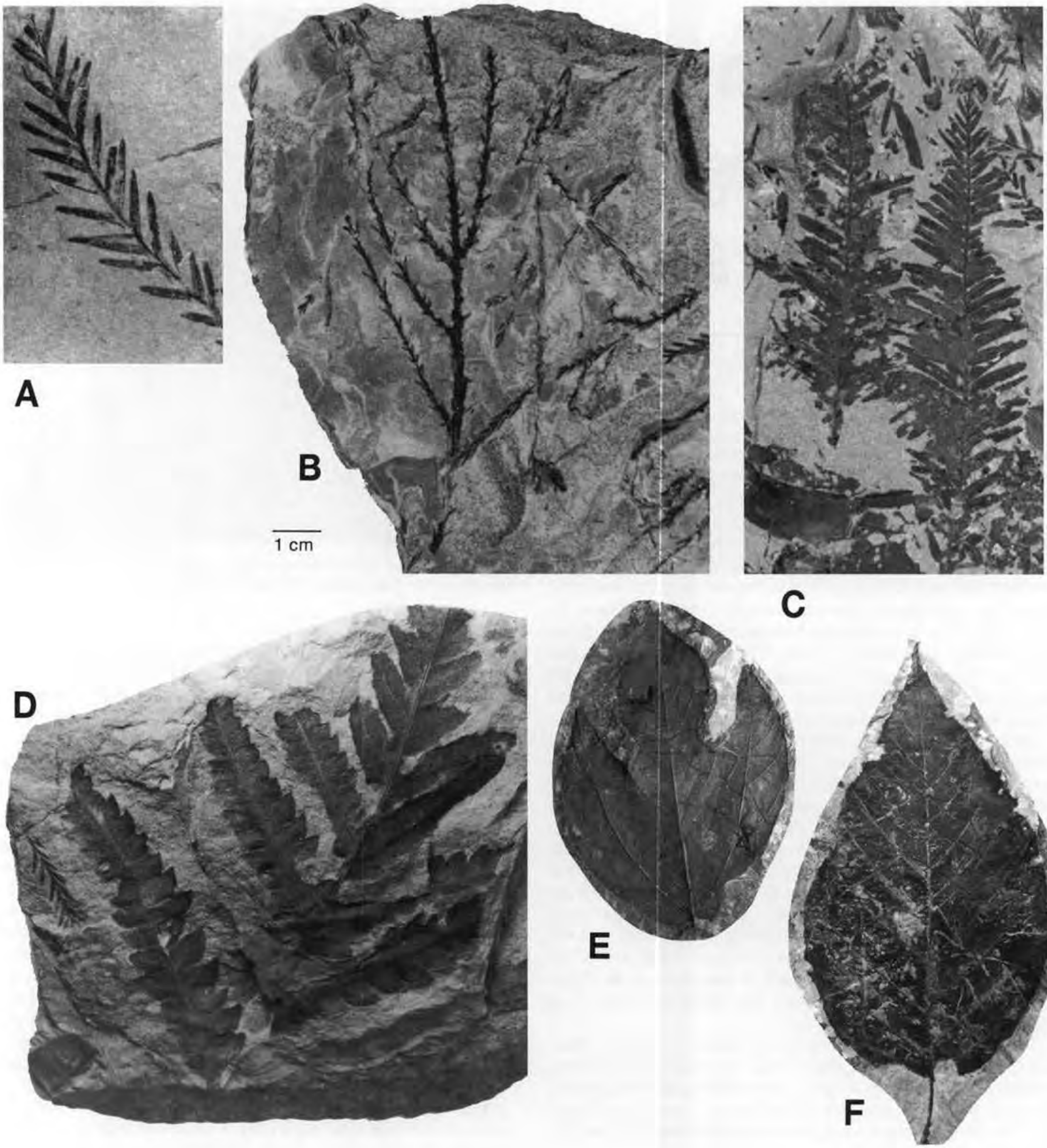
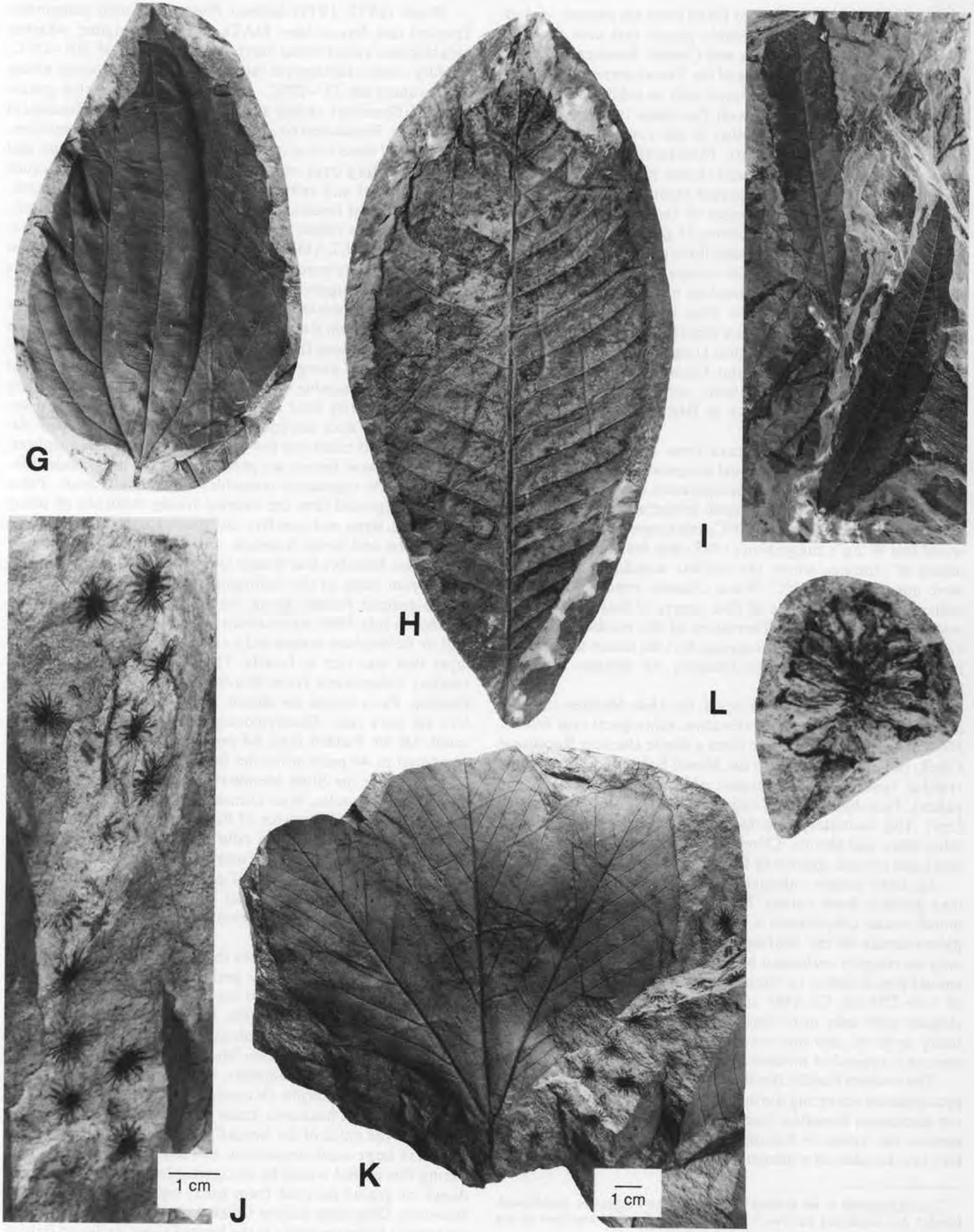


Figure 13. Plant fossils from the Bellingham Bay and Slide Members. **A, B, C.** Ancient conifers: **A**, *Taxodium dubium* Heer; **B**, *Glyptostrobus dakotaensis* (Heer) Brown; **C**, *Metasequoia occidentalis* (Newberry) Chaney. The scale bar with B also applies to A and C. **D.** *Cyathea pinnata* (MacGinitie) LaMotte. Fronds of this tree fern are abundant at Racehorse Creek and other sites in the Slide Mountain Member, where they occur with palm fronds (*Sabalites*) and foliage from *Taxodium*, a swamp-dwelling conifer, 0.65x. **E–K.** Flowering plants from the Bellingham Bay Member: **E**, *Sassafras*, 0.65x; **F**, unidentified leaf, 0.65x; **G**, *Cinnamomum* (cinnamon tree)?, 0.65x; **H**, originally identified as *Tetracera*, a tropical vine, leaves of this type may instead be ancient members of the Fagaceae (oak/beech family), 0.65x; **I**, *Quercus banksiaefolia* Newberry (oak family), 0.65x; **J**, close-up view of *Platanus* (sycamore) flowers; **K**, *Platanus* (sycamore) leaves, with cluster of flowers at right. **L.** *Alnus* (alder) cone, 1.8x.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(Fig. 13). At least 15 species of fossil ferns are present, including many varieties that resemble plants that now dwell in warm, humid regions of Asia and Central America. Lowland conifers consisted of members of the Taxodiaceae and Cupressaceae. *Glyptostrobus* (now found only in southeast China) is particularly common, along with *Taxodium* (swamp cypress), *Mesocyparis* (an extinct member of the cypress family), and *Metasequoia* (dawn redwood). Flowering plants include a mixture of stream-side trees and shrubs (such as alder, birch, sycamore, and hazel) and a diverse assortment of subtropical species that includes two species of fan palms (Mustoe and Gannaway, 1995). Leaf imprints of *Quercus banksiaefolia* Newberry[1] (Fig. 13I) are found throughout the Bellingham Bay Member. This leaf type also occurs at Chuckanut outcrops at Finney Creek and Coal Mountain in Skagit County and at Coal Lake Road near Barlow Pass in Snohomish County. *Quercus banksiaefolia* has been reported from the middle Eocene Clarno Formation of central Oregon (Hergert, 1961), the Manastash Formation in Kittitas County, Washington (D. Q. Hopkins, written commun., 1996), and the Kitsilano Formation, a Chuckanut correlative in British Columbia (Berry, 1926).

CLAMP analysis of 66 taxa from the Bellingham Bay Member indicates a mean annual temperature (MAT) of 15°C, with a mean annual range of temperature (MART) from summer to winter of 10°C. The mean temperature of the coldest month was approximately 10°C, consistent with the Greenwood and Wing's suggestion (1995) that fossil palms are evidence of climates where the coldest monthly temperatures were not lower than 5°C. Warm climatic conditions are also indicated by the presence of five genera of fossil coral in the middle Eocene Crescent Formation of the northern Olympic Peninsula. Their presence suggests that the ocean temperature then exceeded 18.5°C, approximately 10° warmer than it is today (Durham, 1950).

Like the Bellingham Bay strata, the Slide Member contains plant fossils typical of low-elevation subtropical rain forests. Most of our specimens came from a single site near Racehorse Creek, but other outcrops in the Mount Baker foothills contain similar fossils. The dominant plants were *Sabalites* (fan palms), *Taxodium* (swamp cypress), and *Cyathea* (a tree-sized fern). The multistory rain forest also contained a variety of other trees and shrubs. Climbing plants include *Lygodium* (a fern) and several species of flowering vines.

CLAMP results calculated from 30 Slide Member dicot taxa yielded these values: MAT = 16°C, MART = 6°C, cold month mean temperature = 13°C, somewhat milder than the paleoclimate of the Bellingham Bay Member. Rainfall can only be roughly estimated by the CLAMP method, but mean annual precipitation for both members was likely in the range of 150–250 cm. CLAMP scores indicate a frost-free paleoclimate with only mild seasonal variation. Precipitation was fairly uniform, and the wet season occurred during the summer, as is typical of modern tropical and subtropical climates.

The modern Pacific Northwest climate is cooler, with most precipitation occurring during the winter. These conditions favor deciduous broadleaf trees such as alder and maple, which survive the winter by becoming dormant, and evergreen conifers that are able to withstand low temperatures.

Wolfe (1977, 1979) defined three rain forest categories: Tropical rain forests have MATs of 25°C or higher, whereas paratropical rain forests have a MAT range of 20°–25°C. Slightly cooler subtropical rain forests typically occur where MAT values are 13°–20°C. These definitions involve gradational differences rather than sharp climatic or botanical boundaries. Broad-leaved evergreen trees are a dominant component in all three forest types, woody vines are abundant, and swamp-dwelling trees may have buttressed trunks. Canopies of paratropical and subtropical forests are more open compared to tropical forests, and they have greater vertical stratification. Species richness is reduced as mean annual temperature decreases. CLAMP evidence indicates that the earliest Chuckanut forests were subtropical rather than paratropical, as was previously suggested by Mustoe and Gannaway (1995).

Compared to modern plant communities studied by Wolfe (1993), Bellingham Bay and Slide Member CLAMP scores are most similar to those from three sites in southern Japan. These Asian broad-leaf evergreen forests contain plants whose leaf morphologies resemble those of the Chuckanut flora, but they do not necessarily bear a close taxonomic resemblance because CLAMP does not consider taxonomy. The CLAMP database contains relatively few sites in the western hemisphere, and the Japanese forests are probably not the only modern locations where vegetation resembles Chuckanut fossils. Pabst (1968) suggested that the nearest living relatives of many Chuckanut ferns and conifers are species now found in Asia and Central and South America.

Padden Member leaf fossils (Fig. 14) show striking differences from those of the Bellingham and Slide Members. The coarse-grained Padden strata contain relatively few leaf fossils, but in July 1996, excavations at a subdivision on Alabama Hill in Bellingham temporarily exposed a 3-m-thick siltstone layer that was rich in fossils. These specimens supplement smaller collections from Sehome Hill, Lake Padden, and Deming. Palm fossils are absent, and ferns and lowland conifers are very rare. Dicotyledonous leaves tend to be fairly small. Of the Padden taxa, 64 percent have toothed margins, compared to 44 percent for the Bellingham Bay Member and 32 percent for the Slide Members. These foliage characteristics indicate a cooler, drier climate.

CLAMP calculations for 37 Padden Member taxa are MAT = 12°C, MART = 18°C, and cold month mean temperature = 3°C. Freezing would have occurred during part of each winter, consistent with the absence of palms and other subtropical plants. Annual precipitation was 100–200 cm. These parameters seem to document the region's transition to a warm temperate climate.

The cooler, drier conditions that existed during deposition of the Padden Member were perhaps the result of the well-documented episode of global cooling near the Eocene–Oligocene boundary at 34 Ma (Wolfe, 1978; Prothero, 1994). Reiswig (1982) presented palynological evidence for a possible Oligocene age for the Padden Member, and correlative strata at Vancouver, British Columbia, contain late Eocene to early Oligocene palynomorphs (Mustard and Rouse, 1994). An Oligocene age for Chuckanut strata conflicts with the common belief that the uplift of the North Cascades would have brought an end to large-scale deposition, and any sediments deposited during this period would be recognizable because of an abundance of grains derived from local metamorphic terranes. However, Oligocene Bulson Creek rocks in Skagit County and subsurface Miocene strata in the lower Fraser Valley of British

[1] *Q. banksiaefolia* is an extinct member of the Fagaceae (oak/beech family), but botanists believe it is probably not a true member of the genus *Quercus* and needs to be reclassified.

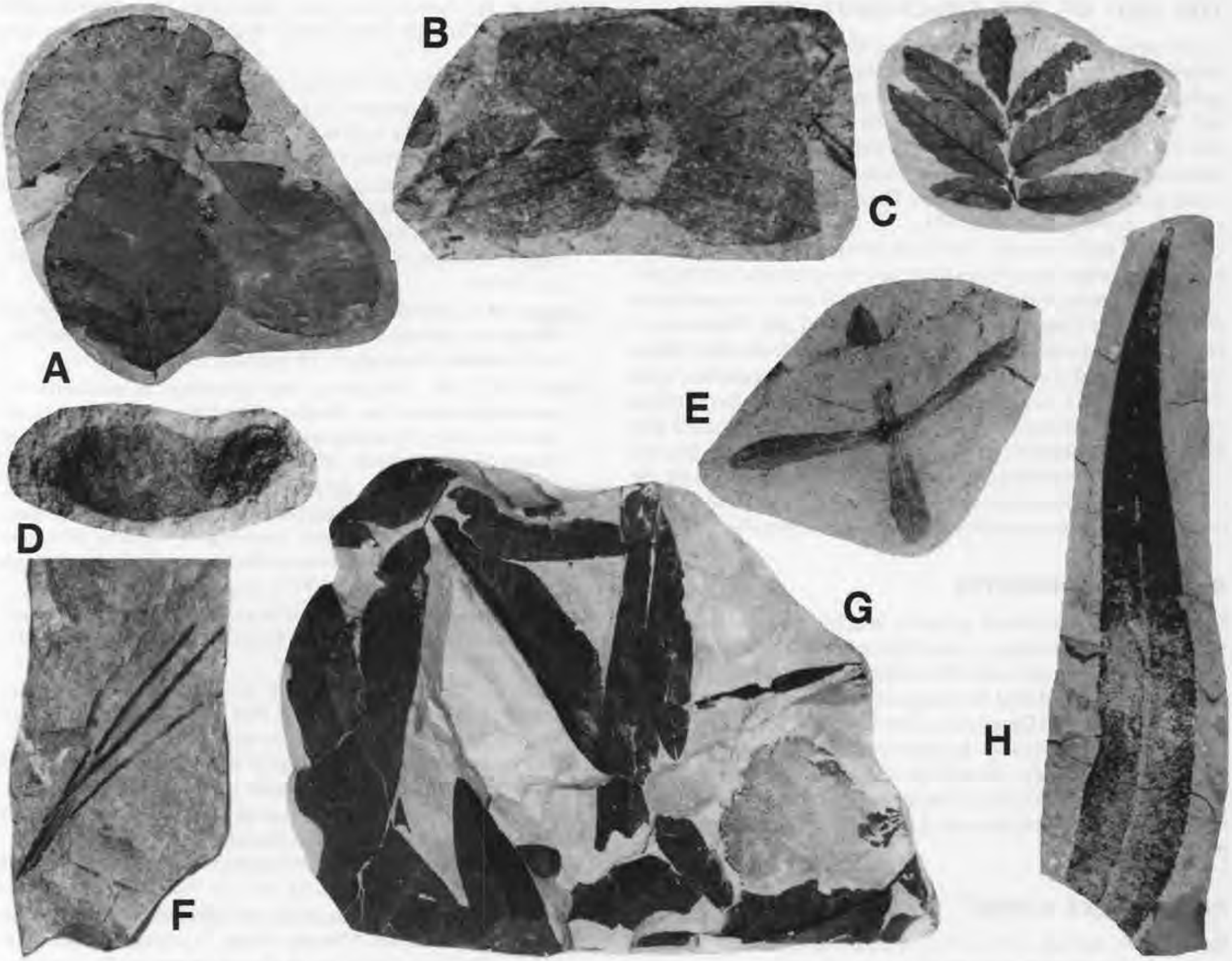

Figure 14. Plant fossils from the Padden Member at Alabama Hill and the Walker Valley florule. **A.** *Cladrastis*, 0.65x, Walker Valley. **B.** *Florissantia* flower, 2x, Walker Valley (Mike Sternberg collection). **C.** Unidentified leaves, actual size, Padden Member. **D.** *Acer* (maple) winged seed, 2x, Walker Valley. **E.** *Cruciptera* (Juglandaceae), winged seed, 2x, Walker Valley. **F.** *Pinus* (pine), actual size, Walker Valley. **G, H.** *Salix* (willow) leaves, G at 0.77x, H at actual size, Padden Member.

Columbia indicate that sedimentation continued throughout the early and middle Tertiary.

Alternatively, the Chuckanut climatic shift may have been caused by a transient cooling event that occurred during the Eocene. Paleoclimate data from the Puget Group in King County, Washington, indicate abrupt decreases in mean annual temperature at about 47 and 40 Ma (Wolfe, 1995), but the floral changes during these episodes do not seem to have been nearly as significant as those that accompanied the cooling event at 34 Ma.

A third possibility is that the Padden Member was deposited during a period of climate change that resulted from local tectonic activity. This hypothesis requires an episode of uplift sufficient to affect temperature and precipitation, a concept that has several drawbacks. Just as modern coastal forests are botanically distinct from nearby montane forests, an elevation increase might have caused changes in the ancient Chuckanut flora. However, the lithology and regional geologic setting of the Padden Member suggest deposition on a low-elevation flood plain rather than on a mountain slope or upland plateau. The uplift scenario is also contradicted by CLAMP evidence. An elevation increase of at least 1,000 m would have been required to account for the reduction in mean annual temperature, and this topographic change would probably have caused an increase in annual precipitation, not the decrease that we observe for the Padden Member.

Fossiliferous siltstones at Walker Valley in western Skagit County may be correlative with the Padden Member; they contain similar floral assemblages (Fig. 14). Palms are not present, and ferns and lowland conifers are very scarce. Leaf fossils include *Salix* (willow) and *Cladrastis*; the latter is a tree fossil that is found in the youngest strata of the upper Eocene Puget Group of King County, but not in older parts of the formation. Walker Valley rocks also contain imprints of *Pinus* (pine) foliage; this conifer is typical of temperate forests. CLAMP calculations based on 41 dicot leaf forms from Walker Valley indicate a MAT = 13°C, MART = 16°C, and a cold month mean temperature of 5°C. Annual precipitation was 100–200 cm. These values resemble those from the Padden Member.

THE END OF THE CHUCKANUT ERA

Chuckanut deposition ended when onset of the North Cascades orogeny caused lowland basins to be uplifted, but the geologic record provides scant evidence of these middle and late Tertiary events. In addition to the changes in depositional environments related to faulting and uplift, volcaniclastic sandstones and bentonite layers in the upper part of Chuckanut strata near Deer Creek in Skagit County indicate episodes of volcanic activity (Cruver, 1981).

By the mid-Tertiary, surficial processes were dominated by erosion rather than deposition, and the geologic record provides few paleogeographic clues. Fossil crabs in sandstone concretions in Pleistocene glacial drift near Lake Whatcom offer enigmatic evidence of Oligocene marine deposition (Mustoe, 1982), and fossil pollen was obtained in samples from deep drill holes near the present U.S.–Canada border that penetrated Miocene deposits (Hopkins, 1968; Mustard and Rouse, 1994). Otherwise, the cessation of Chuckanut deposition closed the curtains on our window into the past, and the transition from lowland semitropical rain forest to temperate coastal and montane environment remains a puzzle.

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SUMMER INTERNS

Community Youth Services sent us three interns this summer. Their participation, hard work, and consistency made a big difference in the amount of work we accomplished. Many projects were completed because of help of these students.

Marco Gonzales has worked for us at the front desk for two summers in a row. He is a student at Yelm Extension School and will graduate this coming June. He expects to be President of the United States in about 25 years. We have no reason to think he won't be.

Phuong Nguyen worked as office support staff and will be a junior at Capital High School this school year. She typed, answered phones, took messages, filed, copied, folded maps, ran errands, sent out mail, prepared file folders, and boosted morale. We see great potential in Phuong, and we wish her well.

Brandy Jones worked on the Geology Library staff this summer. She will be a senior at Capital High School. She did photocopying, proofreading, inventory of books, shelving, and rearranged books on the shelves. She is very sharp, and we expect to hear great things about her in the future.

Preliminary Study of Minerals in Tacoma Smelter Slags

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A smelter for processing raw ore and concentrates from mine mills operated in the Ruston area of Tacoma from 1887 to 1985 (Fig. 1). The facility was the only tidewater smelter in the nation and was the last in Washington to cease operations. This smelter is now undergoing cleanup and site closure. (See Lasmanis, 1993, for a short history of the smelter.)

The original plant was a lead smelter operated by Selby Smelting Co. The Tacoma Smelting Company added a copper blast furnace in May 1902 and a copper refinery the year after. In 1905, both the Selby and Tacoma interests were purchased and placed in a holding company, American Smelters Securities Co. By 1910, lead smelting ceased, and the plant's capacity was increased to treat copper ores and concentrates. In 1916, the first reverberatory furnace was installed. American Smelting & Refining Co. (ASARCO) assumed ownership of the industrial facility in 1923 and is the current owner.

Ores and concentrates from Washington, Oregon, Montana, Alaska, and the Coeur d'Alene mining district in Idaho, as well as from Mexico, Central America, Chile, Peru, Korea, Japan, and the Philippines, were processed at the Tacoma smelter. In addition, high silica flux was brought to Tacoma to be used in the smelting process. Flux lowers the melting temperature of the minerals and promotes the formation of slag.

Some of the flux was also an ore of gold, silver, copper, and other metals. For instance, more than 1 million tons of high silica content gold-silver ore from the Lovitt mine at Wenatchee was shipped directly to the Tacoma smelter. The various fluxes used also contained small amounts of pyrite, calcium-magnesium carbonates, and wallrock silicates such as feldspars, clays, and micas.

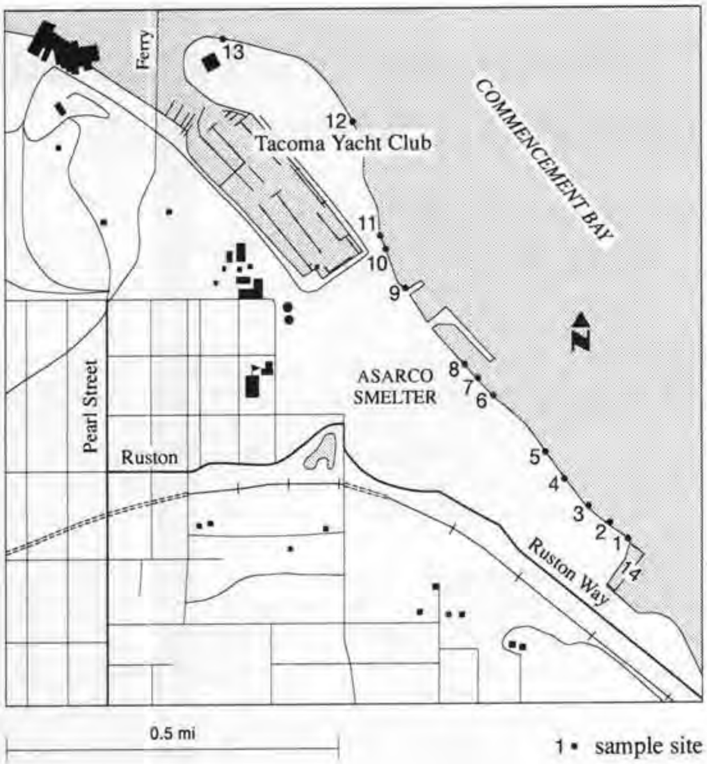
In 1902, slag pots were used to remove the slag from the lead and copper blast furnaces and make a synthetic bedrock peninsula surrounding the smelter site. Some of these conical slag forms, about 5 ft in diameter, can be seen today (Fig. 2) along the northwest and southeast corners of the extended shoreline. Later, less metal-rich blast furnace and reverberatory furnace slag was poured as a liquid over the earlier slag. Photographs and diagrams in a professional journal from 1925 (Young, 1925) show the constructed shoreline and dock locations as we see them today.

In 1996, the Aquatic Resources Division of the Washington Department of Natural Resources funded an initial investigation of metal migration in the intertidal zone through a study of slag, other smelter products, secondary minerals, and chemical compounds. We sampled the intertidal area of the Tacoma smelter property at 14 sites (Fig. 3). Each site was ex-

Figure 1. View of the ASARCO smelter to the west from Commencement Bay taken in 1992 before the smokestack was decommissioned and demolished (Jan. 17, 1993). The smokestack (on the left) was 572 ft 10 in. high. Built in 1917, for many years it was considered the tallest in the world.

Figure 2. Giant slag cones (about 5 ft in diameter) from earlier slag deposits (in the foreground) at sample site 9. Cones have higher metal contents than the molten slag that was later poured on the surface created by the piled cones. Abundant primary minerals were found here, and bright green and blue copper chlorides and copper sulfates were forming at the surface of the slag. Note the barnacles and mussels growing along the sampled area.

Figure 3. Map of the ASARCO smelter property in the Ruston area of Tacoma, as of May 1996, showing the shoreline extended by slag and the numbered sampling sites.



amined and sampled for "whole rock" analysis. Secondary minerals and stained slag showing mobilization of metals were collected for identification by scanning electron microscope and electron-microprobe analysis.

The Smelting Process and the Tacoma Tapping Slags

The smelter (Fig. 4) extracted metals by combining sulfide ores and concentrates with a flux under high heat and reducing conditions in a furnace to produce a layered melt in which heavy base-metal sulfides accumulated into "converter mattes" beneath lighter, iron-rich silicates derived from the mixing of the flux materials and ore minerals. These silicates are known as "tapping slags" and are skimmed and poured off as waste. At the Tacoma smelter, the mostly molten tapping slags were often poured from hoppers directly into the waters of Commencement Bay to form the slag peninsula (Fig. 5), resulting in the formation of spectacular steam clouds.

Early tapping slags at this smelter may have contained rich and visible copper-iron sulfides. In the trade, these are known as "prills", buckshot-size particles of metals or sulfides. Intermediate between tapping slags and converter mattes are "converter slags", which can contain many prills. For obvious economic reasons, discarding of converter slags was minimized.

The major solid waste product from the smelting process is tapping slag. However, due to inefficiencies in the pyrometallurgical process, some matte and speiss (a mix of copper arsenide and antimonide) with high metal contents were also discarded with the calcium-iron silicate tapping slags.

The tapping slags are a dark-brown, fine-grained volcanic-rock-like material that exhibits complex geochemistry. Elongate crystals of fayalite, the iron end-member of the olivine group, are intergrown with this glassy material in minor amounts. Scattered randomly to evenly are rounded crystals of iron oxides, including magnetite, maghemite, and rod-like crystals of wustite. Magnesium, aluminum, and chromium oxides occur in many tapping slags. Tiny (5–30 µm) inclusions of copper and iron sulfides may be observed via light microscope. Less common, but also pervasive, are 2–10-µm inclusions of iron arsenide (loellingite, $FeAs_2$), copper arsenides, and native copper. The tapping slags exhibit, in places, thin discontinuous coatings of relatively simple associations of green, bluish green, and sky blue copper chlorides, sulfates, and sulfate chlorides and yellowish brown iron hydroxides.

The slags have a coarse parting texture (Fig. 6) from the splatter and chill patterns of disposal. Coarse angular voids can occur in the slag pile when chilled slag "skins" are jumbled about by still-molten slag during the dumping of a hopper. Small (1–10 mm) vesicles are also commonly created by volatiles trapped in the slag. The vesicle walls may be lined by feathery, euhedral iron silicate (fayalite) crystals.

Secondary mineral phases are derived from weathering of the primary sulfides. (See Table 1.) The sulfide prills show the start of conversion to secondary phases. Alteration of the exterior 100 µm of the subspherical sulfide prills is common, even at more than 10 cm from the surface of the exposed slag. The penetration of weathering is enhanced by the numerous chill partings created when the slag was poured into cold seawater. Unfractured silicate slag may host prills showing 50–150-µm oxidation skins at depths of as much as 3 cm below exposed surfaces. This indicates that even fresh slags are permeable to oxidizing aqueous solutions.

The scattered boulders and fragments of sulfide and arsenide/antimonide converter mattes have the highest susceptibility to decomposition by weathering and oxidation and also have the highest concentration of metals. Large pieces of slag used as fill along the beach south of the Tacoma smelter site have also shown signs of secondary copper minerals. Along the south end of the smelter site, copper and other unidentified

Figure 4. ASARCO smelter before demolition. Photo taken November 5, 1992.

Table 1. Selected minerals identified in the tidewater samples of Tacoma smelter slags. Identifications are based on work performed at Cannon Microprobe

Alloys, elements: Sb, Bi, Cu, Pb, Sn-Sb alloy, Pb-Cu-Sn alloy, Pb-Cu alloy

Antimonides: Bi antimonide, Cu-Ni antimonide, Fe antimonide, Ni-Fe-Co-Cu antimonide (seinäjokite?), Ni antimonide (nisbite?), Ni-Cu antimonide (zlatogorite?)

Arsenates: Pb-Cl arsenate (georgiadesite?), Pb-Cu arsenate (arsentsumebite, duftite, bayldonite?), Pb-Cu-Cl arsenate, Pb-Cu arsenate (gartrellite?)

Arsenides: Cu-Sb arsenide, Cu-Ni-Sb arsenide (paxite, koutekite?), Fe-Co-Ni arsenide, Fe arsenide (loellingite), Pb-Cu arsenide

Chlorides, chlorates: Cu chloride (atacamite, nantokite, paratacamite(?), botallackite), Cu-Fe-Zn chloride, Pb-Sb chloride (thorikosite?), Pb-Cu-Ag chloride (boleite), Pb carbonate chloride (phosgenite), Pb-Cu chloride (pseudoboleite), Pb-Cu-Sb chloride (mammothite?), Pb chloride (cotunnite), Ag chloride (chlorargyrite), Pb-Ag-Cu-Sb chloride

Hydroxides: Fe hydroxide (goethite)

Oxides: Mg, Al, Fe chromite, Cu oxide (melaconite, cuprite), Fe oxide (hematite, maghemite, wüstite), Pb oxide (litharge?), Mg oxide (periclase?), Fe-Al oxide (spinel)

Phosphates: Cu-Fe-Cl-As phosphate

Silicates: Fe-Mg (Zn) silicate (zincian fayalite), Mg silicate (enstatite?), Ca-Fe silicate (hedenbergite, diopside?), Ca-K-Fe-Al silicate, Pb-Fe-Cl silicate

Selenides: Bi selenide (guanajuatite?), Pb-Bi selenide (padmaite?)

Sulfates: Cu sulfate (langite, posnjakite), Pb sulfate (anglesite), Pb-K-Fe sulfate (plumbojarosite)

Sulfides: Cu-Fe sulfide (chalcopyrite), Fe-Cu sulfide, Pb-Cu sulfide, Cu sulfide (chalcocite), Zn-Fe sulfide (sphalerite?), Pb-Sn-Cu sulfide, In-Cu-Zn sulfide, Cu-Fe-Zn-Sb sulfide (tetrahedrite?), Cu-Pb-Fe sulfide (betekhtinite?), Fe-Cu-Ni sulfide

Tellurides: Pb-Fe-Cu telluride

Figure 5. The central loading dock area near sample site 9 showing vertical walls of slag poured to form the seawall.

Figure 6. Typical wave-cut terrace in thinly bedded slag that was deposited in the molten phase (sample site 11). This site has fewer secondary minerals forming compared to the other sample sites.

metals have been producing the bright green and bluish stains on slag surfaces.

Investigation of Slag Minerals

To determine the overall chemistry of the slag, 11 samples were sent to Chemex Labs in Vancouver, British Columbia, for analysis by x-ray fluorescence, the inductively coupled plasma method, and sulfur analysis using the LECO induction furnace method. Most of these samples were taken where there was distinct color of secondary minerals or ground-water seepage. Although there is some variation among samples, the slag is approximately 37 percent iron and 39 percent silica; abundant metals detected are zinc, copper, lead, antimony, arsenic, and manganese. Minerals have been identified by x-ray diffraction, scanning electron microscope, and wavelength and energy-dispersive electron-microprobe analysis. Some of the minerals identified are listed in Table 1. Photos of these minerals (Figs. 7–15) were taken by Bart Cannon with a scanning electron microscope (SEM) in the backscattered electron (BSE) imaging mode.

It is not practical in a short article to consider all the mineral reactions that must be occurring in the slag–marine–ground-water environment at the ASARCO smelter site. The reactions depend on original slag mineralogy and the composition of the fluids that contact it. Seawater is 96.5 percent water and about 3.5 percent salts. Average salt water contains Cl, Na, SO_4, Mg, Ca, K, HCO_3, Br, and H_3BO_3. The pH of seawater is usually neutral to slightly alkaline (7.8–8.3) (Fairbridge, 1972). The potential exists for chlorides, sulfates, and many other metal-bearing compounds.

Typical Chemical Reactions

Because copper is abundant, easily mobilized, and readily combines with chloride to form copper chloride complexes, the most common secondary minerals detected by the electron microprobe were the trimorphous copper chlorides such as botallackite, and atacamite ($Cu_2Cl(OH)_3$). These minerals are probably formed from the slag by the dissolution of copper oxides and copper-iron sulfides in acidic oxidizing solutions by ground water–mineral interaction and chlorides supplied

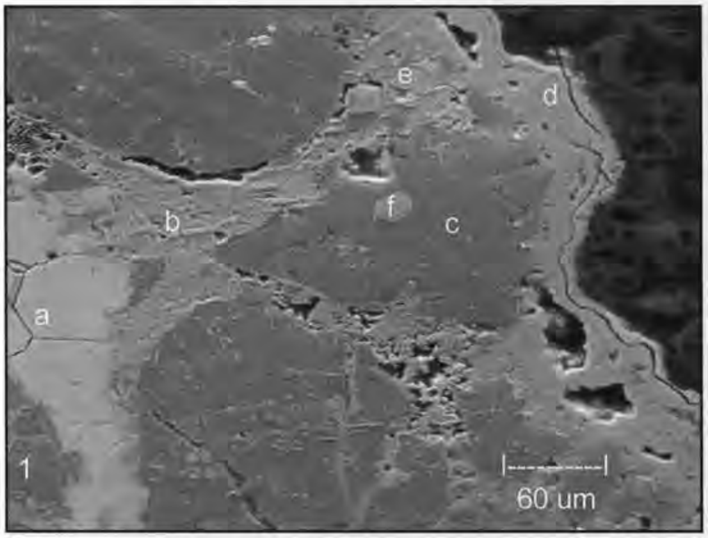


Figure 7. SEM/BSE image of a polished section of converter slag with a bright green surface coating from site 13: **a**, $CuFeS_2$ (chalcopyrite); **b**, intergrowth of Cu>Fe chloride and Fe hydroxide replacements of $CuFeS_2$; **c**, Fe-Ca silicate; **d**, Cu chloride surface incrustation; **e**, Cu>Fe chloride replacement of $CuFeS_2$; **f**, maghemite inclusion.

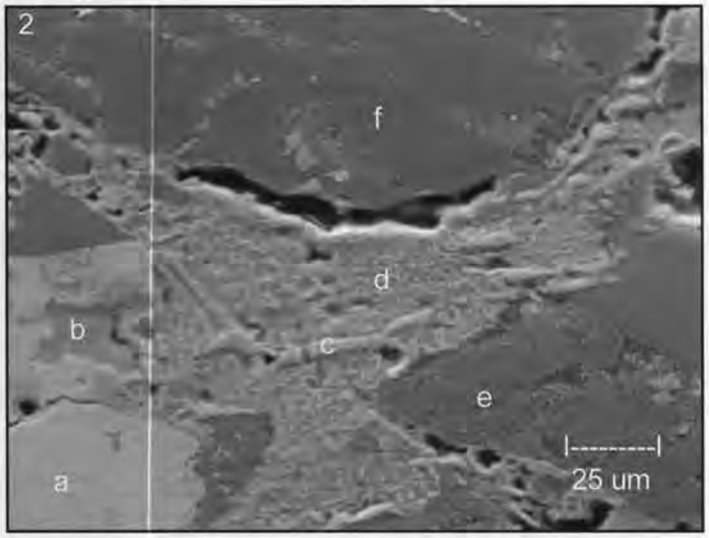


Figure 8. SEM/BSE image of a polished section showing magnified area of Figure 7: **a**, $CuFeS_2$ (chalcopyrite-like); **b**, Cu chloride; **c**, Fe hydroxide; **d**, Fe hydroxide replacements of botallackite in Cu>Fe chloride (both are replacing Cu>Fe sulfide); **e**, higher Ca Fe>Ca silicate; **f**, lower Ca Fe>Ca silicate.

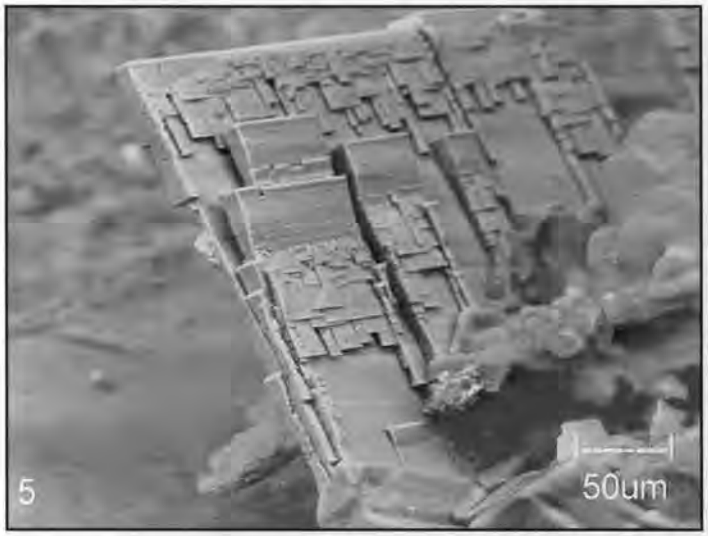


Figure 9. SEM/BSE image of botallackite crystals from a vesicle at site 13. Botallackite is trimorphous with atacamite and paratacamite.

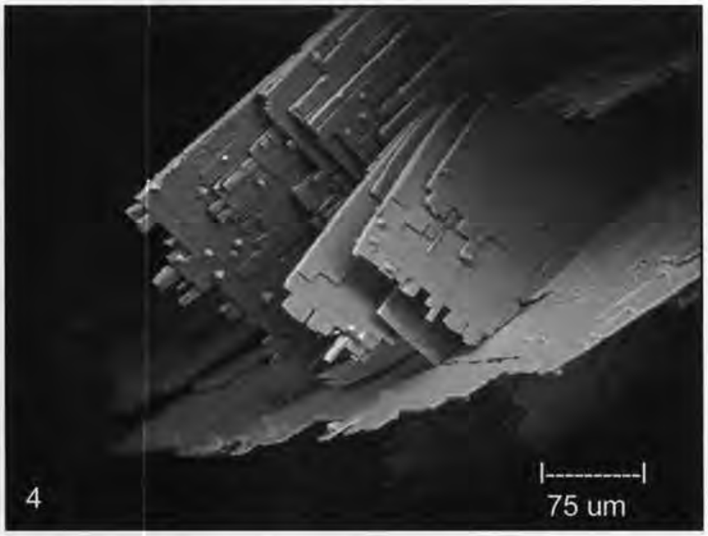


Figure 10. SEM/BSE image of botallackite crystals from a vesicle at site 12.

by seawater from Puget Sound. A possible reaction is the dissolution of copper-iron sulfides (such as chalcopyrite and the idaite/bornite phase) by oxidation and reprecipitation as the copper chloride atacamite: $2Cu_5FeS_4 + 10O_2 + 5Cl^- + 15H_2O \rightarrow 5Cu_2(OH)_3Cl + 15H^+ + 2Fe^{+2} + 8SO_4^{-2} + 8e$.

Slag vesicles can remain filled with seawater for more than a year after hand samples are removed from the site. We observed soluble copper salts and halite forming within hours on the desktop after we removed a sample from the site. The minerals remained in a somewhat stable configuration in the controlled environment of the office. Apparently seawater and copper-rich solutions in the sample moved through fractures to the surface to form this precipitate. Such copper salts at the slag/seawater interface would be washed away by the tides.

Behavior of Other Metals

Other metals that tend to form chloride complexes as strong as the cuprous ion are silver and mercury. In the bulk analysis of the Tacoma slag, both silver and mercury are less abundant than copper and do not appear to be significant in the slag mineralogy. Other more common base metals in the slag pile, such as zinc, lead, and even cadmium, form weaker chloride complexes and more soluble sulfates. They are relatively soluble under conditions in which copper is very insoluble.

Much of the zinc is probably kept from solution because it is incorporated into the silicate structure of fayalite to form zinc fayalite (Zn_2SiO_4). This would account for the high zinc values in the bulk analysis. Zinc sulfides, although less common, are also present and are easily oxidized, mobilizing zinc into solution. Some of the zinc released through oxidation from sulfides is in solution and precipitates on the slag surface and within fractures as zinc chlorides and sulfates. Most of the zinc in solution remains in solution and is probably passed on through fractures and cracks in the slag to the seawater.

Lead sulfides also oxidize easily and release lead into solution. Secondary lead chlorides and sulfates occur, but are only sporadically abundant. (They are very abundant in some samples.) Lead in solution is passed on to the seawater.

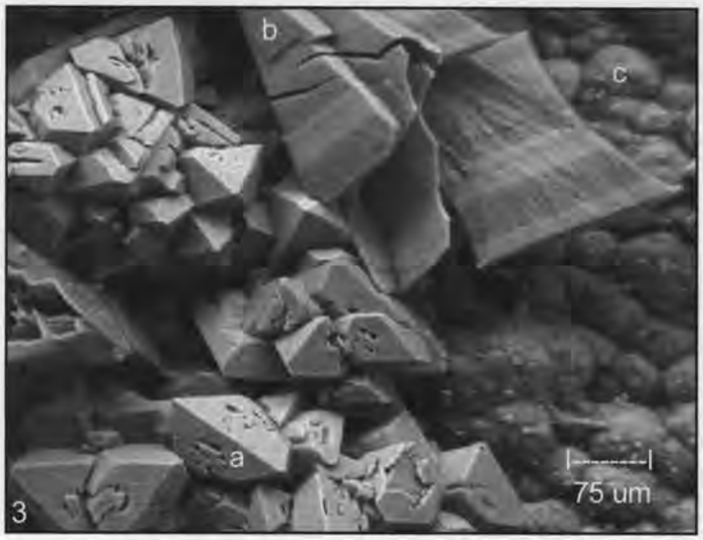


Figure 11. SEM/BSE image of a vesicle lining at site 13: **a**, atacamite crystals; **b**, Fe hydroxide replacement of botallackite; **c**, Fe>Cu hydroxide.

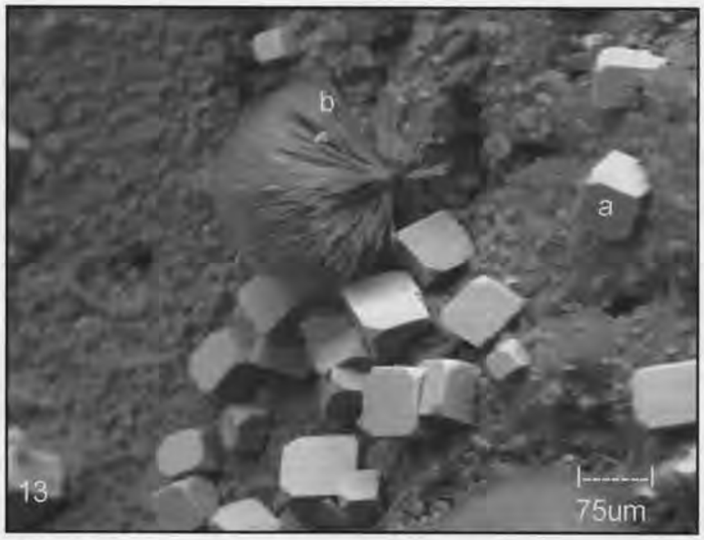


Figure 12. SEM/BSE image of an unnamed emerald green Pb>Cu>Fe chloride from a vesicle at site 13: **a**, undescribed emerald green Pb-Cu-Fe chloride associated with **b**, sky-blue unknown Cu sulfate/chloride.

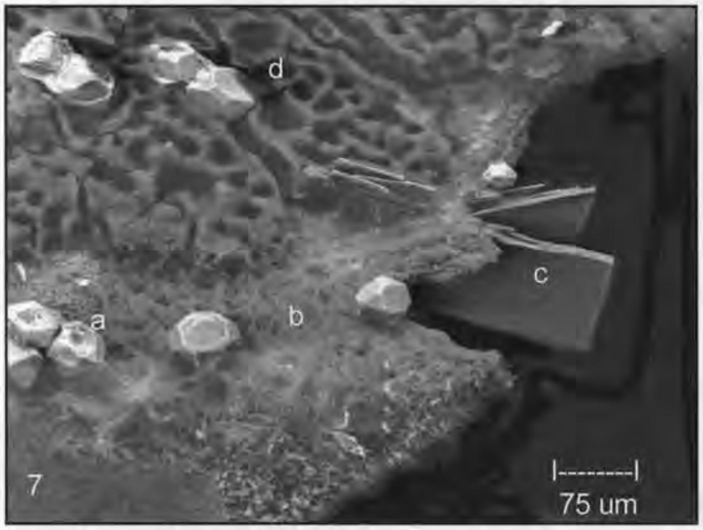


Figure 13. SEM/BSE image of secondary minerals lining a vesicle at site 6: **a**, undescribed emerald green crystals; **b**, cottony bluish Cu chloride; **c**, botallackite; **d**, Ca sulfate that may be gypsum.

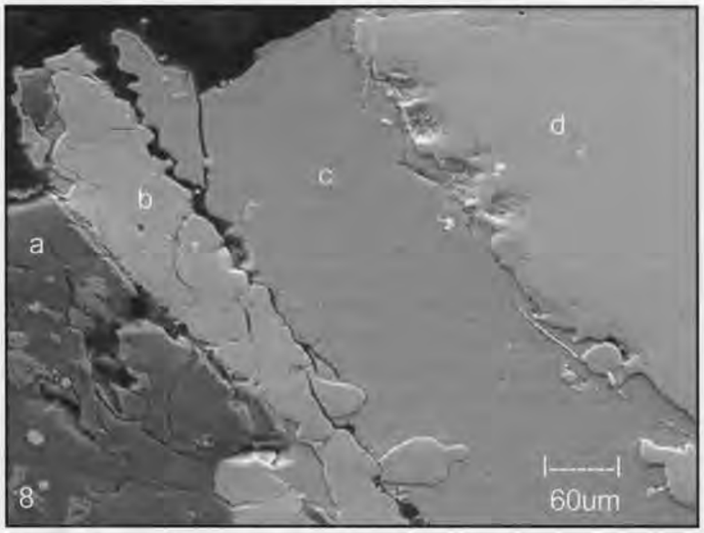


Figure 14. SEM/BSE image of a polished section of arsenian copper prill in slag at site 12: **a**, Fe>Ca silicate; **b**, Cu sulfide, such as chalcocite; **c**, nantokite (CuCl); **d**, arsenian copper.

Another abundant element at the site is arsenic. The primary minerals are lead arsenide and iron arsenide; secondary minerals are generally lead-arsenic chlorides and arsenates, which are probably highly soluble. Most of the arsenic released to solution is probably passed on to the seawater. Arsenic was volatilized during smelting, and some was emitted through the smokestack. Arsenic in sediments near the site was probably deposited as airborne particles from the smokestack rather than dissolved from arsenic minerals in the slag.

Looking Ahead

Slag along the intertidal zone has been exposed to interaction with air, ground water, and salt water for more than seven decades. The formation of a diverse array of oxidation products from primary metallic phases in both the tapping slags and converter mattes indicates that metal ions are circulating within those slags and mattes, and some quantities are escaping into the surface environment. Some elements, such as nickel and cobalt, have not been trapped as secondary minerals and may be fully liberated into the surface environment.

Fish and shellfish can be severely affected by high levels of chemicals in water and sediments. Remediation strategies should be selected that will not destabilize the slag pile and that will prevent unstable or metastable minerals from releasing additional metals that would damage the aquatic habitat and the associated organisms.

The mineralogical work performed here should help determine the best way to clean up the site. Identification of substances and minerals that have formed from slag and other smelter products and understanding mineral and fluid pathways within the slag pile will help agencies and companies choose how to remediate the site to prevent migration of metals into the tidal environment. For example, existing options that need further investigation and modeling are (1) whether to pull the slag pile back from the salt water or (2) leave the slag pile in place and cap it.

Selected References

This bibliography was prepared as part of the contract deliverable to the Aquatic Resources Division of the Department of Natural Resources. This was no easy task: there have been no studies in North America of secondary slag minerals, although investigations have been made in several European countries and Africa. The International Association of Collectors of Slag Minerals does publish a newsletter on secondary minerals in slags. More typically, however, data have been published in references that are not readily available, as in the case of Laurion, Greece, where Athenians have dumped slag into the sea since ancient times, and the secondary minerals have been studied for more than 50 years. This bibliography may assist other researchers in identifying secondary slag minerals and unraveling the complex chemical reactions that lead to their formation and accessibility to the environment.

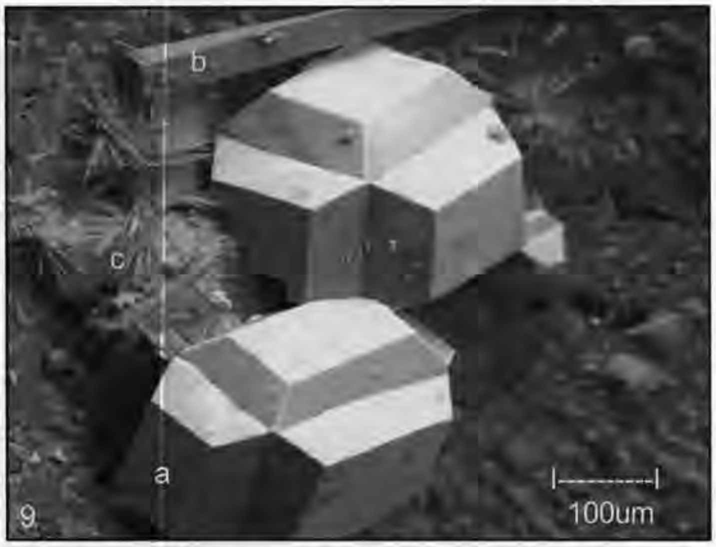


Figure 15. SEM/BSE image of secondary minerals lining a vesicle at site 4: **a**, pseudoboleite ($Pb_{31}Cu^{2+}_{24}Cl_{62}(OH)_{48}$) as epitaxial overgrowths on boleite ($Pb_{26}Ag_{10}Cu^{2+}_{24}Cl_{62}(OH)_{48} \cdot 3H_2O$); **b**, gypsum; **c**, undescribed Cu-Fe sulfate chloride. Silver probably occurs in solid solution in the Cu-Fe sulfides. Oxidation produces Ag chlorides.

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Surface Mine Reclamation Awards

The Department of Natural Resources (DNR) has established annual awards to recognize outstanding reclamation of surface mines (other than coal mines). These awards honor permit holders and individual employees who reclaim mines in an exemplary manner. The awards also recognize reclamation efforts on sites exempt from the Surface Mine Reclamation Act [RCW 78.44] because of size or because the site was abandoned by earlier mine operators prior to 1971. Criteria for evaluating entrants are described below by award category. If no mine reclamation has occurred that meets the stringent criteria of a category, no award may be granted for that year. Nominations for awards can be made by the public, permit holders, DNR, or other agencies. Nominations received by March 1, 1998, will be eligible for the 1997 awards.

Recognition for Reclamation Award

To receive this award, an operation must meet or exceed the DNR-approved reclamation plan. Exemplary reclamation may:

- Demonstrate innovation or creativity in reclamation, such as creating unique wetlands or enhancement of wildlife and fish habitat or topographic elements.
- Include voluntary reclamation of mined land that is exempt from reclamation under the Act.
- Use native plant species in revegetation.
- Use innovative research and approaches to reclamation that can be applied at other mines.
- Show attention to water quality and erosion prevention.
- Display orderly segmental mine development resulting in high-quality reclamation.
- Demonstrate a consistent long-term commitment to reclamation.

Best Reclamation for a Small Operation Award

Criteria are the same as for the Recognition for Reclamation award, except that the operation is less than 16 acres in size.

Good Neighbor Award

The winner of this award works unselfishly with neighbors and the community in a spirit of cooperation. For example, the operator may have developed cooperative projects that benefit the environment and the community.

Reclamationist of the Year

A new category for the 1998 awards is being created to honor individual employees whose skills and efforts have made contributions to successful reclamation.

The Award Process

Winners will be selected by a panel of judges, including representatives of DNR, the mining industry, environmental interest groups, and other state environmental agencies.

DNR surface mine reclamationists will present the candidates to the panel. Because the judges may not have opportunities to visit the nominated operations, 35-mm slides, photos, or videos showing conditions before, during, and after reclamation will help the judges review the nominees. At least twelve slides and six color photos should be submitted. Written descriptions of site reclamation will help the panel reach their decision and may include the history of reclamation, planned development, partnerships made with neighbors, and direct benefits to the immediate environment, as well as specific information about water control, sloping, topsoil handling, revegetation, and other interesting aspects of the reclamation. For Reclamationist of the Year, a written description of why the individual is deserving should be included.

Winners will receive an award and public recognition from the Department. They will also be nominated for national honors if appropriate.

Nominations should be made on the form on the next page. Please feel free to copy this form. ■

Erratum

In the previous issue, "Something old, something new..." by C. Finn and W. D. Stanley, in the citation for Stanley and others, 1997, the missing initial for Rodriguez is B.

NORTHWEST GEOLOGICAL SOCIETY

The Northwest Geological Society holds meetings on the second Tuesday of the month, October through May, at the University Plaza Hotel, just west of I-5 on 45th Ave. Anyone may attend these meetings.

This fall, the Division of Geology and Earth Resources plans to bring copies of important new publications, new Division releases, and papers related to the speaker's subject "for inspection only" to show members what's available.

For membership information, write to Donn Charnley (NWGS Secretary), 19344 11th Ave NW, Seattle, WA 98177-2613. Dues are $20 a year, $5 for students.

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We have 20 or fewer of each of the following publications listed as "out of print" in the current "Publications of the Washington Division of Geology and Earth Resources":

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Geology and mineral deposits of the north half of the Van Zandt quadrangle, Whatcom County, Washington, Bulletin 50, by W. S. Moen, 1962, 129 p., 4 pl.

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We'll send these out to you, at $1 a copy, on a first-come, first-served basis. Please include $1 for postage and handling with your request.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands

RECLAMATION AWARDS NOMINATION FORM

(Please print or type the information. Nominations must be received by March 1, 1998.)

Please check the category for which you wish to nominate the site:

☐ Recognition for Reclamation Award ☐ Good Neighbor Award

☐ Best Reclamation for a Small Operation Award ☐ Reclamationist of the Year Award

Person making the nomination: ______________________ Phone: (____)__________

Organization, business, or person nominated: ______________________

Name of site: ______________________

Location: ______________________

DNR Reclamation Permit Number (if known): ______________________

Description of reclamation: *(You may attach a separate sheet.)* ______________________

Presentation material included with nomination: *(We suggest at least 12 slides and 6 color photos.)*

☐ 35-mm slides (how many?) _____ ☐ Photos (how many?) _____ ☐ Video

All presentation material becomes the property of the Department of Natural Resources.

Your address: ______________________

City/State/Zip + extension: ______________________

Send this nomination form to:

Dave Norman
Regulatory Section
Division of Geology and Earth Resources
PO Box 47007
Olympia, WA 98504-7007

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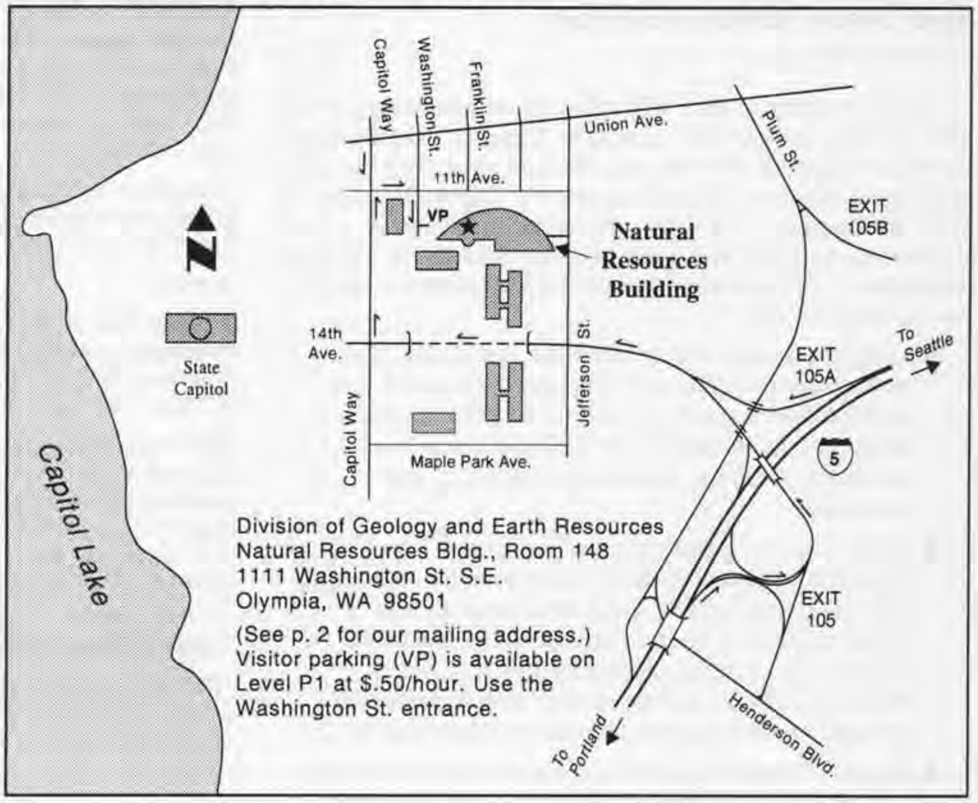

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NORTHWEST MINING ASSOCIATION ANNUAL MEETING

December 1–5, 1997 Spokane, Washington

Cecil Andrus, former Idaho Governor and Secretary of the Interior, is keynote speaker. Also on the program are Jeffrey Todd and Debra Struhsacker, authors of *Environmentally responsible mining*; Leo Pruitt, Phelps Dodge Corp., and Russ Fields, Director, Nevada Div. of Minerals, who will speak on the National Mining Assn./Western Governors Assn. Abandoned Mine Land initiative; Sen. Larry Craig (R-ID), who will discuss mining and the 105th Congress; and Gen. Richard Lawson, Pres. and CEO of the National Mining Assn., who will talk about grassroots coalition building as a means of restoring the multiple-use management principle to public lands.

Technical Sessions will feature the use of global positioning systems (GPS) and other new technologies. Short courses include: Geology, geochemistry, and mineral deposits of the Guiana and West African shields; Photo remote sensing; Prospering in international business; and Issues in mineral exploration.

For more information and registration forms, contact: Northwest Mining Association, 10 N. Post St., Suite 414, Spokane, WA 99201; (509) 624-1158; *fax:* (509) 623-1241.

Ten-Year Direction for Federal and State Earth Science

Continued from page 2

Several recent actions will affect the deliberations of the SST. During the current session of Congress, the National Geologic Mapping Act was reauthorized until the year 2000 and signed into law by the President on August 5. A June 6, 1997, memorandum by White House staff to the heads of executive departments and agencies lists federal FY 1999 research and development priorities. Those pertinent to the geological sciences are:

- *Large-scale networking, high-end computing, and next generation Internet*—Support the research and development needed to assure U.S. technological leadership in computing, including investments in hardware, software, algorithms, modeling, and simulation.
- *Environmental monitoring and research*—Improve the effectiveness of Federal environmental monitoring and research programs. Near-term steps include: (1) production of a report card on the health of the Nation's ecosystems as requested by the Vice President, and (2) definition and implementation of regional monitoring and assessment pilot projects.
- *Natural disaster reduction research*—Promote natural disaster reduction research including risk assessment, improvement of methodologies to assess losses of human life and property, integration of natural disaster information systems, and consolidation of emergency warning/alerting systems.

It is clear from both state and federal initiatives that the future will see the integration of physical and biological sciences resulting in significantly improved understanding of the processes that shape our Earth and its environment. ■

COLOR AEROMAGNETICS MAP AVAILABLE

Carol Finn, U.S. Geological Survey, has made available a "master" color print of the map of merged aeromagnetic data for Washington that appeared as a gray-shaded relief map in Figure 1 of Finn and Stanley, p. 4 in the previous issue of *Washington Geology*. If you would like a color (xerographic) copy, please send us your request along with $1 for postage and handling.

DIVISION RELEASES

Geologic map and interpreted geologic history of the Kendall and Deming 7.5-minute quadrangles, western Whatcom County, Washington, Open File Report 97-2, by J. D. Dragovich, D. K. Norman, R. A. Haugerud, and P. T. Pringle, 39 p., 3 pl. $3.24 + .26 (tax) = $3.50.

Geologic map of the Mead 7.5-minute quadrangle, Spokane County Washington, Open File Report 97-3, by R. E. Derkey, 9 p., 2 pl. $1.85 +.15 (tax) = $2.00

In press:

Geologic map of the Gilbert 7.5-minute quadrangle, Chelan and Okanogan Counties, Washington, Geologic Map GM-46, by J. D. Dragovich, D. K. Norman, R. A. Haugerud, and R. B. Miller, 67 p., 1 pl. Check with us for the price.

Quaternary stratigraphy and cross sections, Nooksack, Columbia, and Saar Creek valleys, Kendall and Deming 7.5-minute quadrangles, western Whatcom County, Washington, Open File Report 97-4, by J. D. Dragovich, Andrew Dunn, K. T. Parkinson, and S. C. Kahle, 8 pl. plus 13 p. text. Check with us for the price.

Publications List Updated

We have recently printed an updated version of our publications list. As always, copies are free, but please include $1 for postage and handling when you request a copy.

Mineralogical Societies Directory in Library

Our library has received the 1997 membership directory for the Northwest Federation of Mineralogical Societies, which lists member clubs in Alaska, Idaho, Montana, Oregon, Utah, and Washington.

SMITHSONIAN RESEARCH FELLOWSHIPS

Once again, the Smithsonian Institution offers research fellowships in the earth sciences for 1998 at postdoctoral, senior, predoctoral, and graduate student levels. Proposals can be made for these topics: meteoritics, mineralogy, paleobiology, petrology, planetary geology, sedimentology, or volcanology. The deadline for submittals is January 15, 1998. More information and application forms are available from the Smithsonian Institution, Office of Fellowships and Grants, 955 L'Enfant Plaza, Suite 700, MRC 902, Washington, DC 20560, or e-mail siofg@ofg.si.edu.

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