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Cover Photo: An exposure of late Pleistocene outwash deposits that underlie the area around Forks. The deposits at this site contain clasts of Olympic core rocks as well as granitic rocks from Canada. The presence of core rocks suggests that alpine glacial sediments were incorporated into the deposit. However, the granitic rocks, poor sorting, and steeply dipping foreset beds suggest ice-proximal deposition by continental ice. See article, p. 30. *Photo by Wendy Gerstel.*

Update on the Crown Jewel Mine

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As noted in my previous columns on this subject, the Crown Jewel is one of the significant major new gold mining projects in the U.S. The deposit is on Buckhorn Mountain east of Chesaw in Okanogan County. The high-profile project has had, and is still receiving, much scrutiny by myriad entities.

During 1997, progress has been made. On Feb. 3, the U.S. Forest Service published the Final Environmental Impact Statement Record of Decision. This was followed by the Bureau of Land Management's Record of Decision on Feb. 7.

The permitting process for the Crown Jewel gold mine was initiated by the operator, Battle Mountain Gold Company, early in 1997. Battle Mountain Gold is earning a 54 percent interest in the project by providing all of the capital costs to bring the property into production at a rate of 3,000 tons of ore per day. Crown Resources will retain a 46 percent interest upon production.

The sequencing of the numerous permits is governed by a Coordinated Permit Process Scheduling Agreement signed, as amended, by the following state agencies: Department of Ecology, Department of Fish and Wildlife, Department of Health, and Department of Natural Resources. To date, the following significant permits have been issued to Battle Mountain Gold:

- Two construction storm-water permits from Ecology
- Five dam safety permits from Ecology
- One hydraulic project approval from Fish and Wildlife
- Two forest practices permits from Natural Resources
- Water rights from Ecology
- Draft air-quality permit from Ecology
- County land-use approval from Natural Resources

Some of the major pending permits and plans are the final air-quality permit, surface mine reclamation permit, waste rock management plan, monitoring plan, plan of operations for the federal agencies, and the National Pollutant Discharge Elimination System (NPDES) and state wastewater discharge permits.

I will continue to inform our readers of the project's progress. ■

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Modern and Ancient Cold Seeps on the Pacific Coast—Monterey Bay, California, and Offshore Oregon as Modern-day Analogs to the Hoh Accretionary Complex and Quinault Formation, Washington

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Sediments deposited on the sea floor initially contain more than half water (by volume), yet the rocks we see exposed on the Earth's surface can contain less than 10 percent water. The geologic processes that occur on an active plate margin—compaction, deformation, and cementation—all contribute to this decrease in volume of marine sediments. Where does the fluid go? How does it move from one place to another? The challenge for geologists is to study something—fluid—that is no longer present.

In our work on the southwestern Olympic Peninsula, we have found an unusual fossil community and related authigenic (formed in place) carbonate that provide a clue to the origin and migration of fluids off the ancient coast of western Washington. To demonstrate what these fossils and the carbonate can tell us about hydrology on continental shelves and slopes, we will first describe active seep communities from offshore Monterey Bay and Oregon and illustrate the factors controlling their distribution. We will then apply knowledge of the processes forming these active underwater seeps and reexamine the Hoh rock assemblage (Miocene) and the Quinault Formation (late Miocene(?) and Pliocene) exposed on Quinault Indian Nation lands in southwestern Washington. In this manner, we will show that the Hoh and Quinault rocks preserve the paleohydrology—the plumbing for fluids buried in marine sediments—that was active during plate collision and sedimentation.

Fluids from depth (driven by tectonic or stratigraphic compression or by buoyancy) are channeled to the surface along permeable fault zones, stratigraphic layers, and mud diapirs in modern continental margin settings. In addition to the original pore water, these fluids contain sulfide and methane produced by diagenesis of buried organic matter. Where these fluids exit the seafloor, they can support unique "cold-seep" communities where the base of the food chain is fueled by microbial oxidation of these chemicals (a process known as chemosynthesis, as opposed to the more familiar photosynthesis). Such environments have been found off the coast of Oregon and in Monterey Bay, California, and provide a conceptual framework for analyzing the relation between the Neogene Hoh Accretionary Complex and the overlying Quinault Formation exposed along the southwest coast of the Olympic Peninsula, Washington.

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The Hoh rock assemblage was deposited in Eocene to Miocene time and was accreted, deformed, uplifted, and eroded by the late Miocene. These rocks are exposed either as coherent, tightly folded turbidites or as intensely sheared mud-matrix mélange units in fault zones or mud diapirs. The Hoh rock assemblage contains abundant evidence of fluids, including petroliferous outcrops, carbonate cements, and veins of carbonate and laumontite (a calcium-aluminum silicate). Fracture permeability of the sheared mud-matrix mélange provided conduits for fluid flow during and after deformation.

The Miocene(?) and Pliocene Quinault Formation was deposited on the Hoh rock assemblage in a piggyback basin, in fluvial/estuarine to bathyal depositional settings. In outer-shelf facies strata, the Quinault preserves evidence for methane-derived authigenic carbonate precipitation. Co-occurring with this unusual carbonate are fossil bivalves (*Solemya, Lucinoma, Modiolus*) that have modern chemosymbiotic counterparts at cold seeps and hydrothermal vents.

The Quinault paleo-seep owes its existence to the fluids funneled to the surface through the Hoh mélange, an association confirmed by the structural and stratigraphic ties between the two rock units. Additional ancient cold-seep deposits have been reported from Eocene to Oligocene siliciclastic forearc sequences of western Oregon and Washington and from Late Jurassic to Late Cretaceous sequences in northern California. Stratigraphic and structural associations preserved between Hoh and Quinault rocks are among the best exposed geologic examples by which we can observe the pathways and products of ancient fluid flow from an accretionary prism (marine sediments scraped off the downgoing plate at an oceanic trench and added to the overriding plate) into an overlying piggyback basin (marine and terrestrial sediments accumulating in bathymetric lows between the trench and volcanic arc).

MODERN COLD-SEEP ENVIRONMENTS ON THE PACIFIC COAST

Present-day Monterey Bay and offshore Oregon both straddle active tectonic boundaries (Fig. 1). In Monterey Bay, the Pacific plate is moving northward relative to the North America plate; the diffuse plate boundary comprises the offshore San Gregorio and Monterey Bay Fault Zones, as well as the San Andreas fault onshore (Greene, 1977; Greene and others, 1989). Off Oregon, the Juan de Fuca plate is subducting beneath the North America plate with offscraping and accretion of the accumulated terrigenous and oceanic sediments. During accretion, water volume in sediments may be reduced to less than 10 percent by compaction, cementation, and deformation (Bray and Karig, 1985). Thus accretion liberates substantial amounts of pore fluid, to which can be added fluids derived from both underthrust sediments (Moore, 1989) and devolatilization reactions (Bebout, 1991). The fluids expelled out of the crust and overlying sediments can support chemosynthetic cold-seep communities. We will briefly discuss the occurrence, hydrogeologic controls, and inferred driving mechanisms for these modern cold seeps and then apply these concepts to interpret the products of ancient fluid flow exposed in the Hoh and Quinault Formations of the southwestern Olympic Peninsula, Washington.

Submarine fluid expulsion from continental margins can be observed both directly and indirectly. Submersible dives, remotely operated vehicle (ROV) dives, or camera tows can be used to document the occurrence of chemosynthetic biota, which indicate localized sulfide- or methane-rich fluid expulsion (Kulm and others, 1986). Sulfide forms as a by-product of sulfate-reducing bacterial activity in buried marine sediments; biogenic methane forms by bacterial CO_2-reduction or acetic acid fermentation at depth (Barnes and Goldberg, 1976). Particular organisms used to track chemically reduced fluid seepage to the sea floor include mats of thiotrophic (sulfur-eating) free-living bacteria as well as specialized bivalves and tubeworms that derive nutrients from symbiotic bacteria within their tissues (Jannasch, 1995). Sulfide and methane are oxidized by these chemosynthetic bacteria to provide energy for biosynthesis (reviewed in Fisher, 1990).

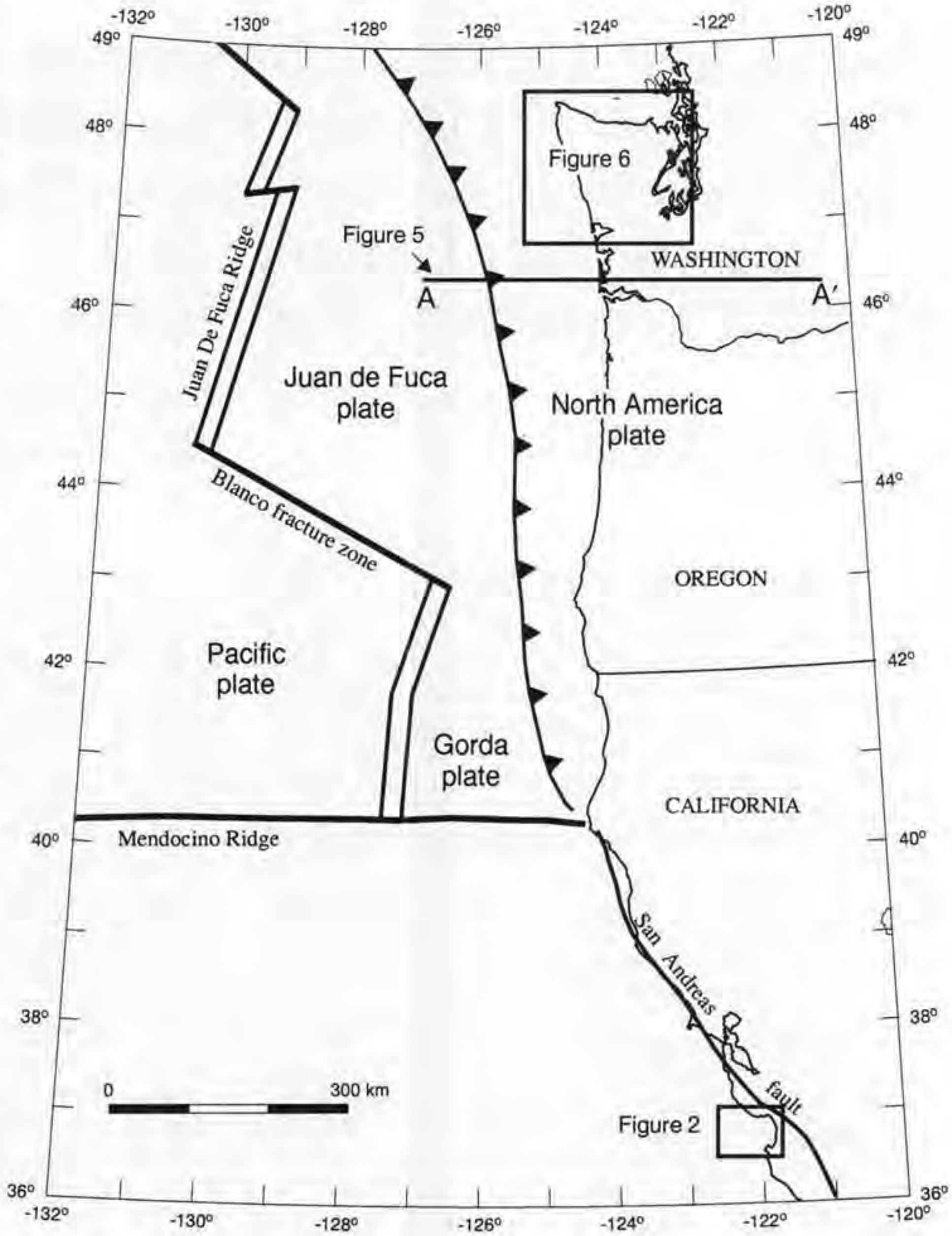


Figure 1. Tectonic setting of active cold seeps along the transpressional margin of Monterey Bay, California (Fig. 2); at the toe of the Cascadia subduction zone, offshore Oregon (Fig. 5); and of ancient cold-seep deposits found on the Olympic Peninsula, Washington (Fig. 6).

Fluid expulsion can also be inferred from the presence of authigenic carbonate on the sea floor (Ritger and others, 1987; Kulm and Suess, 1990). Carbonate precipitates during aerobic bacterial metabolization of methane or by anaerobic bacterial sulfate reduction coupled with methane oxidation at or beneath the sediment–water interface (Alperin and Reeburgh, 1984; Ritger and others, 1987). Regardless of how the methane is oxidized, seep fluids contain bicarbonate anions depleted in ^{13}C that bind with the calcium in seawater to produce isotopically distinctive carbonate (Ritger and others, 1987). In addition, the morphology of seep carbonate precipitates may denote the intensity and style of fluid expulsion: nodular or slab-like carbonates are associated with diffuse fluid flow, whereas chimney structures or "donuts" imply discrete fluid vents (Kulm and Suess, 1990; Campbell and Bottjer, 1993; Roberts and Aharon, 1994). Gas-charged fluid escape can also be indicated by the presence of pockmarks at the sea floor (Hovland and others, 1987).

MODERN COLD SEEPS IN MONTEREY BAY, CALIFORNIA

The Monterey Bay region is characterized by a thick section of Neogene sediment and active transpression between the Pacific and North America plates (Fig. 2). Right-lateral strike-slip motion has occurred on this plate boundary since at least 20 Ma (Atwater, 1989; Nicholson and others, 1994). Modest northeast-southwest-directed compression has also produced offshore thrust faults, folds, and localized uplift (for example, Smooth Ridge; Fig. 2; Crouch and others, 1984; McCulloch 1989). The Neogene basinal sedimentary sequences were rich in organic matter when deposited (Isaacs and Petersen, 1987), and during diagenesis and catagenesis, the organic matter was transformed into natural gas, higher order hydrocarbons (such as oil), and hydrogen sulfide. These chemical constituents can become entrained in the rising, overpressured fluids driven out of the sediment column by compaction (for example, Fertl, 1976; Kastner and others, 1991; Moore and Vrolijk, 1992).

Fluid Expulsion along Fault Zones

Active and dormant cold seeps have been discovered in Monterey Bay along the San Gregorio and Monterey Bay Fault Zones (for example, Orange and others, 1993a; Fig. 2). In both zones, extensive authigenic carbonates occur on the sea floor: the carbon isotopic signatures denote a methane source (Stakes and others, in press). The carbonates contain fluorescent fluid inclusions of higher order hydrocarbons, suggesting that at least some fluids venting here originate in petroliferous units, such as the Miocene Monterey Formation. In addition to the carbonate, chemosynthetic biota (the bivalves *Vesicomya*, and *Solemya*, tube worms, and bacterial mats; for example, Fig. 3; Barry and others, 1993) have been found along the Monterey Bay Fault Zone.

On the San Gregorio Fault Zone, we have observed fields of brachiopods (*Laqueous californica*) that are notably absent away from the fault trace. The relationship of the brachiopods to seep fluids is enigmatic because no living articulate brachiopods are known to be chemosymbiotic. We hypothesize that the brachiopods are abundant only along the fault zone either because they anchor themselves locally on the carbonate, because they are sulfide tolerant and can filter seawater enriched in microbes, or both.

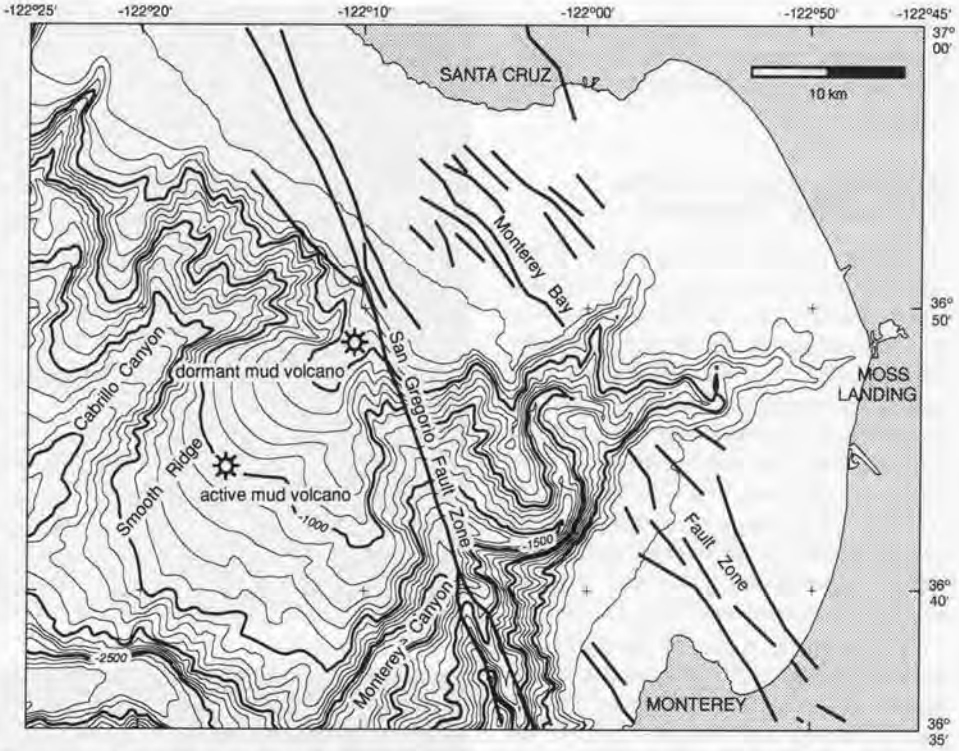


Figure 2. Tectonic setting of Monterey Bay, California, with the cold-seep locations discussed in this paper. Fault zones such as the San Gregorio and Monterey Bay have hosted fluid seepage (recent and current). In addition, an actively erupting mud volcano west of the San Gregorio Fault Zone channels fluids from depth.

Figure 3. Clamfield site, showing chemosymbiotic bivalves (*Calyptogena kilmeri* and *Calyptogena pacifica*). Clams are from 5 to 15 cm long.

Fluid Expulsion at Mud Volcanoes

Active and dormant mud volcanoes have also been detected in Monterey Bay (Orange and others, 1993a; Fig. 2). ROV dives along anomalous reflectivity zones west of the San Gregorio Fault Zone, on an uplifted feature informally named Smooth Ridge (Reed and others, 1992), revealed abundant evidence for fluid expulsion, including robust cold-seep communities of *Vesicomya* clams, bacterial mats, and extensive areas of carbonate precipitation, including high-angle (fracture fill?) veins and sub-horizontal slabs (Fig. 4) from tens of centimeters across to several meters in length (Orange and others, 1994a). Isotopic data from the carbonate clearly signal a methane carbon-source reservoir (Stakes and others, in press). Furthermore, analysis of pore waters obtained from push cores at the seeps suggests that components of thermogenic methane and higher order hydrocarbons are present; they may have originated at depth in the Monterey Formation (Orange and others, 1994a). Regional geologic data imply that these fluids must have migrated at least 2 km from their source to the expulsion sites at the sea floor.

We suggest that beneath this active mud volcano lies a mud diapir that is funneling fluids to the surface. Although mud diapirs have distinctive signatures in reflection seismic data and have been observed off central Washington (Snavely, 1987), no such data exist over the Monterey Bay mud volcano.

MODERN COLD SEEPS OFFSHORE OREGON

Offshore Oregon, subduction of the Juan de Fuca oceanic plate beneath North America is driving off-scraping and accretion of incoming sediment (Fig. 5). Off Oregon, fluid flow produced by accretion has been directly observed by submersible and drilling studies (Moore and others, 1988, 1990). At the toe of the Cascadia accretionary complex, the occurrence of chemosynthetic cold-seep communities and authigenic carbonate implies active fluid expulsion (Figs. 1, 5).

Locations of many of the seeps observed during ALVIN dives are structurally controlled by thrust or reverse faults (Moore and others, 1990) or by high-angle tear faults cutting through the entire accreting section (Tobin and others, 1993). In addition, Orange and others (1995, 1997) reported that many seep sites are geographically and geomorphically correlated with the locations of submarine canyons. Seep communities are characterized by the chemosymbiotic bivalves *Calyptogena* and *Solemya*, tube worms, rare bacterial mats, and associated authigenic carbonate. Isotopic analyses of seep fluids and the authigenic carbonate demonstrate that the fluids are methane-derived and that some far-traveled fluids have interacted with the subducting oceanic basement (Sample and others, 1993). In addition, the Ocean Drilling Program in 1994 documented fluid flow along fault zones (Carson and Westbrook, 1995).

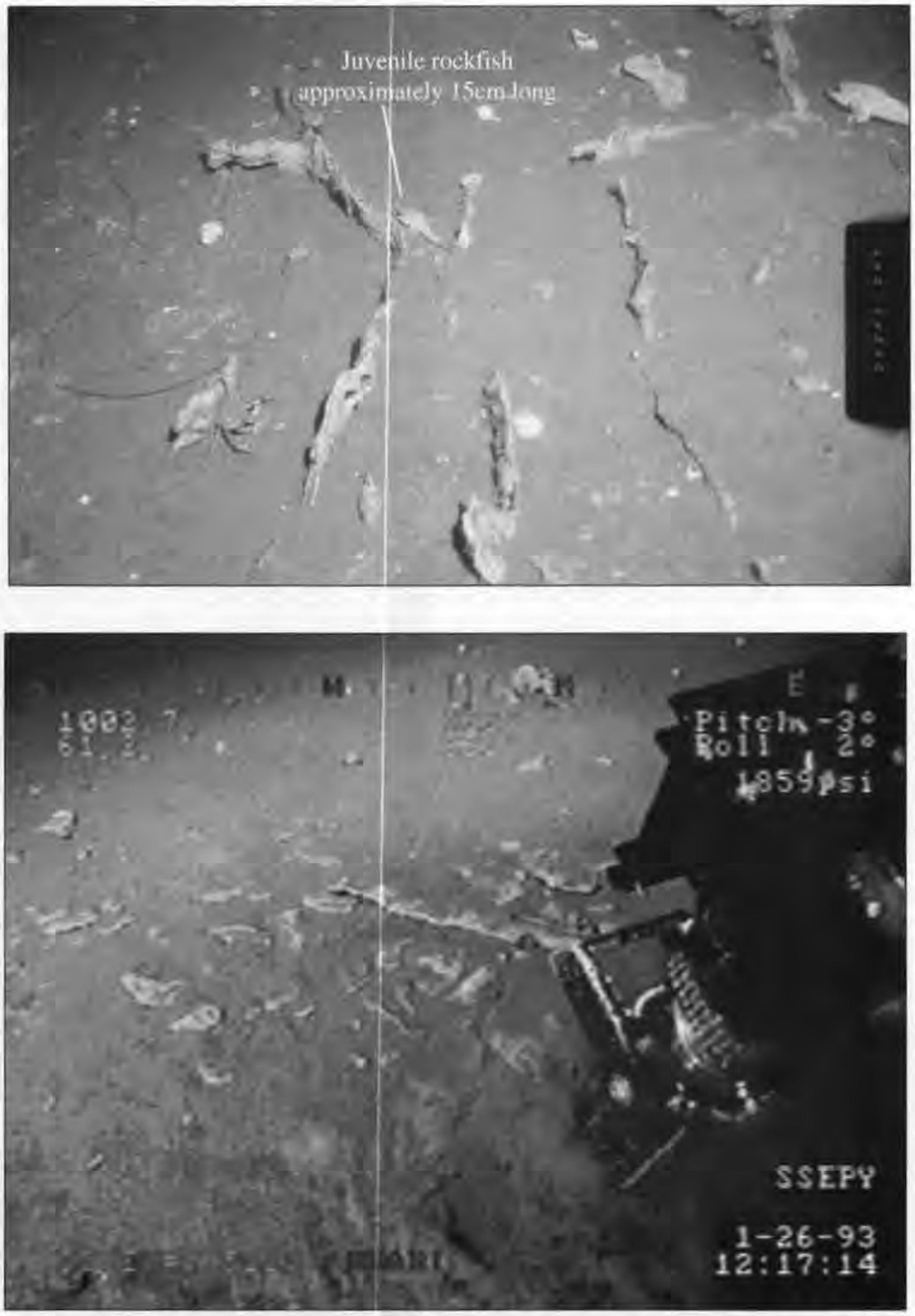


Figure 4. These photographs at the active mud volcano site (Smooth Ridge, Fig. 2) show chemosymbiotic bivalves and authigenic carbonate in two modes: high angle (vein) and surface parallel (slab). Manipulator jaw is 12 cm across.

ANCIENT FLUID FLOW ON THE SOUTHWESTERN OLYMPIC PENINSULA

Sedimentary Rocks of the Quinault Coast—Character and Origins

Hoh rock assemblage

The Olympic Peninsula exposes the products of Tertiary accretion in the Cascadia subduction zone (Fig. 6; Stewart, 1970; Tabor and Cady, 1978; Snavely, 1987; Lingley, 1995). On the western Olympic Peninsula, accreted material includes the Hoh rock assemblage, consisting of (1) coherent packages of sediments, most of which originated as turbidity deposits and are commonly tightly folded and steeply dipping; and (2) mélange or stratally disrupted zones composed of blocks of lithic sandstone, turbidites, conglomerates, and volcanic rocks in a siltstone and claystone matrix. Microfossils from the Hoh sections in the Taholah area (Fig. 7) indicate a middle Miocene age and lower to middle bathyal depositional environments (Rau, 1973, 1975). The zeolite facies metamorphism of the Hoh rock assemblage (Stewart, 1974) attests to limited burial of the accretionary prism.

Rau (1973, 1975) first suggested that the various Hoh mélange belts exposed between Tunnel Island and Point Grenville (60 km north of Grays Harbor, southwestern Olympic Peninsula) represent either thrust zones or mud diapirs, an interpretation supported by more recent work (Orange, 1990; Brown and Orange, 1993; Orange and Underwood, 1995). A fault origin is inferred for some sequences (for example, Hogsback mélange, see below) on the basis of intense matrix deformation, consistent matrix orientations, millimeter-scale scaly fabric throughout the mélange zone, similar orientation of clasts in the mélange, and consistent maximum thermal conditions throughout the unit. In contrast, a diapiric origin of mélange is indicated elsewhere along the Quinault coast (for example, Duck Creek mélange, see below) where matrix deformation increases in intensity toward the margins of the unit, clast and matrix orientations change across the outcrop, large clasts occur only in the central portions of the mélange, and the core of the mélange records higher maximum temperatures than do the margins. (See Orange, 1990; Orange and Underwood, 1995.)

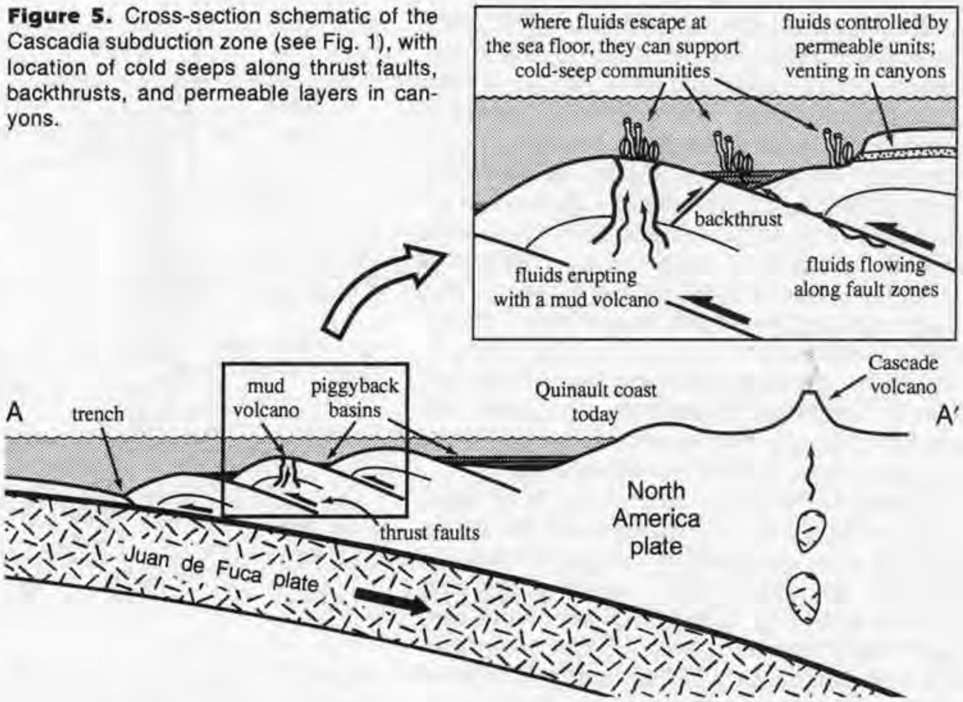
The numerous veins in the mélanges attest to the involvement of fluids during their evolution (Fig. 8). In addition, the Hoh mélanges currently act as fluid conduits, as demonstrated by the presence of modern oil seeps (for example, Jefferson Oil Seep, located above Jefferson Cove north of the Hoh River), active mud volcanoes (such as Garfield gas mound just north of Taholah; Fig. 7), and petroliferous smell muds (such as at Ruby Beach, Fig. 6) in the field area. The fluids leaking from the Hoh rocks contain thermogenic methane ($\delta^{13}C$ values of -34 to -35‰ PDB), ethane, propane, and liquid hydrocarbons (Kvenvolden and others, 1989).

The Hoh rock assemblage is unconformably overlain by the mildly deformed late Miocene(?) and Pliocene Quinault Formation. (See Rau, 1970, 1979; Fig. 7.) The small difference in age between adjacent rocks of the accretionary prism (Hoh) and piggyback basin (Quinault) implies that the Miocene depositional age for the youngest strata of the Hoh rock assemblage is probably close to the emplacement age. Hence, parts of the Hoh rock assemblage in the southwestern Olympic Peninsula were deposited in Miocene time and were accreted, deformed, uplifted, and eroded by the late Miocene (Rau, 1973, 1975). The most recent deformation in the area is recorded by widely spaced northeast-trending strike-slip faults (Rau, 1979).

Quinault Formation

The buff to gray sandstone, conglomerate, and siltstone that comprise the sea cliffs between Point Grenville and

Figure 5. Cross-section schematic of the Cascadia subduction zone (see Fig. 1), with location of cold seeps along thrust faults, backthrusts, and permeable layers in canyons.



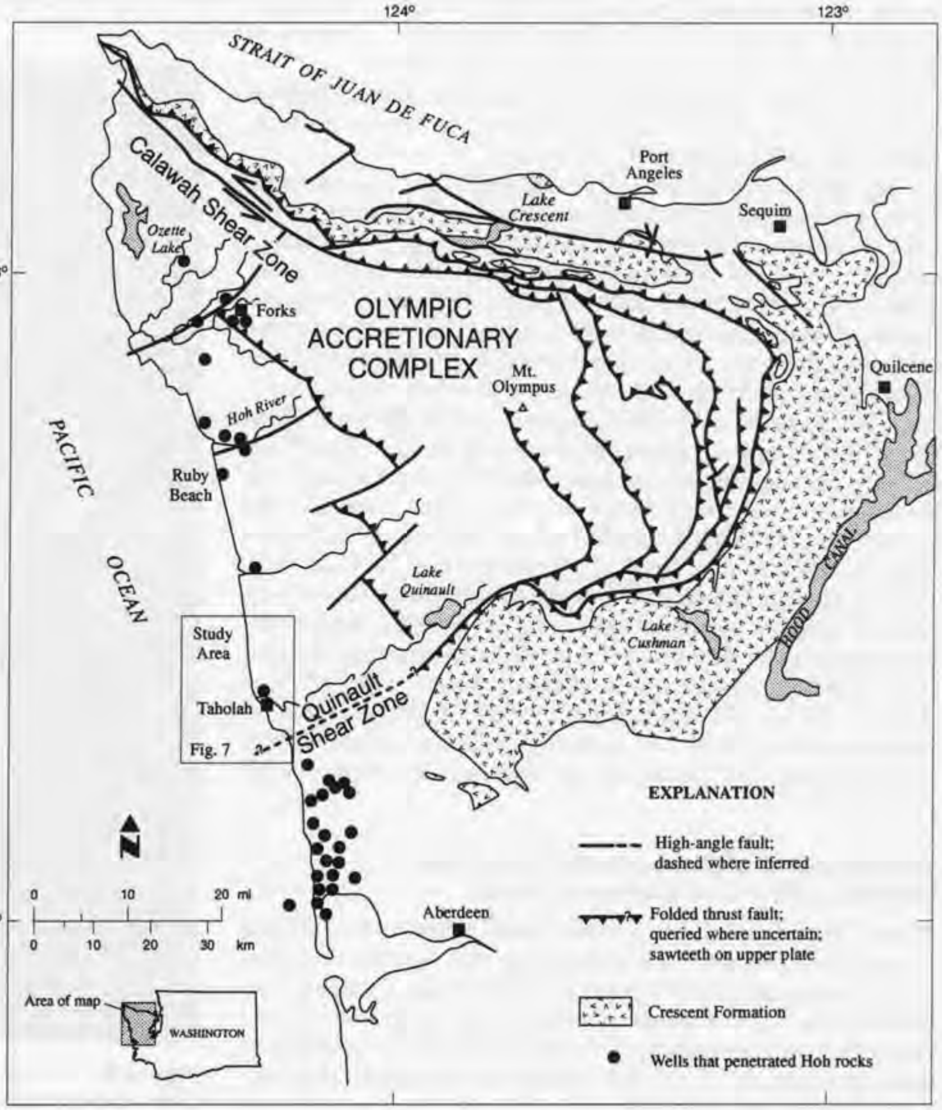


Figure 6. Geologic map of the Olympic Peninsula, Washington, depicting the extent of accreted Tertiary rocks (after Tabor and Cady, 1978), and the Quinault study area.

Tunnel Island are part of the Quinault Formation (of Arnold, 1906; Fig. 7). Microfossils in this mostly marine shelfal sequence indicate a Pliocene (Repettian) age, with a tentative latest Miocene age assigned to the portions of the formation north of Pratt Cliff and at Tunnel Island (Rau, 1970; Fig. 7). Although the Quinault is exposed for only 20 km onshore, seismic studies and offshore drilling imply a much wider extent of equivalent units (Snavely and Wagner, 1982; Wagner and others, 1986; Palmer and Lingley, 1989). Onshore sections are mildly folded in broad east-trending structures that plunge less than 25° landward. Major high-angle faults offset the relatively continuous outcrop, although faulting in each section is minimal (Fig. 7).

Horn (1969) demonstrated that four major stratigraphic sections of the Quinault Formation (Fig. 7) were deposited in marginal marine to offshore conditions. Fauna and lithology indicate the following depositional conditions during Quinault sedimentation: (1) fluvial to estuarine (conglomerates, sandstone and mudstone of the Cape Elizabeth section); (2) deltaic shallow-marine (sandstone and mudstone of the section north of Point Grenville); (3) storm-wave influenced, mid- to outer-shelf (sandstone and siltstone of the Duck Creek–Pratt Cliff section); and (4) bathyal (siltstone of the section south of Taholah) (reviewed in Horn, 1969; Rau, 1970; Campbell, 1992; Fig. 7).

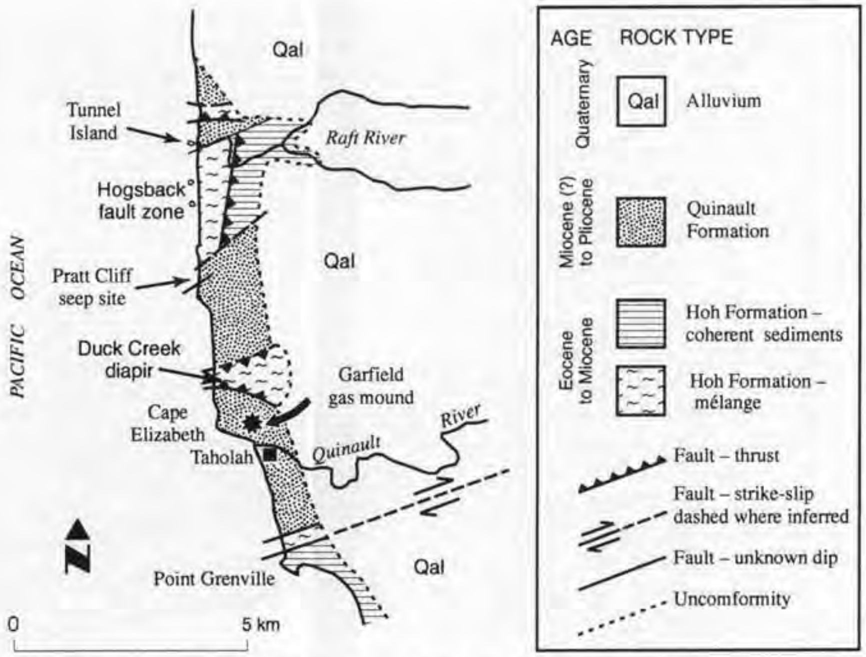


Figure 7. Geologic map of the Point Grenville–Tunnel Island area, elucidating the location of Hoh rock assemblage outcrops (thrust fault mélange and diapiric mélange), the unconformably overlying basinal Quinault Formation, and the actively erupting Garfield gas mound.

The Duck Creek–Pratt Cliff section of Quinault strata preserves evidence of ancient cold-seep activity (Campbell, 1989, 1992). The basal 225 meters of the section (Fig. 7) consists of sandy, bioturbated siltstone and bedded, wave-rippled sandstone (< 1 m thick) with scoured bases. Hoh mud clasts and ripped-up slabs containing trace fossils occur in the scoured sandstone intervals. These facies associations represent depositional conditions on a storm- and wave-dominated marine shelf (< 200 m water depth; Campbell, 1992). Quinault fossil marine bivalves and gastropods preserved north of Pratt Cliff are those occupying similar outer shelf environments off the Washington coast today. However, over a 10-m interval in the section, the carbonate content of the sediments increases (Fig. 9), and dominant fossil types change (Fig. 10; Campbell, 1992). Locally carbonate occurs as nodules and shell- and burrow-fill (Fig. 9; Campbell, 1992, fig. 5, p. 426). Stable isotopic analyses indicate that this authigenic carbonate formed from seawater mixed with methane-rich pore water ($\delta^{13}C$ = -14.0 to -33.5‰ PDB; Campbell, 1992). Moreover, some bivalves associated with the carbonates, such as *Solemya* (Fig. 10), *Modiolus*, and *Lucinoma*, are known to be chemosymbiotic today.

Stratigraphic and Structural Relations Between Hoh and Quinault Rocks

In the Point Grenville to Tunnel Island coastal area, several exposures of the Hoh rock assemblage interrupt the four relatively continuous, undeformed sections of the Quinault Formation (Fig. 7). The structural and stratigraphic relations between Hoh and Quinault rocks in this area provide evidence of fluid dewatering of the Hoh accretionary prism and subsequent development of a Miocene(?) and Pliocene cold seep in the overlying Quinault forearc basin.

Figure 8. The Hoh mélange at the Hogsback fault zone and the Duck Creek diapir has abundant mineralized veins (both syn- and postdeformational), attesting to the importance of these scaly foliated fabrics in facilitating fluid flow from depth through the fault and diapiric conduits.

Hogsback mélange: A fluid-rich fault zone of the Miocene and Pliocene

From Pratt Cliff to Tunnel Island, the sea cliffs expose 3 km of continuous Hoh mélange (Fig. 7). Throughout this area foliation strikes north-northeast and dips steeply southeast. Axes of small, asymmetric folds plunge steeply northeast and have consistent counterclockwise vergence, indicating a component of left-lateral shear (Orange, 1990). These structural features and similar orientation of matrix clasts led Orange (1990) to infer that the Hogsback mélange formed as a thrust fault shear zone. Mapping of other similar mélange zones throughout the coastal Olympic Peninsula reveals that these thrust faults are out-of-sequence—they postdate early folds in the wall rocks (Orange and others, 1993b)—and all yield abundant evidence of fluid migration.

Petroliferous "smell muds" and fluid precipitates in the Hogsback mélange unit attest to abundant fluid involvement throughout its history. For example, cements and veins of carbonate and laumontite represent vestiges of flow. Some post-deformational veins parallel scaly foliation surfaces or cut the foliated mud-matrix fabric (Fig. 8). The deformation that produced the scaly foliation fabric created an anisotropic permeability capable of channeling fluid flow from depth through the mélange during and after deformation. This fluid migration appears to have been driven by overpressuring at depth. If the pressure build-up occurs faster than the permeable mélange can release fluids, diapirism may result.

Duck Creek mélange: A fluid-rich mud diapir of the Miocene and Pliocene

The Duck Creek mélange is a dark mud-matrix mélange that crops out in the sea cliff north of Taholah between two sections of coherently bedded, light-colored Quinault Formation (Fig. 11). Microfossils from both clasts and matrix of the Duck Creek mélange indicate a late Saucesian (early Miocene) age (Rau and Grocock, 1974). Although somewhat obscured by recent slumping, both contacts are high angle and discordant (Fig. 11). Aerial photographs taken in 1959 clearly show that both contacts are steep and subparallel to foliation lines in the mélange. Facies of the Quinault Formation differ north and south of the older Duck Creek mélange: fluvial/estuarine strata of the Cape Elizabeth section are exposed to the south, and mid-outer shelf, storm-wave-influenced sediments are exposed to the north (Rau, 1970; Campbell, 1992; Fig. 7). On the basis of the differences in paleoenvironments of the adjoining Quinault sections, the high-angle Hoh–Quinault contacts, and the differences in ages between the mélange and Quinault rocks, Rau and Grocock (1974) interpreted the Duck Creek mélange as a diapir. Orange (1990) suggested that a pre-existing high-angle fault in the Quinault Formation provided a zone of weakness for diapiric intrusion of overpressured Hoh mélange. Hoh mud clasts in the adjoining Quinault Formation decrease in abundance away from the Quinault–Hoh contact, implying that the diapiric intrusion occurred syndepositionally. Furthermore, vitrinite reflectance indicates a source depth of 5 to 9 km for this diapir, whereas the adjacent Quinault attained a maximum depth of 2 km (Orange and Underwood, 1995). Seismic data from the area directly offshore indicate that several other diapirs rise toward the surface from 2 to 4 km depth (McClellan and Snavely, 1987).

The Duck Creek mélange foliation pattern is arcuate in map view, and pervasive matrix deformation at the contacts decreases toward the core (Orange, 1990). Opposing senses of fold and fault vergence are recorded near opposite margins of

Figure 9. Quinault Formation, north of Pratt Cliff section. Note the unusual carbonate concretions in the outcrop; these carbonates yielded a stable isotopic signature of $\delta^{13}C$ = -14.0 to -33.5‰ PDB, clearly indicating mixing during precipitation with a methanogenic source.

Figure 10. A fossil of *Solemya ventricosa*, a bivalve with modern chemosymbiotic counterparts, which occurs along with *Modiolus* and *Lucinoma* in the same strata of the Quinault Formation as shown in Figure 9. This stratigraphically restricted association of methane-derived carbonate and chemosymbiotic bivalves marks the locus of an ancient cold seep.

the mélange. Evidence for fluid activity associated with emplacement of the mélange includes carbonate and laumontite veins and petroliferous "smell muds". Diapirism alone implies regional overpressuring and unstable buoyancy, so that fluid expulsion is a natural consequence of diapiric rise (as we have seen in Monterey Bay).

Fluid migration paths from the Hoh to the Quinault paleo-seep

Campbell (1992) concluded from a study of the Quinault paleo-seep that during the late Miocene and Pliocene fluids likely seeped from organic-rich Hoh source reservoirs to the Quinault sea floor through either faults or a diapir. The Hogsback fault zone is the most likely candidate conduit for fluid flow to the overlying Quinault forearc during the Miocene and Pliocene (Campbell, 1992). The paleo-seep deposit is in the basal, older part of the Duck Creek–Pratt Cliff section (Fig. 7) 80 m stratigraphically above the basal unconformity with the Hogsback mélange. Moreover, Quinault siltstone and sandstone of the north Pratt Cliff section, which surround the seep carbonates, contain abundant Hoh mud clasts. (See Campbell, 1992, fig. 3, p. 424.) Hence, the shear zone mélange was actively eroding on the sea floor during paleo-seep formation.

Figure 11. Aerial photograph (view to the east) of the Miocene Duck Creek mélange (dark), illustrating the two high-angle contacts with the Pliocene Quinault Formation (light) to the north and south of the diapir.

SUMMARY

Studies of active fluid venting around the Pacific rim, such as those discussed above, demonstrate that chemosynthetic cold-seep communities can be used to determine the processes and structures controlling fluid expulsion on continental margins. Because cold seeps are composed of authigenic carbonate (formed by the oxidation of methane) and are accompanied by unusual and distinctive faunas, they can be preserved and identified in the rock record and can be used to infer the paleoplumbing of ancient continental margins. Thus we can use the seep associations of modern-day California and Oregon to examine the Miocene and Pliocene assemblages on the western Olympic Peninsula.

The seeps exposed in the coastal exposures of the Quinault Formation owe their existence to the deformed rocks of the Hoh mélange (Fig. 12), which had formed during offscraping during latest Miocene time. The Quinault Formation was deposited as a piggyback basin on top of the accretionary rocks of the Hoh rock assemblage. The deformation that produced the fault zone mélange of the Hogsback section also created a scaly foliated matrix fabric that provided the permeability that could channel fluids from depth. Fluids migrated during deformation, but they continued to take advantage of fracture permeability pathways after deformation ceased.

If the fluids were not allowed to migrate to the surface, the mélange became overpressured, resulting in the buoyant rise of mud diapirs (Duck Creek mélange) or mud volcanoes (the currently active Garfield gas mound near Taholah; Fig. 7). Alternatively, the fluids escaping to the surface supported chemosynthetic cold-seep communities in the Quinault Forma-

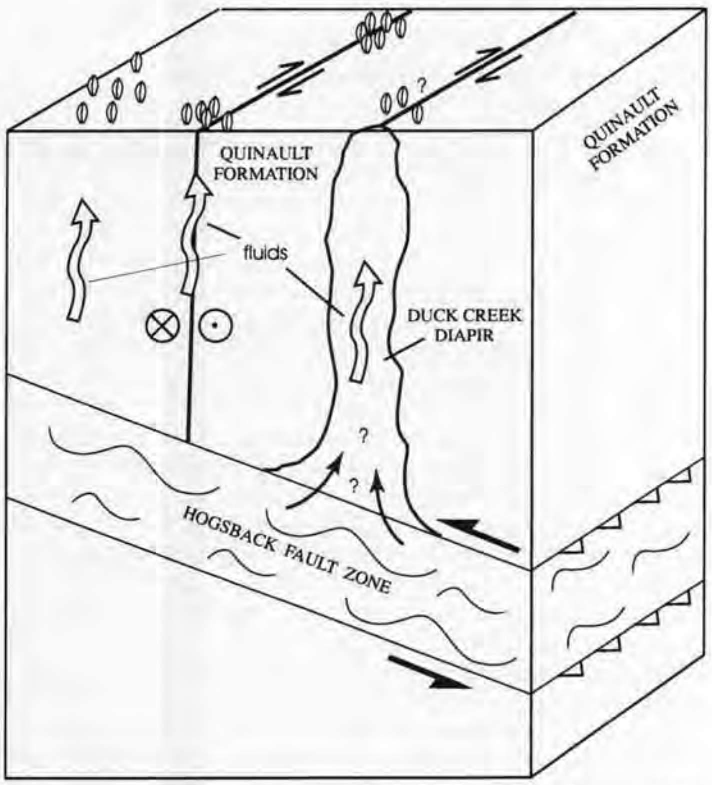


Figure 12. Schematic diagram illustrating the relation of the Hogsback fault zone and Duck Creek diapir to the Quinault Formation. These Hoh mélange units represent the underlying, overpressured material in the accretionary prism. Where fault zones in the overlying Quinault Formation provided a pre-existing zone of weakness, buoyantly unstable portions of the Hoh rose along the fault zones as a diapir (Duck Creek). Where such fault zones were not available, fluids leaked out of the mélange (Hogsback) into the overlying Quinault forearc, hosting a cold-seep paleocommunity. The western Olympic Peninsula therefore exposes the paleohydrology of an ancient cold seep. Given the amount of accreted strata and forearc sequences exposed in western Washington, we suggest that additional ancient cold seeps await discovery.

tion, preserved today as authigenic carbonate and distinctive fossil assemblages (Fig. 12). Thus, the southwestern Olympic Peninsula exposes the geologic products of an active fluid history—the paleoplumbing—associated with ancient subduction processes.

Following the discovery (Campbell, 1989) of the cold seep of the Quinault Formation, more than a dozen Cenozoic cold-seep sites have been found in the Pacific Northwest (Goedert and Squires, 1990; Campbell and Bottjer, 1993; Nesbitt and others, 1994; Goedert and Campbell, 1995; Squires and Goedert, 1995; Campbell, 1995; Goedert and Kaler, 1996; J. L. Goedert, unpub. data). Additional finds of Mesozoic and Cenozoic cold seeps from Washington to California can be expected. Considering the large volume of fluid driven out of marine sediments during accretion, field geologists in the Pacific Northwest should be on the lookout for geologic evidence of fluid seepage and cold-seep paleocommunities when mapping the rest of the Olympic Peninsula. These cold seeps, when placed in the context of the regional geology, can then be used to infer the hydrology at the time of their formation. The fluid may be long gone, but the seeps remain to provide clues about ancient plumbing.

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View to the north of MOUNT BAKER VOLCANO, August 21, 1997. Steam plume rises from Sherman Crater (lower crater), source of increased fumarolic activity that began in 1975. There are no signs to suggest that magma movement has had any effect on this change in heat flow. Rockfalls caused the dark snow and ice adjacent to Sherman Crater. Recent ice-radar measurements by Carolyn Driedger (USGS) and Nadine Nereson (UW) indicate that Summit Crater is filled with as much as 80 m of snow and ice. Mount Baker has had at least four eruptions in the past 14,000 years. Volcanic mudflows have traveled as far as the Puget–Fraser Lowland. Many smaller debris flows have moved down all drainages that head on the volcano. A revised hazard assessment, *Potential volcanic hazards from future activity of Mount Baker, Washington* (Gardner and others, USGS Open-File Report 95-498) is also available in digital form at URL: http://vulcan.wr.usgs.gov/Volcanoes/Baker/Hazards/. Ongoing investigations over the next several years should provide more information about the history of this volcano. *(Photo by Lee Gerhard.)*

Evidence for Quaternary Tectonism Along the Washington Coast

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The Cascadia continental margin has grown by accretion of various terranes during Cenozoic subduction. Relative motion between some of these accreted terranes has resulted in regional structural complexities within the overall subduction regime. North-south-directed shortening observed in coastal Washington may result from such relative motion between crustal blocks. Specifically, the Siletz terrane, composed of Paleogene oceanic basalt and overlying forearc strata (Wells and others, 1984; Tréhu and others, 1994; Snavely and Wells, 1996), is translating northward along the Cascadia margin relative to stable North America (Fig. 1) as well as rotating clockwise about a northern pivot (England and Wells, 1991). North-south shortening observed within the adjacent subduction-complex block (McCrory, 1996) as the terrane drives toward the pre-Cenozoic basement of southern British Columbia (Snavely and Wells, 1996). This study focuses on geomorphic and structural evidence for ongoing north-south convergence between marginal crustal blocks in southwestern Washington.

A distinctive geomorphic pattern along the Washington coast between Grays Harbor and Cape Elizabeth (Fig. 2) evinces the Quaternary tectonism that is hidden beneath the forested hills and stream valleys. Specifically, the series of topographic ridges trending east-west denotes shortening adjacent to the boundary between two major crustal blocks—Siletz and subduction complex—composing the southwest Washington margin. Where exposed, the cores of these ridges display moderately to severely deformed Quaternary deposits. Previous stratigraphers (Baldwin, 1939; Moore, 1965) recognized this localized Quaternary deformation, but they did not map the associated faults and fold axes.

Field studies presented below indicate that many topographic ridges in this region are underlain by thrust faults that offset lower Pleistocene strata. In places these faults cut upward into overlying upper Pleistocene deposits as well. The east-west orientations of concealed faults and folds denote a regional complexity in the overall north-south structural fabric observed elsewhere along the northern Cascadia subduction margin. The skewed orientation suggests that a mechanism—in addition to subduction-related shortening—contributes to tectonism in the Washington accretionary margin.

CENOZOIC STRATIGRAPHIC SEQUENCE OF COASTAL WASHINGTON

Two major rock units, separated by a regional unconformity of late middle Miocene age, underlie much of the Washington coastal area (Rau and McFarland, 1982). The older rocks beneath the unconformity consist of complexly deformed subduction-complex basement. The younger rocks above the unconformity consist of moderately deformed marine overlap

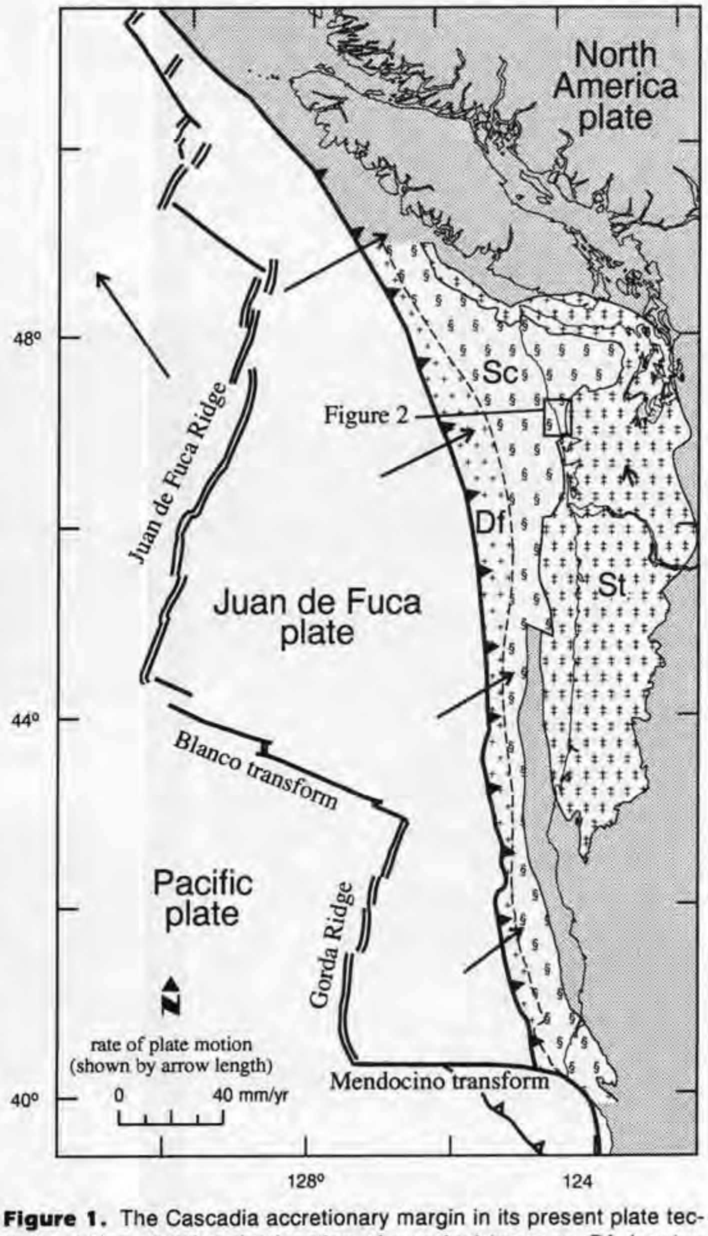

Figure 1. The Cascadia accretionary margin in its present plate tectonic setting showing the location of marginal terranes. **Df** denotes modern deformation front of Cascadia margin; **Sc** denotes subduction-complex rocks including the Olympic subduction complex, the Hoh rock assemblage, and equivalent rocks to the south; **St** denotes Siletz terrane (modified from Snavely and Wells, 1996). The stable North America plate includes terranes accreted in pre-Cenozoic time. Arrows denote modern motion vectors of oceanic plates and Siletz terrane with respect to a fixed North America plate in mm/y (from Wilson, 1993; University of California, Santa Barbara, 1994, unpublished data).

strata. Locally, both rock units are unconformably overlain by shallow marine or nonmarine Quaternary sediments.

Subduction-complex Basement

Basement rocks in the coastal area north of Grays Harbor consist of complexly deformed subduction-complex rocks accreted to the continental margin during Cenozoic time. The subduction complex is divided into two major units, a middle Eocene to lower Oligocene Olympic subduction complex (Tabor and Cady, 1978; Brandon and Vance, 1992) and a middle Miocene Hoh rock assemblage (Rau, 1975; Orange and others, 1993). Subduction-complex rocks are poorly exposed in the study area, but petroleum wells drilled along the coast penetrated subduction-complex basement beneath middle Miocene to upper Pliocene overlap strata (Rau and McFarland 1982). Structural disruption is indicated in some wells by the occurrence of Olympic subduction-complex rocks above the younger Hoh rock assemblage. This geometry suggests that Hoh rocks, in places, were thrust beneath older subduction-complex rocks (Rau and McFarland, 1982) in post-middle Miocene time.

Neogene Overlap Strata

Moderately deformed marine strata of middle Miocene and younger age unconformably overlie subduction-complex basement in the study area (Palmer and Lingley, 1989). These upper continental slope to shelf strata are divided into two units, the middle and upper Miocene Montesano Formation and the upper Miocene and Pliocene Quinault Formation (Rau and McFarland, 1982; Palmer and Lingley, 1989), which are separated by an angular unconformity. Montesano strata are poorly exposed in the coastal area. Petroleum well data and nearshore seismic reflection profiles indicate that slope to inner shelf lithofacies of the Montesano Formation (Fowler, 1965) thin northward from Grays Harbor. Montesano strata are not observed in the subsurface north of the Copalis River. The age of the Montesano Formation is constrained by dated volcanic rocks, the Pomona Member of the Saddle Mountains Basalt (ca. 12 Ma), which intrude basal Montesano strata in the Grays Harbor area (Walsh and others, 1987).

Seismic reflection and well data indicate that the Montesano Formation is unconformably overlain by Quinault strata in the southern part of the study area (Palmer and Lingley, 1989). Onshore, Quinault strata are exposed in the coastal area north of Point Grenville (Horn, 1969; Rau, 1970, 1975) and penetrated in petroleum wells south to Grays Harbor (Rau and McFarland, 1982). Planktonic foraminiferal biostratigraphy (Ingle, 1967, 1976) indicates that the upper slope to deltaic lithofacies of the Quinault Formation (Horn, 1969; Rau, 1970), exposed in the sea cliffs between Point Grenville and Cape Elizabeth, are of Pliocene age (ca. 5–2 Ma).

Post-Quinault Formation Strata

A coarse-grained sedimentary unit overlies Quinault strata between Grays Harbor and Point Grenville. The contact between the Quinault Formation and this unit is not exposed in the study area. (The contact is poorly exposed in the sea cliffs near the Raft River, 12 km north.) Well logs and nearshore seismic

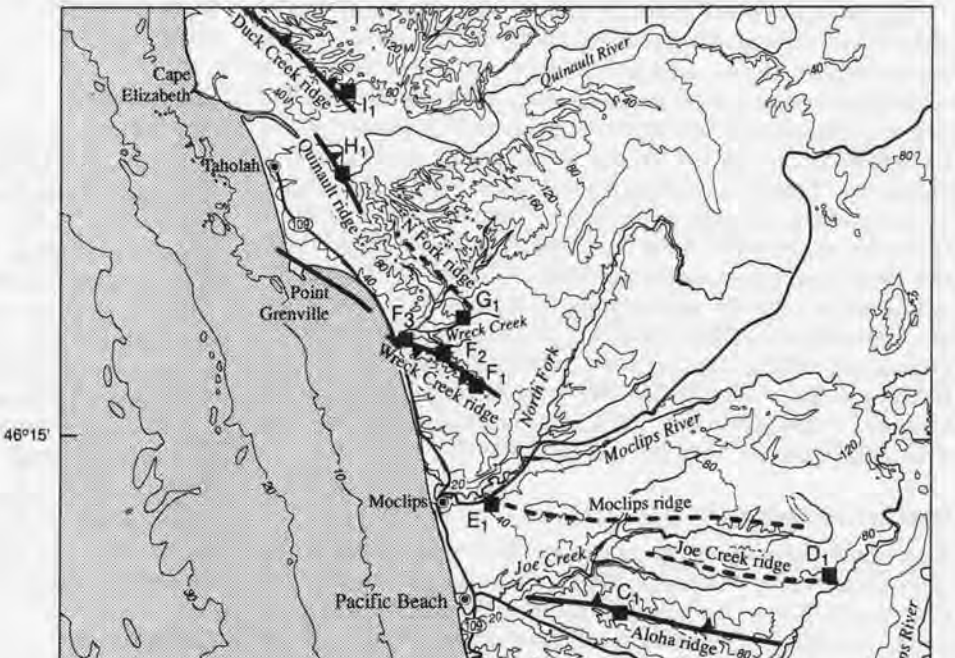

Figure 2. Locations of field sites along Quaternary structures. Note the correlation between topographic ridges and Quaternary thrust faults and fold axes. Bathymetric contour interval is 10 m; topographic contour interval is 40 m, with a supplemental contour at 20 m (modified from USGS-NOS Copalis Beach Metric Map 47124-A1-TB-100). Barbs denote upper plate of thrust faults; dashed lines denote anticlinal axes.

reflection profiles indicate that an angular unconformity (Palmer and Lingley, 1989) separates equivalent strata in the subsurface.

This coarse-grained unit is tentatively assigned an early Pleistocene age (ca. 1.5–0.5 Ma) owing to its relative position above Pliocene Quinault strata and beneath upper Pleistocene glacial sediments (Moore, 1965). These post-Quinault Formation strata were previously assigned to the Pliocene (Moore, 1965) on the basis of local evidence of deep weathering. The correlation between age and depth of weathering is not considered reliable in the Washington coastal area because of the warm humid climate and significant variations in permeability among the stratified surficial deposits (Pringle, 1985) that speed the weathering process.

Exposures of post-Quinault strata reveal a range of fluvial and alluvial lithofacies including poorly sorted gravel lenses, cross-bedded sands, and minor clay beds. Exposures are mostly limited to stream banks and roadcuts, so the distribution and thickness of the lower Pleistocene deposits are poorly known. When correlated to soil type (Pringle, 1985), surficial exposures of these strata suggest that lower Pleistocene deposits are widely distributed between Grays Harbor and Point Grenville. Subsurface well data (Rau and McFarland, 1982) and field investigations for this study indicate wide variation in thickness, with the unit ranging up to about 200 m in thickness. Nearshore seismic reflection profiles indicate that lower Pleistocene strata together with overlying upper Pleistocene sediments reach as much as 300 m in thickness (Palmer and Lingley, 1989). Offshore, the strata thin and pinch out over structural highs (Palmer and Lingley, 1989).

Glacial Sediments

Two major depositional units derived from episodes of alpine glaciation overlie the lower Pleistocene strata in angular unconformity. These two glacial units mainly consist of till lithofacies bounded by moraines and flanked by outwash lacustrine, fluvial, and alluvial lithofacies. The younger, more restricted unit correlates with the major stage-2 glacial advance (ca. 20–15 ka) on the basis of radiocarbon dates (Moore, 1965). Similar radiocarbon ages have been reported for young glacial deposits to the north (Thackray and Pazzaglia, 1994). The older, more widespread unit is tentatively assigned to the penultimate major glacial advance (stage 6, ca. 155–150 ka) based on correlation with the global sea-level curve (Chappell, 1983). Minor intervening glacial advances are recorded in discontinuous sets of glacially derived deposits (Moore, 1965). Along the coast, a marine sand and cobble lithofacies is commonly present beneath the younger glacial sediments. This marine unit accumulated during late Pleistocene interglacial conditions (stage 5, ca. 125–83 ka; McCrory, 1996).

STRUCTURAL CHARACTER OF QUATERNARY TECTONISM

The topography of the coastal area between Grays Harbor and Point Grenville is broken into a series of ridges, 5–10 km long and 1.3–1.5 km wide, with intervening streams (Fig. 2). The ridges rise between 30 and 80 m above the surrounding coastal plain and typically have one flank steeper than the other. This geomorphic pattern denotes "islands" of older Pleistocene strata rising through a "sea" of younger glaciofluvial deposits. The ridges—where cut by streams, quarries, or roads—reveal moderately to severely tilted and thrust-faulted strata in their cores (Fig. 3). The orientation of the deformed strata and faults generally parallels the ridge axes (Fig. 2), evincing the structural underpinnings of the ridges. Upper Pleistocene glaciofluvial sediments that overlie deformed lower Pleistocene strata are typically horizontal to gently tilted.

Between Grays Harbor and Moclips Creek to the north, the ridges trend ENE to ESE (Fig. 2). Between Moclips Creek and Wreck Creek, their trend abruptly shifts to the northwest. North of Cape Elizabeth, the ridges trend NNW. Petroleum wells drilled into three of the ridge crests documented structural disruption in subduction-complex rocks or Quinault strata. Offshore, the entire structural block between Grays Harbor and Point Grenville appears to have been elevated in the late Quaternary because unconsolidated sediments of apparent late Quaternary age (<20 ka) onlap an eroded bedrock high (Nittrouer, 1978; Palmer and Lingley, 1989; Wolf and others, 1997).

Saddle Hill

The 7-km-long Saddle Hill ridge just north of Grays Harbor, trends N70°E. Evidence of structural activity associated with this ridge comes from well data at two sites and a surface exposure (Fig. 2). At site A_1, petroleum well Tidelands State No. 2 was drilled about 3 km offshore along the western extension of this ridge. Rau and McFarland (1982) infer thrust faulting within Hoh rocks penetrated in this well on the basis of a biostratigraphic age reversal. At site A_2, Montesano lithofacies on the northern side of Saddle Hill abruptly thin to the north between wells Union State No. 3 and Shell Sampson Johns No. 2-15, suggesting substantial fault displacement (Rau and McFarland, 1982; Palmer and Lingley, 1989). At site A_3, Moore (1965) documented a thrust fault that offsets Pleistocene gravels on the southern side of Saddle Hill. Slickensides on the fault surface indicate dip-slip offset with no evidence of a lateral-slip component. (See figure 4 in Moore, 1965.)

Langley Hill

Six kilometers north of Saddle Hill, the 9-km-long Langley Hill ridge trends N70°E. Evidence for Quaternary structural activity associated with this ridge comes from surface exposures at four sites (Fig. 2). At site B_1, steeply tilted Pleistocene sands and gravels are exposed in a roadcut at the central crest of Langley Hill. Gravel beds exposed at site B_1 strike N85°E and dip as steeply as 80°S. At site B_2, 1 km east of site B_1, steeply tilted sand beds are exposed in a quarry wall on the crest of the ridge. The beds strike N28°E and dip 61°NW. The upper surface of the sand unit has been eroded and is overlain by flat-lying gravel beds. At site B_3, a kilometer farther east along the crest of Langley Hill, moderately tilted gravels are exposed in a quarry wall. The Pleistocene gravel beds strike N80°E and dip 26°SE. Significant thrust faults (0.5 to 2.5-m offsets; Fig. 3A) displace the gravel beds (McCrory, 1996). The faults generally trend N70°E to N82°E, and dips range from 27° to 63°. Both north- and south-dipping fault planes are observed; however, the dominant dip direction is northward. At site B_4, a quarry wall 2.5 km east of site B_3 exposes flat-lying gravels that display minor thrust faults (1 to 2-cm offsets).

The diffuse nature of thrust faulting observed on Langley Hill is consistent with deformation above a buried thrust fault. The sense of vergence on the buried fault is poorly constrained. The fault at site B_3 that has a large offset (Fig. 3A) verges southward, suggesting that the inferred master fault may also verge southward. However, the asymmetry of

Figure 3A. Offset Quaternary gravel beds along one of several thrust faults exposed at site B_3 on Langley Hill. Fault offset is approximately 2.5 m and appears to disrupt the overlying soil horizon; however, the soil surface has been modified by quarry activities. The fault trends N80°E and accommodates north-south shortening attributed to relative convergence between the Siletz terrane and the Olympic subduction complex.

Langley Hill—with a steeper northern flank—implies the opposite sense of vergence.

Aloha Ridge

Ten kilometers north of Langley Hill, a 9-km-long ridge rises behind the town of Aloha. The N80°W trend of Aloha ridge is oriented about 30° clockwise with respect to the two southern ridges just discussed. Evidence of structural activity beneath this ridge is based on well data at one site (Fig. 2). At site C_1, the Rayonier No. 1-A well was drilled on the crest of Aloha ridge. Rau and McFarland (1982) infer a thrust fault in Hoh rocks penetrated in this well on the basis of a biostratigraphic age reversal. Deep cuts into the ridge are lacking, so field investigations to date have yielded no evidence of faulting in Quaternary strata beneath the ridge.

Joe Creek Ridge

Two kilometers north of Aloha ridge, an 8-km-long ridge extends between the southern and central forks of Joe Creek. Joe Creek ridge trends N80°W. Evidence of structural activity beneath this ridge is based on surface data from one site, site D_1, at the eastern end of the ridge, where Pleistocene gravels are exposed in the bank of the Copalis River (Fig. 2). These gravels strike N82°W and dip 26°N, consistent with an inferred location on the northern flank of an anticline. Aside from the stream cut, deep exposures into the core of the ridge are lacking. Field investigations to date have yielded no evidence of faulting in Quaternary strata.

Moclips Ridge

Two kilometers west of Joe Creek ridge, a 3-km-long ridge rises behind the town of Moclips. This N80°W-trending ridge may be a western extension of the structure underlying Joe Creek ridge. Evidence of structural activity beneath Moclips ridge is based on surface data from one site (Fig. 2). At site E_1, Pleistocene gravels exposed at the west end of Moclips ridge strike N73°W and dip 36°SW, consistent with a location on the southern flank of an anticline. Field investigations, hampered by poor exposures, have yielded no evidence of faulting associated with the deformed Pleistocene strata.

Wreck Creek Ridge

Three kilometers northwest of Moclips ridge, a 5-km-long ridge trends southeastward from the mouth of Wreck Creek. The N55°W trend of this ridge is shifted about 25° clockwise with respect to the three ridges immediately to the south. Evidence of structural activity beneath Wreck Creek ridge comes

Figure 3B. Steeply tilted Quaternary sand and gravel beds exposed at site F_2 just east of the Wreck Creek ridge crest. The gravel bed (darker unit) is about 1.2-m wide. The strata strike N38°W and dip 77°NE, denoting a transitional structural regime between north-south shortening observed to the south and east-west shortening to the north.

from surface data at three sites (Fig. 2). At site F_1, Pleistocene gravel beds exposed at the southern end of the ridge crest strike N53°W and dip 42°SW. A short distance east of the crest, gravel beds strike N02°W to N05°E and dip 33° to 45°SW. A minor thrust fault in Pleistocene gravels at this location trends N22°W and dips 37°SW.

At site F_2, interbedded sands and gravels are exposed in a roadcut east of the ridge crest, 1.5 km northwest of site F_1. These strata strike N38°W and dip 77°NE (Fig. 3B). A significant reverse fault at this site (>5-m offset) trends N62°W and dips 68°NE. This fault juxtaposes compacted lower Pleistocene sand and gravel beds against uncompacted, poorly sorted cobble beds. About 15 m west of the fault, strata dip steeply westward, 75°SW, and strike N60°W.

At site F_3, interbedded sand and gravel are exposed in the bank of Wreck Creek, 1.5 km northwest of site F_2. These strata strike N68°W and dip 58°NE. A steeply dipping thrust fault with minor offset (7 cm) cuts the lower Pleistocene strata and continues upward into a horizontal deposit of poorly sorted cobbles. The overlying gravels may be late Pleistocene in age; they are similar to glacial outwash lithofacies (Moore, 1965) observed elsewhere in the study area.

Structural deformation along Wreck Creek ridge is consistent with deformation above a buried thrust fault. The sense of vergence on the buried thrust fault is poorly constrained. The fault at site F_2 with a large offset verges southwestward, however; ridge asymmetry—with a steeper western flank—implies the opposite sense of vergence for the master fault.

North Fork Ridge

Two kilometers north of Wreck Creek ridge, a weakly defined ridge trends N40°W across the North Fork Wreck Creek. Evidence of structural activity beneath North Fork ridge is based on surface data from one site (Fig. 2). At site G_1, Wreck Creek cuts across the ridge and exposes gravel beds that strike N54°W to N60°W and dip 13° to 16°SW, consistent with a location on the western flank of an anticline.

Quinault Ridge

Six kilometers north of site G_1, steeply dipping sand and gravel beds are exposed on both banks of the Quinault River. An associated topographic ridge is not as well defined as those to the south. Evidence of Quaternary structural activity can be seen in surface exposures along the first 3 miles of river. Strata exposed in the southern stream bank near river mile 1.3 strike N15°W and dip as much as 25°NE (Rau, 1975; this study). Near river mile 1.8, strata strike N09°W and dip 30°NE (Rau, 1975). At river mile 2.1, strata on the northern stream bank dip almost vertically. At site H_1 (Fig. 2), near river mile 2.8, lower Pleistocene sand and gravel beds exposed along the southern bank strike N30°W to N39°W and dip 50° to 65°NE (Rau, 1975; this study). Two reverse faults at this site trend approximately N30°E and dip 55°SE. Together these faults offset the lower Pleistocene strata about 0.5 m.

The faulting and folding observed along the lower Quinault River are consistent with deformation above a buried thrust fault. The sense of vergence of the buried fault is poorly constrained. The consistent eastward dip of strata exposed along the stream banks argues for an eastward-verging fault, but faults observed at site H_1 verge westward. Some researchers (for example, Snavely and Kvenvolden, 1989; Palmer and Lingley, 1989) have inferred a major ENE-trending fault along the lower Quinault River valley on the basis of a topographic lineament. None of these researchers has presented evidence of Quaternary activity along this feature.

Duck Creek Ridge

Across the Quinault River, 2.7 km north of site H_1, a N50°W-trending ridge rises between tributaries of Duck Creek. Quaternary structural activity beneath Duck Creek ridge is based on evidence in surface exposures at several locations along the ridge crest (Rau, 1975; McCrory, 1996). At site I_1, the strike of glaciofluvial sediments along the ridge crest ranges from N45°W to N50°E; all strata tilt eastward with dips ranging from 20° to 47°. A number of thrust faults (0.1–0.5 m offsets) displace the upper Pleistocene sand and gravel beds east of the ridge crest. The trends of these faults range from N24°W to N86°W; the fault planes dominantly dip westward from 27° to 64°. One thrust fault dips steeply to the east (87°NE).

The diffuse nature of thrust faulting observed along Duck Creek ridge is consistent with deformation above a buried thrust fault. The sense of vergence on the master thrust fault is poorly constrained. Observed thrust faults predominantly verge eastward; however, the steeper western flank implies the opposite sense of vergence.

TECTONIC IMPLICATIONS OF QUATERNARY STRUCTURAL ORIENTATIONS

Subduction-complex rocks beneath the study area were accreted to the Washington continental margin during Cenozoic time. Their primary structural fabric is expected to reflect ENE-directed convergence associated with subduction processes. Quaternary structural orientations, however, denote north-south shortening. In fact, structural orientations in the study area are skewed relative to mapped structures in the surrounding region (Wagner and others, 1986). In detail, the nine ridges discussed here show a progressive clockwise shift in orientation from south to north—the southernmost ridges trend east-west and the northern ones trend NW-SE. Farther north, Quaternary thrust fault and fold trends shift to an even more northerly orientation (N10°W) (McCrory, 1996). The progressive shift in structural orientation suggests that the study area serves as a transitional zone between north-south-directed compression to the south and east-west-directed compression to the north. This shift occurs adjacent to a major boundary between crustal blocks of widely differing rheologies. Paleomagnetic data suggest that the relatively rigid southern block, the Siletz terrane, is actively translating northward along the Cascadia margin (England and Wells, 1991). Observed north-south shortening occurs in the relatively ductile subduction-complex block just north of this boundary (Fig. 1). The proximity of the north-south shortening to the crustal block boundary suggests that the shortening may express relative convergence between the Siletz and subduction-complex blocks.

A major ENE-trending fault cuts across northern Grays Harbor (Fig. 2) near the crustal block boundary between Siletz terrane and subduction-complex rocks. This fault extends offshore for about 20 km, then apparently curves southward and continues for an additional 30 km (Wolf and others, 1997). Offshore seismic reflection profiles depict this fault as a 2.5-km-wide zone of reverse faults and back thrusts in a broad anticlinal fold. The upward extent of the fault zone varies from profile to profile. On some profiles, the fault appears to die out in lower Pleistocene strata. On others, individual fault strands in the fault zone reach and offset the seafloor (Wagner and others, 1986). Two petroleum wells penetrate this fault zone and lithologic data reveal stratigraphic reversals in both Quinault strata and subduction-complex rocks. Rau and McFarland (1982) interpret the stratigraphic reversals as evidence of thrust faulting. Moore (1965) documented thrust faulting in Pleistocene strata along the onshore portion of the fault zone.

Palmer and Lingley (1989) suggest that this Grays Harbor fault zone accommodates transpressional motion, primarily on the basis of a mismatch in thickness of Montesano lithofacies across the fault zone in onshore wells. Given the limited evidence for thrust faulting discussed above, the facies mismatch may instead result from the formation of sediment-dispersal barriers during thrust faulting. The 50-km length of this fault and the evidence for late Quaternary activity argue for its potential as an earthquake source. Further study is needed to resolve slip direction along the fault and to constrain its slip rate.

CONCLUSIONS

Field investigations along the Washington coast document Quaternary tectonic activity. This tectonism accommodates north-south shortening in the Washington continental margin, in contrast to east-west subduction-related shortening observed elsewhere. Evidence of skewed structural orientations in a 30-km-wide zone between Grays Harbor and Point Grenville supports the hypothesis (McCrory and others, 1996) that this region marks active convergence between marginal crustal blocks. This crustal block boundary extends northeastward into the urbanized Puget Sound region, underscoring the need to better understand the complex tectonic regime that gives rise to crustal earthquakes in western Washington.

ACKNOWLEDGMENTS

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EARTHQUAKE PREPAREDNESS FACT SHEET

About 1,000 earthquakes occur in Washington each year. Most are not even felt, but we do experience damaging earthquakes from time to time. For guidance on what you can do before, during, and after a quake, the Washington State Emergency Management Division offers an earthquake preparedness fact sheet on the Internet at http://www.wa.gov/mil/wsem/peet/prepare/hazard/eq.htm.

STAFF NOTES

Cathrine Kenner, our new clerical assistant, comes to us through Community Youth Services. She is planning a career in geology.

Patty Jetton, our receptionist for the past 2 months, has left to take a promotion in the Assistant Commissioner's Office of Employment Security. We will miss Patty a bunch.

Philip Dobson is our new receptionist. He comes to us from the Washington State Library Mail Room. Philip wants to pursue a career in natural resources.

Combined Fund Drive

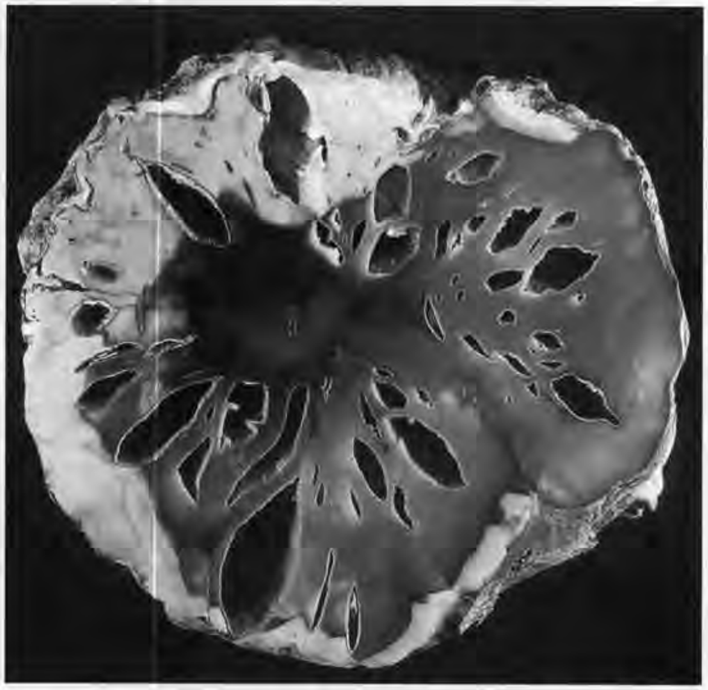
The Division is proud to announce that it raised $1,022.65 to donate to charity during the month of October.

Connie Manson's 20th Anniversary

On January 18, 1998, we celebrate the 20th anniversary of the date Connie, our librarian, joined the Division. Connie is responsible for the enormous collection, thorough bibliographies, dedicated public service, and forward thinking that are the hallmarks of the library. Although frequently presented with interesting job possibilities elsewhere, Connie has loyally stayed with us. Please join us in giving her congratulations and best wishes for another 20 years in the Division.

RICE NORTHWEST MUSEUM OF ROCKS AND MINERALS

The Rice Northwest Museum of Rocks and Minerals in Hillsboro, Oregon, has an excellent collection of minerals, as well as reference materials, that is available for viewing, study, and research to anyone who is interested in the earth sciences. The museum was founded by Richard L. and Helen M. Rice in 1996 for the express purpose of passing on to present and future generations the knowledge and pleasure to be derived from these beautiful specimens.



A specimen of petrified cypress wood from Washington that is on display at the museum. *(Photo courtesy of the Rice Northwest Museum.)*

The museum has an extensive collection of crystallized mineral species: world-class specimens of common quartz and gypsum; colorful copper minerals; one of the two finest red rhodochrosite specimens in the world; rare and beautiful crystals of emerald, ruby, aquamarine, morganite, and amethyst; and thousands of other specimens from around the world.

The collection also displays lapidary works: large cut and polished sections of petrified wood, fossil palm, and cycad; polished specimens of green variscite, rhodochrosite, malachite, lapis lazuli; turquoise, chrysocolla, rutilated quartz, and much more.

A northwest mineral museum would not be complete without agate. The Rices began their collection in 1938 with a handful of Oregon beach agates. The museum displays agates from locations throughout the Americas, including the U.S., Argentina, Brazil, and Mexico. Thunder eggs from many of Oregon's classic localities are featured.

The museum is open to visitors from 1:00–5:00 p.m., Thursday, Saturday, and Sunday. Group tours are by appointment only. Admission is free to the general public.

The museum is located at 26385 NW Groveland Drive, Hillsboro, OR 97124; phone 503-647-2418. Take State Route 26 west from Portland to Exit 61 north. Take the first turn west onto Groveland Drive.

The Canyon River Fault, an Active Fault in the Southern Olympic Range, Washington

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Introduction

Recent work has established that a number of aligned earthquake epicenters are shallow enough to have produced surface rupture in western Washington. (See Rogers and others, 1996, for a summary.) However, only two mapped faults, the Saddle Mountain East and West faults (Fig. 1), have been shown to have Holocene surface rupture (Wilson and others, 1979). We have identified another fault 24 km west-southwest of these that has a similar, that is, reverse sense of separation and apparent Holocene offset. We have named it the Canyon River fault (CRF). It is part of a lineament that is at least 40 miles long. Our preliminary work suggests that the CRF has been active within the last 2,000 years. If the CRF is seismogenic, earthquakes along this fault would likely be large enough to put several dams and small cities at risk.

There are many late Holocene seismically induced features, such as landslide-dammed lakes and uplifted and subsided land surfaces (Rogers and others, 1996; Gower and others, 1985; Atwater and Moore, 1992; Bucknam and others, 1992; Karlin and Abella, 1992; Jacoby and others, 1992; Logan and Walsh, 1995; Schuster and others, 1992; Washington Division of Geology and Earth Resources (DGER), unpublished data; U.S. Forest Service, unpublished data) that are spatially and temporally associated with these faults. This mostly indirect evidence supports the occurrence of several major late Holocene seismic events in the vicinity of the CRF.

The CRF is at the contact between the upper and lower members of the Crescent Formation, as mapped by Tabor and Cady (1978). Glassley, (1974) recognized faulting along this contact in other parts of the Olympics and inferred it to be a fault contact everywhere on the basis of differences in metamorphic grade. Babcock and others (1992), however, found that the faulting is not a single continuous structure and that

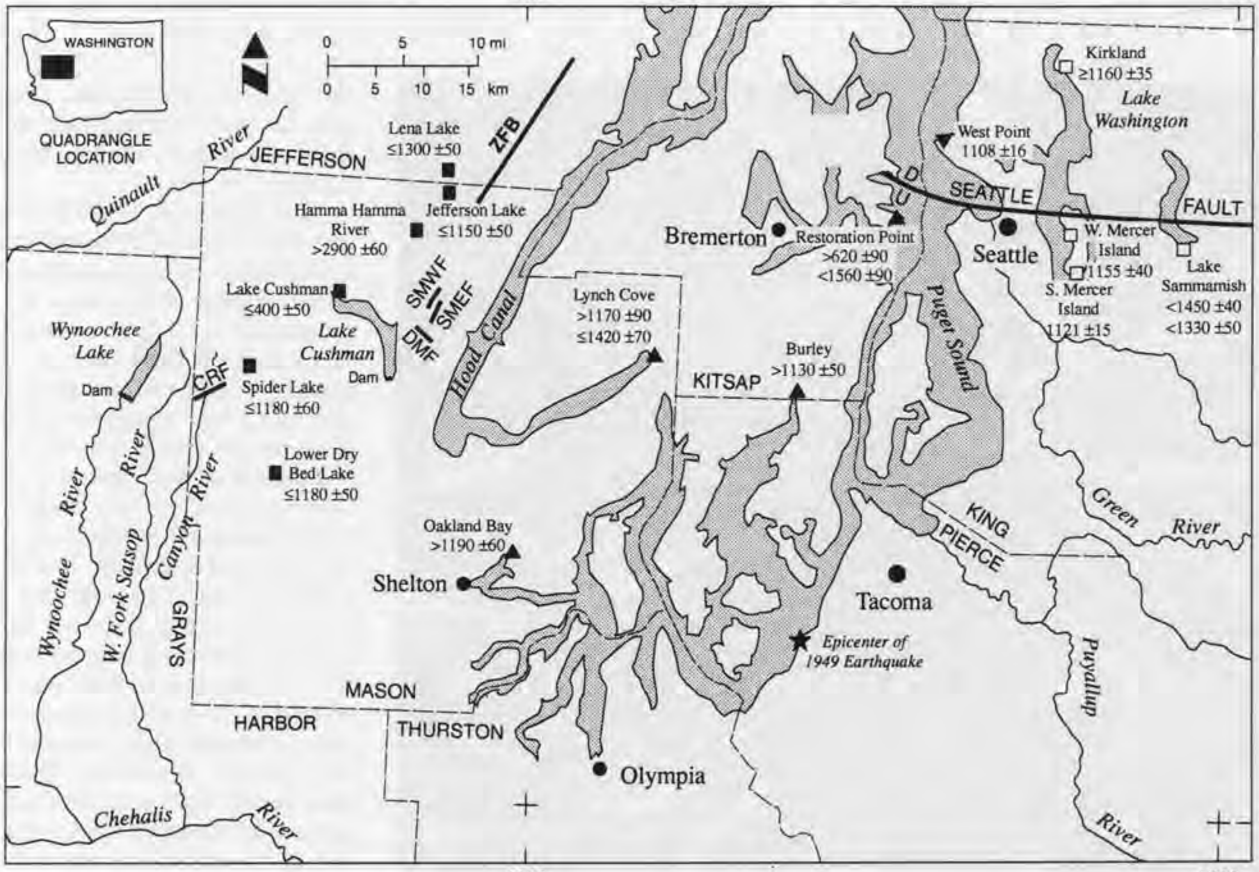

Figure 1. General location of the Canyon River fault (CRF). The fault lies between Wynoochee and Cushman dams, which impound large reservoirs upstream of inhabited areas. Significant nearby features, shown with radiocarbon ages, include: seismically induced landslides (□), landslide-dammed lakes (■), and uplifted (▲) or subsided (▼) estuaries. DMF, Dow Mountain fault; SMWF, Saddle Mountain West fault; SMEF, Saddle Mountain East fault; ZFB, zone of fractured basalt of Glassley, 1974.

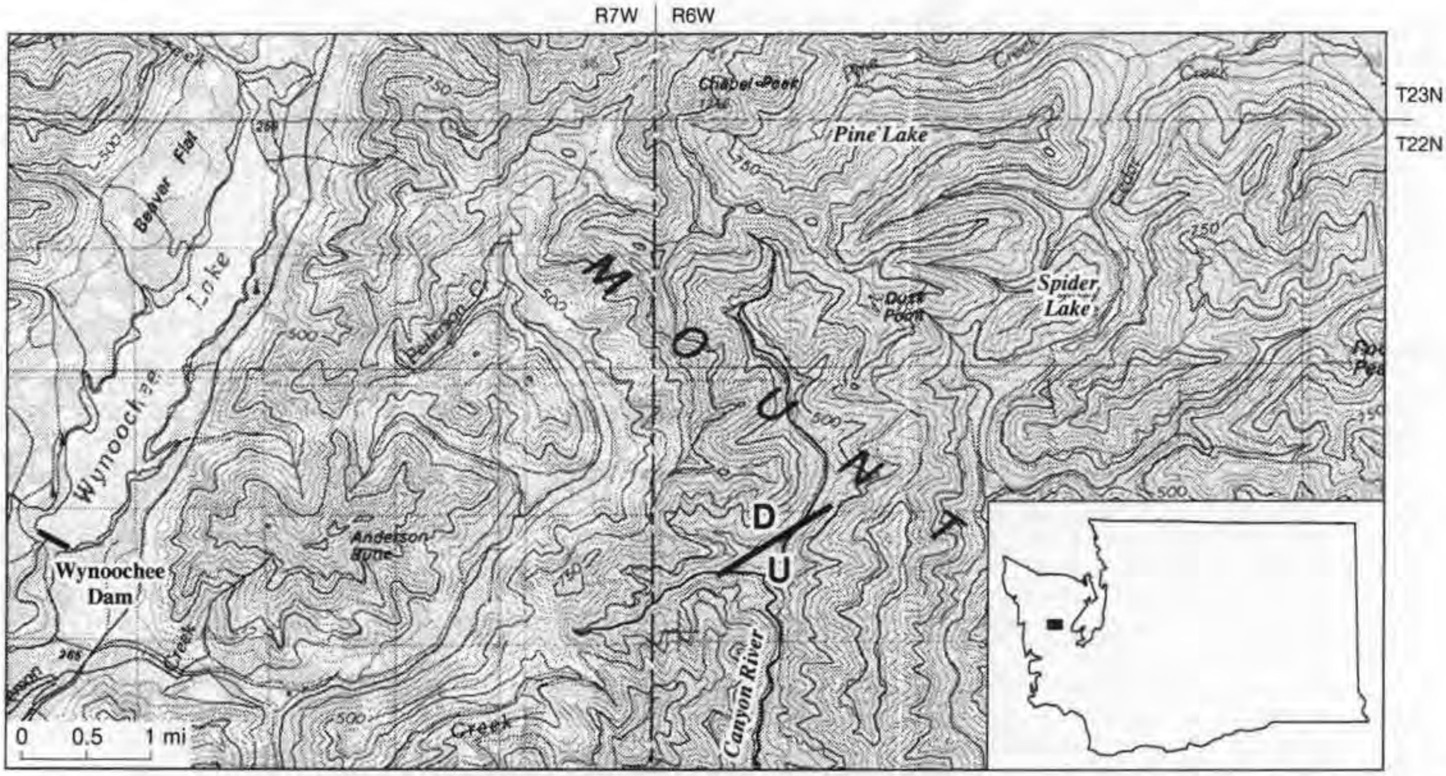

Figure 2. Location and known extent of the N60°E-trending fault scarp. Note that Wynoochee dam, which impounds the water supply for the city of Aberdeen and is upstream of a number of homesites and State Route 12, is located less than 10 km from the scarp. Spider Lake, a suspected seismically induced landslide-dammed lake, is within 3 km. Contour interval is 50 m. Printed from TOPO! ©1997 Wildflower Productions (www.topo.com).

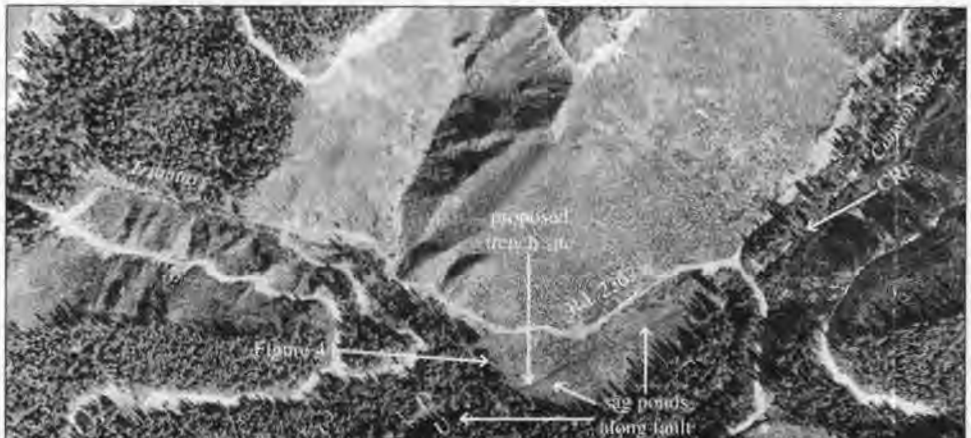

Figure 3. 1992 aerial photo of the Canyon River fault (CRF). The proposed trench site will cross the fault at the center sag pond, which is dry most of the year and is accessible by an overgrown skid road. Note that despite dense regrowth over a previous clearcut, the fault trace remains visible from the air, a rarity in western Washington. Scale is approximately 1:12,000.

the "tectonic disruption...is undoubtedly far more complex than the simple thrust of upper member over lower member".

The CRF strikes N60°E (Figs. 1, 2) and dips between 60°S and vertical. It is well exposed in the southeast Olympic Mountains where, for a distance of several miles, it forms a north-facing scarp on both north- and south-facing slopes. It appears from regional geology and a few ambiguous horizontal slickensides that it may have a small component of right-lateral slip, but the consistency of its scarp suggests that it is principally a reverse fault. It is part of a regional lineament that is readily visible on aerial photography (Fig. 3) and sidelooking airborne radar imagery for a distance of at least 40 miles.

McCrory (1996, this issue) has described faulting and folding in Quaternary sediments along the west side of the Olympic Peninsula. These structures reflect both east-west shortening related to northeastward convergence and north-south shortening related either to broad northwest-southeast shearing between the Pacific and North America plates or to the margin-parallel component of oblique convergence between the Juan de Fuca and North

America plates. She proposed that sediments deposited at the base of the accretionary wedge respond to stresses associated with plate convergence, but that structures higher in the accretionary prism respond to modern north-south compression (Magee and Zoback, 1992; Ma and others, 1996).

We infer that the CRF may have accommodated early thrusting in the Crescent Formation related to Juan de Fuca plate subduction but is now reactivated as a high-angle reverse fault in response to modern shallow north-south compression.

Preliminary Results

The fault trace is most clearly exposed near the western boundary of Mason County in sec. 19 of T.22N., R.6W., W.M., where it is aligned subparallel to the valley floor of the Canyon River and a tributary (Figs. 2, 3). The fault trace has been incised by two unnamed perennial streams. In one of these streams, sediments that were impounded by the upthrown fault block are exposed in stream channel walls (Fig. 4). Sheared basalt bedrock is exposed in the channel and its walls downstream from the fault. Where the other stream crosses the fault at a low angle, the fault scarp has diverted the stream along the fault trace and left a short segment of channel that was incised into basaltic bedrock stranded above the active channel (Figs. 5, 6).

We obtained a radiocarbon age of 1,880±70 yr B.P. (Beta 109347) on abundant detrital charcoal from a silt draped over remnant boulder gravel in the abandoned channel, suggesting fault movement more recent than about 2,000 radiocarbon years ago. We have not yet found piercing points to convincingly demonstrate the direction of slip. The geometry of the channel offset has no apparent lateral component, and the scarp is consistently north-facing, regardless of topography, suggesting to us a pure high-angle reverse slip in the last movement. We have found a few sets of horizontal slickensides, however, that suggest the fault may also have a component of right-lateral slip. We infer that the CRF dominantly accommodates north-south compression but perhaps also a component of Juan de Fuca plate convergence.

Figure 4. This photo (location shown on Fig. 3), taken about 50 m upstream of the CRF, shows horizontal (behind the pick) sediments that were deposited after the the upthrown block dammed the stream. A layer of sediment consisting of poorly sorted angular clasts (probably a debris flow deposit that crops out elsewhere) has been eroded away here. The exposed silt unit weathers orange and is about 15 cm thick. It is underlain by another coarse debris flow deposit. The boulders here are derived from pillow basalts of the lower Crescent Formation (Tabor and Cady, 1978), which is exposed in the stream bed a short distance upstream. The thickness of the fault-dammed sediments is unknown due to poor exposure. Datable material has not yet been found in these sediments.

Figure 5. (See Figure 3 for location.) Truncated colluvium exposed in the south bank of an unnamed tributary to the Canyon River. Note the apparent drag folds in clay layers to the right and left of the 66-cm pick handle. The deformed clay layers contain abundant charcoal and are separated by coarser colluvium. The approximate fault trace is shown by the dashed line. At this locality, the fault trace is easily recognized in the stream bed because the upthrown block is scoured to sheared basaltic bedrock, but the younger alluvium has deposited in the present channel adjacent to the scarp. Shears within the basalt project from left to right directly toward the deformed clay beds.

Surface expression of the fault is a linear break in the valley floor approximately 3 m high. The terrain both north and south of the fault is relatively level and forested and is locally covered by standing water in two sag ponds. We hope to trench the fault adjacent to one of these sag ponds to obtain information on recurrence interval.

Figure 6. The upthrown block, about 15 m downstream of Figure 5. Where the geologist is standing, the stream channel is scoured to bedrock and is covered with basalt boulders. To his left, silt is draped over the boulders and is overlain by a thick sequence of gravelly colluvium . We infer that the silt was deposited by flooding soon after this channel was uplifted. A radiocarbon age of 1,880 +70 yr B.P. (Beta 109347) was obtained from abundant detrital charcoal in the silt.

Figure 7. Sag pond along the Canyon River Fault. This is the southwesternmost sag pond in Figure 3. Smaller trees grow to the edge of the scarp, whereas the downthrown side of the fault is marshy and devoid of trees. View is to the southeast from a road about 150 ft above the pond.

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Eocene Megafossils from the Needles–Gray Wolf Lithic Assemblage of the Eastern "Core Rocks", Olympic Peninsula, Washington

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INTRODUCTION

The central part of the Olympic Mountains, Washington, contains several lithic assemblages that collectively make up what is known as the "core rocks", a term that stems from usage in the 1970s by U.S. Geological Survey mappers. These core rocks have had a complex tectonic history, and it is generally accepted that they are a collage of several imbricated thrust slices consisting of subduction-related mélange and turbidite units that accreted to North America during the Tertiary (Heller and others, 1992; Suczek and others, 1994). Due primarily to the scarcity of fossils, the ages of the core rocks are not well constrained (Heller and others, 1992), but they are generally accepted to be younger than the lower part of the so-called "peripheral rock" (that is, lower part of the Crescent terrane) that border them to the north, east, and south in a horseshoe outcrop pattern.

Fossils are rare within the core rocks (Danner, 1955b; Tabor, 1975). Reasons for this scarcity are that many of the core rocks are turbidites, originally deposited in deep water as the result of turbidity flows. Turbidity flows are, in most instances, not conducive to the preservation of fossils. Many turbidites in the core rocks have also been sheared or otherwise deformed, and some are metamorphosed, destroying any fossils that may have been present.

The Needles–Gray Wolf lithic assemblage, the easternmost of the core rocks, consists of an approximately 6.5 km-thick thrust slice containing sandstone, siltstone, slaty mudstone, and pillow basalt. The dip of this thrust slice is nearly vertical, and the unit is also chiefly eastward and northeastward topping (Cady and others, 1972a) and is one of the structurally highest thrust slices in the accretionary prism that makes up the Olympic core. The Needles–Gray Wolf lithic assemblage is one of the oldest thrust slices, yet it is younger than the lower to middle Eocene pre-subduction zone rocks in the lower part of the Crescent terrane. The Needles–Gray Wolf unit was originally reported (see Previous Work) as ranging in age from late Paleocene to late Eocene, on the basis of scarce megafossil remains. Fission-track studies of detrital zircons in sandstones (Brandon and Vance, 1992a,b) now place the age range from 39 to 33 Ma (late Eocene to early Oligocene). The stratigraphic positions of these detrital-zircon samples versus those of the megafossils are discussed under Previous Work.

This is the first detailed report about the megafossil species in the Needles–Gray Wolf unit. We offer comments regarding provenance, geologic age, and photographic documentation of the species collected. The molluscan stages used in this report stem from Clark and Vokes (1938), who proposed five informal molluscan-based provincial Eocene stages: Meganos, Capay, Domengine, Transition, and Tejon.

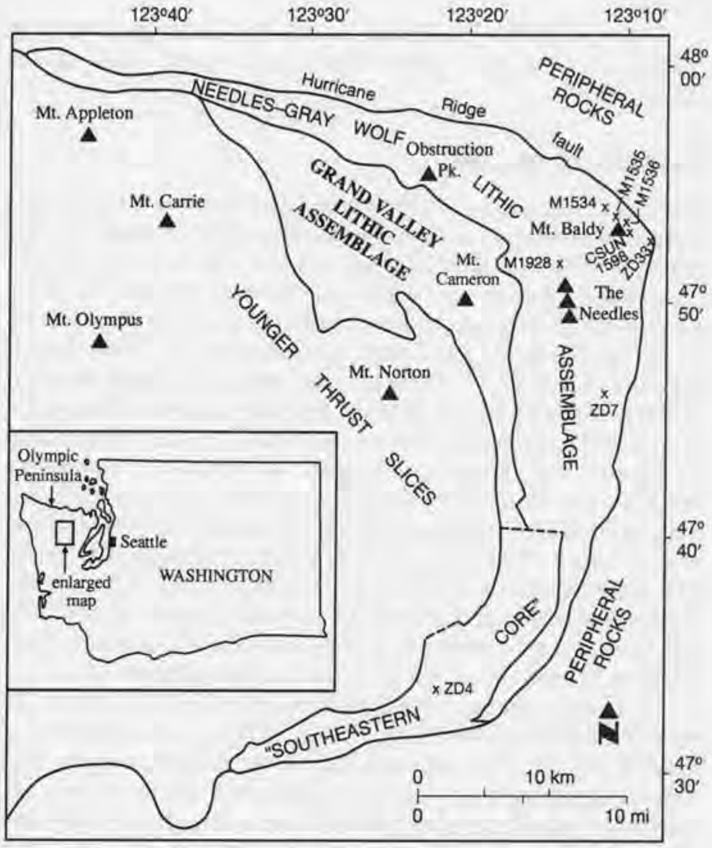

Figure 1. Index map showing the megafossil localities and selected detrital-zircon localities of Brandon and Vance (1992a,b). Modified from Tabor and Cady (1978a, fig. 2).

Abbreviations used are: CSUN, California State University, Northridge; LACMIP, Natural History Museum of Los Angeles County, Invertebrate Paleontology Section; USGS, U.S. Geological Survey; and USNM, National Museum of Natural History, Washington, D.C.

PROCEDURE

The Needles–Gray Wolf megafossils we studied are from five localities. Four of these localities (USGS locs. M1534, M1535, M1536, and M1928) were found and collected by W. M. Cady and his colleagues while mapping for their report on the Tyler Peak quadrangle (Cady and others, 1972a). Localities M1534–1536 are from near Mount Baldy in the upper part of the Needles–Gray Wolf lithic assemblage (Fig. 1).

Locality M1928 is about 6.5 km southwest of the other localities and is north of The Needles, which is a high, steep-sided ridge where rocks of the Needles–Gray Wolf lithic assemblage are prominently exposed. We did not visit the Cady localities; they are remote and extremely difficult to reach. We borrowed the collections of megafossils, which number about 100 specimens, from the USGS at Menlo Park, Calif.

The fifth locality (CSUN loc. 1598) was found by the junior author in 1992. A blizzard in August allowed for only a short visit, but seven fossil specimens were collected.

Preservation of all the fossils from the Needles–Gray Wolf unit is poor, and many specimens are preserved as molds. Latex peels of external molds (made by workers at the USGS and by us) were used to identify the gastropods and some of the bivalves.

The specimens illustrated in this report are deposited at USNM, and the rest of the collection is stored at the USGS (Menlo Park).

PREVIOUS WORK

Cady and MacLeod (1963) reported fragments of megafossils from a fossiliferous horizon in the core of the Olympic Mountains. The interval is 150 to 300 m thick and crops out locally for about 34 km along strike. They also mentioned the presence of the gastropod *Gemmula*? sp. and the bivalves *Acila* cf. *A. decisa* (Conrad, 1855) and *Crassatella?* sp. They further mentioned that W. O. Addicott, who was a molluscan paleontologist with the USGS at that time, had examined the megafossils and considered them to be of early Tertiary (Paleocene to Eocene) age. These fossil molds and casts of fragmentary remains are from three USGS localities (M1534, M1535, M1536) that were plotted within the Needles–Gray Wolf lithic assemblage by Cady and others (1972a) on their geologic map. The localities are in a thin zone of microbreccia in the Mount Baldy area. Cady and others (1972a) also indicated megafossils from the microbreccia at about 5.5 km and about 8.5 km south of Mount Baldy but gave no locality numbers.

Cady and others (1972a) reported planktonic microfossils from a microfossil locality (USGS 3816) 3 km southeast of locality M1928. The reported age of the microfossils as "not older than Tertiary" is not very informative and makes any information gained from megafossils more important. Cady and others (1972a) assigned a minimum age of 42.6 ±0.7 Ma. (late Eocene) to the Needles–Gray Wolf lithic assemblage on the basis of a K-Ar age from a dike that cuts the assemblage about 45 km southwest of the Mount Baldy area.

Cady and others (1972b), Tabor and others (1972), and Tabor and Cady (1978a) reviewed the probable geologic age of the Needles–Gray Wolf rocks but added no new megafossil information. Tabor (1975, fig. 22) provided generalized line drawings of unnamed species of the bivalve *Venericardia* and the gastropod *Turritella* from near locality M1928. He reported that W. O. Addicott considered these fossils to be probably late Eocene in age. Tabor and Cady (1978b) plotted the four above-mentioned USGS mega- fossil localities on their geologic map of the Olympic Peninsula, but they did not list or discuss the megafossil species, nor did they give a precise geologic age. They assigned the Needles–Gray Wolf unit an undifferentiated Eocene age.

Brandon and Vance (1992a,b) reported fission-track ages in the range of 39 to 33 Ma (late Eocene to late Oligocene) for the youngest detrital zircons in two sandstone samples (ZD7 and ZD33) (Fig. 1) from the Needles–Gray Wolf unit. Sample ZD7 was collected about 10.5 km (6.5 mi) south of USGS loc. M1928 and might be stratigraphically higher. Sample ZD33 is 3.2 km (2 mi) southeast of localities USGS M1536 and CSUN 1598 and is from the stratigraphically highest (youngest) part of the Needles–Gray Wolf unit.

Brandon and others (1988) reported a fission-track age of 39 ±4.5 Ma (late Eocene) for the youngest detrital zircons in a sandstone sample (ZD4) (Fig. 1) collected from the Southeastern core rocks (map unit Tsc of Tabor and Cady, 1978b) along the North Fork Skokomish River. The northernmost outcrops of the Southeastern core rocks are about 21 km (13 mi) south of the southernmost megafossil locality in the Needles–Gray Wolf unit. The stratigraphic relations of the Southeastern core rocks and the Needles–Gray Wolf unit are complex and need further study.

The only other megascopic fossils reported from the Needles–Gray Wolf lithic assemblage are large (as much as 8.5 mm diameter) siliceous tubes of a foraminiferid. Danner (1955a,b) reported the tubes as present near Obstruction Peak [his Obstruction Point], which is about 15 km northwest of Mount Baldy (Fig. 1). Obstruction Peak is underlain by rocks of the Needles–Gray Wolf lithic assemblage (Tabor and Cady, 1978b). In 1975, Danner referred to the fossils as the agglutinated tube fossil *Terebellina* and noted that they indicate relatively deep offshore waters. Miller (1995) confirmed that the tubes are actually remains of the siliceous, large foraminiferid *Bathysiphon* and that the genus name *Terebellina* is a junior synonym. However, remains of this foraminiferid, which are also present in the peripheral rocks surrounding the core rocks, are not age diagnostic.

LITHOLOGIES AND PALEONTOLOGY

Rocks from USGS loc. M1928 are dark-gray, well-cemented, very fine grained and well-sorted micaceous sandstone that is brown when weathered. The rock is slightly metamorphosed and contains some deformed gastropods and bivalves. Some of the hand specimens contain localized concentrations of disarticulated bivalve shells that show both concave-up and concave-down positions. The shells are matrix supported and were deposited by grain-flow processes associated with turbidites, which make up most of this rock assemblage.

Seventy-six fossil specimens were collected at locality M1928, and the taxonomic composition of this fauna is listed in Table 1. Taxa identifiable to genus level or lower are illustrated in Figure 2. The dominant faunal components are the gastropod *Turritella uvasana* cf. *T. uvasana uvasana* Conrad, 1855, and the bivalve *?Callista andersoni* (Dickerson, 1915). Most of the gastropods are preserved as external molds, and the *Turritella uvasana* cf. *T. uvasana uvasana* remains consist

Table 1. Megafossils from USGS loc. M1928 in the western part of the Needles–Gray Wolf lithic assemblage, eastern core of the Olympic Mountains. The number of specimens of each species is given in parentheses

Gastropods
Turritella uvasana cf. *T. uvasana uvasana* Conrad (11)
Crepidula? sp. (1)
naticid (1)
unidentifiable gastropods (11)
Bivalves
Glycymeris sp. (3)
Venericardia sp. indet. (1)
?Callista andersoni (Dickerson) (16)
?Callista conradiana (Gabb) (5)

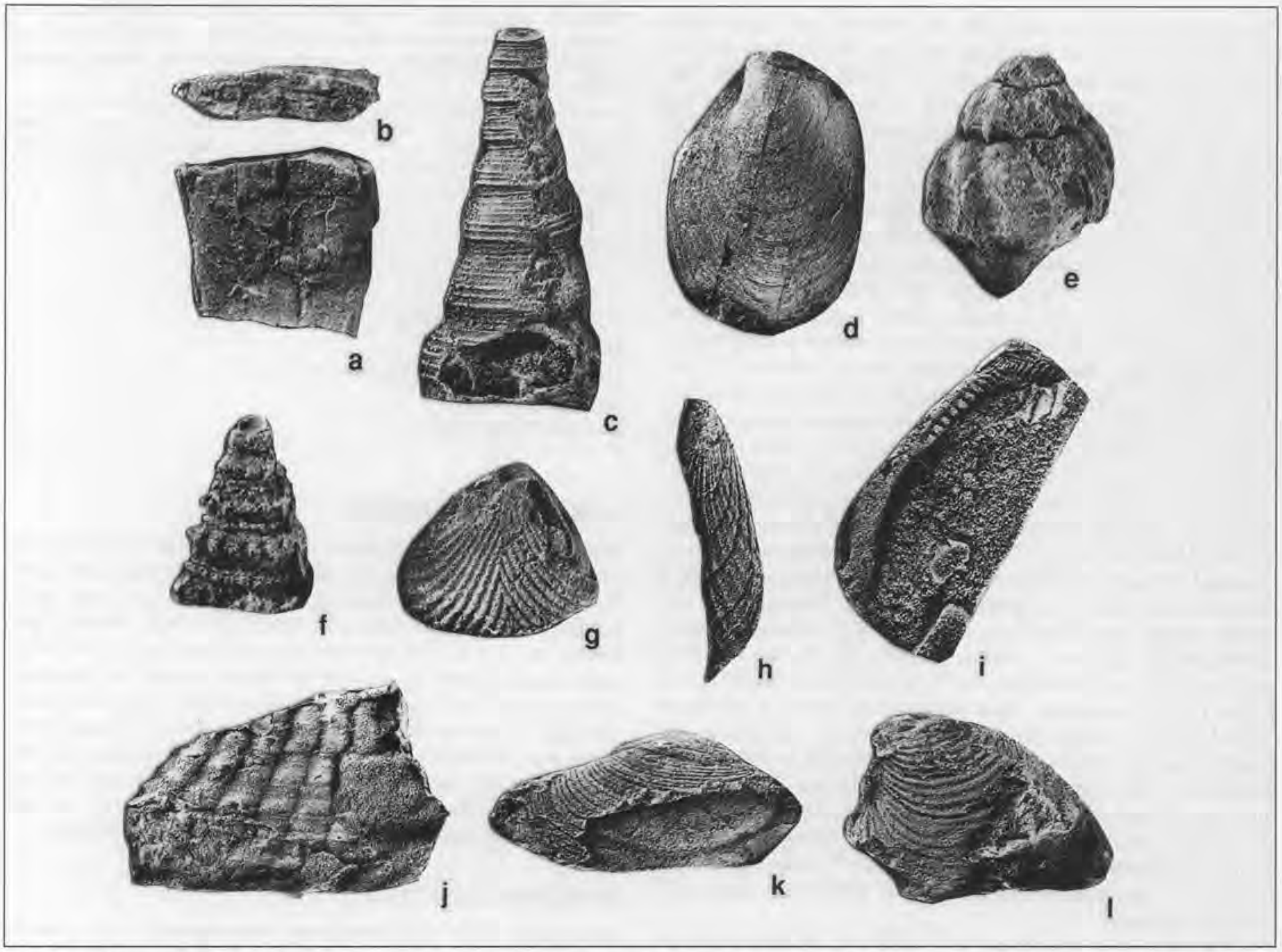

Figure 2. Needles–Gray Wolf lithic assemblage megafossils identifiable to genus or species. All latex casts and specimens coated with ammonium chloride. **a,b.** *Bathysiphon* sp., hypotype LACMIP 7950, CSUN loc. 1598, length 8.5 mm, diameter 8.5 mm, total thickness 2.3 mm, x3.3. **a**, lateral view; **b**, cross-section view. **c.** *Turritella uvasana* cf. *T. uvasana uvasana* Conrad, 1855, USNM hypotype 487983, USGS loc. M1928, latex cast, side view, length 16 mm, x7.3. **d.** *Crepidula*? sp., USNM hypotype 487984, USGS loc. M1928, dorsal view, length 37.6 mm, x1.2. **e.** *Whitneyella*? sp., USNM hypotype 487985, USGS loc. M1535, latex cast, side view, length 16 mm, x2.3. **f.** Gemmula sp., USNM hypotype 487986, USGS loc. M1535, latex cast, side view, length 3.2 mm, x9.7. **g.** *Acila* (*Truncacila*) *decisa* (Conrad, 1855), USNM hypotype 489787, USGS loc. M1535, latex cast, right? valve, height 6 mm, x4.7. **h,i.** *Glycymeris* sp., USNM hypotype 489788, USGS loc. M1928, latex cast of partial specimen, height 23 mm. **h**, exterior view, x1.9; **i**, partial hinge view, x2.2. **j.** *Venericardia* sp. indet., USNM hypotype 487989, USGS loc. M1928, latex cast of fragment of shell, maximum dimension 40 mm, x1.3. **k.** ?*Callista andersoni* (Dickerson, 1915), USNM hypotype 487990, USGS loc. M1928, right-valve exterior, height 7 mm, x3.1. **l.** ?*Callista conradiana* (Gabb, 1864), USNM hypotype 487991, USGS loc. M1928, left-valve exterior, height 10 mm, x2.7.

only of the apical whorls (that is, juvenile whorls). Some of the bivalves are preserved as recrystallized shell calcite, but many are internal molds. Nearly all the bivalves are single valves, and the only articulated ones are three juvenile specimens. All the megafossil taxa found at this locality are found elsewhere along the Pacific coast of North America in shallow-marine (shelf depths) rocks.

The *Crassatella*? sp. reported by Cady and MacLeod (1963) from locality M1928 is a fragmental specimen whose hinge teeth are missing. Positive identification to even the familial level is not possible.

At USGS locs. M1534–1536, as well as at CSUN loc. 1598, the rocks consist of gray to black micaceous siltstone with abundant rip-up clasts and scattered granules and small pebbles that reach 6.5 mm in diameter. Fewer than ten specimens were found at each of these localities. The taxonomic composition at each locality is given in Table 2. Taxa identifiable to genus level or lower are illustrated in Figure 2. Most specimens are preserved as molds. The dominant faunal component at these localities is the bivalve *Acila (Truncacila) decisa* Conrad, 1855, a widespread species found elsewhere along the Pacific coast of North America in shallow-marine rocks (Squires, 1984; Squires and Goedert, 1994).

At CSUN loc. 1598, a thick-walled fragment of the tubular, siliceous foraminiferid *Bathysiphon* sp. was found. At USGS loc. M1536, an external mold of this foraminiferid was also found.

GEOLOGIC AGES

Turritella uvasana cf. *T. uvasana uvasana*, ?*Callista andersoni* (Dickerson, 1915), and ?*Callista conradiana* (Gabb,

1864) provide the best indication of geologic age of any of the megafossils found in the Needles–Gray Wolf lithic assemblage. These taxa were found only at USGS loc. M1928. The specimens of *Turritella uvasana* cf. *T. uvasana uvasana* can be only tentatively identified to subspecies because the specimens consist only of the apical whorls. Nevertheless, a comparison with all the known subspecies of *Turritella uvasana* showed that the locality M1928 specimens are most similar to *Turritella uvasana uvasana*. The similarity concerns the whorl profile and the relatively close spacing of the three to four secondary spiral ribs on the posterior half of the juvenile whorls. The anterior half of the juvenile whorls is occupied by three primary spiral ribs. *Turritella uvasana uvasana* is confined to the Tejon Stage, which spans a considerable interval of time from middle middle Eocene through late Eocene (Squires, 1994). *Turritella uvasana uvasana* is a common subspecies in southern and central California (Merriam, 1941), and its geographic range can now be extended tentatively to Washington.

The *Turritella* specimens at USGS loc. M1928 are also similar to certain specimens of *Turritella uvasana chehalisensis* Merriam, 1941. These particular specimens were considered by Merriam (1941) to be "extreme variants" that have the characteristics of *T. uvasana uvasana*. One of these extreme-variant specimens is a paratype of *T. uvasana chehalisensis* and is figured by Merriam (1941, pl. 16, fig. 14). That specimen is from exposures that Pease and Hoover (1957) and Logan (1987) mapped as Skookumchuck Formation just south of Oakville near Balch in the Chehalis Valley, Grays Harbor County, western Washington. This formation is of late middle Eocene age (Armentrout and others, 1983) and correlative to the Tejon Stage. Although it is not possible to resolve whether the USGS loc. M1928 specimens are *Turritella uvasana uvasana* or extreme variants of look-alike *T. uvasana chehalisensis*, the geologic age of the latter is within the range of *T. uvasana uvasana*.

The *Turritella* specimens at USGS loc. M1928 superficially resemble *Turritella porterensis* Weaver (1912), a species known (Armentrout, 1975) from lower Oligocene strata in western Washington. The whorl profile of the *Turritella* specimens at USGS loc. M1928 differs from that of *T. porterensis* by having much weaker and much less well developed spiral ribs on the posterior half of the whorls.

The specimens of ?*Callista andersoni* and ?*Callista conradiana* from USGS loc. M1928 cannot be positively identified because of poor preservation. Both bivalve species are widespread on the Pacific coast of North America, and *Callista conradiana*, like *Turritella uvasana uvasana*, is confined to the Tejon Stage. *Callista andersoni* ranges from the Transition Stage to Tejon Stage (Squires, 1994). Therefore, the geologic age of the megafossils at USGS loc. M1928 is most likely middle middle Eocene to late Eocene (Tejon Stage).

The single specimen of *Crepidula*? sp. found at USGS loc. M1928 is a large specimen (37.6 mm long) embedded in matrix, but cleaning this specimen to make a positive generic and specific identification would destroy it.

The bivalve *Acila* (*Truncacila*) *decisa* is the dominant faunal component at the localities in the vicinity of Mount Baldy. The geologic range of this species is late Paleocene through the late Eocene (Squires and Goedert, 1994). The specimens in the Mount Baldy area must be either the same age as or younger than the middle middle Eocene to late Eocene rocks at USGS locality M1928 in the lower part of the unit because the specimens are from near the top of the Needles–Gray Wolf unit.

Table 2. Megafossils from localities in the Mount Baldy area in the eastern part of the Needles–Gray Wolf lithic assemblage, eastern core of the Olympic Mountains. The number of specimens of each species is also given

Taxa — Localities:	USGS M1534	USGS M1535	USGS M1536	CSUN 1598
Foraminiferid				
Bathysiphon sp.			1	1
Gastropods				
Whitneyella? sp.	–	1		–
Gemmula sp.	–	1	–	–
unidentifiable gastropods	1	2	–	1
Bivalves				
Acila (Truncacila) decisa (Conrad)	3	7	1	4
Echinoderms				
unidentifiable fragments	–	–	2	–

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Erratum

In the article about the Chuckanut Formation in the previous issue, there is a spurious reference to a Clark Point on the north end of Guemes Island. The Clark Point in question is the one that borders Chuckanut Bay, near Bellingham's southwestern city limits.

EOCENE FOOTPRINTS DISCOVERED

Footprints of several kinds of middle Eocene animals were recently discovered in the Black Diamond coal mine, owned by Pacific Coast Coal Company. The company has offered to help the Burke Museum geologic staff make casts or to collect some of these or similar prints. (We do not know who took this photo. If you recognize it as one of yours, let us know and we'll give you credit in the next issue.)

Progress Report on the Geologic Mapping and Landslide Inventory of the West-central Portion of the Olympic Peninsula, Washington

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Work continues on mapping (at 1:24,000 scale) glacial deposits in the Sol Duc, Calawah, and Bogachiel drainage basins on the west side of the Olympic Mountains (Fig. 1). Also being compiled for the same area is an inventory of deep-seated landslides. The work is funded by the U.S. Forest Service through the Olympic Natural Resources Center in Forks, Washington (under contracts UW 234153 and DNR FY96-165), and contributes to the completion of the northwest quadrant of the state geologic map (1:250,000 scale). The stratigraphic relations of the glacial deposits will be correlated with the Quaternary mapping done by Thackray (1997) to the south in the Hoh and Queets drainages and observations made by Long (1975, 1976) in the Sol Duc and Calawah drainages.

To date, about 5 weeks of interrupted time have been spent mapping glacial deposits, fluvial deposits, and bedrock contacts and field checking landslides identified on air photos during intervening office work. Air photo review has been helpful in revealing glacial features not recognizable from the ground and in finding exposures, such as road and stream bank cuts. Laterally extensive exposures are rare on the west side of the peninsula.

Mapping by Tabor and Cady (1978) and by others differentiates glacial deposits primarily on the basis of clast lithology of tills and outwash. Deposits containing exotic clasts of granitic rocks derived from the Canadian Cordillera delineate areas influenced by the Juan de Fuca lobe of the Cordilleran ice sheet. This is the basis for the mapping of its terminus as shown in Figure 1. Glacial deposits derived from the Olympic Mountains contain the local lithologies: sandstone, shale, conglomerate, and low-grade metamorphic rocks. Difficulties arise in making distinctions between the two groups of deposits in the lowland west of the range-front hills (cover photo). In this area, glacial sediment has been reworked, probably numerous times, by fluvial systems draining alternately from the continental ice in the north and the alpine ice to the east and, to some extent, by lower energy interglacial fluvial systems. The deposits in this area could potentially reveal information on the relative timing of advances from the two different ice sources. It is therefore essential to this study to develop a stratigraphy based on numerical chronology as well as clast lithologies. Heusser (1973, 1974, 1978) reported dates from the Bogachiel and Hoh drainages that constrain the timing of the younger Pleistocene alpine glacial advances. As yet, no datable material corresponding to continental ice advances has been found in the study area.

Figure 1. The western Olympic Peninsula showing major rivers and approximate maximum extent of Juan de Fuca lobe of the continental ice sheet. Also shown are the 1:100,000-scale quadrangles being mapped in this project.

About 1.5 mi northwest of Forks, the Calawah River cuts through a southwest-trending ridge (an "interfluve" between it and the Sol Duc River), exposing till, outwash, and fluvial sediments deposited sometime before the last glacial maximum (Fig. 2A). These sediments have a well-developed soil profile and are oxidized to depths of several meters (Fig. 2B). Younger terrace deposits with weak soil profiles, oxidized to less than 1 m depth, are inset against the lower slopes of the older deposits (right center, Fig. 2A) We hope next field season's efforts will provide opportunities for dating these deposits.

On the Calawah River, about 4 river miles upstream of the exposure shown in Figure 2, is a sequence of fluvial gravels overlying near-vertical sandstone bedrock (Fig. 3). The valley fill in this area is thinner than expected, and the age and relationship of these deposits to those farther west at the valley confluence with the Sol Duc is unclear at this time. With luck, dated samples from the wood protruding midway up the bluff will clarify these relationships.

This and previous studies by Susan Shaw (Washington Department of Natural Resources, Forest Practices Division, unpub. data, 1991–), Logan and others (1991), Fiksdal and Brunengo (1980, 1981), Tabor and Cady (1978), and watershed analyses done on the upper Sol Duc River and north fork of the Calawah River (Washington Department of Natural Resources, 1996, and O'Connor and Cundy, 1993, respectively) show that there are numerous landslides, ranging in age from ancient to active, on the slopes of the western Olympic Peninsula. Although most of these slides are probably shallow-rapid landslides (Shaw, unpub. data, 1991–), generally caused by road construction and improper road drainage design, the area and volume of land affected by deep-seated landslides is probably greater.

Figure 2. **A.** *(top)* View upstream on the Calawah River, about 1.5 mi northwest of Forks, where it has incised through an elongate southwest–trending ridge (interfluve) of deeply oxidized fluvial gravels and till. The finer grained, weakly oxidized sediments exposed in the lower bank to the right of the high bluff suggest deposits of a younger, inset terrace. **B.** Logging road cutslope exposure of the upper stratigraphy on the south side of the interfluve. These dense deeply oxidized sands and gravels dip to the southwest. They are overlain by a loose cobble gravel and capped by till.

Deep-seated landslides appear to be concentrated in three general areas: steep drainage head walls, valley walls plastered with colluvium and glacial deposits, and along terrace edges in glacial deposits in mainstem valleys (Fig. 4).

Field verification of deep-seated landslides on reforested slopes has proven somewhat troublesome, particularly in areas covered by timber stands about 5 to 25 years old. On these slopes, the dense vegetation hampers the observation of ground features (for example, hummocks, tension cracks, and disturbed vegetation) that indicate active or historic landsliding. Landslide identification efforts for this study will therefore be focusing on air photo review in the future.

Access to some of the higher elevations of the study area has been restricted as a result of two winters of severe weather and heavy precipitation. Due to limited federal and state budgets, repair of forest roads damaged by surface erosion and (or) debris flows has been slow. There is still much work to do in these areas, especially in the Sitkum River (upper Calawah River basin) and South Fork drainage of the Calawah basin.

Project completion is scheduled for February 1999 and will be marked by publication of the Forks and Mt. Olympus 1:100,000-scale maps as open-file reports. A proposal has been submitted to the U.S. Geological Survey to digitize these and other 1:100,000-scale maps to complete a statewide digital geologic database.

Figure 3. This exposure along the Calawah River, just upstream of the Highway 101 bridge, shows a thick sequence of fluvial gravels overlying Tertiary sandstone bedrock. The protruding stump (upper middle) may provide useful information on the age of these deposits and their relation to alpine and continental ice advances.

Figure 4. View upstream along the south (left) bank of the Bogachiel River at a sequence of Pleistocene terraces. This photo was taken from the headscarp of an active landslide at the edge of a terrace surface. Other landslides (arrows) can be seen in the distance.

Acknowledgments

Several geologists have laid the groundwork for deciphering the glacial stratigraphy in the western part of the peninsula. Their work has been cited in the references. I also thank the geologists who have accompanied me in the field, discussing concepts, contributing ideas, finding elusive exposures, digging holes, and getting wet: Shannon Ginn, now with the Peace Corps; Josh Logan, Carol Serdar, Hank Schasse, and Tim Walsh of the Division; and Reggie Ward, Jr., of the Quinault Indian Nation. Logistical support from Randy Messenbrink and Chon Clayton has been most helpful and appreciated.

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Rapid Earthquake Notification in the Pacific Northwest

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Introduction

With modern digital seismographs, automatic computer analysis, and high speed communications systems, it is now possible to provide very rapid notification (within minutes) after large, damaging earthquakes. Soon it may be possible to give warnings seconds or even tens of seconds before the onset of severe shaking in the Pacific Northwest at sites distant from the epicenter. Early warnings are possible because of the many seconds it takes seismic waves to travel from the source area of an earthquake to a distant site.

Early warnings are routinely issued hours prior to the arrival of tsunamis on the coast of the U.S. These tsunamis can be caused by distant large earthquakes of magnitude 7.5 or greater (in, say, Alaska or the Aleutian Islands). With improved technology, warnings of at least a few minutes will also be possible for locally generated tsunamis caused by large earthquakes just off the coast of Washington or Oregon. Moreover, seismographs and other instrumentation may someday permit early warnings of major debris and mud flows from the flanks of Cascade volcanoes like Mount Rainier (Fig. 1). Such flows can be generated by earthquakes, volcanic activity, or spontaneous collapse of portions of the volcano. The largest flows (as much as 4 km^3) have traveled from the flanks of Mount Rainier all the way to the Puget Sound in the recent geologic past (Scott and Vallance, 1995; Dragovich and others, 1994).

While practical implementation of a complete earthquake and tsunami early warning system in the Pacific Northwest is still several years away, such a notification system is being planned. The plan now being studied is called Consolidated Reporting of Earthquakes and Tsunamis (CREST); it is a joint project among the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), and Federal Emergency Management Agency (FEMA).

Rapid Earthquake Notification in the Pacific Northwest Today

The Pacific Northwest Seismograph Network (PNSN) at the University of Washington is currently capable of automatically communicating estimates of earthquake location, depth, and magnitude by e-mail, fax, and pager alerts within one minute of an earthquake's occurrence. (See Table 1.) At the present time, the PNSN automatically generates notification for events of magnitude 2.9 and greater. From 1989 to 1993, there were 78 notification (alarm) events. Of these, four were false alarms (earthquakes outside the network mistakenly located inside the network by the rapid automatic system). There

Table 1. Notification time table for the magnitude 5.4 Duvall, Washington, earthquake, May 2, 1996

Time (PDT)	Time after earthquake	What happened
21:04:23		earthquake occurs
21:05:25	62 seconds	e-mail, pager alerts sent to PNSN staff
21:17:31	13 minutes	preliminary faxes to outside agencies
22:32:50	88 minutes	final summary faxes sent out

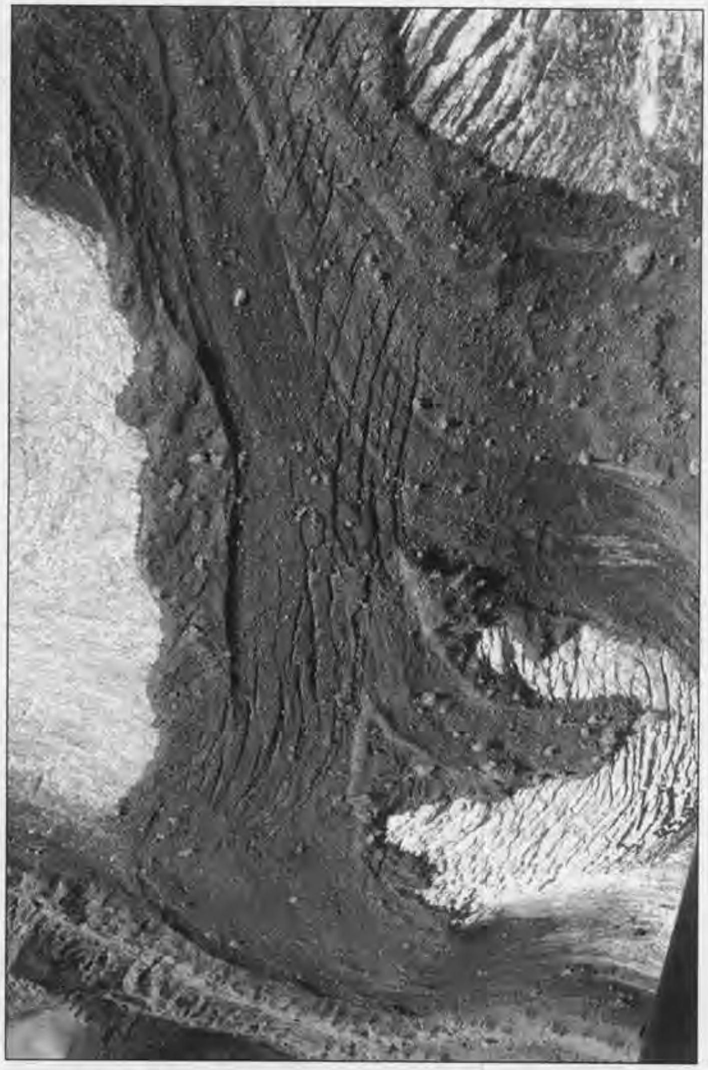

Figure 1. Aerial photo showing the lower section of a rockfall that fell from the Curtis Ridge on the east flank of Mount Rainier on August 16, 1989 (Norris, 1994). This rockfall was widely recorded by seismographs in Washington. The seismic records were used to alert National Park Service officials of the location and time of the rockfall within an hour of its occurrence. The flow direction was from the top of the picture to the bottom. The dark debris contrasts sharply with the ice of the crevassed Winthrop Glacier over which the debris flowed for 4 km. Many crevasses are visible through the rockfall cover. From the top to the bottom of the photo is about 750 m. The large light-colored rock on the debris at the upper right is about 25 m across. (Photo by S. D. Schwarz and Associates, Inc., Bothell, Wash.)

were also nine events of magnitude 3.0 or larger that did not trigger alarms for one reason or another. As false alarms or missed events have occurred, PNSN personnel have examined the data and fine-tuned the computer algorithms of the alarm system to fix the problems. Thus, the PNSN automatic alarm system has become much more reliable over time. It usually takes 30 to 60 minutes before seismologists at the PNSN can significantly improve the preliminary information provided by the automatic notification system.

The PNSN sends automatic rapid earthquake notification faxes and e-mail (within 7 to 30 min of the earthquake occurrence) to a number of agencies. These include state emergency management and geological survey offices in Washington and Oregon, FEMA, and the Army Corps of Engineers. A seismologist is on pager duty 24 hours a day and reviews the earthquake data within 1 to 1½ hours of being paged. The seismologist sends out "final summary" faxes to critical organizations as well as local news groups. Information is available to the general public via the media, the PNSN web-site (http://www.geophys. washington.edu), and a recorded voice-mail message (206-543-7010).

The response time and the types of alarm output available from the PNSN have improved over the years. Table 2 gives historical milestones in PNSN notification capability.

Table 2. Milestones in Pacific Northwest Seismograph Network (PNSN) notification capability

Date	Technology advance	Who notified	Notification time
Pre-1988	Observations from visible drum recorders or reports from the public of felt earthquakes initiates processing of information. Off-hours notification of PNSN staff by University Police as a result of public inquiries about earthquakes.		30–60 minutes (during working hours); 2 hours or more (during off-hours)
1988	HAWK computer system modified to provide: - use of P-wave trigger times (1 sec resolution) in automatic locations - numeric pager	PNSN staff	<12 minutes
1990	- improved magnitude estimates - numeric pager plus e-mail	PNSN staff, outside agencies, and research institutions	<12 minutes
1992	- numeric pager and e-mail - automatic preliminary faxes	PNSN staff, outside agencies, and research institutions	<7 minutes (pager and e-mail); <7–30 minutes (fax)
1995	- introduction of SUNWORM system - more robust location estimates - more robust magnitude estimates	PNSN staff, outside agencies, and research institutions	<1 minute (pager); <7 minutes (e-mail)
1995	- information provided via worldwide web	on demand by anyone with Internet access	>1 day
1996	- automatic web pages after completion of manual analysis	on demand by anyone with Internet access	2 hours
1997	- automatic web page generation based on preliminary information	on demand by anyone with Internet access	<7 minutes
1997	- pager/PC based "RACE"[1] notification	PNSN staff and other outside agencies	<7 minutes
1997	- automatic earthquake intensity (damage) maps		being studied

[1] RACE (Rapid Alert for Cascadia Earthquakes) is a pager system that gives subscribers rapid access to earthquake information via a pager hooked to the subscriber's personal computer. Pager messages are broadcast automatically from the PNSN seismograph network. RACE is based on a similar system called CUBE (CalTech-USGS Broadcast of Earthquakes).

Feasibility of Seismic Early Warning Systems

The tsunami early warning system (Sokolowski and others, 1990) takes advantage of the relatively slow speed (700 km/hr) of tsunami waves in the open ocean to warn communities before the waves reach the shore. It serves as a model for the eventual implementation of an earthquake early warning system in the Pacific Northwest. The goal is to rapidly obtain earthquake information near the source and to use it to warn more distant sites before the arrival of damaging seismic waves.

One of the pioneering efforts is Japan's UrEDAS (Urgent Earthquake Detection and Alarm System) that uses seismic sensors to automatically shut down critical facilities during a large earthquake. In its original implementation several decades ago, the power could be cut to Japan Railway's bullet train when ground motions exceeded a critical value at onsite detectors. The system is now more sophisticated; networking of widely spaced detectors allows ground motions to be predicted at a site several seconds before they occur. The UrEDAS system has not yet been fully tested in a large earthquake. (The January 17, 1995 Kobe earthquake, a potential test case, occurred in early morning hours when trains were not yet operating.)

Another warning system was used during the aftershock sequence of the magnitude 7.1 Loma Prieta, California, earthquake. The USGS used seismic sensors in the epicentral region to transmit radio alarms to rescue workers at the damaged Nimitz freeway in Oakland when potentially damaging aftershocks occurred. This gave the workers as much as 20 seconds warning before seismic waves from the aftershocks reached the freeway site.

Earthquake early warning systems rely on the fact that seismic waves travel only a few kilometers per second, whereas radio and other electronic signals that communicate earthquake warnings travel more than 100,000 times as fast. Significant warning time is possible because the strongest ground shaking usually begins with the arrival of seismic shear (S) waves that travel only 3.5 km/sec. In contrast, primary or P-waves travel about 6 km/sec, and they provide the warning that stronger S-waves will soon follow.

It is feasible to create an early warning system to modify the operation of critical facilities (for example, nuclear power plants, trains, and communications networks) in the urban areas of Washington, Oregon, and British Columbia in the event of a large earthquake in the Pacific Northwest. The following example illustrates the kind of notification that might be possible if there were dozens of continuously monitored strong-motion seismographs in Washington.

A magnitude 7.5 earthquake occurs at 12:00:00 (noon) just east of Olympia at a depth of 55 km below the Earth's surface.

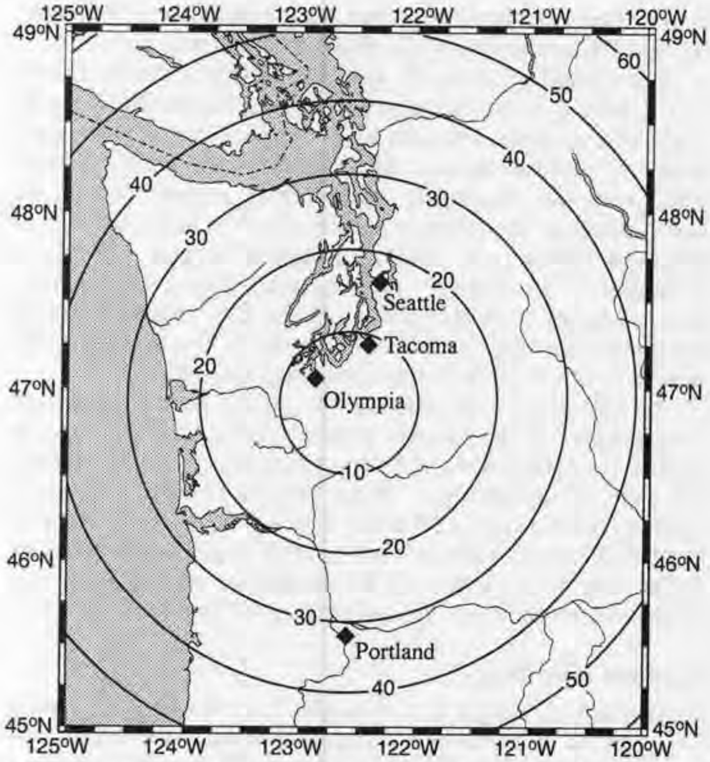

Figure 2. Estimated warning time, in seconds, possible for an earthquake 55 km deep just east of Olympia. This is the interval of time between the instant the earthquake is detected by seismographs on the Earth's surface in the epicentral region and the instant the S-wave reaches a site. (We assume strong ground shaking begins with the arrival of the S-wave.) As shown, Portland would have about 33 seconds warning. For a deep earthquake like this one, there would be about 6 seconds warning even at the epicenter (because of the lag time between P- and S-waves). For shallow earthquakes, the warning would be nearly zero at the epicenter but still significant away from the epicenter.

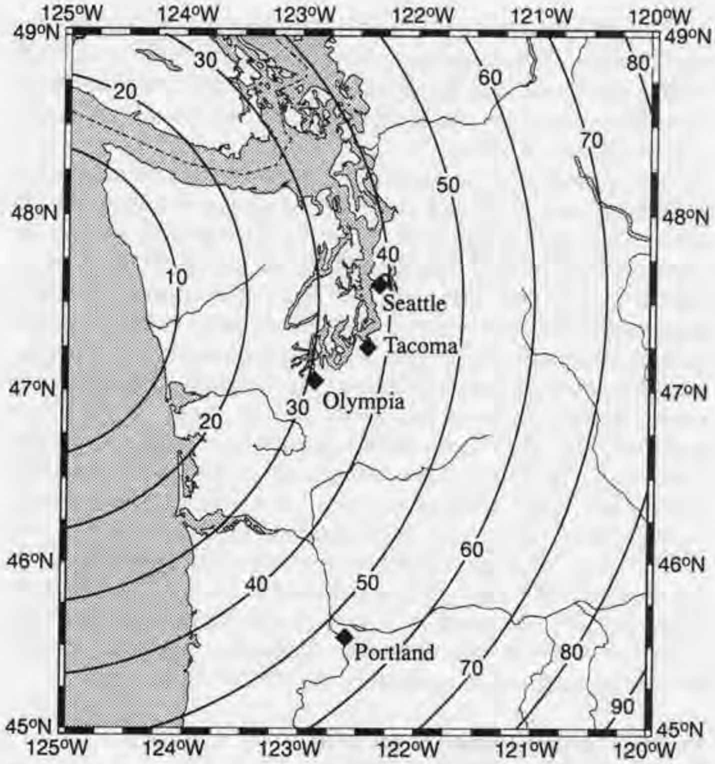

Figure 3. Estimated warning time for an earthquake with an epicenter 110 km (70 mi) offshore on the Cascadia subduction zone. Here, we assume that there are strong-motion seismographs along the coast to detect the earthquake. Such instruments are not now installed.

Seismic P-waves propagate outward from the earthquake focus at about 6 km/sec and reach the Earth's surface about 12:00:08 (that is, 8 sec later). The first strong motion seismographs near the epicenter record the earthquake, and an alert is sent out by radio or telephone line. The P-waves reach Seattle at 12:00:14, and the strong shaking (arrival of S-waves) begins at 12:00:24. Thus, Seattle could have about 16 seconds warning (12:00:08 to 12:00:24) before strong shaking begins (Fig. 2), enough to initiate automatic shutdown procedures. This deep earthquake is similar to the one that occurred between Olympia and Tacoma in 1949. Hypothetical warning times for earthquakes closer to the Earth's surface would be similar to the example above, except near the epicenter where the warning time would be nearly zero.

At least 30 to 40 seconds warning time is possible in the Puget Sound area for large offshore earthquakes (Fig. 3). Consider the example of a magnitude 8.5 earthquake that occurs 70 miles offshore in the Cascadia subduction zone due west of Seattle. P-waves from the earthquake would arrive at strong motion seismographs on the coast (not yet installed) in about 20 seconds, well before the S-waves. Within a few seconds, a preliminary calculation of the location and size of the earthquake could be transmitted to critical facilities at inland sites in the Puget Sound region. There would still be an additional 38 seconds before the S-waves would reach Seattle and 54 seconds before they reached Portland.

A related challenge is to provide early warning of major debris flows initiated on the slopes of Cascade volcanoes; these travel down major river drainages and can cause enormous damage. A recent example is the debris flow that swept down the Toutle and Cowlitz Rivers and into the Columbia River from the May 1980 eruption of Mount St. Helens that was apparently triggered by an earthquake. Much larger debris flows have traveled down river valleys from Mount Rainier all the way to the Puget Sound in the last few thousand years. Cities such as Orting, Buckley, Enumclaw, Sumner, Puyallup, Auburn, and Kent are at risk from such events.

The detection of debris flows is more complex than the detection of earthquakes. Earthquakes are produced by relatively rapid slip on a fault. They produce seismic signals with distinct, easily recognizable P- and S-waves. Seismic signals from debris flows develop gradually and are long lasting; P- and S-waves are difficult to recognize. However, techniques have been developed to provide debris-flow warning systems. Debris flows may or may not be triggered by an earthquake, but they always generate seismic waves in the ground and acoustic waves in the air. In the Cascades, only Mount St. Helens has acoustic debris-flow monitors in place. (See the U.S. Geological Survey's website http://vulcan.wr.usgs.gov/volcanoes/MSH/framework.html.) At least one seismograph capable of detecting large debris flows is in place at every major volcano in the Cascades except Glacier Peak. For example, Mount Baker has one, Mount Rainier five, Mount Adams one, Mount St. Helens eight, and Mount Hood one. However, the computer event detection algorithms currently in use at the PNSN are not tuned to detect debris-flow signals. Only Mount Rainier and Mount St. Helens have enough stations nearby to make a robust debris-flow detection possible using seismographs.

Usually personnel at the PNSN notice the distinctive debris-flow/avalanche signals on continuous drum recorders within one to several hours of their occurrence. A number of these have been reported from Mount St. Helens, Mount Rainier, and Mount Adams.

The possibility of earthquake warning systems raises a number of economic and sociological issues. For example, to what extent should automatic cutoff of utilities and services be implemented in response to a large earthquake? Shutdowns can be costly and damaging, so the notification procedure must minimize false alarms. In Mexico, large offshore earthquakes automatically trigger warning messages to the public at major radio stations in Mexico City, up to 60 seconds before strong ground shaking begins. In Japan, strong shaking can automatically shut down railways, subways, and natural gas lines. Some buildings have strong motion sensors to stop elevators, and many schools and public facilities activate prerecorded safety messages on loudspeakers. In California, the BART commuter train system will stop during earthquakes. All elevators in California are required to have automatic shutdown devices like those in Tokyo. A seismic detection system is also in place to shut down the Alaska gas pipeline. Should similar procedures be applied in the Pacific Northwest?

Future Improvements in the PNSN Notification System

Techniques to improve earthquake and tsunami rapid notification and early warning methods in the Pacific Northwest are now being studied, and improvements will probably be realized in the next few years. The PNSN notification system will include faster communication and new information, such as precise measurements of local ground shaking, that can be used to launch appropriate rescue and relief efforts. In addition, the seismograph network will be integrated with a Pacific-wide tsunami warning system that will provide distant and near-source tsunami warnings with increased reliability.

These improvements will require upgrading selected field sites with modern digital seismographs with broadband frequency response and high dynamic range. Some of these instruments will be designed to stay on-scale during strong shaking with accelerations up to 2g. These upgrades will allow better magnitude estimates and ground motion measurements for medium to large earthquakes.

No one institution has the resources to monitor all of Cascadia. Therefore we must develop the capability of automatic high-speed data exchange between regional data centers. For example, tsunami alerts require coordination among Alaska, British Columbia, Washington, Oregon, California, and Hawaii. It will also be necessary to "harden" instrument components and the communication networks between regional data and emergency response centers so that the notification system does not fail as the result of damage from a large earthquake.

The collaborative CREST program will address notification and warning issues in the next 5 years. CREST goals will require the upgrade of seismograph equipment in Washington, Oregon, California, Alaska, and Hawaii and the development of new techniques to rapidly exchange and analyze data from widely spaced regional centers. The seismic equipment upgrades will be supplemented by new offshore instrument buoys designed by NOAA and funded by the National Tsunami Hazard Mitigation Program to detect tsunami waves in the Pacific Ocean. These buoys will speed up the identification of hazardous tsunamis and decrease the number of false alarms. One such buoy now operates off the coast of Washington and Oregon, another off the coast of Alaska.

The CREST system will also provide rapid determination of the levels of strong ground shaking for onshore earthquakes. Such ground motion measurements can improve estimates of expected damage and, therefore, the level of emergency response required in the epicentral region. Experience has shown that right after an earthquake, it is often difficult to obtain damage reports near the epicenter because power and communications systems are disrupted. Currently, it takes days to weeks to collect data from the few older generation instruments in Washington and Oregon, so this type of information is still of little use in emergency response.

An effective early warning system for locally generated tsunamis should be available within 5 years. An early warning system for earthquakes is more technically difficult because the required reaction time for earthquake shaking is so short (seismic waves travel 30 times faster than tsunami waves). Earthquake early warnings will require improved methods of connecting broadly spaced seismographs with digital networks and much faster ways of processing seismic data.

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ICE AGE FLOODS INSTITUTE

The Ice Age Floods Institute helps communities in areas of Washington, Idaho, Montana, and Oregon affected by the Missoula floods provide opportunities for learning, recreation, and tourism centered around the floods. The institute welcomes your support and participation. For $25, become a member and receive the biannual newsletter. For $50, you will also receive a softcover copy of *Channeled Scablands*. For $100, add the video "The Great Floods".

For more information, contact the institute at 324 S. Pioneer Way in Moses Lake, WA 98837 (509-765-7888 or 1-800-992-6234, ext. IA).

First Record of Cycad Leaves from the Eocene Republic Flora

Dennis J. Hopkins, Jr., and Kirk R. Johnson
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The Eocene flora from Republic, Washington, is known for its high level of angiosperm and gymnosperm diversity. The gymnosperm component of the flora includes at least five families of conifers and one ginkgo. Lisa Barksdale, director of the Stonerose Interpretive Center, has acquired two partial leaves from the Boot Hill locality that we have determined to be related to a modern cycad family (Figs. 1, 2).

Cycads are seed plants that have a fossil record stretching at least 250 million years. Living cycads are relicts and are now represented by only three families, eleven genera, and about 110 species worldwide. They are restricted to tropical and subtropical areas with centers of diversity in Mexico, the Caribbean, Australia, and South Africa. In the United States, Eocene cycads are known from Mississippi, Louisiana, Tennessee, Wyoming, Alaska, Oregon, and Colorado. The discovery of cycad fossils at Republic not only increases our knowledge of the gymnosperms of this Eocene flora but also represents the first Cenozoic cycad from Washington State.

The two specimens have smooth margins, lack any form of a midrib, and have primarily open-dichotomous venation. While both specimens are partial, they share enough characters to suggest that they belong to the same species of cycad. Preliminary comparison indicates the Republic cycad most closely resembles the extant genera *Zamia* (Fig. 3) and *Ceratozamia*, both members of the family Zamiaceae.

Extant cycads are found only in tropical to subtropical regions in areas where frozen winter ground does not occur regularly. Using the physiognomy of angiosperm leaves and associated vegetation at Republic, Wolfe and Wehr (1987) estimated a mean annual temperature of 12–13°C, a cold month mean of less than 1°C, and a paleoelevation of 727–909 m. This conclusion was in concordance with the absence of palms at Republic, although they are common in coeval floras at lower elevations, and suggested the paleoelevation of Republic was high enough to limit the growth of some warmth-loving plants (Mustoe, 1997). The discovery of a cycad with modern affinities and perhaps modern climatic preferences may place some constraint on the minimum cold-month temperature at Republic.

Although more complete specimens need to be collected and more comparative and taxonomic work needs to be done on the Republic cycad, its initial significance is that it expands the floral list of Republic and suggests possible constraints on the climate of this Eocene environment.

Figure 1. *(far left)* Nearly complete cycad pinnule (SR95-13-3), about 1x. The pinnule is lanceolate in shape and appears to taper to a rounded apex. (Base of pinnules is at bottom of photos.) The zone of pinnule attachment narrows where it articulates with the rachis. Found by Eric Smith.

Figure 2. Partial cycad pinnule (SR88-42-3) shows the open-dichotomous venation characteristic of many cycads. Specimen shown at about 1x. Found by Madilane Perry, Republic, Wash.

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Figure 3. Modern *Zamia dictyophlebia* (Zamiaceae) from Costa Rica showing many similarities to the Republic cycad. Individual pinnules are about about 15 cm long.

Museum Specialists Visit Republic's Fossil Site

The first week of September brought an invasion of paleontologists to Republic. Kirk Johnson of the Denver Museum of Natural History and Conrad Labandeira of the Paleobiology Division, National Museum of Natural History, Smithsonian Institution, led about 15 people in five days of systematic work dismantling the top meter of an approximately 3-m section of lacustrine rocks of the Eocene Klondike Mountain Formation. The goal of the visit was to get a detailed, quantitative look at the flora and the associated insect fauna.

These combined efforts were the result of conversations during recent years among Johnson and Labandeira, Wes Wehr, affiliate curator of paleobotany for the Burke Museum of Natural History and Culture in Seattle, and Lisa Barksdale, curator of the Stonerose Interpretive Center in Republic.

The new work site, established by Barksdale, was selected because it exposes undisturbed rocks directly uphill of the "Boot Hill" public collection site at the north end of Republic. The Stonerose Interpretive Center arranged for backhoe work to give the scientists access to this exposure. Michael Sternberg, president of the Northwest Paleontological Association, measured and marked the section in 20-cm intervals.

Eight of the Denver Museum's volunteer Leaf Whackers were joined by Sternberg and Jan Hartford of Anacortes, Barksdale, and a few visitors in cleaning the rock face and layers. The team removed slabs and dried them with a weed burner to facilitate splitting the shale into thin layers. The slabs from each 2-decimeter segment of the section were portioned out, and all fossils discovered were collected as part of the study. Normally only the more complete specimens are retained, but in this study the goal was an unbiased portrait of the lakebed assemblage.

The fossils found by the splitters were taken to a makeshift table for initial sorting by Johnson and his team. Excess rock was then split away from the fossils, and the volunteers numbered, recorded, and wrapped the trimmed fossils. Anderson's Grocery in Republic supplied flat boxes for shipping the selected fossils. The fossils' first stop is Denver, where they will be airscribed, identified, and curated. Then the fossils will be shipped to Labandeira for study in Washington, DC. Denver will ultimately be the permanent home for this collection.

Accompanying the scientists were photographer Robert Burke from the Smithsonian Magazine, and William Cannon, formerly science editor for the University of Washington, who is writing an article for the magazine.

Thanks to the Echo Bay Minerals Company, the work site was protected from rain and broiling sun by a striped tent. Stonerose treated the assembled workers to a barbecue dinner and a pizza lunch.

To date, the many specimens collected at several fossil localities in and around Republic have been cataloged simply by site, not by their stratigraphic position. This September's work is the first organized attempt to define the plant associations in time and the first focused collection of leaves that are to be studied for traces of insect damage. Johnson and his crew were able to catalog more than 1,500 identifiable leaves, seeds, flowers, fruits, and insects. This collection will help reveal the relative abundance of plant remains and begin the slow process of "reconstructing" the local forests and lakeside flora.

The surface of a 20-cm-thick interval of the Klondike Mountain Formation is cleaned.

Mike Sternberg uses a weed burner to dry layers of the fossiliferous rock.

abandeira will examine this unbiased collection of leaves as the basis for his work on insect herbivory; he hopes to determine what kinds of insects were present, what they chose to eat, how intense their use of foliage was, and if there are changes in the patterns of insect damage over time in this deposit.

Labandeira and Johnson gave an evening lecture in the town's Kiwanis Hall. Both noted that Republic is home to one of the world's 20 best fossil sites of any kind and one that is in the top five for the Eocene.

A large crowd, of all ages, heard Labandeira describe the several ways in which scientists can detect and learn about insects in the fossil record. Bodies or impressions of fossil insects are the most direct evidence, but insect traces are found in damaged plants and the insects' eggs and coprolites (fossil feces). In exceptional deposits insects are found in coprolites of other species and even as remains of meals within fossil fish, birds, and other animals. By studying the shapes of modern and fossils insects and of their mouth parts (and the pollen and spores in gut contents) and the kinds of plants they use, it is possible to reconstruct the interrelations of plants and insects through time. At Republic Labandeira has found indications of insects that eat, or mine, the middle layers of leaves, insects that eat the margins of leaves or selectively feed on parts of a leaf and leave holes of specific shapes or patterns, insects that cause galls to form, insects that roll leaves, and insects that lay eggs in arrangements that strongly resemble those of some modern insects.

Conrad Labandeira (left), Smithsonian Institution, and Wes Wehr, Burke Museum, discuss the progress of the project. The tape separates small slabs taken from the 20-cm intervals; each slab will be split to search for plants and insects or their traces

Johnson spoke about other Eocene sites, such as the Green River lake system of Wyoming and Utah and Messel in Germany, and urged fossil hunters to look for the elements in those deposits that have not been found at Republic: turtles, frogs, crocodiles, birds, bats, and other mammals. He noted that the dawn redwood (*Metasequoia*, now native only to a province in China) is present in virtually all Eocene deposits, but it is the rest of the flora and fauna that help define the differences and similarities of sites around the Eocene world,

Kirk Johnson (left) of the Denver Museum of Natural History trims excess rock from around a specimen, while Lisa Barksdale, curator of the Stonerose Interpretive Center, examines a fossil.

Members of the Leaf Whacker team glue broken specimens and attach museum labels to part of the day's yield.

The numbered specimens are listed in a catalog before being wrapped in toilet paper, boxed, and sent by truck to Denver.

from northern Ellesmere Island, to Mongolia, to Republic. He has used many of the fossil leaves from Republic in preparing the model plants in his diorama of the Eocene in the Denver Museum.

Even with the intense work at thc exposure, another year of collection will be needed to work down through the whole marked section. Plans are being made by the museums and Stonerose for a 1998 visit to continue this on-going project.

In the meantime, visitors to the Boot Hill site can aid in Labandeira's study by bringing damaged leaves to the attention of the center.

For information about visiting the public collecting site, please phone the Stonerose Interpretive Center at (509) 775-2295. ■

Trees Ring in 1700 as Year of Huge Northwest Earthquake

Growth rings of ancient trees confirm that an earthquake in North America sent ocean waves to Asia almost three centuries ago, according to two groups of American scientists.

The scientists, in reports appearing in the journals *Nature* and *Geology*, present tree-ring dates for an earthquake and tsunami that had been previously inferred from geology in the Pacific Northwest. They compared these dates with the time of a tsunami known from village records in Japan. The agreement is so remarkable, the scientists say, that the Japanese records become written proof that the earthquake really happened.

At issue is the threat posed by an active fault—the Cascadia subduction zone—that dwarfs the San Andreas fault and underlies the mostly offshore area from southern British Columbia to northern California. This fault caused little concern until the late 1980s, when scientists began recognizing geologic evidence that the fault has produced earthquakes of magnitude 8 or larger. The most recent of these events was soon dated by radiocarbon methods to the decades between 1680 and 1720.

These dates caught the attention of Japanese researchers, who checked Japanese village records for signs of an orphan tsunami between 1680 and 1720. They found just one candidate. They used its size and date to calculate that the Pacific Northwest had an earthquake close to magnitude 9 in January of 1700. Their report appeared in *Nature* in early 1996.

American scientists responded by setting out to learn whether their Japanese colleagues had identified the correct year and season of a huge Pacific Northwest earthquake. One team, led by David Yamaguchi of the University of Washington, studied trees killed by an earthquake near the mouth of the Columbia River. Another team, led by Gordon Jacoby of Lamont-Doherty Earth Observatory in Palisades, New York, focused on trees that barely survived it.

Each tree-ring team concluded that a huge Pacific Northwest earthquake occurred in the months between August 1699 and May 1700—dates that indeed converge on the time of the January 1700 tsunami in Japan. The scientists reported that trees killed by the earthquake died sometime after the 1699 growing-season ended but before the 1700 growing-season began. In addition, the Jacoby team described signs of trauma that begin with the 1700 ring of several of the trees that survived the earthquake.

The Yamaguchi team also addressed controversy about the maximum size of Pacific Northwest earthquakes. Previously, some earth scientists had inferred nothing larger than magnitude 8. Others proposed magnitude 9, which would be about 30 times larger in terms of energy release and several times longer in duration of shaking. Writing in *Nature*, the researchers contend that a huge earthquake is now more plausible because the new tree-ring dates fail to show that 1700 event was smaller than magnitude 9.

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Note: Simple color graphics pertaining to this story can be obtained by anonymous ftp. The files, created in CorelDraw 7.0 (*.cdr), are also available in GIF (*.gif) and Adobe Illustrator (*.ai) formats. At the location prompt on your web browser, type ftp://ftp.geophys.washington.edu/pub/out/tree/. ■

New Exhibits at the Burke Museum

Burke Museum of Natural History and Culture has reopened its doors on a new display of geologic and paleontologic treasures of Washington. Upstairs is "Life and times of Washington State", which displays more specimens than ever before, including new full size models—flying skeletons. The lower floor is devoted to "Pacific voices", a cultural exploration of the Pacific Rim countries. The museum is at the north end of the University of Washington campus. Drive east on 45th Ave. from I-5 to the university entrance, which is directly adjacent to the Burke. Plan to visit during your next trip to Seattle.

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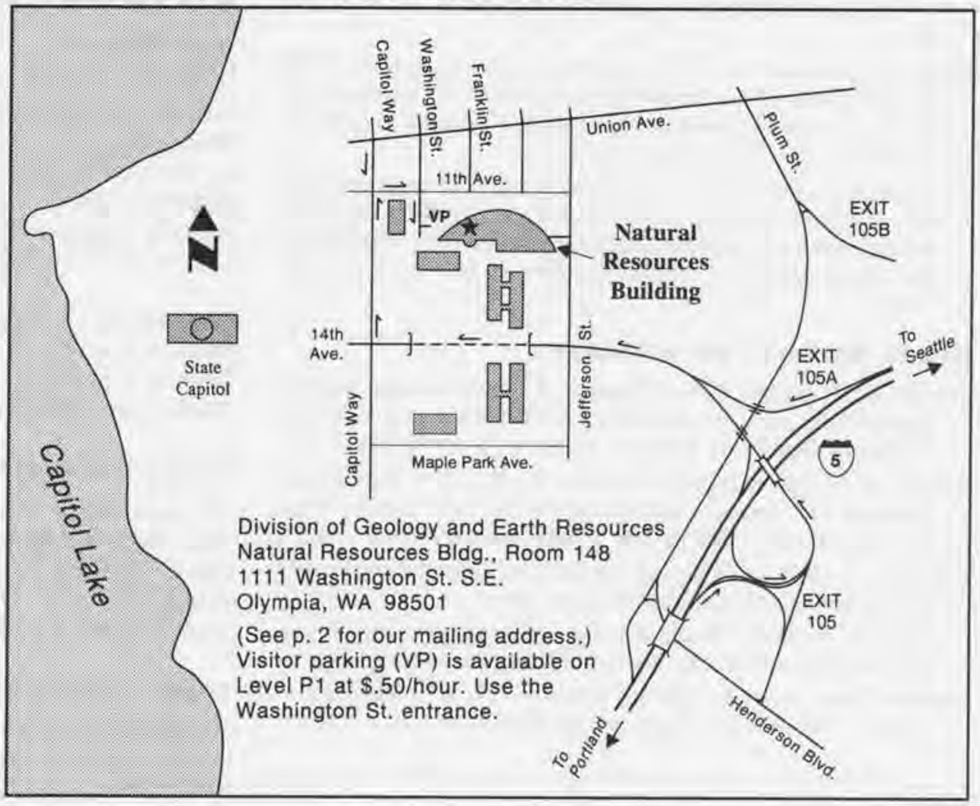

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