Northwest Geological Society

Society Field Trips in Pacific Northwest Geology

Field Trip to the Western Olympic Mountains Washington

Summer, 1998

Dick Stewart
University of Washington

Cover: *Bob Yeats, Oregon State University, taking a picture of Rowland Tabor, U. S. Geological Survey, enjoying the view of Mt. Olympus from the summit of Mt. Carrie in the Bailey Range. The summit (West Peak) of Olympus is a minuscule pyramid above the Snow Dome; the icefall of the Blue Glacier is visible on the left. Joe Vance obtained a fission-track age of 19 Ma (Miocene) from a sandstone collected at the summit of Mt. Tom, the large pyramid in the center of the picture (see Brandon and Vance, 1992).*

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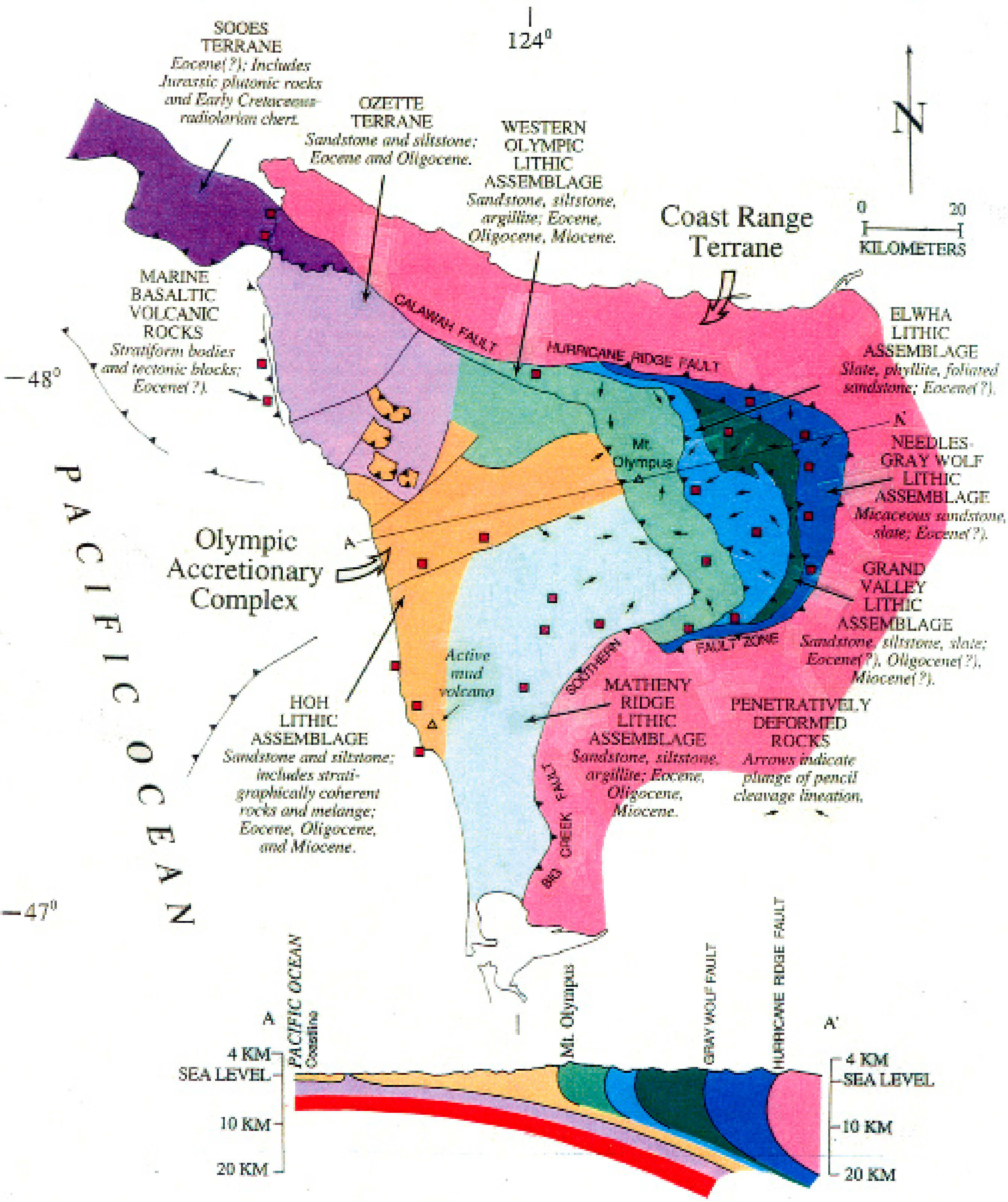

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Abstract:

New fission-track ages from sandstones in the Olympic subduction complex suggest there is a wedge-shaped swath of ~ 20 Ma sediments that extends from the present coastline to the high interior of the Olympic Mountains. These rocks apparently represent accreted and uplifted deposits of the Cascadia accretionary wedge added to western North America by convergence of the Juan de Fuca and North American plates, probably in much the same way that sediments lying west of the subduction complex are being accreted today. The youngest age that we have determined from this sequence of sediments is about 17 Ma, roughly coincident with the onset of volcanism in the Columbia River Basalt Group. Rocks of Miocene age are deformed post-20 Ma, and are flanked on the north and south by older rocks best described as broken formation or melange. Uplift of the subduction complex sufficient to produce clastic debris eroded from it may not have occurred until perhaps 6 Ma. Uplift rates calculated from paleobathymetry and the age of clastic debris shed from the complex as it rose range from 0.1 mm/yr"' near the present Pacific coast to about 0.4 mm/yr'1 over the summit of Mt. Olympus.

Contractual deformation may have been the dominant factor in the Olympic subduction complex for the last 20 Ma, and possibly for the last 40 Ma or more. Uplift and erosion of the complex may have been driven by accretion of sediments from Cascadia Basin into the Cascadia accretionary wedge during this time. High-angle structures in the western Olympic Mountains may be relatively late features superimposed on an earlier low-angle style of deformation. Several localities have been identified where apparently low-angle structures cut Pleistocene deposits, and offshore seismic-reflection data show strong evidence for folds and faults involving sediment as young as Holocene, including some that cut the present-day ocean floor.

Rocks of the Olympic subduction complex may contain the most complete and possibly the best record of sedimentary and tectonic events that affected the Cascadia subduction zone during Tertiary time.

Introduction:

Earthquake hazards, particularly great subduction earthquakes, are a significant threat to populated areas of the Pacific Northwest adjacent to the Cascadia subduction zone (Atwater, 1997). Driven by this observation, many studies of the Quaternary and Holocene geologic record suggest great subduction-zone and/or upper-plate earthquakes have occurred near or within the subduction complex, with recurrence intervals measured in hundreds of years (Atwater and Hemphill-Haley, 1997). Most of the rocks in this subduction zone are not directly available for geological study. This field trip examines highly deformed rocks of the Cascadia accrelionary wedge (Fig. 1) that crop out on the western Olympic Peninsula of Washington state. These rocks may have been accreted to the continental margin of North America in post-Middle Miocene time, in a manner possibly analogous to the way that sediments are currently being accreted at the toe of the Cascadia accretionary wedge (Flueh and others, 1977). New fission-track provide a window into the pre-Holocene tectonics of this complex, and suggests that subduction-related thrust earthquakes have been and may continue to be a significant factor in the evolution of the Cascadia subduction zone.

The Olympic Subduction Complex

Exposed in the Olympic Mountains is an apparently thick, stratigraphically complex, and highly deformed sequence of sedimentary and igneous rocks (Tabor, 1978; Tabor and Cady, 1978). These rocks, the Olympic subduction complex of Brandon and Vance (1992), are dominantly mudstones and sandstones of Tertiary age, but include rocks as old as Jurassic and Early Cretaceous (Snavely and others, 1993). The provenance of these rocks is poorly known, but they are commonly considered the distal equivalents of coeval sediments exposed elsewhere in the Coast Ranges of Oregon and Washington, and may be derived from rocks in the Cascade Range (Heller and others, 1992).
Fossils recovered from a number of localities within the Olympic subduction complex suggested to earlier workers that most rocks of the subduction complex are Eocene in age, and that rocks of Miocene age cropped out only near the Pacific Ocean in the western Olympic Mountains (Rau, 1973, 1975, 1979, 1980, 1986; Snavely and others, 1986; Snavely and others, 1993; Tabor and Cady, 1978). Definitive paleontological control extends inland only about 10-20 km; despite a diligent search, very few fossils have ever been recovered from the glaciated interior of the Olympic Mountains, and interpretation of the age of these assemblages is often difficult (Tabor, 1978; Tabor and Cady, 1978; see Fig. 2).

In a study of the depositional age of sedimentary rocks in the Olympic subduction complex, Brandon and Vance (1992) reported apparently unreset fission-track dates of Miocene age from several localities in the high, glaciated interior of the Olympic Mountains, suggesting portions of the eastern core of Tabor and Cady (1978b; see Fig. 3) may be younger than Eocene or Oligocene. Recently acquired, but unpublished, fission-track data suggests the rocks described by Brandon and Vance (1992) may somehow be an eastern extension of highly-deformed Miocene-age rocks previously described from exposures further west near the

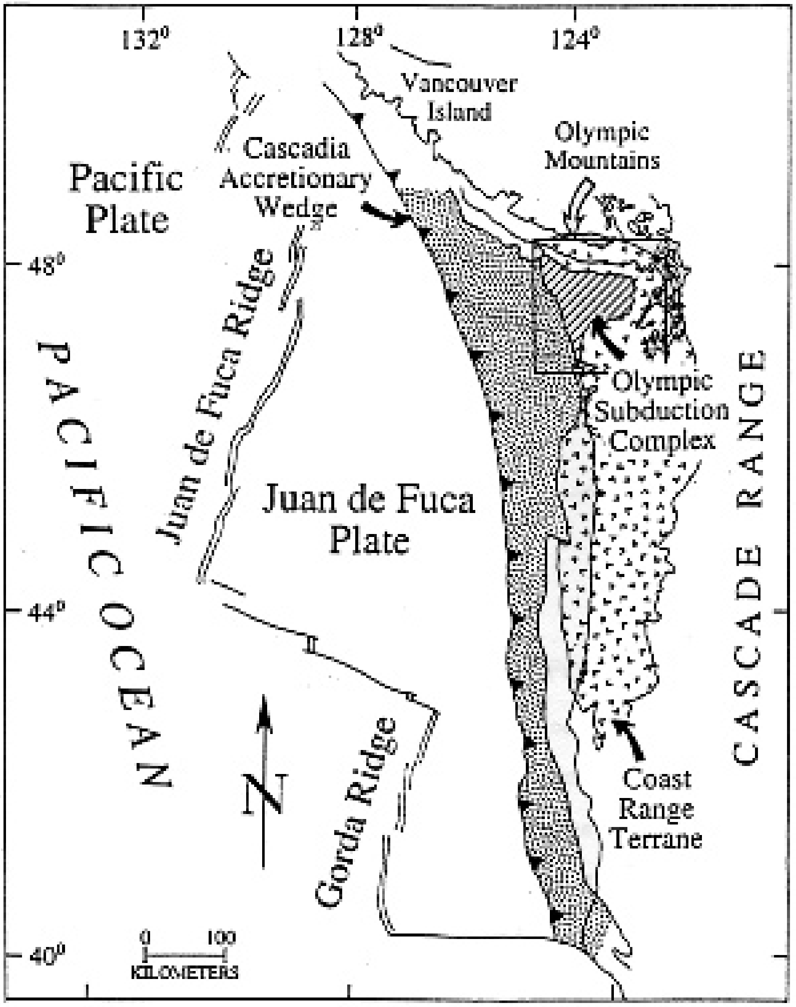


***Figure 1. (Left)** Index map showing location of the Olympic subduction complex in relation to the Coast Range terrane (including the Siletz terrane) of Snavely and Wells (1997), and the Cascadia accretionary wedge.*

Over One-Hundred Years of Exploration in the Olympic Mountains

In some respects, our field trip is very timely, coming about one-hundred years after the first recorded geologic studies in the Olympic Mountains. This Era began with the O'Neil Expeditions in 1885 and 1889-90. and continued with the work of the Press Expedition (1890), Albert Reagan (1909), and Charles Weaver (1937). The first major study of Olympic geology was done by the Olympic Manganese Project of Charles Park, Jr. (1938-41), which included Wally Cady. Hal James, Ralph Roberts, Walt Warren and R. G. Yeats, among others. The Geologic Map of the Olympic Peninsula by Tabor and Cady (1978) certainly was spurred by Park's work, and we all look foreword to the production of the Geologic Map of Washington-Northwest Quadrangle by the Division of Geology and Earth Resources!

My own involvement with things Olympic began in 1967, when I was Wally Cady's field assistant, mapping the Crescent Basalt out of Staircase Ranger Station. In the summer of 1970,1 was fortunate to be one of Rowland's field assistants working in what became known as the "eastern core," and to work with Wally mapping Crescent Basalt and broken formation near Lake Quinault. As I write this, and at every outcrop, I can just feel Rowland, Wally, Parke Snavely, and Weldon Rau looking over my shoulder, waiting to pounce on anything I might say that is not backed up by data at hand.

Rowland should be with us, but Kajsa and he are off in Norway, no doubt enjoying themselves immensely. As a result, you will have to put up with hearing many thoughts that will come at you second-hand, filtered and fouled-up by Stewart. Perhaps this is just as good, however. If memory serves me correctly, Rowland's Mentor, Dwight Crowder, spent a very productive sabbatical in Norway, and returned with many new ideas and techniques, things which were absorbed by Roland and passed on to his own field assistants, including the clarion call to "abandon your brunton and use a Silva." Rowland started his geologic career working with Dwight as a volunteer; among the habits he picked up was the ability to do field geology, on foot, at 60 miles an hour.

Finally, as the accompanying articles by Bill Lingley and Patricia McCrory illustrate, there seems to be a lot of interest right now in the geology of the Olympic Mountains. Has the cream been stripped off, have all of the mysteries been solved? I can only hope not, and that once people begin to see how accessible, and how well-exposed, some Olympic rocks are, that even more interest will be shown in these mountains as a natural laboratory.

Our Field Trip

Our purpose on this field trip to the Washington coast is to examine deformed rocks in the Olympic subduction complex (see Index Map to Field Trip Localities, Fig. 4). Simply put, we will observe outcrops of sedimentary rocks that range in structural complexity from those only gently folded, to rocks that may perhaps be best described as chaotically disrupted. In between, we will examine outcrops that display lithologies considered by many to be clues to the patterns of sedimentation and deformation in the Olympic subduction complex, and we will try and amalgamate our brief and scattered observations into some sort of regional (I didn't say coherent!!) framework.

Most of the rocks we will visit were described by Weldon Rau in a series of publications in the

1970’s and 1980’s (Rau, 1973, 1975, 1978, 1980, 1986; Rau and Grocock. 1974; Snavely and others, 1986). If you do not already have copies of these, especially his exquisite works on the Washington coast (Bulletins 66 and 72), you must get them, as they are already collector’s items. Put another way, how many of us are ever likely to receive a First Place Technical Communication Award, won by Weldon in 1981 from the Society for Technical Communications for Geologic Map 24!

Rainfall in the Olympic Mountains, the “wretched weather” of Lingley (1995), is measured in multiples of meters, rather than fractions of inches. Unfortunately, bathing suits are hardly, if ever, necessary. Appropriate gear for an outing to the west coast is often what one would wear on a fishing boat in the Bering Sea; long underwear is a must, except in the blissful days of August. If time and weather permit, we should be able to engage in a discussion of things geologic after supper on Saturday night. We will arise with the birdies on Sunday morning and take to the hills for a final look at things Olympic. This is intended to be a working field trip, rather than a series of lectures with rock “outcroppings” as background. Some of the comments that you may read below will possibly contain grains of truth; many are clearly large boulders of speculation. Some things you may see will be at odds with what you may have published, or with what are usually considered the correct interpretations of Olympic geology. Some are “plants,” intended to spark conversation and discussion (no fisticuffs please!).

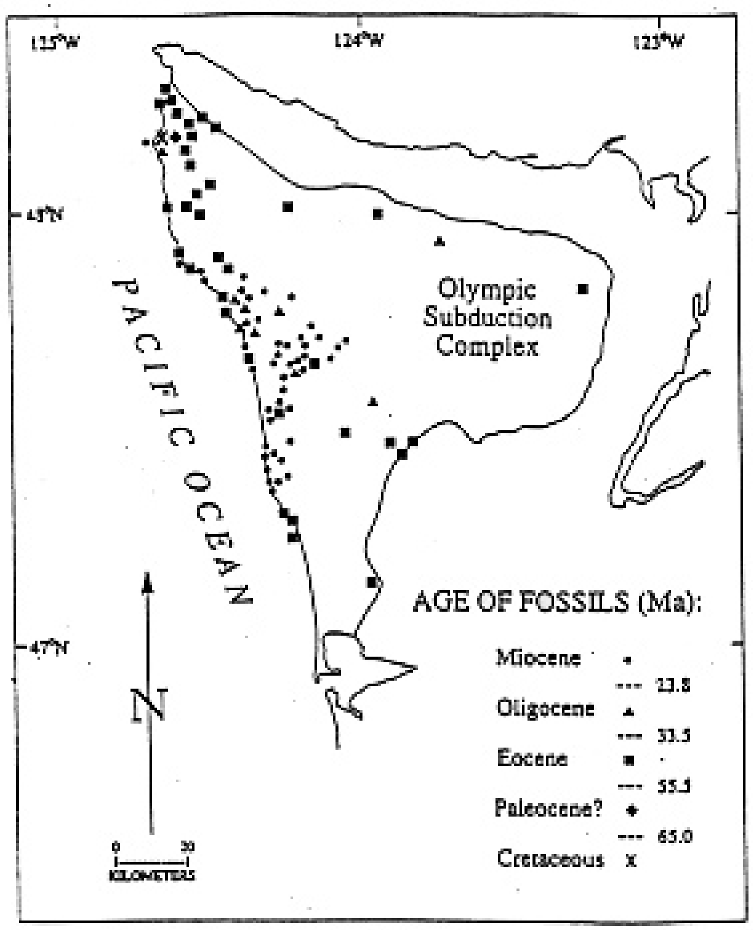


Figure 2. (Above) Summary map of the age of fossil localities in the Olympic subduction complex. Data from Lingley (1995), Rau (1973, 1975, 1979, 1980, 1986), Snavely and others (1986), Snavely and others (1993), and Tabor and Cady (1978).

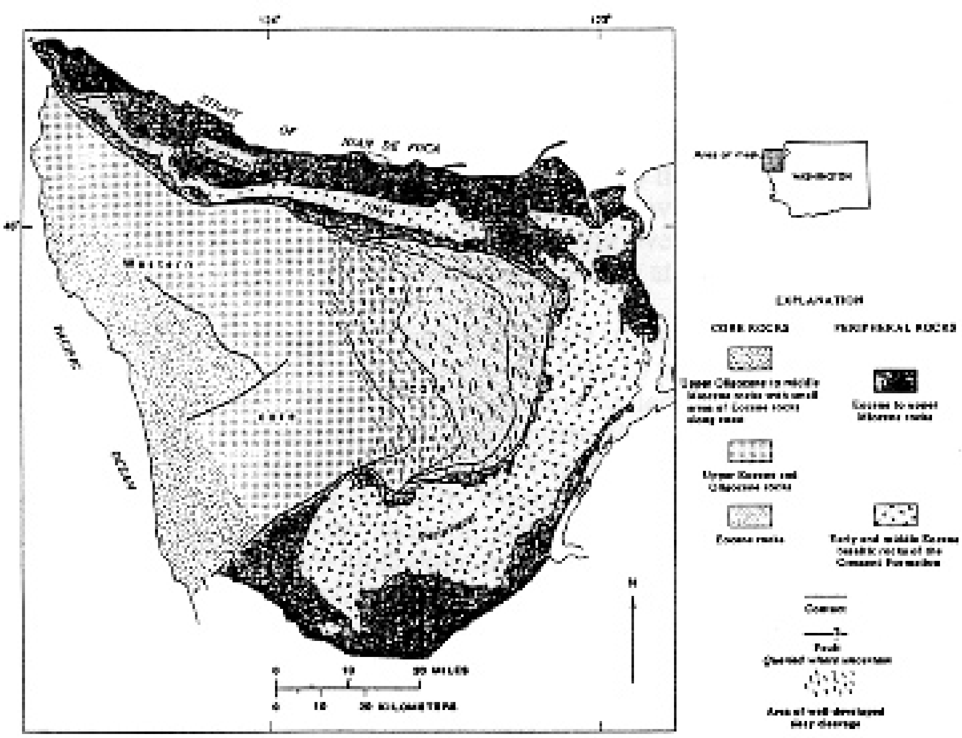


Figure 3. (Left) *Major geologic terranes of the Olympic Peninsula, showing tentative(?) age assignments, and the distribution of areas of well-developed slaty cleavage in rocks of the eastern core. This is Figure 1 in Tabor and Cady (1978b).*

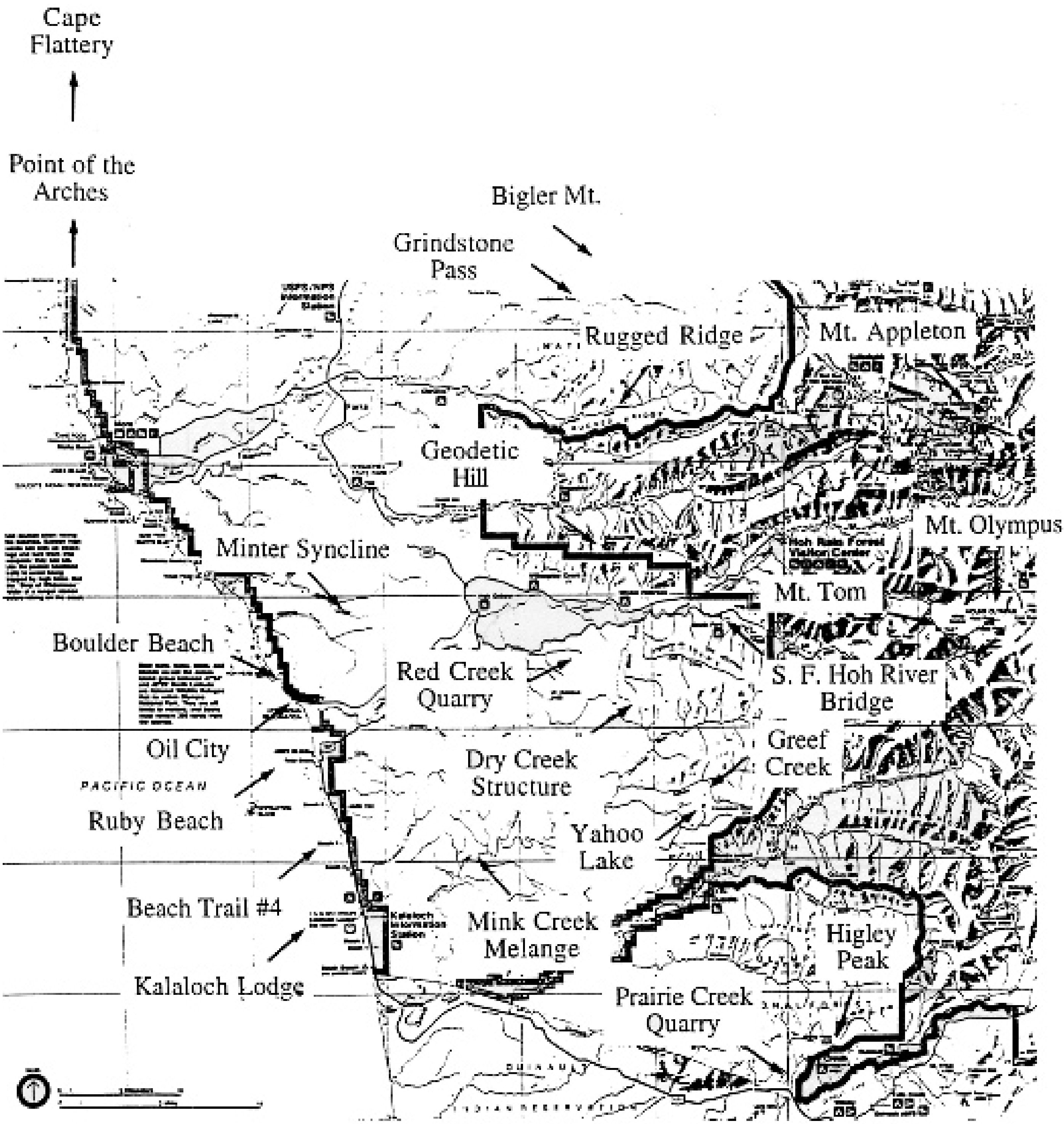


Figure 4 Index map to localities in the western Olympic Mountains that may be visited as part of this field trip, depending on time available, and the vagaries of the weather.

Deciphering the Secrets of the Olympic Subduction Complex

A Structural Dilemma in the Olympic Mountains

Structures mapped in the Olympic subduction complex west of Mt. Olympus bear little resemblance to those mapped to the east (Tabor and Cady, 1978a; Tabor and Cady, 1978b; see Fig. 5). How much of this is a result of the differing backgrounds and prejudices of the people involved in mapping is difficult to say. On the west, structures appear “open,” and folds with subhorizontal axes can be mapped with confidence. In the eastern core, folds at outcrop scale are common, but very few large folds have ever been found, and fold axes are very steeply inclined (read vertical-axis folds).

The western portion of the subduction complex appears cut by both high- and low-angle faults. Synclines stand put. even on satellite imagery, and can usually be mapped through with ease/ Anticlines are far more difficult to define, and may(?) be cored with some variety of “Hoh melange” or “Hoh breccia.”

Low-angle faults, which themselves have been folded, indeed appear to be low-angle structures. A few high-angle structures have been mapped in the western core, and may be strike-slip faults, although no viable estimate of slip on these structures has been offered. In contrast, high-angle (?), or “strike-slip” faults are apparently not present east of Mt. Olympus. Structures with subhorizontal axes are rare, if present. Vergence is a word that is usually not used in discussions of Olympic core-rock deformation, especially in the eastern core.

Are there Great Faults in the Olympic Subduction Complex?

The first “big fault” to be recognized in the core was the Calawah Fault, discovered by Howard Gower of the U. S. Geological Survey (Gower, 1960) in rocks that crop out at Grindstone Pass, near Bigler Mountain, east of Forks (see Figs. 4 and 5). These outcrops had a “San Andreas” aspect, and Howard felt he could carry this structure about 30 km to the west. Parke Snavely and his associates feel that they have found evidence for recent displacement on this fault (MacLeod and others, 1977).

The second “big fault,” the Hurricane Ridge Fault, was discovered by Rowland Tabor while mapping in the Mt. Angeles Quadrangle on Hurricane Ridge, south of Port Angeles. Map relations suggested to him that this fault may be the eastward continuation of the Calawah Fault into rocks of the Olympic core, and that it may be the most major “junction” in the Olympics. This fault is visible as you near the parking lot at the Park Service visitor’s center on Hurricane Ridge, where It consists of a zone of “polished” sediments about 50 m wide. This fault and its extensions, the Calawah

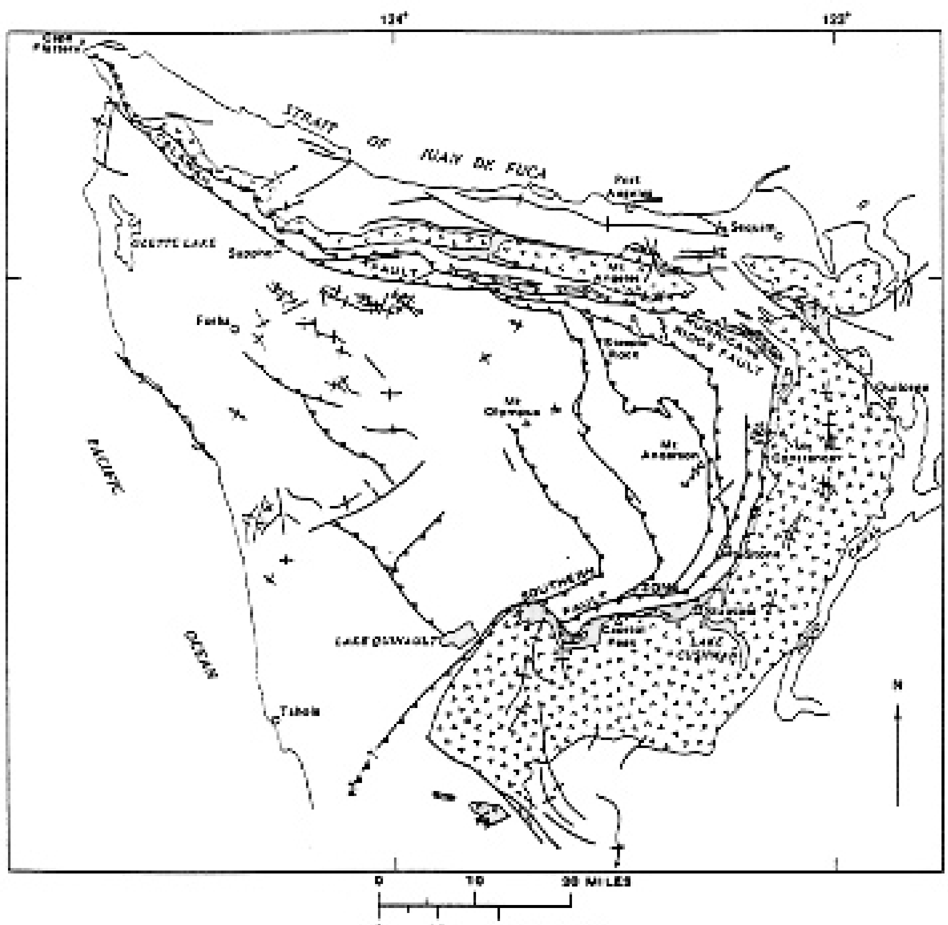


***Figure 5**. Major folds and faults on the Olympic Peninsula, from Tabor and Cady (1978b).*

Fault to the west, and the Southern Fault Zone to the southwest, marks the boundary between rocks of the Olympic subduction complex ("core") and Rowland's "Peripheral rocks" (Fig. 3). The Hurricane Ridge Fault is not drawn at the base of the Crescent Formation, as is commonly assumed. Rather, it separates sediments of the Blue Mountain unit from sediments of the Needles-Gray Wolf Lithic Assemblage (Tabor and Cady, 1978a, b). In this interpretation, rocks of the Crescent Formation stratigraphically and structurally overlie sediments of the Blue Mountain unit. The map criteria for the Hurricane Ridge Fault was the top of the first micaceous sandstone as one worked "coreward," or "downsection" from the base of the Crescent Formation. Because the Blue Mountain unit is shown in a darkish pink on Map 1-994 (Tabor and Cady, 1978a), most people take this map color to represent basalt. The Hurricane Ridge Fault is inferred to be a thrust fault on Figure 5, and on virtually any sketch map or cross-section published since about 1970.

In contrast, Snavely and others (1993) mapped the base of the Crescent Formation as a thrust fault west of Lake Pleasant, and called it the Crescent Fault. The western extension of the Hurricane Ridge Fault on their map is shown as the Calawah Fault (a strike-slip fault?), which mostly separates sediment from sediment on either side of the structure. Snavely and others (1993) mapped two major fault systems in the northwest portion of the Olympic subduction complex. The Ozette Fault is the southernmost of a system of thrust faults mapped in core rocks south of the Calawah Fault, and includes the oldest rocks so far known in the Olympic Mountains in the upper plate. It is shown as a dashed line on Map 1-994 (Tabor and Cady, 1978a). They also map a west-dipping set of thrust faults extending from Portage Head south beyond (?) La Push. These faults are not shown on Map 1-994 or Figure 5, because they were mapped after 1-994 was published.

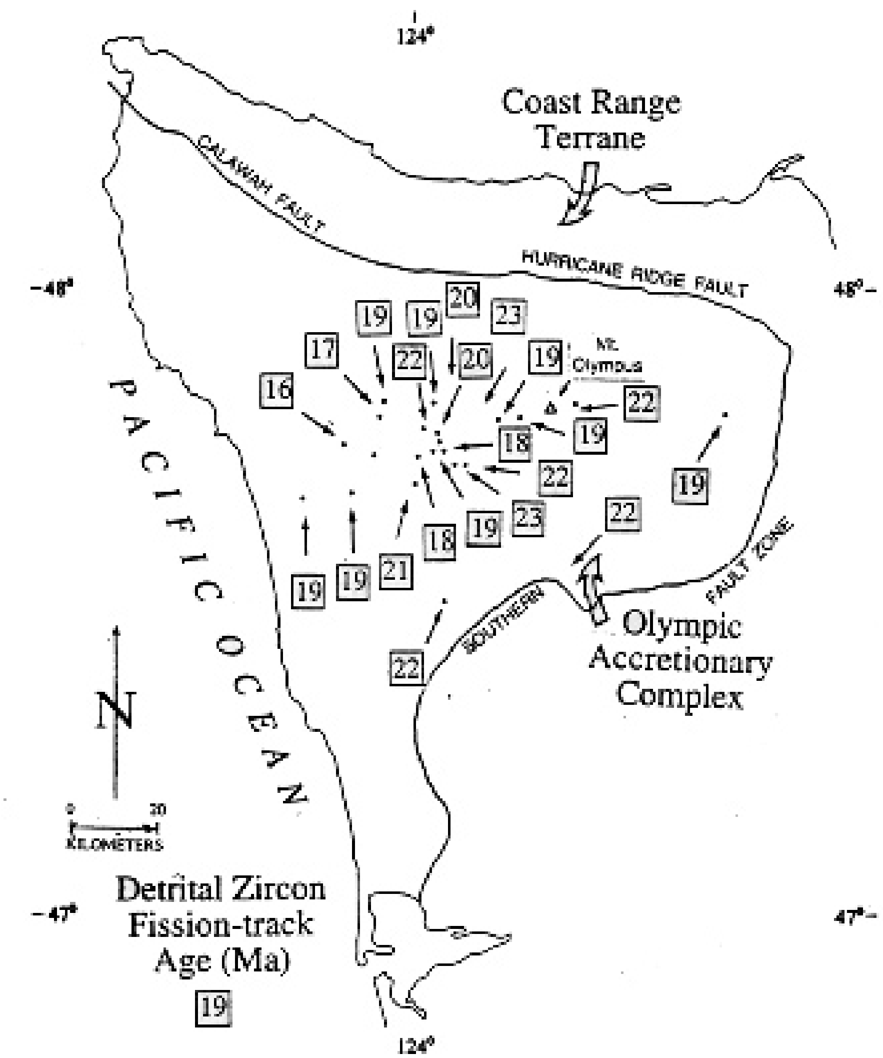


Figure 6. *Distribution of detrital zircon fission-track ages for sedimentary rocks of Miocene age from the Olympic subduction complex. Data taken from Brandon and Vance (1992), and Stewart (unpublished data, 1998).*

How Old are the Rocks in the Olympic Subduction Complex?

There is some degree of fossil control on the age of rocks in the Olympic subduction complex near the Pacific coast (Fig. 2). Fossils of Eocene age were recovered from rocks of the eastern core in the northeast corner of Olympic National Park near Mt. Baldy (Cady and others, 1972: Tabor and Cady, 1978a; Squires and Goedert, 1997), and there is one reported locality of Oligocene (?) age on Mt. Appleton, south of Hurricane Ridge (Tabor and Cady, 1978a). An attempt to recover these fossils from the National Museum in 1970 was unsuccessful.

The lack of fossil control on the age of rocks in most of the Olympic subduction complex has driven people to grasp at any straw they can find to try and determine just how old these rocks may be. One of these straws is fission-track dating. The theory and technique of fission-track dating is covered briefly in an addition at the end of this field trip guide. In essence, fission-track dating is just another geochronologic tool that can be used to decipher the age of a rock, using evidence contained in the tracks of p-particles generated by the spontaneous decay of 238U. In concept, the fission-track technique is very straightforward. In practice, it is a nightmare, fraught with problems and plagued with difficulties that even seasoned fission-track daters do not like to discuss.

Detrital zircon fission-track dates reported by Brandon and Vance (1992) suggest rocks in the eastern core may be mostly Eocene in age, with four localities yielding Oligocene and Miocene ages. A new and a fairly extensive set of detrital zircon fission-track dates (see Figs. 6 and 7), may allow us to extrapolate eastward from the coast with some confidence.

Most workers use the fission-track technique to determine the age of tuffs or tephras, rocks that are likely to contain a grain-age spectrum that is unimodal, and indicative of the time at which the rock was formed (or accumulated). However, in most sedimentary rocks the situation is far more complex. Sandstones can be derived from multiple sources, with multiple ages, and can have grain-age spectrums that are quite "polymodal," indicative of the age of the source terrain, rather than the age at which the sandstone was deposited.

Fortunately, in the Olympic subduction complex, many of the sandstones are "volcanic" sandstones. Some of these may contain grains that were formed (erupted) and then rapidly eroded, perhaps fast enough that the age of the deposit derived from them closely approximates the age of eruption. The detrital fission-track method takes advantage of this assumption, and uses a technique called the "population method" to extract from a sediment the age of the "youngest" group of grains. We need not be concerned with details here. However, it is important that you all realize that the ages reported in detrital fission-track dating are values for the age of the youngest population of zircon crystals in a sample. There is a considerable range in ages of zircons in many populations, a range which is interpreted by fission-trackers as being a signature of the age of the source terrains (terranes?) that provided grains for a sediment.

The possibility of thermal resetting of "depositional" fission-track ages is the foremost bugaboo in interpreting fission-track data from the Olympic subduction complex. We know that some of these rocks have been heated, because Rowland was able to determine 17 Ma ages on whole-rock samples of brecciated mica phyllite in quartz veins from the eastern core (Tabor, 1972; see Fig. 8). In the same general vicinity, Brandon and Vance (1992) found four fission-track ages that did not have any sort of an "old" tail on the detrital age spectrum, which they interpreted as evidence for thermal resetting. Further evidence for the possibility of thermal resetting comes from the work of Brandon and others (1998), whose data indicate apatite ages are almost always considerably younger than zircon ages, determined on splits of the same sample!

In fact, virtually all detrital apatite fission-track dates from the Olympic subduction complex appear thermally reset, and the youngest of these is 2 Ma from a sample up the Hoh River at the base of Geodetic Hill! Curiously, apatite fission-track people feel they they can recognize reset, "partially reset," and unreset samples. So far, there are no "partially reset" zircon fission-track dates.

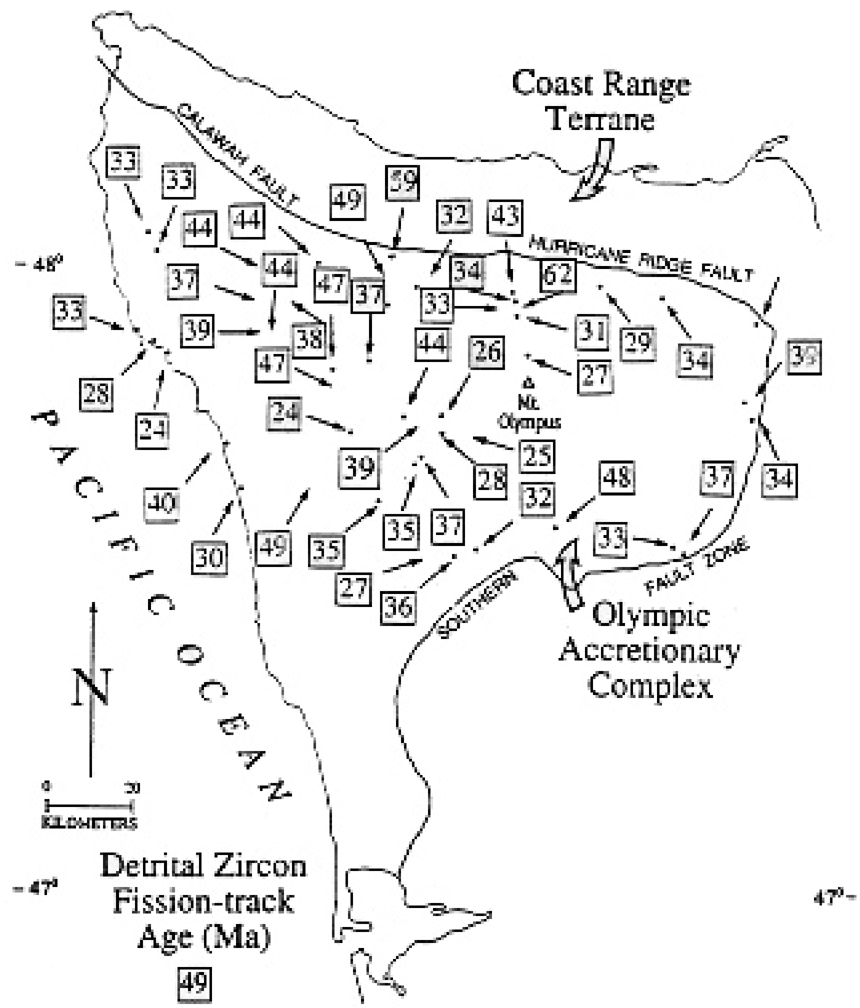


Figure 7. Distribution of detrital zircon fission-track ages for sedimentary rocks of pre-Miocene age from the Olympic subduction complex. Data taken from Brandon and Vance (1992), and Stewart (unpublished data, 1998).

We could try and use vitrinite reflectance measurements as a recording geothermometer to get a handle on how hot rocks have been in the Olympic subduction complex. To many people, vitrinite reflectance measurements are a simple and straightforward tool, easily applied in determinations of thermal history of sedimentary basins. Unfortunately, most simplistic sets of interpretations contain many pitfalls. Some feel time and temperature are both significant in the thermal maturation of vitrinite particles. Others think vitrinite can be used as an “absolute” geothermometer, free of the constraints of geologic time. And still others think vitrinite reflectance values reflect not just temperature, but also the “richness” (or lack thereof) of organic material in sediments.

Reported values of vitrinite reflectance in the Olympic subduction complex range from values below 0.5 percent, mostly near the Pacific coast, to as high as 2.3 percent (Fig. 8). Conventional interpretations of vitrinite reflectance suggest these values may represent temperatures of 100 to 300° C. Conventional interpretation suggests that zircons thermally reset at about 200° C, and apatite resets at about 100° C.

Significance of Top Directions in Core Rocks of the Olympic Mountains

Crucial to any interpretation of the structure of rocks in the Olympic subduction complex is the direction in which sedimentary rocks face, sometimes known as “top direction” or just “tops.” Based on upward fining in size-graded bedding, rocks lying “outside” of the Hurricane Ridge Fault, Rowland’s “Peripheral rocks,” generally top away from the core. Pillows of the Crescent Formation also mostly point away from the core. Beneath, or “coreward” from the Hurricane Ridge Fault, about 70 percent of beds top to the north, east, and southeast, leading to the suggestion that core rocks are bent up and tilted eastward, to the point of being overturned, perhaps in some form of a plunging anticline. This interpretation suggests that core rocks are older “coreward” and westward. So far. evidence seems to suggest that in general rocks lying to the west are as young or younger. This “enigmatic” observation, along with the prevalent top directions in core rocks, lead Rowland and Wally to the interpretation that the major rock units in the Olympic core were fault-bounded (Tabor and Cady. 1978b, p. 7).

Are Any Great Faults in the Olympic Mountains Thrust Faults?

The evidence for Great “Thrust” Faults in the core of the Olympic Mountains is based on two relationships. If the “inner basalts” (like the Needles) are distal ends of “Crescent” lava flows, then the section must be repeated. Furthermore, almost all “tops” in bedding attitudes are to the east in the core, further suggesting a great thickness of strata that must have been repeated (see Fig. 5).

The Significance of Pencil-cleavage in Rocks of the Olympic Subduction Complex

There are very few folds in the eastern core (see Fig. 5). Folds are difficult to map if you do not have some sort of a lithologic marker with which you can define the shape of a fold, and from which you can then derive statements

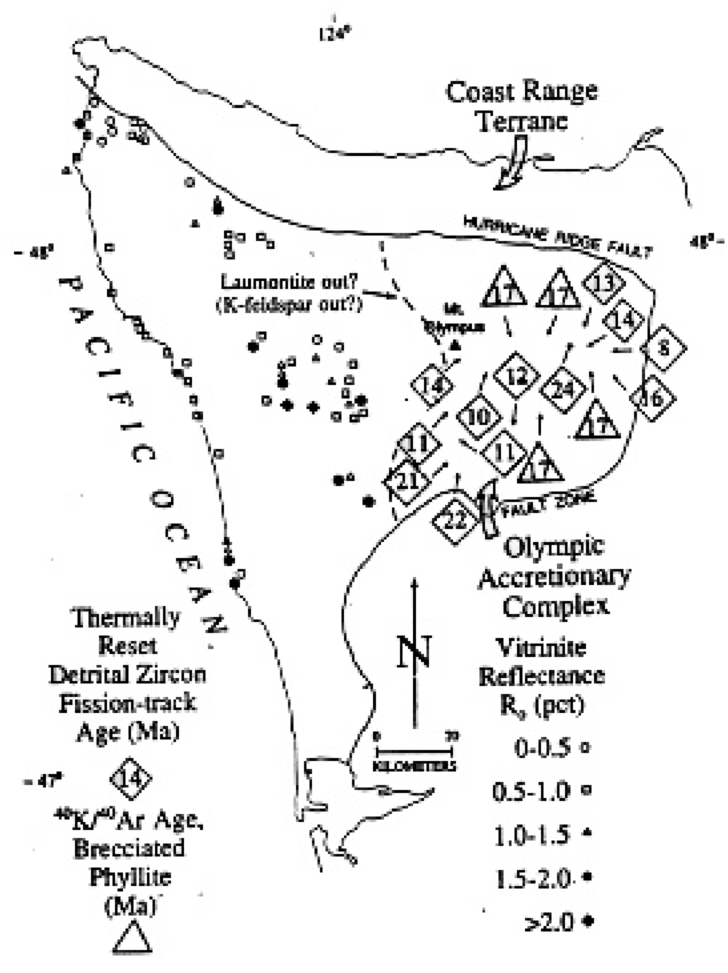


Figure 8. *Reported values of vitrinite reflectance from the Olympic subduction complex. Data from Snavely and Kvendvolden (1989), and Stewart (unpublished data, 1998). Plotted in squares are data from thermally reset detrital zircon fission-track ages for sedimentary rocks from the Olympic subduction complex, from Brandon and Vance (1992), and Stewart (unpublished data, 1998). Triangles represent whole-rock K/Ar determinations on brecciated mica phyllites from Tabor (1972).*

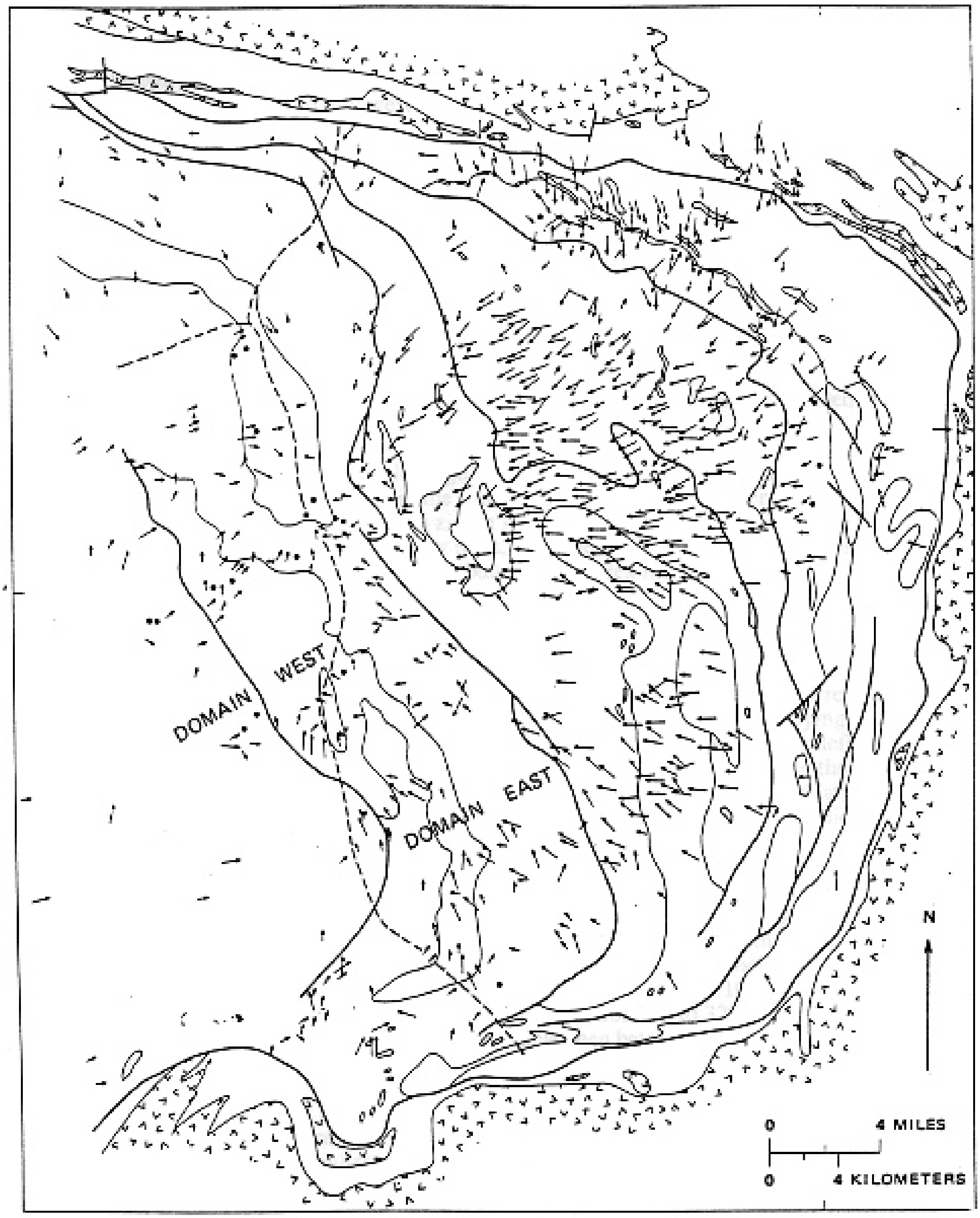


Figure 9. *Distribution of pencil-cleavage lineations in the eastern core of the Olympic subduction complex. This is Figure 24 in Tabor and Cady (1978b). Note that since this diagram was prepared, the occurrence of pencil-cleavage lineations has been extended into the headwaters of the Solleks River.*

as to how your folds may have formed. The most prominent, mapable feature in the eastern core is cleavage. Most all outcrops in the eastern core display cleavage, providing you with a surface you can measure, and something you can plot on a map. Rowland discovered (Tabor and Cady, 1978a, b), that there were commonly two intersecting cleavages in rocks of the eastern core, the intersection of which defined a common structural fabric element known as pencil cleavage. He interpreted this lineation as resulting from two stages of deformation in core rocks, and used this feature to define the orientation of fold axes in the eastern core (see Fig. 9).

Timing of Deformation in the Olympic Subduction Complex

Based on the few fossils found in the eastern core, Rowland Tabor suggested that rocks in the Olympic subduction complex were mostly Eocene in age, while the Oligocene (?) fossil locality on Mt. Appleton indicated these rocks were deformed in Oligocene (or post-Oligocene?) time (Tabor and Cady, 1978b). Rowland also suggested in his Guide to the Geology of Olympic National Park (Tabor, 1975), that deformation may have begun on the east, and moved progressively westward through time.

Sedimentary rocks containing apparently unreset fission-track ages of 19 Ma crop out at Wellesley Peak in the eastern core, and at Mt. Tom, the westernmost peak of the Mt. Olympus massif (Brandon and Vance, 1992). Sedimentary rocks containing apparently completely reset zircon fission-track ages of 14 Ma crop out on the east flank of Mt. Olympus near the Humes Glacier (Brandon and Vance, 1992), leading Brandon and others (1998) to interpret the pattern as evidence for exhumation of a dome of thermally metamorphosed rocks in the core of the Olympic Mountains. The spectrum of zircon fission-track ages reported by Brandon and Vance (1992) from Mt. Tom and the Humes Glacier is startlingly different, suggesting these localities may be juxtaposed, perhaps by a fault, that sets thermally reset rocks on the east against unreset rocks on the west. If this relationship could be demonstrated, it might suggest deformation in the core occurred at 19 or post-19 Ma.

Perhaps significantly, pencil cleavage is also prominently developed in rocks that crop out 20 km west of Mt. Olympus in the headwaters of the Solleks River, rocks from which I have obtained unreset (?) detrital zircon fission-track ages of 23-28 Ma. (see Figs. 6 and 7). If these samples are not thermally reset, their ages suggest that the development of pencil cleavage in rocks of the Olympic subduction complex may record an early Miocene? (or younger ?) event.

Uplift of the Olympic Subduction Complex

Uplift and exposure of the Olympic subduction complex is suggested by a regional unconformity above which Olympic-derived sediments are preserved in basins lying south of the Olympic Mountains (Bigelow, 1987). Uplift is also suggested by strongly deformed rocks of the Miocene Astoria Formation and the Columbia River Basalt Group in the Coast Ranges of Oregon and Washington (Snavely and Wells, 1996), and by 40K/ Ar dating of brecciated rocks from the core of the Olympic Mountains (Tabor, 1972), which indicates an episode of extension that affected these rocks about 17 Ma.

The foraminifer Melonis pompilioides has been reported by Rau (1973, 1978) from 13 localities in highly deformed rocks of Miocene age on the western Olympic Peninsula. This taxa is still living at depths of between 1,500 and 2,500 m in the eastern Pacific Ocean (Ingle, 1980). The youngest fossils recovered from these rock are assigned to the Neogene Relizian stage by (Rau, 1973), and may be as young as 10.2 Ma (Loomis and Ingle, 1994). This taxa occurs in beds at present elevations up to 329 m, suggesting an “average” rate of uplift in post-Relizian time may have been between 0.2 and 0.3 mm/y”2 for rocks lying near the Pacific Coast.

Uplift rates estimated from deformed terrace deposits of Pleistocene age in the western Olympic Mountains range from < 0.1 mm/yr. at the Pacific Coast to about 0.83 mm/yr. at Mt. Olympus, the highest peak in the range, and are comparable to long-term exhumation rates calculated from apatite fission-track data, suggesting topographic relief of the Olympic Mountains is near steady-state conditions (Pazzaglia and Brandon, 1997). These rates are comparable to those observed in other rapidly converging subduction zones, such as the Finisterre Range of Papua New Guinea (Abbott and others, 1997). The data of Pazzaglia and Brandon (1997) also suggests the Cascadia accretionary wedge in the Olympic Mountains presently thickens about 500 m/my. near the coast, and about 1,850 m/my. at Mt. Olympus, with current topography sustained by continuing accretion and thickening (Brandon and others. 1998).

Modern uplift rates inferred from tide-gage records measured between 1940 and 1975 at Astoria, Oregon, and Neah Bay, Washington, suggest values of about 4.0 ± mm/yr at the Pacific coast (Savage and others, 1991). Additional data from repeated leveling and temporary and permanent tide-gage records, corrected for glacial rebound, indicate modern tectonic uplift rates on the west coast of the Olympic Peninsula range between about 1.0 and 4.0 mm/yr (Savage and others, 1991). Mean elevation data from uplifted, discontinuous remnants of a late Pleistocene wave-cut platform on the Pacific coast suggest more modest rates (<0.5 mm/yr) during late Quaternary time (McCrory, 1996).

Constructing Geologic Cross-sections in the Olympic Subduction Complex

Rowland and Wally never published a cross-section with Map 1-994 (Tabor and Cady, 1978a). Perhaps this is just as well, as it has allowed many workers to present schematic cross-sections of the Olympic subduction complex unconstrained by data. However, the map pattern of rocks in the Olympics, especially in the eastern core, is "different" somehow from other fold and thrust belts, with perhaps the possible exception of the Sooes Terrane of Snavely and others (1993). The difference between 1-994 and other fold and thrust belts may be one of scale; many of these are mapped at 1:24,000, whereas the Olympic Map is 1:125,000. More importantly, the difference may represent time. After completing l:62,500-scale mapping of the Brothers, Mt. Angeles, and Tyler Peak Quadrangles, Rowland and Wally mapped the rest of the core in 1969 and 1970, if memory serves me correctly.

In offshore Washington, we are in far better shape. A number of seismic-reflection profiles have been published, for example, those in Snavely and Wagner (1981), Snavely and Wagner (1982), Wagner and others (1985), Palmer and Lingley (1989), and Fleuh and others (1997). Of these, perhaps the most complete is that of Palmer and Lingley (1989). These profiles show clear evidence for thrust faults that cut the stratigraphic section, and for fluid-diapiric (?) bodies that apparently intrude overlying rocks. Note that if diapiric bodies on the Washington shelf are indeed cored by rocks of the Hoh Lithic Assemblage (Hoh melange?), then the age of these bodies can be established by determining the age of the rocks into which they intrude. If some of these bodies indeed cut the modern ocean floor (Wagner and others, 1985), then the age of some of these may be 0.00 Ma.

Parke Snavely and Holly Wagner (Snavely and Wagner, 1981, 1982) published a number of seismic-reflection profiles in rocks of the Olympic subduction complex and the Cascadia accretionary wedge. Figure 10 shows two crossings of the toe of the accretionary wedge, the first off Cape Ffattery, and the second off the mouth of the Columbia River. Both of these sections clearly show Pliocene to Holocene rocks rising along a thrust fault. Off Cape Flattery, the fault system appears to have stopped growing, and the "frontal thrust" is overlaped by deposits of Holocene age. In contrast, the "frontal thrust" off of the Columbia River is oriented the opposite of what one might expect; the fault dips to the west, rather than to the east, and fault appears to cut the ocean floor, suggesting it is an active structure.

Attempting to reconstruct structures in the Olympic subduction complex is not a trivial task. If you were brought up on Marland P. Billings, your first inclination might be to reconstruct these folds by "Busking." Get your mind out of the gutter - "Busking" is a simple geometric technique (pioneered by Mr. Busk) used to reconstruct parallel or concentric folds that has been used with considerable success in the Middle East and in the California Coast Ranges. The method involves construction perpendiculars to bedding surfaces (strikes and dips), and projecting these to where they intersect, which is assumed to be the "center" of the fold. Note that the technique assumes parallel or "concentric" folds, in which the thickness of each bed remains constant perpendicular to bedding during folding. Because of this constraint, the form of these folds cannot extend forever into the subsurface, but must change, both upward and downward. This geometry of parallel folds implies (indeed requires?) some sort of detachment surface or decollement at depth; these folds must have a lower limit, below which the deformation style can be different.

In contrast, one may wish to reconstruct these folds using the geometric techniques pioneered by John Suppe (summarized in Suppe, 1985), which involves interpreting these structures as "Fault-bend Folds." Dipmeter data from holes drilled in many areas in the search for oil and gas resources suggests the concentric-fold model may not be correct for reconstructing subsurface geometry. For our purposes, these folds may be visualized as large-scale "kink-bands." Busking and Fault-bend folds are essentially incompatible interpretations, but our reconstructions can sometimes be constrained if we have outcrop or dip-meter data. Curiously, fault-bend folds virtually require significant areas of exposure on their limbs of essentially "monoclinally-dipping" strata, as opposed to dips that gradually change (parallel folds). Just out of curiosity, you might want to look at Tabor and Cady's (1978a) map of Rugged Ridge north of the Bogachiel River.

Figure 11 is a crude cross-section of Map 1-994 (Tabor and Cady, 1978a), extending from near Mt. Constance on the east to the Pacific coast at Kalaloch. Dips shown are those on the map; I have not attempted to show any change in dip with depth on any bedding surfaces or faults. Note that the scale of this cross-section is approximately 1:125,000, and that the scale of the new Geologic Map of Washington is 1:250,000.

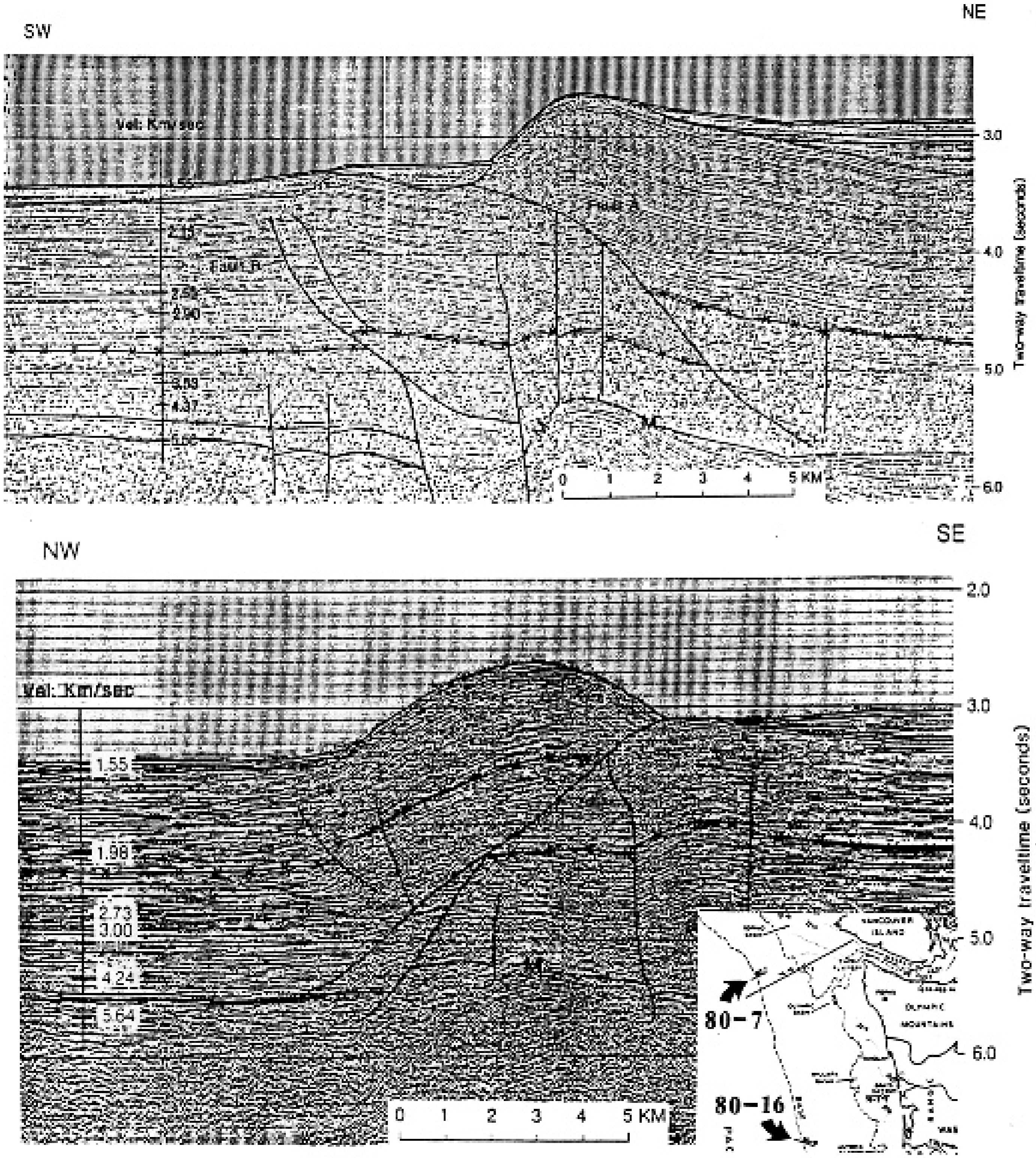
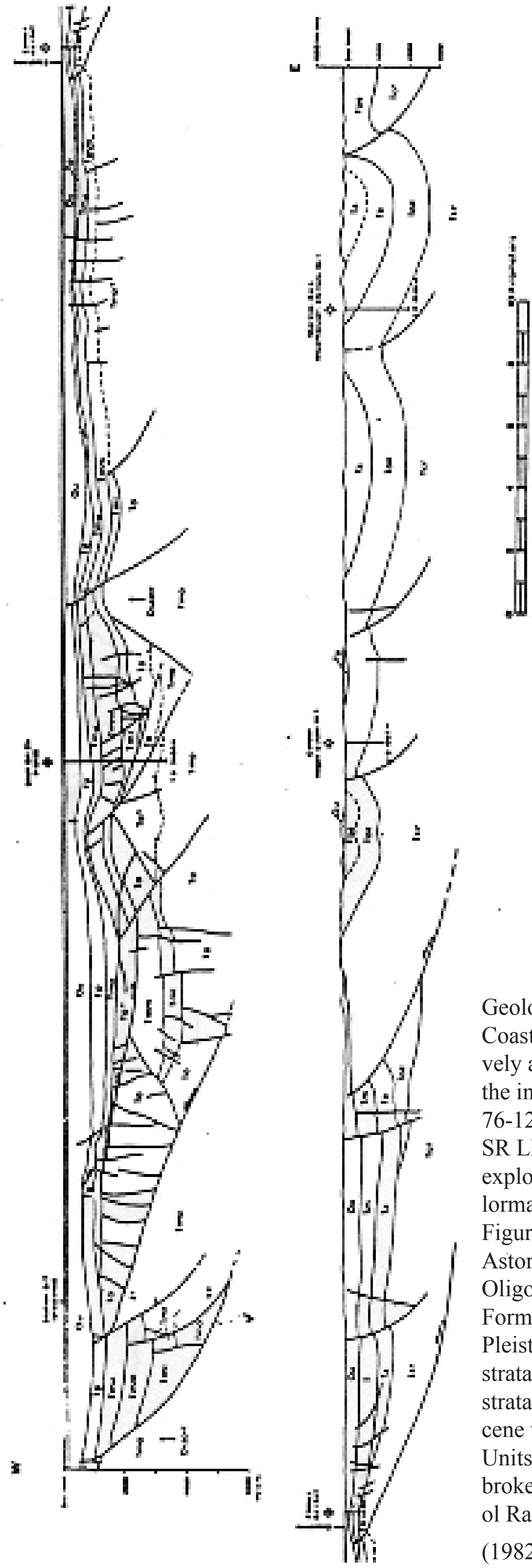
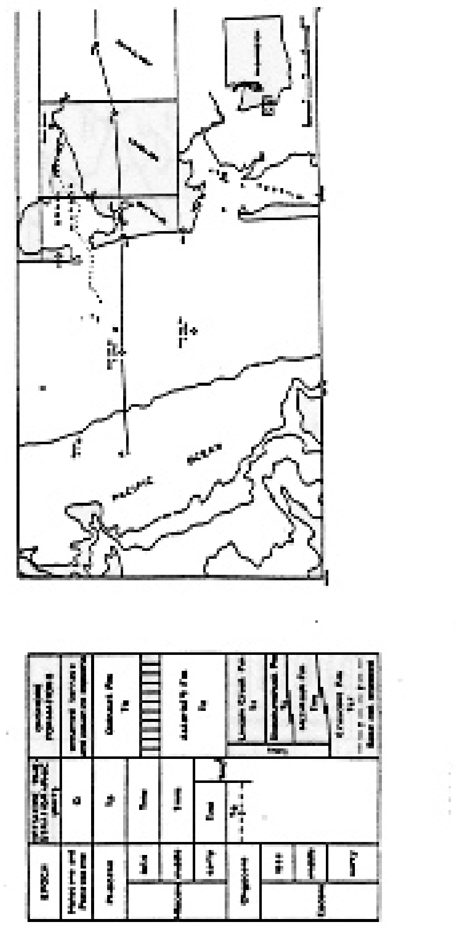


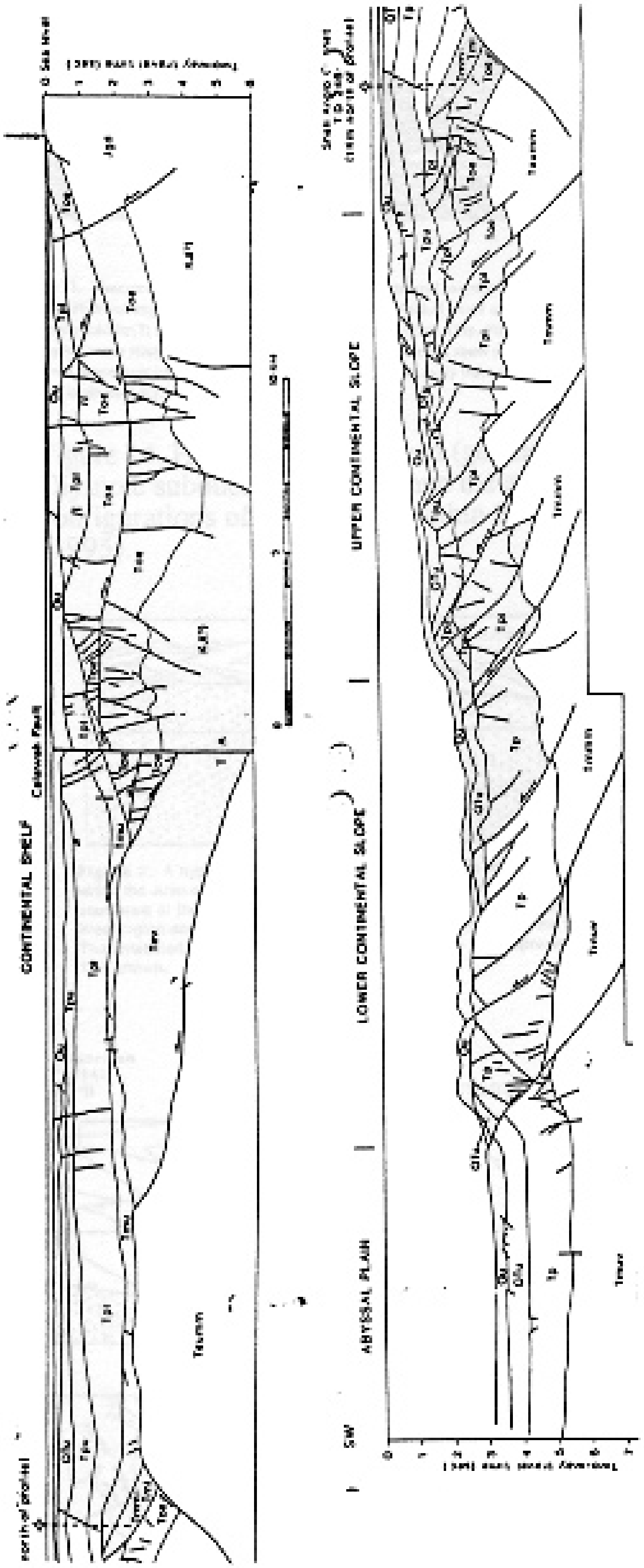
Figure 10*. Seismic-reflection profiles at the base of the Cascadia accretionary wedge west of the Olympic Mountains, from Snavely and Wagner (1981, 1982). Top, Line 80-7, offshore from Cape Flattery, with landward-dipping thrust faults. Bottom, Line 80-16, offshore from the Columbia River, with a seaward-dipping thrust fault. Scale of cross-sections is approximately 1:125,000, the same as Tabor and Cady (1978a).*

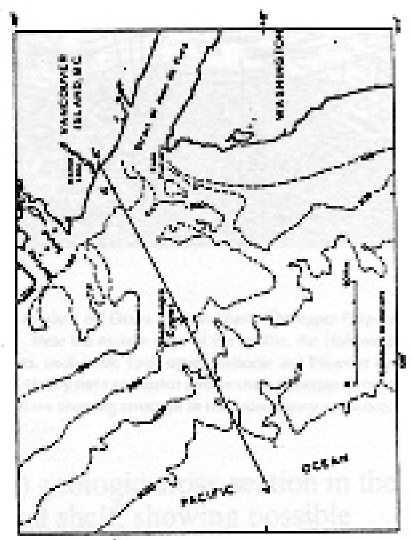


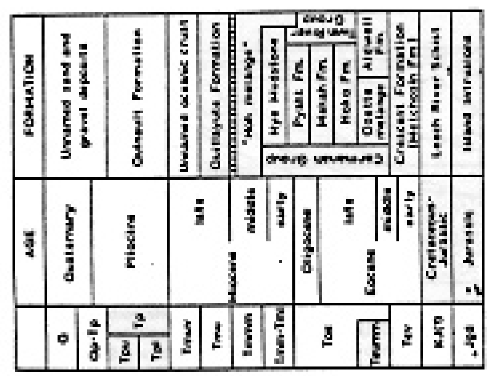


Geologic cross-section across southwestern Washington Coast Range tnd the adjacent inner continental shell (Snavely and Wagner. 1982). Offshore geology is based upon the interpretation ol 24-channd seism'K-retleclion profile 76-12(Figure1)collectedaboard the USGS research vesse/ SR LEE and subsurface data trom Shell Oil Company exploratory well P4155. Onshore Quaternary and Tertiary lormatxmal symbols include: Qu, Quaternary deposits (see Figure 3 lor age ol units); 7m, Montesano Formation; la, Astoria Formation; Joe, unditlerentiatedmiddle Eocene to Oligocene strata; Jet, Crescent
Formation. Offshore time-stratjgraphic units include: Qu. Pleistocene and Hofocene deposits, undivided: 7p, Pliocene strata; Jmu. upper Miocene strata; Tmm, middle Miocene strata; 7m/, tower Miocene strata; Tmo, upper middle Miocene to upper Oligocene strata; and Jo, Oligocene strata. Units 7mm, 7m/, Tmo and 7o are presumably melange and broken tarnation equivalent to the Hoh flodc Assemblage ol Rau '(975, J979). See figure 4 in Snavely and Wagner (1982) lor correlation ol onshore and offshore units.

***Figure 11**. Geologic cross-section across the southern Washington coast range and continental shelf, from Snavely and Wagner (1981).*







geologic cross-section on the continental margin between Cape Flattery, Yfashington. and Vancouver Island. B. C.
. Location shown on Figure
B. Geologic cross-section based upon interpretation of seismic profile by Snavety and Wagner (1981).vertical exaggeration approximately 2:1. Time-stratigrap/uc units include: Qu, Quaternary deposits, undivided: QTu, Quaternary and latest
Tertiary deposits, undivided; Tp, Pliocene strata, undivided; Tpu. upper PCoci strata; Tpf, lower Pliocene strata; Tmu, upper Miocene strata; Tmuv, upper Miocene oceanic crust; Tmmm. middle Miocene melange; Tmm-TmJ, middle and tower Miocene strata; Toe, Oligocene and upper Eocene strata; Teumm, upper and middle Eocene melange; lev, middle and lower Eocene oceanic basalt; KJ(?) Cretaceous and Jurassic sedimentary and metamorphic rocks; Jgd, Jurassic intrusive rocks.

Figure 12. *Geologic cross-section of the continental margin offshore from Vancouver Island, B. C, from Snavely and Wagner (1982).*

Figure 71. Inicrprclcd time section of migrated multichannel seismic-reflection profile of the continental shelf off Grays Harbor. Wash. The upper Oligoccne and middle Miocene Huh melange is inferred to underplale broadly folded strata of late Miocene and Pliocene age. Near the eastern edge of the profile, the Hoh melange appears to underplate ntiddlc(?) Eocene basalt and upper Eocene).1) strata. Qhp, Pleistocene and Holoccnc sediments, undivided; Tpm. upper Miocene and Pliocene strata, undivided; Tc. upper Cocene strata; Teb. middle Eocene basalt. Large arrows show direction of tectonic underplaling. Heavy lines are faults; arrows show direct ion of relative movement: T denotes movement toward the viewer and A is movement away from (he \ic\\cr. Light lines are form lines showing structure in the sedimentary sequence. Vertical exaggeration is about 2.6:1.

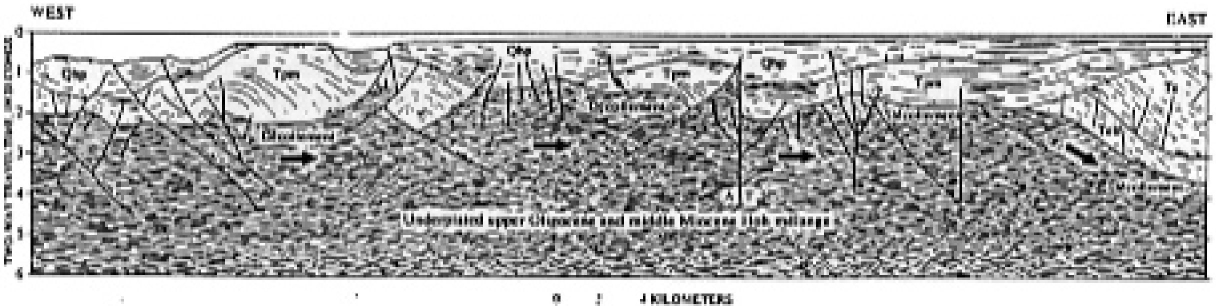
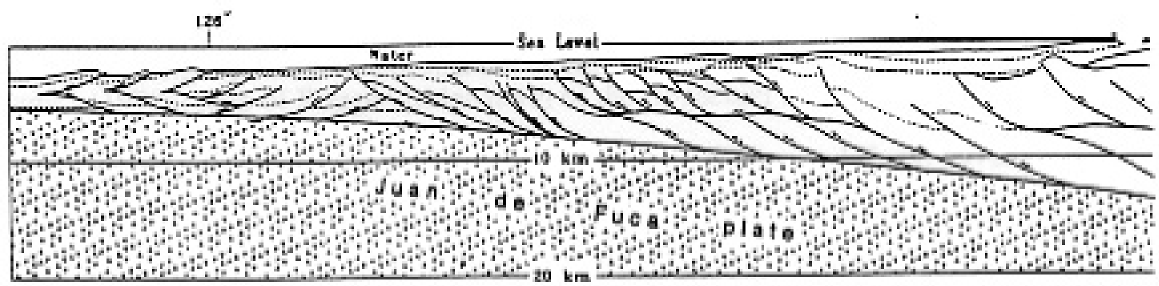


Figure 2. A hypothetical southwest-to-nonheast balanced (geometrically correct) cross section showing possible configurations of thrust faults within the Juan de Fuca accretlonary prism and adjacent regions (section by S. E. Boyer, Univ. of Washington, and the author). Unlabeled polygons southwest of the Hurricane Ridge fault rFigure 13. Geologic cross-section of the continental shelf off Grays Harbor, Washington, from Snavely and Wells (1997).epresent the Core Complex of Tabor and Cady (1978a) and IIS offshore depositlonal continuation on the Washington continental margin. Unlabeled polygons between the Hurricane Ridge and Leech River faults reflect rocks of the Fuca-Toflno basin. The unlabeled polygon northeast of the Leech River fault represents Mesozoic meta-morphlc rocks. The northwestern part of the study area (Fig. 1} is shown.

***Figure 13**. Geologic cross-section of the continental shelf off Grays Harbor, Washington, from Snavely and Wells (1997).*



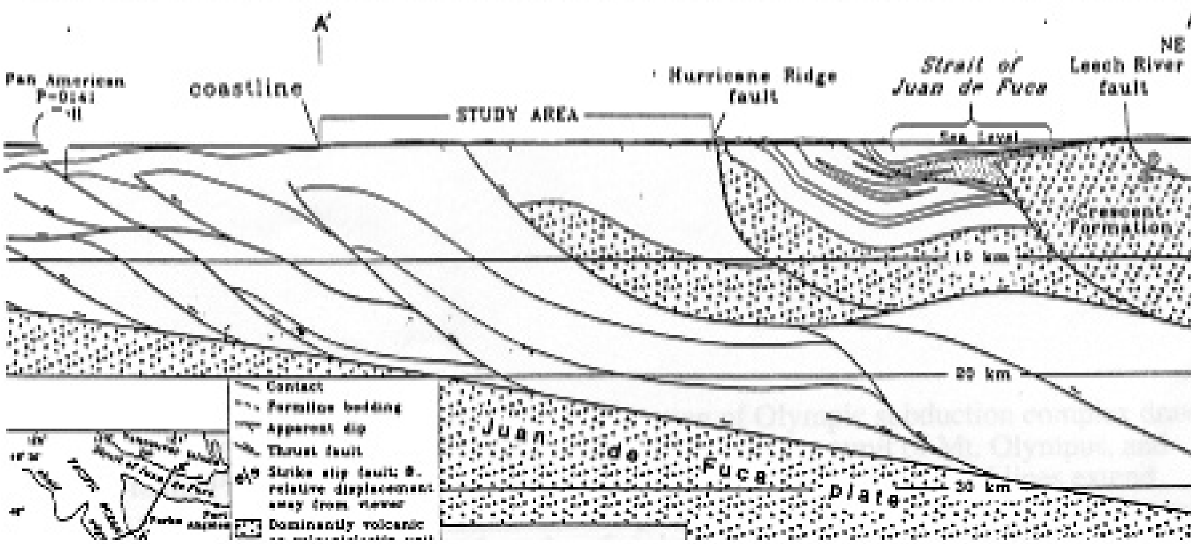


***Figure 14.** Hypothetical balanced (geometrically correct) geologic cross-section in the Olympic subduction complex and the adjacent continental shelf, showing possible configurations of thrust faults within the Cascadia accretionary prisim, from Lingley (1995).*

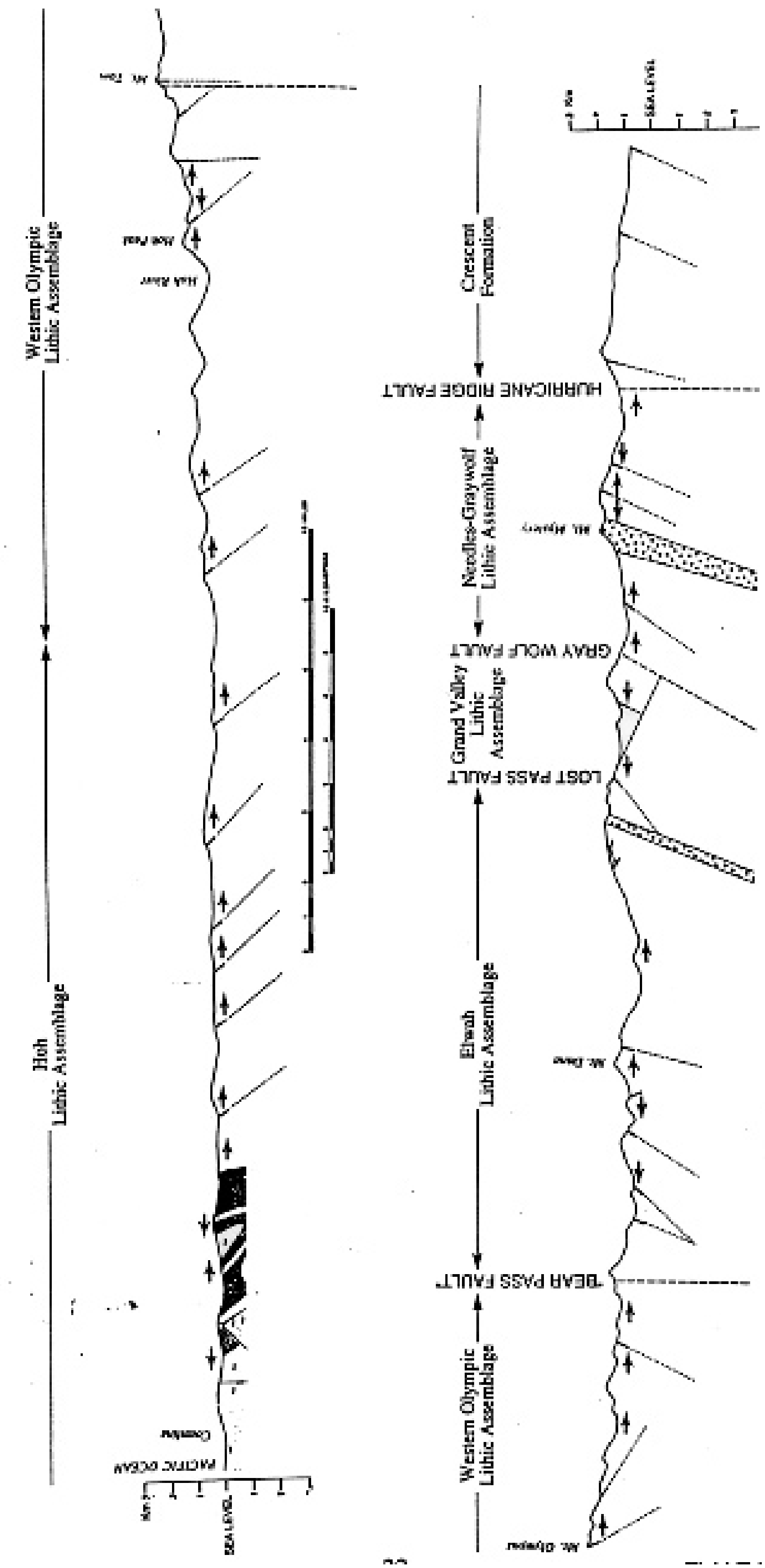


***Figure 11** (left). Geologic cross-section of Olympic subduction complex drawn from near Mt. Constance above Hood Canal, through the summit of Mt. Olympus, and west to the Pacific coast. Dark tics are dips from Map 1-994; short dashed lines extend these dips into the subsurface without bending them. Bold dashed lines are faults mapped on 1-994, and are projected into the subsurface based on a visual estimate of the attitude of these structures; inferred faults are shown as thin black lines. Arrows indicate the directions that bedding tops face in the plane of this cross-section.*

Field Sites

Beach Trail #4

Park in the parking lot and work your way down to the exposures of sandstone where the trail hits the beach. Note that this is the site of daily tours with Park Service Naturalists, and banging on rocks or collecting specimens is verboten; please leave you rock hammers in your vehicles.

These outcrops, and those at the next two localities, are part of the Coastal Strip of Olympic National Park. It is a Federal Offense to collect rock or mineral specimens, flowers, weeds, or sand particles in a National Park, without first obtaining a collector's permit. Unless you really want to enjoy the company of Web Hubbel for several years, do not even think of bringing a rock hammer onto the beach.

Miocene-age rocks on the western Olympic Peninsula are conspicuously and sometimes spectacularly deformed (Rau, 1975, 1979; Tabor and Cady, 1978a, b; Snavely and Kvendvolden, 1989; Snavely and others, 1993). Evidence for crustal shortening in this belt is overwhelming; the average dip is about 70", and beds commonly are vertical or overturned; many folds are overturned, primarily to the west (Rau. 1975, 1979). The monotonous sedimentary succession exposed in this area may be structurally repeated, although the lack of stratigraphic marker horizons does not permit accurate definition at this time. Because of this, the thickness of Miocene-age rocks in the subduction complex cannot yet be accurately determined, but estimates from map relations suggest more than 5 km of strata may be present (Rau, 1975, 1979).

Rocks of Miocene age in the western Olympic Mountains are typically juxtaposed with more highly deformed broken formation and melange of Eocene and Oligocene age by a complex system of both high- and low-angle faults (Rau, 1975, 1979; Tabor and Cady, 1978a, b; Snavely and Kvendvolden, 1989; Snavely and others, 1993). Vergence of most folds is westward and southward, but the vergence of low-angle faults is more difficult to assess, due to poor exposure and possible late-Tertiary folding. Both landward and seaward vergent structures have been described (Rau, 1973, 1979; Snavely and others, 1993). However, these rocks are significantly less deformed than broken formation and melange upon which they may lie (Rau, 1979).

The sandstones that you see before you yield Miocene (and Eocene?) microfossils, a zircon fission-track age of 29.8 ± 1.7 Ma., and an apatite fission-track age of 15.2 Ma. Vitrinite reflectance values from this vicinity of about 0.6 percent (Snavely and Kvendvolden, 1989), suggests zircon fission-tracks may not be thermally reset, but tracks in apatite may be reset. These rocks are obviously part of some fold; your task is to determine what the geometry of this fold might have been, based on the attitudes of these outcrops, and mapping by Weldon Rau (1975). You should probably start by determining the strike and dip of these beds. Then you must do what all "Olympic" geologists must do, namely, determine which way is "up" in these outcrops. "Up" obviously means in which way are the beds stratigraphically "young," or what direction is stratigraphically "up" originally was!

I interpret the geometry of the folds beneath our feet as requiring some sort of slip-surface (detachment surface?) at depth. At what depth I am not sure. As evidence for the possible nature of the surface, and the rocks that may underlie it, I will cite the exposures of "Hoh breccia" or "Hoh melange" that crop out in Weldon's Mink Creek Melange Zone. I suggest that the Mink Creek Melange Zone occupies the core of an anticline, in which older rocks underlie a deformed "cover" of Miocene sediments. As further evidence, I would cite the occurrence of "Hoh Volcanics" (Eocene?) in Weldon's Mink Creek Melange Belt, and a detrital zircon fission-track age of 49.0 Ma from sandstones in the eastern portion of the melange belt. If this interpretation is correct, then much of the western Olympic Peninsula may be underlain by "Hoh melange," overlain by deformed, but not chaotically disturbed, sediments of Miocene age.

The implications of this assessment are obvious, suggesting that the folds that you see at Beach Trail #4, and the faults associated with them, may not extend downward to the base of the oceanic crust. Put another way. this interpretation suggests that deformation of Miocene-age rocks in the western Olympic Mountains may be "thin-skinned," rather than involving deep crustal faults.

Features similar to those at Beach Trail #4 can be found north of the Hoh River in the Minter Creek syncline, where Rau (1979, 1980) noted the distinct difference in deformation between folded, but coherent. Miocene(?)-age rocks that apparently lie above much more deformed, older(?) rocks. Rau (1979) interpreted these relationships to be evidence for an unconformity, which may well be true. Snavely and Kvendvolden (1989) interpreted this feature as deformed rocks lying above a thrust fault.

Rocks of Miocene and younger age continue offshore on the Washington continental shelf, where they are folded, structurally imbricated, and cut by diapiric mudstone intrusions containing Miocene and pre-Miocene rocks (Wagner and others, 1986; Palmer and Lingley, 1989). On the Washington continental shelf, as much as 2,000 m of upper Miocene and Pliocene strata thin against growing anticlines and diapiric bodies, the cores of which consist of Eocene to Miocene melange and broken formation, and the flanks of which contain numerous unconformities, growth faults, and gravity slides (Snavely and Wells, 1996).

These rocks beneath your feet at Beach Trail #4 are part of the "Brown's Point Formation" of Glover (1937). Unfortunately, some "Friends of the Pleistocene" have attempted to usurp this name, and have applied it to Quaternary deposits that overlie these outcrops. As this is an "Enemies of the Pleistocene" Field Trip, little more will be said.

Ruby Beach

Park in the parking lot and work your way down to the exposures of sandstones and other rocks north of the trailhead, and cross the small creek. Note that Ruby Beach is the most visited beach on the Coastal Strip of Olympic National Park. Banging on rocks or collecting specimens is forbidden; please leave you rock hammers in your vehicles.

These exposures at Abbey Island were originally mapped as volcanic rocks by Stewart. This flagrant error was immediately corrected by Parke D. Snavely, Jr., of the U. S. Geological Survey, who suggested that these sedimentary rocks are correlative with similar rocks exposed in the Eocene section near Cape Flattery. Parke went on to suggest that most, if not all, of the volcanic rocks mapped by Stewart in the valley of the Clearwater River were also sediments (conglomerates).

Parke D. Snavely, Jr., was recently awarded the Dibblee Medal of the Geological Society of America for his 53 years with the USGS, and especially his work in the Coast Ranges of Oregon and Washington. Ray Wells lauded Parke's work as having "led to a better understanding of the energy resources and hazard potential of sedimentary basins and accreted terranes in the tectonically active Cascadia forearc."

I do not know the age of the sandstones that stick up as "sharks fins" on the hike up the beach. Weldon apparently was not able to recover microfossils from the exposures here at Ruby Beach. Further on, we encounter a well-bedded sequence of turbidites (which way is "up"?), from which Mary Roden-Tice (Brandon and others, 1998) has liberated an unreset apatite fission-track date of 54.4 Ma, the oldest apatite date so far in the Olympic subduction complex. Vitrinite reflectance values for samples taken in the vicinity of Ruby Beach range from 0.39 to 0.71 percent (Snavely and Kvendvolden, 1989), suggest zircon fission-tracks from these rocks may not be thermally reset, but apatite tracks may not (?) have been reset.

Where the beach narrows, we encounter the "Rocks of Abbey Island," which are also exposed in these cliffs east of the island. Our task is to examine the rocks that are clasts in the Abbey Island "deposit." See if you can determine the nature of the clast types, and see if you can speculate on where these clasts may have come from (read "provenance!"). The rocks at Abbey Island bear striking resemblance to rocks of the upper Eocene Lyre Formation, the "Breccia and conglomerate of Cape Flattery," and the upper Eocene "Conglomerate and sandstone of the Sooes terrane," described by Parke Snavely (Snavely and others, 1993) from rocks north of us at Point of the Arches, Portage Head, and Cape Flattery. If the tides are with us, we will round the cliffs east of Abbey Island, and continue a short distance up the beach, where we will encounter a very typical exposure of "Hoh Breccia." or "Hoh melange." As is so characteristic of Hoh melange, these deposits are part of an active landslide; what you "see" is once-removed from what you "had," but it is difficult to tell how different this material is in outcrop, as opposed to what it looks like in a landslide.

The pioneering work on Olympic melanges can be found in Rau and Grocock (1974), a publication that is widely cited in the melange community. Melanges are tectonic rock associations where the original stratigraphic continuity may have been disrupted, or even totally obliterated, by cataclastic flow and turbulence. Discussions of Olympic melanges can also be found in Orange (1990), and Orange and others (1993).

The most obvious thing about "Hoh melange" is the "scaly clay." Hoh melange sometimes contains (but not here!) rounded fragments of greenish volcanic rocks, normally considered to be marine basaltic volcanic rocks of Eocene age equivalent to the Crescent Formation. Many of these are shown on Tabor and Cady (1978a), with small exposures being labeled Tb. Curiously, Koch (1968) reported that the green volcanic rocks at the Hogsbacks near the mouth of the Raft River (the "type" Hoh melange?) were intrusive and extrusive rocks of andesitic, not basaltic, composition. He reported such rocks as agglomerates, breccias, and crystal- and vitrophyric-tuffs, and no pillow structures. Presumably the green color is due to alteration. Similar volcanic rocks can be found to the south of us in the hills west of the southern reaches of the Clearwater River, and in the Mink Creek melange of Rau (1975).

The age of melange bodies in the Olympic subduction complex is a subject of some debate. Age assignments are commonly based on the age of the fossils found within them, a fundamental error noted by the "Father" of melanges. Ken Hsu, thirty years ago (Hsu, 1968). If melanges are tectonic units, the age of the enclosed fossils may not date the age of deformation of the melange body, but simply the age of the rocks involved in that deformation. To further confuse the issue, I have obtained a zircon fission-track age of 40.1 Ma from sandstones in this outcrop.

Ruby Beach is named for the abundant crystals of garnet that occur in the beach sands. During the depression, miners using crude sluice boxes in the streams that cross the beach could extract $5-10/day in gold from these sands, and others like it that stretch north along the coast to Point of the Arches. At one time, Ruby Beach was the site of a "lodge" somewhat similar to the present Kalaloch Lodge, presumably sited on what is now the parking lot at the Ruby Beach trailhead. If memory serves me correctly, this lodge was removed in 1954, after President Truman added the Queets Valley and the Coastal Strip to Olympic National Park in January of 1953.

Oil City and Boulder Beach

No Oil, no City, what's up? Oil exploration in the western Olympic Mountains closely followed the California model, drill the oil seeps (a version of this scenario has been preserved for all eternity in the opening scene from that most American of situation comedies, the Beverly Hillbillies). About 1930 a number of wells were drilled on a seep just to the north of you up the hill. On our route west from the trailhead, we pass a fairly typical "exposure" of Hoh melange, or "Hoh breccia," as it was once called. Two vitrinite reflectance values reported in Snavely and Kvendvolden (1989) are 0.79 and 0.87 percent. A little further along, ocean waves have brought Boulder Beach to us. If the clasts in the conglomerate at Boulder Beach represent some sample of the source terrain, what was that source terrain made of? Does the material at Boulder Beach resemble the rocks you found at Abbey Island? Finally, what is the age of the conglomerate at Boulder Beach? Is it part of the "Conglomerate and breccia of Cape Flattery" (Snavely and others, 1993), and thus Late Eocene in age, or are these Miocene-age rocks?

Broken Formation on Geodetic Hill

The rocks we will examine here, and in our subsequent stops, are NOT within Olympic National Park. You may bang away at will with your rock hammers.

We have proceeded north of the Hoh River, and are climbing along a strike ridge known as Geodetic Hill and Spruce Mountain. At our first stop we can see sandstones. This would ordinarily be of no consequence, except that Arthur Calderwood collected a sample from this outcrop, which yielded a fission-track age of 46.8 ± 3.1 Ma (Brandon and Vance, 1992). If you walk out the log road ahead of you, you will find yourself in soft, "squishy," shales. Our only age control on these rocks comes from Miocene microfossils Weldon found at the Oxbow in the Hoh River, near the Hoh River Bridge on US 101. Weldon Rau (Rau, 1975, 1979), and Parke Snavely (Snavely and Kvendvolden, 1989), both suggest there is a major fault semi-coincident with the lower course of the Hoh River Valley. This fault is drawn to the south of the exposures that we visited at Ruby Beach. If my mapping is correct, this fault extends beyond the Hoh oxbow, and separates Miocene shales on your left from Eocene sandstones and shales on your right.

At the end of the road on Geodetic Hill we can see an excellent example of what many rocks in the core of the subduction complex look like. In these rocks the original stratigraphic continuity has commonly been disrupted, often by Riedel shears. This type of dislocation, and the pseudostratigraphy which it produces is what Hsu (1968) defined as "broken formation." These rocks are difficult to work with, as "attitudes" taken on "bedding" in these rocks may be highly variable (and perhaps meaningless!?). Units that may give a clue as to the original stratigraphy in these rocks may be difficult, if not impossible to find. Unfortunately, about three-fourths of the Olympic subduction complex is broken formation (Tabor and Cady, 1978a).

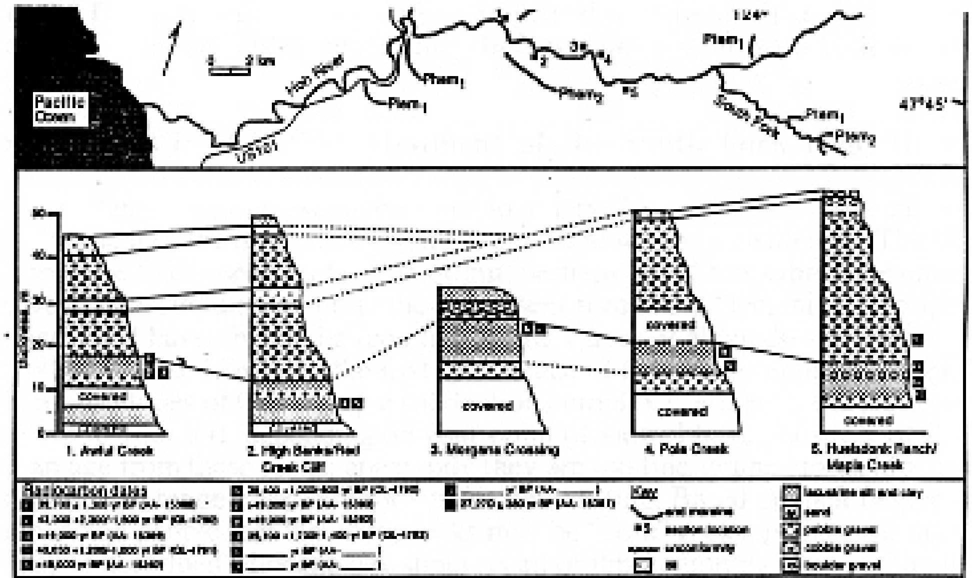
I was able to obtain a fission-track age of 37.0 ± 2.0 Ma from sandstones in this outcrop. At the base of Geodetic Hill in the Hoh River valley, I have obtained fission-track dates of 47.2! ± 2.5 Ma from the west end, 18.8 ± 0.9 Ma from a rock immediately below us in "Fletcher's Quarry," and 23.6 ±3.3 Ma from a rock east of us on the Indian Pass Trail. As the rocks all dip to the north, one might suspect that a fault is located somewhere between us and the base of Geodetic Hill.

Glacial Deposits in the Hoh, Snahapish, and Clearwater River Valleys

The stratigraphic sequence in the middle portion of the Hoh valley, visible in the prominent "High Banks" or Red Creek Cliff on the south side of the river, consists of middle Wisconsin lacustrine sediments overlain by outwash and till (Thachary, 1996). Wood samples from the lake beds yield radiocarbon dates ranging from >49,000 yr BP to 27,270 yr BP, suggesting a sizable lake occupied the middle portion of the Hoh valley for a substantial length of time.

The High Banks stratigraphic section indicates that the Hoh valley experienced at least two distinct glacial advances (Thachary, 1996). In the first advance, represented by a lower outwash and till, the glacier reached the Hoh Oxbow area near the bridge over US 101 on the Hoh River. Outwash separating two till units suggests that the glacier retreated well upvalley before readvancing to deposit an upper till and construct the late-phase Hoh Oxbow end moraine about 0.5 km downvalley from the High Banks/Red Cliff section.

A 40 m-high linear scarp separates glacial deposits in the Hoh valley from these in the Snahapish River drainage, which heads south from our viewpoint A minimally dissected outwash valley train descends southwest from the scarp head, filling the Snahapish valley. The drainage of the Queets and the Hoh Rivers was connected during at least two glacia-



Correlated sections in the middle Hoh River valley, showing middle and late Wisconsin stratigraphy and chronology.

Figure 12 *(Left) (Not labled on original document)*

tions by the Snahapish River system, which channeled ice and meltwater southwestward into the valley of the Clearwater River. The Clearwater River aggraded thick gravel fills during glacial episodes; the result is a series of thick alluvial fills, now represented by a series of terraces, in the lower Clearwater.

The Red Creek Quarry

This is a mundane place, at best. However, for work in the Olympic Mountains, this is a very typical exposure, if not "supertypical" as these rocks are fresh! The rocks are shale-chip sandstones, which contain abundant volcanic rock fragments and about 5 percent detrital potassium feldspar. On fresh surfaces, these rocks are remarkably "blue." In additon to sandstone, they contain relatively abundant fragments of coal, and some veins of caJcite, so we can entertain thoughts of doing some quantitative work!

The rocks in this quarry yield a zircon fission-track age of 17.0 ± 1.2 Ma. I do not yet know the apatite fission-track age of the sample from Red Creek, but it should be available soon from Mary Roden-Tice. Vitrinite reflectance values determined from coaly debris in this quarry is R0=0.81 percent, suggesting that these rocks have never been heated high enough (or long enough?) for the zircon fission-tracks to have been thermally reset. I have not measured equilibration temperatures on fluid inclusions from any of the large calcite crystals that you can see, but such information could be quite valuable.

The date from the Red Creek quarry is not the youngest fission-track date so far in the western Olympic Mountains. That honor(?) goes to a rock collected near the summit of Mt. Octopus (the rounded peak to the south of you, on a clear day), which came in at 16.4 Ma. If true, these young dates are particularly significant, as they cause one to speculate on just what other units these rocks may correlate with in western Washington and Oregon. These dates are also astonishingly similar to those found in the Grande Ronde Member of the Columbia River Basalt Group, forcing one to speculate on just what that might mean!

The Dry Creek "Structure"

We are now on the south side of the Hoh River, almost due south of where we stopped to examine the broken formation on Geodetic Hill. Our purpose here is to examine what we see, and try and come to some cosmic conclusions concerning the rocks exposed before us. A zircon fission-track date from just up the road suggests these rocks are again Miocene in age. If they are, then what is the "age" of this structure? For that matter, what is this structure? Rather than dominate the conversation, I will sit back and listen. However, be forewarned that you will be required to vote on what you think this structure is, and its possible significance, before you are allowed to leave this outcrop!

Deformed Rocks in the West Abutment of the South Fork Hoh River Bridge

No matter what conclusion you came to at Dry Creek, the rocks beneath your feet at the west abutment of the South Fork Hoh River bridge will be a challenge. The question is simple; are these folds "sedimentary" in origin, perhaps formed as submarine landslides on some subsea fan accumulation, or do they represent something "tectonic." The age of these rocks is unclear. I have obtained zircon fission-track ages of about 20 - 25 Ma. from the hills surrounding you. However, the first occurrence of the metamorphic(?) mineral prehnite in sandstones of the Olympic subduction complex is either up the hill to your right, or up the hill to your left, depending on your point of view. I have not successfully obtained an age from these rocks; apparently they are too fine-grained to yield zircon crystals in the size range necessary for fission-track dating. Based on their degree of induration, some people feel that these rocks may be "core" rocks, perhaps sitting under some cover of deformed Miocene-age strata (is all of this beginning to sound familiar?). You all have exactly the same rocks to work with. As before, you will not be allowed to leave until you have voted on what the significance of these folds may be!

For what it is worth, at least three Branch Chiefs of the U. S. Geological Survey, two members of the National Academy of Sciences, and two past-Presidents of the Geological Society of America have examined these outcrops, with notable lack of agreement on what these folds mean.

Volcanic Rocks at Greef Creek

Note: the exposures at Greef Creek are at the base of an active landslide that extends over 100 meters above your head: dallying at the outcrop can be dangerous to your health. Samples delivered to you by this landslide are abundant on the road. I suggest you take advantage of this fact.

After a short trot up a logging-access road, we come to one of the enigmas of the Olympic subduction complex. The rocks at Greef Creek are greenstones. While there is nothing wrong with this observation, in the Olympic Mountains such a statement carries with it many connotations.

As is so typical of Olympic "greenstones," we do not have available to us any analysis indicative of the age of this particular rock. Despite this, most workers would consider these rocks to be marine basaltic volcanic rocks of Eocene age, and correlative with the Crescent Formation. The volcanic rocks at Greef Creek are surrounded by "wet" sediments. Furthermore, the closest outcrops of the Crescent Formation lie about 30 km southeast of our position, which forces the question: did these chunks of Crescent Formation come up from below, or did they drop in from the sky? The question is not trivial. If these rocks came up from below, then perhaps they are fault-bounded, and the faults tapped the Crescent Formation at some depth. How does one reconcile this observation with the young age (~ 10 Ma) of oceanic crust that is supposed to underlie us here at Greef Creek? If they dropped in from the sky, were they transported as part of a "thrust sheet," the remains of which have now been eroded from over our heads?

I have not been able to determine the age of the volcanic rocks at Greef Creek; they do not contain any zircon, and the small amount of apatite in them is undoubtedly thermally reset. I do have two fission-track dates from sandstones relatively nearby. One is 39.6 ± 3.4 Ma from a "greensand" (a basaltic sand?) about 1 km northeast of us, and a 43.8 ± 2.8 Ma from a sandstone at the top of the ridge north of us. Both of these samples were run after the possible presence of Eocene sedimentary rocks in the vicinity of the Greef Creek volcanic rocks was pointed out to me by Parke D. Snavely, Jr.

The Yahoo Lake Tuff

After we climb the steep hill to this overlook, we have a chance to enjoy the view (on a clear day). In front of you are a series of "concordant" summits, some of which appear to be mantled with gravels, much like Kalaloch Ridge. Why? Behind you are some apparently well-bedded rocks. Your task is to examine these rocks, and see if you can tell what kind of rocks they are!

This "flaggy" bed is the Yahoo Lake tuff, discovered by Parke D. Snavely, Jr. We now have several fission-track age determinations on this tuff, including a sample of slender, tuffaceous zircons kindly provided by H. W. Schasse in 1992. The results of the age determination on this sample are given on the following pages. All of these grains have exactly the same physical characteristics. One must stop and ask if the spread in grain ages for this sample represents mixing of grains of different ages (and different sources?), or is an expression of the range in grain ages that the fission-track technique gives you from a unimodal population.

Perhaps the most important point that one can make about this rock is that it is not Eocene in age. The original age determination, by Joe Vance, brought to my attention the presence of Miocene-age sediments in what Rowland and Wally had mapped on 1-994 as "undifferentiated rocks," their unit Tur. This sample, combined with Joe's date from a rock that I collected with Bob Yeats from the summit of Mt. Tom in 1970, opened the possibility that rocks of Miocene age may be much more extensive in the Olympic Mountains than previously thought, and have kept me busy counting fission-tracks ever since!

"Yahoo's" were an imaginary race of brutes having the form of men in Gulliver's Travels, by Jonathan Swift (1726). In today's common usage, it refers to uncouth or rowdy individuals; what connection this has with this lake is unknown to me.

The Greef Creek Gabbro

If we are unable to hike up the road to the Greef Creek Volcanic rocks, we can attack them from the top, by driving out the short road that takes off to the left just east of the Yahoo Lake tuff. We may have to chase some boulders and cobbles to do so, but once we are beyond the first turn we are in fat city!

At the end of this access road, we can walk down a short spur to an exposure of gabbroic rocks. On the way, we may find several items of interest, considering what we have just seen at Yahoo Lake. Unfortunately, I do not have a date available from this gabbro; it does not contain any zircon, and the small amount of apatite in it is undoubtedly thermally reset.

The Mink Creek Melange

Rocks of Weldon's Mink Creek melange zone are exposed where Shale Creek enters the Clearwater River. If we walk down to the fish apparatus, we can examine well-exposed, deformed sands and shales (is this a broken formation, or a melange?). These rocks contain about 10 percent potassium feldspar, and I have a date of 49.0 ± 2.8 Ma from them. In the Clearwater River exposure, these rocks are much more shaly and scaly, and more typical of Weldon's melange.

Marine Basaltic Volcanic Rocks (Eocene?) in the Prairie Creek Quarry

In Washington, any rock that is green and ugly and crops out west of Snoqualmie Pass is often considered part of the Eocene Crescent Formation. Nowhere in western Washington is that mapping hypothesis used as extensively as on the Olympic Peninsula. In this part of the world, all marine basaltic volcanic rocks are virtually defined as part of the Crescent, which in turn leads to some interesting conclusions.

We will not discuss the geology of the Crescent Formation; volumes have been written on it, and they are available to any interested person. These rocks include pillow basalt, and show no apparent evidence for any sort of an intrusive relationship. These rocks are particularly common in the Olympic subduction complex, and especially in the eastern core, where these pods are considered to be the distal ends of lava "flows" of the Crescent inserted in some fashion along with the great thrust faults of the Olympic core. Curiously, I obtained a zircon fission-track age from a crystal-lithic tuff in this quarry of 22.2 ± 1.3 Ma.

However, there is another alternate hypothesis that may be of help. We now know that similar-appearing rocks are exposed in the Humptulips Formation of Late Eocene age (40 - 45 Ma?) in the hills east of highway 101 from Hoquiam to Lake Quinault (Rau, 1986). Many of these exposures include gabbroic rocks, and are thought to be sill-like bodies with baked contacts that invaded Eocene sediments in post-Crescent time. If so, this suggests that some of the "Crescent basalts" in the subduction complex may not be Crescent-equivalent, and that their podiform nature may be more primary than structural.

Grande Ronde Basalt in Hoquiam, Washington.

Some of the basalt flows of the Columbia River Basalt Group in eastern Washington somehow made it west of the Cascade Range. Exactly how this was done is a matter of some conjecture; did they flow over, under, around, or through the present Cascades? To complicate matters, some workers feel that the basalts found along the Oregon-Washington coasts resulted from eruptions, essentially in place, and from a magma source having exactly the same crystallization history, and exactly the same chemical composition (to the nearest part-per-billion?), at exactly the same time as those erupted from near the Idaho-Washington border.

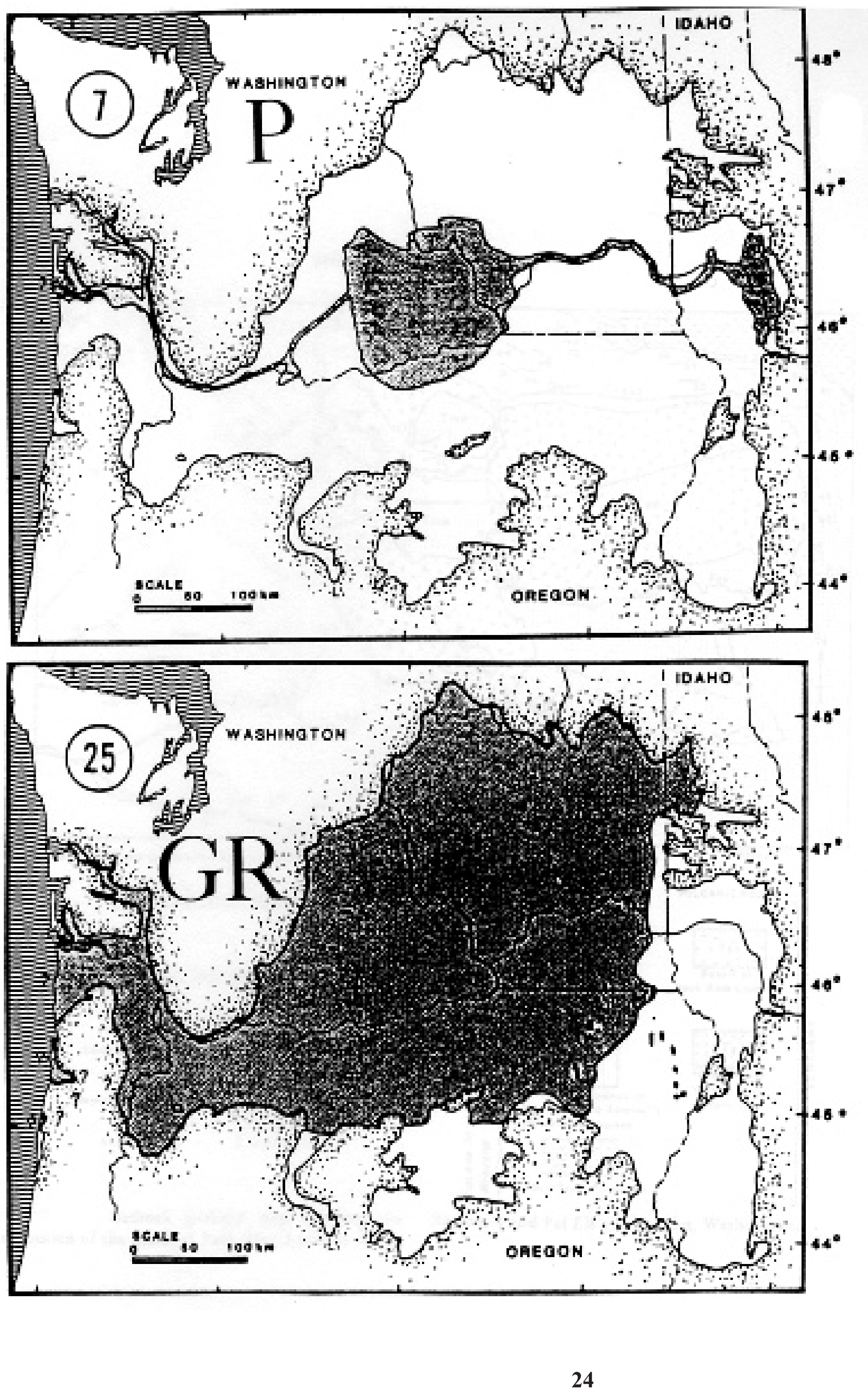
This particular outcrop has been correlated, on the basis of major-element geochemistry, with similar rocks exposed at Depoe Bay, Oregon. The rocks at Depoe Bay yield ^K/^Ar ages of about 16 Ma, suggesting these rocks may be part of the Grande Ronde Basalt. This outcrop, and its extension to the north in one subsurface well location, represents the northernmost reported occurrence of CRBG flows in coastal Washington.

At our locality, Grand Rhonde basalt has been interpreted as lying on top of the Astoria Formation (Rau, 1986), presumably (?) on a surface that may represent an unconformity (?). Further east, in the hills south of Highway 12, the Pomona Flow of the CRBG crops out at a place called Pack Sack Lookout (Snavely and others. 1973). This flow dates at about 12 Ma, and has been used as the approximate boundary that divides the Astoria and the Montesano in the Chehalis Basin.

Montesano Formation Sediments in Aberdeen, Washington.

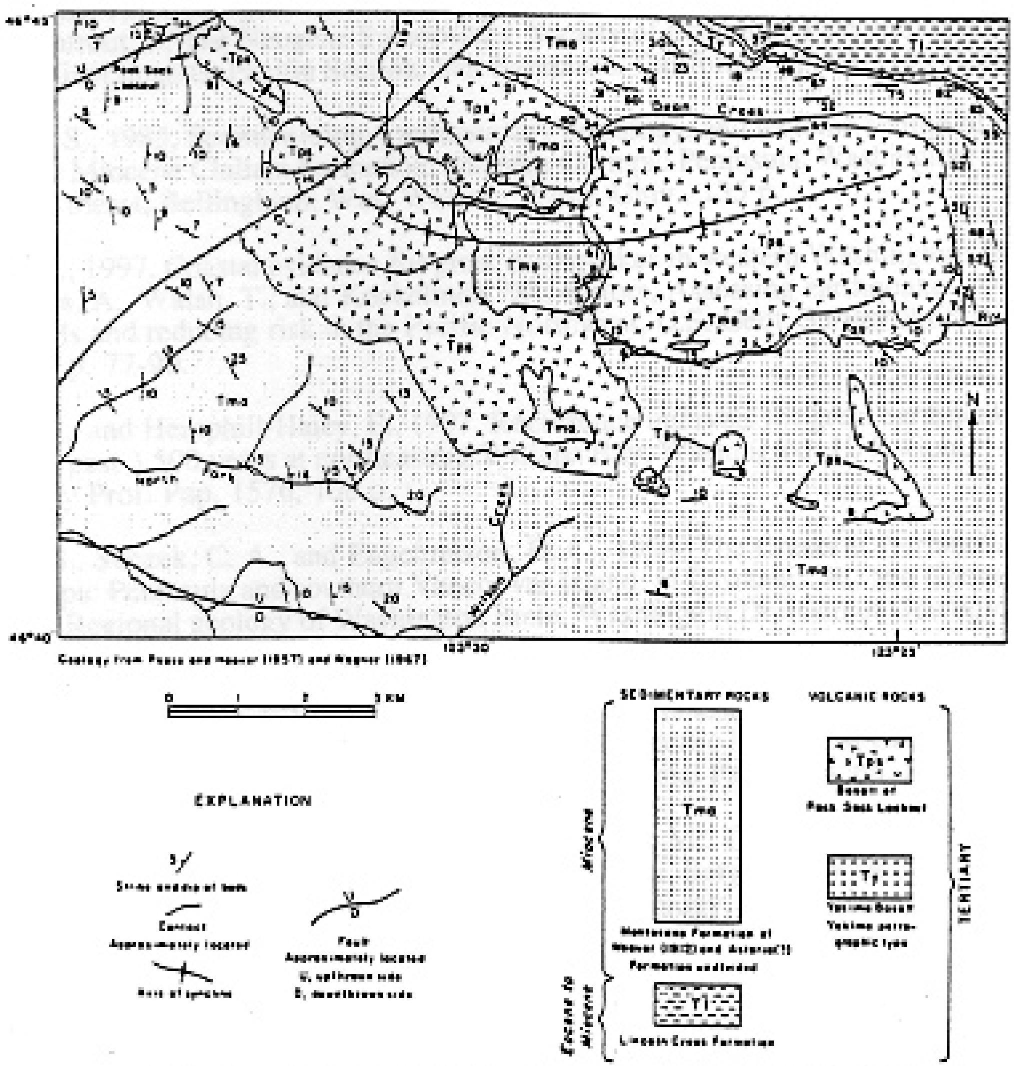
Perhaps this outcrop is rather like the end of a long suspense novel. Many workers consider sediments of the Montesano Formation to be evidence for debris derived from the uplift of the Olympic Mountains. Curiously, the Olympic Mountains are constructed mostly of graywacke sandstone, shale, and marine basaltic volcanic rocks. This outcrop, like most of the Montesano Formation, is clearly arkose. To derive this particular debris from the Olympic Mountains would be a significant assignment. To complicate the problem, the detrital mineralogy of the Montesano at this locality includes abundant kyanite. Professor Joe Vance has outlined the tectonic and stratigraphic significance of detrital kyanite in sedimentary rocks of Tertiary age in coastal Oregon and Washington, and suggests that this index mineral points to some eastward, rather than northward, source for these deposits.

East of our locality, in the drainage of the Satsop River, the Montesano Formation contains conglomerates with clasts of sedimentary and volcanic rocks possibly derived from the Olympic core. These rocks which may represent debris stripped from the Olympic Mountains in its initial phase of uplift and erosion. Becky Chrisfield intends to determine the spectrum of fission-track ages from these clasts. If successful, her data may well provide the evidence for the age of core rocks, and thus provide critical new data on the timing of events in this portion of the Cascadia accretionary wedge (Figure 1).



Maps showing the inferred original extent of units in the Columbia River Basalt Uroup: (7) Pomona Member, (25) Grande Ronde Member. (Note: the previous text is taken from the figure caption for these diagrams as they appear in GSA Special Paper 239. North of the Columbia River in Washington these maps do not show the inferred original extent of units in the Columbia River Basalt Group. Rather, these are maps that show the present-day distribution of outcrops of specific members of the CRBG. The original distribution could possibly be reconstructed by using a method of analysis like that you used on the Yost Quadrangle).

SNAVELY AND OTHERS



Bedrock geologic map showing the distribution of the basalt of Pack Sack Lookout in the Raymond and Pel Ell quadrangles, Washington.

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Editors Note: The original field document included two reprints from Washington Geology. These are not included in this issue. They include:

Lingley, W.S. (1995) Preliminary Observations on Marine Stratigraphic Sequences, Central and Western Olympic Peninsula, Washingotn Washington Geol ogy 23 #2 p 9-19

McCrory, Pa.A. 1997 Evidence for Quaternary Tectonism along the Washington Coast Washington Geology 25 #4 1997 p 14-20