JUAN DE FUCA/NORTH AMERICAN PLATE CONVERGENCE: SEISMIC OR ASEISMIC SUBDUCTION?

By

Dr. Gregory A. Davis
University of Southern California

Dr. Howard A. Coombs
University of Washington

Dr. Robert S. Crosson
University of Washington

Dr. John A. Kelleher
Redwood Research

Mr. David D. Tillson
Consultant

Mr. William A. Kiel
Washington Public Power

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INTRODUCTION

Geologic, geodetic, and geophysical studies in the Pacific Northwest during the past six or seven years have focused much new attention on the interactions between the Pacific, North American, and Juan de Fuca plates, the latter a vestigial remnant of the former Farallon oceanic plate. Subduction of the Juan de Fuca oceanic lithosphere beneath the western margin of southern British Columbia, Washington, and Oregon, along what has since become known as the Cascadia (or Juan de Fuca) subduction zone, was first suggested by McKenzie and Parker (1967) in their pioneering analysis of the plate tectonics of the northeastern Pacific region. Most early investigators accepted the premise that subduction, if it was active, was aseismic, i.e., the Juan de Fuca and North American plates were decoupled. Atwater (1970) for example, in her still highly relevant analysis of plate interaction, giving rise to the present plate configuration, raises this possibility because of the extreme youth and inferred high temperature of the Juan de Fuca plate. More recently, several investigators have begun to question the interpretation that subduction is aseismic along this boundary. These questions have arisen from the realization that seismic quiescence alone cannot be used to rule out the possibility of large subduction earthquakes since quiescence, in the proper context, may be a normal state during certain intervals along seismogenic subduction zones. Quiescence alone may reflect either aseismic (creeping) subduction or a locked state in which stress is accumulating prior to rupture. In many if not most cases, the issue is resolved by a history of past activity and/or by patterns of current seismicity, e.g., a quiescent segment bordered by segments of ongoing seismicity. In the case of the Juan de Fuca zone, we are not afforded this luxury in that the past 150 year history provides no evidence of large subduction events nor does research based on the current seismograph network reveal evidence of any small or intermediate sized earthquakes which can be directly attributed to slip on the inferred subduction zone.

The purpose of this paper is to focus attention on the critical scientific issues needed to address the fundamental question: is subduction proceeding seismically or aseismically? We make no claim to have exhausted all of the relevant issues, but have attempted to assess the present state-of-the-art, focusing on what we consider the most important questions. We have attempted to address both published and unpublished scientific information where possible. While we have attempted to present a balanced view of the evidence and analysis, and while more work remains to resolve this issue, we believe that the weight of currently available evidence favors aseismic subduction as the primary mode of plate interaction. Although the most recent papers published on this issue have tended to emphasize the enhanced possibility of occurrence of a great earthquake along this segment of the North American plate margin, all of the critical questions have not been aired adequately in the literature. It is our belief that the resolution of this question is not settled.

EVIDENCE FOR ACTIVE PLATE CONVERGENCE

Vector triangle analysis of present relative motions between the Pacific and Juan de Fuca plates (divergent with sea-floor spreading at ca. 55 mm/yr; Hyndman and Weichert, 1983), and the Pacific and North American plates (transform motion, ca. 55 mm/yr; ibid.) have led most workers since McKenzie and Parker to conclude that the North American-Juan de Fuca plate interaction is one of northeasterly convergence at rates between 30 and 40 mm/yr. Riddihough (1977) for example, concluded that the two plates converge at approximately 35 mm/yr in a N 50^{O}E direction. This direction is oblique to the north-northwest trending and north-trending continental margins of Washington and Oregon respectively. His oblique rate of convergence is equivalent to a somewhat lesser rate (ca. 32 mm/yr) as measured at right angles to the plate boundary. Nishimura and others (1984), using a pole of rotation analysis, have recently concluded that the "average absolute velocity of the Juan de Fuca plate is approximately 15 mm/yr thereby making it the slowest moving of the oceanic plates." This velocity is not equivalent to the rate of convergence between the Juan de Fuca and North American plates because the absolute velocity of North America is not considered.

In light of the lack of historic interplate seismicity, direct physical evidence for present convergence between the two plates is perhaps best documented by the folding, faulting, and dewatering of latest Pleistocene and Holocene(?) sediments (less than 0.3 m.y. old) in the vicinity of the interface between the Cascadia Basin and the lower continental slope off central and southern Washington (Kulm, 1983, p.31). Seismic reflection lines across the Nitinat Fan off northern and central Washington reveal youthful flexures and multiple faults that "appear to extend to the surface cutting the most recently deposited sediments of the fan" (Kulm, op. cit., p. 17). Kulm believes that such deformation must have occurred within the "past few thousand or, at the most, tens of thousands of years".

Several investigators have attempted to calculate the annual rate of compression of youthful marine sediments at the base of the continental slope. Silver (1972) and von Huene and Kulm (1973) estimated rather similar rates of compressional strain -- 20 mm/yr and 16-27 mm/yr respectively. In the most detailed study to date, Barnard (1978), using seismic reflection profiles across the lower continental slope off Washington, calculated that folding and thrusting with just the outermost marginal ridge of the slope has occurred at an average rate of 7 mm/yr (range 4 to 15 mm/yr) over the past 0.5 m.y. According to Kulm (1983, p.21) ridges which lie 10 to 28 km east of the outermost ridge appear to be progressively older (0.4 to 2.0 m.y.) than the marginal ridge, a geometry that indicates that "successively younger material is being accreted to the lowermost continental slope in the form of marginal ridges."

Adams (ms.), not limiting his strain analysis to only the outermost ridge, concludes that total shortening of the continental margin by permanent deformational mechanisms (folding, faulting, and tilting) may approximate 25 mm/yr, occurs primarily (80%) in the westerly 40 km of the North American plate, and probably represents "a sizeable fraction of the plate convergence rate." If he is correct, then a considerable degree of coupling exists between the two plates in their offshore interface area, although deformation in this part of the accreted wedge appears to be occuring aseismically (cf. WNP-3 FSAR, 1982, Figures 2.5-26 and 2.5-36b).

Given the impressive deformation of latest Pleistocene and Holocene(?) marine sediments along the base of the Washington and northern Oregon continental slope, plus their striking morphological and deformational similarities to accreted wedge sediments in known areas of subduction (e.g. the northern Gulf of Oman, the Andaman province south of Burma, and the Barbados fore-arc; cf. Kulm, 1983), the conclusion appears inescapable that underthrusting is presently occuring beneath the continental margin and at rates compatible with those predicted from plate kinematic models for the northeastern Pacific region.

GEOMETRY OF THE SUBDUCTED JUAN DE FUCA PLATE

The large scale geometry of the subducted Juan de Fuca plate beneath the submerged portion of the Oregon and Washington continental margin and the mainland as far east as the Cascade volcanic chain appears to be moderately well established. A number of workers using various approaches (Davis, 1977, geologic and seismic analysis; Riddihough, 1979, regional gravity interpretations; Langston, 1981, analyses of long-period teleseismic P-waves) had previously concluded that the plate consists of a shallow-dipping ($10^0 \pm 5^0$) western segment and a more steeply-dipping segment (up to 50^0) beneath the Cascade volcanic arc.

Crosson (1983) provided significant new information on the geometry of the subducted slab beneath west-central Washington with the publication of a N 60^0 E cross-section showing a deep (40-70 km) subplanar zone of earthquakes hypocenters lying below the Puget trough. This zone is distinctly separate from the diffuse zone of shallower seismicity (less than 30 km) that characterizes the upper plate in this region. The line of section (Figure 1) contains hypocenters projected into it from distances of 150 km to either side (Victoria to Portland), although almost all of the deeper events lie between Victoria and Olympia. Crosson implied that the deep zone is related to the subducted Juan de Fuca plate, a relationship since supported by seismic refraction data (Taber, 1983) which places the zone near, but not at the top of the oceanic slab. The distribution of the deep hypocenters suggests that the northeast-dipping slab steepens from approximately 8-9^{0} to 17^{0} along an ill-defined bend 30 to 35 km below the western part of the Puget trough. The slab must continue to steepen eastward, probably below about 60 km, in order to reach appropriate depths (Dickinson, 1975) beneath the Quaternary Cascade volcanoes (120 km below Glacier Peak, "GP", along the line of section). However, such steepening is not directly indicated by the pattern of earthquake hypocenters. Figure 1 shows that the down-dip length of the slab between its "trench" (taken to be at the base of the continental slope in the absence of a physical trench) and the axis of the Quaternary volcanic arc is approximately 435 km; the gentle bend between shallow and more steeply-dipping portions lies 250 km inland from the buried trench at the foot of the continental slope.

The approximate 40^{0} dip inferred (Figure 1) for eastern parts of this section beneath the Cascades is compatible with Riddihough's (1979, p.360, his Figure 2) modeling of the geometry of the subducted slab in this area using regional gravity data (a dip between 40^{0} and 50^{0}). The 40^{0} dip for the subducting plate in Figure 1 may not be appropriate for portions of the plate beneath the volcanic chain to the north (southwestern British Columbia) or south (southern Washington and Oregon). This possibility is raised by different geometries for the subducted slab deduced from modeling of regional gravity data (Riddihough, 1979). The possibility that the subducted Juan de Fuca plate may be segmented and that such segmentation may influence upper-plate tectonic and seismic behavior is treated in a subsequent section of this report.

Although the Gorda plate off southern Oregon and northernmost California may not be subducting at the present time beneath the continent (Riddihough, 1980), the distribution of seismicity beneath the continental margin and an analysis of the isostatic residual gravity field over northern California lead Jachens and Griscom (1983) to conclude that the top of the formerly(?) subducted Gorda plate dips 11° eastward.

MODES OF PLATE CONVERGENCE

We assume that subduction of the Juan de Fuca oceanic plate beneath the North American plate is an ongoing process. However, we submit that underthrusting along the 750 km-long Cascadia subduction zone between the Juan de Fuca and North American plates is unusual when compared with most other subduction zones because of its seismic quiescence. A pattern of earthquakes occurring along the shallow-dipping interface between the two plates has not been observed, nor have isolated seismic events produced by thrust displacements along the plate boundary been recognized. As described above, Crosson's deep (greater than 40 km), gently inclined planar zone of earthquakes beneath Puget Sound is apparently located within the upper part of the Juan de Fuca plate, not along its upper contact. Focal mechanisms (Taber and Smith, in press) for most of 16 analyzed events in the deep inclined zone are those for normal faulting with P axes normal to the slab and generally shallow-dipping T axes. According to Taber and Smith "the average T axis lies in the average downdip direction of the slab." In fact, several of Taber and Smith's mechanisms for earthquakes which occur apparently near the top of the subducted slab show mechanisms which, if the low angle solution corresponding most closely to the thrust plane is chosen, would indicate a stress system precisely opposite in the sense of slip to that expected for underthrusting. The fault motion would be that of the lower plate moving westward as opposed to underthrusting.

A somewhat similar hypocentral pattern of intraplate seismicity is seen within subducted portions of the Gorda plate (Figure 2; Jachens and Griscom, 1983, using seismic data from Smith and Knapp, 1980). Jachens and Griscom conclude that the top of the Gorda plate lies several kilometers above the top of a gently eastward inclined seismic zone within that plate. Thus, here too, the plate interface with the overlying North American plate lacks seismic definition. Curiously, but perhaps of importance as discussed subsequently, focal mechanisms within the Gorda plate beneath North America exhibit strike-slip fault solutions similar to those seen in the Gorda plate west of the continental margin. Riddihough (1980) has proposed that current plate motion between the offshore Gorda plate and the continental margin is one of transform (right-slip) type.

The absence of seismic activity along the top of the subducting Juan de Fuca plate, i.e. along the Juan de Fuca-North American plate interface, can be explained by either of two phenomena: (1) that slip or flow between the two plates is aseismic and essentially continuous; or (2) that the interface is locked, that it must experience periodic stick-slip behavior, and therefore has the potential to produce future earthquakes, perhaps of very large magnitude. Both possibilities have their advocates. Brief summaries of published and in press literature advocating either aseismic or seismic behavior are presented below.

Geodetic Arguments

Down-to-the-east crustal tilt along 1400 km of the continental margin, in southwestern British Columbia, western Washington, and western Oregon has been documented by precise leveling, analysis of tide gauge records, and studies of tilted coastal marine terraces (Ando and Balazs, 1979; Reilinger and Adams, 1982; Riddihough, 1982; Adams, ms.; and Pelton, 1983). Uplift of the outer coastal areas (up to 2-3 mm/yr in Washington and British Columbia) is accompanied by subsidence (1-2 mm/yr) east of a hingeline that extends southward from Hecate Strait, through the Strait of Georgia, Victoria, and the eastern edge of the Olympic Peninsula (Riddihough, op. cit.; Reilinger and

Adams, op. cit.). Studies of Quaternary coastal terraces in Oregon and Washington indicate that eastward tilting is not just characteristic of this century, but has occurred during at least the past 0.25 m.y. Ando and Balazs (op. cit.) interpret the tilting pattern as an expression of continuous aseismic subduction of the Juan de Fuca plate beneath North America. Reilinger and Adams (op. cit.) and Riddihough (op. cit.) favor this interpretation, but admit that other alternatives may exist. Riddihough, for example, reports that western uplift and eastern subsidence occurs in British Columbia inland from the Queen Charlotte transform boundary between Pacific and North American plates, as well as adjacent to the convergent plate boundary west of Vancouver Island. Finally, Adams (ms.) of Reilinger and Adams (1982) concludes that contemporary landward tilting and shortening of the western continental margin in the Pacific Northwest provides no definitive evidence for either ongoing aseismic or seismic subduction.

The problems in using uplifted coastal terraces above subducting plates as an indication of the aseismic or seismic nature of the subduction process are exemplified by the southern coast of Shikoku Island, Japan, north of the Nankai Trough. There, late Quaternary uplift and landward tilting of coastal terraces has occured above a seismogenic subduction zone that is responsible for great earthquakes in 1854 and 1946. Although the coastline experienced pre-seismic ("interseismic" according to the terminology of Thatcher, 1984) trenchward tilting between the two earthquakes, the cumulative strain pattern based on elevated shorelines indicates a relatively constant rate of maximum uplift of about 2 mm/yr over periods since 6,000, ca. 120,000, and ca. 180,000 years before present (Thatcher, op. cit.). This rate and the duration of late Quaternary uplift (ca. 300,000 years) are comparable to those reported for the Oregon and Washington coastlines (see above)

However, it is worth reemphasizing that while the southern Shikoku coast exhibits preseismic (interseismic) trenchward tilting in those areas nearest the trench, this geometry of strain has not occurred along the Washington and

Oregon coasts during the past 70 years (Ando and Balazs, 1979). If the Juan de Fuca/North American plate interface is currently in a pre-seismic (interseismic) locked state, why is seaward tilting of the Washington-Oregon coastline not observed? This question seems particularly appropriate in light of several factors, all originally pointed out by Ando and Balazs: (1) the close similarity in dip (ca. 10^o) of the subducting Juan de Fuca and Philippine Sea plates (Figure 5); (2) the relative youthfulness of oceanic lithosphere being consumed at the two subduction zones and the relatively slow rates of consumption (see later discussion); (3) the nearly identical distances (ca. 135-140 km) between the Washington coast (at Grays Harbor) and Shikoku (at Muroto; Thatcher, 1984) coastlines to their respective "trenches"; and (4) the significantly longer period of historic interplate seismic quiescence (at least 150 years) in the Pacific Northwest. Suggestions that seaward tilting of the Washington and Oregon continental margin is not observed simply because its coastline is too far from the offshore "trench" seem invalid in light of the above comparisons.

A geodimeter survey in the Puget Sound basin conducted between 1972 and 1979 by the U. S. Geological Survey was interpreted by Savage and others (1981) as indicating crustal shortening at a rate of about .13 microstrain/yr in approximately a N 71^o E direction, with extension at about half that rate in an orthogonal direction. These strain measurements were interpreted by Savage et al. (op. cit.) to be consistent with "preseismic" strain buildup due to a locked interface and oblique convergence of the Nortn American and Juan de Fuca plates. Their results have been widely cited and used by other investigators as a fundamental piece of quantitative data. Crosson (ms.) has pointed out that the USGS strain data has a significant component of non-linear time behavior that suggests that there was areal dilatation until 1975, followed by contraction on all lines measured on the western side of the Puget basin. This time dependent behavior indicates a significantly more complex character in the strain field than previously recognized, and tends to invalidate, or at the very least complicate the simple picture of uniform accumulation of compressional strain resulting from a locked zone. The observation of significant positive areal dilatation prior to 1975, presented by Savage et al. (their Figure 5), is in fact difficult to reconcile with any notions of subduction driven strains. Until more high quality strain measurements are made over a much longer time interval and over a much wider geographic area relative to the Juan de Fuca-North American plate interface, we believe that extreme caution should be exercised in the use of their interpretation.

Melosh (1983) has interpreted both the USGS geodetic data near Seattle and the leveling data of Ando and Balazs (1979) for western Washington. Using techniques of finite element analysis he concludes that the two sets of strain data, if correct, are best but not perfectly reconciled with a model in which the western shallow-dipping interface between the Juan de Fuca and North American plates is now locked (and has perhaps been so for hundreds of years). He concludes, however, that the two plates are mechanically decoupled from each other in the area of a downward bend in the plate interface that lies more-or-less beneath the USGS geodimeter grid in Puget Sound. A careful look at Figures 11 and 12 of Melosh's report reveals, however, that the patterns of both uplift and strain for this model are extremely complex, as acknowledged by Melosh, and neither observed strain nor observed uplift data confirm this model in any detail. In fact, the regional pattern of landward tilting reported by Ando and Balazs (1979) as well as other investigators is not predicted by Melosh's model. His model, for example, predicts seaward tilting at the coastline which is not observed. However, Melosh starts from the basic premise that the secular strain variation interpreted by Savage and others (1981) is correct, and as noted above, this basic starting point may be open to question. Furthermore, even if this initial premise is correct, Melosh assumes in his analysis that the plate interface dips at a constant angle of 17^{0} eastward beneath the Cascade Range, whereas we have seen from geometrical constraints that the initial angle of dip must be closer to 8.5^{0}, steepening gradually to perhaps 40^{0} beneath the Cascades as illustrated in Figure 1. This geometric complexity would likely change the results of his modeling calculations. Finally, Melosh's analysis is only two-dimensional and cannot account for possible three-dimensional complexities which most likely exist in the strain field.

Arguments from Earthquake Focal Mechanism Studies

The geodimeter data of Savage and others (1981) suggesting ENE subduction-related compression of the crust in the Seattle area (and NE compression in the Hanford area east of the Cascades) are not easily reconciled with stress orientation data obtained from fault plane solutions of upper-plate (North America) earthquakes in the Pacific Northwest (cf. Crosson, 1972; Davis, 1977, Figure 2R C-6; Rogers, 1979; Crosson, 1983; Yelin and Crosson, 1982; WNP-3 FSAR, 1982, Figure 2.5-29; Yelin, 1983). Such solutions characteristically indicate an approximately north-south orientation for the focal mechanism determined P tectonic axis, which is widely believed to approximate the orientation of the true principal compressive tectonic stress axis.

Yelin (1983) has proposed that the Seattle area focal mechanism data may indicate partial plate coupling, but not enough to modify seismogenic stresses produced by other modes of plate interaction (see paragraph below). This suggestion, unfortunately, does not lead to a testable hypothesis. Alternatively, Sbar (1983) proposes that strains released by earthquakes develop over significantly longer periods of time than the geodimeter surveys of Savage and others, and are probably more reliable for tectonic studies than strain measurements taken from geodetic surveys of only a few years duration. The latter, he believes, may record short-term strain fluctuations that are averaged out during longer periods of pre-seismic strain accumulation. There are strong theoretical reasons based on the work of McKenzie (1969) to utilize only thrust or normal focal mechanism solutions when attempting to determine the true azimuths of P or T axes from earthquake data. Some preliminary analysis (Crosson) indicates that when this principle is applied to the Puget Sound data, an even more consistent picture of NS compression is obtained than when all mechanisms are included. In particular, it is not justified to utilize strike-slip events on presumed pre-existing fault planes to infer the P axis direction since for these events, if the true tectonic P axis is nearly horizontal, it may lie anywhere within a 90° quadrant. More fundamental research is clearly needed to fully explore the implications of McKenzie's work.

It can be argued that north-south compression in portions of the North American plate east of the Cascadia subduction zone indicates a lack of coupling between that plate and the underlying Juan de Fuca plate with its N 50° E direction of relative convergence. A number of workers (among them Crosson, 1972; Davis, 1977; Sbar, 1982) have proposed that the north-south compressional field in the Pacific Northwest is a direct expression of transform motion between the Pacific and North American plates, despite the presence between them of the small, hot Juan de Fuca plate in the offshore area. This general line of reasoning may favor weak coupling and hence aseismic subduction of the Juan de Fuca plate, but there are several subsidiary questions that complicate the picture.

There is an unfortunate absence of upper plate focal mechanism solutions in the Oregon and Washington Coast Ranges above the shallow - dipping segment of the subducted plate (one north-south compressional mechanism is known from an onshore coastal earthquake west of Salem, Oregon; Dehlinger and others, 1970). Most fault plane solutions come from the Vancouver Island, Puget Sound, and Columbia Plateau regions, with only scattered solutions from the Cascade Mountains. Hence, the state of crustal strain, and by extrapolation the upper plate stress field, is very poorly defined for critical coastal areas in Washington and Oregon where the question of a locked or aseismically slipping plate interface is of greatest interest.

An apparent contradiction to the ubiquitous NS compression observed from upper plate focal mechanism solutions in the Pacific Northwest is the recent recognition of a 90 km-long, N 15^{o} W trending crustal earthquake zone in southwestern Washington named the St. Helens seismic zone by Weaver and Smith (1983). Focal mechanism solutions for earthquakes in the zone, including the M = 5.5 Elk Lake earthquake (2/81), indicate right-slip along a plane oriented practically NS, corresponding to a P axis which is oriented NE. Weaver and Smith view this difference with the Puget Sound region as significant and interpret the northeast-trending P axes as indicating a locked Juan de Fuca - North America plate interface southwest of the St. Helens seismic zone, although not necessarily extending as far to the west as the Coast Range. The St. Helens zone itself is hypothesized to separate a western, locked plate interface from a sliding interface to the east. In their interpretation, right slip along the zone would be compatible with intraplate strain due to oblique (N 50^{o} E) subduction of the Juan de Fuca plate beneath western Washington -- assuming some degree of interplate coupling. Weaver and Smith suggest on the basis of their focal mechanism data alone, that the St. Helens zone is a manifestation of a previously unrecognized stress regime in the Pacific Northwest. For reasons stated previously, we question their assertion that they are observing a fundamentally different stress regime in the St. Helens region. If the St. Helens zone is reactivation of older faults (possibly many faults rather than a single fault), then the analysis of McKenzie (1969) tells us that the true P axis azimuth may lie virtually anywhere in the dilatational quadrants of the mechanisms presented by Weaver and Smith. Thus the true P axis could range from slightly west of north to about N 80^{o} E, possibly entirely consistent with the observations made elsewhere in the Pacific Northwest. While we cannot rule out the model presented by Weaver and Smith, a simpler model of uniform tectonic stress in the overlying plate is also consistent with their observations.

Although it is intuitively appealing to assume that the upper plate tectonic stress field should directly reflect subduction kinematics if the plates are strongly coupled, with the direction of convergence coinciding with the P tectonic axis, the actual situation is probably much more complex. Savage et al. (1981), for example, have shown that due to oblique convergence and the geometry of the North American plate margin, the theoretically predicted P axis direction resulting from the N 50^{o} E convergence direction of the Juan de Fuca and North American plates is actually N 70^{o} E; i.e., there is a tendency for the principal compressive stress axis to be rotated more orthogonally to the plate margin relative to the oblique convergence direction. Thus the actual discrepancy between the focal mechanism data (from Puget Sound) and the convergence generated stress in the case of a locked zone is 70^{o} rather than the expected 50^{o}. This same effect, although of different magnitude, should be observed at other zones where oblique subduction occurs as well. Despite the fact that there is relatively little high quality data in the literature comparing focal mechanism determined stresses in the overlying plate with the stresses expected from seismogenic subduction (the Puget Sound data may be the best available) cases of both agreement and disagreement can be found. Nakamura and Uyeda (1980) have studied the stress trajectories in overriding plates at subduction zones using data such as dike swarms, focal mechanisms, volcanic rift zones, and faults. They conclude (p. 6427) "In the front zone of convergence, compressional stress prevails usually, but its strength varies greatly depending on several factors, including the age of the oceanic plate, properties of the plate interface, absolute motions of the overriding plate, and the position of the trench. Because of the nonrigidity of the upper plate, the compressional stress is not directly transmitted far into the plate, and sigma h_{max} decreases landward. When sigma h_{max} becomes smaller than sigma v (vertical stress), it changes from sigma_1 to sigma_2." In New Zealand, Reyners (1980) found a great deal of consistency between the P axis determinations from micro-earthquake analysis and the current direction of coupled underthrusting. Results of a study by Chinn and Isacks (1983) for the Peru Chile region also show essential agreement between the convergence directions and the P axis determinations from focal mechanisms.

On the other hand, the subduction of the Philippine Sea plate beneath the Eurasian plate of southwestern Japan (Shikoku and Honshu) provides interesting (and conflicting) data that bear on this topic. As mentioned in the preceding section, great thrust-type earthquakes are generated along this plate interface -- a behavior compatible with recurrent preseismic (or interseismic) coupling between the two plates. Nakamura and Uyeda (1980, p. 6420, Fig. 6) state that in the upper plate the "general trend of the sigma H_{max} direction is coincident with that of plate convergence (N 50 W)...." The direction of plate convergence was determined largely from seismic slip vectors for low-angle thrust events, including those of the great Tonankai (1944) and Nankaido (1946) earthquakes along the plate interface. Ukawa (1982) disagrees with their concusion about the parallelism of plate convergence and the direction of sigma h_{max} in the upper plate. Relying on a large number (greater than 50) of P-axis determinations from upper crustal eartnquakes (generally less than 20 km deep), he concludes that compressional stress trajectories in the upper, Eurasian plate are nearly east-west beneath eastern Shikoku Island and adjacent parts of Honshu. They are thus (p. 550) "significantly deviated ... from the moving direction of the Philippine Sea plate relative to the Eurasian plate." He attributes the east-west compression to the direction of convergence between the Eurasian and <u>Pacific</u> plates, not to Eurasian-Philippine Sea plate convergence. If Ukawa's analysis is correct, a N-S orientation for the principal axis of compressive stress in the Pacific Northwest versus the NE-SW direction of Juan de Fuca/North American plate convergence cannot be relied upon to indicate a lack of coupling along the plate interface (since the Eurasian/Philippine Sea interface is clearly coupled to a significant degree). The discrepancy which appears to exist for the Puget Sound situation between the P axis orientation interpreted from earthquakes and that predicted from a locked subducting interface is substantially larger than the difference reported by Ukawa in southwest Japan.

We have looked carefully at Ukawa's data in an attempt to ascertain the quality of the data upon which his conclusions depend. He presents detailed focal mechanisms, including polarity plots, for 42 crustal (upper plate) earthquakes. Of these only 12 have thrust mechanisms which are reasonably well constrained. Most of his mechanisms are strike slip, (reported also by Shiono, 1977), and if they represent rupture on preexisting faults they may not be representative of the present stress field. This suspicion is strengthened by the independent results of Nakamura and Uyeda (1980) in which they discovered evidence for nearly EW P axis directions in the same region based on geological evidence (faulting, and dikes), indicating that patterns of present faulting may be controlled by geologically old structures. The angular dispersion of Ukawa's complete data set is approximately 90°, a spread which encompasses both the Pacific-Eurasian and the Philippine-Eurasian convergence directions (Ukawa's Figure 8). With only a 35° difference between the two convergence directions, the ability of Ukawa's data in any case to resolve this difference is open to question. An even more important difference exists between the Pacific Northwest and Southwest Japan when considering focal mechanisms -- that of the large earthquake seismicity. Shiono (1977) has analyzed 56 earthquakes of magnitude 6 and greater which have occurred since 1920 due to interaction of the Philippine and Eurasian plates. He found that those along the Nankai trough were characterized by low-angle thrusting consistent with the subduction of the Philippine plate. In the Pacific Northwest, no such earthquakes have been observed.

Comparisons with other Subduction Zones

Given the uncertainties outlined above from geodetic and seismic data in determining the character of the Juan de Fuca - North American plate interaction, comparisons with other subduction zones have become increasingly important in attempts to assess the aseismic vs. "seismic gap" nature of the Cascadia subduction zone. Such comparisons seem to be in the minds of NRC and USGS reviewers of the WNP-3 project, as evidenced by the following Seismology Review Questions 230.1 a, b, and c:

The work by Ruff and Kanamori (1980) and others appears to support the view that the subduction of the Juan de Fuca plate creates a potential for large magnitude earthquakes in the subduction zone beneath WNP-3. In addition:

a) Kanamori (1983) has published an equation relating the age of the subducting plate, convergence velocity, and the largest expected magnitude event. Does this equation apply to the Juan de Fuca plate and if not, why not? Alternatively are there other convincing models that allow the estimation of the magnitude of subduction zone earthquakes under the site to values lower than would be predicted by the Kanamori (1983) relationship?

b) Are there specific examples of aseismic subduction zones which share the following features with the Juan de Fuca subduction zone: young subducted lithosphere, low convergence rate, shallow oceanic trench, low free-air gravity anomaly, small variation in surface topography of the subducted plate and, particularly complete seismic quiescense down to the magnitude 5 level?

c) Crustal uplift rates of approximately 2 mm/yr were observed in the region from 120 to 220 km inland of the Nankai Trough for the 50 years preceding the 1944, M = 8 Tonankai and 1946, M = 8.2 Nankaido earthquake. Why shouldn't the crustal uplift and NE compressive strain reported by Savage (1981) for western Washington be considered consistent with a similar pre-seismic deformation? How is the Juan de Fuca subduction zone any different from the subduction zone in the Nankai Trough and the subduction zone associated with the Rivera plate?

The Ruff and Kanamori reference cited in the Review Question proposes that a correlation exists on a worldwide basis between the maximum seismicity (M) of convergent zones and two principle variables, the age of the subducting oceanic lithosphere and the rate of plate convergence. According to their analysis, increased seismic coupling (and hence, larger resultant seismic events) occurs along zones where ocean lithosphere is young (hot and buoyant) and convergence rates are high. Heaton and Kanamori (1984) conclude that Ruff and Kanamori's global analysis for maximum earthquake magnitude (M_w) along subduction zones is "well fit by the following relationship

$$M_w = -0.00889T + 0.134V + 7.96$$

where T is the age of the subducting plate in millions of years, V is the convergent rate in cm/yr, and the standard deviation of the observed M_w around the predicted value is 0.4".

Inserting values appropriate to the Juan de Fuca plate (T = 10 - 15 m.y., their estimate,[1] and V = 3-4 cm/yr), this equation predicts a future great earthquake along the Cascadia subduction zone with a maximum moment magnitude of 8.3 $\pm$ 0.5. Their plot of worldwide T vs. V relations is presented as Figure 3. The strong coupling between the Juan de Fuca and North American plates represented by a magnitude 8.3 earthquake is supported, they believe, by additional relations: the shallow ($10-15^0$) dip of the subducting plate east of this "trench", the "relatively subtle" topographic development of the trench, the topographic smoothness of the Juan de Fuca plate (a "featureless plain"), and, quite importantly to them, the absence of an active back-arc basin in the Pacific Northwest. They further conclude that "if slip is occurring aseismically on the shallow part of the subduction zone, then this particular example would have to be considered unique." Heaton (1984) believes the the Cascadia subduction zone resembles most closely in trench bathymetry, seismic quiescence, and age of subducted plate the Nankai Trough of southern Japan, the southern Chile trench, and perhaps, northern New Zealand and parts of Mexico.

Kanamori and Astiz (in press) have addressed the problem of whether Ruff and Kanamori's empirical relation between T, V, and M_w is valid for the Juan de Fuca subduction zone, given the youthfulness of the subducting plate and the slow rate of convergence. Essentially, they conclude that it is, drawing upon a large (M_s=7.7) earthquake that occured in 1983, along the western coast of northern Honshu near its crustal boundary with the Sea of Japan. They

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[1] Analysis of magnetic anomalies of the Juan de Fuca plate (e.g., Atwater, 1970) and the results of DSDP drilling (e.g., von Huene and Kulm, 1973) indicate that the oldest unsubducted oceanic lithosphere in the plate is only 8 to 10 million years old.

interpret this event, the Akita-Oki (or Nihonkai Chuba) earthquake as the consequence of the subduction of young (T = ca. 15 m.y.) oceanic crust eastward beneath Honshu at a rate (V) of only 1.1 cm/yr. Using these T and V parameters the Ruff and Kanamori equation predicts a M_w = 8.0 event versus the M_w = 7.8 actually determined. Thus, Kanamori and Astiz conclude that the "good agreement between the predicted and observed magnitudes suggests that the empirical relation is valid for subduction zones with very small T and V such as the Juan de Fuca subduction zone." They further conclude that a M_w = 8.4 earthquake predicted by Heaton and Kanamori (1984) for the Juan de Fuca subduction zone would, on the basis of other empirical relations and several assumptions, have "a repeat time of 126 years if the slip at the plate boundary is completely seismic; if only 30% of the plate motion is taken up by seismic slip, it is 420 years."

As acknowledged by Kanamori and Astiz, there are two potential problems with their analysis of the Akita-Oki earthquake and its implications for the Juan de Fuca subduction zone: (1) the 1.1 cm/yr rate of convergence is speculative because it is based on a plate model that is controversial and not accepted by all Japanese tectonicists -- specifically that the earthquake represents subduction of the Eurasian plate (Japan Sea and southwestern Honshu) beneath the North American plate (northern Honshu); if this plate interpretation is not correct, the rate of convergence between northern Honshu and the Sea of Japan is not known; (2) there is some uncertainty as to which of two possible fault planes derived from a well constrained focal mechanism solution should be selected; one plane which dips 30° E is compatible with the subduction model; the other plane, which dips 60° W, is not. A much more serious objection, however, is the fact that there is no well-developed subduction boundary dipping eastward beneath the island of Honshu. All of the data on which Ruff and Kanamori (1980) base their relations among age of lithosphere, convergence rate, and earthquake size are derived from zones with well developed subduction boundaries. Convergence certainly exists near western Japan based on the occurrence of several large thrust events (1940 Hokkaido, 1964 Niigata, 1983 Akita-Oki). There is, however, no documentation of a well developed east-dipping subduction zone or lithospheric slab beneath the island of Honshu. In fact, some good evidence suggests that west-dipping thrust planes should be chosen for these events rather than east-dipping planes (i.e., western Honshu may be thrusting beneath the Japan sea rather than vice versa). The 1964 Niigata earthquake occurred between the island of Awashima and the west coast of Japan about 200 km south of the Akita-Oki earthquake. The island can be seen in Figure 1 of Kanamori and Astiz (1984) and the earthquake occurred almost exactly on the thrust boundary indicated in that figure. Nakamura, et. al. (1965) studied ground deformation associated with the 1964 earthquake. They found uplift of coastal terraces along the east coast of the island combined with westward tilting. These crustal movements are consistent with a steeper west-dipping fault plane and inconsistent with a shallow east-dipping plane.

Woodward-Clyde Consultants (1984) have prepared a comprehensive and detailed comparison of the Cascadia (Juan de Fuca) subduction zone with 28 other zones or segments in the Pacific, Indian, and Atlantic oceans. Comparisons are made for 29 geologic, seismologic, geophysical, and kinematic characteristics of subduction zones. Using these data the report attempts to assess the seismic potential of the Cascadia (Juan de Fuca) subduction zone. Special attention is paid to primary (T, V) and secondary parameters considered by Kanamori and his colleagues (Ruff and Heaton) to indicate strong coupling of convergent plate interfaces, including that between the Juan de Fuca and North American plates. The WCC analysis provides a wealth of data and ideas regarding what is known and what is not known about the subduction process. No attempt will be made here to review this analysis, although specific aspects of it are discussed below. The conclusion of their report is, however, worth stating here (WCC, 1984, p. 19):

> "The comparative analysis shows that there is great uncertainty regarding both the details of the subduction process in the Pacific Northwest and the seismic potential of the Juan de Fuca subduction zone. The relationship between specific subduction zone parameters and seismic potential is often not definitive and comparisons between the Juan de Fuca and other zones can be used to support alternative models. At present, the classification of the Juan de Fuca plate as strongly or weakly coupled is indeterminate. The most direct evidence, which is the historical seismicity data, strongly suggests that the zone has a low seismic potential."

Arguments From The Concept of Seismic Gap

The patterns of seismicity, both historic and instrumental, displayed by the Cascadia subduction zone provide arguments against the likelihood of a great thrust earthquake at some future time along it. Among these arguments, each of which is developed more fully below, are the following: 1) the quiescence within a seismic gap which preceeds a great earthquake differs distinctly from the quiescence currently observed along the Cascadia subduction zone; 2) the complete absence of a historic record of great earthquakes at any point along the entire Cascadia subduction zone differs from other subduction zones where at least one great earthquake has occurred at some point along the zone in historic time; 3) great thrust earthquakes are accompanied and preceded by thrust earthquakes of moderate size ($5 < M < 7$); the complete absence of even a single thrust earthquake of moderate size at any point along the entire Cascadia zone argues that any underthrusting which takes place along this zone does not occur seismically or by brittle failure; and 4) aseismic convergence is not a phenomenon unique to the Cascadia zone.

1) Seismic gaps preceding great earthquakes were identified precisely because the quiescence within the pending rupture zone contrasted sharply to the abundance of activity in adjoining areas of the larger zone. Every seismic

gap selected by either Fedotov (1965), Mogi (1968) or Kelleher et al (1973) was selected not because of quiescence alone, but rather because there existed a zone of quiescence within a larger zone of activity. Thus an essential feature of seismic gaps used to identify future earthquake locations has been the strong patterns of seismic activity along other segments of the same seismic zone. These statements apply to both subduction and strike-slip boundaries.

As an example, there exists at the present time a virtual absence of any seismicity along the "big bend" region of the San Andreas fault, northwest of Los Angeles, which last ruptured in 1857. In fact, seismicity is so low that deployment of sensitive portable instruments would probably fail to even detect or identify the location of the active San Andreas Fault. Nonetheless, when viewed in a larger scale of the total seismic zone extending from the Gulf of California to Cape Mendocino it is obvious that this probable seismic gap is in fact defined by the abundance of activity in adjoining areas.

Figure 4 displays epicenters reported from both the USGS in central-northern California (CALNET) and the Caltech network of southern California from 1971 to 1981. Notice the obvious gaps in activity along those segments of the San Andreas that ruptured in 1857 and 1906. Notice, however, the strong seismic activity along other segments of this same seismic zone. Our interpretation is that tectonic loading of a 300 km fault segment to the point of failure requires some seismic indication of stress accumulation in adjoining areas. Furthermore, these seismic indications (i.e., moderate size earthquakes) are a response to the same tectonic stress field as the great shock and thus should display a similar type of focal mechanism. Thus, while there is no question that quiescence may extend to extremely low levels in a seismic gap that precedes a great earthquake, there is also no question that seismic gaps have consistently been characterized by moderate or heavy activity in adjoining areas. To argue otherwise is to argue for a unique and abrupt discontinuity in rock properties that exists on a regional scale.

2) The Cascadia subduction zone has sufficient length (about 750-800 km) to generate perhaps 4 great thrust earthquakes, each with a rupture length of about 200 km. Yet there exists no historic record of a great earthquake at any point along the thrust boundary. By contrast if any seismically active subduction zone is examined for the past 150 years, there exists a record of at least one great earthquake at some point along the boundary. Thus while a single seismic gap may persist for 150 years or longer (i.e., the approximate extent of the historic record of the Cascadia zone) the global seismic record indicates that all segments along an active subduction boundary would not remain quiescent simultaneously for a similar period.

Neither is it reasonable to argue that the entire Juan de Fuca boundary will rupture during a single extraordinary earthquake. The greatest thrust earthquakes along various plate boundaries (e.g., 1960 Chile, 1964 Alaska, 1707 Southwest Japan, 1932 Western Mexico) have a maximum dimension of no more than about 15% of the maximum plate dimension. There is no record whatever of a single rupture along an entire plate boundary or even along any large fraction (e.g., 40-50%) of a single plate boundary.

3) Great thrust earthquakes do not occur in total isolation from lessor thrust events. Even though the actual zone of a pending rupture may be quiet, it is common to find thrust-type events of moderate size in adjoining areas or in other locations along the subduction zone. By contrast there is no record of even a single thrust event in the range $5 < M < 7$ anywhere along the entire Cascadia subduction zone. During the past several decades by comparison, there is little difficulty finding thrust-type events of moderate size somewhere along any boundary which has experienced an historic great thrust earthquake.

4) Aseismic convergence is not a unique phenomena and many examples can be cited. The causes of aseismic convergence are arguable and probably varied. The convergence zone, for example, between the South American - Antarctic

Plates (i.e., Chile about 46^{o}S to 51^{o}S) shows striking similarities with the Cascadia zone including low convergence rate (2-3 cm/yr, Minster and Jordan, 1978) subducting lithosphere much of it less than 10 my (Herron, et al, 1977; Herron, et al, 1981) an absence of great historic earthquakes (Lomnitz, 1970; Kelleher, 1972), an absence of known thrust-type focal mechanisms (Forsyth, 1975) and a virtual absence of seismicity anywhere along the boundary (Forsyth, 1975). Major differences are that both the South American and Antarctic plates are far larger than the Juan de Fuca plate, and lack an adjacent volcanic arc.

COMPARISON OF THE CASCADIA AND NANKAI TROUGH SUBDUCTION ZONES

Heaton and Kanamori (1984) believe that the Cascadia (Juan de Fuca) subduction zone shares many features in common with seismically active zones that produce great earthquakes (magnitudes greater than 8). In terms of T and V parameters, which they believe most control maximum seismic energy release, the Juan de Fuca and Nankai Trough (S.W. Japan) subduction zones appear to be most similar to each other (Figure 3). Thus the occurrence of the M=8 Tonankai (1944) and M=8.2 Nankaido (1946) thrust-type earthquakes along the latter zone are called upon to support the case that the Juan de Fuca zone is currently in a state of pre-seismic quiescence (as was experienced before the 1944 and 1946 Japanese events). As an aside, the repeat time for major earthquakes in the Nankai-Shikoku area is approximately 120 years (Kanamori, 1977).

It is our opinion that the Heaton and Kanamori comparison of the Nankai and Juan de Fuca subduction zones relies too much on inferred similarities in age of subducted crust which in fact may differ by a factor of two or more (ca. 15-17 m.y., Kobayashi, 1984, and c.a. 8-10 m.y., respectively) and velocity of convergence (both said to be 3-4 cm/yr)[2], and neglects other important differences. Differences in age of subducting crust, possible differences in rate of subduction, and differences in geological parameters discussed below may well account for the absence of seismicity along the Juan de Fuca-North American plate interface and strengthen the case for aseismic slip between the two plates. Among the significant differences not treated by Heaton and Kanamori are: (1) the configurations of the two subducting plates and the presence (Cascade Range) versus the absence (S.W. Honshu) of subduction-related arc volcanism; (2) the sediment-flooded Cascadia "trench" versus the sediment-starved Nankai Trough.

Configuration of the Subducted Juan de Fuca and Philippine Plates Beneath Western North American and Southwestern Honshu

As previously discussed, the subducted Juan de Fuca plate apparently dips gently (ca. 10°) beneath the Washington continental margin for a distance of approximately 250 km and to a depth of 30 to 35 km before plunging at a steeper angle (up to 40°) beneath the Quaternary Cascade volcanic chain (Figs. 1, 5A, 5C). No volcanic chain lies above the Nankai subduction zone on the island of Honshu. Kanamori (1972) explained this relation by concluding that subduction of the eastern Philippines plate (Shikoku Basin) beneath Honshu was a very youthful event and that the downgoing plate has not yet reached levels deeper than 60 km (the lower limit of seismicity). Sachs (1983), however, in reporting the work of others (especially Hirahara, 1981),

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[2] The rate of Eurasian-Philippine Sea plate convergence is not well constrained because the Philippine Sea plate is bounded by two convergent boundaries and lacks an internal connection to the world rift system. The 3.5 cm/yr rate is a seismic slip rate derived from historic seismicity along the Nankai Trough, but Kanamori (1977) acknowledges that the convergence rate (seismic plus aseismic slip) could conceivably be as high as 9 cm/yr. Kanamori and Astiz (in press) calculate that the ratio of seismic slip to total plate motion is 0.88 for the Nankai Trough, but admit that determination of this ratio is "very uncertain".

states that the top of the subducted plate appears to dip downward to a depth of about 60 km below the island of Shikoku (ca. 175 km from the trench), but then flattens horizontally beneath Honshu for an additional 280 km (Figs. 5A, 5B). Thus the two lithospheric plates (continental and subducted oceanic) remain in contact, without an intervening asthenospheric wedge, for perhaps as much as 450 km. Not only would this geometry account for the absence of an active volcanic chain in southern Honshu, but it would help explain the coupling represented by the periodic seismic history of the plate interface at depths above 60 km. Thus, a physical basis for a possible difference in coupling between the two pairs of plates (Japanese and Pacific Northwest) is available that goes beyond similarities in convergence rate and age of subducted crust.

Sedimentation in the Juan de Fuca and Nankai "Trench" Areas

Heaton (1984) has stated that the trench bathymetry of the Juan de Fuca-North American plate boundary compares closely with the Nankai Trough. Figures 6 (Honshu) and 7 (Pacific Northwest) clearly indicate that there is no basis for such a statement, nor can even a "relatively subtle" (Heaton and Kanamori, 1984) oceanic trench be detected off the coast of the Pacific Northwest. The closed depression of the Nankai Trough (depths below 4400 m or 2400 fathoms) is clearly defined on Figure 6, whereas no topographic depression is present at the base of the Oregon and Washington continental slope (Fig. 7). The base of this slope lies only half as deep (2300 m or 1200-1300 fathoms) as the closed portion of the Nankai Trough.

The reasons for these pronounced topographic differences are due primarily to differences in late Cenozoic sedimentational history along the two convergent zones. The main Nankai Trough is described by Ludwig and others (1973) as a depressed section of oceanic crust conformably overlain by a densely stratified, northwestward-thickening wedge of sediments. According to these authors (p. 2514) the "addition of turbidites has increased the total sediment thickness in comparison with that in the adjacent (Shikoku) basin and has produced a narrow zone in which the sea floor is notably flatter than in the rest of the trough." On the basis of a seismic refraction profile Yoshii and others (1973, Table 1, their Fig. 1) provide an estimate for total sediment thickness in the main Nankai trough of approximately 0.76-0.86 km. Terrigenous sedimentation appears not to be going on at present within the trough. The floor of the sediment-containing trough now dips slightly towards the base of the continental slope where the sediments become abruptly uplifted and deformed. It is reported (Ludwig and others, 1973, p. 2515) that continental slope ridges, presumably composed of deformed and accreted older sedimentary rocks, "act as a dam that traps sediments transported by the many rivers draining Japan ... and hence prevent the sediments from reaching and filling the main Nankai trough."

In marked contrast to the sediment-starved Nankai Trough are the impressively large sediment accumulations of the Astoria and Nitinat deep-sea fans across much of the floor of the Cascadia Basin (Fig. 7). Sediment thickness including fan deposits at the base of the continental slope ranges up to 2.5-2.8 km (Kulm, 1983). Even though Barnard (1978) estimates Pleistocene rates of sedimentation within lower slope basins of 0.5 to 1 m/1000 years, he reports that two-thirds of the total sediment derived from upper slope canyons during the Pleistocene were routed by turbidity currents into the deep-sea fans of Cascadia Basin. Scholl and Marlow (1974) estimate that the total volume of these basinal turbidites is approximately 140,000 km^3 and that all were deposited within just the past 1.0 m.y. As described by Kulm (1983) the head of the Nitinat fan along the base of the Washington continental slope is now being deformed by plate convergence, but it seems evident that extremely high rates of Quaternary sedimentation at least temporarily exceeded the rate of convergent tectonic processes and led to the filling and burial of any trench that may have existed prior to one million years ago.

Jacob and others (1977) were among the first to suggest that thick sedimentary accumulations in trenches may impede, perhaps even abort, the subduction process. Either might be accomplished by: (1) adding low density material to the downgoing slab, thus making it more buoyant; and/or (2) by covering young and relatively warm oceanic lithosphere in some trench areas and slowing its cooling before it enters the subduction zone. The second process has been described by Kulm (1983) as occuring along the Cascadia subduction zone. Reasons why sediment burial of warm oceanic lithosphere might facilitate aseismic subduction (rather than impede subduction as suggested by Jacob and others) are developed below.

THE "UNIQUENESS" OF THE CASCADIA SUBDUCTION ZONE AND THE CASE FOR ASEISMIC SUBDUCTION ALONG IT

Heaton and Kanamori (1984) have stated that "the best examples of seismically quiescent plate boundaries are ones that have experienced great earthquakes but that could be considered as otherwise locked." If the Juan de Fuca plate is being subducted aseismically then, they argue, the Juan de Fuca subduction zone would have to be considered "unique". Philosophically speaking, there is nothing inherently wrong with uniqueness in nature. Practically speaking, there are indeed reasons to consider the Juan de Fuca subduction zone as unusual, if not "unique" -- apart from its remarkable history of seismic quiescence.[3] Four factors <u>combine</u> to set the Cascadia zone apart:

(1) the extreme youthfulness (ca. 8-10 m.y.) of the oceanic plate being subducted; none of the 21 subduction zones studied by Ruff and Kanamori (1980) have younger lithosphere descending along them;

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[3] Strictly speaking, the zone appears to have a close counterpart. As discussed above, it shares a number of similarities with the aseismic convergent zone between the South American and Antarctic plates (ca. 46° - 51°S).

(2) the relatively slow (3.5 cm/yr) convergent rate; only 3 of the 21 subduction zones (Ruff and Kanamori, 1980) have slower rates;

(3) the existence of an active adjacent volcanic arc; such arcs are absent inland from the youthful (ca. 14 m.y.) subducting lithosphere at the south end of the Chile trench between 43^{0} and 46^{0} S latitude, and the youthful (15-17 m.y.) subducting lithosphere along the Nankai Trough; and

(4) the presence at this convergent plate boundary of the Pacific rim's most voluminous Quaternary sediment "trench" accumulation (Scholl and Marlow, 1974, Table 1) as measured in volume per length of trench (the total volume of the southern Chile trench between 37^{0} and 56^{0} is 30% greater, i.e. 185,000 km^{3}, but the trench is nearly twice as long); two of the North American continent's greatest rivers (the Columbia and the Fraser) have carried sediment to the subduction site and the volume of that sediment was dramatically increased during the last glacial period ending only about 10,500 years ago (Barnard, 1978).

It can be argued that the combination of factors (1), (2), and (4) -- i.e. the slow subduction of a hot, sediment-flooded plate gives the Cascadia zone its remarkably quiescent behavior. Why should a hot, sediment-laden plate subduct quiescently? Firstly, because sediments above the subducting slab at the buried "trench" will have higher temperatures than "normal" since they are buried up to 2.8 km and rest on a basaltic substratum that according to calculations from heat flow data by McClain (1981) and Blackwell and others (1982) must be at temperatures of 200^{0} C. or more. Such high temperatures, either in the subducting sediments or the basaltic rocks beneath them may lead to low-grade regional metamorphism and deformation by ductile, rather than brittle processes. Subducted Eocene to middle Miocene marine sediments, largely of terrigenous origin, are exposed beneath folded, upended, and accreted Eocene Crescent volcanic rocks on the Olympic Peninsula. The highest (and oldest) sedimentary rocks in this offscraped, accreted assemblage were metamorphically recrystallized and penetratively deformed, presumably during subduction about 29 m.y. ago (Tabor and Cady, 1978). The highest metamorphic grades in the Olympic core are of the prehnite-pumpellyite facies, indicating a temperature range of formation compatible with upper temperature estimates (ca. 280^{0} C) by McClain (1981) for the deepest sediments now being subducted beneath the continental margin.

Not only are sediments of the Cascadia Basin being heated to abnormally high temperatures at the convergent boundary, but they are being impressively dewatered near the slope-basin interface, presumably because of horizontally induced stresses related to plate convergence and deformation at the outer ridge. Kulm (1983) discusses this phenomenon at length. Sediments deformed in the outermost marginal ridges at the base of the continental slope are being mechanically consolidated. Their water content ranges between 17 and 30% (wet weight) compared with 55 to 70% in similar, but undeformed sediments of the Cascadia Basin. Dewatering has two pronounced mechanical effects -- the process must increase fluid pressure in the dewatered sediments and it significantly lowers their shear strengths. Both factors could be expected to contribute to aseismic slip along the plate interface if even a thin layer of such hot, overpressured sediments are subducted.

Langston (1981) presents an interpretation of crustal structure beneath the Oregon continental margin based on analysis of long-period teleseismic P waves (Figure 8). He infers the existence at the plate interface beneath western Oregon of a thick (ca. 10-15? km) low-velocity zone which separates higher, older oceanic crust and upper mantle from younger, subducted oceanic lithosphere, the latter with a depth of 40 km or more beneath Corvallis. Langston postulates (p. 3863-64) that the low velocity zone contains "melange-like materials pervasively sheared near the top and grading downwards to largely undeformed subducting oceanic crust. The higher 'mixing zone' may contain an assortment of rock types including some trench sediments, oceanic crust, and previous oceanic upper mantle." Along the same lines, Crosson (1976) detected the apparent presence of a low velocity zone above the transition to upper mantle velocities beneath the Puget Sound basin. This zone lies at a depth of 30 to 40 km at that locality, coincides with a zone of absence of small earthquake hypocenters, and lies geometrically above the dipping zone of deep hypocenters which defines the Benioff zone in this region. The upper mantle compressional wave velocity (Pn) in this region is about 7.7-7.8 km/sec and appears to reflect the velocity of the upper mantle in a relatively hot, subducted slab. This low velocity zone (Crosson, 1976) fits both geometrically and seismically with a model of a plate boundary consisting of partially metamorphosed and dewatered sediments and volcanics which have been dragged into the subduction zone mechanically and which are deforming plastically (aseismically) in response to the shear stresses at the megathrust. Current work on velocity determination appears to be confirming the reality of this low velocity zone, although this work is still in progress. Due to the lack of data, the presence of the low velocity zone has not been confirmed elsewhere in western Washington. The work of Taber (1983) would not be expected to reveal the presence of a low velocity zone due to his use of first arrivals from surface sources.

Perhaps a similar zone of low-velocity (fluid pressurized?) materials also lies along the top of the subducted Gorda plate (Figure 2). That seismically quiescent interface separates upper and lower plates that seem to be responding to the <u>same</u> stress regime, one responsible for strike slip deformation in a north-south compressive regime. The interface zone, however, although apparently experiencing the same stress regime, does not respond to it in a brittle manner. In yet another example, very high fluid pressures in undeformed sediments being subducted beneath the Barbados Ridge accretionary wedge are credited (Westbrook and Smith, 1983) for permitting decoupling to occur at the base of the thick accretionary prism and between the two plates.

The aseismic nature of accreted wedge materials in forearc settings around the world has been investigated by Chen and others (1982). They report that the accreted wedges (defined as composed of material clearly removed from the subducted plate) of subduction zones deform aseismically. Materials of the forearc marginal wedge can probably not be expected to accumulate significant elastic strains, they conclude, because of their high water content and low strength. Possibly, they suggest (p. 3688) "the mixture of soft, wet sediments which are sheared off from the surface of the subducting slab behave like plastic or viscous materials under compressive stresses."

It is probably not inappropriate to consider most upper-plate rocks of the Oregon and Washington continental margin (including those beneath the Coast Ranges) as constituting a forearc marginal wedge (Figure 5C). A thick portion of this accreted wedge is upturned steeply and exposed to view in the Olympic Mountains. Recent cross-sections drawn through the Oregon and Washington continental margins (Snavely and others, 1980, Figure 9 this paper: Snavely and Wagner, 1982, Figure 10 this paper) imply the existance of comparable, but shallower dipping imbrications of accretionary structures in those areas. Taber and Smith (in press) comment on the general absence of seismicity in accreted core sediments of the Olympic Mountains and ponder if deformation there might not be occuring plastically.

Pavlis and Bruhn (1983) have recently examined thermal and mechanical aspects of the evolution of forearc ridges and the accretionary prisms of off-scraped lower-plate materials that lie between the ridges and their trenches. Their research has particular significance to subduction tectonics in the Pacific Northwest since the Cascadia (Juan de Fuca) zone was one of four zones specifically analyzed in terms of rheological models. In a discussion pertinent to accretionary prisms such as that along the continental margin of Washington and Oregon (Fig. 5C) they state the following (p. 486):

> "The calculated depth to the brittle-ductile transition varies with heat flow from a depth of 20 km for a surface heat flow of 40 mW/m^2 to less than 10 km for heat flow of 60 mW/m^2. Thus we conclude that for the

> range of heat flow <u>normally</u> anticipated in the subduction complex (40-50 mW/m^2), the rocks will transition from brittle to ductile at depths of 15-20 km ...."

They go on to state (p. 492, 494) that if a subduction "system is subjected to anomalously high temperature conditions as the subduction complex grows ... (e.g., if a ridge system encroaches on the trench), the base of the subduction complex will increase in temperature, the viscosity of the ductile region will be reduced, and the brittle to ductile transition may rise to relatively shallow levels (10 km). As a result of this anomalous thermal regime, flow at depth may become a significant factor .... the Cascade arc trench system may be an example of this type ...."

Heat flow data from the Cascadia Basin eastward across the continental margin has been summarized by Blackwell and others (1982) and Kulm (1983). Heat flow values in the sediment-covered portions of the Cascadia Basin range between 100 to 300 mW/m^2; those measured in sedimentary deposits of the lower continental slope range from 40 to 142 mW/m^2 ("a factor 2 to 3 higher than those normally associated with the so-called 'cool' forearch regions of the world"; Kulm, 1983, p. 22). Heat flow determinations from the Washington and Oregon Coast Range province are sparse, but several measurements are only slightly below 40 mW/m^2 (Kulm, 1983, Fig. 6.1; Blackwell, 1974). These limited data suggest, if Pavlis and Bruhn are correct in their interpretations, that a brittle-ductile transition would likely occur below the Washington Coast Ranges at a depth of approximately 20 km. Indeed, most upper-plate seismicity in this area and to the east (Crosson, 1983; Fig. 1) does occur at depths less than 15-20 km. The anomalously high heat flow beneath the lower continental slope would presumably produce a significantly shallower brittle-ductile transition there.

Another possible direct indication of elevated temperatures in the Juan de Fuca plate and its corresponding subducted extension beneath the North

American plate is the low Pn velocity found for western Washington. Pn velocities are presumably low where the lithosphere is forming near spreading ridge systems due to the high temperatures. As the lithosphere cools, shrinks and becomes more rigid, Pn velocities should increase to maximum values in excess of 8.0 km/sec. The value of 7.7 to 7.8 km/sec found beneath the Puget Sound basin by McCollom and Crosson (1975) has since been confirmed by Crosson (1976) and is being refined in a current study. Taber found that 7.9 km/sec near the coastline south of the Olympic Mountains was consistent with his travel time modeling. The only measurements that do not fit the general picture of low Pn velocity (hence hot subducted lithosphere) in the Juan de Fuca plate are those of Shor and others (1968) who found low Pn velocities from the spreading ridge across the Cascadia Basin (7.7 - 7.9 km/sec) but apparently encountered values as high as 8.1 km/sec beneath the continental shelf. Values this high have not however been confirmed by later investigators (e.g., McClain, 1981) and since Shor and others encountered apparently rapidly thickening crust beneath the continental shelf, structural effects may have distorted their interpretation.

It is possible in light of the studies by Chen and others (1982) and Pavlis and Bruhn (1983) that the aseismic behavior postulated by some for the Juan de Fuca-North American plate interface might justifiably be extended to major portions of the accreted upper plate of westernmost North America in the Pacific Northwest. If the special (accreted) character of the leading edge of the upper plate is considered, then the "unique" (aseismic?) behavior of the plate boundary at its base may seem less inexplicable.

SEGMENTATION OF THE JUAN DE FUCA PLATE
BENEATH THE PACIFIC NORTHWEST?

Until recently it has been generally assumed that oceanic lithosphere of the Juan de Fuca plate is being (or has been) subducted as an unbroken slab along its 750 km long north-south interface with North America (Gorda-North American and Explorer-North American plate interactions are not considered here). However, several recent papers have proposed that the Juan de Fuca plate is segmented beneath the Pacific Northwest and that such segmentation influences or controls upper plate volcanism and tectonics and the seismicity patterns in both plates. The confirmation (or refutation) of a segmented subducting plate has obvious implications for the assessment of seismic risk in the Pacific Northwest related to a potentially locked Juan de Fuca-North American plate interface.

Barnard (1978) was among the first earth scientists to suggest that upper-plate tectonics, specifically fold and thrust-fold patterns on the continental slope west of Washington, might be influenced by differences in the character of the subducting Juan de Fuca plate. He proposed that deformational patterns on the lower slope change across a "rather narrow" N 50^o E-trending zone that might be related to a parallel "offset" in magnetic anomalies beneath the adjacent Cascadia Basin (A, Figure 11). Prounced changes in continental slope topography (and, hence structure) also occur along a parallel trend west of the Oregon coastline between 44^o 30' and 45^o N latitude (B, Figure 11; Kulm, 1983, Plates 2.0 and 2.3).

Hughes and others (1980) were perhaps the first to formally suggest that the Quaternary Cascade volcanic chain was not continuous, but could be divided into segments that presumably reflect segments in the underthrust Juan de Fuca plate. Six segments with an average width of 175 km were defined between Mt. Garibaldi in British Columbia and Mt. Lassen in northern California (C, Figure 11). Segment boundaries were drawn parallel to the N 50^o E direction of plate convergence and through the following volcanic centers (from north to south): Mt. Garibaldi, Glacier Peak, Mt. Adams, the Three Sisters, Crater Lake (Mt. Mazama), Mt. Shasta and the Medicine Lake Highlands, and Mt. Lassen. The boundaries were drawn to separate alignments of specific volcanics (e.g. Garibaldi-Baker-Glacier Peak-Rainier-St. Helens to the south) and without regard to other upper plate structures, although segment boundaries drawn through Mt. Adams and the Three Sisters coincide with deflections at the base of the Oregon continental slope near 44^0 and 42^0 20' N latitudes respectively. None of the segment boundaries selected by Hughes and others coincide with the zones, noted above, of topographic/structural change observed on the Washington (Barnard, 1978) and Oregon (Kulm, 1983) continental slopes (cf. Figure 11). The boundary drawn through Glacier Peak, lies subparallel to, but 30 to 40 km north of, Weaver and Smith's (1983) line delineating the southeastward limit of deep (presumably lower plate) earthquakes in western Washington (D, Figure 11).

Mt. Rainier and Mt. Hood, two volcanoes neglected by Hughes and others (1980) in delineating their segmented Cascade arc (and the underlying Juan de Fuca plate), are selected by Weaver and Michaelson (1983) as coinciding with northeast-striking boundaries that divide the Cascade arc into three zones "related to changes in the geometry of the subducting plate" (E, Figure 11). The contrasting interpretations of Hughes and others (1980) and Weaver and Michaelson (1983) illustrate present uncertainties within the scientific community about segmentation.

Briefly, Weaver and Michaelson regard the Rainier to Hood interval as a transitional zone between a subducting plate that dips more shallowly to the north (Washington and British Columbia) than to the south (Oregon). As a consequence of dip variation they believe that the northern zone is characterized by horizontal compression of the upper plate, whereas the southern zone is one of extensional tectonics (at least within and east of the Cascade chain). Partial support for their hypothesized southward steepening of the subducted Juan de Fuca plate comes from Riddihough's analysis of lower plate geometry (1979) based on the modeling of regional gravity data. He (Riddihough) concluded that deeper (i.e. more eastern) portions of the subducted slab are <u>progressively</u> steeper to the south -- from about 20^0 northeast of Vancouver Island to about 40^0 beneath the southern Washington Cascades (south of Rainier, north of St. Helens and Adams).

We know of no other data, however, that indicate additional steepening of the subducted plate south of St. Helens and Adams. Averages of the "trench"-arc distances for Rainier, Glacier Peak, and Baker (northern arc zone) and for Hood, Jefferson, and the Three Sisters (southern arc zone) are suprisingly similar -- 385 km to 355 km respectively. If a more-or-less common depth of magma generation is assumed for the six volcanoes (an assumption that appears valid, cf. Dickinson, 1975) then there appears to be little basis to conclude that the subducted slab dips more steeply south of Mt. Hood than north of Mt. Rainier. The Mt. Rainier-defined northern boundary of their transitional zone (Rainier to Hood) does not coincide with the southern limit (Weaver and Smith, 1983) of deep seismicity in western Washington (Figure 11), thus providing another basis for skepticism regarding the Weaver-Michaelson hypothesis. That boundary <u>does</u> lie between a subparallel "offset" zone of magnetic anomalies in the Cascadia Basin and the change in topography and structure of the Oregon continental margin described above. Their southern (Mt. Hood) boundary projects S 50° W to an area along the base of the continental slope (ca. 43° 20' N latitude) which corresponds to the southern limit of subduction of the Juan de Fuca plate (as opposed to the Gorda plate to the south).

Because of conflicting interpretations on segmentation of the Cascade arc and problems with both major models proposed to date (Hughes and others; Weaver and Michaelson), the case for segmentation of the Juan de Fuca plate is not clear. The most obvious change in lower-plate behavior is represented by the northeast-trending cut-off of deep (greater than 35 km) Puget Trough seismicity delineated by Weaver and Smith (1983) using Crosson's (1983) data. The most important change in upper-plate deformational behavior, in our opinion the northeast-trending southern limit of the continental slope ridge and basin province (Kulm, 1983) off the Oregon coast, does not coincide with the change in intraplate seismicity within the subducting slab.

Finally, there is no clear correlation of either of these features (lower plate seismicity; upper plate continental slope morphology) to either of the two major "offsets" separating oceanic crust of slightly different age in the nonsubducted Juan de Fuca plate (F and G, Figure 11; Pavoni, 1966; Atwater, 1970; Hey, 1977).

If the subducting plate is segmented we are presently uncertain as to where segment boundaries should be drawn. If multiple segments are present then all appear to share the same lack of seismicity along their interfaces with the overlying North American plate. This is a situation that seems improbable to us. As stated by Woodward-Clyde Consultants (1984, p. 13), if the subducting plate is broken into segments "... each with its own geometry and behavior ... it is unlikely that the entire plate boundary would rupture in one event. With independent segments seismic activity should be more common. While one segment was in a state of preseismic quiescence, adjacent segments might be expected to display interseismic or postseismic activity. The preseismic segment would be expected to display some form of anomalous activity such as precursory swarms, foreshocks, clustering, or activity at segment boundaries. However, none of these types of activity is observed. In this regard, the observed quiescence of the Juan de Fuca subduction zones is even more striking and suggests that it is not related to precursory phenomena but may reflect an aseismic condition."

CONCLUSIONS

We have attempted in this report to assess the nature of the physical interaction between the Juan de Fuca and North American plates. Our understanding of that interaction is complicated by the remarkably quiescent nature, from the standpoint of seismicity, of the plate interface beneath western British Columbia, Washington, and Oregon. Nevertheless, the very youthful, presumably ongoing compressive deformation of marine sediments at the base of the continental slope, is compelling evidence for present day subduction of the Juan de Fuca plate beneath the continental margin. The absence of interplate seismicity along the converging boundary can be explained as the consequence of either steady, aseismic slip (or flow) or as the consequence of the accumulation of pre-seismic elastic strain along a thoroughly coupled or locked plate boundary. At the present time neither geodetic data nor studies of fault plane solutions <u>within</u> the upper and lower plates are able to resolve which of the two interplate kinematic alternatives is correct.

Recently, comparative studies between the Cascadia (Juan de Fuca) subduction zone and subduction zones elsewhere have been used to support the hypothesis that the Juan de Fuca-North American plate boundary is strongly coupled and capable, upon seismic release of energy stored along that boundary, of producing a future great earthquake. We do not discount this possibility, but we are strongly of the opinion that subduction zone comparisons relying primarily on rate of plate convergence and age of subducting oceanic lithosphere alone are overly simplistic. For example, although similarities in these two parameters may exist between the aseismic Cascadia and the seismogenic Nankai Trough subduction zones (our skepticism as to the closeness of similarity has been expressed above), significant differences exist between these two zones that have heretofore received little attention. Among these differences are the configuration of the subducted oceanic plate beneath Japan and the Pacific Northwest, the absence of a volcanic arc in Japan, and the vastly different quantities of terrigeneous sediments supplied to the "trench" between the two pairs of plates in late Cenozoic time.

We believe that the non-seismic nature of the boundary between the Juan de Fuca and North American plates may be indicative of aseismic subduction related to three factors that set the Cascadia subduction zone apart from others: (1) the extreme youthfulness of the subducting crust; (2) the relatively slow rate of convergence; and (3) the burial of the offshore plate boundary beneath the most voluminous late Cenozoic sedimentary accumulation (per km of trench) to be found around the Pacific Ocean rim. Aseismic subduction may be the combined consequence of (1) an elevated thermal state for subducted and accreted materials (basaltic crust and/or overlying sediments), and (2) high fluid pressures in subducted terrigeneous sediments generated by their dewatering at the offshore plate interface (buried base of continental slope) and below the thick accreted forearc wedge. Most portions of the upper plate beneath the continental slope, shelf and Washington-Oregon Coast Ranges are part of a mid- to late Cenozoic accreted wedge. Wedges of this type are characteristically aseismic, a phenomenon that may put the low seismicity of upper plate areas west of the Puget trough and Willamette Valley in a clearer perspective.

We have reviewed recent suggestions that the subducting Juan de Fuca plate is internally segmented, but no compelling evidence yet exists in our opinion to support these suggestions. If, the plate is indeed broken into multiple segments, each with its own geometry and behavior, then the observed seismic quiescence of the entire Cascadia subduction zone may reflect a fundamental mode of aseismic underthrusting above all segments.

Finally, the case for aseismic subduction of the Juan de Fuca plate is enhanced when comparisons are made between the Cascadia zone and other convergent zones characterized by "seismic gaps". Seismic gaps are just that, gaps along seismically defined, hence seismically active plate boundaries.

It cannot be effectively argued, we believe, that the entire Juan de Fuca/North American plate boundary is locked. No great thrust earthquakes have ever ruptured an entire plate boundary (10 to 15% rupture is common) and great thrust earthquakes do not occur in total spatial and temporal isolation from lesser thrust events. The absence of any historical thrust events in the range 5 M 7 along the entire Cascadia zone clearly sets it apart from the strongly seismogenic convergent zones with which it is increasingly, and we believe, mistakingly, being compared.

REFERENCES

Adams, J., (1983 ms), Active Deformation of the Pacific Northwest Continental Margin, Contributions of the Earth Physics Branch, Energy, Mines and Resources, Ottawa, Canada.

Ando, M. and E. I. Balazs, 1979, Geodetic Evidence for Aseismic Subduction of the Juan de Fuca Plate,; JGR, Vol. 84, No. B6, p. 3023-3028.

Atwater, T., 1970, Implications of Plate Tectonics for the Cenozoic Tectonic Evaluation of Western North America, GSA Bull., Vol. 81, p. 3513-3536.

Barnard, W. D., 1978, The Washington Continental Slope: Quaternary Tectonics and Sedimentation, Marine Geology, Vol. 27, p. 79-114.

Blackwell, D. D., 1974, Terrestrial Heat Flow and Its Implications on the Location of Geothermal Reservoirs in Washington, Washington State Department of Natural Resources, Division of Geology and Earth Resources, Information Circular 50, Energy Resources of Washington, p. 21-33.

Blackwell, D. D., Bowen, R. G., Hull, D. A., Riccio, J., and Steele, J. L., 1982, Heat Flow, Arc Volcanism and Subduction in Northern Oregon, JGR, Vol. 87, No. B10, p. 8735-8754.

Chen, A. T., C. Frohlich, and G. V. Latham, 1982, Seismicity of the Forearc Marginal Wedge (Accretionary Prism), JGR, Vol. 87, No. B5, p 3679-3690.

Chinn, D. S., and B. L. Isacks, 1983, Accurate Source Depth and Focal Mechanisms of Shallow Earthquakes in Western South America and in the New Hebrides Island-Arc, Tectonics, Vol. 2, No. 6, p. 529-563.

Couch, R., C. Kienle, and G. Connard, 1978, The Continental Margin of the Pacific Northwest: A summary of the Geological and Geophysical Data, report prepared for U.S. Department of State by Geophysics Group, School of Oceanography, Oregon State University, Corvallis, OR.

Crosson, R. S., 1972, Small Earthquakes, Structure, and Tectonics of the Puget Sound Region, BSSA, Vol. 62, p. 1133-1171.

Crosson, R. S., 1976, Crustal Structure Modeling of Earthquake Data 2. Velocity Structure of the Puget Sound Region, Washington, JGR, Vol. 81, 3047-3054.

Crosson, R. S., 1983, Review of the Seismicity in the Puget Sound Region from 1970 through 1978, USGS Open File Report, 83-19, Proceedings of Workshop XIV, Earthquake Hazards of the Puget Sound Region, Washington.

Crosson, R. S., (1984 ms), Comment on "Geodetic Strain Measurements in Washington" by J. C. Savage, M. Lisowski, and W. H. Prescott, Journal of Geophysical Research, manuscript.

Davis, G. A., 1977, Tectonic Evolution of the Pacific Northwest, Precambrian to Present, WPPSS WNP 1/4 PSAR, Appx 2R-C.

Dehlinger, P., R. W. Couch, D. A. McMannis, and M. Gemperle, 1970, Northeast Pacific Structure, *The Sea*, Vol. 4, p. 133-190, Wiley Interscience, New York, 664 p.

Dickinson, W. R., 1975, Potash-Depth (K-h) Relations in Continental Margin and Intra-Oceanic Magmatic Arcs, Geology, 3:2, p. 53-56.

Fedotov, S. A., 1965, Regularities of the distribution of strong earthquakes in Kamchatka, the Kuril Islands and northeast Japan, Trudy Inst. Fiz. zemli., Acad. Nauk. SSSR, 36, p. 66-93.

Forsyth, D. W., 1975, Fault Plane Solutions and Tectonics of the South Atlantic and Scotia Sea, JGR, Vol. 80, p. 1429.

Heaton, T. H., 1984, Northwest U.S. Subduction Zone Seismic Risk Assessment, First Quarter Report-FY84, USGS Research Program for the U.S. Nuclear Regulatory Commission, Work in Progress.

Heaton, T. H. and Kanamori, H., 1984, Seismic Potential Associated with Subduction in the Northwestern United States, BSSA, Vol. 74.

Herron, E., R. Bruhn, M. Winslow, and L. Chaqui, 1977, Post-Miocene tectonics of the Margin of Southern Chile, in Talwani, M., and Pitman, W. C. III eds, *Island Arcs, Deep Sea Trenches and Back-arc Basins*, Amer. Geophys. Union Maurice Ewing Series, 1, 2 and 3.

Herron, E., S. Cande, and B. Hall, 1981, An Active Spreading Center Collides With A Subduction Zone: A Geophysical Survey of the Chile Margin Triple Junction, in Kulm V., and others eds, *Nazca Plate: Crustal Formation and Andean Convergence*, Geol. Soc. Amer. Mem. 154, 683p.

Hey, R., 1977, A New Class of "Pseudofaults", and Their Bearing on Plate Tectonics: A Propagating Rift Model, Earth and Planetary Science Letters, v. 37, p. 321-325.

Hirahara, K., 1981, Three-dimensional Seismic Structure Beneath Southwest Japan: The subducting Philippine Plate, Tectonophysics, Vol 79, p. 144.

Hughes, J. M., R. E. Stoiber, and J. M. Carr, 1980, Segmentation of the Cascade Volcanic Chain, Geology, 8, p. 15-17.

Hyndman, R. D., and D. H. Weichert, 1983, Seismicity and Rates of Relative Motion on the Plate Boundaries of Western North America, Geophys. J. R. Astr. Soc., Vol. 72, p. 59-82.

Jachens, R. C. and A. Griscom, 1983, Three-Dimensional Geometry of the Gorda Plate Beneath Northern California, JGR, Vol. 88, No. B11, p 9375-9392.

Jacob, K. H., K. Nakamura, and J. N. Davies, 1977, Trench-Volcano Gap Along the Alaska-Aleutian Arc: Facts, and Speculations on the Role of Terrigenous Sediments for Subduction, in Island Arcs, Deep Sea Trenches and Back-Arc Basins, p. 243-258, AGU Maurice Ewing Series 1, 470 p.

Kanamori, H., 1972, Tectonic Implications of the 1944 Tonankai and the 1946 Nankaido Earthquakes, Phys. Earth Planet Interiors, Vol. 5, p. 129-139.

Kanamori, H., 1977, Seismic and Aseismic Slip Along Subduction Zones and their Tectonic Implications, in Island Arcs, Deep Sea Trenches and Back-Arc Basins, p. 163-174, AGU Maurice Ewing Series 1, 470 p.

Kanamori, H., (1983, ms.) Global Seismicity, Calif. Inst. of Tech., Pasadena, CA.

Kanamori, H., and L. Astiz, in press, The 1983 Akita-Oki Earthquake (Mw = 7.8) and Its Implication for Systematics of Subduction Earthquakes, Earthquake Prediction Research.

Kelleher, J., 1972, Rupture Zones of Large South American Earthquakes and Some Predictions, JGR, Vol. 77, p. 2087.

Kelleher, J., L. Sykes and J. Oliver, 1973, Possible Criteria For Predicting Earthquake Locations and Their Application to Major Plate Boundaries of the Pacific and Caribbean, JGR, Vol. 78, p. 2547.

Kelsey, H. M. and S. M. Cashman, 1983, Wrench Faulting in Northern California and its Tectonic Implications, Tectonics, Vol. 2, No. 6, p. 565-576.

Kimura, T., 1974, The Ancient Continental Margin of Japan, in The Geology of Continental Margins, Burk, C. A., and Drake, C. L. Editors, p. 817-830, Springer-Verlag, New York, 1009 p.

Kobayashi, K., 1984, Subsidence of the Shikoku Back-Arc Basin, Tectonophysics, Vol. 102, p. 105-117.

Kulm, V., 1983, A Study of the Western Washington-Oregon Margin and Adjacent Juan de Fuca Plate, report prepared for WPPSS, Richland, WA, 41 p.

Langston, C. A., 1981, Evidence for the Subducting Lithosphere Under Southern Vancouver Island and Western Oregon from Teleseismic Wave Conversions, JGR, Vol. 86, No. B5, p. 3857-3866.

Lomnitz, C., 1970, Major Earthquakes and Tsunamis in Chile During the Period 1535-1955, Geol. Rundsch., 59, p. 948.

Ludwig, W. J., Den, N., and Murauchi, S., 1973, Seismic Reflection Measurement of Southwest Japan Margin, JGR, Vol. 78, p. 2508-2516.

McClain, K. J., 1981, A Geophysical Study of Accretionary Processes on the Washington Margin, Ph.D. Thesis, University of Washington, Seattle, WA, 141 p.

McCollom, R. L., and R. S. Crosson, 1975, An Array Study of Upper Mantle Velocity In Washington State, BSSA, Vol. 65, 467-482.

McKenzie, D. P., 1969, The Relation Between Fault Plane Solutions for Earthquakes and the Direction of the Principal Stresses, BSSA, Vol. 59, 591-601.

McKenzie, D. P. and B. Julian, 1971, Puget Sound, Washington, Earthquake and Mantle Structure Beneath the Northwestern United States, Geol. Soc. America Bull., Vol. 82, p. 3519-3524.

McKenzie, D. P. and R. L Parker, 1967, The North Pacific: An Example of Tectonics on a Sphere, Nature, Vol. 216, p. 1276-1280.

Melosh, H. J., 1983, Finite Element Investigation of Uplift and Strain in the Puget Sound Region, report prepared for WPPSS, Richland, WA, 33 p.

Minster, B. and T. Jordan, 1978, Present-day Plate Motions, JGR, Vol. 83, p. 5331.

Mogi, K., 1968, Some Features of Recent Seismic Activity In and Near Japan, Bull Earthquake Res. Inst., Univ. Tokyo, 46, p. 1225.

Nakamura, K., K. Kasahara and T. Matsuda, 1965, Tilting and Uplift of An Island, Awashima, Near the Epicentre of the Niigata Earthquake In 1964, Jour. Geodetic Soc. Japan, 10, p. 172-179.

Nakamura, K., and S. Uyeda, 1980, Stress Gradient in Arc-Back Arc Regions and Plate Subduction, JGR, Vol. 85, 6419-6428.

Nishimura, C., Wilson, D. S., and Hey, R. N., 1984, Pole of Rotation Analysis of Present-Day Juan de Fuca Plate Motion, EOS, Transactions, American Geophysical Union, Vol. 65, No. 17, abstract.

Pavlis, T. L. and R. L. Bruhn, 1983, Deep-Seated Flow As A Mechanism For The Uplift of Broad Forearc Ridges and Its Role In The Exposure of High P/T Metamorphic Terranes, Tectonics, Vol. 2, No. 5, pp. 473-497.

Pavoni, N., 1966, Tectonic Interpretation of the Magnetic Anomalies Southwest of Vancouver Island, Pure and Applied Geophysics, V. 63, p. 172-178.

Pelton, J. R., 1983, Analysis of Geodetic Data, Report prepared for Washington Public Power Supply System.

Raleigh, C. B., K. Sieh, L. R. Sykes, D. L. Anderson, 1982, Forcasting Southern California Earthquakes, Science, Vol. 217, p. 1097-1104.

Reilinger, R. E. and J. Adams, 1982, Geodetic Evidence for Active Landward Tilting of the Oregon and Washington Coastal Ranges, Geophysical Research Letters, Vol. 9, No. 4, p. 401-403.

Reyners, M., 1980, A Microearthquake Study of the Plate Boundary, North Island, New Zealand, Geophys. J. R. Astr. Soc., Vol. 63, p. 1-22.

Riddihough, R. P., 1977, A Model for Recent Plate Interactions Off Canada's West Coast, Can. J. Earth Sci., Vol. 14, p. 384-396.

Riddihough, R. P., 1979, Gravity and Structure of an Active Margin: British Columbia and Washington, Can. J. Earth Sci., Vol. 16, p. 350-362.

Riddihough, R. P., 1980, Gorda Plate Motions From Magnetic Anomaly Analysis, Earth and Planetary Science Letters, Vol. 51, p. 163-170.

Riddihough, R. P., 1982, Contemporary Movements and Tectonics on Canada's West Coast: A Discussion, Tectonophysics, Vol. 86, p. 319-341.

Rogers, G. C., 1979, Earthquake Fault Plane Solutions Near Vancouver Island, Can. J. Earth Sci., Vol. 16, p. 523-531.

Ruff, L. and H. Kanamori, 1980, Seismicity and the Subduction Process, Physics Earth Planet. Inter., Vol. 23, p. 240-252.

Sacks, I. S., 1983, The Subduction of Young Lithosphere, JGR, Vol. 88, No. B4, p. 3355-3366.

Savage, J. C., M. Lisowski, and W. H. Prescott, 1981, Geodetic Strain Measurements in Washington, JGR, Vol. 86, No. B6, p. 4929-4940.

Sbar, M. L., 1982, Delineations and Interpretation of Seismotectonic Domains in Western North America, JGR, Vol. 87, p. 3919-3928.

Sbar, M. L., 1983, An Explanation for Contradictory Geodetic Strain and Fault Plane Solution Data in Western North America, Geophysical Research Letters, Vol. 10, No. 3, p. 177-180.

Scholl, D. W., and M. S. Marlow, 1974, Sedimentary Sequence in Modern Pacific Trenches and the Deformed Circum-Pacific Eugeosyncline, Soc. Econ. Paleo. Min., Spec. Publ. 19, p. 193-211.

Shiono, K., 1977, Focal Mechanisms of Major Earthquakes in Southwest Japan and Their Tectonic Significance, J. Phys. Earth, 25, 1-26.

Shor, G. C., P. Dehlinger, H. K. Kirk, and W. S. French, 1968, Seismic Refraction Studies Off Oregon and Northern California, JGR, Vol. 73, p. 2175-2194.

Silver, E. A., 1972, Pleistocene Tectonic Accretion of the Continental Slope Off Washington, Marine Geology, Vol. 13, p. 239-249.

Smith, S. W. and J. S. Knapp, 1980, The Northern Termination of the San Andreas Fault, in Studies of the San Andreas Fault Zone in Northern California, Spec. Rep. Calif. Div. Mines Geol., Vol. 140, p. 153-164.

Snavely, P. D., Jr., H. C. Wagner, and D. L. Lander, 1980, Interpretation of the Cenozoic Geologic History, Central Oregon Continental Margin: Cross-Section Summary, GSA Bull., 91:3, p. I143-I146.

Snavely, P. D., Jr., H. C. Wagner, 1982, Geologic Cross Section Across the Continental Margin of Southwestern Washington, U.S. Geol. Surv. Open File Report 82-459.

Taber, J. J., 1983, Crustal Structure and Seismicity of the Washington Continental Margin, Ph.D. Thesis, University of Washington, Seattle, WA.

Taber, J. J., and S. W. Smith, (in press), Seismicity of the Cascadia Subduction Zone, Olympic Peninsula, Washington, Submitted to BSSA, December 27, 1983.

Tabor, R. W. and W. M. Cady, 1978, Geologic Map of the Olympic Peninsula, U.S. Geol. Surv. Misc. Invest. Map I-994.

Thatcher, W., 1984, The Earthquake Deformational Cycle at the Nankai Trough, Southwest Japan, JGR, Vol. 89, No. B5, p. 3087-3101.

Ukawa, M., 1982, Lateral Stretching of the Philippine Sea Plate Subducting Along the Nankai-Suruga Trough, Tectonics, Vol. 1, No. 6, p. 543-571.

von Huene, R., and L. D. Kulm, 1973, Tectonic Summary of Leg 18, Initial Reports of the Deep Sea Drilling Project 18, U.S. Gov't. Print. Off., Washington, D.C., p. 961-976.

Weaver, C. S., and S. W. Smith, 1983, Regional Tectonic and Earthquake Hazard Implications of a Crustal Fault Zone in Southwestern Washington, JGR, Vol. 88, No. B12, p. 10,371-10,383.

Weaver, C. S., and C. A. Michaelson, 1983, Segmentation of the Juan de Fuca Plate and Volcanism In The Cascade Range, Abstract, Transactions Of The American Geophysical Union, EOS, Vol. 64, No. 45.

Westbrook, G. K. and M. J. Smith, 1983, Long Decollements and Mud Volcanoes: Evidence from the Barbados Ridge Complex for the Role of High Pore-fluid Pressure in the Development of an Accretionary Complex, Geology, Vol. II., p. 279-283.

Washington Public Power Supply System (WPPSS) 1982, Final Safety Analysis Report for WNP-3, Satsop, WA.

Woodward-Clyde Consultants (WCC), 1984, Juan de Fuca Plate Comparison, report prepared for WPPSS, Richland, WA.

Yelin, T. S., 1983, The Seattle Earthquake Swarms and Puget Basin Focal Mechanisms and their Tectonic Implications, M. Sc. Thesis, University of Washington, Seattle, WA, 96 p.

Yelin, T. S. and Crosson, R. S., 1982, A Note on the South Puget Sound Basin Magnitude 4.6 Earthquake of 11 March 1978 and its Aftershocks, BSSA, Vol. 72, No. 3, p. 1033-1038.

Yoshii, T. W., J. Ludwig, N. Den, S. Murauchi, M. Ewing, H. Hotta, P. Buhl, T. Asanuma, and N. Sakajiri, 1973, Structure of Southwest Japan Margin Off Shikoku, JGR, Vol. 78, No. 14.

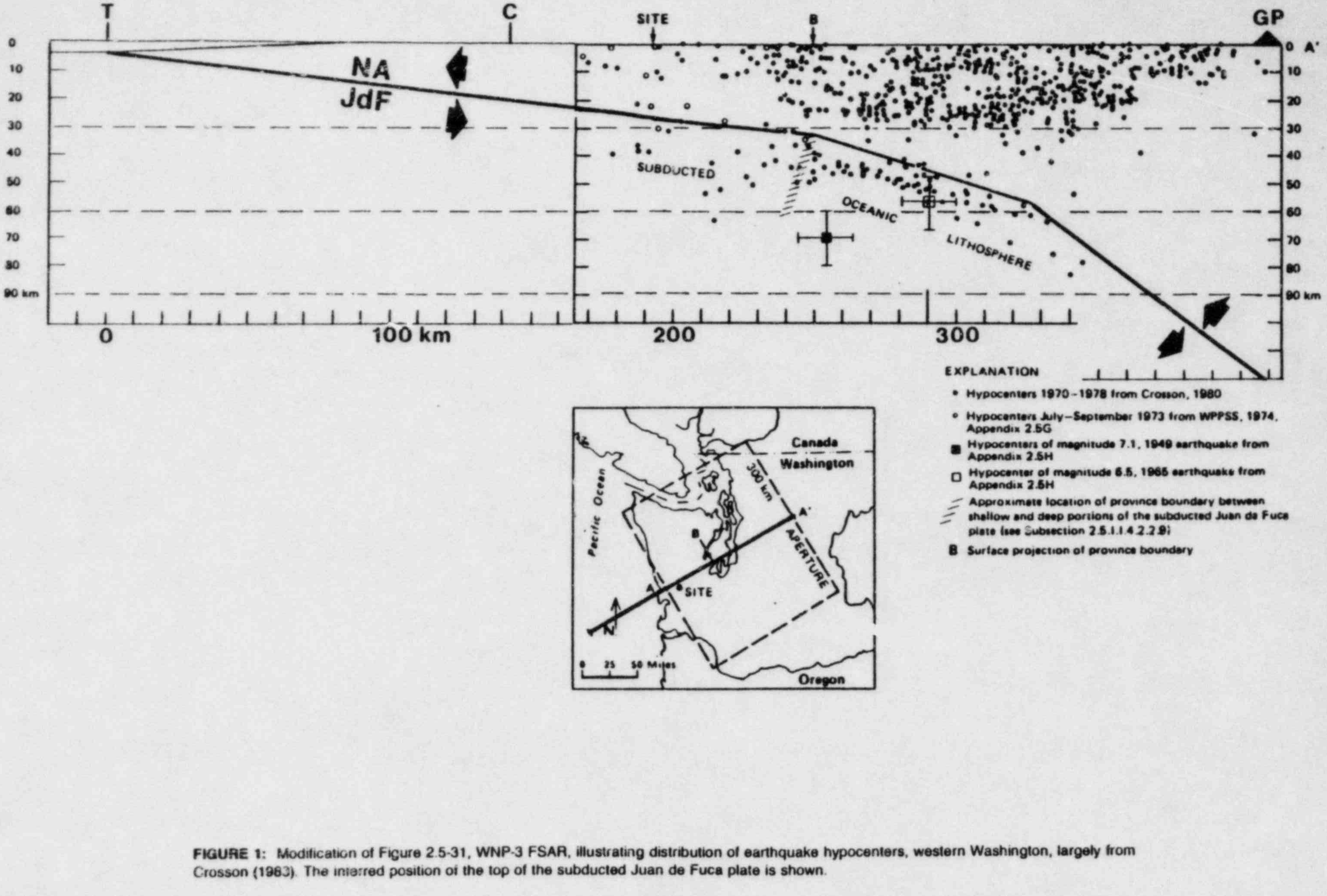


FIGURE 1: Modification of Figure 2.5-31, WNP-3 FSAR, illustrating distribution of earthquake hypocenters, western Washington, largely from Crosson (1983). The inferred position of the top of the subducted Juan de Fuca plate is shown.

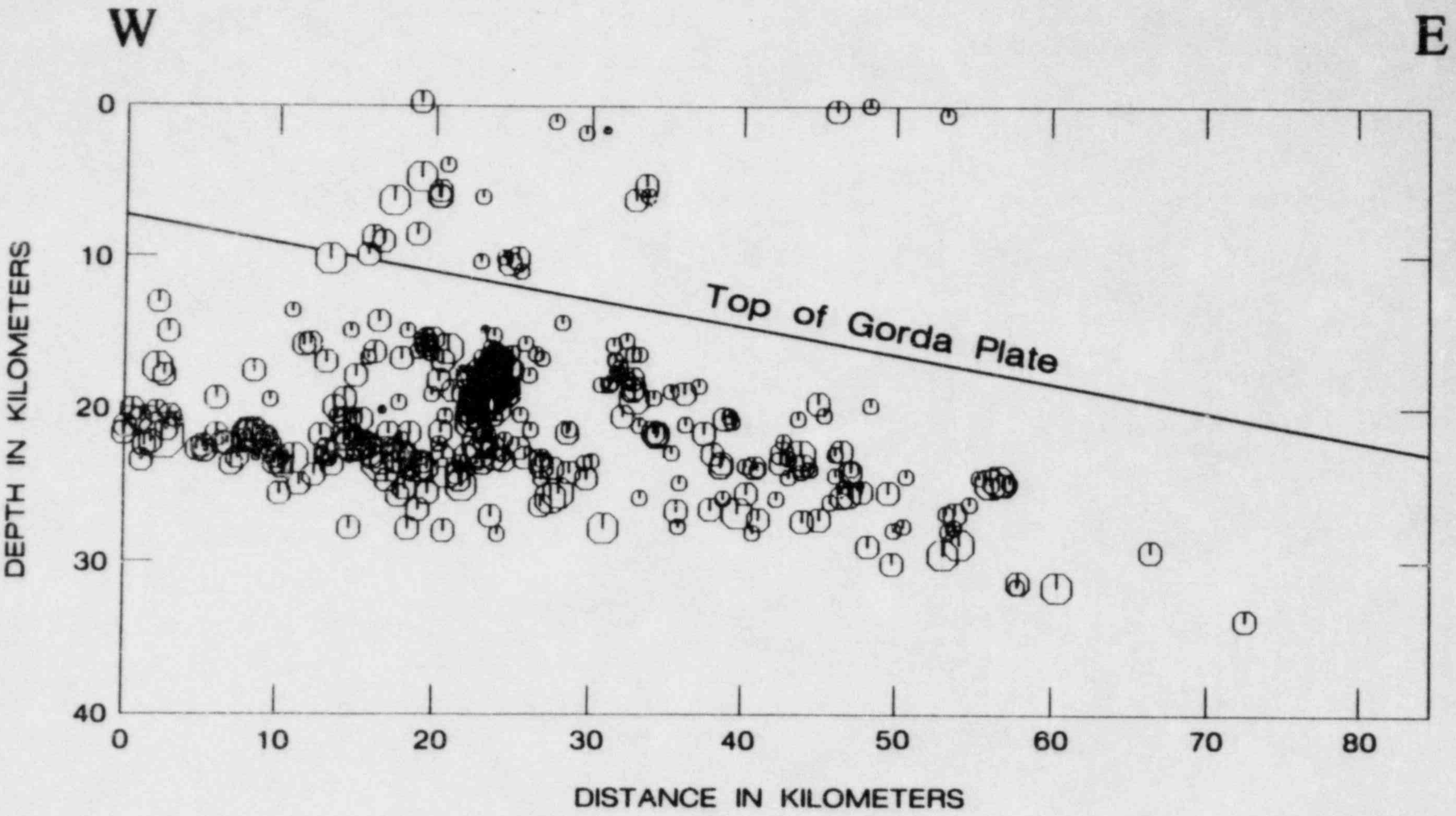


FIGURE 2: Distribution of seismicity and inferred location of top of Gorda plate, northwesternmost California (Figure 10 from Jackens and Griscom, 1983.)

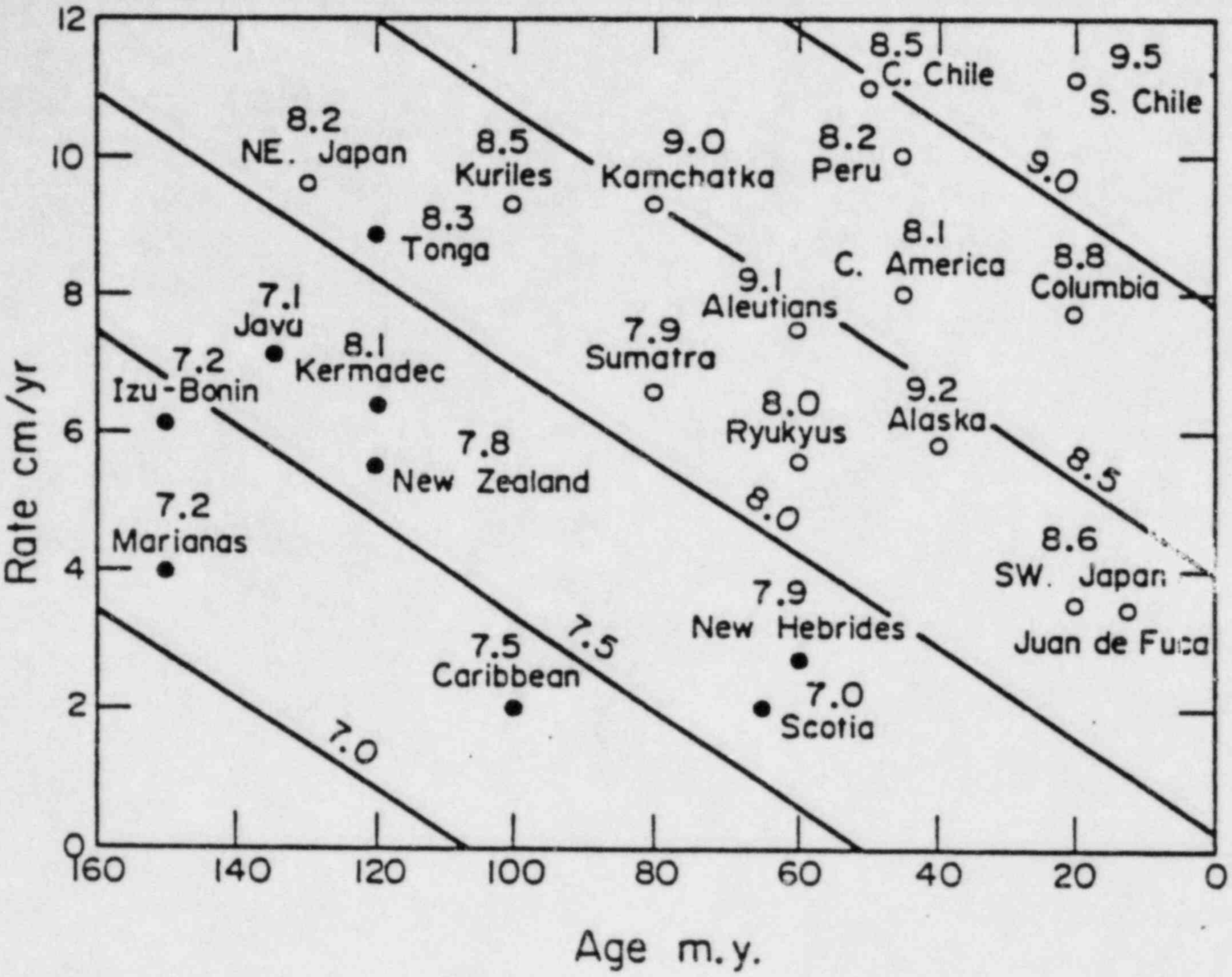


FIGURE 3: Relationship of maximum energy magnitude M_W to convergence rate and age of subducted lithosphere for major subduction zones. The contours of M_W are the predicted maximum earthquake magnitude against the other two variables. Open and closed circles are subduction zones with and without back-arc basins, respectively. (Figure 1 from Heaton and Kanamori, 1984).

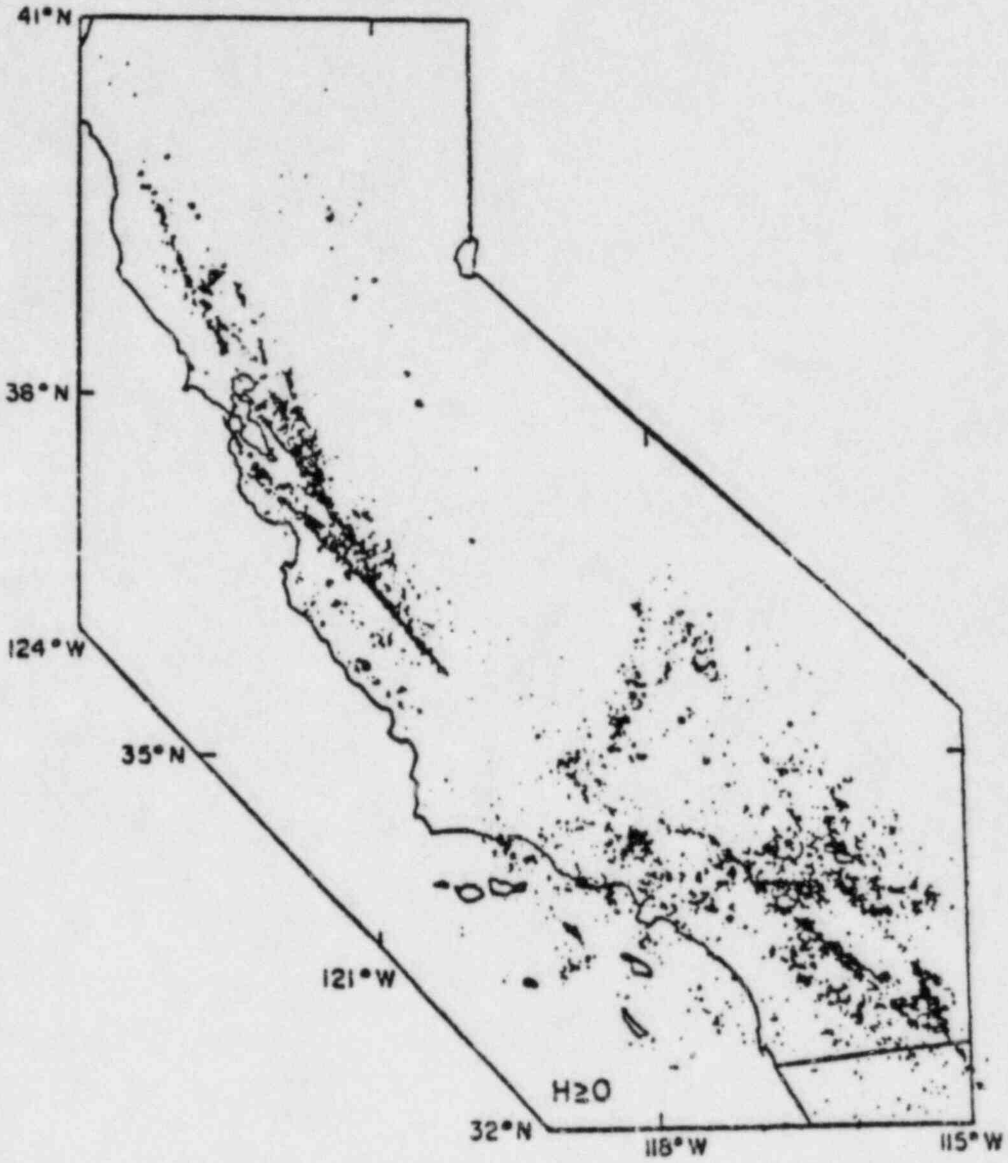


FIGURE 4: Epicenters reported from both the USGS in central-northen California during the period 1971 to 1981. (See text for discussion.)

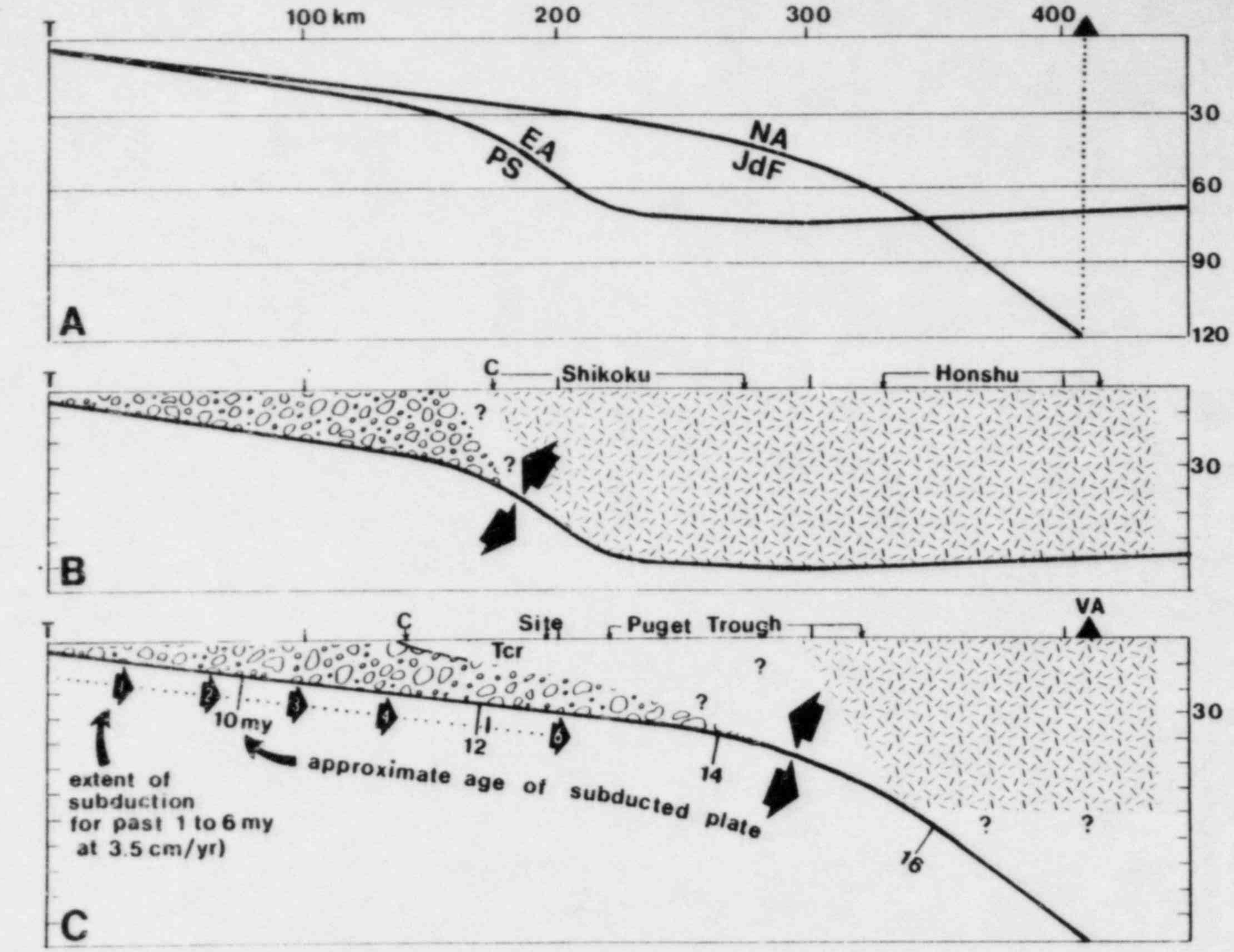


FIGURE 5: Comparative geometry and geology of the Juan de Fuca/North American and Philippine Sea/Eurasian plate interactions.

A. Comparative profiles of the plate interfaces. The geometry of the Juan de Fuca/North American interface is taken from Figure 1; that of the Philippine Sea/Eurasian interface is largely from Hirahara, 1981.

B. Crustal geology of the Eurasion upper plate along a NW-SE section from the Nankai Trough (trench), T, to Honshu Island. Pre-Cenozoic continental lithosphere extends to at least the southern coastline (C) of Shikoku Island (Kimura, 1974). Cenozoic accreted deposits are shown by the pattern between T and C. No contemporary volcanic arc is present in Honshu.

C. Crustal geology of the North American plate along the line of section illustrated in Figure 1. The boundary between pre-Cenozoic accreted terrane and Cenozoic rocks accreted to North America underlines the Puget Trough. The major low-angle fault near the coastline (C) separates hanging wall Eocene basalts of the Crescent Formation from Eocene to Pleistocene sediment of the underlying accreted wedge. Location of this thrust fault is from Snavely and Wagner (1983). Figures in the lower Juan de Fuca plate indicate that the age of oceanic lithosphere beneath the WNP-3 site is approximately 12 m.y. and that the oceanic lithosphere beneath the site was beneath the offshore trench (now filled) only 6 million years ago. VA = volcanic arc.

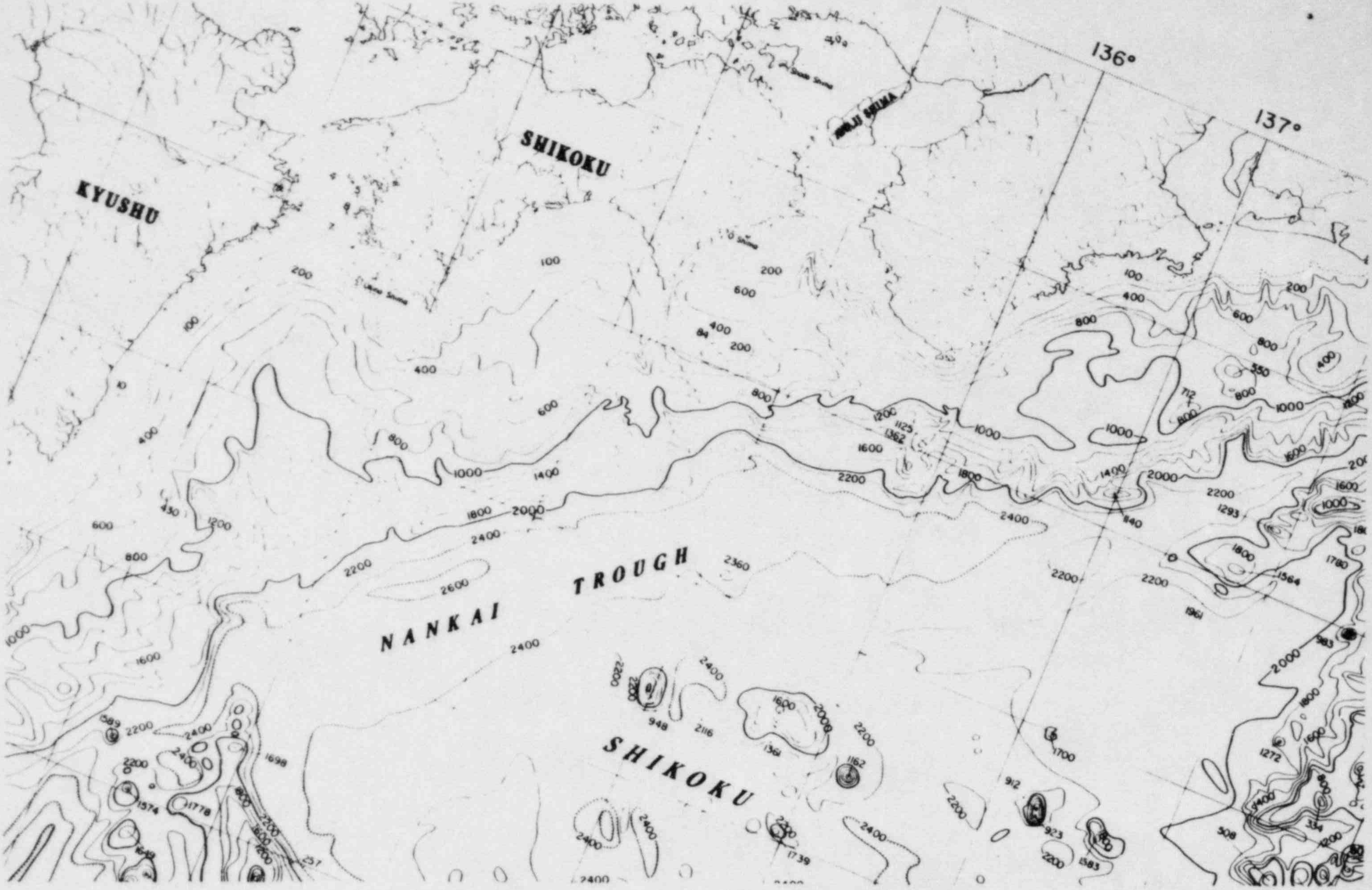


FIGURE 6: Bathymetry of the Nankai Trough south of Shikoku and Honshu Islands, Japan. Lines are 1º apart; depths in fathoms. From map 2306N, Bathymetric Atlas of the Northwestern Pacific Ocean, U.S. Naval Oceanographic office H.O. Pub. No. 1301, 1969.

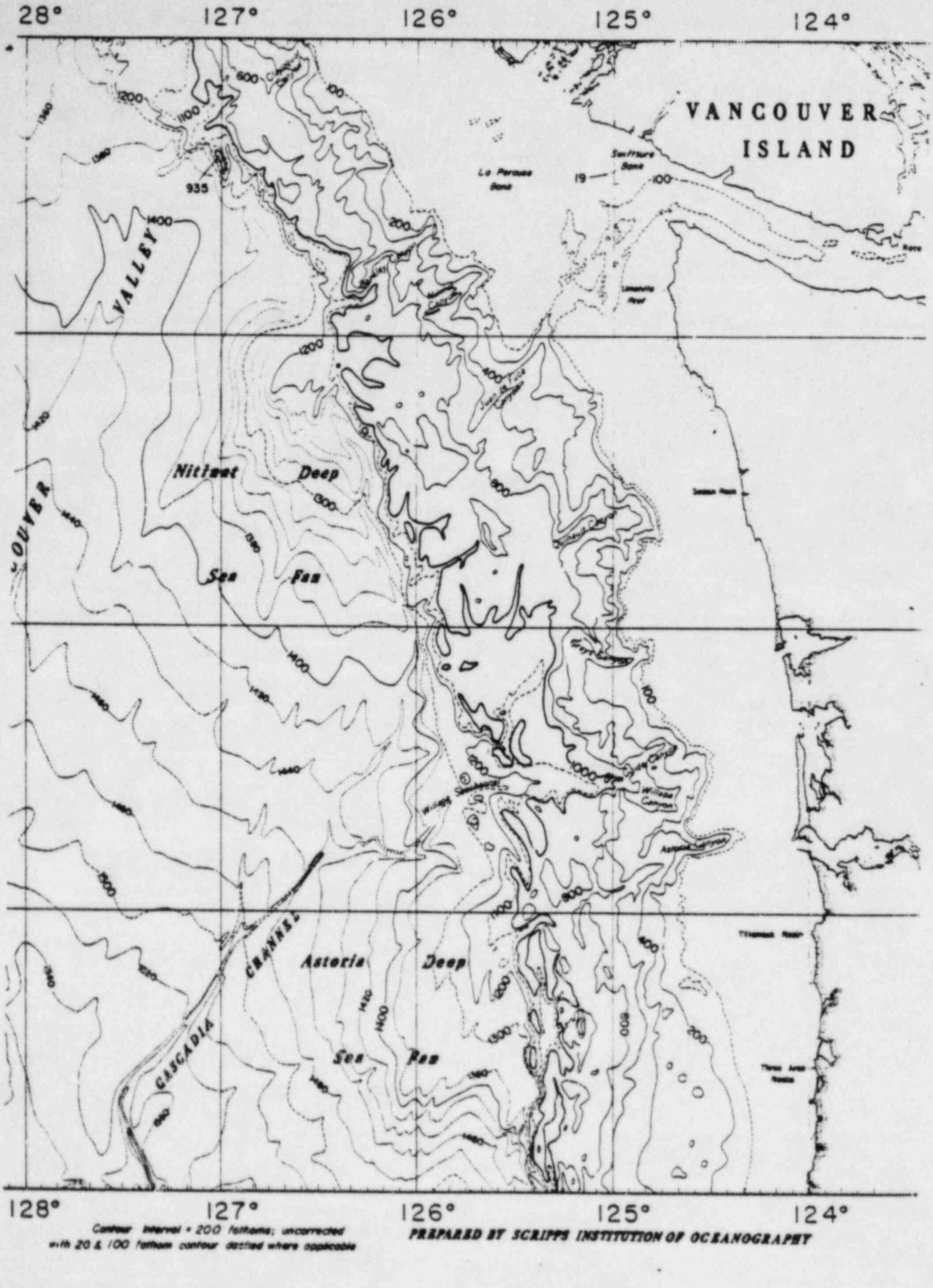


FIGURE 7: Bathymetry of the Cascadia Basin and continental margin, southwestern British Columbia, Washington, and northwestern Oregon. Lines are 1° apart; depths in fathoms. From map 1390N, Bathymetric Atlas of the Northeastern Pacific Ocean, U.S. Naval Oceanographic office H.O. Pub. No. 1301, 1971.

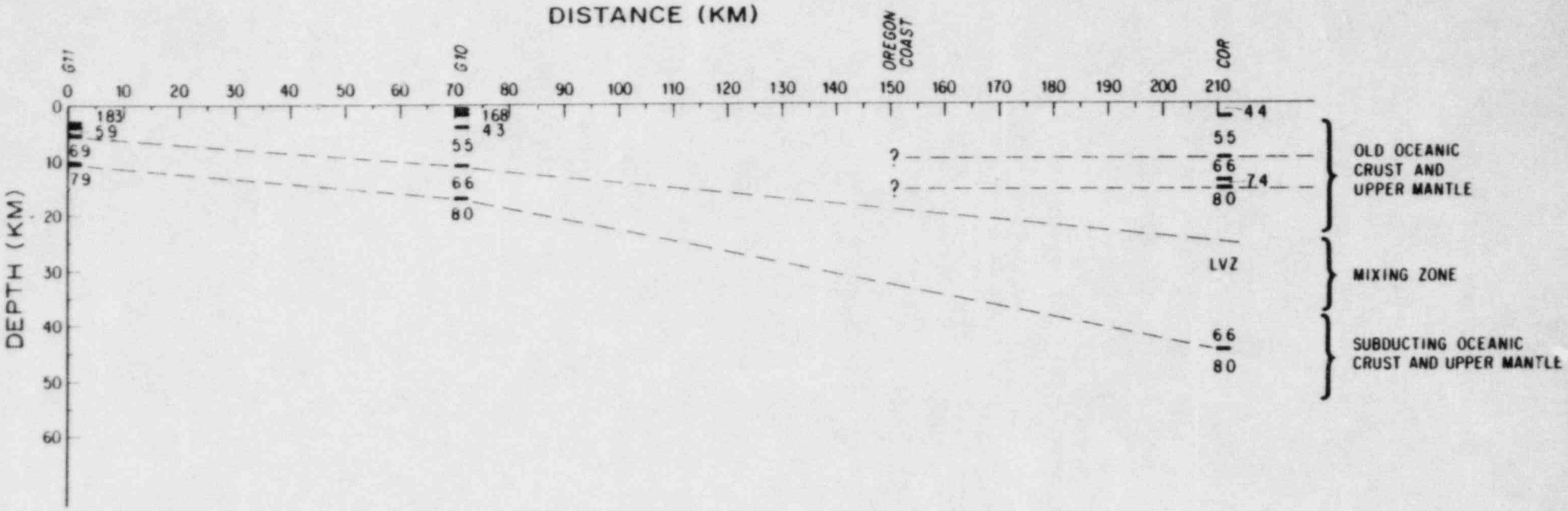
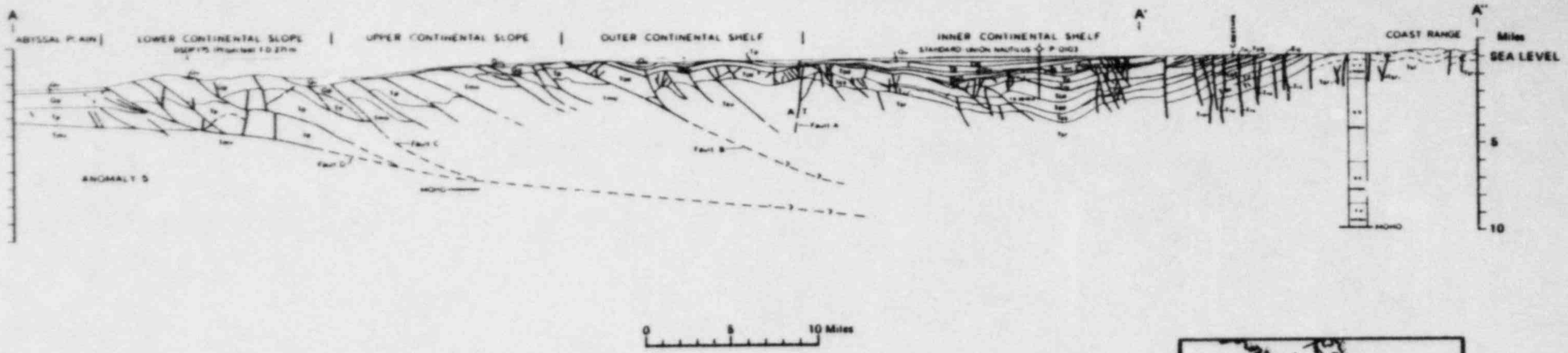


FIGURE 8: Schematic cross-section of inferred upper plate/lower plate relations, central Oregon Coast Ranges and western margin of Willamette Valley (COR = Corvallis). Figure is Figure 8 of Langston (1981). (See text for discussion.)



EXPLANATION

– – ?– ? Geologic Contact

Fault

Qu	Holocene and Pleistocene semi-consolidated shell-bearing marine micaceous fine-grained lithic sand and silt
Qp	Pleistocene semi-consolidated, slightly calcareous marine siltstone and very fine-grained sandstone
Tp	Pliocene sedimentary rocks
Tmu	Upper Miocene (?) sedimentary rocks
Tmv	Upper Miocene tholeiitic basalt (oceanic crust)
Tcf	Cape Foulweather Basalt (middle Miocene)
Twc	Sandstone of Whale Cove (middle Miocene)
Tdb	Depoe Bay Basalt (middle Miocene)
Tfu	Intrusive basalt (middle Miocene)
Ta	Astoria Formation (middle Miocene)
Tyq	Yaquina Formation (lower Miocene and upper Oligocene)
Tmo	Inferred middle Miocene to upper Oligocene melange
Tn	Nye Mudstone (lower Miocene)
Tic	Camptonite intrusive and extrusive rocks (lower Oligocene and upper Eocene)
Toe	Oligocene and upper Eocene sedimentary rocks
Ty	Yamhill Formation (upper and middle Eocene)
Tt	Tyee Formation (middle Eocene)
Tes	Middle Eocene marin siltstone and sandstone
Tsr	Siletz River Volcanics (lower and middle Eocene)
Teu	Inferred lower Eocene arkosic and lithic marine sandstone

INDEX MAP

SOURCE: modified from Snavely et al. (1980)

FIGURE 9: Geologic cross-section of the Continental Slope and Shelf through central Oregon (modified from Snavely and others, 1980).

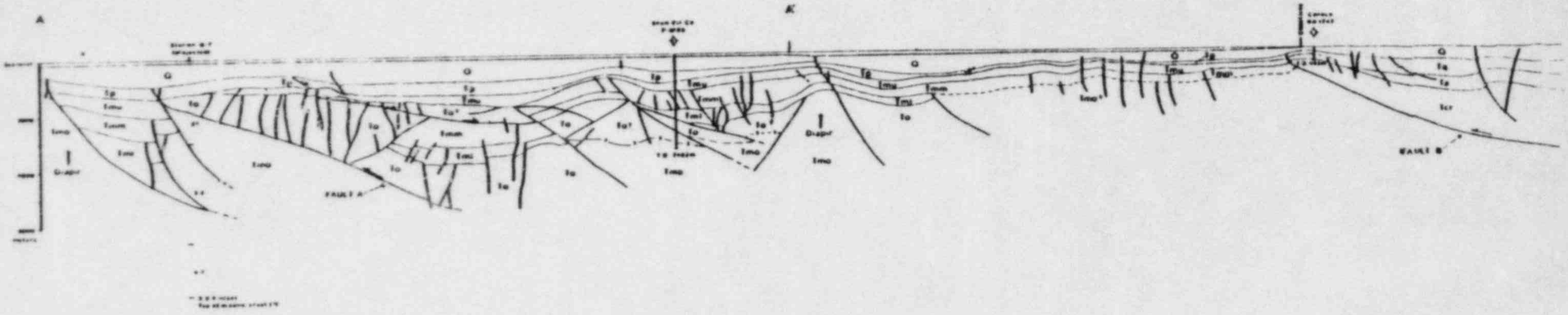


FIGURE 10: Preliminary geologic cross-section A-A across the continental margin of southwestern Washington (Figure 3, Snavely and Wagner, 1983).

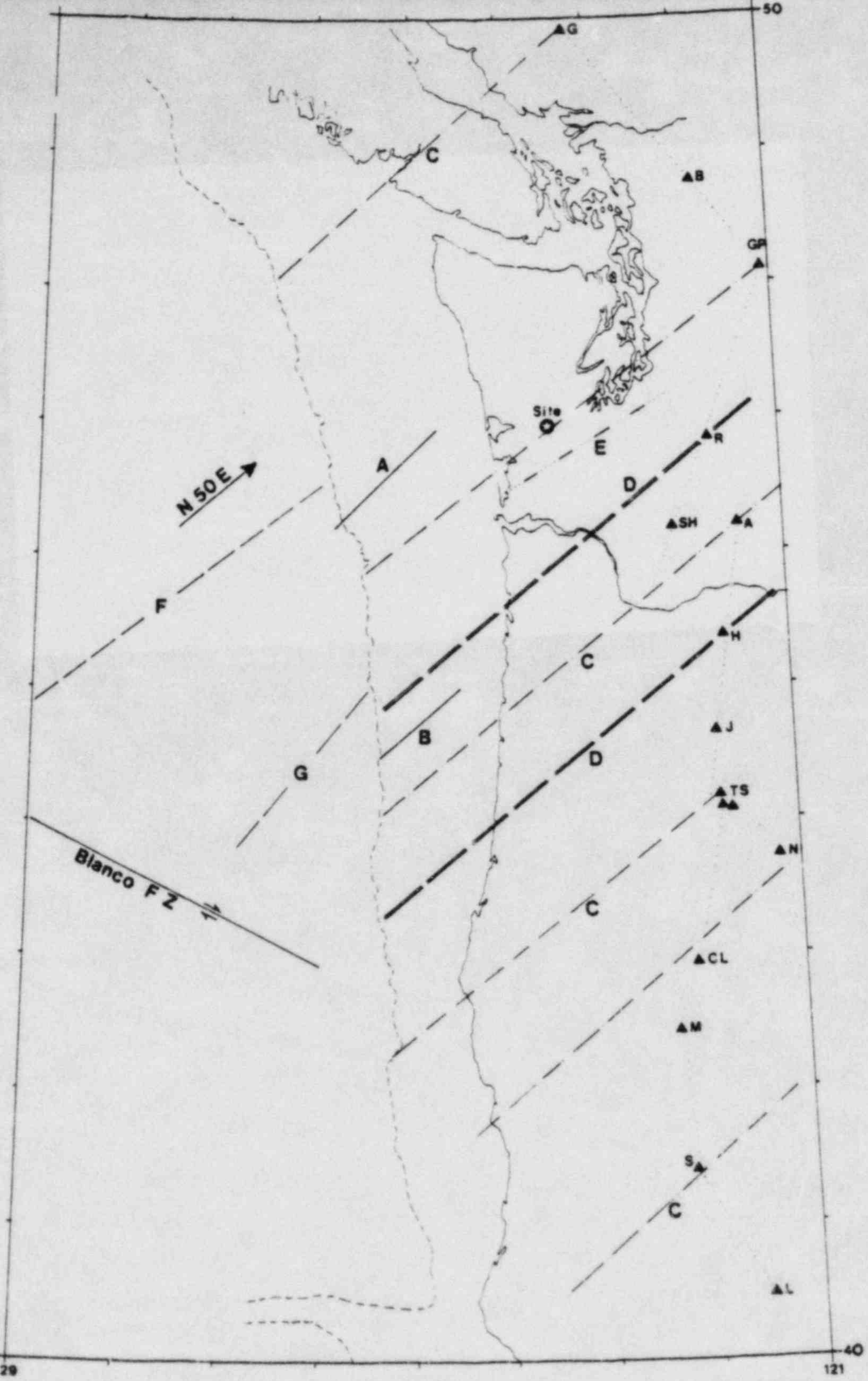


FIGURE 11: Map of the Pacific Northwest showing lineaments postulated by various workers. Dashed line west of coast is base of continental slope. See text for discussion of lineaments as follows: A (Barnard, 1978); B (Kulm, 1983); C (Hughes and others, 1980); D (Weaver and Smith, 1983); E (Weaver and Michaelson, 1983); F and G, zones of "offset" in offshore magnetic anomalies (Pavoni, 1966; Atwater, 1970). N50E arrow indicates relative orientation of inferred North American-Juan de Fuca plate convergence. Cascade volcanoes are from north to south: G = Garibaldi; B = Baker, GP = Glacier Peak; R = Rainer; SH = St. Helens; A = Adams; H = Hood; J = Jefferson; TS = Three Sisters; N = Newberry; CL = Crater Lake (Mazama); M = McLoughlin; S = Shasta; L = Lassen.

Mr. Singh -

This is the Original letter,
Addressed to G. Knighton.

Molly
McHugh