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Juan de Fuca Plate Comparison
Task JFP-2

Prepared for

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Richland, Washington

By

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1.0 INTRODUCTION

Presently available geologic, seismologic, and geodetic data permit a variety of interpretations regarding the nature of interaction along the shallow interface between the Juan de Fuca and North American plates. This results in a wide range of uncertainty in assessing the seismic potential of the interface. As used in this report, seismic potential refers both to the ability of the interface to rupture and produce large earthquakes and to the magnitude of these events. Interpretations of plate interaction and seismic potential include: present-day accumulation of strain on the plate interface using trilateration data (Savage and others, 1981); a strongly coupled plate boundary with the potential for large thrust earthquakes based on comparison with other subduction zones (Heaton and Kanamori, in press); a locked plate interface interpreted from the orientation of P-axes along the Mt. St. Helens seismic zone (Weaver and Smith, 1983); aseismic subduction based on leveling surveys and tide gauge measurements (Ando and Balazs, 1979); and an unlocked subduction zone with aseismic subduction based on the lack of interplate earthquakes, the north-south orientation of P-axes of earthquake fault plane solutions, and amount of seismicity observed since 1900 (Rogers, 1983).

For most subduction zones the seismicity that has occurred during this century forms an adequate basis for evaluating the seismic potential of the zone (Ruff and Kanamori, 1980). However, the Juan de Fuca subduction zone is not known to have produced any interplate earthquakes during the historical record of approximately 150 years (Washington Public Power Supply System, 1982). This lack of interplate seismicity can be interpreted to mean that subduction is not occurring, that it is occurring aseismically, or that the zone is in the quiescent phase of a seismic cycle that is significantly longer than the historical record. Because the seismicity data alone cannot be used to unequivocally evaluate the seismic potential of the zone, and because geodetic

and geologic data are subject to alternative interpretations, other approaches to assessing seismic potential must be used.

In the absence of any single observation or set of data that uniquely defines the seismic potential of the shallow plate interface the approach taken in this report is a comparative one. A broad range of parameters encompassing seismological, geological, geophysical, and kinematic characteristics of the subduction process have been selected as the basis for comparison between the Juan de Fuca and other subduction zones. To evaluate the seismic potential of the Juan de Fuca subduction zone on a comparative basis with other zones it is necessary look at the variability in a specific subduction zone parameter for the worldwide data set, the uncertainty in the value of a specific parameter for an individual subduction zone, and the the data base for the Juan de Fuca subduction zone. This report for Task JFP-2 summarizes data from 29 subduction zones and presents a discussion of those parameters that appear to be most relevant for assessing the seismic potential of the Juan de Fuca subduction zone on a comparative basis.

2.0 COMPARATIVE DATA BASE

As part of the comparative evaluation, a data set has been assembled that contains seismologic, geologic, and geometric information in 29 categories for 29 subduction zones (Figure 1). The approach to compiling the data set has been to select subduction zones that provide information for characterizing the full range of styles of subduction zone behavior. The specific parameters listed are those that have been used by various investigators to compare aspects of subduction zone development, mechanical behavior, and evolution; only some of these parameters directly compare basic subduction zone features that relate to the evaluation of seismic potential. Parameters were selected on the basis of extensive discussions with Dr. John Kelleher, as well as informal discussions with Dr. H. Kanamori and Dr. L. Ruff. This data set provides a basis for qualitatively and quantitatively comparing characteristics of the Juan de Fuca plate with those of other subduction zones. It also serves as a basic reference source for addressing comparative subduction tectonics and for use in post-FSAR licensing activities.

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The basic data are tabulated in Tables 1A and 1B. The numbered parameters in the tables are keyed to descriptive notes and comments in Appendix A. The type and quality of data for each subduction zone are not uniform. For some zones information on a specific parameter may not be available, and this is indicated by a blank entry (dashed line). Tables 2A and 2B contain numbered references for the data points in Tables 1A and 1B, respectively. Each number is keyed to a reference in the list of references in Appendix A. The ordering of subduction zones in the tables follows the approach developed by Lay and others (1982), which ranks zones by asperity model number.

3.0 REVIEW OF PREVIOUS WORK

Although the correlations between various physical characteristics of subduction zones have been studied by numerous authors, those that are of most interest for the present evaluation relate physical characteristics of subduction zones to seismic potential. Two types of correlation have been developed. One is qualitative and groups subduction zones into broad categories such as "strongly coupled" or "weakly coupled". The other is quantitative and uses physical characteristics as a basis for estimating the size of earthquakes on a subduction zone.

3.1 Qualitative Comparisons

Kanamori (1977) and Uyeda and Kanamori (1979) placed subduction zones into broad categories in which the size of the largest historical earthquake is interpreted as an expression of the degree of coupling across the plate interface. Strong coupling means that slip and energy release across the plate interface is accomodated mainly by large earthquakes whereas weak coupling means that the relative plate motion across the interface occurs mainly through aseismic slip. The strength of coupling is inferred to be governed by the contact area between the plates and the average breaking stress of asperities (localized areas of high strength), with strong coupling resulting from large asperity area and high friction coefficient (Lay and others, 1982).

A comparative study of the seismic potential of subduction zones was made by Kanamori (1977). He noted a variation in the rupture length and magnitude of the largest interplate earthquakes among the various subduction zones of the northwest Pacific. To explain this, Kanamori (1977) proposed an evolutionary model in which a youthful, strongly coupled subduction style is gradually modified through the subduction process itself into a mature, weakly coupled subduction style that is characterized by back-arc spreading and the formation of marginal seas. Uyeda and Kanamori (1979) further examined the relationship between seismic potential and back-arc spreading. They concluded that great interplate earthquakes occur along subduction zones whose back-arc regions are not actively spreading, but do not occur along zones where back-arc spreading is active. They inferred a significant difference in the degree of coupling in these two cases, and attributed these differences to different stages of evolution of the subduction process. Kelleher and others (1974) discussed the relationship between the width of the contact zone along the interface and the length of rupture zones, and showed that regions with broad interface contact areas had the longest rupture zones and a corresponding greater degree of coupling.

Lay and others (1982) reviewed variations in the mode of rupture of large earthquakes and the degree of coupling for 20 subduction zones. Using maximum rupture length, seismicity patterns, percentage of aseismic slip, and source-time function characteristics, they characterized the stress regime in each zone to develop a framework for evaluating future large earthquake activity, and they defined four basic categories of subduction zone behavior. Category 1 is characterized by the regular occurrence of great events with rupture lengths greater than 500 km. A large percentage of the relative plate motion occurs seismically. Increased seismicity occurs prior to main events. Category 2 is characterized by variations in rupture length with occasional ruptures to 500 km, clustering of large earthquake activity, and doublets. Precursory quiescence prior to large events is frequent. Category 3 is characterized by repeated rupture over zones of 100 to 300 km in length, multiple rupture events, and complex failure zones. Recurrence intervals are 100 years long or longer. Category 4 is characterized by the absence or infrequent occurrence of large thrust earthquakes. Back-arc spreading is

known or suspected to occur, and a large percentage of aseismic slip is inferred.

3.2 Quantitative Comparisons

Ruff and Kanamori (1980) provided the first comparative study that quantitatively correlated subduction zone characteristics and seismic potential. They compared seismicity (maximum earthquake), penetration depth, length, age of the subducting lithosphere, and convergence rate for 21 subduction zones. Using multivariate regression analyses they found that the size of the largest historical interplate earthquake on a subduction zone is correlated (correlation coefficient of 0.802) with convergence rate and age of the subducting lithosphere. These two parameters are regarded as determining the horizontal and sinking rates, respectively, of slabs, and thereby influence the degree of seismic coupling in the subduction zone. Earthquake magnitudes are generally larger in subduction zones with high convergence rates and young lithosphere, and relatively aseismic subduction occurs in zones with slow rates and old lithosphere.

Heaton and Kanamori (in press) compared some of the physical characteristics of the Juan de Fuca subduction zone with other subduction zones. They conclude that the Juan de Fuca subduction zone shares many characteristics with other subduction zones that have historically generated large thrust earthquakes and that are interpreted as strongly coupled. Based on a relationship between convergence rate, plate age, and observed maximum earthquakes for worldwide subduction zones, they also suggest a possible thrust earthquake with a moment magnitude (M_w) of 8.3 $\pm$ .5 on the shallow plate interface between the Juan de Fuca and North American plates.

4.0 COMPARISON BETWEEN THE JUAN DE FUCA AND OTHER SUBDUCTION ZONES

Heaton and Kanamori (1983; in press) use comparisons between convergence rate and age of subducted lithosphere, back arc spreading, depth of seismicity, depth of the oceanic trench, dip of the Benioff zone, topography of the subducted slab, presence of an accretionary prism, uplift of the overriding

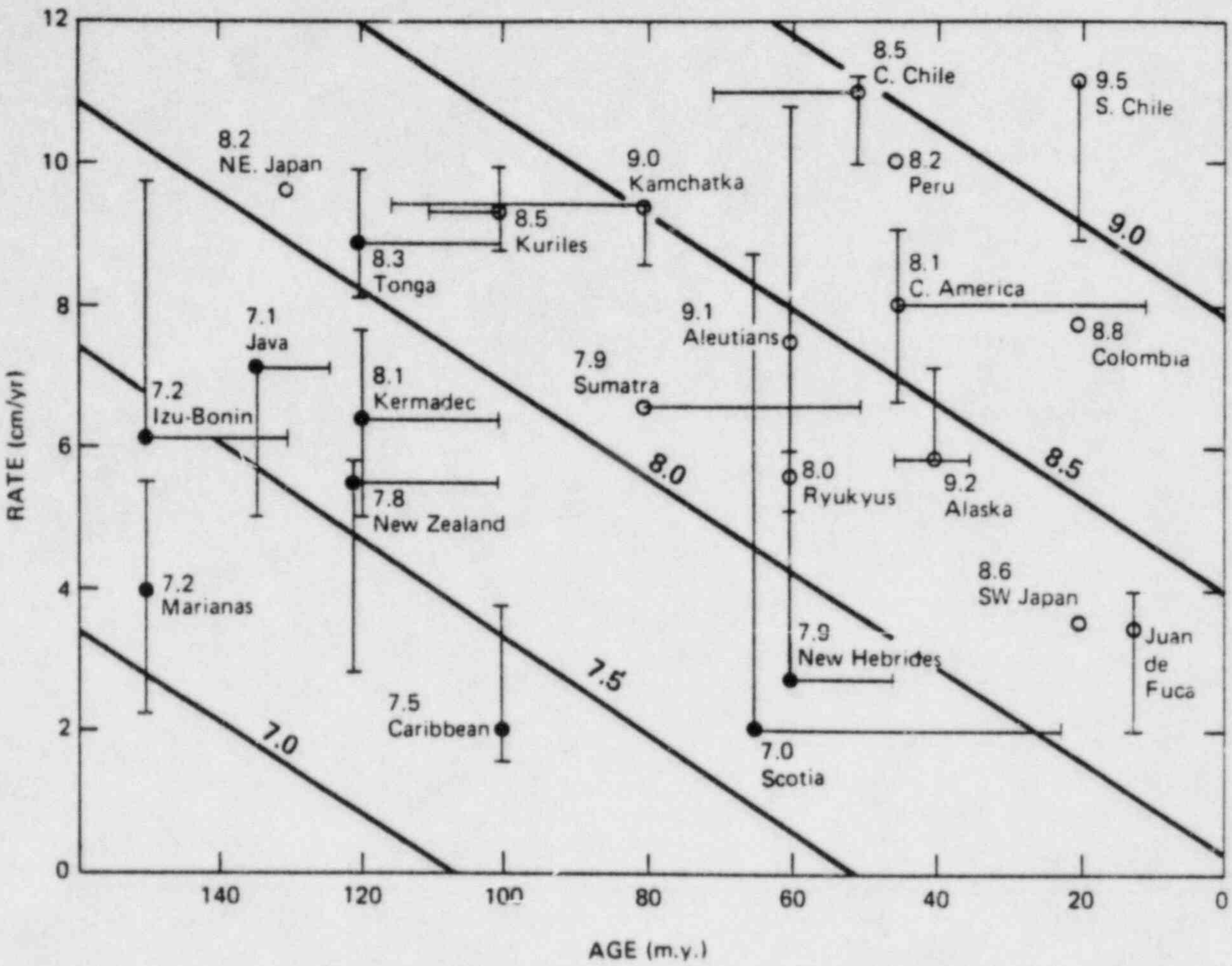
plate, and seismic quiescence to evaluate the degree of seismic coupling across, and estimate potential maximum earthquake on, the shallow Juan de Fuca-North American plate interface. This section discusses these parameters (Sections 4.1 to 4.7), and others that may have a bearing on evaluating seismic potential such as focal mechanisms in the subducting plate in the vicinity of the trench, focal mechanisms in the overriding plate, focal mechanisms in the back arc region, transverse structures and segmentation, and heat flow (Sections 4.8 to 4.12).

Two types of parameters are used in the comparison. The first are parameters that may directly affect the nature of plate interaction and the degree of coupling. These include convergence rate, lithospheric age, topography of the subducting slab, transverse structures, and heat flow. The other parameters are characteristics that may express, or result directly from, the nature of plate interaction and the degree of coupling.

4.1 Convergence Rate and Age of Subducting Lithosphere at the Trench

Ruff and Kanamori (1980) developed an empirical correlation between the magnitude (M_w) of the largest historical earthquake on an individual subduction zone, convergence rate, and age of the subducting lithosphere. Figure 2 shows regression curves for magnitude on convergence rate and plate age. The general trend in this relationship is an increase in magnitude as convergence rate increases and the age of the subducted lithosphere decreases. Ruff and Kanamori (1980) concluded that convergence rate and lithospheric age may control the degree of coupling and the size of the largest earthquakes that can occur. Heaton and Kanamori (in press) used this relationship to estimate the maximum moment magnitude for the Juan de Fuca subduction zone. Using values of 3 to 4 cm/yr for convergence rate and 10 to 15 m.y. for age they obtained a maximum magnitude value of 8.3 $\pm$ .5.

Several aspects of this relationship should be carefully considered in applying it to the Juan de Fuca subduction zone and in using it to calculate precise maximum earthquake magnitudes. The Juan de Fuca subduction zone has several characteristics that distinguish it from other zones used to establish



RELATION OF MAXIMUM ENERGY MAGNITUDE, Mw, TO CONVERGENCE RATE AND AGE OF SUBDUCTED LITHOSPHERE: CONTOURS OF Mw ARE PREDICTED MAXIMUM EARTHQUAKES MAGNITUDES BASED ON LINEAR REGRESSION OF OBSERVED MAXIMUM EARTHQUAKE MAGNITUDE ON CONVERGENCE RATE AND AGE; DOTS AND CIRCLES ARE SUBDUCTION ZONES WITH AND WITHOUT BACK ARC SPREADING, RESPECTIVELY (from Heaton and Kanamori, in press). ERROR BARS SHOW THE POSSIBLE RANGE OF VALUES FOR CONVERGENCE RATE AND AGE FOR EACH SUBDUCTION ZONE (see Table 1B)

Project No. 15529A	Satsop Licensing	SUBDUCTION ZONE MAGNITUDE–CONVERGENCE RATE–AGE RELATIONSHIP	Figure 2
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the relationship. The age of the subducting lithosphere at the trench (9 my) is younger by a factor of two than the youngest lithosphere for other zones. There is also a complete absence of known interplate earthquakes along its entire length. Although the age is compatible with strong coupling, the convergence rate is low. The combined rate and age parameters for the Juan de Fuca subduction zone place it in an extreme part of the relationship for which there are few other data.

The values for convergence rate and lithosphere age that are used in the regression analysis are also subject to considerable variability. The range in published convergence rates and ages of subducting lithosphere for individual subduction zones is listed in Table 1B and is shown by error bars on Figure 2. Because of this, the standard deviation may be larger than .4 magnitude units. While magnitude appears to increase with increased convergence and decreased age in a general way, the calculation of precise potential maximum earthquakes for the Juan de Fuca plate using this relationship may be subject to considerable error.

4.2 Back-Arc Spreading

Kanamori (1977) and Uyeda and Kanamori (1979) suggest that the presence or absence of back-arc spreading is a reflection of the degree of coupling between the upper and lower plates, and that great thrust earthquakes occur only along subduction zones where back-arc spreading is absent. Ruff and Kanamori (1980) show that back-arc spreading and formation of marginal basins are associated with subduction zones that have slower convergence rates and older lithosphere. They note that smaller magnitude earthquakes are associated with these zones and interpret this to be a reflection of weak coupling and partial aseismic subduction.

Back-arc spreading is not known to be occurring behind the volcanic arc in the Pacific Northwest. However, as discussed in Sections 4.9 and 4.10, the tensional axes of earthquakes in the overriding plate and back-arc region are oriented generally east-west or vertical, suggesting extension in the overriding plate and a low degree of coupling across the plate interface.

4.3 Depth of Seismicity

Ruff and Kanamori (1980) correlated penetration depth with maximum earthquake magnitude, convergence rate, and age of the subducted plate for 21 subduction zones. The correlations between depth and earthquake magnitude and depth and convergence rate are poor and have correlation coefficients of .287 and .118, respectively. The correlation coefficient between depth and age, on the other hand, is .837.

Heaton and Kanamori (in press) refer to this parameter (penetration depth) as depth of seismicity and note that three out of the four subduction zones that have produced historical earthquakes of $M_w \geq 9.0$ have maximum depths of seismicity of less than 200 km. They also note the shallow depth of seismicity for the Juan de Fuca zone of approximately 100 km and state that this is characteristic of subduction zones with strong coupling. However, review of the Ruff and Kanamori (1980) data base shows that only two zones with maximum earthquakes $\geq$ 9.0 have penetration depths of less than 200 km. These are Alaska and southern Chile with depths of 140 and 160 km, respectively. Given the poor correlation between penetration depth and the maximum observed earthquake magnitude, and the observation that thrust earthquakes occur along the plate interface in the upper 35 to 40 km, it appears that penetration depth (depth of seismicity) does not provide a basis for evaluating seismic potential.

4.4 Trench Bathymetry

Heaton and Kanamori (in press) cite Uyeda and Kanamori (1979) as suggesting that a) strongly coupled subduction zones are accompanied by shallow oceanic trenches, while weakly-coupled subduction zones are accompanied by very deep oceanic trenches, and b) free-air gravity anomalies tend to be larger for those trenches with weak seismic coupling. A review of Uyeda and Kanamori (1979) shows that they do not systematically correlate, or even discuss, the relationship between trench bathymetry, seismicity, and coupling. They only show a shallow trench and a deep trench associated with Chilean and Mariana-type subduction zones, respectively, in a conceptual end-member cross-section

(their Figure 7). Uyeda and Kanamori (1979) also recognized that there are problems in both observations and models of the outer gravity high, and they state that final conclusions must await further investigation. Nonetheless, Heaton and Kanamori (in press) note that the trench offshore of the Pacific Northwest is a relatively subtle topographic feature and that the free air gravity anomaly over the trench is lower than from some other subduction zones. On this basis they conclude that these features corroborate the interpretation that the Juan de Fuca subduction zone is strongly coupled and capable of large, shallow thrust earthquakes.

In the Pacific Northwest, a bathymetric trench is not present at the base of the continental slope offshore of Washington and Oregon. However, Scholl (1974) suggests that a structural trench exists but is filled by approximately 1 to 2 km of Miocene to Quaternary sedimentary deposits. Near the southern edge of the Astoria fan, a flat-lying terrigenous sequence of middle to late Pleistocene fan deposits forms a turbidite wedge that overfills the axial part of the trench and thins westward (Scholl, 1974). Scholl (1974) suggests that the rapid infilling of the central portion of the Washington-Oregon trench began less than 1 m.y. ago.

Riddihough (1979) compiled gravity anomaly data for the Pacific Northwest and compared it to the characteristics of gravity fields over oceanic-continental subduction boundaries around the world. The gravity anomaly pattern in the Pacific Northwest that is parallel to the coast is expressed as a linear low-high pair having an amplitude of about 1000 milligals. The amplitude of the anomaly pair is in the low range for most active subduction boundaries, which Riddihough (1979) suggests may reflect infilling of the trench. Riddihough (1979) notes that the 120 km wavelength of the pair is comparable to the pattern observed at world-wide active margins.

The rapid filling of the Washington-Oregon trench in the past 1 m.y. may reflect high sedimentation rates related to glacial periods (von Huene, 1974), or a reduction in convergence rate (Riddihough, 1981). There appears to be little statistical or physical basis for correlating shallow trenches with strong coupling. In fact, filled trenches are associated with subduction

zones that have had extremely limited historical seismicity, such as Chile between 46° and 52°S and the southern Lesser Antilles (Table 1B; Section 4.6).

4.5 Dip of Benioff Zone

Yokokura (1981) reviewed 28 subduction zones and subduction zone segments and correlated dip angle with slab length, penetration depth, relative plate velocities, absolute velocity of the descending plate, absolute velocity of the upper plate, and dip direction of the slab. He concluded that the dip angle is strongly controlled by the negative buoyancy force of the descending slab and by the relative velocity of the two converging plates. Heaton and Kanamori (in press) cite Uyeda and Kanamori (1979) as concluding that strong seismic coupling is usually associated with subduction zones having relatively gentle dip angles. They state that the 10 to 15 degree dip of the subducted slab beneath Puget Sound is characteristic of subduction zones with strong seismic coupling.

Uyeda and Kanamori (1979) proposed an evolutionary sequence of subduction zone development ranging from "Chilean" to "Mariana" type zones and showed that dip angles were shallower in the more strongly coupled Chilean type zone. However, the part of the Benioff zone used for the comparison of dips was deeper than 100 km, well below the depth at which interplate thrust events occur. No discussion was made of the variability in the dip of the shallow interface or of the bend and steepening in dip of subducting slabs that often occurs in the depth range of 35 to 40 km. Therefore, the conclusion by Heaton and Kanamori (in press) that the dip angle of the shallow interface is characteristic of strong coupling needs to be carefully qualified.

4.6 Seafloor Topography

Kelleher and McCann (1977) suggest that the subduction process may be modified by the interaction of topographic features of the subducting seafloor with the overriding plate. They note that large rupture zones are associated with smooth seafloor topography and an absence of large transverse structures segmenting the zone. Lay and others (1982) have similarly noted that very

large subduction earthquakes tend to occur in regions where the subducted plate has smooth topography. They explain this observation in terms of an asperity model in which irregular seafloor topography produces a heterogeneous strength distribution that limits the occurrence of large rupture events. The Juan de Fuca plate is topographically smooth and relatively featureless, and Heaton and Kanamori (in press) interpret this as indicating that the subduction zone is strongly coupled.

As discussed in Section 4.4, a thick sedimentary sequence fills the trench. Thick sedimentary prisms and filled trenches are observed in the southern Lesser Antilles subduction zone and in the Chile subduction zone between 46° and 52°S. The largest earthquake associated with the southern Antilles zone was a magnitude 7 1/2 in 1888 and seismicity has been extremely sparse during this century; southern Chile appears to be aseismic. Stein and others (1982) suggest that a thick sedimentary sequence may modify the subduction processes and perhaps act to inhibit subduction in the southern Caribbean. Therefore, while smooth topography may be a necessary condition for the occurrence of very large earthquakes, it alone is not an expression of strong coupling. Conversely, the presence of a thick sedimentary sequence may act to modify subduction.

4.7 Preseismic Quiescence

Preseismic quiescence in the epicentral region of large interplate earthquakes is commonly observed (Kanamori, 1981). This is referred to as a seismic gap of the second kind (Mogi, 1979). In some cases, the quiescent region is surrounded by an active region termed a doughnut (Mogi, 1979). Other changes in seismicity that are observed to occur before some large interplate earthquakes include precursory swarms, foreshocks, and clustering of activity.

In order to recognize quiescence in a subduction zone prior to the occurrence of a large earthquake, it is necessary to establish that earthquakes would have been detected if they had occurred during the preseismic period. Because the preseismic period extends back to times when earthquake detection capability was poor in some subduction zones, it is difficult to establish the

existence of preseismic quiescence in these zones. This is the case for subduction zones that experienced large earthquakes at the turn of the century, such as for the southern Lesser Antilles earthquake of 1888 and the North Peru-South Ecuador earthquake of 1901. It is also true of subduction zones that have had more recent earthquakes but for which seismicity data are not available, or for which space-time plots of seismicity have not yet been compiled from available data. Examples of such cases are the 1932 Rivera earthquake, the 1935 Sumatra earthquake, and the 1953 Java earthquake. In other subduction zones, the seismic detection capability prior to the occurrence of large earthquakes has been sufficient to identify the approximate onset and duration of a period of seismic quiescence. Examples of such subduction zones are Kamchatka during the period 1920- 952, southern Chile between 1952 and 1960, and Alaska between 1944 and 1954 (Kelleher and Savino, 1975), and the Nankai Trough between 1924 and 1944 (Kanamori, 1981). The longest reported duration of quiescence prior to a large subduction zone earthquake is the 32-year period preceeding the M_w 9.0 Kamchatka earthquake of 1952 (Kelleher and Savino, 1975).

There exists no historical record of earthquakes anywhere along the boundary between the Juan de Fuca and North American plates that could be interpreted as large thrust events of the kind typically associated with relative motion on an interface zone. The period of time for which such an event would have been documented, had it occurred, is longer than 150 yrs. In addition, the shallow plate interface lacks the smaller-magnitude earthquakes that would be expected to define a typical interface zone. From local network data in northern Washington (Crosson, 1983) and southern Vancouver Island (Milne, 1981, personal communication), and from a local microearthquake array (Washington Public Power Supply System, 1974), only scattered earthquakes with low ($M \leq 4$) magnitudes are observed near the inferred plate interface. None of these was large enough to permit the determination of focal mechanisms. There is also striking variability in the distribution of seismicity within the slab along the length of the plate boundary. The geometry of the subducted slab beneath Washington is based on the projection of seismicity to a plane centered on southern Puget Sound, and the aperture for the projection is 300 km. In contrast, the geometry of the subducted slab is not defined

beneath Oregon because there is an almost complete absence of seismicity, including intraplate events, along this 400 km segment of the arc (Weaver and Smith, 1983).

Heaton and Kanamori (in press) state that the best examples of quiescence are observed along boundaries that have experienced great earthquakes but could presently be considered locked. They note that because the entire plate interface of the Juan de Fuca subduction zone is seismically quiescent it can be inferred to be in a state of preseismic quiescence. They conclude that if aseismic subduction is occurring along the shallow Juan de Fuca-North American plate interface it would have to be considered a unique example. As discussed in Section 4.11, the subducted Juan de Fuca plate may be comprised of at least three segments, each with its own geometry and behavior. If this is the case, 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.

4.8 Focal Mechanisms in the Subducting Plate in the Vicinity of the Trench

Christensen and Ruff (1983) reviewed worldwide data on the occurrence of outer-rise earthquakes (events within the oceanic plate in the vicinity of the trench) and related them to seismic coupling in subduction zones. They suggested that in strongly coupled subduction zones, large subduction zone earthquakes are sometimes preceded by compressional outer-rise earthquakes, and are often followed by tensional outer-rise earthquakes that result from transmittal of tensional stress by slab pull. In contrast, in zones that are weakly coupled only tensional outer-rise events occur as a result of constant

slab pull; these events can occur at anytime and are not related to thrusting on the interface.

The magnitude 5.6 (m_b), 5.1 (M_L) earthquake of 16 June 1973, which occurred approximately 60 km west of the trench off Oregon, has a tensional mechanism with T-axis oriented northeast normal to the trench. This earthquake could be classified as a tensional outer-rise event and it is clearly unrelated to a subduction zone earthquake. This is characteristic of weakly coupled subduction zones; however, the degree of coupling cannot be assessed on the basis of one event.

4.9 Focal Mechanisms in the Overriding Plate

The focal mechanisms of earthquakes in the overriding plate above the shallow plate interface generally show horizontal compression normal to the arc, reflecting strong coupling of stress across the plate interface (Yoshii, 1979). This stress level is expected to be highest just before large interplate earthquakes. When the coupling of stress across the plate interface is weak (which may occur immediately after a large earthquake in a strongly coupled subduction zone, or which may be the normal state in a weakly coupled subduction zone), focal mechanisms in the overriding plate may reflect the orientation of stresses within the overriding plate that originate within that plate.

Focal mechanisms of earthquakes within the overriding North American Plate in Washington indicate a dominant north-south horizontal compressional stress field throughout the region. This is consistent with weak coupling between the Juan de Fuca and the North American plates. In contrast, Weaver and Smith (1983), based on focal mechanisms of shallow crustal earthquakes along the Mt. St. Helens seismic zone, infer a northeast direction of maximum compression that is approximately parallel to the direction of plate convergence. They interpret the focal mechanism data as evidence of a locked subduction zone.

The focal mechanisms of Weaver and Smith (1983) are exceptions to the general north-south trend, and may be an expression of the tectonics within the

volcanic chain. All but two of their eight events have focal depths of less than 10 km. A study of focal mechanisms by Yellin (1982) in the Puget Sound region showed that shallow crustal events in the depth range of 0 to 8 km have widely variable P-axis orientations, ranging from northwest to northeast. This suggests that the stress field at shallow crustal depths in the North American plate is heterogeneous. However, the P-axes of events in the North American plate in the depth range of 15 to 26 km, are oriented uniformly north-south beneath the Puget Sound region (Yellin, 1982). These deeper events are located closer to the interface between the North American and Juan de Fuca plates, and should provide a better expression of the state of stress across the interface. The observation that the P-axes are oriented north-south is not consistent with strong coupling, for which a northeast orientation of the P-axes would be expected.

4.10 Focal Mechanisms in the Back-Arc Region

The presence of back-arc spreading is believed to be an important indication of the degree of coupling in subduction zones (Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980). Weakly coupled subduction zones are characterized by the presence of spreading. Focal mechanisms of earthquakes in the back-arc region can provide estimates of contemporary stress orientation in the region, and thus complement the interpretation of back-arc tectonics based on other geological and geophysical observations.

There is no back-arc spreading associated with the Juan de Fuca subduction zone. Focal mechanisms of earthquakes landward of the volcanic chain (back-arc region) of the Juan de Fuca subduction zone are characterized by north-south compression, with tensional axes ranging from vertical to east-west. This suggests the possibility of extension behind the arc, consistent with a low degree of coupling across the shallow plate interface.

4.11 Transverse Structures/Segmentation

As shown in Table 1B, many subduction zone are segmented. Segmentation may result from the intersection of transverse topographic or bathymetric features

with a trench, particularly aseismic ridges. Segmentation in the form of warps, bends, or breaks in the downgoing slab may also occur as a result of major changes in the orientation (curvature) of a zone along its strike. Weaver and Michaelson (1983), on the basis of changes in earthquake distribution, style and volume of late Cenozoic and Quaternary volcanism, and teleseismic P-wave delay patterns, suggest that the Juan de Fuca plate is divided into at least three segments along northeast striking boundaries. The segments extend from Mt. Rainier north, Mt. Rainier to Mt. Hood, and from Mt. Hood south. They interpret the data as indicating a steeper dip of the slab at Mt. Hood with associated extensional tectonics, a shallower zone north of Mt. Ranier with associated compressional tectonics, and a transition zone in between. They suggest that segment boundaries roughly parallel offsets in marine magnetic anomalies offshore

In reviewing gravity data for the Pacific Northwest, Riddihough (1979) noted that between 42°N and about 45.5°N the width of the negative anomaly is relatively narrow and coincides with the base of the continental slope. Between 45.5°N and about 47.5°N, the maximum negative anomaly decreases in amplitude and steps eastward beneath the continental slope. Riddihough (1979) suggests that these changes may be related to spatial variation in the geometry of the subducted slab. Based on these observations and the assumption that the gravity minimum defines the location of the structural trench, it was suggested that the changes in continuity and amplitude of the anomaly might also reflect segmentation of the subducted slab (WPPSS, 1982). The locations of these changes are generally coincident with segment boundaries proposed by Weaver and Michaelson (1983).

Kulm (1983) and Kulm and Embley (1983) describe significant differences in the bathymetry, morphology, and structural evolution of the continental shelf and slope between southern Washington and central Oregon. The morphology of the lower continental shelf off southern and south central Oregon is characterized by relatively steep escarpments. At about 44.5°N it changes to prominent elongate north-northwest trending ridges and intervening basins, referred to as the ridge and basin province, which extends the length of the lower continental slope off Washington. The change at 44.5°N is approximately

concident with Weaver and Michaelson's (1983) proposed boundary between the southern and central Juan de Fuca plate segments.

Segmentation of the Juan de Fuca plate has implications for assessing seismic potential. If the plate is segmented, each segment may have a distinctly different geometry and behavior. The occurrence of segments suggests that the potential for rupture of the entire shallow interface is remote. Instead, segments may limit rupture and/or delimit potential rupture segments. Recognition of segments may provide an important basis for constraining fault parameters, especially potential rupture length, that can be used to estimate potential earthquake magnitudes. In addition, the occurrence of distinct segments affects the estimation of earthquake recurrence along the length of the boundary.

4.12 Heat Flow

Heat flow for oceanic crust adjacent to trenches is listed in parameter 29. In general, the heat flow for these areas generally averages less than 75 mW/m^2 (1.79 $\mu cal/cm^2$-sec). Korgen and others (1971) showed that heat flow in the east Cascadia Basin ranged from 54 (1.31) to 148 (3.55) and averaged 101 (2.43). Connard and others (1983) show that heat flow in the Cascadia Basin varies from 100 to 300 and, on the basis of generalized contours, indicate that values of 100 to 200 occur along the entire length of the oceanic plate west of the base of the continental slope. In addition, values of 40 to 142 are measured on the lower slope of central Oregon.

Kulm (1983) states that heat flow values for the Juan de Fuca plate are significantly higher than those observed in normal ocean basins. This is likely a result of the thick sedimentary sequence overlying the young warm basalt crust, which impedes loss of heat by convective processes such as hydrothermal circulation. Kulm (1983) also states that the heat flow values for the lower slope are a factor of two to three higher than those typically associated with forearc regions in other subduction zones.

The measured heat flow for the Juan de Fuca plate is high with respect to the heat flow from other subduction zones. Sacks (1983) discusses the subduction of young lithosphere and concludes that the difference in temperature between the subducted slab and overriding plate controls the basalt-eclogite transformation and affects the buoyancy of the downgoing slab; slabs with ages less than 20 million years are probably buoyant. The degree to which buoyancy may affect seismic potential is uncertain. It is noted that the available heat flow data for the Juan de Fuca plate are from off of south central Oregon, directly opposite a section of the plate interface along which the subducted slab is not defined by seismicity data. Modeling of the offshore heat flow as an expression of temperature at depth could be important for evaluating mechanical and physical properties of the interface, especially in regard to brittle versus ductile behavior of the plate interface. This is particularly relevant for evaluating coupling and seismic versus aseismic slip along the interface.

5.0 SUMMARY

Thirteen subduction zone parameters have either been used by other investigators to categorize the seismic potential of subduction zones or appear to be useful in evaluating seismic potential. These are: convergence rate, lithosphere age, back-arc spreading, depth of seismicity, trench bathymetry, dip of the Benioff zone, seafloor topography, preseismic quiescence, focal mechanisms in the subducting plate in the vicinity of the trench, focal mechanisms in the overriding plate, focal mechanisms in the back arc region, transverse structures/segmentation, and heat flow.

Convergence rate, lithosphere age, transverse structures/segmentation, and heat flow are inherent characteristics of the subducting slab that can directly affect the nature of plate interaction and seismic potential. For the Juan de Fuca subduction zone the youthfullness of the oceanic crust and the high heat flow suggest that the subducting slab is buoyant, which may be suggestive of strong coupling. Conversely, the high heat flow may affect the style of deformation (brittle versus ductile) along the interface, and this is a factor in evaluating the alternatives of seismic and aseismic subduction.

The occurrence of segments with distinct lengths and down-dip geometries directly affects not only potential rupture lengths and earthquake size, but also earthquake recurrence for the zone.

The remaining parameters are an expression, both direct and indirect, of the style and rate of plate interaction. As discussed in Section 4.0, the correlations between seismic potential and depth of seismicity, trench bathymetry, dip of the Benioff zone, and seafloor topography are weak. Focal mechanisms in the outer-rise region, the overriding plate, and the back arc region may be expressions of the state of stress and nature of coupling. These data for the Juan de Fuca subduction zone are compatible with weak coupling; however, the data are sparse and are subject to alternative interpretation. The absence of back-arc spreading supports strong coupling across the shallow plate interface. On the other hand, seismic quiescence along the zone is remarkeable given the length of the historical record, the convergence rate, and the contact area of the shallow interface. While this does not demonstrate aseismic subduction, it is compatible with aseismic subduction.

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.

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APPENDIX A

DESCRIPTION OF SUBDUCTION ZONE PARAMETERS

TABLES 1A AND 1B

INTERPLATE SEISMICITY (TABLE 1A)

1. Subduction Zone Category. There is wide variation in the size of the largest interplate earthquake in different subduction zones. Ruff and Kanamori (1980) interpret this as representing significant differences in coupling between plates. The variations have been described and explained by an asperity model (Lay and others, 1982), in which a suite of subduction zone characteristics is used to define four subduction zone categories. Category 1 is characterized by the regular occurrence of great events with rupture lengths greater than 500 km. A large percentage of the relative plate motion occurs seismically. Increased seismicity occurs prior to main events. Category 2 is characterized by variations in rupture length with occasional ruptures up to 500 km, clustering of large earthquake activity, and doublets. Precursory quiescence prior to large events is frequent. Category 3 is characterized by repeated rupture over zones of 100 to 300 km in length, multiple rupture events, and complex failure zones. Recurrence intervals are commonly 100 years longer. Category 4 is characterized by the absence or infrequent occurrence of large thrust earthquakes. Back-arc spreading is known or suspected to occur, and large ratios of aseismic slip are inferred.

   The subduction zones in Tables 1A and 1B are ordered according to these categories. Four subduction zones not treated by Lay and others (1982) have here been assigned the category number 4, which is shown in parentheses. All four of these are characterized by the infrequent occurrence or absence of large events.

2. Largest Magnitude (M_S or M_W). This category contains the largest known interplate earthquake and its year of occurrence. All of the events, except those for the Nankai Trough and southern Lesser Antilles, occurred during this century. Magnitudes for the pre-1900 events are estimated from intensities. There is some uncertainty as to whether the 1888 southern Lesser Antilles, 1929 Marianas, and 1953 Java earthquakes are thrust or intraplate events. Also, the 1932 Rivera plate earthquake may

have ruptured the northern end of the Cocos plate (Mexico zone) rather than the Rivera plate (Elssler and McNally, in press). Earthquake magnitudes range from 7.1 to 9.5.

3. Maximum Rupture Length (km). The largest known rupture lengths are listed for interplate earthquakes. References to figures showing rupture locations and lengths are listed in Table 2A. Rupture lengths vary from less than 100 km to 1000 km, and lengths of 100 km to 200 km are most common.

4. Repeat Time. The repeat time represents the interval between large events that rupture nearly the same part of a plate boundary. It is derived from historical and instrumental seismicity data. Some of the earlier earthquakes used in estimating repeat times have not been definitely established as interplate earthquakes. However, the sizes of the largest earthquakes are such that it is unlikely that many of them are intraplate events.

5. Seismic Slip (%). This category represents the percentage of relative plate convergence that occurs seismically in large or great interplate earthquakes, as discussed by Lay and others (1982). It is the ratio of the seismic slip rate to the convergence rate. Seismic slip rate is estimated from the cumulative seismic moment released along a subduction zone during interplate earthquakes.

6. Aseismic Segments and Zones. For some subduction zones, the rupture zones of the largest earthquakes tend to cover the entire length of the plate interface without appreciable overlap. In this case, a segment of the plate interface that has not ruptured recently in a large earthquake may be identified as the likely site for the next large event. Such a segment is termed a seismic gap of the first kind (Mogi, 1979), and denotes a segment along the plate boundary that has not ruptured recently but lies adjacent to segments that have.

Some subduction zones contain segments that have not ruptured in large earthquakes during this century, although adjacent segments have ruptured. These segments could be identified as seismic gaps. However, the absence of previous large earthquakes on these segments, and their association with features such as bathymetric highs on the subducting slab (Kelleher and McCann, 1976) suggest that these segments may be more appropriately regarded as aseismic segments, where the term "aseismic" indicates the absence of large earthquakes. Small interplate earthquakes may occur along aseismic segments.

In some subduction zones, there has been a complete absence of great or large interplate earthquakes along the complete length of the zone during this century. These zones are referred to as aseismic zones, where "aseismic" means the absence of large earthquakes. Small interplate earthquakes may occur in aseismic subduction zones. These subduction zones are regarded as lacking the potential to produce great or large subduction zone earthquakes (Kelleher and McCann, 1976; Ruff and Kanamori, 1980).

Aseismic segments and aseismic zones have been identified by McCann and others (1979) and are placed in Category 5 of their evaluation of the seismic potential of major plate boundaries. This category contains subduction zone segments and entire zones that have no historical record of a great earthquake and that may not have the potential for such earthquakes.

Based on the descriptions given above, notation is made in parameter 6 where data suggest that a subduction contains an aseismic segment or segments, or where the entire zone may be classified as aseismic.

7. Preseismic Quiescence. The seismicity of the shallow plate interface typically shows a considerable degree of temporal and spatial variation. Some of these variations are attributed to changes that occur before and after large interplate earthquakes, and take various forms including precursory swarms, preseismic quiescence, "doughnut" patterns

of seismicity, foreshocks and aftershocks (Kanamori, 1981). These variations may be viewed as perturbations on the background seismicity that characterizes the plate interface during the interval between large earthquakes. Preseismic quiescence and doughnut patterns are termed seismic gaps of the second kind by Mogi (1979), and represent a temporal decrease in the frequency of smaller magnitude earthquakes before large earthquakes. The longest reported duration of quiescence prior to a large subduction zone earthquake is the 32-year period preceding the M_W 9.0 Kamchatka earthquake of 1952 (Kelleher and Savino, 1975).

Parameter 7 lists the available data for the longest known period of quiescence associated with an earthquake, which is identified by its year of occurrence. In addition, Table 2A contains references to space-time seismicity diagrams in which preseismic quiescence gaps may be identified.

8. Interplate Focal Mechanisms. Earthquakes located on the shallow plate interface that have focal mechanisms indicative of interplate thrust faulting are a direct indicator of relative motion between plates. Interplate focal mechanisms of earthquakes located on the shallow plate interface are generally observed over the entire range of observed earthquake magnitudes, from great earthquakes to the microearthquake level.

Parameter 8 qualitatively characterizes the occurrence of earthquakes other than large or great events that have interplate focal mechanism solutions. References to figures showing seismicity cross-sections and seismicity distribution are listed in Table 2A. There is a considerable degree of variability in the quality and quantity of data available for characterizing this parameter. The quality of data may range from excellent, where local seismograph networks have been operated for a significant period of time and many studies have been made, to poor where any teleseismic data are available and few studies have been made. Where data are of poor quality or unavailable no information is entered.

9. Interface Definition. The shallow plate interface is typically delineated by a planar distribution of earthquake hypocenters. Parameter 9 notes the degree to which the plate interface is delineated by earthquake hypocenters. References to seismicity cross-sections of subduction zones are given in Table 2.

BENIOFF ZONE SEISMICITY (TABLE 1A)

The Benioff zone as defined by Davies and House (1979) is the more steeply dipping part of a subducted plate, which lies adjacent to, and down-dip from, the shallow plate interface. It is typically delineated by a spatially and temporally uniform distribution of earthquakes. These are intraplate earthquakes that reflect the internal deformation of the subducted plate. The transition from interplate faulting on the shallow plate interface to intraplate faulting within the subducted slab on a worldwide basis occurs in the depth range of 35 to 70 km.

10. Largest Magnitude (M_S or M_W). The largest known Benioff zone earthquake in the depth range 35 to 70 km and its year of occurrence are listed.

11. Shallowest Depth. The shallowest depth of earthquakes having intraplate focal mechanisms is listed. This depth appears to define the updip extent of the Benioff zone.

INTRAPLATE STRESS NORMAL TO ARC

12. Focal Mechanisms in the Benioff Zone. Intraplate stress has been used by as an indicator of the interplate stress regime and degree of coupling (Ruff and Kanamori, 1980). The state of stress in the shallower part of the Benioff zone, determined from the focal mechanisms of earthquakes not more than 100 km deep, is listed. P denotes compressional stress (maximum compressional axis) and T denotes tensional stress (minimum compressional axis).

13. Focal Mechanisms in the Subducting Plate in the Vicinity of the Trench. The stress normal to the arc in the vicinity of the trench, as inferred from focal mechanism solutions, is characterized in Parameter 13. P denotes compressional stress, T denotes tensional stress, and N denotes the absence of earthquakes. In strongly coupled subduction zones, large interplate earthquakes are sometimes preceded by compressional intraplate earthquakes and are often followed by intraplate earthquakes in the vicinity of the trench having horizontal tensional axes oriented normal to the trench (Christensen and Ruff, 1983). In contrast, weakly coupled subduction zones are characterized by the occurrence of temporally isolated tensional earthquakes in the vicinity of the trench.

14. Focal Mechanisms in the Overriding Plate. Parameter 14 lists the general orientation of stress within the part of the overriding plate that lies above the shallow plate interface, as determined from earthquake focal mechanisms. P denotes compressional stress and T denotes tensional stress. Focal mechanisms of earthquakes in the overriding plate above the shallow plate interface generally show horizontal compression normal to the arc, reflecting strong coupling of stress across the plate interface (Yoshii, 1979). This stress level is expected to be highest just before large interplate earthquakes. When the coupling of stress across the plate interface is weak (which may occur immediately after a large earthquake in a strongly coupled subduction zone, or which may be the normal state in a weakly coupled subduction zone), focal mechanisms in the overriding plate may reflect the orientation of stresses that originate within the overriding plate.

15. Focal Mechanisms in the Back-Arc Region. Based on focal mechanism solutions, the orientation of stress in back-arc regions are characterized and listed. P denotes compressional stress and T denotes tensional stress. Focal mechanisms of earthquakes in the back-arc region can provide estimates of contemporary stress orientation in the region, and thus complement the interpretation of back-arc tectonics based on other geological and geophysical observations.

GEOLOGIC/GEOMETRIC CHARACTERISTICS (TABLE 1B)

16. Convergence Rate (cm/yr). Convergence rates are given in cm/yr. For individual subduction zones, there is generally a range in published convergence rates. In some zones the convergenece rate does vary along the length of the zone.

17. Age of Subducting Lithosphere at Trench (my). The age of the subducting lithosphere at the trench is listed. For individual subduction zones published ages vary from only a few to as much as 30 percent. For some zones the age of the lithosphere entering the trench varies along the strike of the trench.

18. Velocity of Upper Plate with Respect to the Trench (cm/yr). This parameter represents values of the horizontal velocity (cm/yr) of the overriding plate normal to the trench, assuming the trench to be fixed relative to the mantle. A negative sign indicates divergence and no sign indicates convergence.

19. Motion Vector. The direction of motion of the subducting plate with respect to the trench is indicated qualitatively as normal or oblique. For some subduction zones this changes along the length of the zone.

20. Back Arc Spreading. The occurrence or lack of back-arc spreading for each subduction zone is listed under this parameter. Uyeda and Kanamori (1979) suggest that the occurrence or lack of back-arc spreading is a reflection of the degree of coupling between the upper and lower plates, and that great thrust earthquakes occur only along zones in which back-arc spreading is absent.

21. Seafloor Topography. This parameter lists a qualitative description of the topography of the sea floor that is being subducted. It is described in terms of general smoothness, presence of seamounts, overall relief, presence of ridges, and presence of thick sedimentary prisms.

22. Transverse Structures/Segmentation. The occurrence of transverse structures, including ridges and fracture zones, that may affect the distribution of seismicity, the style of subduction, or segmentation of the zone, are listed. It is apparent that to varying degrees, and by a variety of processes, many subduction zones are segmented. For some zones, such as the New Hebrides, it has been suggested that segment boundaries delimit rupture zones; in others, either the relationship between segment boundaries and the extent of rupture is uncertain, or ruptures have crossed apparent segment boundaries.

23. Trench Bathymetry. The general bathymetry of the trench is qualitatively described. Notation is made where trenches are filled with sediment.

24. Dip of Subducted Slab. Published values for the dips of subducted slabs are listed. In most cases the dip refers to the deeper part of the slab. There is generally sparse information on the dip of the shallow interface or on changes in dip with depth that allow a bend in the slab to be precisely located.

25. Penetration Depth (km). The penetration depth of the subducted slab is listed. This is the depth to which the subducted slab is defined by intraplate seismicity.

26. Contact Width (km). The width of the contact zone between the subducting slab and overriding plate along the shallow plate interface is listed. Although the smallest contact widths are associated with the aseismic Izu-Bonin and Marianas zones, the generally small range in widths for the overall data set suggests that contact width may not be a significant parameter for assessing seismic potential of a shallow plate interface.

27. Coastal Deformation. The available data on the style and amount of coastal deformation along the length of different subduction zones are sparse. The available data suggest that there is a variation in style and also in the distance from the trench axis at which deformation may occur.

28. Trench Length (km). This parameter lists the length of the trench associated with each subduction zone.

29. Heat Flow mW/m^2 ($\mu cal/cm^2$-sec). The range in heat flow values for the oceanic plate in the vicinity of the trench are listed. The first number is heat flow in milliwatts/m^2 (mW/m^2). The number following in parentheses is heat flow in microcalories/cm^2-sec ($\mu cal/cm^2$-sec). The lower number in parenthesis is the number of measurements for each zone.

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