Earthquake Hazards on the Cascadia Subduction Zone

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Large subduction earthquakes on the Cascadia subduction zone pose a potential seismic hazard. Very young oceanic lithosphere (10 million years old) is being subducted beneath North America at a rate of approximately 4 centimeters per year. The Cascadia subduction zone shares many characteristics with subduction zones in southern Chile, southwestern Japan, and Colombia, where comparably young oceanic lithosphere is also subducting. Very large subduction earthquakes, ranging in energy magnitude (M_w) between 8 and 9.5, have occurred along these other subduction zones. If the Cascadia subduction zone is also storing elastic energy, a sequence of several great earthquakes (M_w 8) or a giant earthquake (M_w 9) would be necessary to fill this 1200-kilometer gap. The nature of strong ground motions recorded during subduction earthquakes of M_w less than 8.2 is discussed. Strong ground motions from even larger earthquakes (M_w up to 9.5) are estimated by simple simulations. If large subduction earthquakes occur in the Pacific Northwest, relatively strong shaking can be expected over a large region. Such earthquakes may also be accompanied by large local tsunamis.

DESPITE COMPELLING EVIDENCE THAT THE GORDA, JUAN de Fuca, and Explorer plates are actively subducting along the 1200-km-long Cascadia subduction zone in the Pacific Northwest, there have been no large historic shallow subduction earthquakes of the type experienced at most other subducting plate boundaries. Is the Cascadia subduction process benign, with the differential plate motion occurring through aseismic creep, or is the zone storing elastic strain energy to be released in future great subduction earthquakes? If the Cascadia subduction zone is storing strain energy, how large might the earthquakes be, how often might they occur, and what might the ground motions be? These are all difficult, but vital, questions whose answers dramatically affect the estimation of seismic risk in the Pacific Northwest.

Active Subduction in the Pacific Northwest

The geometry of the major plate boundaries and seismicity in the Pacific Northwest is shown in Fig. 1. A half-spreading rate of 3 cm/year was inferred for the Juan de Fuca ridge by Delaney *et al.* (*1*) who reported that 43 km of new oceanic crust has formed since the 700,000-year-old Brunhes-Matuyama magnetic reversal. Nishimura *et al.* (*2*) calculated a convergence rate of 3.5 to 4.5 cm/year across the Cascadia subduction zone from sea-floor magnetic lineation data. The suitability of this kinematic model to present-day plate motions is supported by work of Hyndman and Weichert (*3*) who showed that historic seismicity is compatible with slip rates expected from magnetic lineation data on all the plate boundaries of the Pacific Northwest except on the Cascadia subduction zone. It seems difficult to construct a model of plate motions that slips 5 cm/year on plate boundaries both north and south of the Cascadia subduction zone, but with no convergence on the subduction zone.

Subduction of Young Lithosphere

The oceanic lithosphere that is subducting beneath the Pacific Northwest is very young, about 10 million years old (*4*). Several characteristics of the Cascadia subduction zone distinguish it from most other worldwide subduction zones, and most of these can be attributed to the youthfulness of the subducted oceanic lithosphere. More specifically, there is no significant bathymetric trench or large gravity anomaly for the Cascadia subduction zone. The sea floor adjacent to the continental margin is only about 3 km deep, and the average heat flow is relatively high (*5*); both of these features are directly attributable to the youth of the oceanic lithosphere (*6*). Furthermore, although there is a distinct Benioff-Wadati seismicity zone in the Pacific Northwest (*7*), it stops at a much shallower depth than in most other subduction zones, extending to a depth of less than 80 km.

Uyeda and Kanamori (*8*) suggested that the seismic coupling of subducting plate boundaries (the fraction of plate slip that occurs during earthquakes) is related to the physical characteristics of the plate boundary. Ruff and Kanamori (*9*) demonstrated that weakly coupled zones tend to have slow subduction of very old oceanic crust, whereas strongly coupled zones tend to have fast subduction of young crust. They suggested that old lithosphere is dense and subducts spontaneously with oceanward retreat of the trench and subsequent opening of back-arc basins (Marianas type, weakly coupled). Young, buoyant lithosphere tends to subduct only when it is overridden by continental lithosphere, as is the case along much of the western coast of North and South America (Chilean type, strongly coupled).

Comparison of Cascadia with Other Subduction Zones

Heaton and Kanamori (*10*) pointed out that the Cascadia subduction zone has physical characteristics very different from those of the traditional "aseismic" subduction zone (weakly coupled, Marianas type). Furthermore, they reported that the Cascadia

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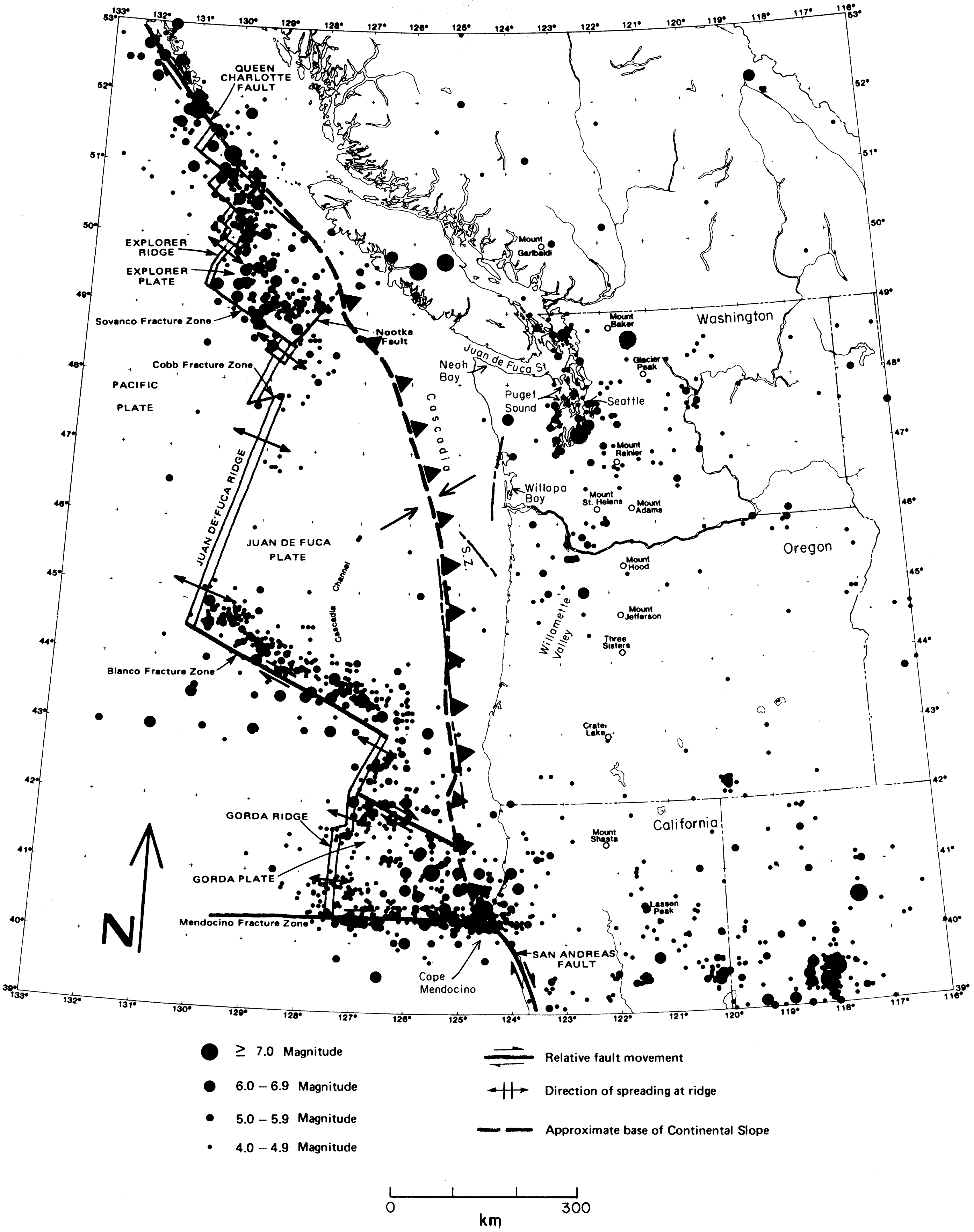

Fig. 1. Seismicity and plate tectonics of the Pacific Northwest.

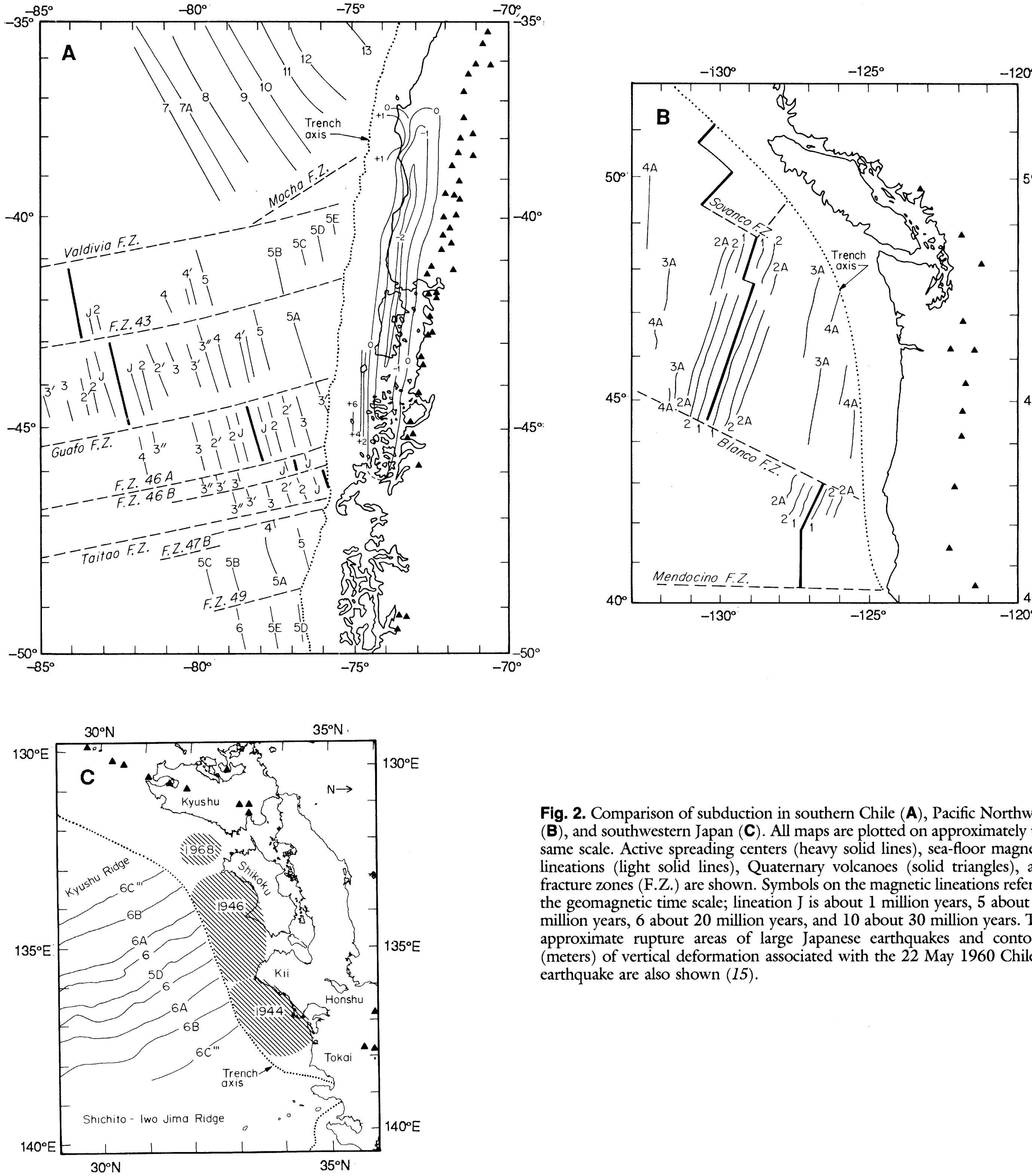

Fig. 2. Comparison of subduction in southern Chile (**A**), Pacific Northwest (**B**), and southwestern Japan (**C**). All maps are plotted on approximately the same scale. Active spreading centers (heavy solid lines), sea-floor magnetic lineations (light solid lines), Quaternary volcanoes (solid triangles), and fracture zones (F.Z.) are shown. Symbols on the magnetic lineations refer to the geomagnetic time scale; lineation J is about 1 million years, 5 about 10 million years, 6 about 20 million years, and 10 about 30 million years. The approximate rupture areas of large Japanese earthquakes and contours (meters) of vertical deformation associated with the 22 May 1960 Chilean earthquake are also shown (*15*).

subduction zone has many similarities to other strongly coupled subduction zones (Chilean type). Heaton and Hartzell (*11*) concluded that of all worldwide subduction zones, the Cascadia subduction zone seems most similar to those in southern Chile, southwestern Japan, and Colombia. Very young oceanic lithosphere is subducting in each of these locations, and very large, shallow, thrust earthquakes have occurred at each of these other zones. Maps comparing the geometries of the subduction zones in the Pacific Northwest, southern Chile, and southwestern Japan are shown on the same scale in Fig. 2, which shows the similarity of the overall dimensions of these plate boundaries.

Kanamori and Astiz (*12*) have suggested that as the age of the subducted plate approaches 0 years, we may expect increasing aseismic slip to result from high temperatures at the subducting boundary. Perhaps the Cascadia subduction zone is so hot that slip along this boundary is occurring as aseismic creep. Unfortunately, we do not know the age at which this mechanism may become important. However, at other locations where the youngest oceanic lithosphere is subducting (less than 5 million years in southern Chile) (Fig. 2), major slip has occurred during great earthquakes (*11*).

One of the most remarkable features of the Cascadia subduction zone is the striking paucity of historic shallow coastal seismicity. Although this may indicate aseismic slip along the plate boundary, the sections of the San Andreas fault that are currently creeping have a relatively high level of small earthquake seismicity, whereas the sections of the fault that experienced great earthquakes in 1857 and 1906 are currently devoid of any measurable activity. One explanation for this behavior is that stress increases smoothly and uniformly on fault zones that are coupled over large areas, whereas numerous stress concentrations occur on faults having large areas that undergo aseismic slip. Heaton and Hartzell (*11*) noted that significant periods of low seismicity have been observed at subduction zones similar to the Cascadia subduction zone, whereas subduction zones of the Marianas type (mainly aseismic slip) show a low, but steady, rate of seismicity. Heaton and Hartzell (*11*, pp. 697–698) stated that "although [the comparison study] does not prove that great earthquakes will occur on the Cascadia subduction zone, it does suggest that it is inappropriate to assume that great earthquakes will not occur based on observations of bathymetry, lithospheric age, trench sediments, heat flow, convergence rate, physiography, overall size of the subducted plate, Quaternary volcanism, or the rate of background seismicity."

Cascadia Subduction Zone—Locked or Unlocked?

Although comparison of the Cascadia subduction zone with other subduction zones leads us to believe that there may be a potential for large subduction earthquakes, it would be far more satisfying to have both direct evidence that elastic strain is accumulating and evidence for prehistoric large earthquakes. Since the question of large subduction earthquakes has been asked only recently, the search for direct evidence is still in a very early stage.

Geodetic strain. Savage *et al.* (*13*) and later Lisowski and Savage (*14*) discussed Geodolite surveys made in the Seattle region from 1972 to 1986 and triangulation surveys along the Strait of Juan de Fuca from 1892 to 1954. Their analyses indicate that both regions show a maximum contraction in a direction that is nearly parallel to the east-northeast plate convergence directions at rates of 0.03 ± 0.01 and 0.2 ± 0.07 microstrain per year for the Seattle and Strait of Juan de Fuca regions, respectively. Unfortunately, ambiguity exists in the interpretation of the strains from the Seattle Geodolite network, at least partly because of a poor signal-to-noise ratio (*15*). Repeated leveling surveys along much of the coastline adjacent to the Juan de Fuca plate show uplift of the coast regions at a rate of up to 3 mm/year and subsidence of the inner coastal areas at a rate of about 1 mm/year (*16*). Lisowski and Savage (*14*) showed that the combined Geodolite, triangulation, and leveling data can be explained by a model in which the shallow thrust zone is locked between the trench axis and the coastal region. Coseismic extensions ranging from 25 to 50 microstrain were observed in the central valley of southern Chile for the 22 May 1960 Chilean earthquake (*17*), and coseismic extensions from the 28 March 1964 Alaskan earthquake ranged from about 15 microstrain in the inner coastal areas to more than 50 microstrain in the outer coastal areas (*18*). At the current strain rates, it would take several hundred to a thousand years for comparable strains to accumulate along the Cascadia subduction zone.

Holocene shorelines. Holocene geomorphic and depositional features often record the occurrence of great subduction earthquakes. However, such features are relatively rare since they are preserved only when there are high, long-term uplift rates, large coseismic uplifts, and moderate to low coastal erosion rates. From reviews of the sparse literature on Pleistocene marine terraces, Adams (*19*) reported relatively slow emergence and possible submergence for most of the coastline of Washington and northern Oregon. He further reported moderate uplift rates of less than 1.5 mm/year in southern Oregon. Coastal erosion rates are high, and few, if any, uplifted Holocene strand lines have been identified along the coast of Washington and Oregon. The highest geologic uplift rate (3.6 cm/year) documented along the Cascadia subduction zone occurs near Cape Mendocino, California, in the region of the Gorda–Pacific–North America triple junction (*20*). A flight of nine emergent terraces and beach ridges has formed during the past 5000 years at Cape Mendocino (*20*), but it is uncertain whether these terraces have any bearing on the problem of large subduction earthquakes in the Pacific Northwest.

The lack of raised Holocene terrace in Oregon and Washington may be due to coseismic coastal subsidence, a commonly observed by-product of great subduction earthquakes. Most of the coastal areas adjacent to the 22 May 1960 Chilean earthquakes subsided by 1 to 2 m, whereas uplift occurred only at the outer islands and at the northern end of the rupture zone (Fig. 2). In a reconnaissance study of Holocene relative sea levels on the Washington coast, Atwater (*21*) found evidence that a tidal marsh subsided suddenly near Neah Bay (northwesternmost tip of Washington) approximately 1100 years ago. He also found similar evidence for multiple jerks of subsidence in the Willapa Bay region 200 km to the south. Atwater (*21*) proposed that each jerk of subsidence may mark a great prehistoric earthquake on the Cascadia subduction zone.

Holocene turbidites. Adams (*4, 22*) has suggested that extensive Holocene turbidites studied by Griggs and Kulm (*23*) may have been triggered by large earthquakes along the continental shelf. Since the deposition of Mazama ash 6600 years ago, there have been approximately 16 major turbidites in the Cascadia Channel, which is consistent with an average earthquake repeat time of 410 years. Adams (*22*) pointed out that two separate channels separated by 50 km, and that also feed the main Cascadia Channel, have turbidite sequences comparable in number to those seen in the main channel. This seems to be evidence that turbidity currents were simultaneously triggered in separate channels, perhaps by great subduction earthquakes.

Historical records. Although first explored by Europeans in the late 1700s, coastal Washington had no permanent Caucasian settlements until 1810. There being no known written accounts of any event that can be interpreted as a great subduction earthquake, it seems unlikely that any such events have occurred for at least 200 years. However, a few legends of Washington coastal Indians suggest the occurrence of a large tsunami along the northwestern Washington coast (*24*). There are also legends of large earthquakes and disturbances of the coastal waters from coastal Indians in northernmost California (*24*). Unfortunately, these legends are too vague to constitute proof that large subduction earthquakes have occurred.

Hypothetical Subduction Earthquakes

If the Cascadia subduction zone is locked, what sort of earthquakes may occur there? Although this question is central to the assessment of seismic hazards, at this point our answers are speculative. For simplicity, we assume that earthquakes on the Cascadia subduction zone may resemble earthquakes on the subduction zones that seem to be the most similar to the Cascadia zone—namely, southern Chile, southwestern Japan, and Colombia. Heaton and

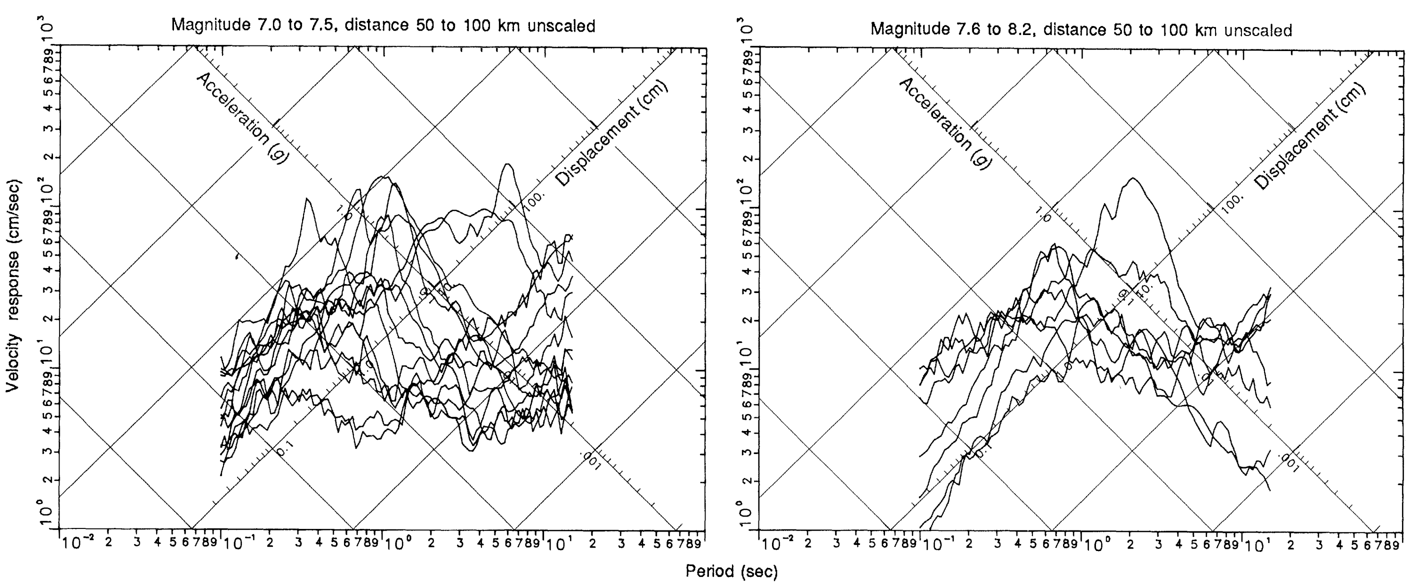

Fig. 3. Pseudovelocity response spectra (5% damped) of horizontal components of ground motion for sites at distances between 50 and 100 km for large subduction earthquakes.

Hartzell (*11*) summarized historic earthquake activity for these subduction zones and chose several historic earthquake sequences that they considered to be plausible for the Pacific Northwest if, in fact, the subduction zone is locked. In the first scenario, a sequence of four or five earthquakes similar to the 1944 and 1946 energy magnitude (M_w) 8.1 southwestern Japan earthquakes (Fig. 2) would be sufficient to cover the length of the Cascadia subduction zone. Such earthquakes might be closely spaced in time, as has been the case for many sequences in southwestern Japan. Plate convergence rates in southwestern Japan are comparable to those in the Pacific Northwest. The average earthquake recurrence interval in southwestern Japan is about 180 years (*25*).

Another scenario calls for an earthquake similar to the 1906 M_w 8.8 Colombian earthquake. An average dislocation of about 5 m over a rupture length of about 500 km has been estimated for this event (*26*). The section of the zone that ruptured in 1906 seems to have ruptured again in a sequence of smaller earthquakes (1942, 1948, and 1979) whose moment sum is only one-fifth that of the 1906 event (*26*). The convergence rate at Colombia is about 8 cm/year, but the historic records are insufficient to allow an estimation of the recurrence interval of great Colombian earthquakes.

The 22 May 1960 Chilean earthquake is the largest documented earthquake of this century (M_w 9.5). The rupture covered a length of about 1000 km and ruptured through many different segments of the South Chile subduction zone (Fig. 2). The dimensions of the 1960 rupture zone are comparable to those of the entire Cascadia subduction zone (Fig. 2), and thus we consider the 1960 earthquake to represent the largest earthquake feasible in the Pacific Northwest. The convergence rate in southern Chile is about 9 cm/year, and large earthquakes also occurred in this region in 1575, 1737, 1837, and 1960—an average recurrence time of about 128 years. However, there is strong evidence that average dislocations of greater than 20 m accompanied the 1960 earthquake (*17*), and thus a recurrence interval of 128 years seems inconsistently short with respect to the long-term convergence rate. There is evidence that the 1960 earthquake may have been significantly larger than previous historic events in this area (*11*). If earthquakes similar to the 1960 Chilean earthquake do occur on the Cascadia subduction zone, their average recurrence interval would probably exceed 500 years.

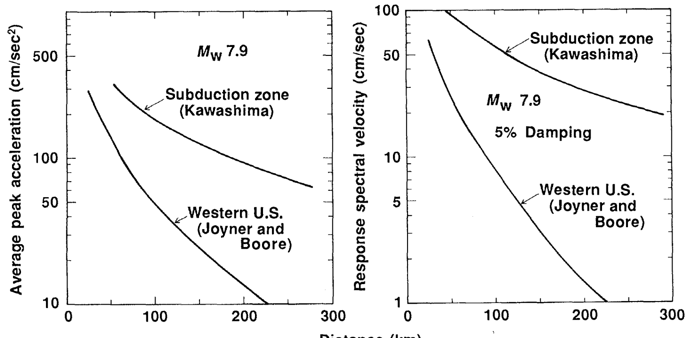

Fig. 4. Comparison of predictions of average peak ground motions obtained by regression analysis of data from the southwestern United States (*29*) and from Japan (*31*). Soil sites and 5% damping are assumed for the response spectra.

Rupture Process for Large Subduction Earthquakes

We have argued that the very young age of the subducted lithosphere in the Pacific Northwest may determine the seismic coupling of the plate boundary. Is there a systematic difference with the age of the subducted plate in the nature of seismic energy release during large subduction earthquakes? Hartzell and Heaton (*27*) studied broad-band teleseismic *P*-waves from 63 of the largest shallow earthquakes in the last 45 years. The earthquakes studied occurred in 15 subduction zones with a wide range in the ages of subducted lithosphere and represent a wide range of convergence rates and maximum size of earthquakes. Hartzell and Heaton derived teleseismic time functions in the period band from 2 to 50 seconds and characterized those functions in terms of roughness, overall duration, multiplicity of sources, spectral slopes, and duration of individual pulses. These measures varied widely from one earthquake to another, although earthquakes within the same subduction zone seem to be similar. Comparing the time functions with age, rate, and maximum M_w of the subduction zones does not yield obvious global trends. These observations indicate that inherent differences are not expected in the nature of energy release from earthquakes at subduction zones that are similar to the Cascadia subduction zone.

Strong Ground Motions Observed During Large Subduction Earthquakes

Heaton and Hartzell (*28*) discussed the nature of strong ground motions that might be expected if large subduction earthquakes occur in the Pacific Northwest. They assumed that gap-filling earthquake sequences that are similar to those already observed in southern Chile, southwestern Japan, and Colombia may also occur in the Pacific Northwest. The largest earthquakes in these sequences range in size from M_w 8 to M_w 9.5. Strong motion records are available for shallow subduction earthquakes as large as M_w 8.2, but strong ground motions have not yet been recorded for larger earthquakes. Heaton and Hartzell assumed that ground motions from M_w 8 earthquakes on the Cascadia subduction zone would not be systematically different from the motions recorded during M_w 8 earthquakes on other subduction zones. For earthquakes of M_w less than 8.2, their approach is to simply construct suites of ground motions that were recorded under conditions similar to those existing at sites for which ground motion estimates are desired.

Heaton and Hartzell (*28*) collected 56 recordings of strong ground motion from 25 shallow subduction earthquakes of $M_w \geq 7.0$ for their study. Pseudovelocity response spectra for ground motions recorded in the distance range from 50 to 100 km are shown in Fig. 3. They also prepared similar figures for other distance ranges out to 300 km. One of the most striking features is the large degree of scatter in the spectra for ground motions observed at similar distances and from similar sized earthquakes. This scatter is troublesome when it is necessary to estimate the ground motion that a particular site will experience. Even if the earthquake magnitude and distance are known, the resulting ground motions are still uncertain by a factor of 10. Much of this scatter can be attributed to differences in the response characteristics of individual recording sites (*28*). Thus, refined estimates of ground motion should be obtained by determining the site response from the ground motions of small earthquakes.

Another feature of ground motions recorded during large subduction zone earthquakes is their large size at very large distances. In Fig. 4, we compare ground motion levels for M_w 7.9 earthquakes predicted from regression analysis of earthquakes in the western United States (*29, 30*) with those predicted from regression analysis of large subduction earthquakes in Japan (*31*). At distances of more than 50 km, ground motions from large subduction earthquakes are expected to be far larger than those from large crustal earthquakes in the southwestern United States. As can be seen in the response spectral velocities at 1 second, this effect is pronounced at periods of concern to large structures. Unfortunately, the western United States curves are uncertain since there have been no strong motion recordings from earthquakes of this size in the western United States and these curves are extrapolations outside the data. Peak ground accelerations and velocities for earthquakes of magnitude less than 7 are not dramatically different for Japanese and western United States earthquakes (*32*). The origin of the difference between ground motion estimates at large distances for large subduction earthquakes and large crustal earthquakes in the southwestern United States is not yet fully understood.

Simulating Ground Motions for Giant Earthquakes

If the Cascadia subduction zone is strongly coupled, earthquakes far larger than any of the events for which we have strong motion records can be postulated. What might the ground motions look like from a giant earthquake such as the 1960 Chilean earthquake? Its seismic moment is at least 100 times that of the largest earthquake for which we have strong motion data (*33*). Heaton and Hartzell (*28*) simulated the ground motions from giant earthquakes ($M_w > 8.5$) by summing records from smaller earthquakes in such a way that they simulate the occurrence of larger earthquakes. That is, the records from smaller earthquakes are used as Green's functions, and this technique is often referred to as the empirical Green's functions technique. A schematic diagram of a model in which the 22 May 1960 Chilean earthquake is simulated by a collection of smaller earthquakes, in this case the 12 May 1978 M_w 7.5 Miyagi-Oki earthquake, is shown in Fig. 5. In this example, the 1960 Chilean earthquake is simulated by the superposition of 120 Miyagi-Oki earthquakes. Models of this type can be used to simulate teleseismic *P*-waveform data as well as strong ground motions. Although there are no strong motion records from giant earthquakes, there are records of teleseismic *P*-waves (*27, 28*) that are used to constrain the modeling parameters used in the empirical Green's function technique. The teleseismic data suggest that a large part of the seismic energy associated with giant earthquakes is of very long period. This very long period energy is outside the frequency band of earthquake engineering interest. Heaton and Hartzell (*28*) concluded that summing 120 Miyagi-Oki records simulates short-period energy from the 1960 Chilean earthquake even though the ratio of the total seismic moments for the two earthquakes is at least 1000:1.

The results of the empirical Green's function simulations are summarized in Fig. 6. These curves represent a best guess of the average response spectral levels (5% damped) for horizontal ground motions observed at points located about 50 km inland from the

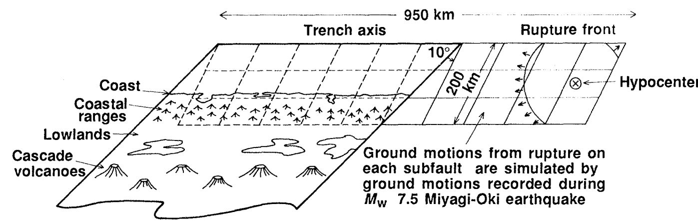

Fig. 5. Schematic drawing of the simulation of an earthquake similar to the 22 May 1960 Chilean earthquake (M_w 9.5) by the superposition of 1978 Miyagi-Oki earthquakes (M_w 7.5).

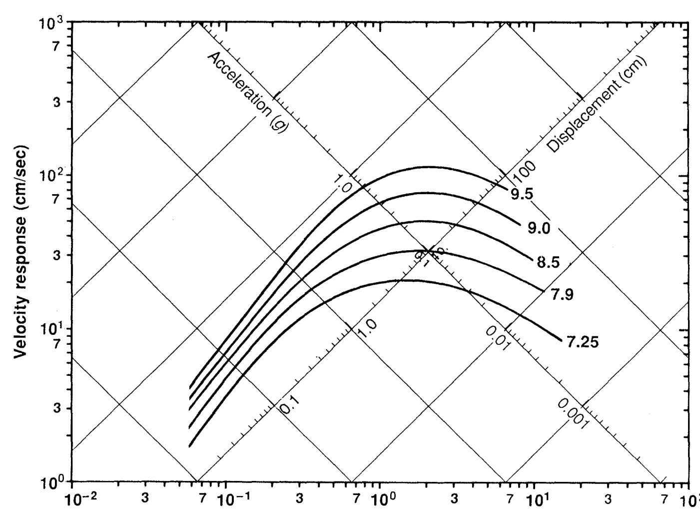

Fig. 6. Estimates of the variation in average horizontal ground motion response spectra (5% damping) as a function of energy magnitude for sites located 50 km inland from the coast. Scatter of actual data about mean values may be similar to that in the data observed in Fig. 4.

coast and for a variety of sizes of subduction earthquakes. Ground motion estimates for earthquakes of $M_w < 8$ are based on the direct observation of strong motion data, whereas the ground motions for larger earthquakes are estimated by the empirical Green's functions technique. Large scatter about these averages (about a factor of 2) can be expected for suites of actual data. For the very largest earthquakes, motions may be about 25% larger at coastal sites and about 67% as large at sites in the Puget Sound. The duration of strong shaking during such giant earthquakes is expected to exceed 2 minutes. Average peak accelerations may be in the range of 600 cm/sec^2 for coastal sites and 250 cm/sec^2 for Puget Sound sites.

Tsunami Hazards

All of the regions that we considered to be potential analogs for the Cascadia subduction zone have experienced large local tsunamis. The 1944 M_w 8.1 and 1946 M_w 8.1 earthquakes in southwestern Japan generated local tsunamis that had maximum run-up heights of 7.5 and 6.0 m, respectively, and the 1707 southwestern Japan earthquake ($M_w > 8.5$) probably generated an even larger tsunami (*34*). The 1906 Colombian earthquake also generated a large local tsunami that extensively damaged much of the coastal regions of southwestern Colombia and northern Ecuador (*34*). The 1960 Chilean earthquake generated one of the largest tsunamis in recent times, with heavy damage occurring both locally (*35*) and also in Hawaii and Japan. Although the maximum local run-up may have exceeded a height of 20 m, it seems likely that most of the coastal regions adjacent to the earthquake experienced run-up heights of less than 10 m. If very large subduction earthquakes do occur in the Pacific Northwest, they will almost certainly be accompanied by tsunamis. It is difficult at this point to reliably estimate the tsunami run-up heights that may follow any large earthquake on the Cascadia subduction zone. However, run-up heights ranging from several meters to several tens of meters have been observed along other subducting boundaries after events of the type that we consider to be feasible for the Cascadia subduction zone.

Conclusions

Strong evidence exists for active convergence at about 4 cm/year on the 1200-km Cascadia subduction zone. Furthermore, the physical characteristics of the Cascadia subduction zone resemble those of other subduction zones that have experienced large shallow earthquakes. Even though there have not been large historic subduction earthquakes in the Pacific Northwest for at least 150 years, the Cascadia subduction zone may be storing strain energy to be released in future great earthquakes. If the Cascadia subduction zone is locked, a sequence of several great earthquakes (M_w 8) or a giant earthquake (M_w 9) would be necessary to fill this gap. If great subduction earthquakes occur, then relatively strong shaking can be expected over a large area of the Pacific Northwest, including the Puget Sound and Willamette Valley regions. Large and potentially destructive local tsunamis would be expected if large subduction events do occur. Great earthquakes, such as those in southwestern Japan or southern Chile, have caused great damage over very large regions. The suggestion of similar events in the Pacific Northwest is disturbing.

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