Articles

Giant Earthquakes Beneath Canada's West Coast

R.D. Hyndman, G.C. Rogers,
H. Dragert, K. Wang
Pacific Geoscience Centre
Geological Survey of Canada
P.O. Box 6000
Sidney, British Columbia V8L 4B2

J.J. Clague
Geological Survey of Canada
Vancouver, British Columbia V6B 1R8

J. Adams
Geological Survey of Canada
Ottawa, Ontario K1A 0E8

P.T. Bobrowsky
British Columbia Geological Survey
Victoria, British Columbia V8V 1X4

SUMMARY

Compelling evidence for past great earthquakes along the Cascadia subduction zone and for the present build up of elastic strain have been revealed through a multidisciplinary research effort. From Vancouver Island to northern California, there is paleoseismic evidence of sudden subsidence of the coast and of strong shaking from huge earthquakes at irregular intervals averaging about 500 years. The last was 300 years ago, before the historical period. Several independent techniques show the present shortening and buckling of the coastal region diagnostic of strain accumulation on a locked subduction thrust fault. The pattern of strain and the temperature at depth on the fault allow definition of the maximum landward extent of future events. Although the earthquakes are very large, up to magnitude 9, the predicted ruptures are mainly offshore some distance from the major cities, limiting the severity of the expected shaking.

RÉSUMÉ

Une recherche multidisciplinaire a permis de mettre en lumière des preuves certaines démontrant que de trés forts séismes se sont produits le long de la zone de subduction de Cascadia, et que cette dernière est présentement en état de contrainte élastique. De l'île de Vancouver jusqu'au nord de l'État de Californie, des indices paléosismiques montrent que la côte a subi des épisodes de subsidences brusques et que de forts séismes l'ont secouée à intervalles irréguliers d'une durée moyenne d'environ 500 ans. Le dernier de ceux-ci s'est produit il y a 300 ans, soit avant le début de la période historique. Plusieurs méthodes de mesure indépendantes démontrent que l'actuel rétrécissement et le bombement mesurés de la région côtière permet de diagnostiquer une accumulation de contraintes à l'endroit d'une faille de subduction coincée. Les caractéristiques des contraintes ainsi que la température au lieu de la faille permettent de prédire le prolongement maximal sur le continent des événements sismiques à venir. Bien

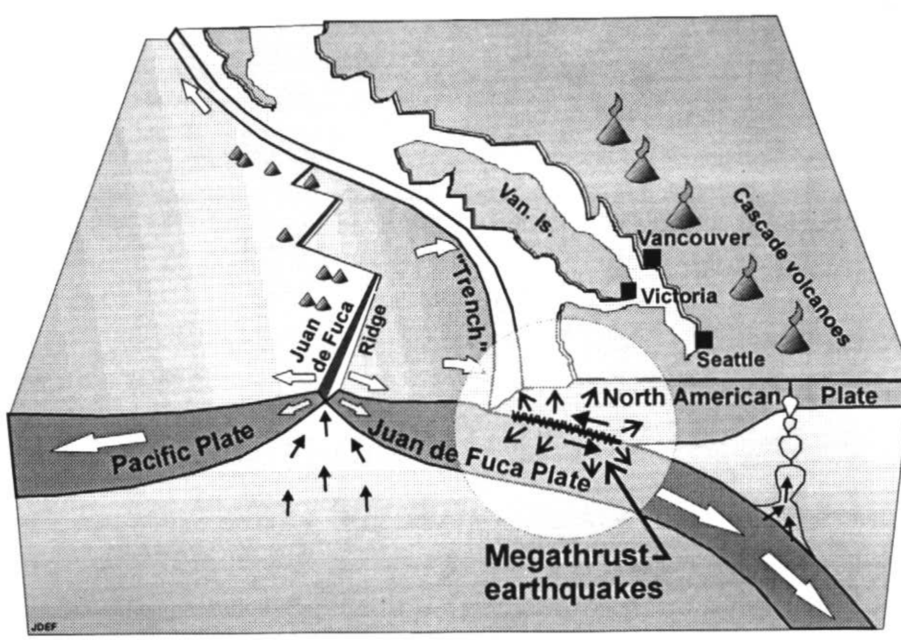

Figure 1 *The Juan de Fuca plate is produced by spreading at the Juan de Fuca ridge several hundred kilometres offshore. It moves landward and beneath the continent at an average rate of 40 mm·a⁻¹. Great earthquakes occur on the Cascadia subduction zone thrust fault contact. Cascade volcanoes such as Mt. Garibaldi and Mt. St. Helens are produced by melting above the downgoing plate where it reaches a depth of approximately 100 km.*

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qu'il s'agisse de très forts séismes, jusqu'à 9 sur l'échelle Richter, les ruptures prévues se produiront surtout au large, à bonne distance des principales villes, réduisant d'autant l'intensité locale des tremblements de terre.

INTRODUCTION

Few people question that Canada's west coast has a substantial earthquake hazard. There have been four large (magnitude 7) earthquakes this century in southwestern British Columbia and northwestern Washington. However, no giant subduction earthquakes of the type characteristic of convergent margins have struck the coast in historical times, and until recently many believed that there was little risk of such events (Fig. 1). The warning that such events should not be ignored was made some ten years ago (Heaton and Kanamori, 1984; Heaton and Hartzell, 1987; Rogers, 1988), but the supporting data were limited. In the past several years, however, the accumulated evidence has left little doubt that great earthquakes have occurred in the past and that they will occur in the future (*e.g.*, Hyndman, 1995).

EARTHQUAKE STATISTICS AND SEISMIC HAZARD

The hazard from subduction thrust earthquakes in this region has been difficult to estimate. To appreciate why this is so requires an understanding of the way in which earthquake hazard is usually determined. The locations and frequency of occurrence of large and damaging, but infrequent earthquakes normally can be estimated from the pattern of more frequent small events. The systematic recurrence relation between earthquake magnitude and frequency of occurrence for active fault zones was first presented by B. Gutenberg and C. Richter many years ago. The average number of earthquakes in a particular source region decreases with increasing size in a regular way up to the maximum magnitude. This is shown for the Queen Charlotte transform fault in Figure 2. The maximum magnitude is determined by the event that breaks the entire fault zone from end to end. The average occurrence of very large earthquakes can thus be estimated even if there have been no such events in the historical record. Assessment of earthquake hazard at a site is usually based on this relation. The recurrence relation is used to calculate the probability that a particular magnitude of ground shaking will be exceeded in a specified period of time. Buildings and other structures can be designed accordingly (*e.g.*, National Building Code, 1995).

Unfortunately, in a few areas this relation does not hold. The failure of the magnitude-frequency of occurrence approach is especially serious in the coastal region of western North America between Cape Mendocino in northern California and the Queen Charlotte Islands in British Columbia (Fig. 3). In

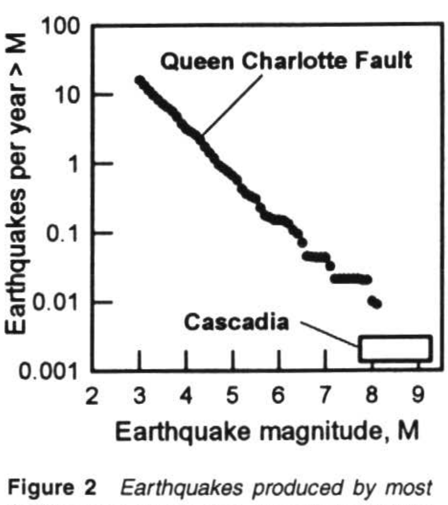

Figure 2 *Earthquakes produced by most fault zones follow the Gutenberg-Richter relation. The average number of earthquakes per year decreases with increasing magnitude. The Queen Charlotte transform (strike-slip) fault zone along the coast to the north of Vancouver Island is typical. The Cascadia thrust fault is unusual in that it produces no small earthquakes, only infrequent very large events.*

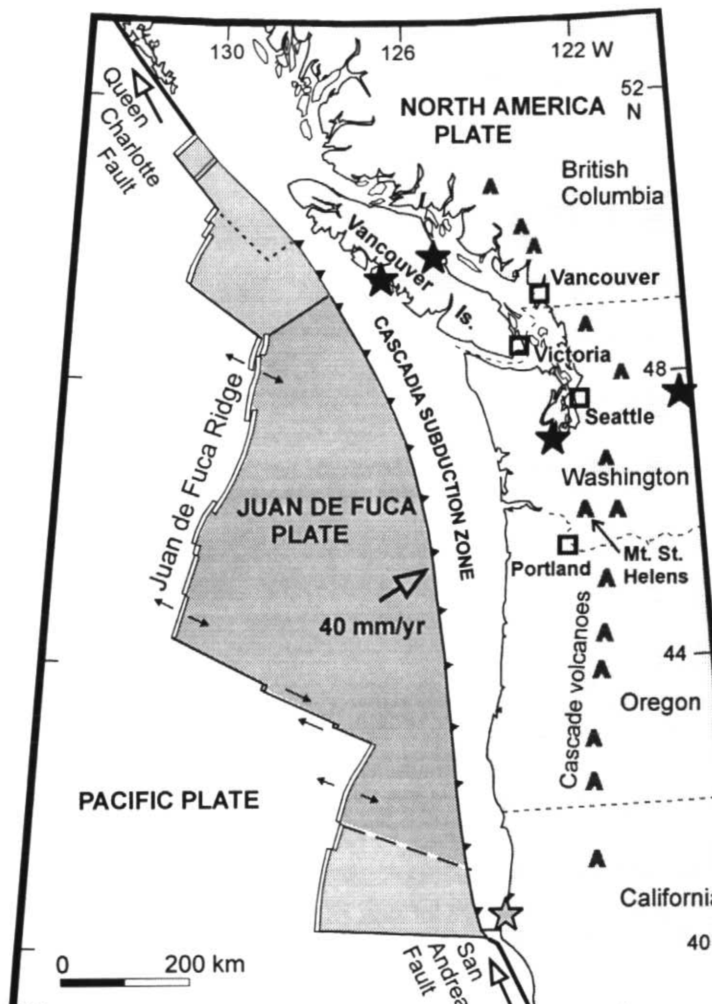

Figure 3 *The Juan de Fuca plate lies offshore between Vancouver Island and northern California. Complex sub-plates are present at its north and south ends. The San Andreas transform fault extends to the south and the Queen Charlotte fault to the north. The barbed line marks where the subduction thrust fault approaches the sea floor. The Cascadia volcanoes (triangles) are limited to the region where the Juan de Fuca plate is underthrusting the continent. The stars mark magnitude 7 historical earthquakes.*

this region, the Juan de Fuca oceanic plate is underthrusting the North American continent at the Cascadia subduction zone (Fig. 1). Although the regional earthquake activity is quite high in some areas (magnitude 7 events occurred in 1872, 1918, 1946 and 1949), no earthquakes of any size have been detected on the subduction thrust fault itself (Fig. 4). This is so even with the extensive seismograph networks established in southwestern British Columbia and western Washington during the past 20 years. The lack of small events on the subduction thrust fault means that the recurrence relation cannot be used to estimate the frequency of occurrence of large thrust earthquakes.

In a global perspective, the lack of large thrust earthquakes is surprising. Most of the world's great earthquakes (defined as magnitude 8 and greater) have occurred on subduction zone thrust faults, and most subduction zones have experienced historical great earthquakes. Such events are especially concentrated around the Pacific Ocean where the majority of subduction zones are located. The Cascadia subduction zone appears to be an anomaly, but we need to remember that the written historical record in this area is short. It is only a little more than 200 years since the first visits to the region by Captains Juan Perez in 1774 and James Cook in 1778. This limited written history is in marked contrast to the detailed Japanese record of great subduction zone earthquakes and tsunami waves that extends back to the 7th century (*e.g.*, Ando, 1975).

There are three possible explanations for the lack of historical great earthquakes along the Cascadia coast: 1) the Juan de Fuca plate is no longer converging and underthrusting North America; 2) underthrusting is continuing, but it is accommodated by smooth stable sliding, not punctuated by the stick-slip behaviour of earthquakes; and 3) the thrust fault is completely locked with not enough motion to generate even small earthquakes. The first two explanations imply that the earthquake hazard estimates for the region based on historical seismicity are appropriate. The third explanation implies that there is a potential for very large and damaging earthquakes that has not been included in most past hazard estimates.

Twenty years ago the first explanation was much discussed, and Riddihough and Hyndman (1976) presented a variety of evidence that there is present convergence and underthrusting. Since that time, extensive studies have been carried out across the Cascadia continental margin. They allow us to now say with considerable assurance that convergence is indeed continuing. One type of evidence is the folding and faulting seen in seismic reflection images of young sediments at the base of the continental slope. These sediments were laid down on the deep sea floor as flat layers, but even the Quaternary sequences less than 1 million years old are strongly folded and faulted (*e.g.*, Davis and Hyndman, 1989). They continue to be scraped off the underthrusting oceanic crust by the bulldozer blade of the continental crust. Perhaps the most dramatic evidence for active subduction was the volcanic eruption of Mt. St. Helens in 1980. Such eruptions have their origin in melting that occurs when the oceanic crust reaches a depth of approximately 100 km beneath the continent (Fig. 1). A chain of "arc" volcanoes inland of the coast extends from northern California to southern British Columbia. They are geologically active, although many are historically dormant. The north-south geographic limit of the volcanoes corresponds to the extent of the subducting Juan de Fuca plate (Fig. 3). The principle of plate tectonics, that arc volcanoes only occur where there is active subduction, indeed applies here.

The debate over the second possibility, smooth aseismic underthrusting, has continued until quite recently. Again, the contrary evidence is now strong, especially from paleoseismicity (the traces of past great earthquakes preserved in the geological record), and from measurements of present elastic strain building up in the continent near the coast. The observed deformation corresponds to that expected for a locked thrust fault. These two types of evidence are discussed below.

We are left with the third alternative. Great earthquakes do occur, but the last one occurred more than 200 years ago, prior to the historical written record. Thus, we must face the serious consequence that the earthquake hazard is substantially greater than previously thought.

PAST GREAT EARTHQUAKES IN THE GEOLOGICAL RECORD

Great earthquakes have occurred on the Cascadia continental margin at in-

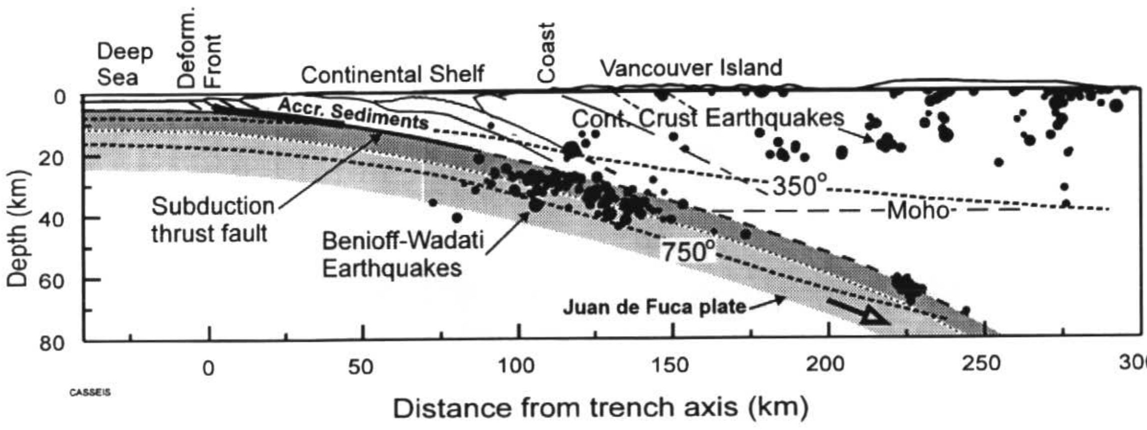

Figure 4 *Earthquakes are common in the continental crust of the northern Cascadia coastal region at depths less than 35 km, which corresponds to a maximum temperature of approximately 350°C. "Wadati-Benioff" earthquakes occur to a greater depth within the downgoing oceanic plate (to approximately 750°C). However, no earthquakes have been detected on the subduction thrust fault (the solid line beneath the accreted sediments, grading to a dashed line beneath Vancouver Island). The circle sizes are proportional to the earthquake magnitudes.*

tervals of several hundred years to more than one thousand years, according to paleoseismicity data from the coasts of British Columbia, Washington and Oregon. In sheltered inlets and bays, marsh vegetation develops at a level between high and low tides. Excavations beneath the marshes reveal a remarkable record. At depth intervals of one-third of a metre to one metre there are buried peat layers consisting of vegetation identical to that of the present marsh surface (the data are summarized by Atwater *et al.*, 1995). An example from the west coast of Vancouver Island is shown in Figure 5 (Clague and Bobrowsky, 1994a). The peat layers are interpreted to be former intertidal marsh vegetation that was submerged by abrupt coastal subsidence at the time of past great earthquakes. Following each great earthquake, coastal mud accumulated on the drowned marsh, building the surface to mid-tide level, whereupon vegetation became re-established. In Chile and Alaska, such buried marshes were produced by the magnitude 9 earthquakes that occurred in 1960 and 1964, respectively.

What makes the story even more convincing is that many of the buried marsh surfaces are covered by sand layers (*e.g.*, Clague and Bobrowsky, 1994b). The sand was carried in by the waves of the great tsunami that rushed into the subsided coastal region. Both theoretical modelling and effects preserved in the geological record on the coast indicate that the waves may have had heights of 5-10 m on the open coast and much higher still in some confined inlets. Radiocarbon dating and ring studies of drowned trees at sites from northern California to southern British Columbia both show the last Cascadia great event to have occurred approximately 300 years ago (*e.g.*, Atwater *et al.*, 1995). One recent tree ring study concluded that the last event was in 1700 (Jacoby, 1995). The intervals between successive great earthquakes have been irregular, but the average is approximately 500 years.

Other evidence for past great earthquakes comes from sediment deposits far off the coast on the floor of the Cascadia deep sea basin. Core samples up to 8 m in length taken by Oregon State University show fine-grained mud layers alternating with sandier layers (Fig. 6), a repeated sequence usually denoted as turbidites. The coarser layers have been interpreted as formed by submarine landslides triggered by great earthquakes (Adams, 1990). The landslides carried sediment from the continental slope to the deep sea floor. The intervening mud layers in the cores formed by the slow continuous rain of finer sediment settling from the ocean between the turbidite events. Adams provided arguments that the turbidite layers in cores from 500 km along the coast were simultaneous, and thus probably triggered by the same great earthquake. The timing of the earthquakes is again difficult to determine accurately, but an important marker is present near the base of some of the cores that gives the average interval between events. This layer contains volcanic ash from the eruption of Mt. Mazama in Oregon

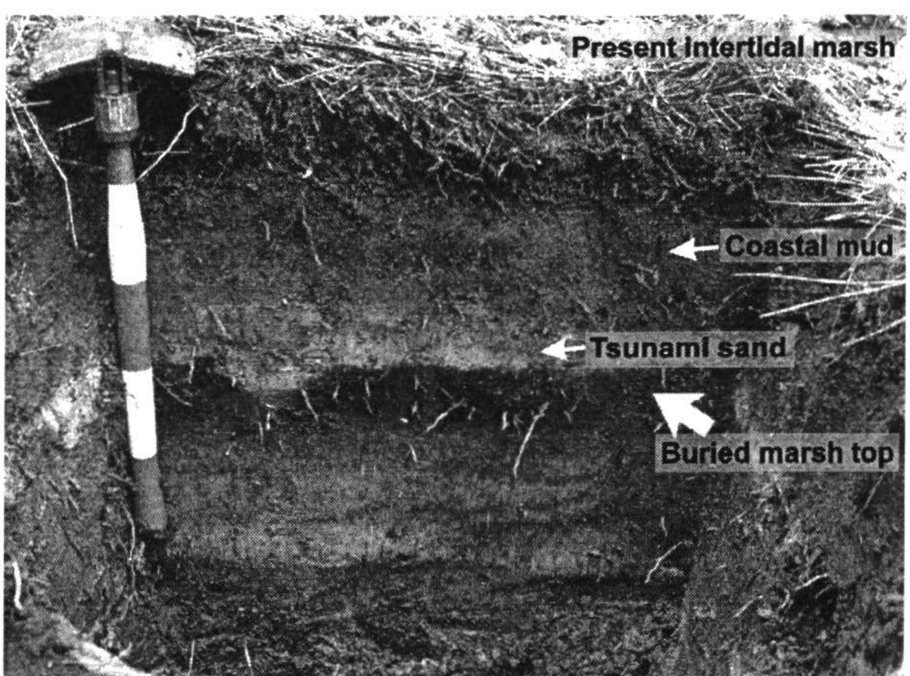

Figure 5 *A trench cut through a coastal intertidal marsh exposes a peat layer, the remains of a former, now buried, marsh. The marsh abruptly subsided 0.5-1 m in a great earthquake approximately 300 years ago. The sand above the buried peat layer was swept into the subsided coastal region by the waves of the resulting great tsunami (after Clague and Bobrowsky, 1994a).*

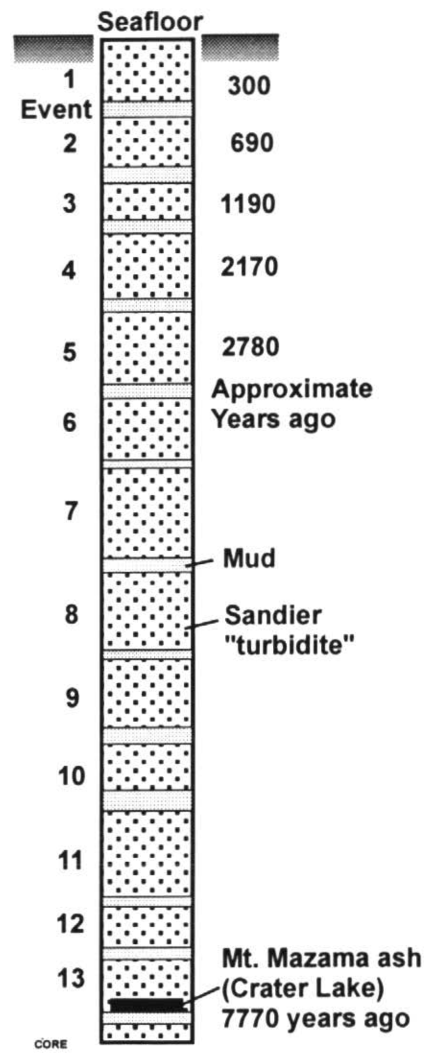

Figure 6 *A 6-m long core sample taken from the deep sea floor shows fine-grained mud layers alternating with sandier layers. The latter are interpreted to have been deposited from submarine landslides triggered by great earthquakes. The mud layers formed by the slow continuous rain of finer sediment settling from the ocean. The volcanic ash at the bottom is dated as 7700 years old (after Adams, 1990).*

(now known as Crater Lake) dated at 7700 years ago, a huge explosion of the type of the recent Mt. St. Helens eruption. The inferred chronology for great earthquakes, assuming a constant rate of mud deposition, is similar to that obtained from the coastal marshes. The most recent turbidite event in the cores was approximately 300 years ago. The intervals for the last 13 events range from 300 years to 900 years with an average of 590 years.

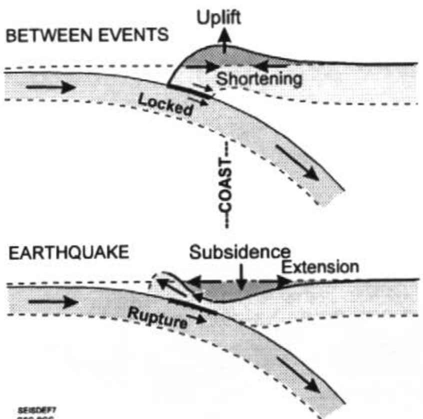

Figure 7 (**Top**) *Elastic deformation builds up between great earthquakes if the thrust fault is locked. The seaward edge of the continent is dragged down and a flexural bulge forms farther landward.* (**Bottom**) *During a great earthquake, there is uplift of the seaward edge and collapse of the flexural bulge. The abrupt uplift generates the tsunami, and the collapse of the bulge causes the subsidence recorded in buried coastal marshes.*

An additional clue may allow us to date the most recent great Cascadia earthquake precisely. It has been recognized for some time that great Cascadia earthquakes should have produced tsunamis with waves large enough to be reported on the coasts of Asia, even after travelling across the Pacific Ocean. The most recent Cascadia tsunami may have been found in Japanese written records. A tsunami in the year 1700 with wave heights of 2-3 m, not caused by a local Japanese earthquake, has been documented for five sites along the coast of Japan by Satake *et al.* (1996). Satake *et al.* provided arguments for excluding sources other than Cascadia. Correcting for the tsunami travel time to Japan and the time zone difference, the source great earthquake must have occurred along the North American coast on 26 January at approximately 9:00 p.m.

Support for the conclusion of a great earthquake on a winter night is provided by an event preserved in the oral tradition of the coastal native people (Heaton and Snavely, 1985; Clague, 1995). In the period not long before European contact, a strong earthquake occurred at night. It was followed by a large tsunami that destroyed the village at the head of Pachena Bay on the west coast of Vancouver Island (Arima *et al.*, 1991). In another account, the canoes came down in the trees.

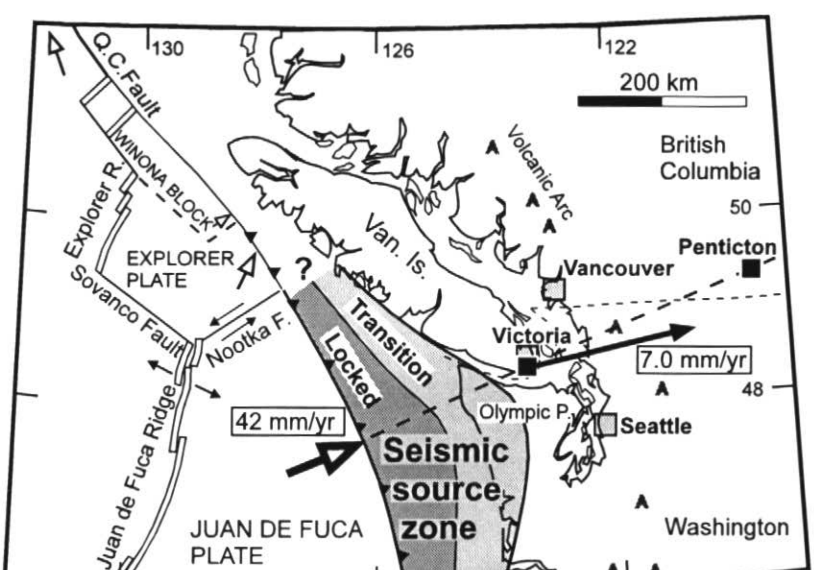

Figure 8 *With the thrust fault locked, the 40 mm·a⁻¹ convergence of the Juan de Fuca plate is taken up as elastic shortening across the continental margin. GPS measurements show Victoria to be moving landward at a rate of 7 mm·a⁻¹ with respect to the stable North American continent (Penticton site) (after Dragert and Hyndman, 1995). The remainder of the shortening is across the continental shelf.*

THE GREAT EARTHQUAKE CYCLE

Like all earthquakes, great subduction zone events are complex when considered in detail. However, the basic process is simple and may be represented by the elastic rebound model first developed for the San Andreas Fault. Ongoing convergence of the oceanic plate results in elastic bending and buckling of the continental crust and the accumulation of elastic stress in the vicinity of the locked fault. After some time, the stress exceeds the sliding strength of the fault and there is abrupt slip. The stored elastic energy radiates as earthquake waves. The fault then relocks and the cycle resumes. For the Cascadia subduction zone, the rate of convergence between the Juan de Fuca plate and North American plate is approximately 40 mm·a^{-1}. This represents a shortening between events of 20 m if the event interval is 500 years. A slip this large could thus occur in a great earthquake. Other subduction zones commonly exhibit great earthquakes every 100-200 years. The unusually long intervals between Cascadia events means that there may be larger than normal stress buildup and very large earthquake slip.

Modern distance measurements using satellite and space geodesy show that present plate motions away from their boundaries are remarkably constant and equal to long-term geological averages. Elastic deformation of the earthquake cycle is limited to a zone several hundred km wide close to the plate boundaries. The deformation through the earthquake cycle includes a viscous component that gives a time dependence to the deformation pattern and rate (*e.g.*, Wang *et al.*, 1994), but to a first approximation the response is elastic and at a steady rate between earthquakes. In the simple subduction earthquake model, ongoing convergence drags down the seaward nose of the continent and causes an upward flexural bulge farther landward (Fig. 7). There is also a region of crustal shortening (Fig. 8). At the time of the earthquake, the seaward portion of the continent springs back and the bulge collapses. The abrupt uplift of the outer continental shelf is responsible for the great tsunamis. The collapse of the flexural bulge further landward causes the sudden coastal subsidence recorded in intertidal marshes.

THE LOCKED ZONE

Only a portion of the thrust fault ruptures in great earthquakes. The extent of the seismic source zone (actually the locked plus transition zones as defined below) is limited both updip and downdip. The landward downdip limit is important for seismic hazard since it determines the closest approach to the major population centres located 100 km inland of the outer coast. The seaward updip limit is important for tsunami generation. The total seismogenic width perpendicular to the margin has an important influence on the maximum size of great earthquakes.

The extent of the locked zone on the thrust fault may be determined from the pattern of interseismic crustal deformation (*e.g.*, Fig. 9). If the locked zone is narrow, extending only a short distance downdip, the zone of elastic deformation is narrow. If the locked zone is wide, the deformation zone will extend a long distance inland. Comparison of the pattern of vertical and horizontal deformation determined from geodetic surveys with the predictions of models for a locked thrust fault shows that the subduction thrust fault is probably locked along the whole coast from southern British Columbia to northern California. The geodetic data have also allowed the variations in downdip width of the locked zone along the coast to be mapped (Hyndman and Wang, 1995). Figure 9 also illustrates the effect of locked zone width through a comparison of the vertical deformation over the narrow locked zone of northern Cascadia at Vancouver Island and the wider locked zone of southwest Japan.

The rates of deformation are very slow and very precise measurements are required, able to resolve deformation rates of a few millimetres per year. Five types of geodetic data have defined the pattern of current deformation across the Cascadia margin (Fig. 10). They include: 1) repeated survey levelling lines, 2) long-term tide gauge records, 3) repeated gravity surveys, 4) repeated positional survey networks, and 5) continuously recording global positioning networks. The repeated levelling lines employ standard techniques, *i.e.*, sighting to calibrated rods at horizontal distance intervals of approximately 40 m. However, special procedures and great care are required to obtain the required accuracy, even with repeat survey intervals of 20 years or more. Several exceptional levelling surveys have been carried out by the Geodetic Survey of Canada specifically for study of deformation associated with earthquakes. One survey of 100 km across Vancouver Island and back had a total vertical error of only 1 cm, a remarkable achievement (reported by Dragert *et al.*, 1994).

Tide gauges, usually mounted on coastal bedrock, continuously record the sea level relative to the land. Physical oceanographers may be astonished at the idea of using the unsteady ocean as a reference for monitoring land vertical motion. However, with gauges that have recorded continuously for 20 years or more it is possible. The recording must be long enough to allow removal not only of the tidal changes but also of longer term oceanographic variations such as El Niño. The steady global (eustatic) sea-level rise of ap-

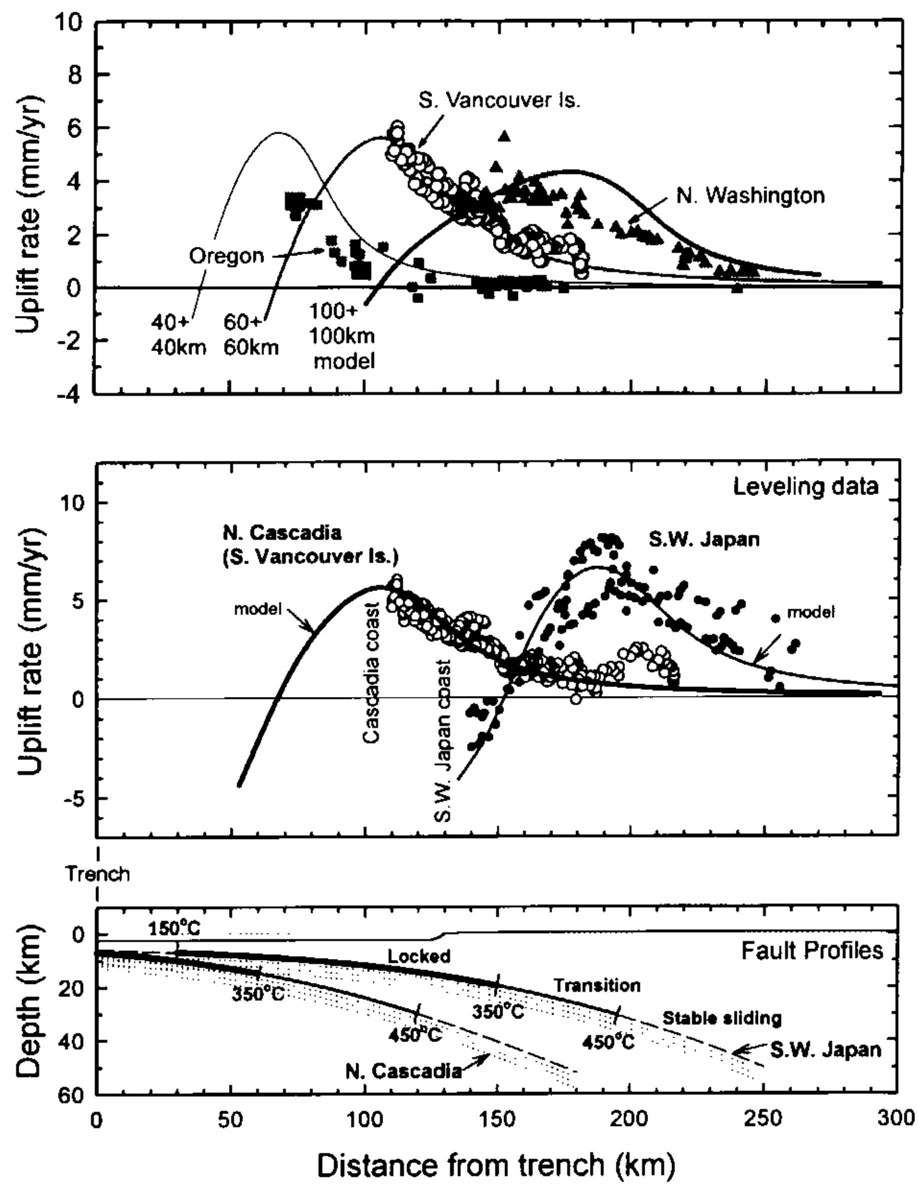

Figure 9 (**Top**) *Uplift rates from levelling (small symbols) and tide gauges (large symbols) for three coastal regions of the Cascadia margin. The open circles are for Vancouver Island, the triangles for northern Washington, and the squares for Oregon. Three model uplift profiles are shown for comparison (40+40 km etc. are dimensions of locked and transition zones).* (**Middle**) *Uplift rates from repeated levelling lines in N. Cascadia (open circles) compared to southwest Japan (filled circles). The model curves are the predictions for the temperature-controlled locked and transition zones shown in cross section in the lower diagram* (**Bottom**).

proximately 2 mm·a^{-1} that continues today from the melting of the Pleistocene ice must also be subtracted. And finally, all measured vertical motions must be corrected for postglacial (isostatic) rebound, the slow land recovery from depression by the ice load that continues to the present. The acceleration or force of attraction due to gravity (g) varies with the square of the distance from the centre of mass of the earth. It has been possible to use very accurate measurements of g, repeated a few years apart, to estimate the coastal uplift rate.

All three types of measurements of vertical motion, levelling, tide gauges, and gravity give similar results (Dragert *et al.*, 1994). For the Cascadia margin there is present uplift at rates that vary along the coast from 1-4 mm·a^{-1}. The value for the southwest coast of Vancouver Island is approximately 4 mm·a^{-1} (Hyndman and Wang, 1995). The uplift rate decreases to near zero 100 km inland from the point of maximum uplift.

Horizontal deformation across the coastal region has been found from two types of surveys. The first is repeated distance measurements using laser ranging between benchmarks on mountain tops up to 50 km apart. Shortening perpendicular to the Cascadia coast, ascribed to the buildup of great earthquake strain, was first shown for the Seattle-Olympic Peninsula region (*e.g.*, Savage *et al.*, 1991). This is a difficult and costly procedure, especially on the rain- and mist-bound coastal mountain tops. In the past several years, the satellite Global Positioning System (GPS) has permitted horizontal and vertical level measurements over distances of hundreds of kilometres with sufficient accuracy to detect earthquake related strain build-up. Using continuous GPS recording over several years, a rate of shortening of 7 mm·a^{-1} has been measured between Victoria on the coast and Penticton 300 km inland (Dragert and Hyndman, 1995) (Fig. 8). The uncertainty is only approximately 1 mm·a^{-1} over this distance. The Penticton site is essentially fixed relative to the stable part of the North American plate. The rate of shortening based on all of the horizontal measurements, is approximately 10 mm·a^{-1} across the 100 km wide coastal zone. This is one quarter of the 40 mm·a^{-1} plate convergence rate. The remainder is taken up as shortening farther seaward across the continental shelf. An experiment to measure the offshore crustal shortening is in progress using very accurate acoustic ranging to sea floor benchmarks and GPS ranging from the sea surface to land stations. The horizontal rate measured on land, if continued, represents 10 km·m.y.$^{-1}$; the vertical rates represent 1-4 km·m.y.$^{-1}$ These are very fast rates on a geological time scale. They would produce very high coastal mountains in a short time, mountains that are not present. Coastal geological studies have also shown much smaller vertical motions over longer time periods (*e.g.*, Clague *et al.*, 1982). We therefore conclude that the current deformation is primarily elastic and that it will be released in the rebound accompanying the next great earthquake.

The downdip extent of the locked zone has been estimated by comparing the geodetic data with mathematical models of the deformation (*e.g.*, Dragert *et al.*, 1994; Hyndman and Wang, 1995). The models include a transition zone on the fault between the fully locked and downdip fully free slip portions, since an abrupt transition is physically unrealistic. The rupture displacement of great earthquakes is assumed to decrease to zero at the downdip limit of this transition zone. The map of Figure 10 shows geodetic data for the whole Cascadia margin (Hyndman and Wang, 1995) (summary of data in Fig. 9). There are clear variations along the Cascadia margin in the pattern of uplift and shortening. The inferred widths of the locked

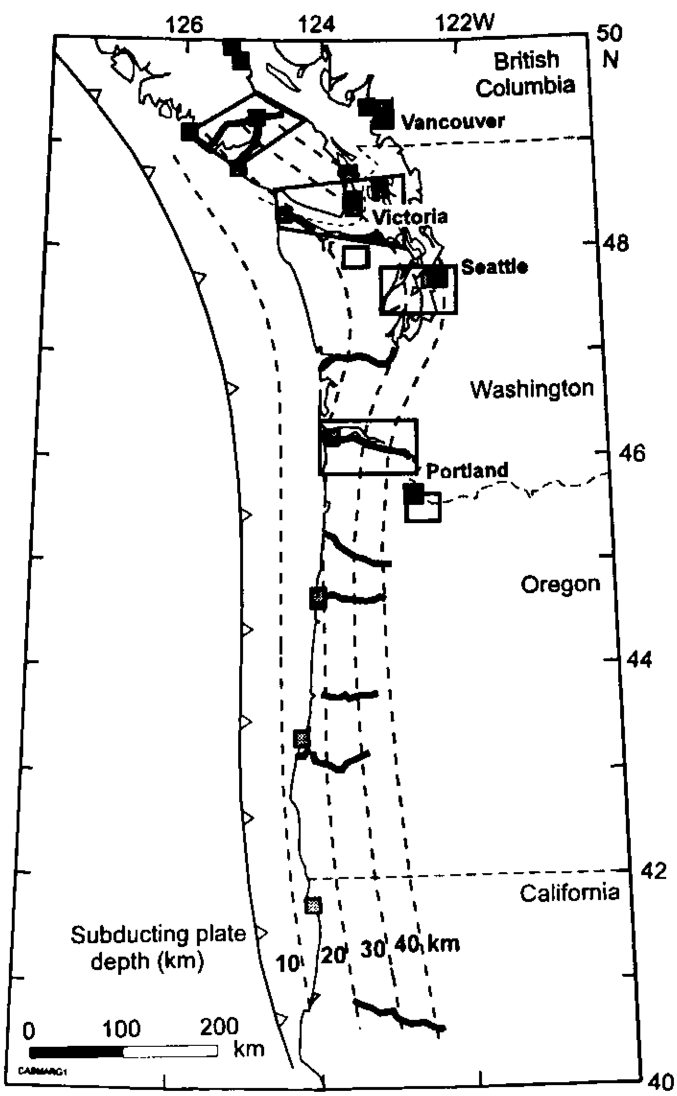

Figure 10 *Locations of the geodetic data that constrain the current deformation associated with the locked subduction thrust fault. The thick solid lines are repeated levelling, the squares are tide gauges, and the boxes are distance survey networks. The dashed lines mark the depth to the top of the subducting plate.*

and transition zones are widest off the Olympic Peninsula of northern Washington and narrowest off central Oregon (Fig. 11). A cross section across the Vancouver Island continental margin illustrates the positions of the locked, transition and free slip zones (Fig. 12).

Important support for the conclusions of the geophysical modelling is provided by a comparison of predicted coastal earthquake subsidence with that inferred from the studies of buried marshes. The present coastal uplift rate of 1-4 $mm \cdot a^{-1}$, accumulated over an interseismic period of 500 years, gives an expected earthquake subsidence of 0.5 m to 2 m. The marsh burial depths, after allowing for eustatic sea-level rise, postglacial rebound and the interseismic earthquake cycle uplift, give similar earthquake subsidence. Variations along the coast are also in general agreement, *i.e.*, the smallest present uplift rate and shallowest marsh burial depth are for the coast of central Oregon. However, there are differences in detail that remind us that we have simplified the complex earthquake process.

WHAT LIMITS THE WIDTH OF THE DOWNDIP SEISMIC ZONE?

The pattern of current deformation allows us to estimate which part of the thrust fault is locked. But what controls the limits of the locked seismogenic zone? Many factors have been suggested (*e.g.*, discussion by Tichelaar and Ruff, 1993), but temperature appears to play a dominant role, at least for continental subduction zones such as Cascadia (Hyndman and Wang, 1993). The seismic zone is bounded seaward by a region that does not generate earthquakes. Free slip in the latter zone may be a consequence of the stable sliding clay minerals that are common in the region of subduction zone faults. With increasing temperature these clays become dehydrated and transform to stronger minerals. The fault becomes seismogenic where the temperature reaches about 150°C (see discussion by Hyndman and Wang, 1993). If this hypothesis is correct, the seaward limit of the Cascadia locked zone is beneath the lowermost continental slope.

The downdip limit of the seismogenic zone may also be thermally controlled. At some depth, a temperature is reached on the thrust fault where the rocks behave plastically. The "brittle-ductile" transition has often been taken as the reason that crustal earthquakes are confined to depths less than 20-30 km. More precisely, the critical depth is not the result of a downward change in bulk properties, but rather where the fault zone no longer exhibits frictional instability (Scholtz, 1990). The transition is between velocity-weakening (seismic) to velocity-hardening (stable-sliding) on the fault. The former is analogous to classical friction in which the coefficient of starting friction is greater than the coefficient of dynamic sliding friction. Once motion has started, there is runaway release of the stored elastic strain and an earthquake occurs. Velocity-hardening is analogous to viscous behaviour in which an increasing rate of slip results in increasing resistance.

Laboratory measurements on continental crustal rocks indicate that the critical temperature marking the transition to stable-sliding is approximately 350°C (*e.g.*, references listed by Hyndman and Wang, 1993). This temperature corresponds well with that estimated for the maximum depth of earthquakes in many continental areas, including the crustal earthquakes landward of the Cascadia subduction zone. The maximum depth is greatest in low-heat flow cool areas where the temperature increases slowly with depth. It should be noted, however, that the maximum temperature for earthquakes below the crust in mantle rocks is much higher, *i.e.*, 750-800°C (Fig. 4). Great earthquakes that are initiated where the temperature is less than 350°C may rupture downdip to where the temperature reaches approximately 450°C. The 350-450°C region thus corresponds to the transition zone used to model the geodetic data.

The temperatures on the Cascadia thrust plane are unusually high because the young incoming oceanic plate is hot and because there is a thick insulating sediment cover. As a result, a temperature of approximately 225°C is reached

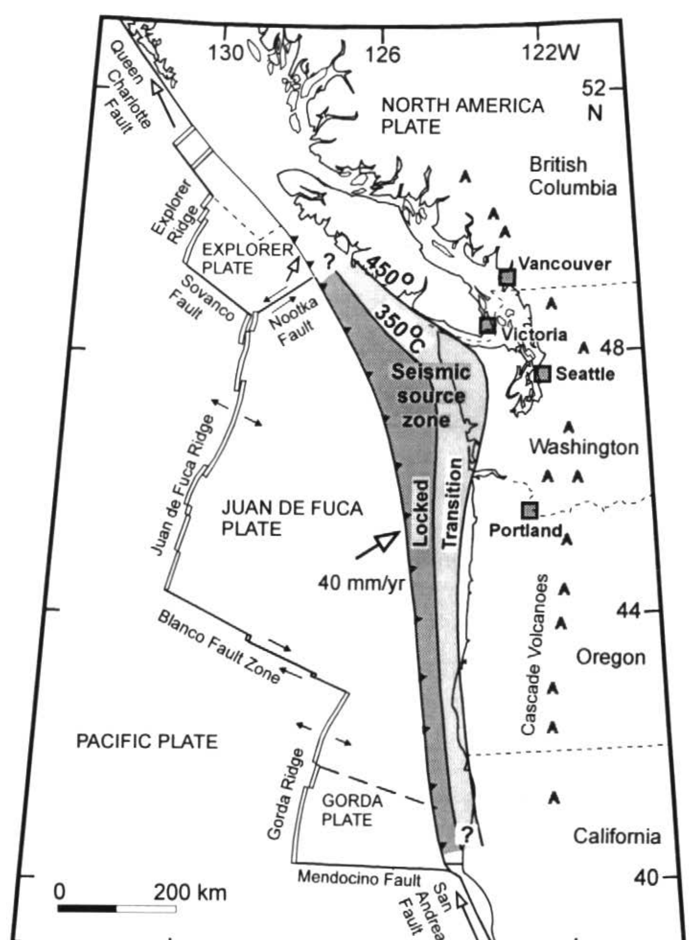

Figure 11 *Plan view of the extent of the locked and transition zones on the subduction thrust fault based on current deformation data (after Hyndman and Wang, 1995).*

at the top of the oceanic crust at the base of the continental slope. The high temperatures on the thrust plane mean that the 350°C and 450°C temperatures are reached at an unusually short distance landward on the fault.

How well do the thermally predicted downdip limits correspond to the actual limits obtained from the current deformation data? Thermal modelling has been carried out for a series of profiles across the Cascadia margin to obtain the temperatures on the subduction thrust fault (Hyndman and Wang, 1993; 1995). Measurements of the heat flux from the earth, both on land and the sea floor, provide a model constraint. The positions of the 350°C and 450°C temperatures are in good agreement with the downdip limits of the locked and transition zones inferred from the deformation data (Fig. 12). Figure 12 also shows that the seismogenic zone lies beneath the prism of sediments scraped off the incoming oceanic crust. At a depth of 10 km, the sediments are no longer unconsolidated muds and sands, but rather have been compressed and lithified to sedimentary rock with sufficient strength to sustain elastic strain buildup.

One more obvious question remains; how do we know that the inferred locked portion of the subduction thrust fault corresponds to the area of great earthquake rupture? We noted above one supporting correspondence. The predicted earthquake subsidence generally agrees with that deduced from studies of buried coastal marshes. Another approach has been to apply the Cascadia type of analysis to subduction zones marked by well documented, historical, great earthquakes. For the Nankai margin of southwest Japan, the downdip rupture areas of the 1944 and 1946, magnitude of 8, great earthquakes correspond closely to the locked seismogenic zone, inferred from analysis of current deformation data and from thermal modelling (Hyndman *et al.*, 1995) (Fig. 9).

THE HAZARD

A detailed discussion of the hazard associated with great subduction zone earthquakes is beyond the scope of this article. We present here only a few general comments. The distribution of ground shaking expected from a great Cascadia earthquake can be estimated in two ways. The first is to make comparisons with the experience from great earthquakes elsewhere. The other approach involves theoretical models based on the estimated seismic rupture area and displacement. The conclusions are similar; the ground shaking in coastal areas will be strong for the expected events with magnitudes well over 8. The larger cities of Vancouver, Seattle and Portland, that lie 100-200 km inland from the outer coast, are fortunate that the earthquake-generating portion of the fault is restricted to beneath the continental shelf. It extends little, if at all, below the coast. However, the shaking for such large earthquakes decreases rather slowly with distance, so the hazard at these cities is still large.

The maximum magnitude for Cascadia thrust earthquakes depends mainly upon the along-coast length of rupture. Simultaneous rupture of the whole locked zone from British Columbia to California would be an unusual occurrence in the global experience. Such long narrow rupture areas are rare, but there is increasing evidence that this has occurred, at least for the most recent Cascadia event (*e.g.*, Atwater *et al.*, 1995; Satake *et al.*, 1996). The long inter-event period allows for truly giant earthquakes of magnitude 9 if the whole Cascadia-locked area of nearly 100,000 km^2 ruptures at once. There have been only two events of this size in the 100 years of global earthquake recording: the 1960 earthquake along the coast of southern Chile, and the 1964 earthquake off the coast of Alaska. For such giant earthquakes, strong ground shaking lasts for a long time, at least several minutes, a feature that presents an increased hazard from some structures.

The earthquake threat from smaller events for coastal regions of British Columbia and Washington is large even without great earthquakes. The new evidence for giant subduction zone events results in hazard estimates that are similar to those for regions well known for very large earthquakes, such as California and Japan.

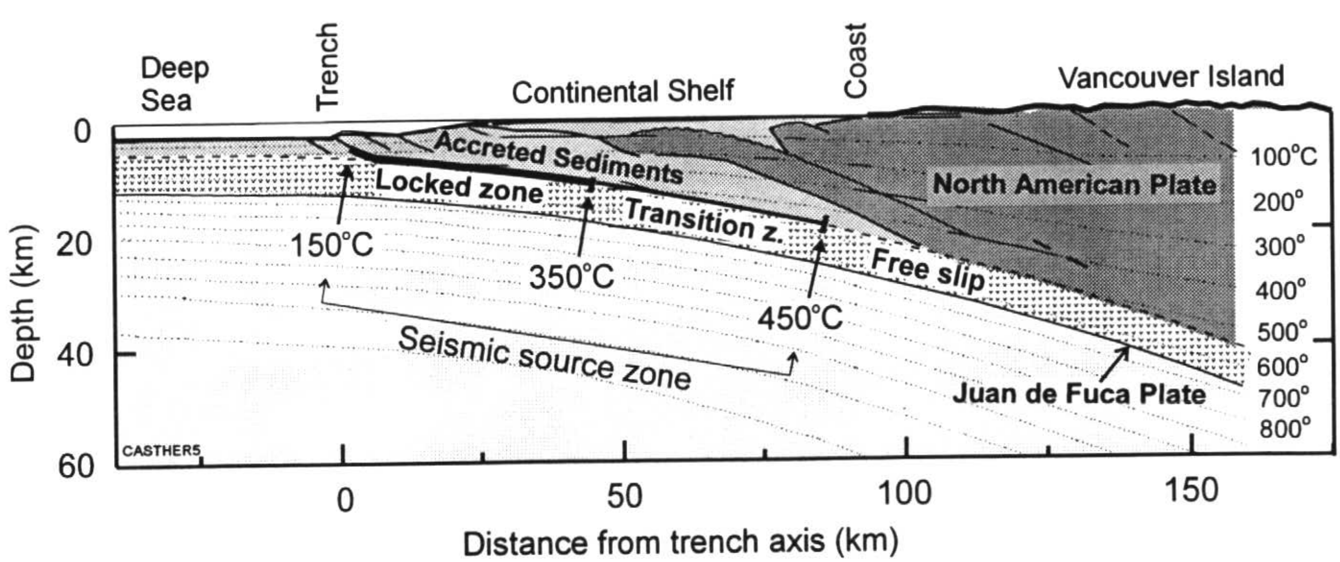

Figure 12 *Cross section through the northern Cascadia margin showing the geological structure and isotherms (lines of constant temperature). The landward limits of the locked and transition zones corresponds to temperatures of approximately 350°C and 450°C, respectively.*

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