The Threat of a Great Earthquake in Southwestern British Columbia

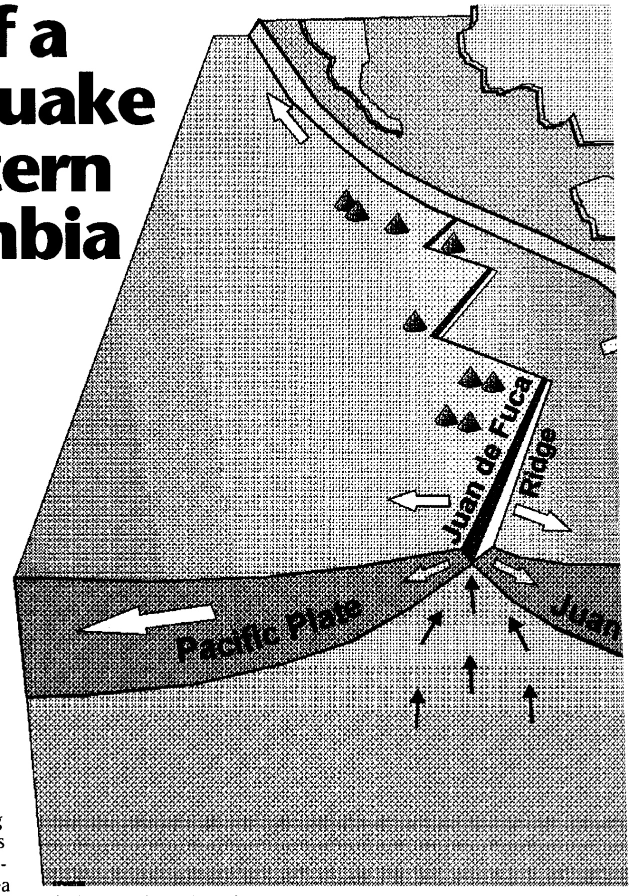

Fig 1: **Tectonic setting of western British Columbia and Washington state.**

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Public awareness of southwestern BC's significant earthquake hazard has increased considerably in the last decade, due largely to media coverage of recent geological and geophysical findings in the area as well as the effects of destructive earthquakes in Mexico (1985), California (1989, 1994) and Japan (1995). During this period, earthquake preparedness initiatives have intensified, earthquake education has become more common in Vancouver-Victoria area schools, and some critical facilities, including dams, bridges, schools and hospitals, have been seismically upgraded or replaced.

An accurate assessment of seismic hazards requires knowledge of the causes, sources, frequencies and effects of earthquakes of different magnitudes, which is obtained through a wide range of geological and geophysical studies. In addition, ground motions produced by different sizes and types of earthquakes and ground motion attenuation with distance from the earthquake source zone must be determined. Local site conditions must also be assessed.

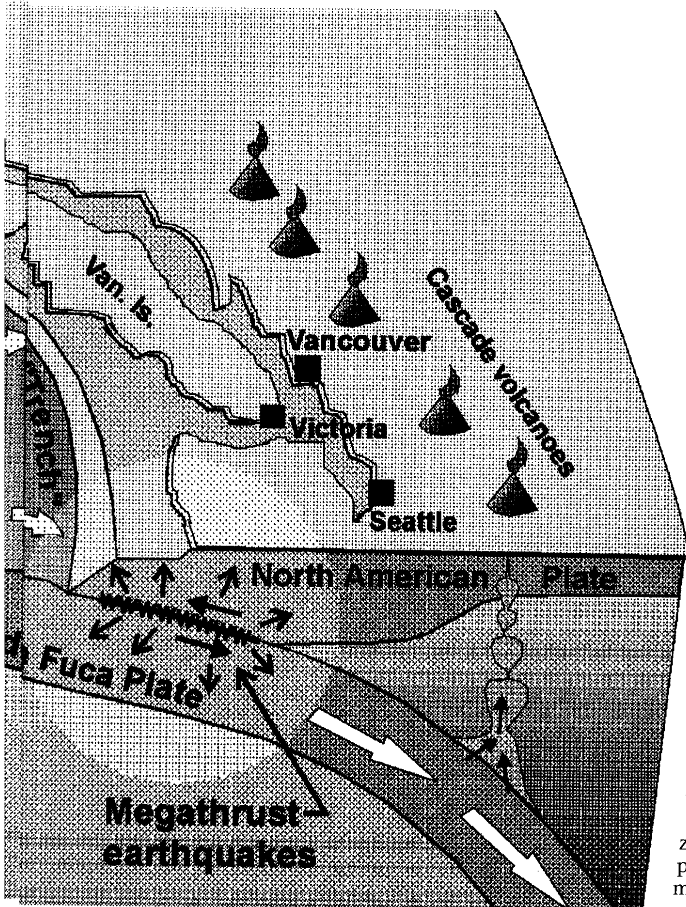
Written and instrumental records from the past 200 years show that there have been many moderate to large (Richter magnitude 6 to 7) earthquakes in southwestern BC and in adjacent Washington state. All well-located earthquakes have originated either in the continental crust of the North America plate or deeper within the underthrusting Juan de Fuca oceanic plate, which moves beneath the North America plate at a rate of about 40 mm/year (Fig 1). Until recently, it was thought these were the only types of earthquakes to affect the region, but there is now strong evidence that much larger (M8 to 9) earthquakes have occurred beneath the continental shelf and slope off the west coast in the more distant past. These "great" quakes originate on the 1,000 km long thrust fault that separates the Juan de Fuca and North America plates in what is known as the Cascadia subduction zone.

For engineers involved in structural design, the first source of information on earthquake hazard requirements is the National Building Code of Canada (NBCC), whose seismic zoning and earthquake provisions currently reflect smaller (M6 to 7), more frequent and more widely distributed earthquakes, although the Code is being revised to more adequately incorporate the hazard associated with great subduction earthquakes. For some structures, additional detailed seismological and engineering studies are required to adequately deal with the earthquake hazard.

The following reviews the geophysical and geological evidence for great subduction earthquakes in southwestern BC and argues that they must be considered in assessments of seismic hazard for the region.

Geophysical Evidence

Like all earthquakes, great subduction earthquakes are complex when considered in detail. However, the basic



locked and stable sliding portions of the thrust fault that extends to the vicinity of the west coast of Vancouver Island (Fig 3). It is the locked zone and most of the transition zone within the subduction thrust fault that are expected to rupture in the next great earthquake.

The downdip limit of the locked and transition zones, which is controlled by temperature, is important in assessing seismic hazard since it determines the landward extent of the earthquake source zone. From detailed thermal modelling, the key conclusion in terms of seismic hazard is that the subduction thrust fault is locked at present, but the earthquake source zone is narrow and probably does not extend beneath Vancouver Island.

process is simple and may be approximated by the elastic rebound model first developed for the San Andreas fault. For the Cascadia subduction zone, ongoing convergence within a locked thrust fault drags down the seaward nose of the continent beneath the continental shelf and causes an upward flexural bulge farther inland (Fig 2), also creating a zone of crustal shortening. At the time of the earthquake, the seaward portion of the continent springs back, the leading edge of the plate is uplifted and the bulge collapses.

Several types of geodetic measurements define the pattern of current deformation across the Cascadia margin. The data show that the west coast of Vancouver Island is rising at a rate of about 4 mm/year. Most of the elastic shortening caused by the Juan de Fuca/North America plate convergence occurs on the continental shelf. However, the shortening extends as far as Victoria, which global positioning satellite measurements show to be moving landward at a rate of 7 mm/year relative to Penticton. This pattern of deformation is consistent with a locked zone 60 km wide beneath the continental slope and outer shelf, and a transitional zone between the fully

Geological Evidence

Past great earthquakes along the Cascadia subduction zone are preserved in the geological record through the effects of sudden land-level changes, tsunamis and strong ground shaking.

The clearest evidence for past earthquakes comes from tidal marshes along the outer coasts of Vancouver Island, Washington, Oregon and northern California. Outcrops, excavations and cores at more than a dozen estuaries along the length of the Cascadia subduction zone have revealed buried peat layers, interpreted to be former intertidal marsh surfaces that were submerged by abrupt coastal subsidence during past great earthquakes (Figs 4, 5a). These layers consist of vegetation identical to that growing in the tidal marshes today. Analysis of plant and animal fossils shows that submergence and burial of marshes at many estuaries resulted from at least 0.5 m of sudden subsidence. Radiocarbon dating and tree growth rings suggest that the last earthquake occurred about 300 years ago and that hundreds of kilometres of coast subsided during this event. Rupture lengths along the subduction zone that are implied by such widespread subsidence are consistent with M8 or larger earthquakes, but not with smaller events. The pattern of subsidence during the last earthquake is similar to the widespread subsidence of historic great earthquakes along subduction zones in Chile, south-central Alaska and Japan.

Sheets of sand deposited by tsunamis that rushed into the subsided coastal zone mantle some of the buried peat layers (Fig 4). Stems and leaves of fossil plants rooted in the uppermost buried soil are covered by, or extend into, the overlying sand, providing evidence of rapid burial (Fig 5b). This suggests strongly that the tsunami was triggered by the same earthquake that caused the coast to subside.

Liquefaction features, which provide evidence of ground shaking during the last great earthquake on the Cascadia subduction zone, have been observed in banks of the lower Columbia River between Washington and Oregon up to 60 km inland from the coast. The features are about 300 years old and include sand dykes and sand blows that formed when liquefied sediment was injected upward along fractures and expelled onto a subsided surface (Fig 5c). Sand dykes and blows are also common on the Fraser River delta directly south of Vancouver. Some of the most spectacular and best dated of these features, discovered recently on Annacis Island, are about 1,700 years old, which is about the time of one of the great Cascadia subduction earthquakes.

Shaking from earthquakes on the Cascadia subduction zone also has been inferred from turbidites in deep-sea channels off the Pacific coast of Washington and Oregon. Turbidites are deposits of sediment-laden, swift-moving, bottom-flowing currents that travel down a subaqueous slope. They originate in various ways, such as by storm waves, tsunamis and earthquake-induced sliding. It has been argued that turbidites in five separate channels were deposited simultaneously during great subduction earthquakes and that there have been 13 such events in the last 7,600 years, an average of one earthquake about every 600 years.

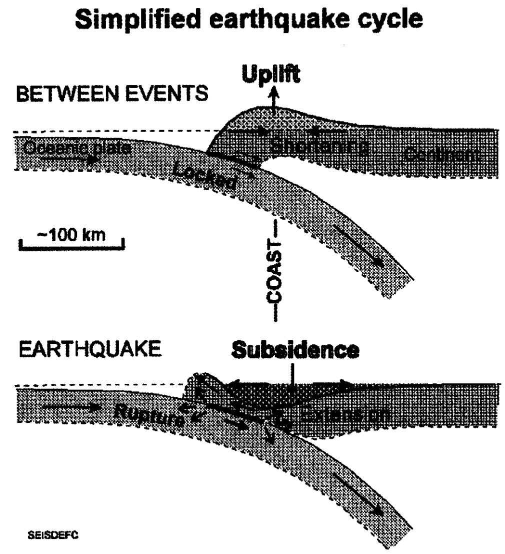


Fig 2: **Interseismic and coseismic deformation associated with a subduction thrust fault.**

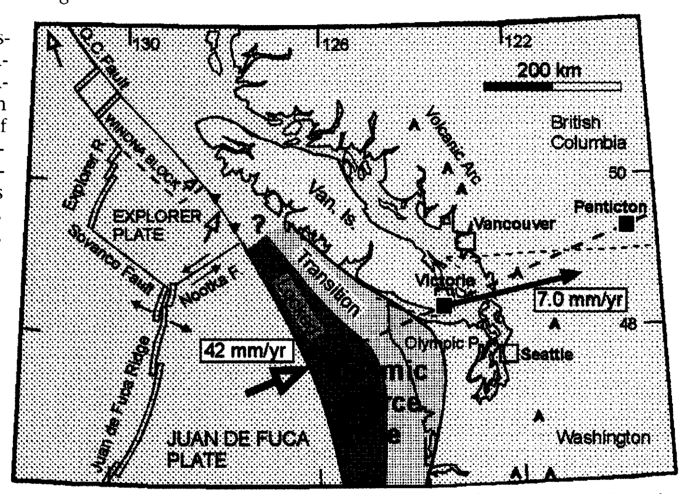


Fig 3: **Source zone for great Cascadia subduction earthquakes. (Dragert and Hyndman, 1995)**

Great Earthquake Magnitude and Hazard

Although there is little doubt that grea earthquakes have occurred in the region and will occur in the future, there is uncertainty as to how much of the Cascadia subduction zone ruptures during such events. Conceivably, the entire 1,000 km length of the subduction zone could rupture, producing an earthquake in excess of M9. Although unusual in global experience, the great Chile earthquake in 1960 had such a rupture length. Alternatively, sections several hundred kilometres in length might fail, producing more numerous M8+ events. It is unlikely that plate convergence and underthrusting are accommodated by earthquakes smaller than M8 because so many are required that some should have occurred during the 200-year historical period.

The issues of segmentation and the maximum magnitude of subduction earthquakes have not yet been resolved; however, the geophysical data indicate that the whole subduction zone is locked at present, and radiocarbon and tree-ring dating do not rule out the possibility that the last great earthquake ruptured the entire subduction zone. Historical evidence from Japan supports the idea that this was a single giant (M9+) earthquake rather than a series of lesser (M8) earthquakes. There are records of a tsunami at a number of sites along the Japanese coast on January 27, 1700. There is no indication of a local earthquake at this time and, after eliminating other sources, researchers concluded that the tsunami was generated by an earthquake along the Cascadia subduction zone during the evening of January 26, 1700. The observed amplitude and pattern of the tsunami suggest that the earthquake ruptured most of the Cascadia margin.

Effects on Southwestern BC

The foregoing issues are critical in evaluating the threat posed by subduction earthquakes. A M9 earthquake releases approximately 30 times the energy of a M8 quake. Should the entire Cascadia subduction zone release during a M9 event, all cities in western Oregon, western Washington and southwestern BC might be affected. The intensity of shaking during such an earthquake might be less than that of a nearby large crustal earthquake, but the duration of shaking would be longer, as much as several minutes, resulting in greater damage to some structures. Shaking would decrease slowly with distance inland; thus, the hazard to coastal cities such as Victoria, Vancouver and Seattle is considerable, even though they are 100 to 200 km from the source.

A M8 subduction earthquake would affect a smaller total area than a M9 event. The shaking would not last as long, but would be just as severe along the coast adjacent to the rupture. Although a M8 earthquake centred on the southernmost part of the Cascadia subduction zone might have no effect on Vancouver, a succession of such earthquakes, rupturing different parts of the subduction zone over a short period of time (days to perhaps years), might produce more damage to the entire coastal Pacific Northwest than a single M9 event. A disturbing prospect is that an M8 earthquake would not fully release the accumulated strain along part of the plate boundary and might lead to another earthquake in the same area some time later. The fear of a second or third large earthquake would impede reconstruction and the resumption of normal economic activity and life in cities affected by the first earthquake.

On a probability basis, estimates of accelerations and velocities in the Vancouver and Victoria areas might not be increased by including great earthquakes in seismic hazard assessments; however, the greater duration of shaking is something new that must be considered in the design of some buildings. In general, the hazard from great earthquakes is largest for sensitive structures (for which failure, even at low probabilities, is not acceptable) as well as structures likely to be damaged by lengthy shaking. It is also important to note that the provisions of the NBCC and most seismological studies estimate ground motions at bedrock sites. Additional site-specific studies are required to determine the effects of local soil conditions, as considerable amplification of ground motion can occur at resonant frequencies at some sites on thick soils.

Preparing for the Big One

The probability of a great Cascadia earthquake in the near future is low. The geological record suggests that they occur, on average, once every 600 years, although intervals between successive earthquakes differ considerably. Uncertainties in the number and ages of events result in a broad range of probabilities, from a few percent to perhaps 30%, that a great earthquake will occur somewhere along the Cascadia subduction zone in the next 50 years.

While a Cascadia subduction earthquake poses new challenges to engineers and emergency planners, it must be remembered that a large local crustal earthquake can also be devastating. One need only look at Kobe, Japan for

Fig 4: **Tidal marsh excavation near Tofino, BC exposing a buried peat layer (arrow), the remains of a former marsh that subsided about 1m during an earthquake about 300 years ago. The peat is sharply overlain by a sand layer (tip of knife) deposited by the tsunami that immediately followed the earthquake. (Photo: J J Clague)**

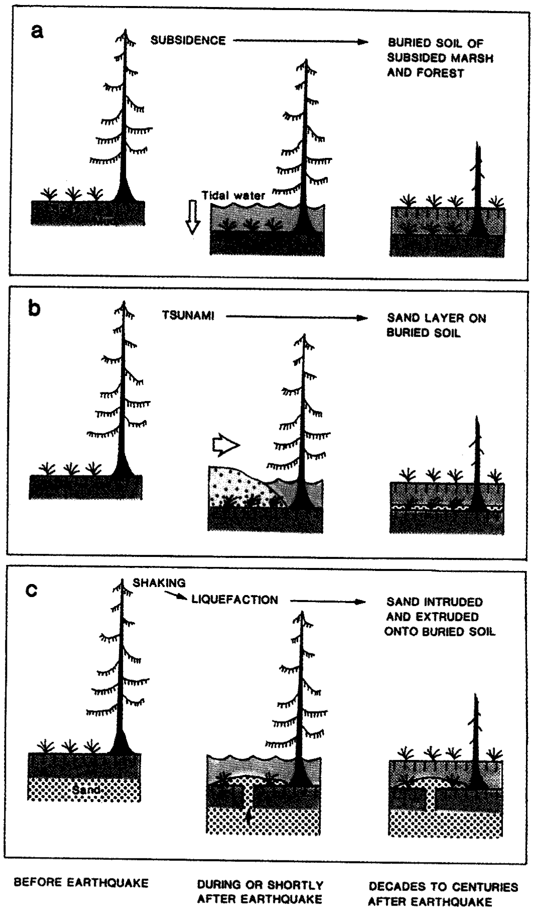


Fig 5: **Origin of the main coastal features that provide evidence for subduction earthquakes in the Pacific Northwest. (a) A peaty soil is buried by tidal mud after an earthquake lowers the land into the intertidal zone. (b) A sheet of sand is deposited on a coseismically subsided surface by a tsunami shortly after an earthquake. (c) Liquefied sand moves upward through cohesive sediments and is ejected onto a subsided surface as a result of earthquake shaking. (Modified from Atwater et al, 1995)**

an example. Kobe's building code and earthquake preparedness plans, intended for a great earthquake on the Japanese subduction zone some 150 km away, proved to be totally inadequate for a much smaller, closer earthquake.

BC's Ministry of Education has recently completed a $3 million seismic vulnerability assessment of most of its schools. About $600 million will be spent annually on upgrading schools, of which $30 million is specifically targeted for structural improvements related to earthquakes. Since 1985, BC Hydro has spent about $120 million upgrading its dams in southwestern BC, with a significant portion of this amount going to seismic improvements. The City of Vancouver has spent $1.1 million, and will be spending an additional $2.8 million, on three critical road bridges. Vancouver also has commissioned seismic vulnerability assessments of public buildings and is examining proposals to assess some 1,200 private buildings.

Some people question the value of spending large sums of public money preparing for a damaging earthquake. However, the devastation wrought by the Kobe earthquake, which resulted in 5,470 deaths and damage likely to reach $200-300 billion CDN in a country widely acknowledged to have the highest level of earthquake preparedness in the world, provides a timely reminder of the need for a coordinated and well-funded plan to assess hazard and reduce structural damage and loss of life due to a strong earthquake in southwestern BC.

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