Observations of Tectonic Processes and the Geometric Constraints along the Cascadia Subduction Zone that Control Megathrust Earthquakes

By

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Abstract:

Understanding the tectonic processes and geometric constraints along the Cascadia subduction zone provides accurate information for future implications of megathrust-type earthquakes. Preferred trajectory is a function of both rates of convergence and oceanic lithosphere age and is a reliable indicator for large earthquake generation. The research findings show that Cascadia is capable of generating megathrust earthquakes due to (1) its high rate of convergence, (2) its young hot oceanic lithosphere and (3) its nearly horizontal preferred trajectory (large coupling area). A confined zone of locking in the south is likely a result of the Basin and Range Extension. Subduction of excess trench sediments between two slabs could result in megathrust earthquakes and episodic tremor and slip may explain further areas of decoupling.

Introduction:

The Cascadia subduction zone (boundary between two tectonic plates, one riding over the other) stretches roughly 1,000 kilometers in length from Vancouver Island to Northern California (Figure 1). The zone is characterized as the boundary between the subducting Juan de Fuca Plate and overlying North American Plate. The surface trace of this boundary lies 60-130 km offshore.

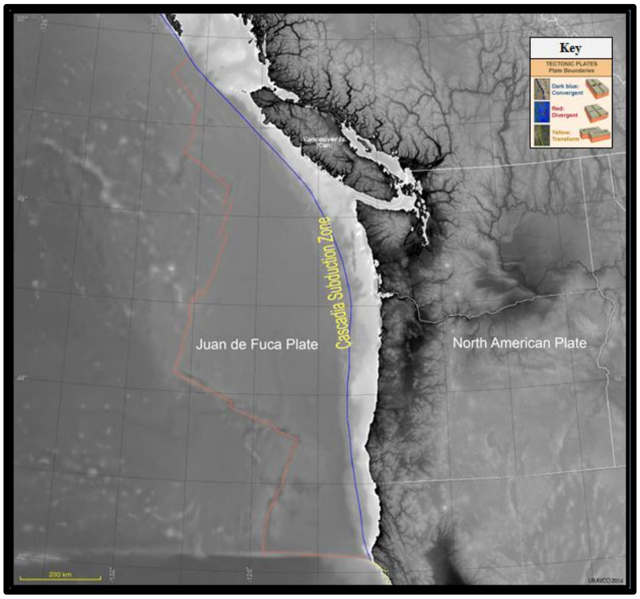


Figure 1: Regional overview of the Cascadia subduction zone off the coast of the pacific northwestern United States. Tectonic margins are represented in solid colored lines; red is for spreading center, blue is for subduction zone and yellow is for strike slip margins. (Jules Verne Voyager)

Sudden releases of compressional stresses along this boundary are capable of resulting in large megathrust (magnitude 8 to 9) earthquakes. Subsided tidal wetlands overlaid by tsunami related sands in North America were the first substantial evidence for megathrust earthquakes along the Cascadia Subduction Zone (Atwater, 1987).

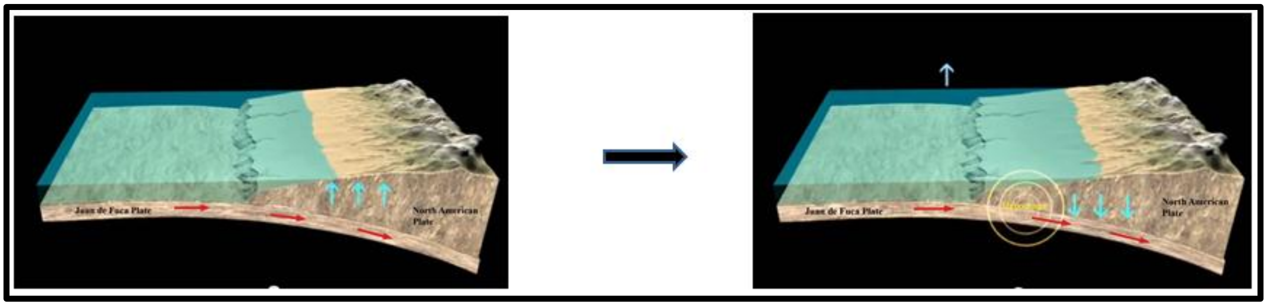


Figure 2: Modeled subduction zone depicting the Juan de Fuca plate being subducted beneath the North American plate. The left shows the overlying plate flexing upwards from the drag of the underlying plate moving beneath. The picture to the right depicts the origin of a megathrust earthquake in yellow circles. The earthquake allows the overlying plate to move out to sea removing the upward flexure causing a lowering of the coastline and an accompanying rise in sea level (modified from film: Active Earth Awareness: The Silent Subduction Zone).

Previously it was thought that the Cascadia Subduction Zone was not capable of such large earthquakes. This was primarily due to the lack of historical large earthquakes in the region and it was not until Heaton and Kanamori (1984) that conventional thinking was questioned. In their research they compared Cascadia to other subduction zones around the world and concluded that due to the geometry of the plate and the young age of subducted oceanic lithosphere the Cascadia subduction zone was in fact capable of producing large earthquakes.

Before Heaton and Kanamori (1984) conventional classification systems referred to Uyeda (1979) by classifying a subduction zone as either a Chilean-type –shallow dipping subduction resulting in strong coupling between the two plates- or a Mariana-type –steeply dipping subducting lithosphere resulting in weak coupling between the plates- subduction zone (Figure

3). After Heaton and Kanamori (1984) Cascadia was reclassified from a Mariana-type to a Chilean-type subduction zone.

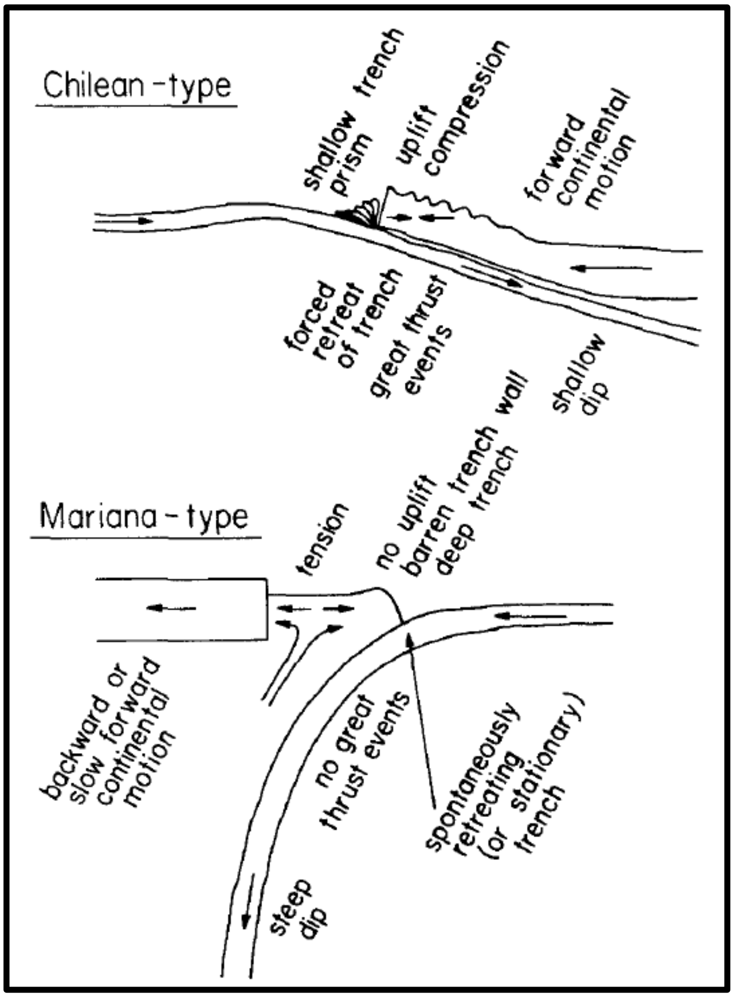


Figure 3: Comparison of both Chilean-type and Mariana type subduction zones. Chilean type subduction is characteristic of a shallow dip and large contact area at the plate contact margin. The Mariana type subduction zone has a steep dip of the down going plate which results in less contact area with the overlying plate (from Uyeda (1979)).

In the time since Heaton and Kanamori (1984) researchers have looked for reliable indicators in the stratigraphic record for evidence of past large earthquakes. Paleotsunami and turbidite –submarine debris slides- sediments have proved to be the best evidence for past megathrust events (Goldfinger (2003), Peterson (2013) and Nelson (2006)). On January 26, 1700 an enormous earthquake occurred off the coast of the Pacific Northwest causing 600-1,000 km of coastline to subside 1-2 m below sea level (Goldfinger (2003)). This event generated local tsunamis that were likely 10-12 m high, and were recorded in Japan. Paleoseismic data (paleotsunami sediments correlated to offshore turbidites) observed along the pacific northwestern United States indicate that the event was a magnitude 9-subduction type earthquake. This strong evidence for megathrust type earthquakes sparked the scientific community's interest. Further research into both paleotsunami and turbidite sediments supports evidence of up to six such events in the last 2,000 years and up to 12 separate tsunami events over the past 5,000 years (Nelson (2006)).

With such well-defined evidence of past megathrust-type earthquakes it is necessary to determine:

What tectonic processes and geometric constraints along the Cascadia subduction zone control megathrust earthquakes?

Observations/Discussion:

The Cascadia subduction zone was thought to be relatively aseismic, but has since been reevaluated (Heaton and Kanamori (1984)). Geodetic measurements along the coast from the Vancouver Islands to the southern part of the zone in Northern California have shown both vertical and horizontal deformation which is consistent with a locked plate of a subduction zone indicating that large amounts of compressional stress are building up along Cascadia (Figures 4, 5 & 6).

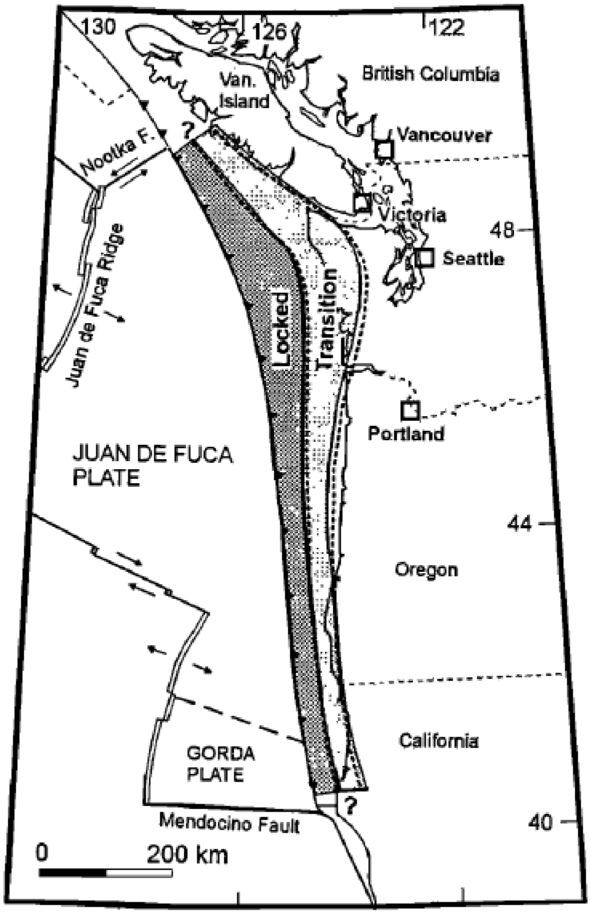


Figure 4: Regional overview of the Cascadia subduction zone. Shaded zones show 3-D model locked data where the lighter shaded zone represents the transition zone widths for deformation data (From Fluck (1997)).

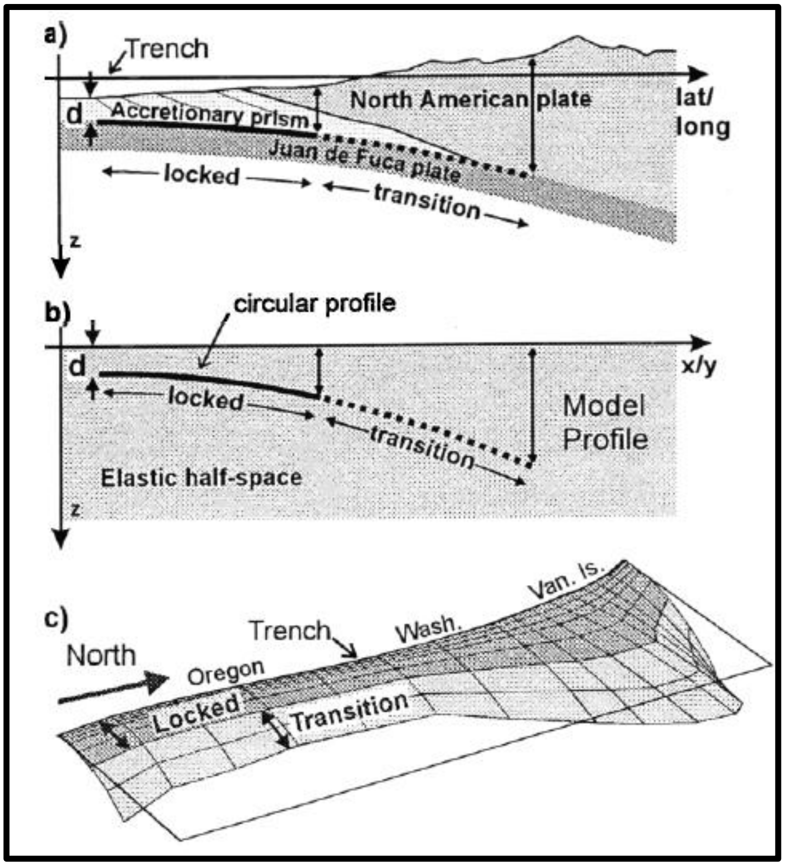


Figure 5: Cross sectional and three dimensional view of Cascadia displaying both locked and transitional zones (From Fluck (1997)).

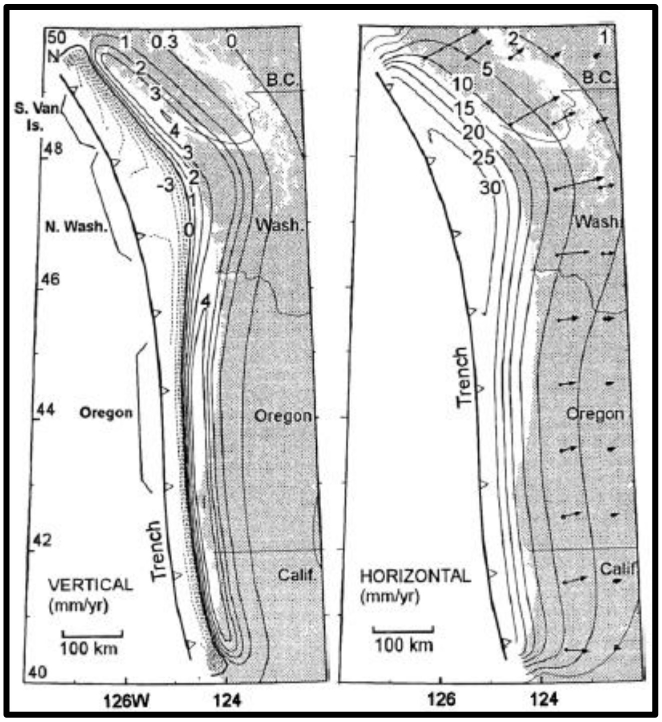


Figure 6: Regional map of Cascadia with contours of interseismic uplift rates (mm/yr) on the left and directional vectors with accompanying contours of magnitudes of horizontal velocity (mm/yr) on the right (From Fluck (1997)).

The nature of seismic coupling –the connection that two tectonic plates make with one another along a subduction zone- works well for evaluating the processes along a subduction zone. In his paper, Ruff (1983) his colleagues and him made the observation that earthquake size was a function of both the age of the subducting lithosphere and the rate of convergence of the two plates (Figure 7 & 8).

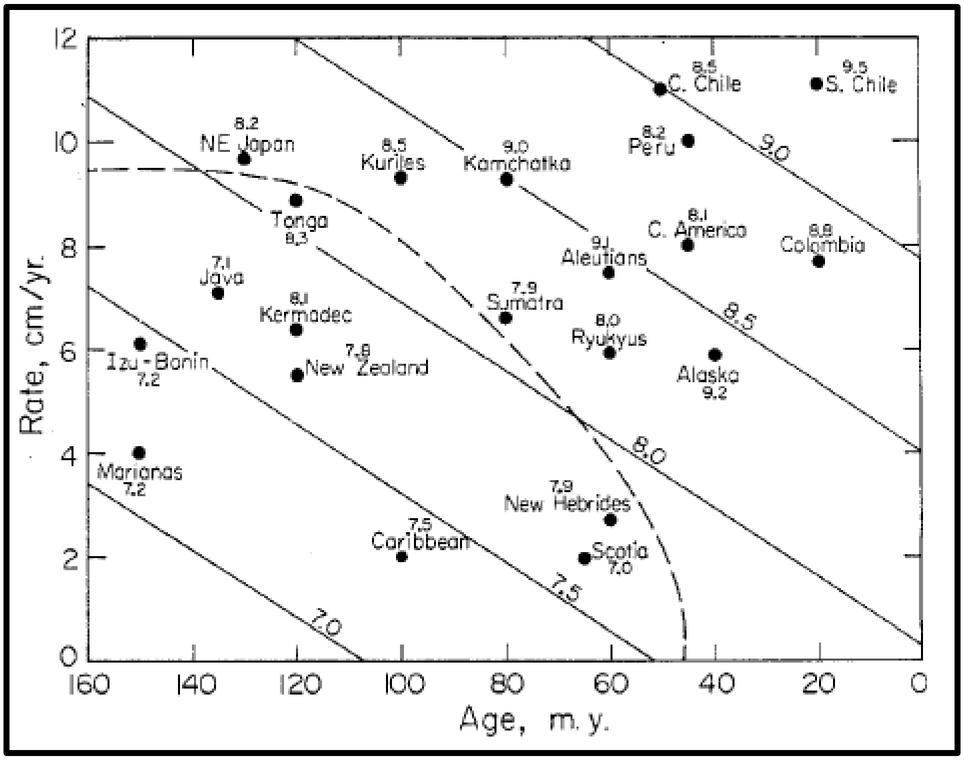
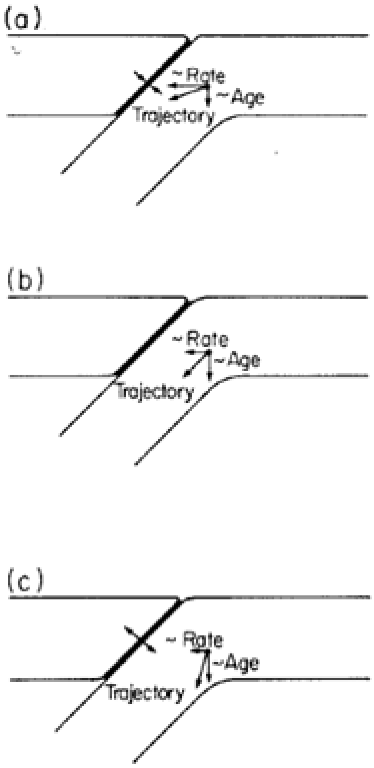


Figure 7: Large earthquakes are plotted by both their convergence rate and the age of the subducting lithosphere. Solid contoured intervals are statistically associated with their predicted convergence rate and age of subducting lithosphere. Notice that megathrust-type earthquakes are associated with both fast convergence rates and young subducting lithosphere (From Ruff & Kanamori (1983)).



Rate of Convergence	Oceanic Lithosphere Age	Preferred Trajectory
Fast	Young	Horizontal (Largest Earthquakes)
Median	Median	Median
Slow	Old	Vertical (Relatively Aseismic)

Figure 8: Generalization of a subduction zone cross section representing preferred trajectory. The horizontal vector is determined by the rate of convergence and the downward vector is given by the oceanic lithosphere age of the subducting slab (Modified from Ruff & Kanamori (1983)).

While the largest earthquakes have both young lithospheric crust and a relatively high convergence rate, Ruff & Kanamori (1983) observe that they are also associated with large asperities –regions within the subducting lithosphere that resist the motion between the converging plates-. As asperities are subducted they resist the downward motion of the subducting lithosphere and may create locking zones where stress is able to build up.

These asperities could be in the form of large oceanic plateaus or generate from excess trench sediments (ETS) as proposed in Ruff (1989). Ruff points out that the global survey of megathrust-type earthquakes at subduction zones occur in zones of ETS.

There are two proposed theories for what happens to ETS. One is that some of the sediment is subducted with the down going plate, and the second is that the sediments are delaminated to make up the accretionary prism along with continental derived detritus. Ruff speculates about the first theory (Figure 9).

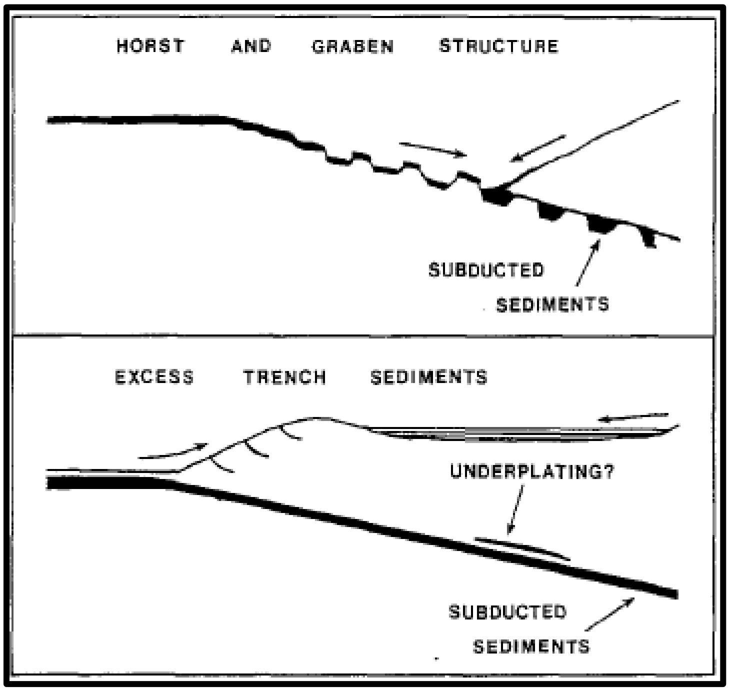


Figure 9: Two proposed methods for the fate of subducted ETS. The top cross section depicts ETS being collected in pockets formed by horst and graben structures and the second is a thin lamination of sediments that is then subducted until it under plates the accretionary prism (From Ruff (1989)).

It is important to note that only a small fraction of the ETS is subducted, the evidence being the large accretionary prism. However, if these sediments are subducted in to the zone of contact between the two plates there would be two outcomes, one for each above situation. In the case of the horst and graben structure, the subducting slab would look to the overplated slab as consisting of a composition of alternating oceanic sediment and basalt. In the alternative case in-between the contact of the two plates would be a thin uniform layer of metamorphosed sediments. In either case this would surely affect the seismicity derived from the contact zone of both plates.

In Oleskevich (1999) the Cascadia 1-D thermal model revealed that temperatures of the down going slab are high, 225°C to 260°C due to the young oceanic lithosphere and thick insulating trench sediments (Figure 10).

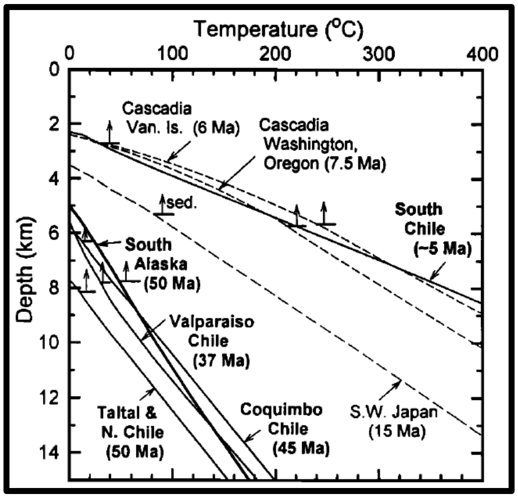


Figure 10: Temperature versus depth of subducting plate based off of 1-D thermal models. The horizontal bars with arrows represent the base of the ETS. Cascadia has a very high temperature because it is young oceanic lithosphere and is insulated by the trench sediment (From Oleskevich (1999)).

Due to the oblique convergence of the Juan de Fuca plate with the North American plate stress is building up at different rates along locked zones of Cascadia. In McCaffrey (2000) his colleagues and him looked at the rotation and locked zones of Cascadia along the southern region. They observed that western Oregon was rotating clockwise relative to a pole in eastern Washington. This rotation is largely driven by Basin and Range extension from the East, however, the shortening from the Cascadia subduction zone is significant enough to deflect the deformation upwards.

Episodic tremor and slip –low frequency long lasting tremors observed at deep depths in subduction zones- is being used as an analogue for stress loading along Cascadia. In Rogers & Dragert (2003) they propose that observing episodic tremor and slip could lead to recognizable onsets of megathrust earthquakes along Cascadia.

In Trehu (2008) an analysis of the 2004 central Cascadia forearc earthquakes were proposed to be low angle thrust faults. They proposed that because these earthquakes were recorded at the same depth as observed episodic tremor and slip this was likely the locked or transitional part of interpolate margin. Their seismic reflection model (Figure 11) provides strong constraints for the plate interface.

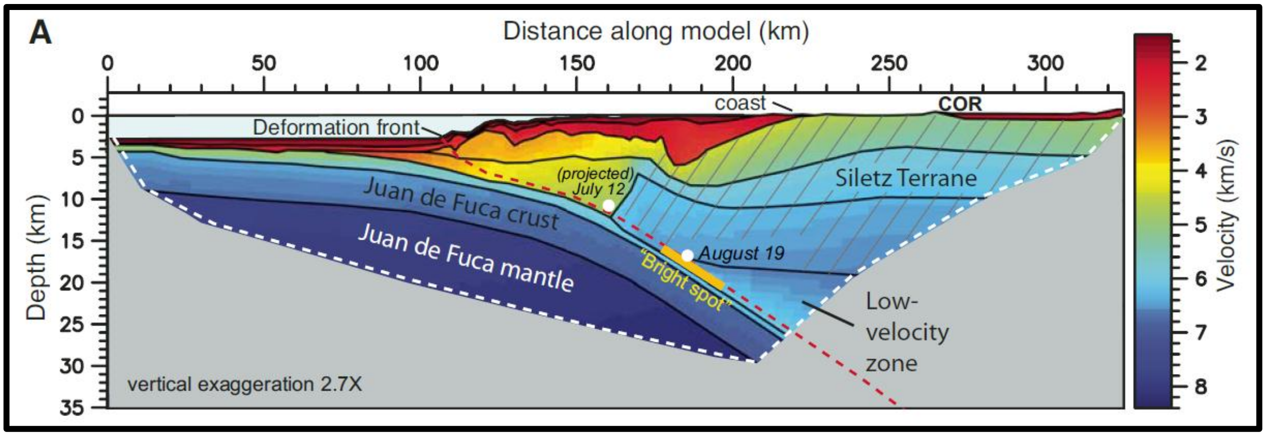


Figure 11: Cross sectional model of Cascadia developed from seismic reflection data. The red dashed line represents the plate boundary (From Tréhu (2008)).

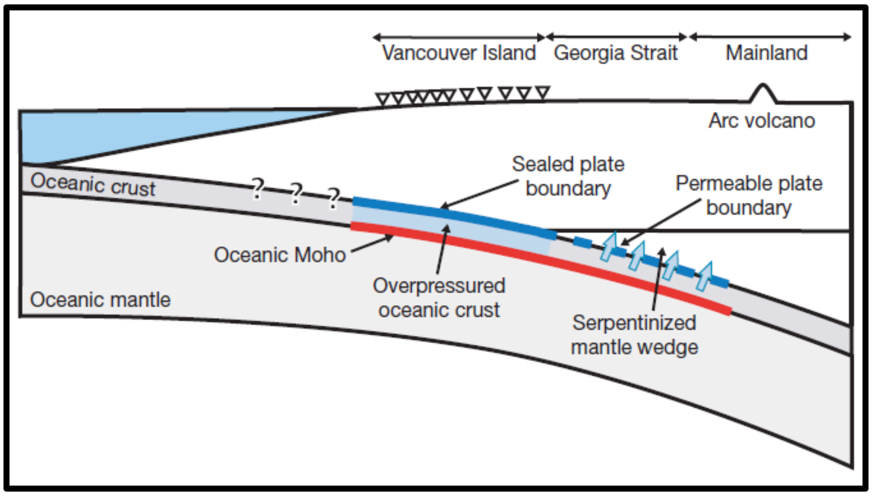


Figure 12: The inverted triangles on the overlying plate represent the receivers used in the study. This is an inferred cross section of Cascadia along the Vancouver islands. Note that the boundary is sealed below the receivers, but must be unsealed below the arc volcano (From Audet (2009)).

In Audet (2009) the onset of crustal eclogitization and mantle serprentinization is the process explaining the transition from low- to high permeability plate interface between the mantle wedge. This so called "hydro fracturing of the seal" between plates may be the cause of episodic tremor and slip (Figure 12).

Interpretation:

In Figure 4 from Fluck (1997) Cascadia is depicted as having a confined zone of locking and as you trace the outline of Cascadia North the locking zone broadens. This broadening begins off the coast of the Oregon/Washington border.

This broadening can be explained by McCaffrey (2000) when he concluded that western Oregon was rotating clockwise relative to eastern Washington due to extension from the Basin and Range and compression along Cascadia in the west. In Figure 4 there is a transitional zone in the locking of the two plates that begins above Oregon. This zone of locking extends moving north into Washington. This transition is likely due to the decrease in distance from the forces felt by the Basin and Range.

Looking at Figure 6 the largest rates of horizontal velocity occur just north of the Washington/Oregon border. This can be explained by the decreasing effects of force generated from the extension of the Basin and Range.

Figures 7 & 8 model subduction zones by the preferred trajectory of the subducting slab. In the case of Cascadia, the rate of convergence is fast and the oceanic lithosphere is young indicating that the preferred trajectory is close to horizontal. This relationship between upper and lower slab provides a large area of contact between the two. The combination of a fast rate of convergence, young oceanic lithosphere and this large area of contact is a good combination for large megathrust-type earthquakes.

In Ruff (1989) he observes that in the global survey of great earthquakes along subduction zones that many of the earthquakes occurred in zones of ETS, however, he does note that many zones with ETS are relatively aseismic. An example of one of these zones would be Cascadia. Perhaps Cascadia is underplating ETS?

The close proximity of the spreading center to the North American plate means that the Juan de Fuca plate is young and hot along Cascadia. The abundance of trench sediments traps this heat and explains the anomalously high temperatures seen in Figure 10.

Trehu (2008) discussed the possibility of the 2004 earthquakes being triggered by slip along subducted asperities which are likely derived from the abundance of trench sediments. More importantly is that the model, Figure 11 provides accurate constraints on crustal velocity and the plate interface.

Figure 11 depicts a known positioning for the sealed plate boundary. The zone of decoupling must be under the Georgia Strait, and it is from here that episodic tremor and slip is thought to be derived. The dewatering of the down going slab is likely driving the decoupling of the two plates.

Conclusion:

There exists a lot of evidence for megathrust-type earthquakes along the Cascadia subduction zone and it comes in the form of paleo-tsunami sediments, turbidites and even historical recordings from Japan. The Cascadia subduction zone is capable of continuing to generate megathrust earthquakes because of (1) its high rate of convergence, (2) its young oceanic lithosphere and (3) its nearly horizontal preferred trajectory (large coupling area). The high rate of convergence is impeded in the south by the extension of the Basin and Range which creates a confined zone of locking which broadens as you trace the outline of Cascadia North. The young oceanic lithosphere is very hot and the large amounts of sediment infill derived from both oceanic and continental detritus act as an insulator resulting in hot oceanic lithosphere being subducted. It is conceivable to think that this excess trench sediment is being subducted with the oceanic lithosphere. These asperities would be positioned between the two slabs. Slip along these subducted asperities might lead to a megathrust earthquake. The actual decoupling is likely a result of dewatering of the down going slab and episodic tremor and slip might be conducive of this phenomenon.

References:

Atwater, B. F. (1987). Evidence for great Holocene earthquakes along the outer coast of Washington State. *Science*, *236*(4804), 942-944.

Flück, P., Hyndman, R. D., & Wang, K. (1997). Three-dimensional dislocation model for great earthquakes of the Cascadia Subduction Zone. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *102*(B9), 20539-20550.

Goldfinger, C., Nelson, C. H., & Johnson, J. E. (2003). Holocene earthquake records from the Cascadia subduction zone and northern San Andreas Fault based on precise dating of offshore turbidites. *Annual Review of Earth and Planetary Sciences*, *31*(1), 555-577.

Heaton, T. H., & Kanamori, H. (1984). Seismic potential associated with subduction in the northwestern United States. *Bulletin of the Seismological Society of America*, *74*(3), 933-941.

McCaffrey, R., Long, M. D., Goldfinger, C., Zwick, P. C., Nabelek, J. L., Johnson, C. K., & Smith, C. (2000). Rotation and plate locking at the southern Cascadia subduction zone. *Geophysical Research Letters*, *27*(19), 3117-3120.

Nelson, A. R., Kelsey, H. M., & Witter, R. C. (2006). Great earthquakes of variable magnitude at the Cascadia subduction zone. *Quaternary Research*, *65*(3), 354-365.

Oleskevich, D. A., R. D. Hyndman, and K. Wang. "The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile." *Journal of Geophysical Research: Solid Earth (1978–2012)* 104.B7 (1999): 14965-14991.

Peterson, C. D., Clague, J. J., Carver, G. A., & Cruikshank, K. M. (2013). Recurrence intervals of major paleotsunamis as calibrated by historic tsunami deposits in three localities: Port Alberni, Cannon Beach, and Crescent City, along the Cascadia margin, Canada and USA. *Natural hazards*, *68*(2), 321-336.

Ruff, L., & Kanamori, H. (1983). Seismic coupling and uncoupling at subduction zones. *Tectonophysics*, *99*(2), 99-117.

Ruff, L. J. (1989). Do trench sediments affect great earthquake occurrence in subduction zones?. In *Subduction Zones Part II* (pp. 263-282). Birkhäuser Basel.

Tréhu, A. M., Braunmiller, J., & Nabelek, J. L. (2008). Probable low-angle thrust earthquakes on the Juan de Fuca–North America plate boundary. *Geology*, *36*(2), 127-130.

Uyeda, S., & Kanamori, H. (1979). Back-arc opening and the mode of subduction. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *84*(B3), 1049-1061.