Strain monitoring at the bend in the Cascadia Subduction Zone

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Introduction

The Cascadia Subduction Zone (Figure 1) stretches over 1000 km from the offshore triple junction with the San Andreas Fault in northern California to mid Vancouver Island in British Columbia, Canada. It accommodates ~40mm ENE convergence of the Juan de Fuca Plate with the North American Plate and produces the Cascade volcano chain.

The region is recognized as a seismic gap, and measured uplift of up to 5mm/yr and horizontal compressional strain rates of order 100nstrain/yr indicate seismic potential which has been confirmed by paleoseismology. Deformation modelling has detected a narrow, locked zone averaging 60km width and dipping ~10°, with more marginal evidence of an adjacent, downdip transition zone. A significant change of strike at the Olympic Peninsula is accompanied by a local decrease of dip and widening of the locked and transition zones.

Proximity to land means the zone is ideally placed for intensive study of subduction processes of the plate boundary. Until borehole strainmeters are deployed little can be known about aseismic events in this significant component of the boundary. We propose a major array of borehole strainmeters with tiltmeters for the Olympic peninsula, and a small reference array at Cape Blanco in southern Oregon. These arrays will be tightly integrated with a GPS proposal in the region, and with existing GPS, tide gauges, and seismic arrays. Annual absolute gravity measurements at selected sites are also proposed to improve vertical GPS accuracy.

Scientific objectives

1. Do aseismic events play a significant role in Cascadia subduction?

An important outstanding question for the Cascadia subduction zone is the role of short to medium term aseismic slip. Aseismic events, as single or episodic slow earthquakes (typically hours to days duration) or propagating slip over weeks to months, have been detected by borehole strainmeter arrays at transition regions on the San Andreas Fault (eg Linde et al 1996, Gwyther et al 1996) and downdip of the seismogenic part of a subduction zone in the Japan Sea (Linde et al 1988).

The role of aseismic events in subduction is difficult to measure. The events reported above were too slow to produce measurable seismic signals, with static moments too small for the geodetic/GPS detection thresholds. Borehole strainmeters and tiltmeters have sufficient sensitivity to detect typical signals in the period range, but strain attenuates rapidly with source distance, and for many subduction zones the faults of interest are too far offshore or too deep.

Cascadia is a potentially productive region to study aseismic subduction processes because the locked region is only ~50km offshore in several places and shallow (<=12km). Also the downdip transition zone suggested by Hyndman et al (1995) underlies parts of the Olympic peninsula and to a lesser extent Cape Blanco in Oregon, at depths around 12-20km. A strainmeter deployment will determine the presence or absence of aseismic event activity, in the context of absence of moderate seismicity.

2. The influence of young, hot oceanic crust on aseismic processes

As the spreading centre is relatively close (150-400km) to the subduction zone, Cascadia also provides an opportunity to study the influence of young, hot oceanic crust, together with thick sediments and a narrow locked zone, on aseismic processes.

3. **Geometry and dynamics of the transition zone**

   There are important questions about the transition zone, which is poorly resolved by current GPS measurements. Does the transition zone have significant width at all? If so, does it slip at a steady rate less than the convergence velocity, gradually loading the zone above, and catch up with reduced coseismic slip propagating downdip from the seismogenic zone above? Fluctuations in slip rate should be detectable by strainmeters and tiltmeters. Alternatively, is the transition zone a manifestation of slip heterogeneity? This would be analogous to aseismic and seismic slip on adjacent patches of transition zones of the San Andreas Fault, but in Cascadia involve aseismic and strongly locked patches.

   Aseismic events of sufficient moment and appropriate periods will be detectable by strainmeters. In particular, episodic aseismic events have been seen on the San Andreas at San Juan Bautista (Gladwin et al 1994) and for 5 months prior to the M7.7 Japan Sea earthquake 1983 (Linde et al 1988). The latter were located downdip of the earthquake and may have added 20% of the seismic stress release. Is similar updip loading of the seismogenic zone by the transition zone present in the thermal and compositional conditions of Cascadia?

4. **Heterogeneity of the locked zone**

   Heterogeneity along strike in the locked zone strongly affects the extent of eventual rupture. Aseismic patches tend to decouple adjacent locked patches from stress transfer during seismic failure, reducing the probability of mega-thrust events involving the whole subduction zone. Strainmeters may detect aseismic slip events on such patches that are invisible to GPS. Bends in faults have been recognised as important influences on rupture propagation (eg King and Nabelek 1985), and a significant bend in the strike of the Cascadia subduction zone occurs opposite the Olympic Peninsula. Furthermore the Olympic peninsula is apparently a region of N-S compression. Is there any detectable difference in aseismic processes in this region from the rest of the subduction zone?

5. **Improving constraint of seismic rupture**

   Although seismicity is very low in the region, there have been several deep M5-7 events beneath Puget Sound in the last 50 years, and two M7+ events in central Vancouver Island last century. Strain could provide additional constraint on the static moment, the source dimensions, and accompanying afterslip for such events.

Background

The Cascadia Subduction Zone (Figure 1) accommodates ENE convergence of the Juan de Fuca Plate with the North American Plate at a rate increasing northwards from 37 to 47mm/yr (Riddihough 1984, deMets et al 1990). The opposite boundary of the JDF plate is a spreading center adjoining the Pacific Plate some 400km to the west: the narrowness of the plate results in subduction of unusually young, hot oceanic crust that strongly influences tectonics of the subduction zone. The region is very quiet seismically, though three deep intraplate earthquakes between M6 and M7.1 have occurred beneath Puget Sound in the last 50 years.

Paleoseismology studies (eg Atwater et al 1995) have produced evidence of great thrust earthquakes with the last event an M~9 in 1700 (Satake et al 1996) and an irregular recurrence interval of about 600 years. Geodetic studies confirm the seismic potential of the region. Extensive data sets from resurveyed levelling lines, tide gauge records, gravity surveys, geodetic networks and more recently GPS arrays have demonstrated uplift of up to 5mm/yr, decreasing inland to below 2mm/yr for much of coastal Oregon and below 1mm/yr for Puget Sound, horizontal strain rates of order 100 nanostrain/yr compression in the direction of convergence, and peak tilts of 50 to 200 nanoradians/yr.

Deformation modelling of this data (eg Savage et al 1981, Fluck et al 1997) indicates a narrow, locked zone averaging 60km width, with marginal evidence for a downdip transition zone of similar width. The narrowness of the locked zone is responsible for the anomalous interseismic coastal uplift, and through thermal modelling is attributed to high temperature of the subducted plate and thickness of overlying sediments (Hyndman and Wang 1995).

Contours of the thrust fault depth inferred from seismic studies (Hyndman and Wang 1995) show a prominent change of strike at the Olympic Peninsula. This is accompanied by a decrease in average dip to 7° from the more typical 11° beneath Oregon and mid-Vancouver Island. Similarly the locked and transition zone widths (figure 1) offshore of the Olympic peninsula, inferred from uplift modelling, are about 100km compared with 40km for most of Oregon. However the subduction zone appears locked along its entire length, at least at the ~100km sampling resolution currently available along strike. Expected coastal coseismic subsidence from 600 years of accumulated uplift at current rates range from 3m on the Olympic peninsula and Cape Blanco in Oregon to ~1m for most of the Oregon Coast. Consequent high tsunami potential is confirmed in the paleoseismicity studies.

More recent GPS based studies additionally resolve clockwise rotation of the Oregon coastal block and N-S compression in north-western Washington. McCaffrey et al (2000), also Savage et al (2000), find evidence for clockwise rotation of ~1.7°/m.y. of most of Oregon about a pole in eastern Oregon, close to a pole inferred from geology by Wells et al (1998). It is suggested the motion is driven by extension in the Basin and Range region to the south-east, and deflected by resistance on the subduction zone into northward motion which is accommodated by N-S shortening in Washington State and Canada. Khazaradze et al (1999) using data from 7 permanent GPS sites in the PANGA array found a N-S compression of ~16nstrain/yr in western Washington.

Proposed deployment of instruments

There are currently no strainmeters or tiltmeters monitoring the Cascadia portion of the N American plate boundary. We propose to install two separate arrays, one of 18 borehole tensor strainmeters with tiltmeters in the Olympic peninsula, and a smaller array of 4 instruments in the Cape Blanco region of SW Oregon, to address the scientific objectives above.

These regions were chosen for their proximity to the fault to increase the probability of detectable signals. The locked zone of Hyndman and Wang (1995) is between 20 and 50km seaward of Cape Blanco and 30 and 120km from coastal Olympia. The transition zone extends some 50km inland in Olympia and 10-20km near Cape Blanco, and is between 12 and 20km below in both regions. Figure 3 shows modelled strains and east tilt for a 3x3km patch at 14km depth, slipping 1m (M5.6), as might be expected in the transition zone. With an instrumental detectability of a few nanostrain over days, such events are resolvable by a number of instruments in the array.

The Olympic peninsula was also chosen to exploit potentially larger signals produced by the wider locked and transition zones compared to other regions, and the possibility of interesting signals associated with the bend in strike and regional N-S compression. We will be seeking collaboration with Canadian institutions actively studying Cascadia for instrument installations on Vancouver Island to extend the effectiveness of the array.

Nine sites spaced ~20km along the Olympic Peninsula west coastal region, from Neah Bay to Gray's Harbour provides adequate monitoring with some redundancy for 150km along strike, giving distances to the fault between 12 and 40km. See Figure 2. A further six sites will be placed 20-40km east of the coast, spaced N-S ~40km, to improve E-W location of events. Three sites west of Puget Sound, some 70-100km from the west coast, will further constrain the extent of slip on the subduction zone, help locate of any compression events in the Olympics, and provide some minimal monitoring of events in the vicinity of Puget Sound .

The Cape Blanco region was chosen, apart from its fault proximity, to provide a more typical Cascadia region as a reference for the Olympic array, and also to increase probability of event detection should the northern section prove to be in aseismic quiescence during the PBO lifetime. It further provides some continuity with studies of the triple junction some 300km to the south. Three instruments will be spaced ~20km apart NS near the coast, with a fourth instrument ~15km inland.

At all sites, inclusion of two component borehole tiltmeters increases by 70% the constraints on slip available from the borehole at a marginal increase in cost. Figure 3 shows that for the modelled aseismic event tilt signals well above the few nanoradian detection threshold are produced, and tilt is a particularly sensitive indicator of the extent of slip patches.

We further propose to provide tightened constraints on vertical motions measured by GPS and tide gauges by occupying selected bedrock sites with our FG5 absolute gravimeter (and/or the NSF instrument) on yearly maintenance visits.

Integrating with other instrumentation

The proposal for GPS networks by the PANGA consortium includes a profiling line through the Olympic peninsula from the west coast to Puget Sound, and profiles perpendicular to the Oregon coast at several latitudes including lines just north and south of Cape Blanco. The proposed lines are designed to integrate well into existing leveling lines. These will significantly extend the capabilities of the existing PANGA and CORS networks in the region.

The Olympic peninsula is adequately covered by seismometers of the Pacific Northwest Seismograph Network (PNSN). Coverage of the Cape Blanco region is sparse.

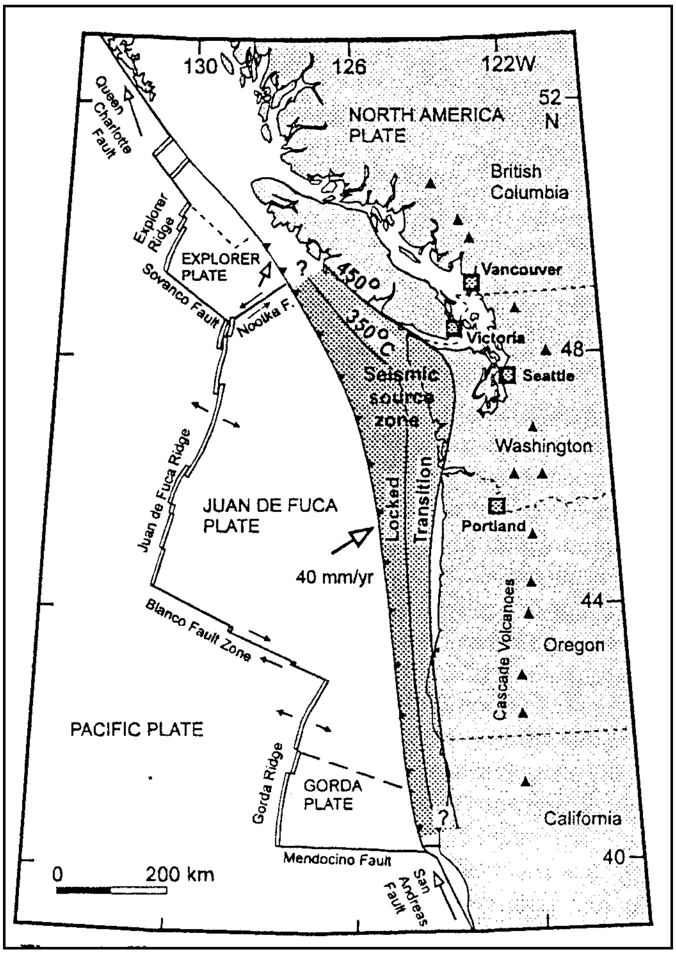

Figure 1 Cascadia subduction zone and locations of locked and transition zones inferred from modelling of geodetic data. From Hyndman and Wang 1995.

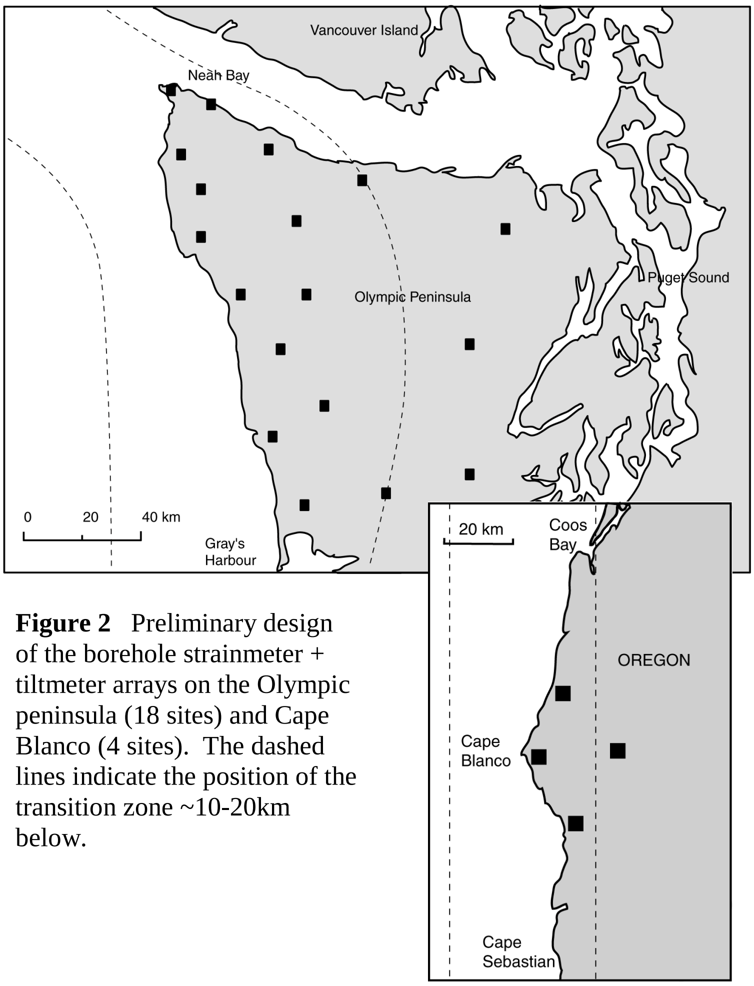

Figure 2 Preliminary design of the borehole strainmeter + tiltmeter arrays on the Olympic peninsula (18 sites) and Cape Blanco (4 sites). The dashed lines indicate the position of the transition zone ~10-20km below.

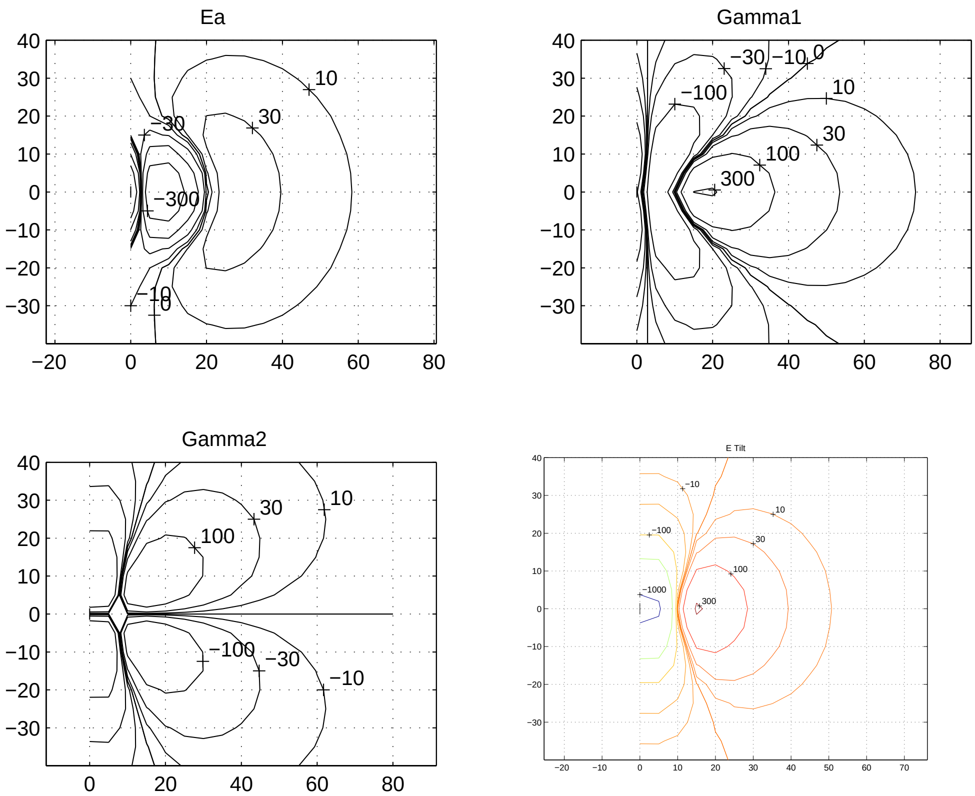

Figure 3 Surface areal and shear strains, and E tilt, from 1m of dip slip on a 3kmx3km patch, strike NS, dipping 6° to east, midpoint of top edge at (0,0) and 14km depth. The magnitude is 5.6, contour units are nanostrain and nanoradians, and axis units are km. The coast lies at E ~0km for the regions to be studied. Instruments can provide detectability at the few nanostrain/nanoradian level for short term (hours to days) signals.