

**Determining Temperatures of the Eastern Edge of the Cascadia Subduction Zone:
Shallow Water Heat Flow Measurements in Puget Sound**

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Abstract: Temperature in the sub-surface is the primary controlling parameter for most of the physical and chemical processes associated with a subduction zone. Within the Cascadia Subduction Zone, the young, heavily sedimented Juan de Fuca plate subducts obliquely at about 40 mm/year beneath Washington, Oregon and British Columbia, and is one of the warmest subduction zone slabs in the world. Large magnitude megathrust earthquakes have been shown to rupture the entire fault zone from Mendocino, CA to northern Vancouver Island on several hundred-year time scales. In addition, less dramatic but still dangerous intraslab seismicity beneath the heavily populated Puget Sound region extends to 60-km depth, with some small seismic events reaching depths as great as 100 km. Knowing the distribution of subsurface isotherms is critical for understanding these active tectonic processes, including those that ‘lock’ the relative motion of the plates, cause the large megathrust earthquakes, produce the intra-slab seismic activity, and induce deep fluid flow attributed to the episodic tremor and slip (ETS). However, within Western Washington, models of the sub-surface isotherm distribution are based largely on extrapolation of heat flow data from distant areas that may represent fundamentally different thermal environments. We propose a pilot study of shallow water heat flow stations within the larger Puget Sound area, to develop a technique that can eventually produce a complete E-W profile of sub-surface temperatures - from the Washington coast to the western slopes of the Cascade Mountains.

Rationale: The up-dip (seaward) and down-dip (landward) limits of future rupture zone of the Cascadia megathrust have been proposed to be the intersection of the décollement and the 100°C and 350°C isotherms, respectively (Hyndman and Wang, 1993). The position of the down-dip limit controls the intensity of ground shaking in the heavily populated forearc region. There are large uncertainties in the location of this critical eastern limit beneath western Washington because of the lack of reliable heat flow data from the area. Heat flow measurements from the shallow inland waters of Western Washington would provide the critical vertical thermal gradients necessary for downward projection of isotherms to the décollement that underlies the region. The shallow water heat flow experiments proposed in this White Paper would provide the necessary vertical thermal gradients, and when combined with seismic data from the region, would allow identification of the intersection of the critical 350°C and the décollement.

In addition to the catastrophic mega-thrust earthquakes associated with the CSZ, which occur infrequently at intervals of hundreds of years, mid-plate earthquakes associated with the subducting slab occur much more frequently (i.e., the Nisqually earthquake of 2001). Even though localized to smaller regions than mega-thrust seismic activity, these earthquakes can be destructive with significant societal impact. These smaller intraslab earthquakes also appear to be temperature controlled, although perhaps indirectly through the dehydration embrittlement of the subducting plate. Thermally controlled metamorphic dehydration and hydration processes are expected to be responsible for episodic tremor and slip (ETS) (Wech and Creager, 2008; Abers et al, 2009). Whether the focus is on mega-thrust earthquakes of $M_w 9$, intraslab quakes of smaller magnitude, or ETS events which may provide fundamental insight into subduction zone plate coupling, it is clear that the sub-surface thermal environment will be a primary variable in any model of Cascadia Subduction Zone seismicity.

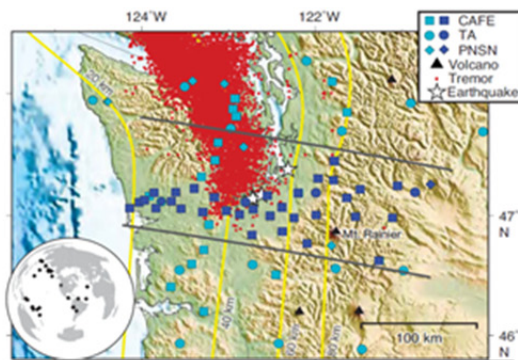
Specific Questions Addressed by the Experiment: The primary question addressed by the experiment proposed by this White Paper is *“what is the vertical distribution of isotherms beneath Western Washington – from the coast to the foothills of the Cascades?”* The scale of this question is too large and

the methodology too uncertain to be answered by a single experiment. We propose a pilot study that would test the feasibility of measuring heat flow in shallow in-land waters which, if successful, would allow us to measure heat flow along a full E-W profile, from the continental margin to the Cascades.

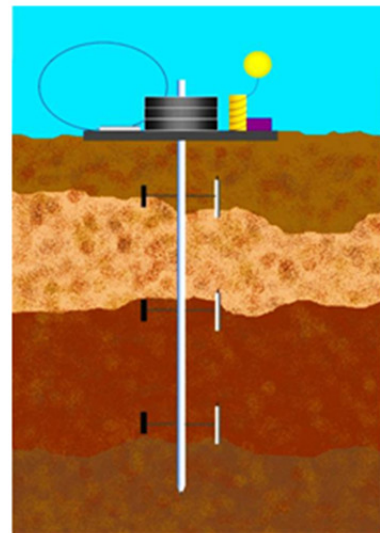
Methodology: Previous terrestrial heat flow studies of the Pacific NW have used wells drilled into aquifers as their primary data set (Blackwell et al, 1990). However, there are few such measurements in Western Washington, and aquifers with mobile ground water may not provide the most accurate vertical thermal gradients. We propose to use the thick impermeable pelagic mud cap present in (a) Puget Sound, (b) Hood Canal and (c) some freshwater lakes as our experimental heat flow measuring sites. While this impermeable mud provides an excellent media for the measurement of geothermal gradients, the shallow water (~200 m) and seasonal temperature variations of these sites provides a major noise source for the extraction of the relatively small geothermal gradient. However, prior studies in the Western Pacific (Hamamoto et al., 2005, 2011) have demonstrated that by measuring the thermal gradient continuously over the period of a year permits removal of the high frequency bottom water variations. Further, selecting sites where bottom water temperatures have previously been measured for periods of 5 to 10 years (in Puget Sound, Hood Canal and on the Washington margin) for other un-related experiments would allow the removal of long-period seawater variations (i.e., ENSO). We have identified several sites where semi-continuous bottom water measurements have been made over long intervals, some since 1998, and propose to deploy test probes at one of those sites as a pilot study for eventual measurement of the full E-W profile. After careful removal of the bottom water variations with both long (5 to 10 years) and short (monthly/annual) periods, the geothermal gradient obtained would be downward continued into the subsurface, using thermal conductivities derived from seismic velocity (EarthScope) and electrical resistivity proxies (Patro and Egbert, 2008); methods which have been shown to be effective in the deep Kola Superdeep Borehole.

Proposed Pilot Study: We plan to use standard piston core technology to insert a thermal probe at 200 meters water depth into pelagic mud, probably at the Hood Canal site, where bottom water temperatures have been monitored continuously since 2005. The thermal probes will use multiple autonomous temperature loggers (Antares) at 0.5 m intervals and have a planned probe insertion depth of 4 to 6 meters. We first plan a short period (12 hours) test deployment prior to the long-term experiment, followed by a possible 'mid-course strategy modification' based on that short-period data and then insertion of two probes at a single site for a period of a year before recovery. Two probes deployed at the same site would both allow for instrument failure after a year-long deployment, and if both are successful, provide additional confidence in the data acquired.

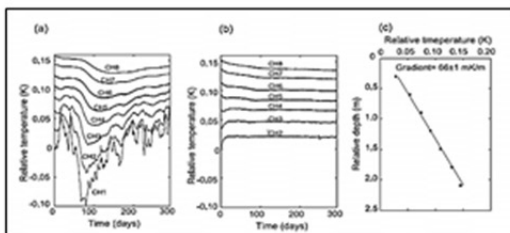
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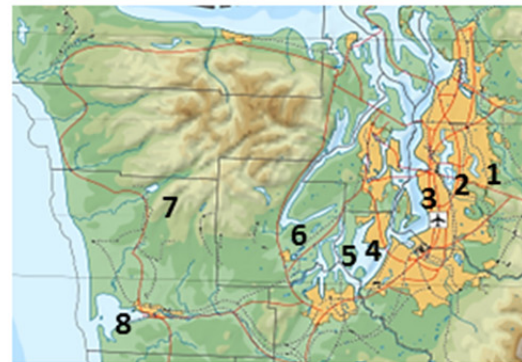
Red dots are ETS locations; blue squares seismometers, yellow contours are slab depth, stars are epicenters of $3 M_w > 6.5$ intraslab quakes. Abers et al, *Geology*, 2009



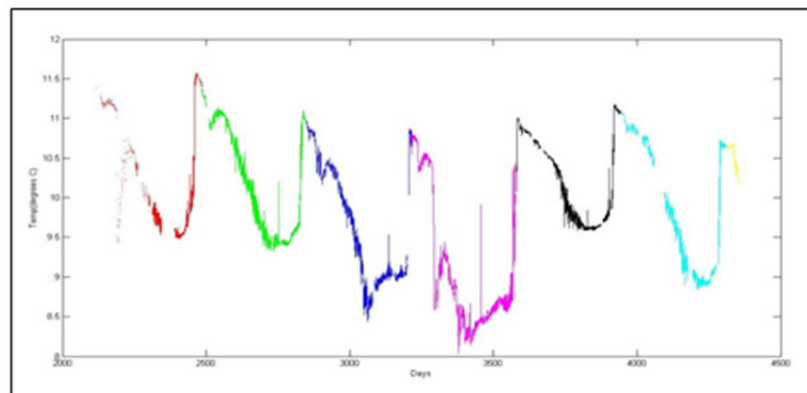
Proposed 4 m long probe for insertion at sites where prior long-term bottom water temperature records exist.



Shallow water Heat Flow from Nankai showing corrections for bottom water temperature variations; Hamamoto et al, 2011.



Right: Potential sites for E-W heat flow profile
 1. Lake Sammamish. 2. Lake Washington, 3. Puget Sound central basin, 4 and 5. South Puget Sound. 6 Hood Canal. 7. Lake Quinault. 8. Grays Harbor.



Left: CTD bottom water temperatures from Hood Canal (site #6) from 2005 to present time (A.Devol, pers. comm., 2012).