# Kinematics and geodynamics of the Cascadia convergent margin

A proposal from the PANGA Investigator Community*

## Observing North America's plate boundary

The Cascadia subduction zone (Fig. 1a) occupies nearly half of the North America plate boundary in the lower 48 states. Considered aseismic by many earth scientists until two decades ago, paleoseismology now tells us that the1,300 km-long Cascadia earthquake factory has generated great earthquakes every 500-600 years on average, with a record that extends back at least 11,000 years [*Atwater and Hemphill-Haley*, 1997; *Goldfinger*, 1999; *Nelson*, 1999]. The most recent great earthquake, in 1700 AD, ruptured the entire plate boundary in a Mw 9 event [*Satake et al.*, 1996]. Cascadia's seismic moment release dwarfs other parts of the plate boundary outside of Alaska. Geodesy (leveling, precise gravity, laser ranging, GPS) repeated during the last 15-70 years indicate elastic strain accumulation in preparation for the next earthquake [*Savage et al.*, 1991; *Dragert et al.*, 1994; *Mitchell et al.*, 1994; *Khazaradze et al.*, 1999; *Miller et al.*, 2000]

Geologic and paleomagnetic data demonstrate that continental deformation and strain partitioning, such as rotation of the forearc and northward penetration of the Eastern California shear zone (Fig. 1b,
c), characterize this convergent margin [*Magill et al.*, 1982; *Pezzopane and Weldon*, 1993; *Wells et al.*, 1998]. This partitioning reveals the architecture and rheology of continental crust, the role of the Cascade arc, Basin and Range, and Yakima fold belt in accommodating or, locally, driving deformation; it has consequences for the distribution of crustal seismicity. The deformation pattern implies that: 1) Shear dominates the westernmost 500 km of the continent while the interior simultaneously experiences gravitational collapse. 2) Northwesterly motion of the Sierra Nevada block and dilation of the Basin and Range (i.e., the activity of the

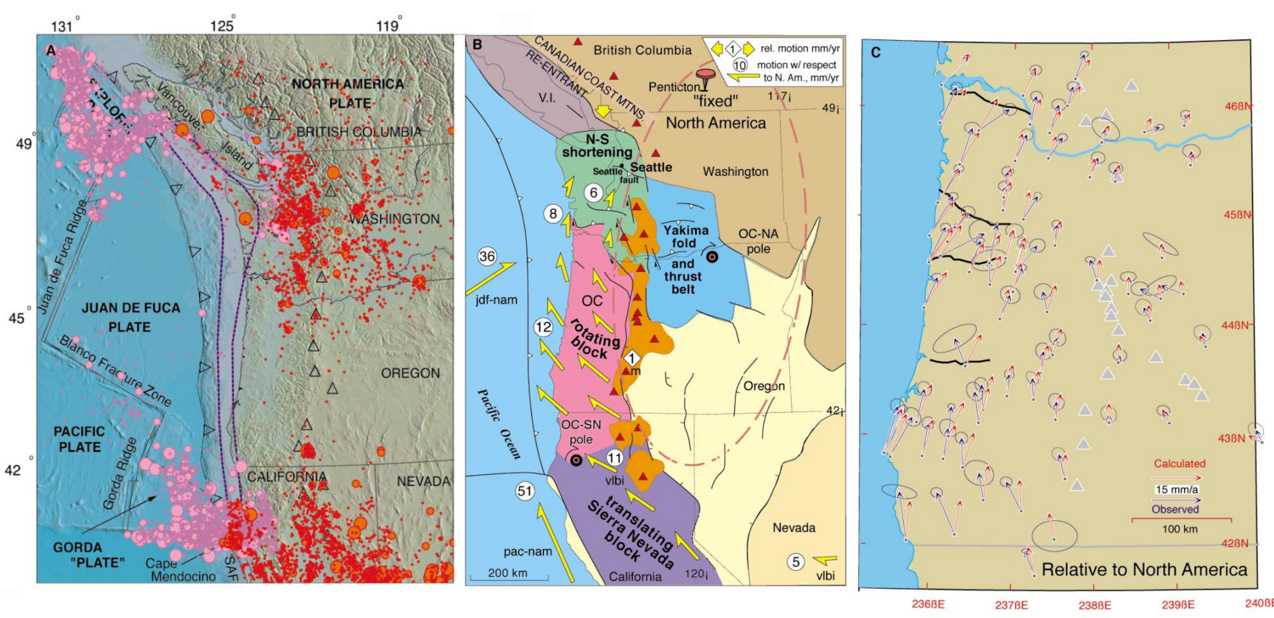


Figure 1. a) The Cascadia convergent margin; physiography, seismicity,and downdip limits to the locked and transition zone on the plate boundary (modified from [*Weaver et al.*, 1981; *Hyndman and Wang*, 1995]). b) Cascadia plate motion model; long-term velocity field calculated from geologic and paleomagnetic data [*Wells and Simpson*, 2000]; compare to c) GPS velocity field [*McCaffrey et al.*, 2000]. Difference is elastic deformation above megathrust locked zone.


*Dragert, Dzurisin, Freymueller, Goldfinger, Henton, Humphreys , Hyndman, Johnson, Johnson, Kelsey, Lisowski, Mazotti, Melbourne, Miller, Meigs, Ning, Oldow, Qamar, Wells, Willet & others. See http://www.geodesy.cwu.edu/

transform-bounded continent) are both accommodated by overriding the Cascadia subduction zone. 3) The ~1 cm/yr of shear in the Eastern California shear zone, the rate of Sierra Nevada entrainment, approximates the rate of Cascadia subduction obliquity (its transform component), suggesting establishment of a long, slow transform boundary that penetrates deeply into the continent. This is simultaneously active with the shorter, faster San Andreas system near the continent's edge, and accommodates 20-25% of the transform plate interaction across the PNW. GPS results confirm that northward motion isoccurring along the Cascadia margin (Figs 1 and 2; [*Magill et al.*, 1982; *Pezzopane and Weldon*, 1993; *McCaffrey et al.*, 2000; *Savage et al.*, 2000]), but the distribution of deformation and its driving forces are unclear.

The Cascadia subduction zone strongly influences the kinematic and geodynamic behavior of the North American plate margin; yet we have only rudimentary knowledge of Cascadia's contemporary velocity field, its spatial and temporal variation, and its relationship to the subduction seismic cycle and tectonic driving forces. We propose a major effort to map the velocity and strain fields along the Cascadia convergent margin at the highest possible precision. Two principal scientific objectives drive this plan for a 135 site continuous GPS array organized into 4 transects and two clusters (Fig. 2):

• *To establish the character and behavior of the Cascadia megathrust and its geodynamic role in western North America:* We need to precisely determine the spatial and temporal variations in strain rates along the subduction zone, their relationship to geologic structure, potential asperities and barriers, and to the paleoseismic history. These observations constrain 3-D physical models of the subduction zone and behavior of the megathrust earthquake cycle. Monitoring potential transient strain signals on this, the hottest of all subduction zones, will clarify the relationship between geodetic strain, plate boundary rheology, and earthquake recurrence interval. This requires an array of

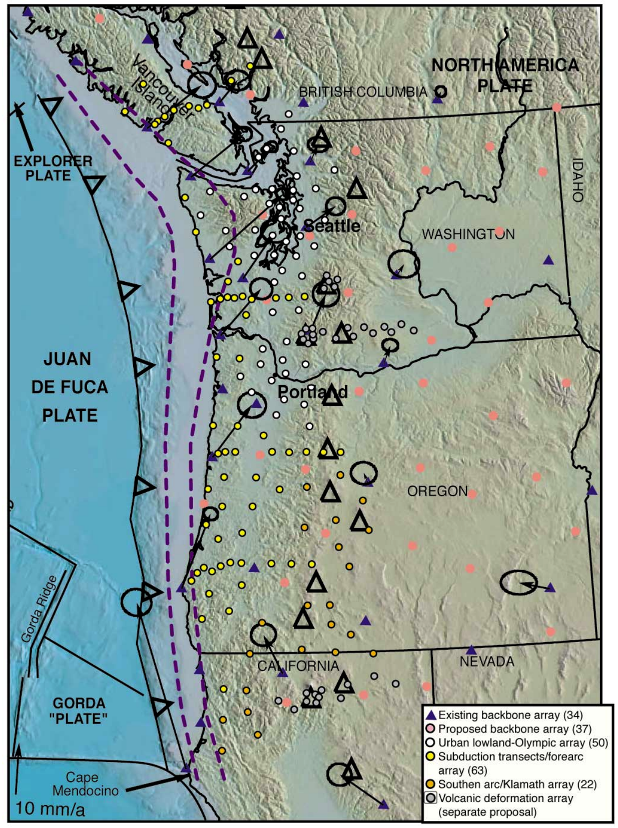


Figure 2. Proposed deployment of PBO clusters in the Pacific Northwest. The backbone (pink) at a nominal spacing of 150 km. PANGA station velocities are shown in a GPS-defined North America reference frame that proves robust (stable) with updated solutions [Miller et al., 2000].

receivers that captures the horizontal velocity field, yet is co-located and calibrated with independent techniques to maximize the diagnostic vertical signal in the forearc.

• *To determine the extent of strain partitioning in the convergent margin, and the role of continental extension, distributed transform faulting, contraction, and arc magmatism in accommodating deformation*: We need to characterize the kinematics and patterns of continental deformation, such as the migrating forearc, resolve the strain accumulation where velocity gradients are localized (such as the Puget Lowlands, Klamath Mountains, and southern Oregon back arc), identify the role of rheology in defining crustal block boundaries and seismic zones, and ultimately establish the relationship between the subduction zone dynamics, crustal deformation, and the magmatic arc. Two arrays support this approach (Fig. 2); a relatively dense array straddling the northern, seismically active transpressive deformation zone along the densely populated Puget-Willamette Lowland and Olympic Mountains, and a second, less dense array across the southern Cascade extensional arc boundary between the migrating forearc and the Basin and Range. Two volcano deformation arrays (in a separate proposal) will be linked to those proposed here in order to determine how major volcanic centers and their short-term magmatic processes interact with the very different regional strain fields in the transpressive and extensional arc segments.

## Cascadia Megathrust: Character and Behavior

The occurrence of great earthquakes along the Cascadia subduction zone is now well established, and horizontal deformation determined from continuous and campaign GPS measurements confirms the locked interplate fault zone (Figs. 1, 2). Current elastic dislocation models do not account for the unexpected inland extent of NE-directed horizontal deformation and the low uplift rates at the outer coast (Fig 3). Preliminary viscoelastic models promise that time-variant deformation better describes current, sparse observations (K. Wang, unpublished results), yet these are still too sparse to be unambiguous. Horizontal strain lacks the sensitivity required to differentiate key aspects of the models. At present, a seismogenic thrust zone that extends significantly inland and is therefore closer to large urban centers, cannot be rejected.

*Deployment Strategy:* The study of vertical deformation is the key to addressing the behavior of the megathrust (Figure 2). Vertical deformation constraints, which provide a diagnostic constraint in deformation models for moderately dipping faults, presently suffer from poor precision and apparent contradictions in estimates based on different techniques (MSL, leveling, absolute gravity, GPS). Four dense profiles of continuous GPS stations normal to the margin will precisely observe interseismic uplift rates by better characterizing transient, non-tectonic signals and resolving possible aseismic tectonic transients. Comparison of GPS-determined uplift rates with independent ground-techniques will provide a calibration of the GPS vertical and address the problem of potential temporal changes in vertical strain rates over periods of years to decades (Fig 3).

We propose four transects from the coast to the arc, each consisting of 11 continuous sites, spaced 5-10 km apart in the forearc and increasing to 20 km inland (Figure 3). The proposed transects are located in Vancouver Island, southwest Washington, central Oregon, and southern Oregon. Each transect follows a leveling profile with up to 4 first order leveling surveys, anchored to tide gages, is co-located with existing or planned absolute gravity transects, and coincides with geophysical profiles which have determined the structure of the plate boundary (e.g., [*Trehu et al.*, 1994; *Parsons et al.*, 1998]). The four dense profiles are embedded in a sparser forearc cluster that will capture along-strike variation inferred from thermal data and elastic dislocation models [*Mitchell et al.*, 1994; *Hyndman and Wang*, 1995; *McCaffrey et al.*, 2000; *Miller et al.*, 2000]. At the international boundary, convergence is more orthogonal and fore-arc migration terminates. The Vancouver Island transect has a history of leveling, gravity, tide gauges and established continuous GPS

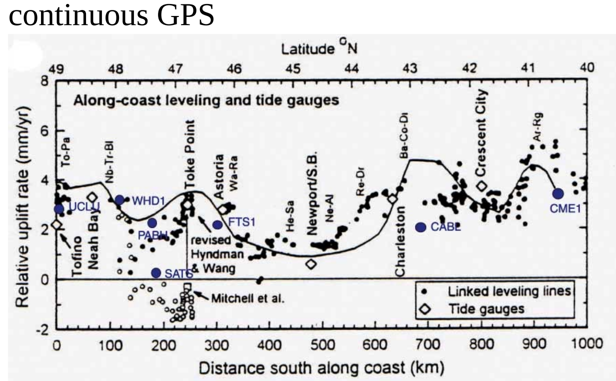


Figure 3. Comparsion of preliminary GPS-determined coastal uplift rates (blue) with leveling and tide gauge constraints. GPS rates rely on differential uplift. Station SATS is inland of the coast and should lie below the coastal profile. Ben Pauk (unpublished data).

stations end points. The Washington transect addresses an area where leveling results are equivocal and the poorly constrained locked zone is inferred to be intermediate in width. The central Oregon coast transect crosses an anomalous area with no resolvable historic uplift and an inferred narrow locked zone. The southern Oregon transect follows a leveling line that has recorded landward tilting and coastal uplift at 2-4 mm/yr.

## Strain Partitioning in the Continent Margin

In Cascadia, a remnant of the oblique-convergent Farallon plate margin, plate boundary deformation reaches far into the back-arc. The best examples of continental dynamics come from migration of the fore-arc, penetration of the transform boundary north of the triple junction, and the superposition of Basin and Range extension.

Geologic, paleomagnetic, and geodetic data confirm northward migration of the Cascadia forearc at up to a centimeter per year (Fig 4), probably as a semi-rigid block in Oregon, rotating clockwise about a pole in the backarc (Fig 1). As the forearc rotates toward the trench, away from the extending Cascade arc and the Basin and Range, it impinges against the Canadian Coast Mountains restraining bend, much as it did during mid-Cretaceous time. Geodetic, seismic, geologic, and plate circuit data consistently indicate north-south shortening in Washington of 2-10 mm/yr, but paleoseismic and seismic strain rates underestimate GPS and geologic time-scale results by a factor of 2 to 4. Similarity between predicted long-term forearc motion and preliminary GPS velocities suggest that most of the contemporary margin parallel motion is efficiently partitioned into the Seattle, Devil's Mountain and other upper plate thrust faults, implying seismic hazard for Seattle and Portland. The role of the Olympic Mountains in transmitting margin-normal strain is also poorly known, as is the role of the right-lateral St. Helens and West Rainier seismic zones, which may form the diffuse eastern boundary of the migrating forearc.

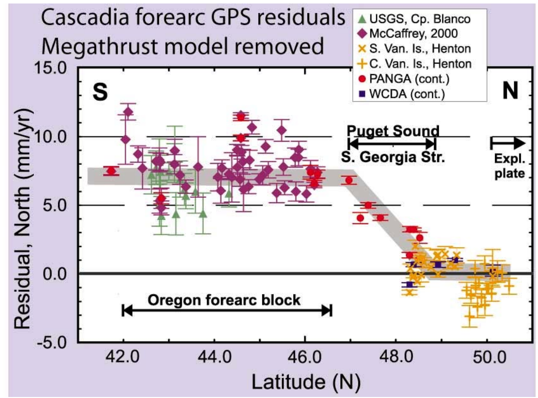


Figure 4. Northward velocities of the fore-arc from residual to elastic dislocation model. Stephane Mazzotti (unpublished compilation).

In southern Oregon, the Cascade extensional arc defines a major tectonic boundary between the migrating forearc block and the expanding Basin and Range province. The arc itself accommodates deformation through a magmatism and faulting along a discontinuous axial graben. Heat flow, magma production rates, and Holocene fault slip rates, indicate arc extension up to 3 mm/yr, and may be accommodated by magmatic buoyancy and aseismic dike emplacement. The sparse available GPS data paradoxically indicate that the arc may be contracting, suggesting a time-dependent response to the subduction zone seismic cycle or to transient magmatic episodes.

*Deployment Strategy:* Localized strain gradients within the continental margin have low strain rates (10 to 80 nanostrain/yr). CGPS observations are required, in concert with robust knowledge of subduction zone interseismic deformation. Likewise, understanding transients within the arc and their relationship to the subduction zone deformation cycle requires continuous GPS monitoring.

Two arrays address intraplate deformation in Cascadia: a relatively dense array straddling the northern, seismically active transpressive deformation zone that encompasses the densely populated Puget-Willamette Lowland and Olympic Mountains, and a second, less dense array that straddles the southern Cascade extensional arc boundary between the migrating forearc and the Basin and Range (Figure 3). The Urban Lowland-Olympic array consists of

60 sites comprising 3 overlapping clusters: 1) the active thrust faults of the Puget Lowland (30 sites), 2) the growing Olympic Mountains (10 sites), and 3) the dextral shear zones of the Portland Hills and western Cascades (20 sites). The Puget Lowland fault cluster will instrument the Vedder-San Juan, Devil's Mountain, Whidbey Island, Seattle, Tacoma and Olympia faults, which collectively may be accommodating between 4-10 mm/yr N-S shortening, from paleoseismic and limited geodetic evidence. Similar shortening is expected in the Olympic Mountains, along with elastic and permanent shortening in the direction of convergence. The Portland Hills sub-cluster straddles the active Mount Angel-Gales Creek and Portland Hills fault zones and links with the central vent arrays around Mt. St. Helens and Mt. Rainier, in order to capture dextral slip in the Cascade arc along the eastern margin of the forearc.

The Southern Cascade array consists of 20 continuous sites that straddle the active boundary between the Basin-Range and the Cascade arc. Along this discontinuous axial graben, faulting and large central vent complexes both accommodate extension. Six sites between the two Oregon coast transects (Part 1) cross a zone of Holocene volcanic and tectonic activity in central Cascade graben. The rest of the sites are distributed southward across the active Klamath graben toward Mount Shasta. Embedded in this array is the Mt. Shasta-Medicine Lake cluster proposed to investigate how major volcanic centers respond to regional transients and short-term magmatic processes (under separate proposal).

**Integration with other efforts**

*Canada:* The Cascadia subduction zone crosses the international boundary with Canada, and so does PANGA and its cooperative arrangement with the Western Canada Deformation Array (WCDA), run by the Pacific Geoscience Centre (PGC) in Sidney, B.C. This integrated proposal is rooted in the need for a strong Canadian component in PBO. The full request for monitoring in the Canadian Cordillera includes at sparse backbone of 51 new stations complemented by 13 existing. Another twelve to fifteen are needed to meet the goals of this proposal and will be part of the Cascadia fore-arc array (Figure 2). These stations will be operated by PGC. PGC scientists have more than a decade of experience with continuous GPS, and they play crucial roles in understanding and modeling of the transient behavior of continuous GPS sites (*Dragert, Henton*), the thermal and mechanical behavior of the subduction zone (*Hyndman and Wang*), and the long term viscoelastic behavior of the local mantle and lithosphere needed to interpret coastal and vertical deformation (*James*).

*Other U.S. arrays:* PANGA is collaborating with BARD, EBRY, and the BARGEN arrays, and with RPI, USGS, OSU, UW, CWU, UI, and HSU campaign GPS networks. It is a collaborator with the Cascade Volcanic Processes group and their proposal to monitor Shasta-Medicine Lake and St. Helens-Rainier volcanoes, and the effort to install strainmeters above the plate boundary on the Olympic Coast and at Cape Blanco. PANGA also supports acquisition of LiDAR as part of PBO deformation surveys in the PNW.

*Duplication:* Should adjacent clusters also be funded, certain economies result. Of the 135 stations proposed here, 6 of the cluster stations (plus 2 backbone stations) could be eliminated if the Mendocino Triple Junction proposal is funded by the San Andreas panel. Another twelve of the stations included here (plus 51 in the backbone) are in Canada. No cluster stations are common to the Basin and Range proposal, but 2 – 4 backbone stations are duplicated by that cluster. There is no overlap with the CVO volcanic monitoring proposals; these three efforts tightly complement each other.

Detailed **References** for Cascadia tectonics, full participant list in the PANGA 2000 Investigator Community meeting, and Figure 2 at full scale can be found at: http://www.geodesy.cwu.edu

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