Tectonic deformation in western Washington from continuous GPS measurements

Giorgi Khazaradze¹ and Anthony Qamar
Geophysics Program, University of Washington, Seattle, USA

Herb Dragert
Pacific Geoscience Centre, Geological Survey of Canada, Sidney, Canada

Abstract. The analysis of 3 years of continuous data from 7 permanent GPS stations along the western Washington section of the Cascadia Subduction Zone indicates that the direction of the observed horizontal velocities (with respect to station DRAO, nominally representing the stable North American continent) is roughly parallel to the relative plate convergence direction of the Juan de Fuca and North America plates and that their magnitude decreases away from the trench. Most of this deformation can be attributed to interseismic strain accumulation due to the locking of the thrust trench. When the dislocation model predictions are subtracted from the observed velocities, there is evidence for an additional N-S oriented contraction at a rate of ~4 mm/yr over a distance of 250 km. This signal presumably represents a more long-term deformation pattern than the periodic accumulation and release of elastic strain connected with subduction earthquakes and is most likely related to the occurrence of shallow earthquakes in western Washington that are characterized by predominantly N-S oriented maximum principal stress.

Introduction

The Cascadia Subduction Zone (CSZ) results from the convergence of the Juan de Fuca (JDF) and North America (NA) plates. Western Washington, the area of our investigation, lies in the fore-arc of the CSZ. Comparison of subduction zones around the world focused attention on the great seismic potential of the CSZ [Heaton and Kanamori, 1984] and today the CSZ is widely recognized as a source of major megathrust earthquakes in the recent geologic past. The most compelling evidence comes from paleoseismological investigations of buried coastal marshes, offshore turbidites and tsunamis [Atwater et al., 1995].

Previous estimates of tectonic deformation in western Washington are based on tide gauge records and geodetic surveys using leveling, triangulation and trilateration [Savage et al., 1991; Mitchell et al., 1994]. These measurements were crucial in establishing the existence (and the geometry) of a “locked” zone on the CSZ [Dragert et al., 1994; Hyndman and Wang, 1995; Flück et al., 1997]. Continuous GPS monitoring in the Pacific Northwest began in 1991, with the establishment of the Western Canada Deformation Array by the Geological Survey of Canada (GSC) [Dragert et al., 1995]. In the summer of 1995, the University of Washington, in cooperation with the GSC, installed the first two continuously recording GPS stations in Washington state, located at Seattle (SEAT) and Neah Bay (NEAH) (Figure 1). In early 1996, the US Coast Guard and the National Geodetic Survey established three additional permanent GPS stations: at Fort Stevens (FTS1) in Oregon, Whidbey Island (WHD1) and Robinson Point (RPT1) in Washington. They are part of a nationwide network of Continuously Operating GPS Reference Stations (CORS) [Strange, 1994].

General features of the tectonic deformation in western Washington based on an analysis of 36 months of continuous GPS observations are relatively simple: 1) the magnitude of the observed horizontal velocities decreases away from the deformation front. Maximum velocities (relative to DRAO) are observed at stations along the coast: approximately 11 mm/yr at NEAH, 9 mm/yr at FTS1 and 6 mm/yr at ALBH. Away from the plate boundary, in the Puget Lowland, velocities decrease to 6 mm/yr at WHD1 and 3 mm/yr at SEAT and RPT1 (Table 1). However, the velocity decrease is not as rapid as predicted by existing dislocation and thermal models of the CSZ [Dragert et al., 1994; Hyndman and Wang, 1995; Flück et al., 1997]. This is illustrated by the fact that stations ALBH and WHD1 have approximately equal velocities. 2) The direction of the GPS station velocities located in the north is roughly parallel to the JDF/NA convergence direction of N06°E [Riddihough, 1984]. However, the stations located in the south exhibit a higher north component of motion. This change in the direction of the observed velocities is in agreement with the results obtained from GPS “campaigns” conducted in western Washington [Khazaradze, 1999] and Oregon [Goldfinger et al., 1999].

GPS Data and Analysis

All the data presented here come from 7 continuously operating GPS instruments that are presently part of the Pacific Northwest Geodetic Array (PANGA) [Khazaradze et al., 1997; Miller et al., 1998]. Each of the analyzed GPS stations has at least 2.5 years of continuous data. We used GIPSY software developed at the Jet Propulsion Laboratory to estimate daily fiducial-free positions, spanning the time period from October 1995 to October 1998. The satellite orbits and clock corrections were fixed at values computed by JPL. We decimated pseudo-range and phase data to 5

¹Now at GeoForschungsZentrum Potsdam, Germany
Dislocation Model

Our model of the “locked” portion of CSZ is a modification of one originally proposed by Flück et al. [1997]. The model is based on elastic dislocation theory and incorporates a summation of point source solutions following Okada [1985]. This approach enables one to account for non-planar fault surfaces and to include a “transition” zone with a slip that decreases linearly with distance. The former is especially important because the margin of the CSZ changes direction and the subducting JDF plate arcs upw ard beneath western Washington [Weaver and Baker, 1988].

An initial grid of 33 points defines the boundaries of the “locked” and “transition” zones of the seismogenic portion of the JDF/NA thrust interface (Figure 1). For the final integration, this grid is divided into 100,000 triangular elements, each with an area of ~1 km². The dip of the slab is constrained by locations of intra-slab earthquakes determined by the Pacific Northwest Seismograph Network and by teleseismic receiver function analysis [Croson and Owens, 1987; Cassidy, 1991]. The downdip limits of the “locked” and “transition” zones are allowed to vary in the direction of the fault dip but not along the strike of the fault. This is done in order to avoid divergence from the seismically determined geometry of the JDF slab. The “locked” and “transition” zone depth limits for the “preferred” model, obtained by minimizing the L1 norm, correspond to 15 and 38 km depth, respectively. These depth limits are in agreement with the locations of 350°C and 450°C isotherms as predicted by thermal models [e.g., Youngman and Wang, 1993], as well as, with a maximum depth of seismic coupling of 40±5 km suggested by Tichelaar and Ruff [1993].

The amount and the direction of slip on the “locked” portion of the fault used in our “preferred” model is based on the JDF/NA plate motion estimate by Riddihough [1984] (42 mm/yr; N60°E), which predicts ~10° more northward motion than the NUVEL-1A model [DeMets et al., 1994]. The choice of the above convergence parameters is justified for two reasons: 1) The azimuth of N60°E as opposed to N69°E gives better agreement between the observed and modeled velocities; 2) The use of convergence parameters estimated directly from local magnetic anomalies in the JDF plate is felt to be more accurate than the use of parameters based on global reconstructions used in NUVEL-1A model.

The main differences between the “preferred” model and the model of Flück et al. [1997] are: 1) The N-S extent of our model is limited to the Washington section of the CSZ, due to the limited spatial coverage of the analyzed data. 2) The slab dip is increased slightly to match the seismically determined geometry of the JDF plate. This helps to reduce the amount of predicted horizontal velocities at the coast. 3) The width of the “locked” and “transition” zones

<table>
<thead>
<tr>
<th>Station</th>
<th>North</th>
<th>East</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V_{\text{model}}</td>
<td>V_{\text{model}}</td>
<td>V_{\text{model}}</td>
</tr>
<tr>
<td>ALBH</td>
<td>3.8 (0.1)</td>
<td>2.1</td>
<td>5.9 (0.2)</td>
</tr>
<tr>
<td>FTS1</td>
<td>7.0 (0.2)</td>
<td>2.4</td>
<td>9.4 (0.4)</td>
</tr>
<tr>
<td>NEAH</td>
<td>5.9 (0.2)</td>
<td>2.2</td>
<td>10.8 (0.3)</td>
</tr>
<tr>
<td>RPT1</td>
<td>3.3 (0.2)</td>
<td>0.3</td>
<td>3.4 (0.4)</td>
</tr>
<tr>
<td>SEAT</td>
<td>2.6 (0.2)</td>
<td>0.5</td>
<td>3.3 (0.3)</td>
</tr>
<tr>
<td>WHD1</td>
<td>3.9 (0.3)</td>
<td>3.2</td>
<td>5.7 (0.4)</td>
</tr>
</tbody>
</table>

Details regarding the derivation of velocities relative to DRAO are given in “GPS Data and Analysis” section.

a Weighted RMS of the regression in mm.

b Azimuth in degrees (measured clockwise from north) for the horizontal velocities.
Discussion

For 5 out of 6 analyzed stations located in the fore-arc of the CSZ, our model predictions match the observed tectonic deformation rates reasonably well, apart from an additional northward component discussed below. The model does not explain the unexpectedly high velocity observed at WHD1 (6 mm/yr), located 260 kilometers away from the deformation front. The observed velocity at WHD1 is twice as large as that at SEAT and RPT1 (WHD1 is a US Coast Guard CORS site and its antenna is located on top of a 10 m high metal pole), and, for now, we have chosen to ignore the motion at WHD1 in our models.

If we subtract the JDF/NA subduction related deformation rates (predicted by the dislocation model) from the observed velocities and examine the northern component of the "residual" velocity field, a trend of decreasing velocities with increasing latitude is apparent (Figure 3), suggesting N-S contraction at a rate of \(-0.016\pm0.006\ \mu\text{strain/yr}\). This observation is consistent with the N-S shortening of the western Washington crustal block proposed by Wells et al. [1998] and may be related to the prevalence of N-S oriented F axes of fault plane solutions for crustal earthquakes in much of western Washington [Qamar and Ludwin, 1992; Ma et al., 1996].

Conclusions

Three years of GPS measurements of crustal deformation in western Washington indicate that geodetic strain accumulation in the region is mainly influenced by the convergence of the JDF and NA plates. This result is in agreement with previous interpretations of geodetic measurements [Savage et al., 1991; Drate et al., 1994] and is consistent with the hypothesis that geodetic measurements in the Pacific Northwest (including GPS) are mainly sensitive to short term stress variations, reflecting elastic strain accumulation during the interseismic period between large (\(M_{w}\geq8\)) megathrust earthquakes on the CSZ [Wang et al., 1995]. However, it appears that current GPS measurements in western Washington are also detecting more slowly accumulating north-south contraction, which could be due to squeezing of the fore-arc sliver against the Canadian Coast mountains buttress [Wang, 1996; Wells et al., 1998], driven by the Pacific-North America dextral shear [Pezzopane and Weldon, 1993] and/or by the obliqueness of subduction across the southern CSZ [McCaffrey, 1992]. To release all of the geodetically observed N-S oriented "residual" strain rate (Figure 3) by earthquakes within the crust of western Washington would require one M7.6 or more than 200 M6.0 earthquakes every hundred years. This represents a significant seismic hazard. Obviously, further investigations are required to make sure that this additional signal in the observed GPS velocities is indeed real.

Acknowledgments. We thank Kelvin Wang and Roy Hynesman, from the Geological Survey of Canada, who kindly provided the computer code for 3-D dislocation modeling, initially written by Paul Flick; Rob McCaffrey, Jeff Freymueller and an anonymous reviewer for helpful suggestions and corrections; the US Coast Guard and the National Geodetic Survey for making the CORS data available to the general public via the Internet; Figures were generated using the Generic Mapping Tools software [Wessel and Smith, 1995]. This work was supported by the National Earthquake Hazard Reduction Program of the USGS.
References


G. Khazaradze and A. Qamar, Geophysics Program, University of Washington, Seattle, WA, 98195-1670, USA. ([gia@gfrp-potsdam.de; tony@geophys.washington.edu])

H. Dragert, Geological Survey of Canada, Pacific Geoscience Centre, West Saanich Road, Sidney, B.C., V8L 4B2, Canada. ([dragert@psc.emr.ca])

[Received February 25, 1999; revised July 21, 1999; accepted July 27, 1999.]