Earth Planets Space, **53**, 275–283, 2001

Northward migration of the Cascadia forearc in the northwestern U.S. and implications for subduction deformation

Ray E. Wells and Robert W. Simpson

U.S. Geological Survey, Menlo Park, CA 94025, U.S.A.

(Received August 7, 2000; Revised September 18, 2000; Accepted September 19, 2000)

Geologic and paleomagnetic data from the Cascadia forearc indicate long-term northward migration and clockwise rotation of an Oregon coastal block with respect to North America. Paleomagnetic rotation of coastal Oregon is linked by a Klamath Mountains pole to geodetically and geologically determined motion of the Sierra Nevada block to derive a new Oregon Coast–North America (OC–NA) pole of rotation and velocity field. This long-term velocity field, which is independent of Pacific Northwest GPS data, is interpreted to be the result of Basin–Range extension and Pacific–North America dextral shear. The resulting Oregon Coast pole compares favorably to those derived solely from GPS data, although uncertainties are large. Subtracting the long-term motion from forearc GPS velocities reveals ENE motion with respect to an OC reference frame that is parallel to the direction of Juan de Fuca–OC convergence and decreases inland. We interpret this to be largely the result of subduction-related deformation. The adjusted mean GPS velocities are generally subparallel to those predicted from elastic dislocation models for Cascadia, but more definitive interpretations await refinement of the present large uncertainty in the Sierra Nevada block motion.

1. Introduction

Northeast oblique subduction of the Juan de Fuca plate beneath North America has created a complex, seismically active convergent margin and volcanic arc in the northwest U.S. and adjacent Canada (Fig. 1). Great earthquakes, most recently in 1700 AD, have occurred along the Cascadia subduction zone (Yamaguchi *et al.*, 1997; Satake *et al.*, 1996), and shallow crustal events up to M 7 have occurred in the forearc (Fig. 2), including at least one on the Seattle fault about 1000 years ago (Bucknam *et al.*, 1992). However, the relationship between earthquakes and crustal deformation is poorly understood, in part because of the short historical record, sparse data on deformation rates, and poor exposure of active structures. Better earthquake hazard assessments for the Northwest will depend on identifying Cascadia's tectonic building blocks, their relative motions, and zones of likely strain accumulation. In this paper, we use a plate motion model to assess long term motion of the Cascadia forearc, its potential contributions to GPS velocities, and its effect on models of subduction zone coupling.

The Cascadia forearc appears to be migrating northward along the coast relative to stable North America, as indicated by geologic and seismic evidence for margin parallel compression (Snavely and Wells, 1996; Wang, 1996) and recent GPS results (Savage *et al.*, 2000; McCaffrey *et al.*, 2000; Khazaradze *et al.*, 1999). The forearc is also rotating clockwise with respect to North America, as indicated by its Cenozoic history of paleomagnetic rotation (Fig. 3, Table 1) and new GPS data (Savage *et al.*, 2000; McCaffrey *et al.*, 2000). The rotation has long been explained as the result of margin parallel dextral shear (i.e., oblique subduction) and/or Basin–Range extension (compare Sheriff, 1984 and England and Wells, 1991 with Magill *et al.*, 1982), processes which are still occurring today. Pezzopane and Weldon (1993) and Walcott (1993) link deformation in Cascadia to Pacific–North America dextral shear and northwest migration of the Sierra Nevada block (Fig. 1). In a modification of these models, Wells *et al.* (1998) link the clockwise rotation of the Oregon Coast Range block (OC) to contemporary northwestward motion of the Sierra Nevada microplate (about 10 mm/yr from VLBI, Argus and Gordon, 1991) and calculate a pole of rotation and microplate velocity field for the forearc.

The block motion model for Cascadia (Fig. 4(a)) shows a good fit between the predicted forearc velocity field and patterns of volcanism, seismicity, and Quaternary deformation along the convergent margin. Long term motion of the forearc (averaged over many seismic cycles) was estimated to be about 11 mm/yr WNW in the southern forearc, away from the extensional part of the Cascade arc, and 4–7 mm/yr northward in the northern forearc, nearly normal to east-west thrusts like the Seattle fault, which accommodate arc parallel shortening in western Washington. The Canadian Coast Mountains restraining bend was interpreted to be moving more slowly relative to North America based on VLBI and GPS results from Penticton, British Columbia, and thus is acting as a temporary backstop for northward migrating terranes (2±3 mm/yr northward, Argus and Gordon, 1996; 2.7±3 mm/yr, NASA Goddard Space Flight Center VLBI Group, 1999, available electronically at `http://lupus.gsfc.nasa.gov/global`; <1±1 mm/yr from

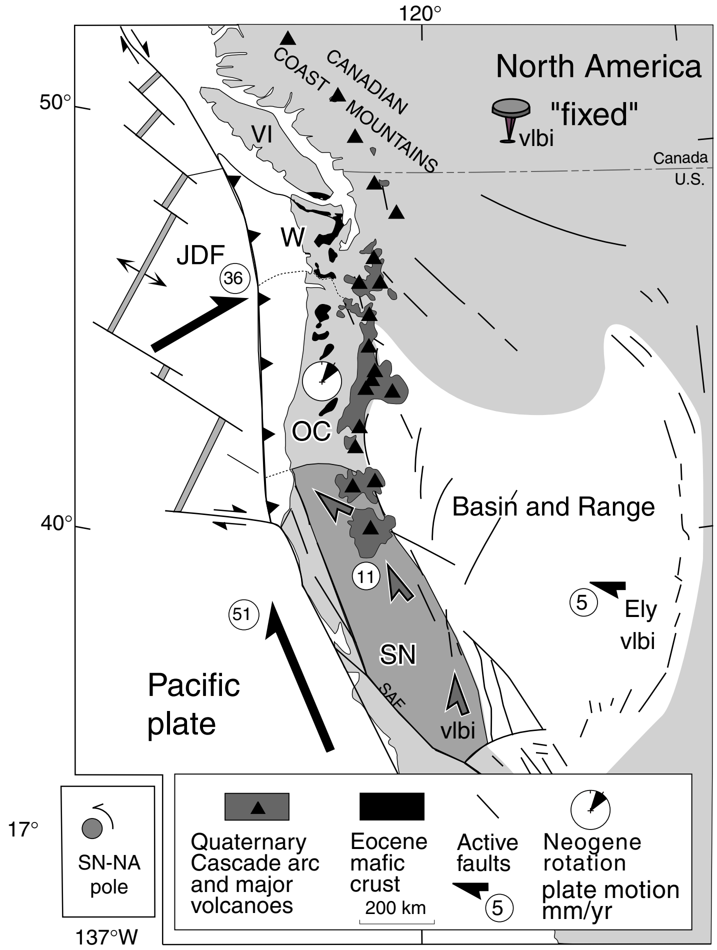

Fig. 1. Tectonic setting of Cascadia. Juan de Fuca plate (JDF) is subducting (barbed fault) beneath North America. Migrating Cascadia forearc terrane divided into: Washington (W), Oregon Coastal (OC), and Sierra Nevada (SN) blocks. Instantaneous Euler rotation poles for SN shown relative to North America. VI=Vancouver Island. (Modified from Argus and Gordon, 1991; Dixon *et al.*, 2000; Pezzopane and Weldon, 1993; Walcott, 1993; Wells *et al.*, 1998.)

GPS, W. Prescott, written communication, 2000).

In this paper, we revise the microplate model and provide uncertainty estimates for the long term forearc velocity field. Because our model is derived independently from paleomagnetic and far-field geodetic data, we can compare it to models derived solely from Pacific Northwest GPS data. Assuming that GPS velocities contain both long term plate motion and interseismic deformation caused by coupling with the subducting Juan de Fuca plate (e.g. Khazaradze *et al.*, 1999; Savage *et al.*, 2000), we can subtract long term forearc microplate velocities from current GPS velocities to derive an adjusted forearc velocity field due to subduction. The adjusted GPS results are then compared to velocities predicted from elastic dislocation models for subduction zone coupling.

2. Block Model

In the revised block model (Fig. 4(b)), a semi-rigid, Oregon coastal block is presently rotating clockwise at the average Cenozoic paleomagnetic rate of $1.19\pm0.10^\circ$ /my (Table 1, Fig. 3) and is linked to the Sierra Nevada block, determined to be moving N$47\pm5^\circ$W at 11 ± 1 mm/yr from GPS (Dixon *et al.*, 2000). We assume that the time averaged paleomagnetic rate is close to the present rotation rate, and is to a first order comparable to geodetic rates of plate motion (e.g. DeMets and Dixon, 1999). The Sierra Nevada motion determined from GPS is similar to that determined from VLBI and in a general way from geologic estimates (Argus and Gordon, 1991; Wernicke and Snow, 1998). The hinge point between the Sierran and Oregon coastal blocks is in the Klamath Mountains, where the north-south Cascade Range trend intersects the more northwesterly Sierra Nevada trend, and the Mesozoic orogen takes a pronounced eastward bend. We infer that an Oregon Coast–Sierra Nevada Euler pole (OC–SN) lies close to this oroclinal bend in the Klamath Mountains and links clockwise rotation of the Oregon forearc block to counterclockwise motion of the Sierra Nevada about its rotation pole (SN–NA; Table 2). Summing OC–SN with SN–NA gives the revised Oregon Coast–North America pole (OC–NAws) and the velocity field for the Oregon forearc block with respect to North America (Fig. 4(b), Table 2).

The revised pole is geologically reasonable and lies between the dominantly compressive regime to the north and an extensional regime to the south, consistent with the predicted velocity field with respect to fixed North America

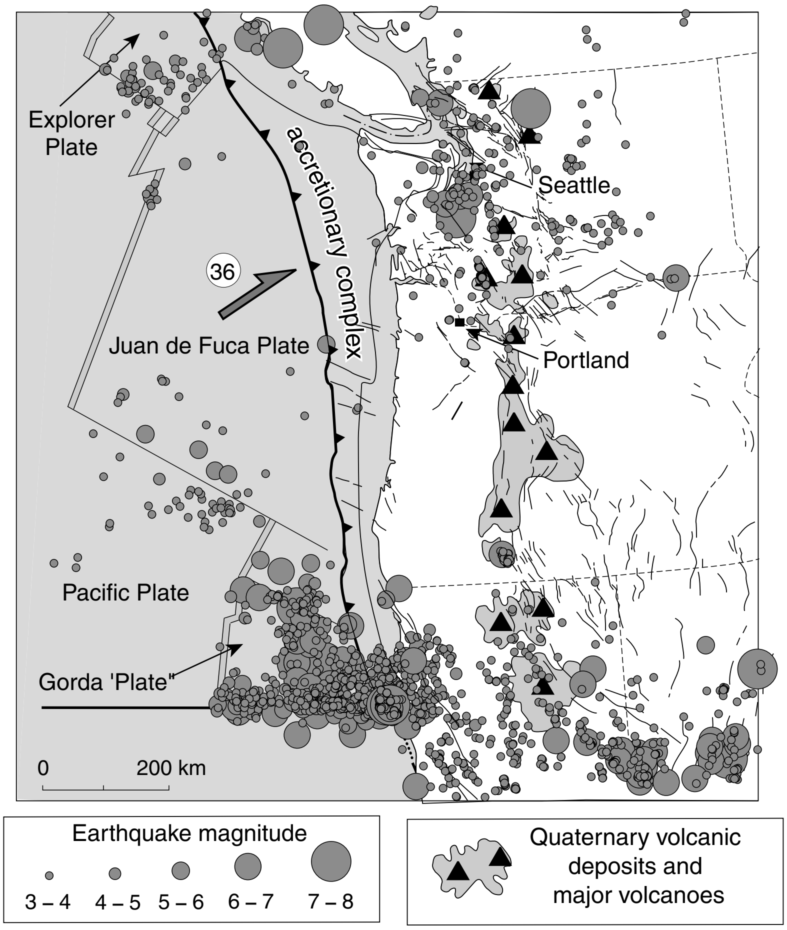

Fig. 2. Cascadia earthquakes, late Cenozoic faults, and volcanoes. Major volcanoes—open triangles, Quaternary volcanic rocks—dark shading.

Table 1. Paleomagnetic rotations.

Unit	Rotation (CW is +)	±	Age (my)	Rot. rate (°/my)	±
Oregon Coastal microplate					
Pomona Mbr., Saddle Mts. Basalt PO(1)	16	3.2	12	1.33	0.25
Ginkgo flows, Wanapum Basalt G (2)	25	10.5	15	1.66	0.67
Grand Ronde Basalt G, CRB on plot (3)	23.5	15	15.6	1.51	0.95
Eocene Intrusions EI (4)	53.0	23.9	45	1.18	0.53
Tillamook Volcanics TV (4)	45.3	8.7	43	1.05	0.21
Tyee Formation TF (4)	67.5	14.5	49	1.38	0.29
Siletz River Volcanics SV (4)	69.5	9.1	56	1.24	0.16
Klamath Mountains area					
N. Calif. western Cascade arc NC (5)	18	7.8	18–32	0.72	0.32
Preferred weighted av. Cenozoic rate; °/my				1.19	0.10
Sierra Nevada microplate					
SN batholith (6)	−3.6	16.5	90	−0.04	0.10
From GPS pole wrt IGRF (Dixon *et al.*, 2000)				−0.37	0.03

Sources: 1) Magill *et al.* (1982); 2) Sheriff (1984); 3) Wells *et al.* (1989); 4) compilation of Gromme *et al.* (1986); 5) Beck *et al.* (1986); 6) compilation in Frei *et al.* (1984), revised using N. Am. Cretaceous reference pole of Globerman and Irving (1988) (plat 71 N; plon 196 E; A95 = 4.9). Letter designations (e.g. PO) keyed to selected units shown in Fig. 3; only well dated units in Table 1 were used in weighted average.

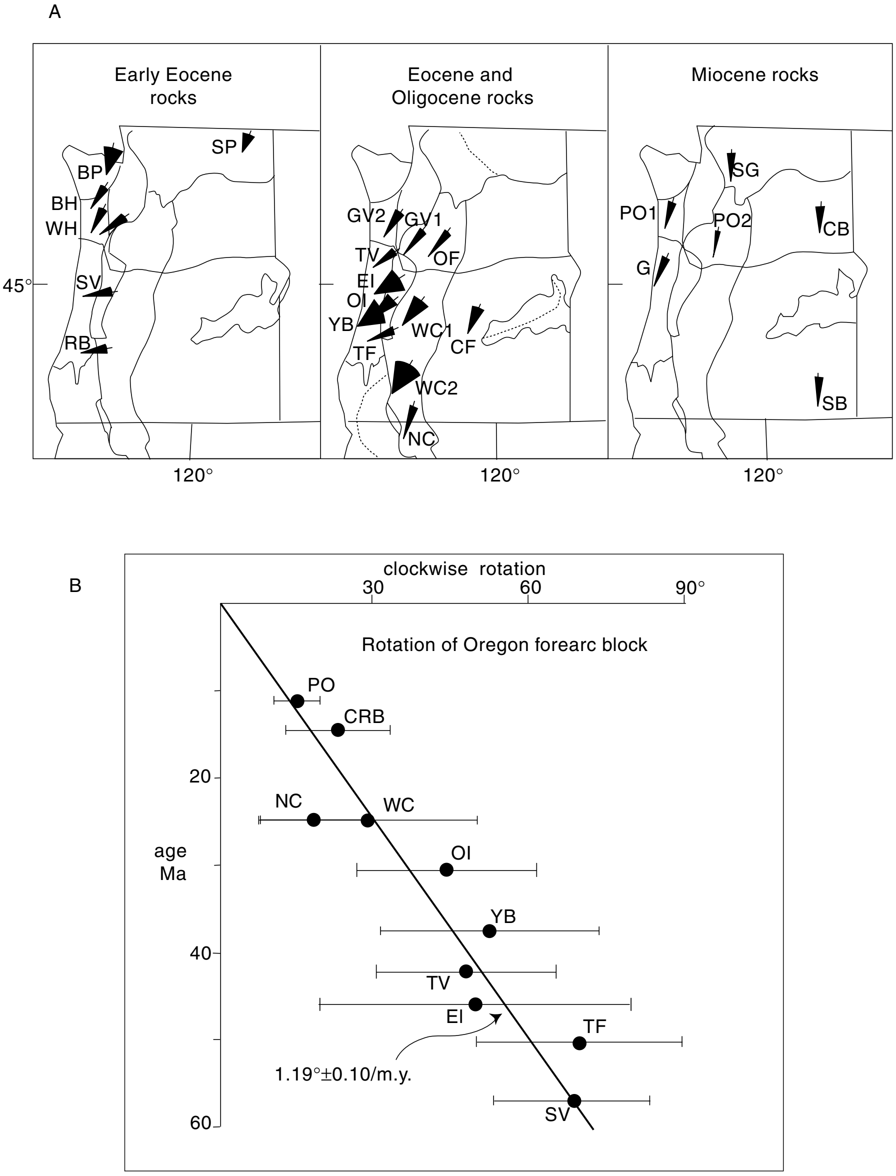

Fig. 3. Clockwise paleomagnetic rotation of Cascadia forearc strata ranging in age from 58 to 12 Ma. A) Map view. Coastal Oregon has the largest rotations; pie-shaped wedges are 95% uncertainties about site mean rotations plotted with respect to present north. Dotted line shows trend of clockwise oroclinal bend in Mesozoic orogen. B) Rotation rate of Oregon forearc block. See Table 1 for key to selected data (From Gromme *et al.*, 1986; Magill *et al.*, 1982; Wells *et al.*, 1989; England and Wells, 1991; Sheriff, 1984.)

(Fig. 4(b)). The forearc velocities are a bit more northerly and somewhat faster than those predicted by Wells *et al.* (1998), but show the same pattern of forearc motion away from the southern extensional arc and toward the actively deforming Washington forearc, where the forearc is being compressed against the Canadian Coast Mountains restraining bend.

The 2-sigma uncertainty estimates in the pole location and velocities are much larger, however, than one might expect from the good agreement with the geology (Fig. 5). The main source of uncertainty is in the location of the SN-NA pole. The Dixon *et al.* (2000) pole has conservative error estimates, which account for both geometric and time correlated noise, and are expected to improve over time (Dixon, written communication, 2000). Similar errors are observed when using the VLBI-derived pole of Argus and Gordon (1991). Until the large uncertainty in Sierran block motion is resolved, our model velocities have large formal uncertainty estimates, although the means are geologically quite reasonable. A smaller source of uncertainty is in the location of the hinge point (i.e., OC–SN pole) between the clockwise rotating Oregon Coast (OC) and the counterclockwise rotating Sierra Nevada (SN) microplates (Fig. 5). The Klamath Mountains can be modeled as part of the SN microplate (e.g. Wells *et al.*, 1998), or as part of the OC microplate, similar to Willamette plate of Magill *et al.* (1982). In this paper, we have chosen the latter and constrain the hinge to lie in a triangular region between the northern hinge of Wells *et al.* (1998), the Mendocino triple junction (MTJ on Fig. 5), and the Yolla Bolly junction (YB on Fig. 5)—a point where the Klamaths, California Coast Range, and Sierra-Great Valley all come together (Blake *et al.*, 1999). The preferred pole

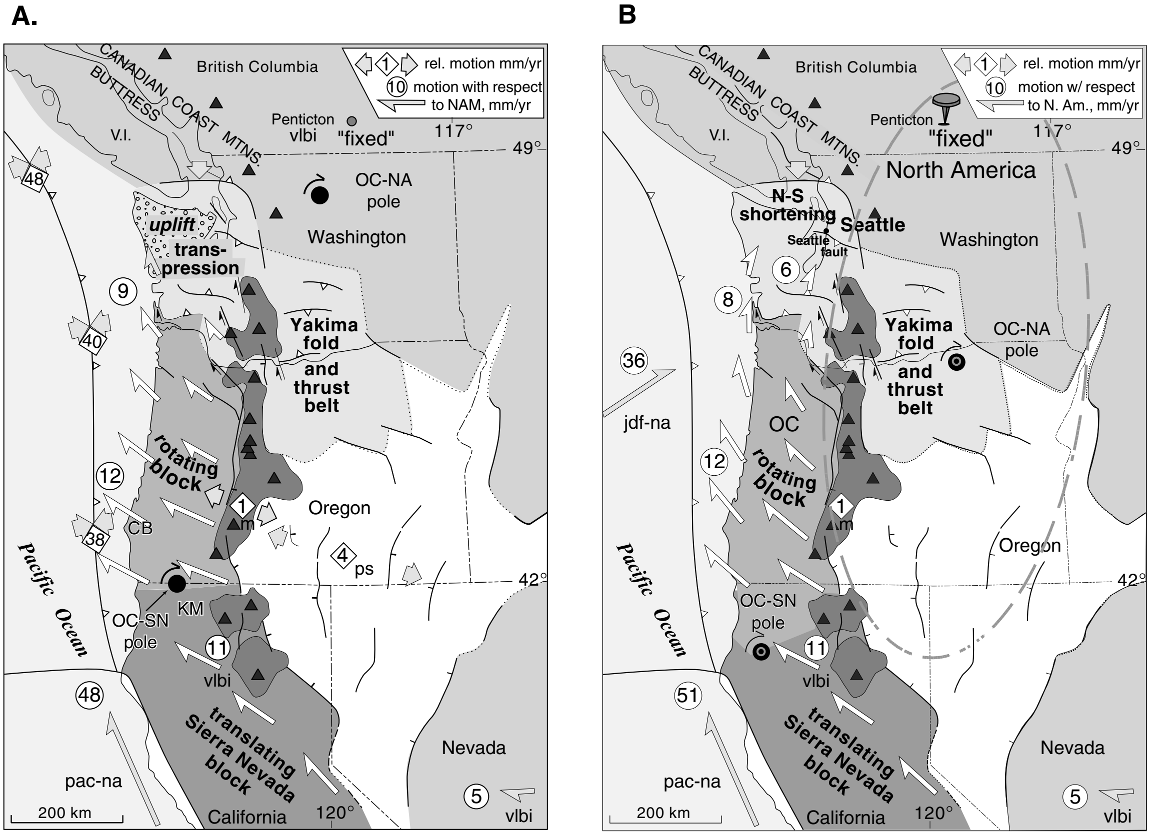

Fig. 4. A) Velocity field for Oregon forearc microplate calculated from OC–NA pole (from Wells *et al.*, 1998). Oregon block (OC) rotating at Neogene paleomagnetic rate is linked to Sierra Nevada block moving at vlbi rate by Euler pole (OC–SN) in Klamath Mountains. Extensional arc forms along trailing edge of Oregon fore-arc block which absorbs Sierra Nevada displacement by rotating over trench. North end of Oregon block deforms Washington forearc against Canadian re-entrant in the margin, causing N-S compression, uplift, thrust faulting, and earthquakes. Rates from very long baseline interferometry (vlbi); paleoseismology (ps); magmatic spreading (m); other symbols as in Fig. 1. B) Revised microplate model. Note change in rotation poles and velocity field.

Table 2. Rotation poles.

pole	Lat °N	Lon °W	Angvel °/Myr	±°/Myr	95% smajaxis °/az	minoraxis °
SN-NAd (1)	17.0	137.3	0.28	0.07	16.8/326	1.9
OC-SNws (2)	40.88	123.56	−1.56	0.10	1.75/180	1.02
OC-NAws (2)	45.54	119.60	−1.32	0.16	5.1/010	2.96
JDF-OCws (2)	67.40	147.94	0.627	0.23	4.78/176	2.78
SOR-NA (3)	43.5	120	−1.66	0.33	0.7/090	0.17
WO-NA (4)	45.9	118.7	−1.05	0.31	1.2/090	1.0

Sources: (1) Dixon *et al.* (2000), (2) This paper, (3) Savage *et al.* 2000, (4) McCaffrey *et al.* (2000). Rotation pole describes the motion of the first plate with respect to the last plate (e.g. Sierra Nevada wrt North America = SN–NA); Angvel is angular velocity in degrees per million years, counterclockwise is positive (right-hand rule); 95% smajaxis °/az is the semi-major axis in degrees of the 2-sigma error ellipse and its azimuth; 2-sigma errors on rate.

lies in the southern part of the triangle on a prominent bend in the Mesozoic orogen (Fig. 5), sandwiched between margin parallel Neogene folds on the west and margin perpendicular Neogene folds on the east (Jennings, 1977).

Our rotation rate for the OC–SN pole is the weighted mean of the paleomagnetic rotation rate for the OC with respect to the North American reference poles (spin axis) minus the geodetic rotation rate of the SN block with respect to the spin axis, ($-1.19-0.37 = -1.56\pm0.10$°/my). This simplifying assumption only works because the paleomagnetic sites lie within a few degrees of the rotation pole. The uncertainty ellipse for the OC–SN pole is constructed to encompass the triangular region of geologic uncertainty and is assumed to be a 95% confidence ellipse, given the constraints imposed by the southern limit of clockwise paleomagnetic rotation (Beck *et al.*, 1986 and Fig. 3) and the northern limit of counterclockwise rotation inferred from VLBI (NASA Goddard Space Flight Center VLBI Group, 1999, available electronically at `http://lupus.gsfc.nasa.gov/global`).

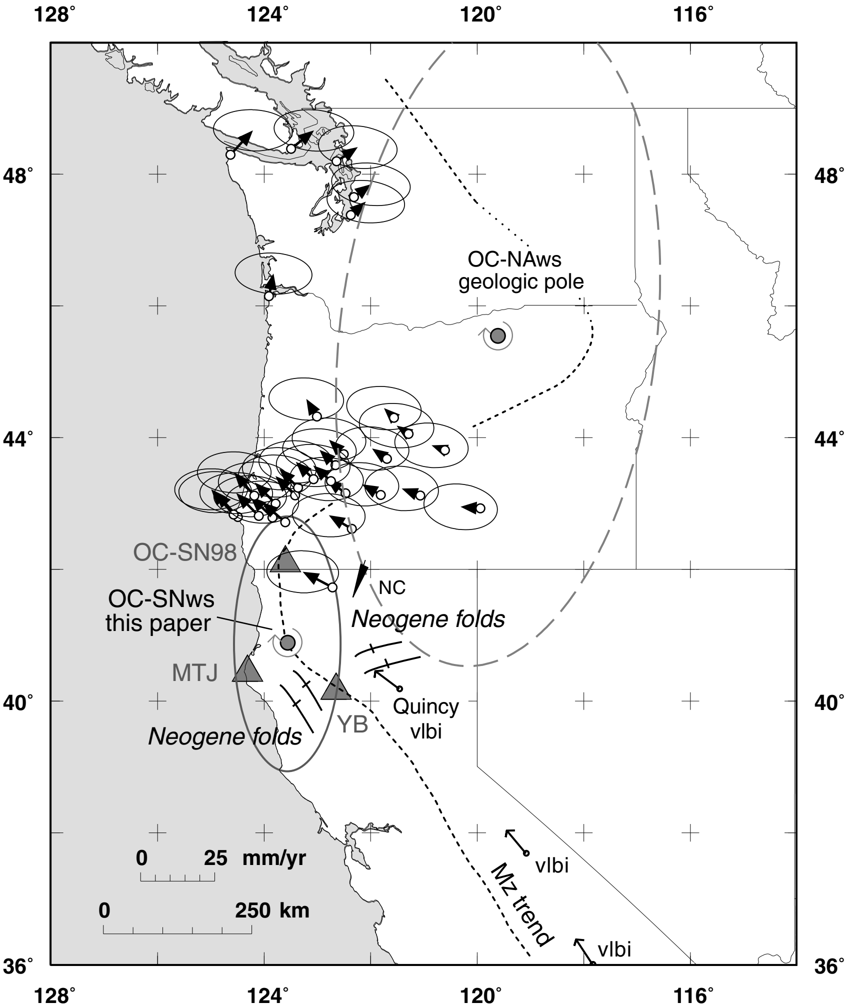

Fig. 5. Rotation pole (OC–NA) and 95% confidence ellipse for Oregon Coast forearc block with respect to North America. Calculated velocities from the OC–NA pole are shown for published GPS sites (Savage *et al.*, 2000; Khazaradze *et al.*, 1999). Klamath Mountains hinge point (OC–SN pole) lies between clockwiserotating OC block and counter-clockwise rotating Sierra Nevada block and is constrained to be in the triangular region outlined by the Mendocino triple junction (MTJ), Yolla Bolly junction (YB), and the pole used by Wells *et al.* (1998); see text for discussion.

3. Block Motions and Their Relationship to GPS Results

Published GPS results for the Pacific Northwest are shown in Fig. 6. GPS velocities in the forearc are northeasterly, rather than northwesterly, as predicted by the long-term motion. Northeast motion in the direction of plate convergence, evident in the Coast Range GPS measurements, is interpreted to be elastic deformation above the locked Cascadia subduction zone (Dragert and Hyndman, 1995; Flück *et al.*, 1997; Khazaradze *et al.*, 1999; Savage *et al.*, 2000). North-directed residuals not accounted for by elastic models are thought to represent northward migration of the forearc (Khazaradze *et al.*, 1999).

Because our block model does not use Northwest GPS data, we attempt to independently resolve interseismic deformation in the GPS data by removing the geologically constrained secular plate motion. In the block model, we interpret the velocity field to represent the long term effect of Pacific–North America dextral shear and Basin–Range extension on the forearc. Subtracting this motion from the GPS should show velocities with respect to a fixed OC block, presumably related to Juan de Fuca convergence. In Fig. 7, the vector differences are shown after subtraction of block rotation. Although the uncertainties are large, residual velocity fields in the Cascadia forearc are subparallel to the calculated Juan de Fuca–forearc convergence vector and decrease inland, consistent with deformation related to coupling with the slab. At present, the uncertainty estimates do not allow quantitative estimate of the width of the locked zone. The velocities are similar to those predicted by the Flück *et al.* (1997) model, which, although the model used a uniform convergence vector, it was fortuitously close to the actual JDF–OC convergence vector (Wang *et al.*, 2001).

4. Discussion

Both Savage *et al.* (2000) and McCaffrey *et al.* (2000) have determined that the Oregon forearc block is presently rotating clockwise about a pole in the Oregon backarc (Fig. 6). The geologic pole of rotation for the Oregon coastal block compares favorably with those determined solely from the GPS velocities (Savage *et al.*, 2000; McCaffrey *et al.*, 2000; Table 2), and all effectively account for the northward

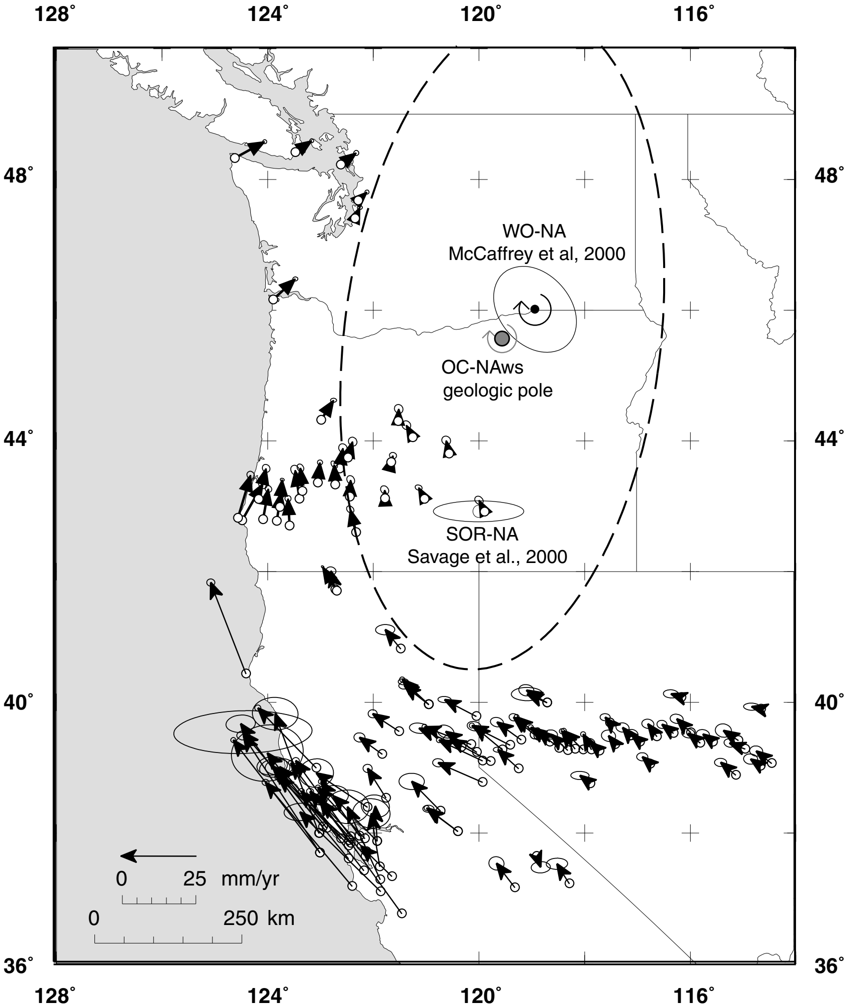

Fig. 6. Selected GPS velocities with 95% uncertainty estimates relative to stable North America reference frame. Note that Oregon GPS observations are more northerly than the expected JDF–NA convergence direction, although most observations in Washington are nearly parallel. (Thatcher *et al.*, 1999; Savage *et al.*, 2000; Khazaradze *et al.*, 1999; W. H. Prescott, `http://quake.wr.usgs.gov/QUAKES/geodetic/gps/Bard/`). WO–NA is Oregon–Washington pole of McCaffrey *et al.* (2000); SOR–NA is pole of Savage *et al.* (2000) for southwest Oregon.

drift of coastal Oregon and the shortening in the Washington forearc. The block model pole OC–NAws and the pole of McCaffrey *et al.* (WO–NA, Fig. 6) are very close in location and rate and effectively account for extension in the Cascade arc that is implied from Quaternary basaltic magmatism, faulting, and seismicity at least as far north as Mount St. Helens in southern Washington. These poles also are consistent with the style and rate of Quaternary deformation in the backarc, which is dominantly extensional south of the pole and compressional north of the pole. This appears true even though the back arc is internally deforming and is not strictly a rigid plate (McCaffrey *et al.*, 2000). The north-south shortening in the Yakima fold belt and the similar shortening in the Washington forearc can both be explained as part of the same northward drift of outboard blocks around a pole near the eastern end of the fold belt. The more southerly pole of Savage *et al.* (2000), however, fits the Cape Blanco GPS data better and could indicate that the Oregon forearc consists of more than one block. To the north, western Washington is clearly deforming internally, has a different rotation history, and does not appear to be part of the Oregon coastal block (compare Magill *et al.*, 1982, and Wells and Coe, 1985).

5. Conclusions

A revised block motion model provides long term velocities for a clockwise rotating Oregon Coastal microplate in the Cascadia forearc. By subtracting microplate model velocities from GPS velocities we extract an adjusted GPS velocity field with respect to the forearc that is inferred to be due to compression by the Juan de Fuca plate. The adjusted forearc velocities are parallel to JDF–OC convergence and are similar in overall trend to those predicted by a 3-D elastic dislocation model. The uncertainty estimates are large and do not yet allow a quantitative estimate of the width of the locked zone. The block model rotation pole, however, is very close in location and rate to that determined independently from the GPS data by McCaffrey *et al.* (2000). Both are in the backarc near the Columbia River and are consistent with the changes in the young deformation field and distribution of Quaternary volcanism observed along the Cascadia margin.

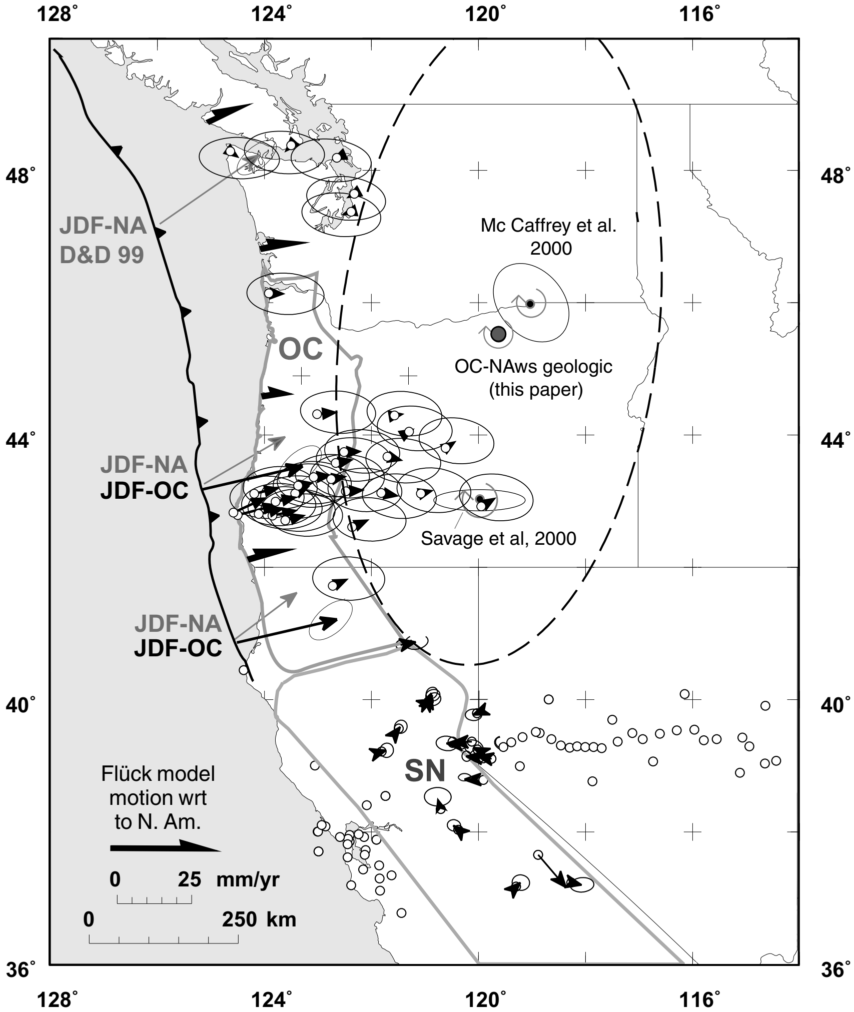

Fig. 7. Oregon Coast GPS vectors adjusted to a fixed forearc OC plate using the OC–NAws pole closely parallel Juan de Fuca plate convergence direction with respect to the forearc. GPS velocities in Washington are still relative to NA; those in California are adjusted relative to the Sierra Nevada block. JDF velocity vectors are calculated from Demets and Dixon (1999) and DeMets *et al.* (1994). Also shown are velocities predicted by the Flück *et al.* (1997) model.

Acknowledgments. We thank Herb Dragert, Kelin Wang, and Rob McCaffrey for fruitful discussions on forearc deformation. Reviews by Gene Humphreys, Stephane Mazzotti, Jim Savage, and Rick Blakely substantially improved the manuscript.

References

Argus, D. F. and R. G. Gordon, Current Sierra Nevada-North America motion from very long baseline interferometry: Implications for the kinematics of the western United States, *Geology*, **19**, 1085–1088, 1991.

Argus, D. F. and R. G. Gordon, Tests of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from very long baseline interferometry, *J. Geophys. Res.*, **101**, 13,555–13,572, 1996.

Beck, M. E., Jr., R. F. Burmester, D. E. Craig, C. S. Gromme, and R. E. Wells, Paleomagnetism of middle Tertiary volcanic rocks from the western Cascade series, northern California, *J. Geophys. Res.*, **91**, 8219–8230, 1986.

Blake, M. C., Jr., D. S. Harwood, E. A. Helley, P. Irwin, A. S. Jayko, and D. L. Jones, Geologic Map of the Red Bluff 30′ × 60′ Quadrangle, California, U.S. Geological Survey Miscellaneous Investigations Map I-2542, scale 1:100,000, 1999.

Bucknam, R. C., E. Hemphill-Haley, and E. B. Leopold, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington, *Science*, **258**, 1611–1614, 1992.

DeMets, C. and T. H. Dixon, New kinematic models for Pacific-North America motion from 3 Ma to present, I: Evidence for steady motion and biases in the NUVEL-1A model, *Geophys. Res. Lett.*, **26**, 1921–1924, 1999.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, 2191–2194, 1994.

Dixon, T. H., M. Miller, F. Farina, H. Wang, and D. Johnson, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American Cordillera, *Tectonics*, **19**, 1–24, 2000.

Dragert, H. and R. D. Hyndman, Continuous GPS monitoring of elastic strain in the northern Cascadia subduction zone, *Geophys. Res. Lett.*, **22**, 755–758, 1995.

England, P. C. and R. E. Wells, Neogene rotations and continuum deformation of the Pacific Northwest convergent margin, *Geology*, **19**, 978–981, 1991.

Flück, P., R. D. Hyndman, and K. Wang, Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone, *J. Geophys. Res.*, **102**, 20,539–20,550, 1997.

Frei, L. S., J. R. Magill, and A. V. Cox, Paleomagnetic results from the central Sierra Nevada: constraints on reconstructions of the western United States, *Tectonics*, **3**, 157–178, 1984.

Globerman, B. R. and E. Irving, Mid-Cretaceous paleomagnetic reference field for North America; restudy of 100 Ma intrusive rocks from Arkansas, *J. Geophys. Res.*, **93**, 11,721–11,733, 1988.

Gromme, C. S., M. E. Beck, Jr., D. C. Engebretson, and R. E. Wells, Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest, *J. Geophys.*

Res., **91**, 14,089–14,103, 1986.

Hyndman, R. D. and K. Wang, The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime, *J. Geophys. Res.*, **100**, 22,133–22,154, 1995.

Jennings, C., Geologic Map of California, California Division of Mines and Geology Geologic Map Data Series, scale 1:750,000, 1977.

Khazaradze, G., A. Qamar, and H. Dragert, Tectonic deformation in western Washington from continuous GPS measurements, *Geophys. Res. Lett.*, **26**, 3153–3156, 1999.

Magill, J. R., R. E. Wells, R. W. Simpson, and A. V. Cox, Post-12 m.y. rotation of southwest Washington, *J. Geophys. Res.*, **87**, 3761–3776, 1982.

McCaffrey, R., M. D. Long, C. Goldfinger, P. C. Zwick, J. L. Nabelek, C. K. Johnson, and C. Smith, Rotation and plate locking along the southern Cascadia subduction zone, *Geophys. Res. Lett.*, **27**, 3117–3120, 2000.

Pezzopane, S. K. and R. J. Weldon, II, Tectonic role of active faulting in central Oregon, *Tectonics*, **12**, 1140–1169, 1993.

Satake, K., K. Shimazaki, Y. Tsuji, and K. Ueda, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700, *Nature*, **379**, 246–249, 1996.

Savage, J. C., J. L. Svarc, W. H. Prescott, and M. H. Murray, Deformation across the forearc of the Cascadia subduction zone at Cape Blanco, Oregon, *J. Geophys. Res.*, **105**, 3095–3102, 2000.

Sheriff, S. D., Paleomagnetic evidence for spatially distributed post-Miocene rotation of western Washington and Oregon, *Tectonics*, **3**, 397–408, 1984.

Snavely, P. D., Jr. and R. E. Wells, Cenozoic evolution of the continental margin of Oregon and Washington, in *Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest*, edited by A. M. Rogers, T. J. Walsh, W. J. Kockelman, and G. R. Priest, U.S. Geological Survey Professional Paper **1560**, pp. 161–182, 1996.

Thatcher, W., G. R. Foulger, B. R. Julian, J. Svarc, E. Quilty, and G. W. Bawden, Present-day deformation across the Basin and Range Province, Western United States, *Science*, **283**, 1714–1718, 1999.

Walcott, D., Neogene kinematics of western North America, *Tectonics*, **12**, 326–333, 1993.

Wang, K., Simplified analysis of horizontal stresses in a buttressed forearc sliver at an oblique subduction zone, *Geophys. Res. Lett.*, **23**, 2021–2024, 1996.

Wang, K., J. He, H. Dragert, and T. James, Three-dimensional viscoelastic interseismic deformation model for the Cascadia subduction zone, *Earth Planets Space*, **53**, this volume, 295–306, 2001.

Wells, R. E., R. W. Simpson, R. D. Bentley, M. H. Beeson, M. T. Mangan, and T. L. Wright, Correlation of Miocene flows of the Columbia River Basalt Group from the central Columbia River Plateau to the coast of Oregon and Washington, in *Volcanism and Tectonism in the Columbia River Flood Basalt Province*, edited by P. Hooper and S. Reidel, Geol. Soc. Amer. Special. Paper **239**, 113–130, 1989.

Wells, R. E. and R. S. Coe, Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington, implications for mechanisms of tectonic rotation, *J. Geophys. Res.*, **90**, 1925–1947, 1985.

Wells, R. E., C. S. Weaver, and R. J. Blakely, Fore-arc migration in Cascadia and its neotectonic significance, *Geology*, **26**, 759–762, 1998.

Wernicke, B. and J. K. Snow, Cenozoic tectonism in the central Basin and Range: motion of the Sierran-Great Valley block, in *Intergrated Earth and Environmental Evolution of the Southwestern United States*, edited by W. G. Ernst and C. A. Nelson, pp. 111–118, Bellwether Publishing, Ltd., 1998.

Yamaguchi, D. K., B. F. Atwater, D. E. Bunker, B. E. Benson, and M. S. Reid, Tree-ring dating the 1700 Cascadia earthquake, *Nature*, **389**, 922–923, 1997.

R. E. Wells (e-mail: rwells@usgs.gov) and R. W. Simpson