GPS velocity field and hazards assessment for the Pacific Northwest: Collaborative research with Rensselaer Polytechnic Institute, University of Washington, and US Geological Survey

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Conclusions

GPS measurements from the Pacific Northwest reveal a rapid clockwise rotation of most of Oregon relative to North America. Such rotation must be taken into consideration when assessing regional kinematics. Inversions of the GPS results indicate that the permanent shortening rate across Puget Lowlands region near Seattle is 5.5 +/- 0.3 mm/a and coupling on the Cascadia thrust extends farther landward in central Oregon than it does elsewhere along the margin.

Investigations

Campaign GPS measurement: During the summer of 2001 we occupied 170 GPS sites in Northern Oregon, throughout Washington, and in SW British Columbia. Approximately 30 of these were new sites and the rest were occupied earlier (Figure 1). These measurements were made in cooperation with Anthony Qamar at University of Washington and Herb Dragert of the Geological Survey of Canada. The goals were to improve the accuracy of the GPS results in the metropolitan areas of both Seattle and Portland and to expand the velocity field to the east and north to see how strain dies off into the continent. These constraints on the velocity field are necessary to assess seismic hazards on the plate boundary thrust and on crustal faults. To do this we took advantage of the numerous GPS sites in eastern Oregon and Washington (Figure 2) installed and measured by the National Geodetic Survey (a large regional survey was done in 1998).

During the first week we focussed on the Portland and Seattle regions where often repeated GPS surveys will be required to resolve small spatial variations in strain rates. In the second week the survey moved to Eastern Oregon and Washington and in the third week, for three days we occupied 16 sites in British Columbia installed this year by Herb Dragert and us.

Data processing: We processed all available campaign and continuous data from the Pacific Northwest using the GAMIT/GLOBK software analysis package. We processed campaign data collected since 1992 by USGS, CVO, NGS, UW, RPI, and OSU. The campaign data set comprises separate 26 campaigns with over 3500 site-days from more than 500 sites (Figure 2). In addition we process simultaneously any regional continuous sites operating during the campaigns (from PANGA, Western Canada Deformation Array, and NGS CORS sites). Orbits, Earth orientation data and regional and global GPS data are obtained from the Scripps Orbit and Permanent Array Center (SOPAC).

We estimated all site positions and velocities in the ITRF97 reference frame by fitting a straight line to the positions through time. We apply common mode corrections, correct for the 2001 Nisqually quake, scale uncertainties in positions so the reduced chi-squared misfit is approximately unity, and add random walk uncertainties. The velocities are then rotated about a NA-ITRF97 Euler pole estimated from 19 NA GPS sites to put them in a North America reference frame (Figure 3). This resulted in about 250 velocities for Oregon and Washington.

Modeling: We continued to develop 3-dimensional dislocation and finite-element models to help understand the observed GPS results. We now use the geodetic results to solve for both block rotations and coupling on the Cascadia thrust fault using a simultaneous inversion (McCaffrey, 1995; 2002), as it is clear that the entire PNW velocity field is subject to both plate coupling strain and rigid body rotation. This work is an extension of our earlier modeling in which we developed 3D elastic halfspace dislocation models of the subduction zone for Oregon (McCaffrey et al., 2000) and a 2D finite element model of the Portland section of the Cascadia thrust (Williams and McCaffrey, 2001a). We have also enhanced the finite element inversion approach to develop 3D models of the thrust (Williams and McCaffrey, 2001b). We can also use other types of data in our inversions, notably uplift and tilt rates that are available for the Pacific Northwest.

Results

Pacific Northwest velocity field: The velocity field in a NA reference frame (Figure 3) reveals a strong rotation of Oregon about a pole in NE Oregon. The manifestations of rotation are the east to west increase in velocities and the north to south change from westerly to easterly. (Shear strain would produce one of these velocity gradients, but not both.) The pattern of rotation is modified near the coast by approximately eastward contraction doe to pate coupling.

The principal strain rates (Figure 4) estimated from the GPS vectors reveal that the contraction due to plate locking is uniaxial and nearly normal to the coast. This indicates that the rotation of the Oregon block results in convergence at the Cascadia thrust that is more normal to the coast than is the Juan de Fuca - North America convergence direction. The strain field also suggests an increase in the strain rates near the Olympic - Wallowa lineament (OWL) compared to inland regions in Oregon. Hence, the OWL may mark the boundary between NA and the rotating Oregon block (McCaffrey et al., 2000).

Interpretation: The expanded network resulting from our 2001 campaign will allow us to further separate the strains from rigid body rotations and to follow the rotating Oregon block into Washington. Modeling the GPS velocities from the southern part of the array (south of 47N) results in rotation of the Oregon forearc at about 0.7 degree per Ma about a pole in NE Oregon near Pendleton, OR (Figure 5). This pole is very close to the one estimated from geology and paleomagnetism by Wells et al. (1998) indicating that the rotation has probably been going on for the past 10-12 Ma. We separated the Oregon block from North America (NA) along the Olympic-Wallowa Lineament which agrees well with the GPS data. If that is indeed the boundary then rotation of the Oregon block relative to NA produces a shortening rate of 5.5 +/- 0.3 mm/a across the Puget Sound region near Seattle (McCaffrey, 2002).

Results from Washington State also indicate the possibility of rotation. We separated the Oregon block from the Washington block along the Olympic-Wallowa Lineament and solved for separate blocks motions. An F-test based on the fits to the residuals indicates that there is a 97% chance that a clockwise rotating Washington block is distinct from North America.

We also estimated the distribution of plate locking on the southern Cascadia thrust in Oregon by a formal inversion using both GPS and tilt data as constraints [McCaffrey, 2002]. The results suggest that plate locking is largely offshore (Figure 6). We tried models in which the coupling on the thrust fault is constrained to decrease with depth (Constrained model in Fig. 6) and in which the coupling is not constrained in that manner (Unconstrained model in Fig. 6). In the constrained model, the local high in coupling that appears as a peak beneath central Oregon in the unconstrained model is more spread out. Both models fit the data with a reduced chi-squared of about 1 indicating the data are satisfied. The constraints reduce the fit to the data by only 5%, which has a 36% chance of being random (i.e., the fit to the constrained model is not significantly worse).

The resulting models reveal a smooth transition from highly coupled in the offshore regions to low coupling beneath the land areas (Figure 7; the unconstrained model shows a large peak along the 44N profile (green line) which spreads out to a broader high in the constrained model). It is useful to note that the flat, broad distribution of coupling beneath the central Oregon section of the Cascadia thrust fits the low uplift rates there. Hyndman and Wang (1995) attributed the low uplift rates to reduced coupling only in the offshore region. This result demonstrates that the uplift data alone can be ambiguous and additional data are required.

The south to north increase in slip deficit is largely due to the northward increase in convergence rate along the Cascadia thrust. The increase is caused by the motion of Oregon relative to North America.

Residuals relative to the rotation / plate locking model do not show large regions of correlated, unmodeled vectors at the level of the uncertainties, which is about 1 mm/yr (Figure 5), indicating that the majority of the motion of Oregon sites relative to North America is explained by rotation and subduction zone coupling. SW of the OWL, no additional rapidly-slipping, upper plate faults are indicated by these results.

Future work

Future directions of research include repeating the GPS measurements to continue to decrease the velocity uncertainties. Greater accuracy in the crustal strain will allow us to examine details of both subduction zone strain and upper plate faulting which both lead to significant earthquake hazards. We feel also that the use of half-space dislocation models for the interpretation of geodetic data and subsequent assessment of hazards must be looked at carefully. Our preliminary work with finite-element models based on a plate model and with force-balance constraints give results and implications for hazards that are significantly different than those inferred from half-space dislocation models.

Non-technical summary

Measurements with the Global Positioning System are successfully showing the motions and deformation of Oregon and Washington. We are finding that the motion is largely a rigid-body rotation possibly caused by a push from the Basin and range to the southeast, from California to the south, or from drag of the subducted seafloor beneath. The rigid rotation of Oregon is consistent with its lack of seismicity, at least as compared to Washington State. The rotating Oregon block appears to converge with North America in Northern Washington state along the Olympic - Wallowa lineament and across Puget Sound. Coupling on the Cascadia thrust increases from south to north largely as a consequence of the convergence rate increasing in that direction. Coupling is largely offshore except in central Oregon where it extends well below land areas.

Data availability

Raw GPS data and published site velocities are archived at UNAVCO.

Collaborations

The field work in 2001 was done in close collaboration with Tony Qamar at University of Washington. The measurements in Canada were done with Herb Dragert of the Geological Survey of Canada. Charles Williams contributed to the field work and finite element modeling. Numerous other people helped with the field work - they are listed on our 2001 campaign web site http://www.rpi.edu/~mccafr/gps/gps2001.htm

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Sumatra, and Alaska, ***Eos Trans. AGU***, 2001b.

Papers published from this work

- McCaffrey, R., M. D. Long, C. Goldfinger, P. C. Zwick, J. L. Nabelek, C. K. Johnson, and C. Smith, Rotation and Plate Locking at the Southern Cascadia Subduction Zone, ***Geophysical Research Letters***, vol. 27, no. 19, p. 3117-3120, October, 2000.
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Meeting Presentations

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- Long, M. D., R. McCaffrey. C. K. Johnson, Estimation of Forearc Rotation and Strain in Western Oregon and SW Washington Using GPS, ***Eos Trans. AGU*** Spring 2000.
- McCaffrey, R., A. Qamar, Z. Ning, M. Long, and C. A. Williams, US Pacific Northwest GPS Velocity Field Inferred from Campaign Measurements: Evidence for Large-scale Rotation and Plate Locking, ***Eos Trans. AGU*** Fall 2000.
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Figures

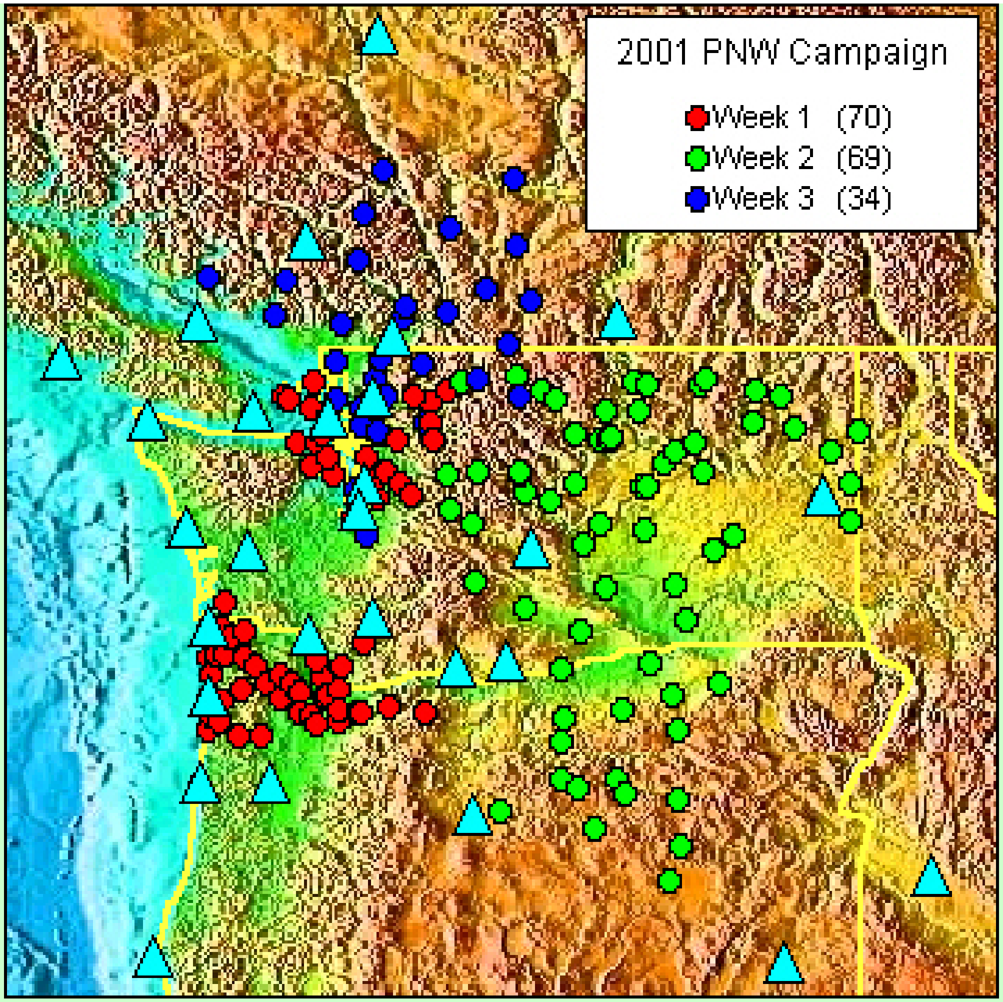


Figure 1. GPS sites occupied during 2001. Triangles are continuous sites.

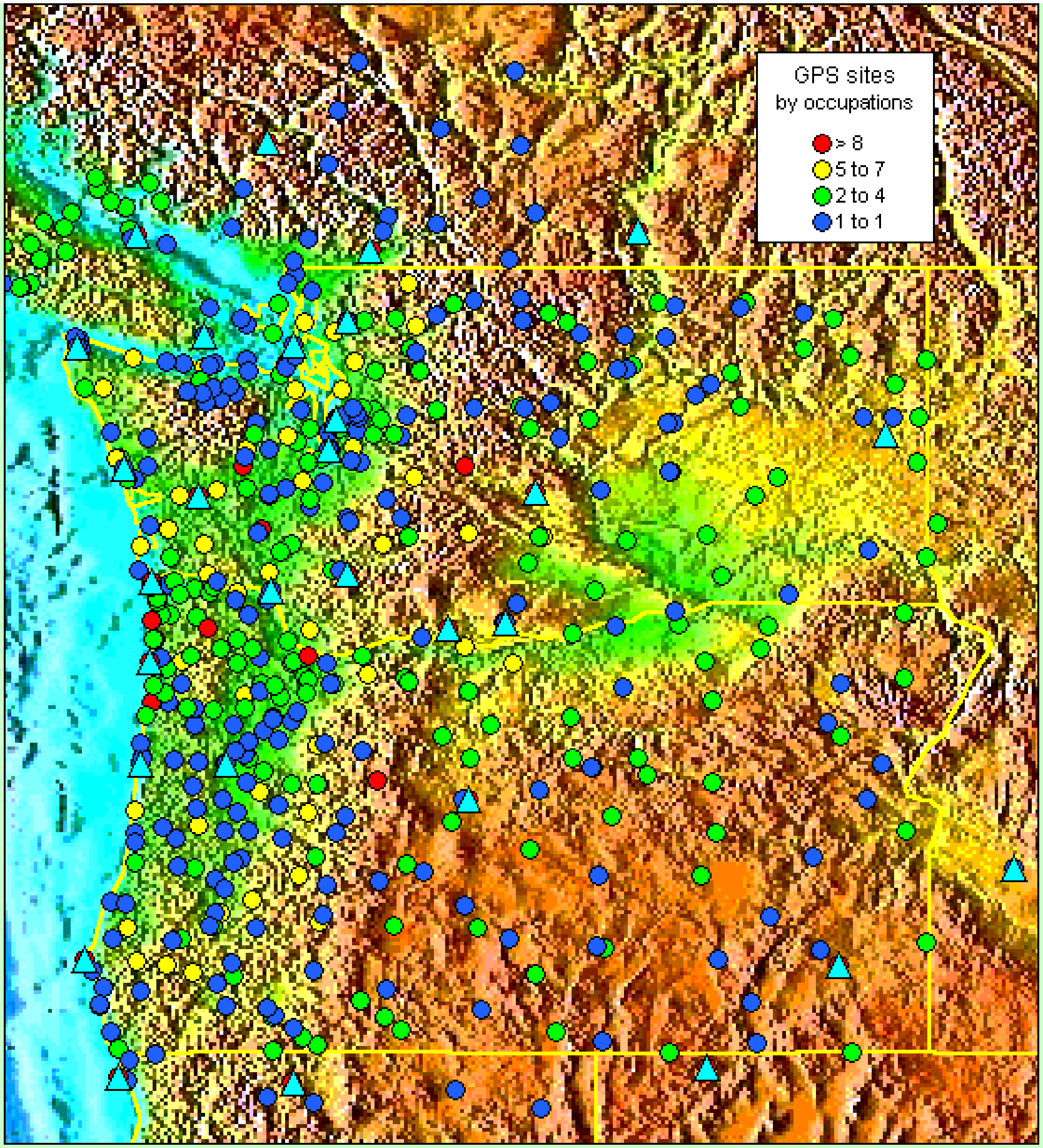
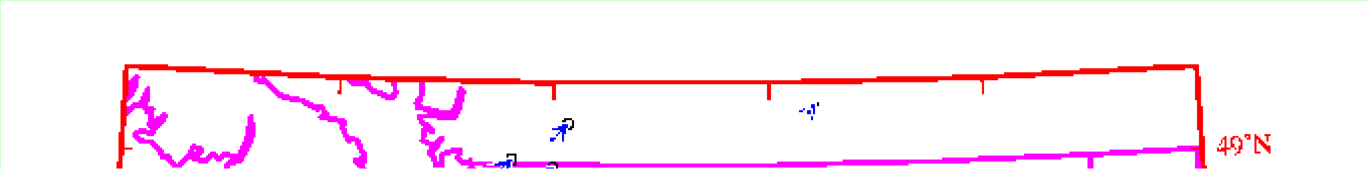


Figure 2. GPS sites occupied at least once since 1992 and data processed at RPI. Symbol colors refer to the number of times the site has been occupied. Triangles are continous sites.



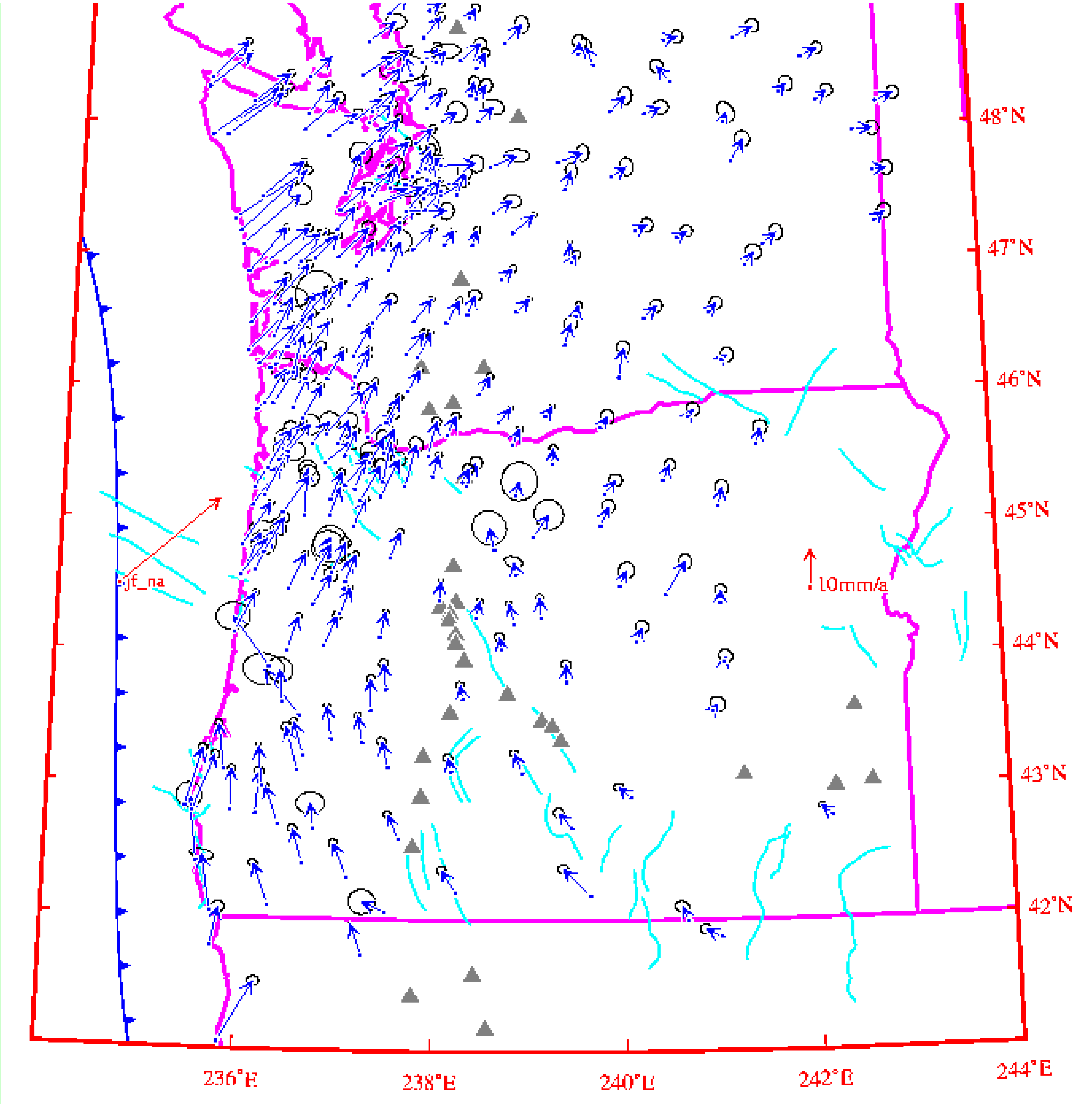
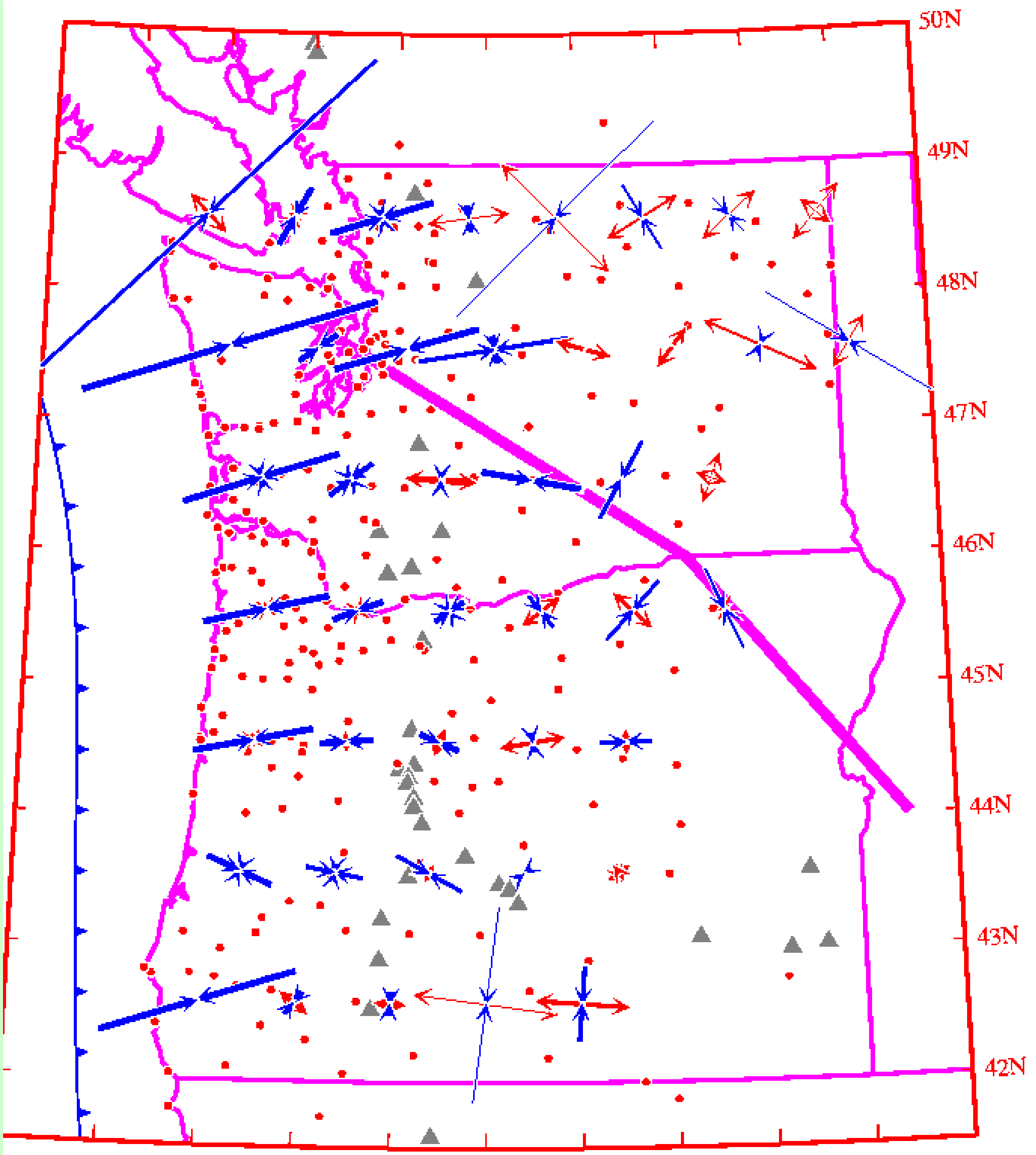


Figure 3. GPS site velocities in the North America reference frame. This view shows the strong rotation of western Oregon and Washington relative to North America. Error ellipses are 1-sigma. Red arrow at trench shows Juan de Fuca motion relative to North America.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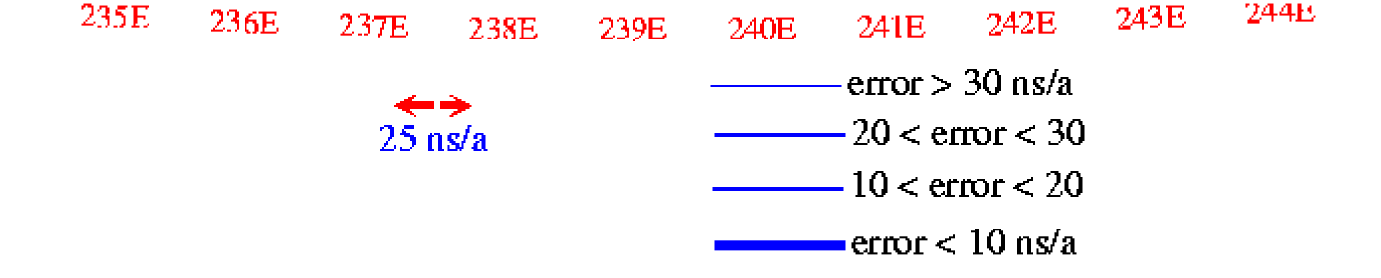
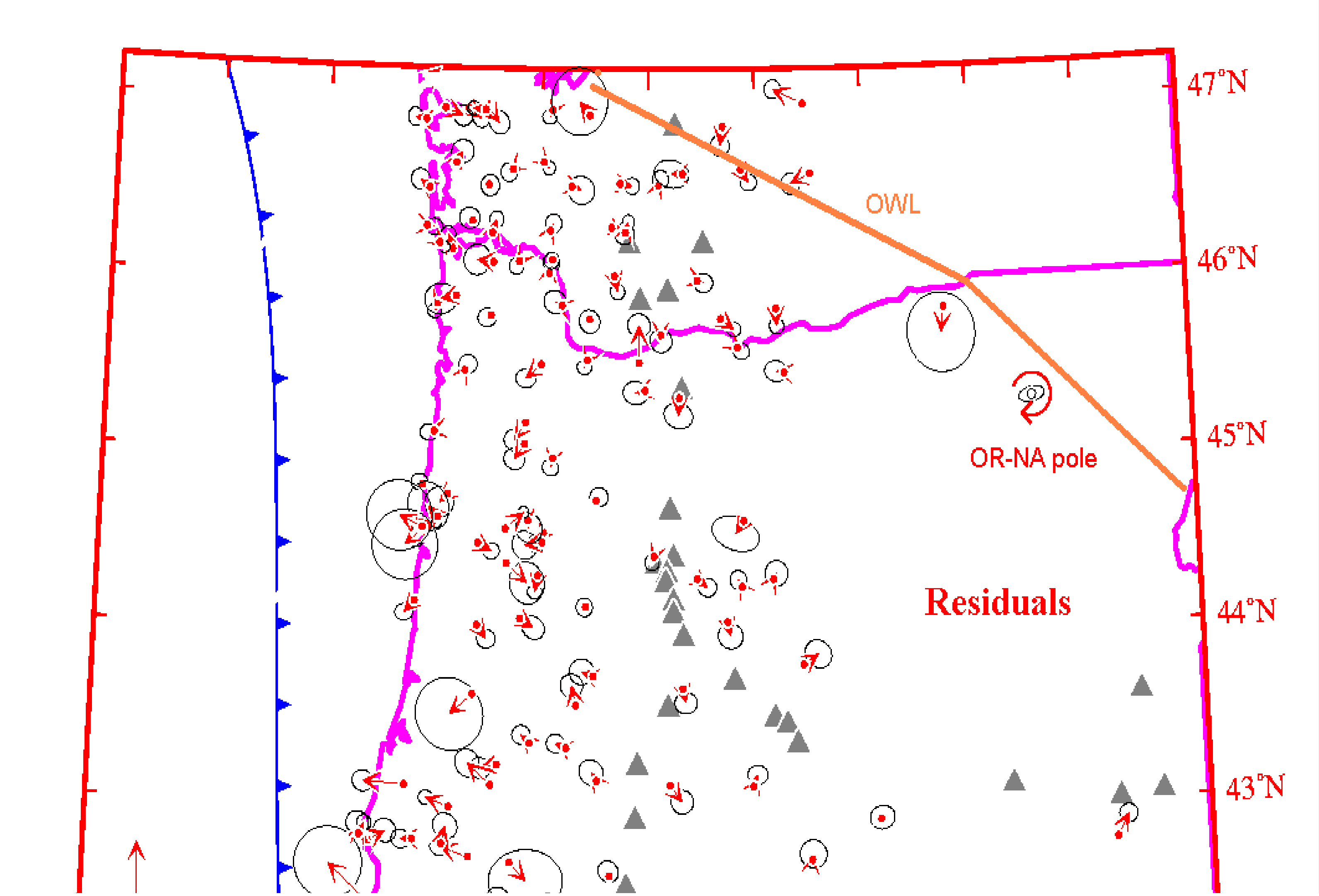


Figure 4. Principal strain rates estimated from GPS site velocities. Blue arrows show contraction directions and red are for extension. Thickness of arrows is related to uncertainty as given in scale (ns/a = nanostrain/year). Each strain rate tensor is estimated by weighted least-squares from the GPS velocities in a 1.4 x 1.4 degree region. Heavy purple line shows the Olympic-Wallawo lineament (OWL).



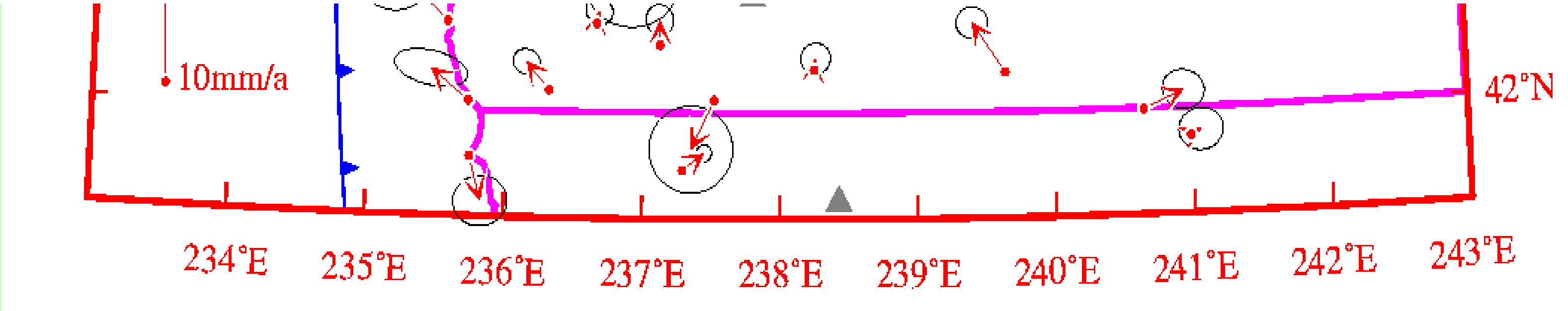
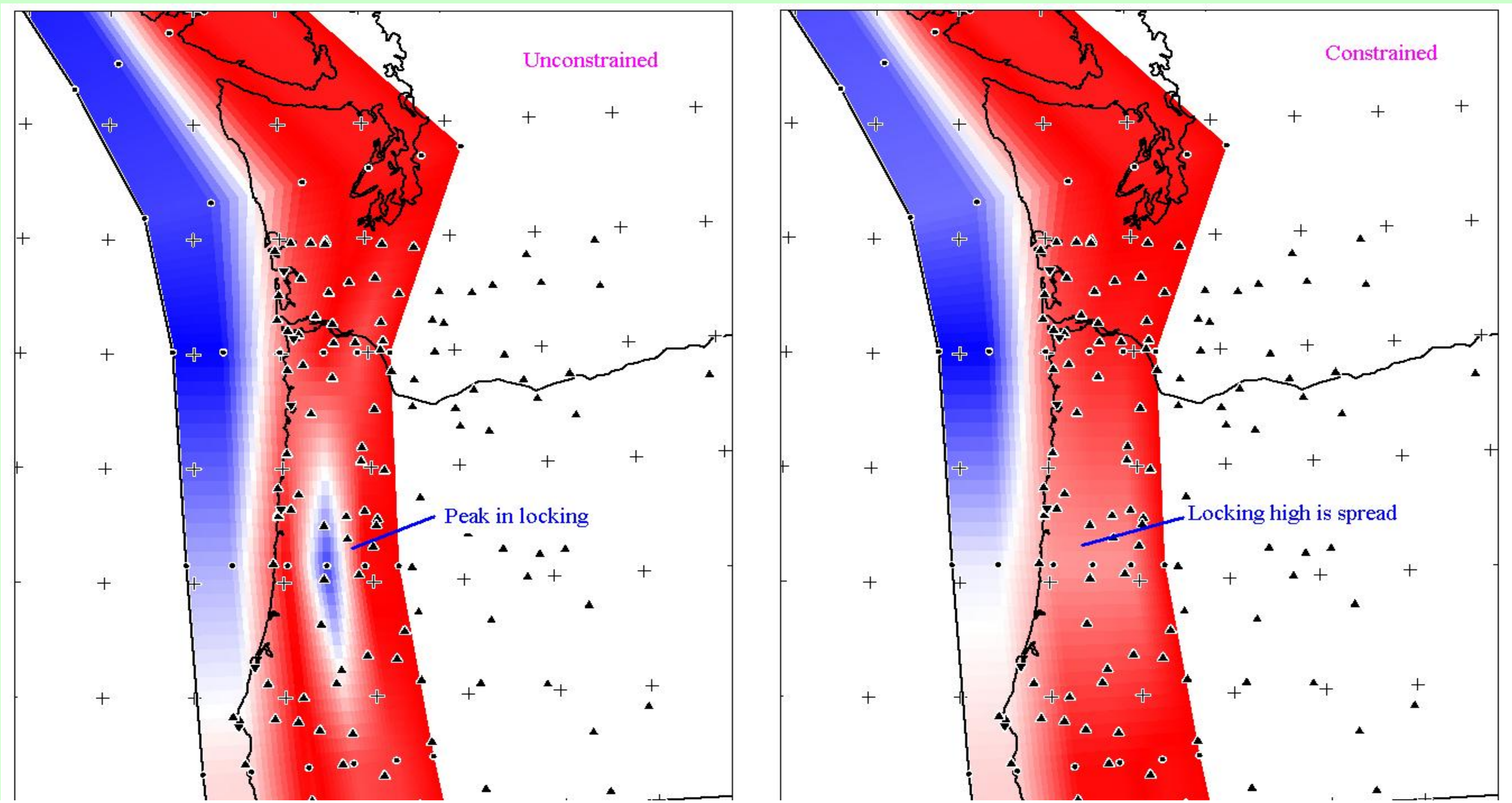


Figure 5. GPS residual vectors (1-sigma ellipses) for best-fit plate locking model based on inversion of GPS data from Oregon and SW Washington. Orange line shows trend of OWL. OR-NA pole is for the rotation of Oregon (SW of OWL) relative to North America. Rotation rate is -0.79 +/- 0.04 deg/Ma. Gray triangles show active volcanoes.



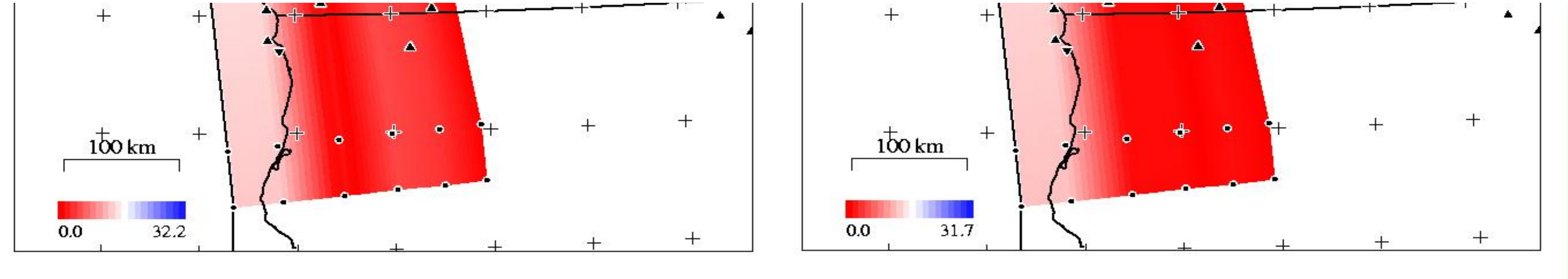
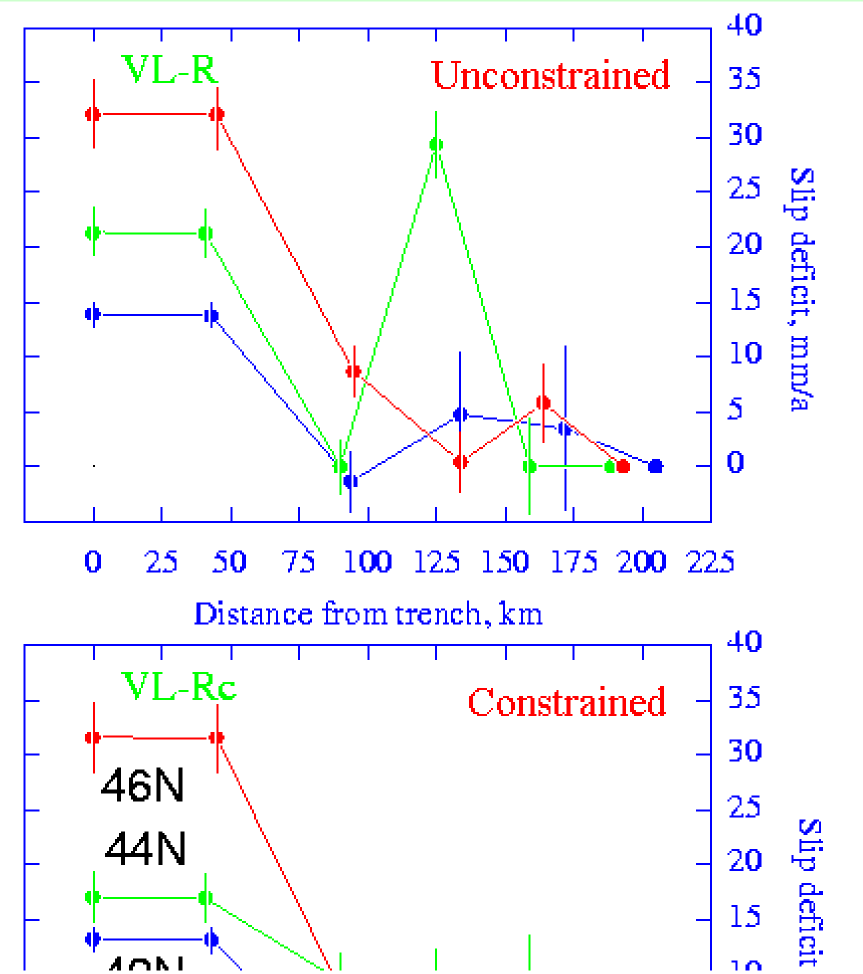


Figure 6. Best-fit plate locking models based on inversion of GPS (triangles) and uplift rates (inverted trianges). Model at left has no constraints on the distribution of locking while model on right is forced to have downdip decrease in slip deficit. Colored shading shows estimated slip deficit (rates given by scale bar at lower left). Dots show node locations on thrust fault. Nodes are aligned along depth contours every 10 km and are the parameters estimated in the inversion (from McCaffrey, 2002). Tic spacing is 1 degree.



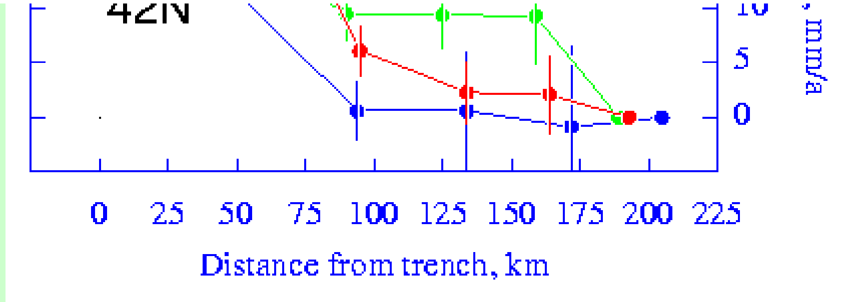


Figure 7. Profiles of the slip deficit estimated from inversion of GPS and uplift rate data. The profiles are E-W at 42N, 44N, and 46N across Oregon and show the slip deficit along the thrust surface with distance from the deformation front. The Unconstrained model (no constraints on node values) shows a large peak beneath 44N- when the slip deficit is constrained to decrease downdip (Constrained model) this peak broadens out. In either case central Oregon (44N) shows a deeper coupling profile than to the South and North (from McCaffrey, 2002).
