**Final Report**
**Earthquake Hazards Program Assistance Awards**

**USGS Award Number(s)**

G12AP20021 and G12AP20032.

**Title of award**

Contemporary strain rates across the Yakima fold-thrust belt estimated with GPS: Collaborative research with Portland State University and Massachusetts Institute of Technology

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**Abstract:** GPS observations were made in the Yakima fold-thrust belt (YFTB) of central Washington and northern Oregon in 2012 and 2013 with the goal of resolving in more detail the distribution of slip rates across the region. The results indicate that the YFTB is truncated along its eastern boundary by a zone of convergence, coincident with the 2009 Wooded Island swarm. While the YFTB shortens in a rotational manner, like a fan closing about a pivot to the east, the rate of deformation in the forearc, west of the Cascades, is faster than is expected if the forearc were part of the same mechanism. This suggests that there is some deformation along the Cascades that can accommodate the relative motion.

**Report**:

*Investigations undertaken*

We conducted GPS field work in September 2012 and September 2013 to occupy geodetic benchmarks within and around the Yakima fold-thrust belt (YFTB) of northern Oregon and central Washington State. Our target sites were those that had not been occupied within the past 10 years with the aim of obtaining site velocities with uncertainties as low as 0.3 mm/yr. The scientific goal is to understand the distribution of strain across the Yakima fold-thrust belt and its implications for earthquake hazards in western Washington. At the same time we established 13 new benchmarks (Table 1) to be used by future researchers to outline in more detail the deformation in the YFTB. The focus of the new sites was on the narrow zone of deformation that truncates the Yakima folds at their eastern end.

**2012 Field season**. We borrowed (at no cost) five high-precision field GPS units from the UNAVCO pool for six weeks from early September to mid October, 2012. The UNAVCO engineers were very helpful in fixing some small problems with the receivers. McCaffrey and Portland State undergrad Matt Lancaster were in the field 12 days and occupied 22 sites. King and a volunteer spent 10 days in the field occupying 15 sites. We established 5 new marks (Table 1) and made initial observations at them. Our proposed goal was to occupy ~60 sites so we were well on schedule.

**2013 Field season**. The field work in 2013 followed the same procedure as in 2012. We were able to re-occupy some sites that showed spurious results from our 2012 measurements, to occupy most of the remaining sites as originally planned and to establish 8 new marks (Table 1). However, we were unable to obtain permission to occupy several sites on the Yakama Tribal Lands, after more than 2 years of negotiations. Access to sites on Hanford facility land was done through Ray Clayton who helps with the Pacific Northwest Seismic Network. Walter Szeliga of Central Washington University occupied one site, WENA, for us.

We are now nearly finished processing the field data we collected along with data from continuous GPS sites in the region (the PANGA and PBO networks). We acquired data from USGS survey-mode lines in the area that were measured by Wayne Thatcher and colleagues. The processing is being done with GAMIT and GLOBK (Herring et al., 2010) largely in the manner described in McCaffrey et al. (2007).

Fig. 1 shows the sites we occupied and the regional continuous networks (PBO and PANGA). We were able to re-occupy most of the existing survey-mode sites (blue dots).

Fig. 2 shows estimates of the site velocities calculated in September, 2014. The data include the PBO and PANGA observation as well as our own survey observations.

The new velocities are much more systematic and have greatly reduced uncertanties relative to the previous field. One notable feature at this point is the abrupt change in the orientation of the velocity vectors from NE to NW along the NE edge of the YFTB (blue dashed line in Fig. 2). It suggests that shortening in the YFTB may be localized along this edge. This result was unexpected and was examined in more detail in the 2013 field season (re-occupying some sites and establishing several new ones along that trend).

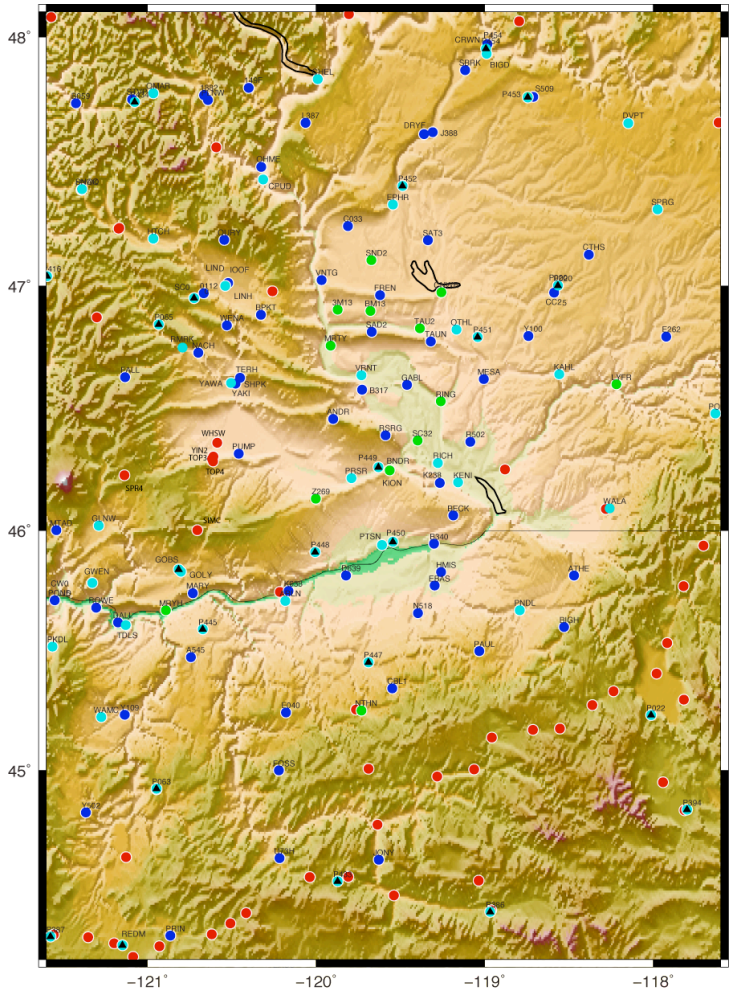


Figure 1. Map of the Yakima fold-thrust belt of Washington and Oregon showing GPS site locations. Blue dots show locations of GPS sites done by us in 2012 and 2013; green are new sites established by us in 2012 and 2013; turquoise dots are continuous GPS sites of the PANGA and PBO (with triangle) networks that we have included; and red dots are other survey-mode sites that we did not re-occupy (many in south are in 2010 USGS occupations we are processing).

Fig. 3 shows the same velocity field but now in an Eastern Washington reference frame, obtained by finding a pole of rotation of E Washington relative to North America and removing it from all site velocities. This perspective allows a clearer picture of the eastward motion of the sites in the YFTB relative to eastern Washington. These results suggest that the YFTB deformation is truncated at its

eastern edge by a ~E-W directed convergence zone. A swarm of earthquakes occurred along this line in 2009 and are consistent with NE-directed thrusting (Fig. 4) (Blakely et al., 2011; Wicks et al., 2011). The GPS results suggest that those earthquakes are tectonic in nature and may be part of a ~200-km-long continuous feature that could produce a large earthquake close to the Hanford facility. The slip rate across the convergence zone inferred from GPS is about 1 mm/yr.

As we observed earlier (McCaffrey et al., 2013), the rate of south-to-north shortening across the YFTB increases from east to west (Table 2). Thus the YFTB deforms in the manner of a fan closing with its pivot in eastern Washington. Along longitude 123W in the forearc the shortening is 3.6 mm/yr and this drops to 2.0 mm/yr along the arc (122W longitude). To the east the drop in rate is about 0.5 mm/yr for each degree of longitude (Table 2). The big drop across the arc indicates that deformation in the forearc is faster than expected if the forearc were an extension of the rotational closing of the YFTB.

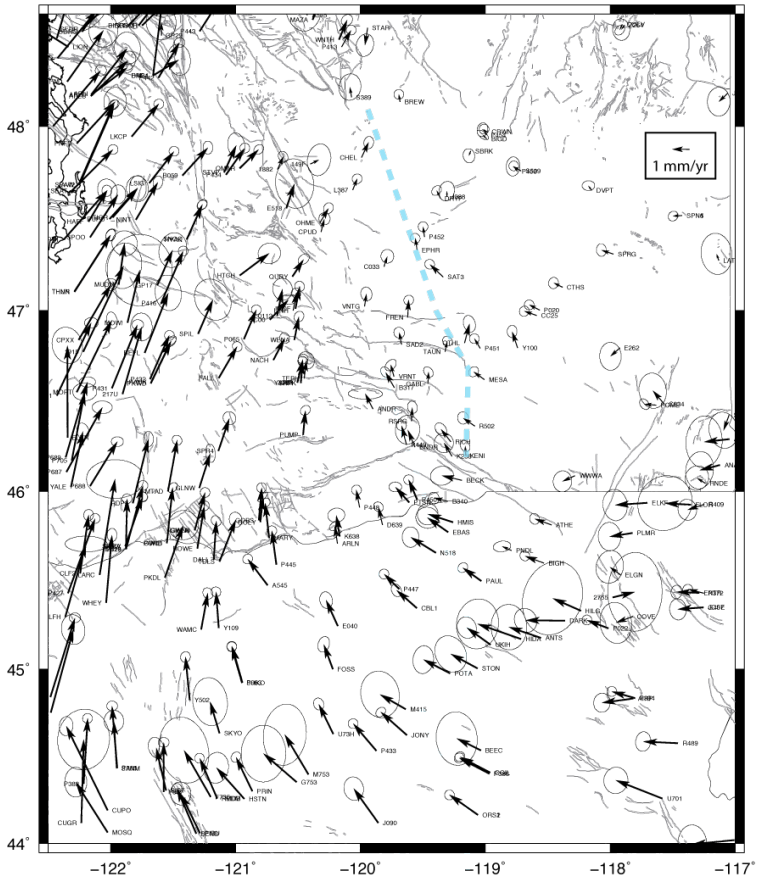


Figure 2. Velocities relative to North America with 70% confidence ellipses. Blue line shows abrupt change in velocities at the eastern margin of the fold-thrust belt.

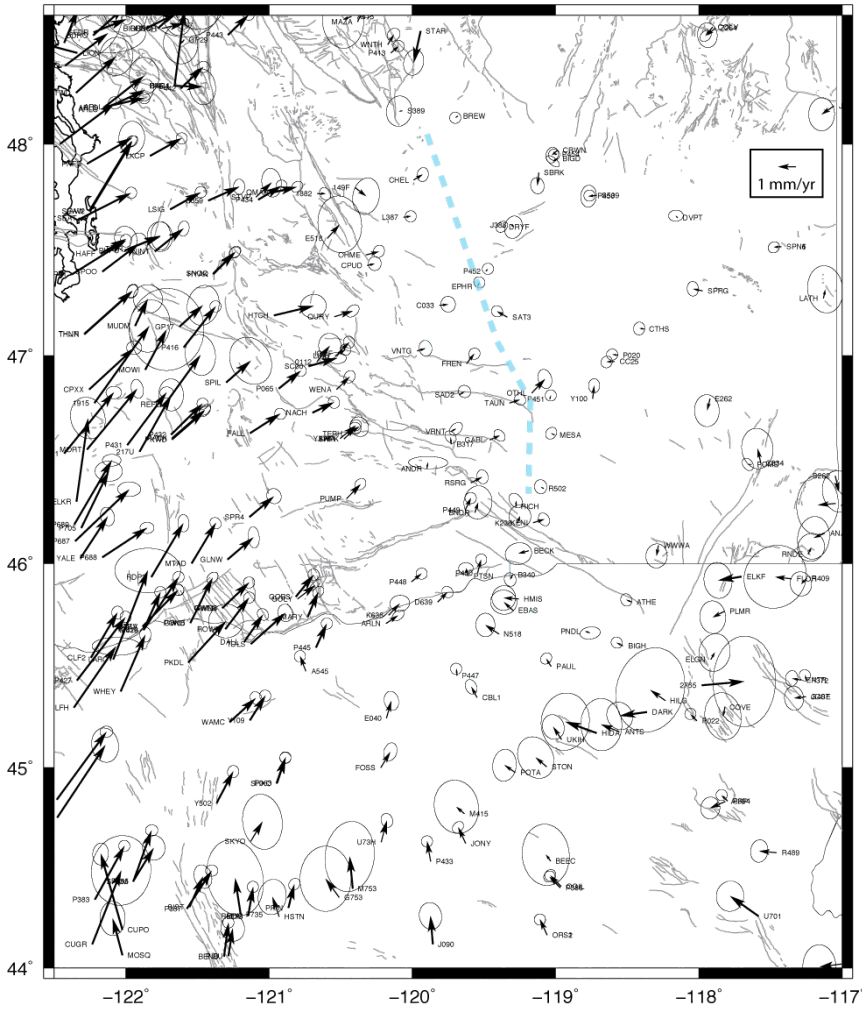


Figure 3. Velocities relative to eastern Washington with 70% confidence ellipses. Blue line shows abrupt change in velocities at the eastern margin of the fold-thrust belt where sites west of the line move east relative to east Washington. This suggests some ~E-W shortening truncates the folds of the YFTB.

The results of preliminary block modeling are shown in Fig. 5. The map shows the residuals for the velocites (black vectors with 70% confidence ellipses) and the estimated slip rates along the block boundaries. The methods of the block modeling are described in detail in McCaffrey et al. (2007; 2013) and are not repeated here. For this model we included block boundaries along most of the mapped faults, and connected them from the YFTB through the arc to the Puget Lowlands following Blakely et al. (2011). This connection is not completely obvious and we will model other possibilities in the final product.

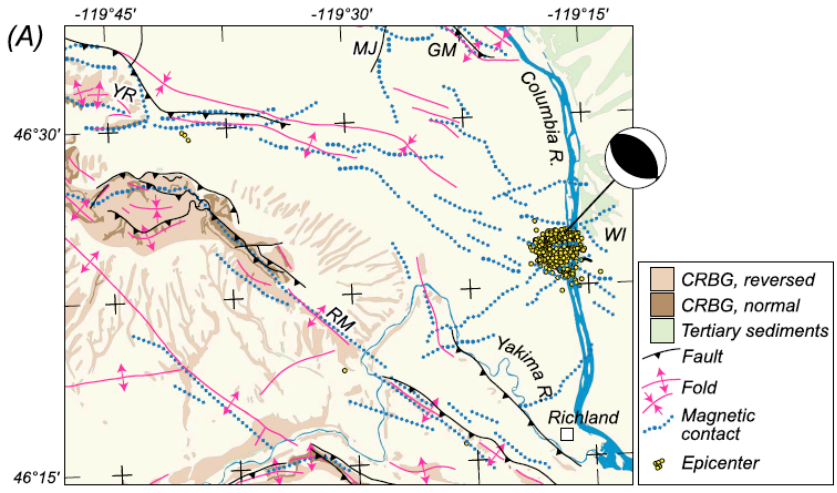


Fig. 4. Location and mechanism of the Wooded Island swarm (from Blakely et al. 2011). The change in GPS velocities and the inferred shortening zone runs through the swarm and suggests a similar mechanism.

*Problems encountered*

Two sites, in Walla Walla, WA (code WALA) and Peshastin, WA (code E518), were not recoverable (destroyed). We were unable to access sites TOP3, TOP4, YIN2, SPR4 and SIMC (Fig. 1) that are on Yakama Tribal Lands.

*Data availability*

GPS field data (raw and rinex form) and logsheets collected for this project are archived at UNAVCO (see Bibliography for data DOI). Final velocities will be included in publications.

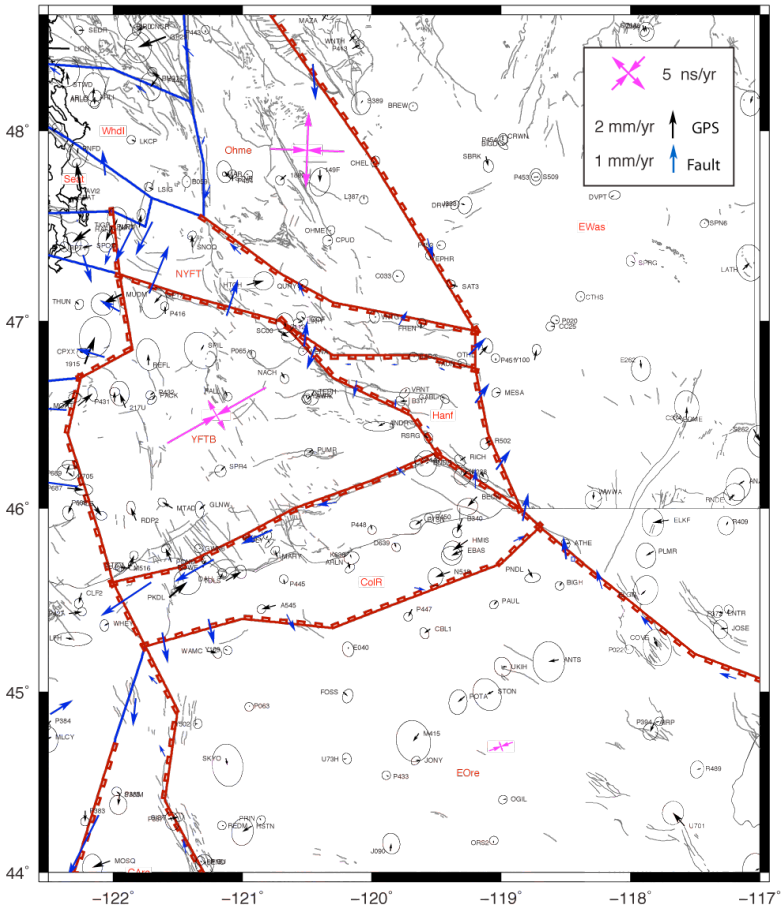


Fig. 5. Preliminary block model of the Yakima fold-thrust belt based on GPS observations. GPS vectors (black) are residuals relative to the model and have 70% confidence ellipses. Blue vectors show fault slip directions and rates as motion of hanging wall (with barbs) relative to footwall (if the vector has a component pointing toward the fault it is compressional). Purple opposing arrows are strain rate estimates for selected blocks; the scale is in nanostrain/yr = $10^{-9}$ /yr. Thin black lines are mapped faults.

Table 1. New survey-mode sites

| Site code | Longitude | Latitude | Elevation, km | Date started |
|---|---|---|---|---|
| 3M13 | 240.1271 | 46.9040 | 0.3528 | 2012.705 |
| BM13 | 240.3215 | 46.8989 | 0.3383 | 2013.714 |
| CNWR | 240.7428 | 46.9741 | 0.2858 | 2013.714 |
| KION | 240.4358 | 46.2475 | 0.6027 | 2012.705 |
| LYFR | 241.7811 | 46.5996 | 0.1711 | 2012.705 |
| MRTY | 240.0856 | 46.7569 | 0.2035 | 2013.714 |
| MRYH | 239.1093 | 45.6686 | 0.2189 | 2012.705 |
| NTHN | 240.2677 | 45.2514 | 0.7778 | 2012.705 |
| RING | 240.7397 | 46.5298 | 0.2474 | 2013.714 |
| SC32 | 240.6011 | 46.3700 | 0.1132 | 2013.714 |
| SND2 | 240.3284 | 47.1041 | 0.3444 | 2013.714 |
| TAU2 | 240.6144 | 46.8274 | 0.1721 | 2012.705 |
| Z269 | 239.9987 | 46.1305 | 0.5725 | 2013.714 |

Table 2. Rate of shortening north of 44N across the YFTB at different longitudes.

| Longitude | Rate, mm/yr |
|---|---|
| -123 | 3.6 |
| -122 | 2.0 |
| -121 | 1.5 |
| -120 | 1.2 |
| -119 | 0.7 |
| -118 | 0.5 |

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Wicks, C., W. Thelen, C. Weaver, J. Gomberg, A. Rohay, P. Bodin, (2011). InSAR Observations of Aseismic Slip Associated with an Earthquake Swarm in the Columbia River Flood Basalts, J. Geophys. Res. 116.

**Miscellaneous notes on GPS sites**

**TAUN**
On land of D M Ranches, 2516 W. Highway 26, Othello WA
Owner: Dwayne Michel 509-488-9819
Darin Michel (509-989-2000) for permission and combination to lock on gate.
Gate at intersection of Kuhn Road and Bench Road (46 47.536'N, 119 20.147W). 2.6 mile drive, ~15 minutes, need 4WD

**ANDR**
Anderson Land & Livestock Co. 2240 Lewandowski Rd., Sunnyside WA
Owner: Richard Anderson 509-837-5111. Cell 509-840-4033
Mr Anderson told us to go in at gate on Hwy 241. Gate is 8.8 miles north of Lewandowski Rd along Hwy 241, just south of mile 19 marker. No locked gates, about 2.2 mile drive up to the site, need 4WD.

**GABL**
Observed by Ray Clayton 509-554-9959, ray.clayton@pnnl.gov

**RSRG**
Access through Ray Clayton.

**FREN**
Access is unrestricted. Come in from the south, from Royal City. North on Royal Road which turns into Road G SW, left on Royal Slope Rd SW then quick right on Road G.5; after 0.7 miles turn right on second dirt road after crossing the aqueduct. Follow east then climb up around the grape fields; head east again to the mark near the towers. There are reference marks but the main mark is north of the gravel road. Owner of nearby vineyard is Mr Justin Brown

**HMIS**
Hermiston Airport, along runway. Call ahead 541-567-3694

**MRTY**
On property of Marty Charvet, 23001Hwy 243 South, Mattawa. 509-831-6026

**RING**
Access through an orchard, asked at the house for permission. Roads through the orchard can be slippery when they are watering. Could walk from the house, ~400 meters if necessary.

**SAD2**
Long drive (10 miles) on gravel and sand roads, need 4WD. Gate at north end of Road O is open. Sign says no public access, ignore it.