Final Technical Report USGS Cooperative Agreement for Geodetic Monitoring Operations

Geodetic Monitoring Project Name:
Operation and Maintenance of the Wasatch Front, Utah, GPS Network (Monitoring, Upgrades, Data Recording, and Processing)
Operator: University of Utah

Cooperative Agreement Number: 07HQAG0027

Principal Investigator: Robert B. Smith

Geodetic Project Web Sites:
http://www.uusatrg.utah.edu/
http://www.uusatrg.utah.edu/ts_wasa.html
http://www.uusatrg.utah.edu/RBSMITH/public_html/RESEARCH/UUGPS.html

Term covered by report (all 3 years): 03/01/2007 to 02/28/2010

Focus of Operations
The University of Utah's Wasatch Front, Utah, GPS network monitors ground deformation across the Wasatch fault and other large faults. The Wasatch fault is a major seismogenic structure that has experienced at least 17 paleoearthquakes, 6.8<Mw<7.1, in the past 5,600 years. The earthquake hazard is associated with high earthquake risk, for 80% of the state's 2.7-million population lives within 50 km of the Wasatch fault. Understanding fault dynamics is key to evaluating earthquake hazards, and GPS data comprise an important component of fault studies.

Project Summary and Main Accomplishments
The final technical report for Year 3 of the Cooperative Agreement evaluates regional deformation and earthquake hazard of the Wasatch Front, Utah, including large regional faults that pose a hazard to Salt Lake City, Ogden, and Provo. These faults include the segments of the Wasatch fault, the East Great Salt Lake fault, East Cache fault, and Hansel Valley fault. This project was conducted within the framework of the USGS National Earthquake Hazards Reduction Program.

This project requires the integration of various types of data into the earthquake hazard evaluation: paleoearthquake slip rates, historic seismicity, and geodetic data. The geodetic component is obtained from processing the University of Utah network of 6 GPS stations, supplemented by 50 stations from the Plate Boundary Observatory (PBO) and 4 stations from the National Geodetic Survey (NGS)(Fig. 1). University of Utah GPS data are transmitted daily to the UNAVCO archive and are web accessible to any user. The permanent GPS station data are supplemented by multiple campaign-style GPS measurements. Together these geodetic data allow the determination of contemporary fault loading rates.

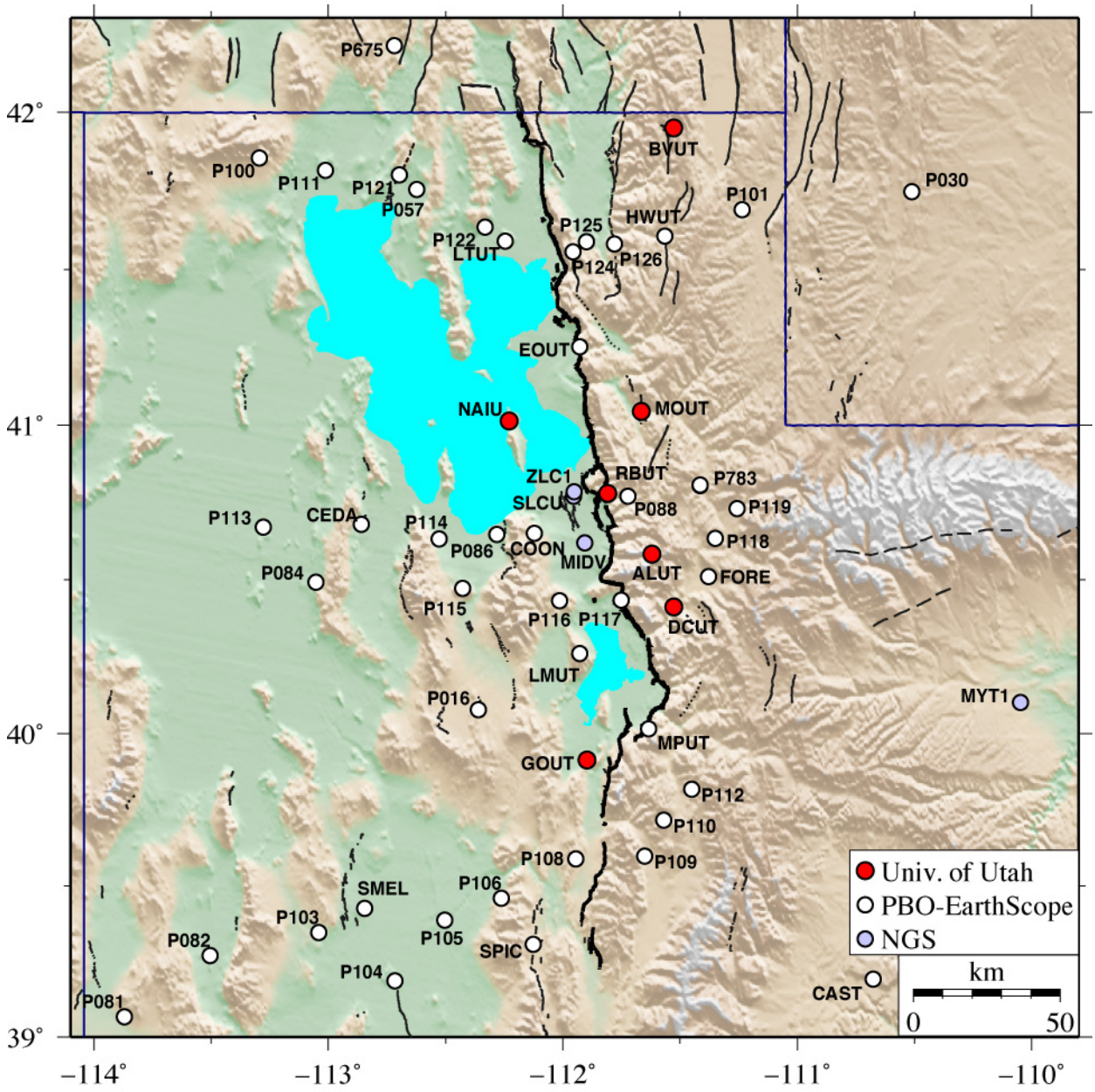

Figure 1. Index map showing the distribution of permanent GPS stations in Utah. Sites operated by the University of Utah are shown in red.

The University of Utah has routinely processes the 60 stations in the Utah region, including those supported by the USGS, PBO stations and some other agency station. We employ the Bernese 4.2 GPS processing software. In late 2009 and early 2010, a Dell PowerEdge R410 computer was purchased and installed at the Center for High Performance Computing for faster and more reliable processing. The Bernese 5.0 software was successfully installed on the new computer and has been processing the GPS data concurrently with Bernese 4.2, that will eventually replace Bernese 4.2. In the data processing scheme, the precise (final) GPS orbit data, available with a ~10-day latency, are acquired from International GNSS Service (IGS).

Daily processing solutions are combined to create GPS station time series, updated monthly, and ground velocity maps, updated every 4-6 months. These data products are posted on the University of Utah Seismology Research Group (UUSRG) web page at http://www.uusatrg.utah.edu. As an example of our data, Fig. 2 shows the GPS time series for some of the stations in the Wasatch Front area. Fig. 3 shows the velocity vectors for the network.

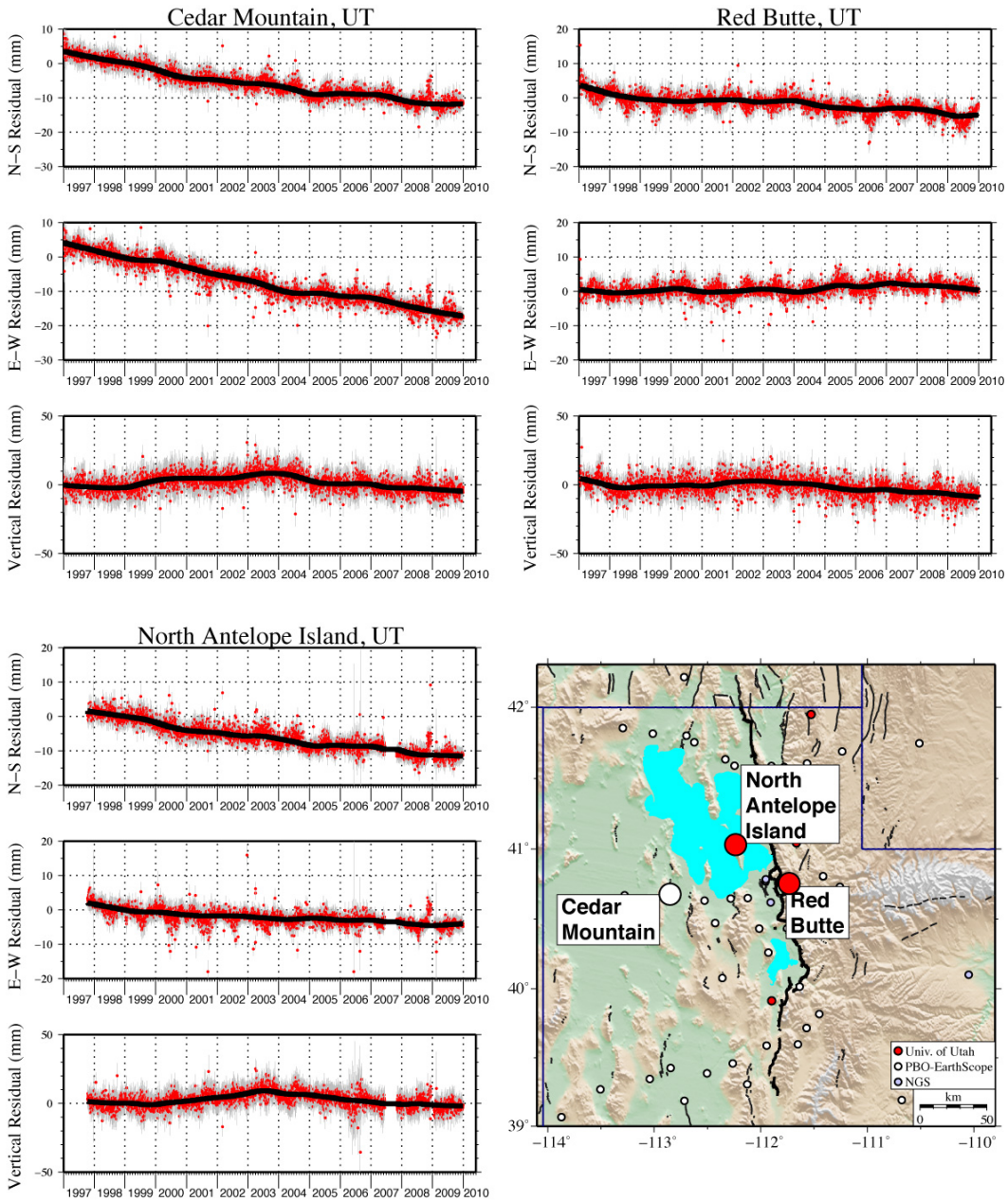

Figure 2. Examples of GPS-derived time series for selected long-operating stations in the University of Utah network. The time series show the change in position over time for two horizontal components (north-south and east-west) and the vertical component.

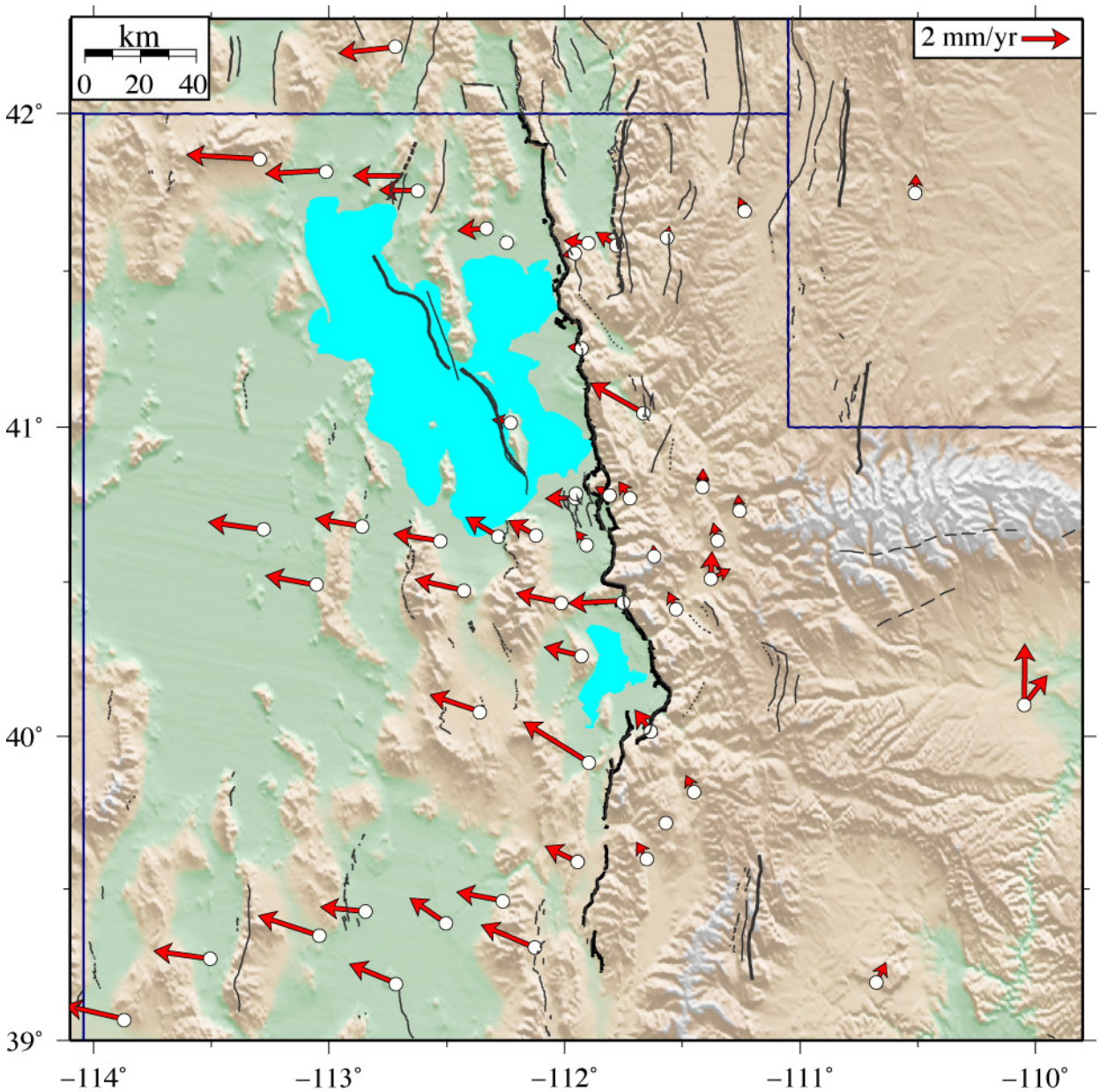

Figure 3. GPS-derived horizontal velocity vectors for the Wasatch Front, Utah, 2007 to 2009.

Coordinate solutions are saved in SINEX-formatted files that can rigorously be combined with solutions determined by other institutions using different processing software.
For redundancy of different methods, the EarthScope PBO GPS system processes four of our six stations as well as the Basin-Range PBO Extensional network and data of the BARGEN network. This multiplicity of different processing schemes is needed to assure data quality and reliable solutions.

The Utah GPS data are employed in probabilistic seismic hazard modeling by converting the deformation rates to equivalent seismic moment rates and comparing the results to historic earthquake rates and geologically determined fault-loading rates. Velocity data are plotted in profile across segments of the Wasatch fault to constrain the distribution of deformation. Strain

rates are interpolated to

Work Performed During the 3-Year Award Period
Since the start date of the Cooperative Agreement, our efforts have included:

- Operating and maintaining six permanent stations. An additional six stations were transferred to PBO management in 2008. However, the University of Utah still assists with maintenance of PBO stations.
- Installation of a new station in the Wasatch fault hanging-wall at the Deer Creek, UT (DCUT, summer of 2008). This station is needed to provide deformation information on the lateral E-W extension of the Provo segment of the southern Wasatch fault.
- Installation of a new station in the Wasatch fault hanging-wall at the Morgan, UT (MOUT, summer of 2008). This station is needed to provide deformation information on the lateral E-W deformation of the Weber segment of the southern Wasatch fault.
- Planned installation of a new station in northern Utah at Beaver Mountain, Utah-Idaho border in spring 2010. This station will provide coverage necessary to help resolve deformation of the East Cache fault to the east of the Brigham City segment of the Wasatch fault.
- GPS data processing of a total of 60 stations encompassing the Wasatch fault (Fig. 1), including 6 from the University of Utah, 50 from the EarthScope PBO network, and 4 from other cooperative CORS stations. Updated time series of these stations are posted on our website: http://www.uusatrg.utah.edu/ts_wasa.html, as are velocity plots (Fig. 2, 3)
- Our level 1 raw GPS data are transmitted daily to the UNAVCO archive center and are web accessible to any user in near-real time: http://facility.unavco.org/data/gnss/per_sta.php.
- Presented invited and contributed papers on our research that used data from the Utah GPS network at the following scientific meetings:
  1. 2008 fall meeting of the American Geophysical Union
  2. 2008 Geological Society America National meeting
  3. 2009 fall meeting of the American Geophysical Union
  4. 2009 Geological Society America National meeting
  5. 2008 Utah Quaternary Fault Parameters and Ground Shaking Workshop
  6. 2008 Utah Ground Shaking Working Group meeting
  7. 2009 Utah Quaternary Fault Parameters Working Group Meeting
  8. 2010 Utah Quaternary Fault Parameters Working Group Meeting
  9. 2007 EarthScope National Meeting
  10. 2008 UNAVCO Science Meeting
  11. 2009 EarthScope National Meeting
- Organized and assisted with planning of the eastern Basin-Range part of the PBO network, including the Wasatch fault. The University of Utah has assisted PBO engineers with siting and permitting issues for their sites in northern Utah (Fig. 1).
- Assisted with planning of the 2008 EarthScope LIDAR study of the Wasatch fault that will include use of GPS data for registration of the radar imaging.

Data Management Practices
All University of Utah continuous GPS observed data are made available to the interested user and public in near real-time via the Internet. The data are sampled in 30-second intervals and downloaded hourly, archived in RINEX format at the UNAVCO (University NAVSTAR Consortium) data management center, Boulder, Colorado at http://facility.unavco.org/data/gnss/perm_sta.php.

University of Utah processed GPS data are also posted on our own website at http://www.uusatrg.utah.edu/ts_wasa.html. Interpretative-level research products including ground motion vectors, error analyses, etc. are available on our website http://www.uusatrg.utah.edu/wasvels.html.

An important local user component of our GPS monitoring provides the surveying community with our data for base station referencing via access to our data at the UNAVCO data web site. In addition, daily GPS data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network.

Continuity of Operations and Response Planning

The University of Utah operates the GPS recording facility in parallel with the University of Utah Seismograph seismic network. As reported in our last annual report, we proposed an effort for the Utah GPS data and recording "Continuity of Operations" that is similar to that planned for the Utah and Yellowstone seismic networks. The primary goal of that plan is to ensure that data can be retrieved and processed either by University of Utah personnel or an outside entity following an interruption to normal operations. However, we specifically note that no funds were made available for this project.

As a reminder for our Continuity of Operations plan, we proposed in our 2007 proposal to the USGS GPS management office a design for "Continuity of Operations" plan for two scenarios: (1) an incident preventing access to our Utah GPS data while leaving the facilities intact and functional (e.g., telemetry links down, major road closures, etc.), and (2) an incident that renders the University of Utah facilities inoperable. For the first scenario (facilities intact) we proposed to develop methods for working remotely (e.g., from home or another office). For the second scenario (facilities inoperable) we are developing automated systems to continue data collection and distribution for at least a subset of our stations.

The Utah GPS network now has limited capabilities for continuity of operations including:

- Diverse but no redundant telemetry routing.
- An uninterruptible power supply (UPS) for our computer recording systems
- If we still need these items, then they shouldn't be listed with the available capabilities above:
- Need for larger battery and solar systems for field stations.
- Need for high-speed Internet connections in the field for our staff.

To achieve the goal of an automated GPS recording system that continues collection and distribution of data when University of Utah facilities plans include:

- The installation of the new processing computer on the University of Utah Center for High Performance Computing now provides redundant recording and processing of our GPS data.
- The development of a failover site for collection and processing.
- Redundant GPS recording systems off-site of the University of Utah, preferably at a remote location such as the to-be-identified national earthquake response office. This would provide redundant recording system. For this purpose we are in negotiations with PBO for

processing all of the Utah data in parallel with the University of Utah processing all of the PBO data.

As noted, no funds have been provided for the Continuity of Operations tasks, thus little progress has been made on it.

We recommend that a coordinated USGS effort be made to develop these types of plans with technical support for all the USGS funded efforts. Following that plan, a possible unified scheme done by a single entity would assist us with software and hardware development as well as being cost effective.

We also are interested in high-rate GPS streaming as well as near real-time GPS processing that we believe are important for monitoring precursor and immediate post-seismic event measurements. However we realize that these are multiple institution goals that would best be achieved by the USGS NEHRP coordinated effort.

Problems or Concerns Encountered

We have not encountered any major logistical or technical problems during the report period. However we continue to depend on local Internet providers at such sites as Morgan, Utah where we have to provide smart routers to use their network access (free to us). In addition, site permit requests are routinely delayed by federal agencies (BLM and Forest Service) because of their limited resources.

The Wasatch Front GPS network has been operating for thirteen years (1997-2009), beginning from a skeletal three-station network that is now up to a sixty-station array. Our seven continuous GPS sites (Fig. 1) are designed to operate in high-mountain, cold weather.

We emphasize that the mountainous winter environment of the Wasatch Range requires robust systems and redundant power supplies. Spread spectrum digital radio links to the University of Utah campus transmit the GPS data, which are then recorded on a Sun computer. Data are sampled at a 30-second rate.

Other Information and Comments

In addition to GPS monitoring, we also used the resulting GPS data of the Wasatch Front, UT, to determine the contemporary crustal loading rates based on the derived horizontal velocity field (Fig. 3). Our results show that the horizontal extension is up to 3 mm/yr across the Wasatch fault, implying a loading rate of 5-6 mm/yr on a ~30° west-dipping, fault plane at ~10 km deep. The high loading rate of this fault system, if assuming all of the stress is concentrated on the seismogenic fault, implies a higher earthquake ground-shaking hazard from the fault compared with that calculated only by historic seismicity and paleoearthquake data. Note that the 3-mm/yr rate is fully a fourth of the entire 12-mm/yr westward extension of the entire Basin-Range province.

In addition we began to examine the vertical component of deformation from the highest quality permanent stations (Fig. 4). These results revealed the following: 1) the unexpected subsidence of the Wasatch fault footwall, 2) laterally variable subsidence of the Wasatch fault footwall, and 3) the highest subsidence rates along the northern segments of the fault where fault stress interaction between the Wasatch and East Cache faults may be occurring.

Detailed E-W profiles of deformation (Fig. 4) clearly demarcate the high strain rate gradients across the Wasatch fault zone. The deformation pattern extends up to 100 km west of the fault, suggesting seismically quiescent slip on shallow dipping parts of the Wasatch fault likely in depths of ~10km. We point out that our USGS grant does not provide support for scientific studies of these phenomena, but they will be examined as time permits with existing University of Utah resources.

We also examined the rate of energy release by computing the equivalent seismic moment converted from the observed GPS-strain rate and compared it with the observed seismic moment rate released by earthquakes for the period 1975-2009 (Fig. 5 and Table 1). Moment release rates were calculated for three sections of the Wasatch fault: the north section includes the Brigham City and Weber segments, the central section includes the Salt Lake City and Provo segments, and the south section includes the Nephi and Levan segments. These results show the profound difference of observed strain that is on average 100 times larger than the seismic moment rate and implies that there is a large component of stored strain accumulating on the Wasatch fault, i.e. in preparation for a large future earthquake.

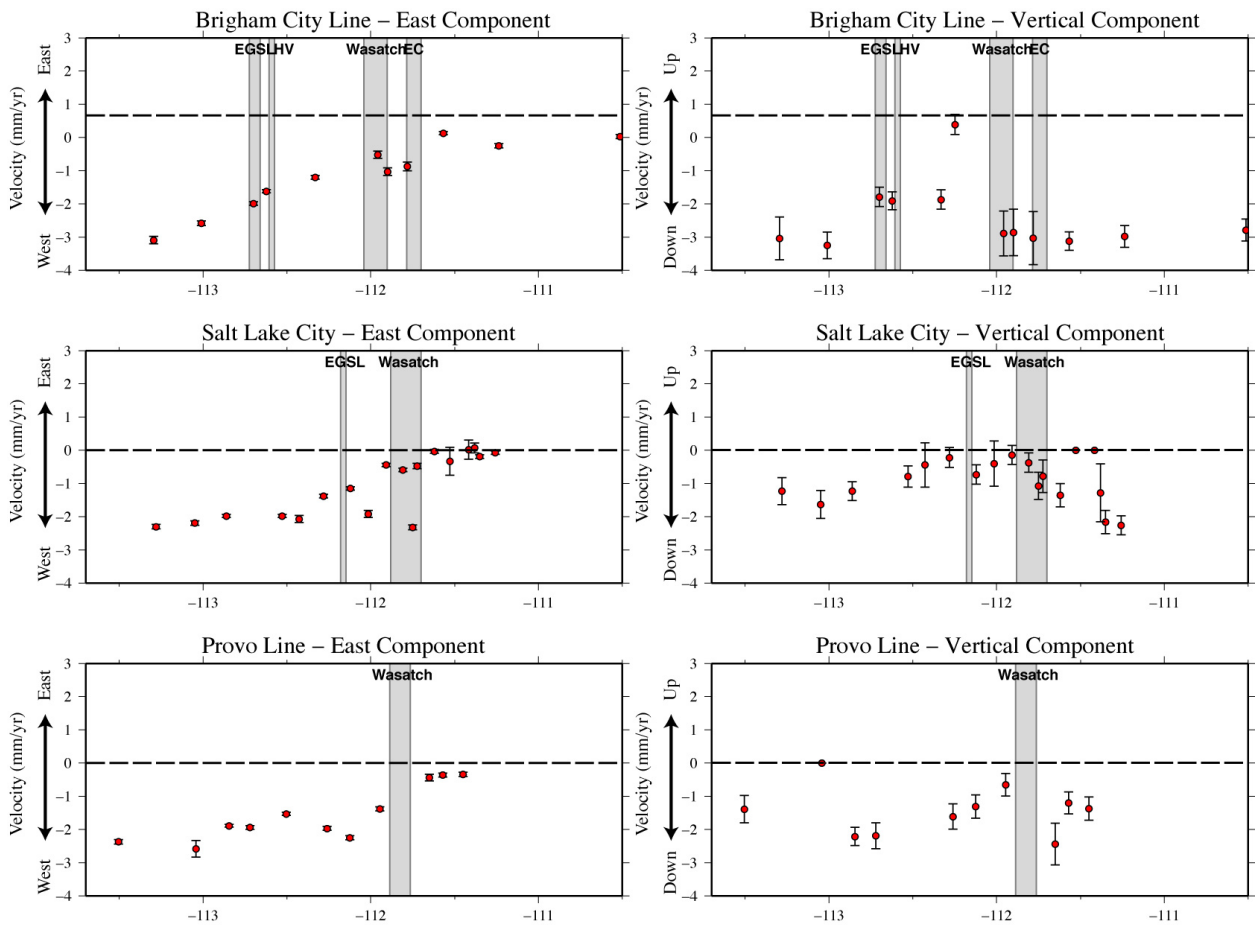

Figure 4. Westward (left) and vertical (right) ground motions across the Wasatch fault. Profiles are plotted for the three sections of the fault: 1) the north section includes the Brigham City and Weber segments, 2) the central section includes the Salt Lake City and Provo segments, and 3)

the south section includes the Nephi and Levan segments. Areas of the surface traces of major faults are shown in light gray.

Area of the Wasatch fault zone	Seismic Moment Rate (dyne cm/yr)	Total Moment Rate (dyne cm/yr)
North (Weber+Brigham City)	5.94×10^{22}	2.18×10^{24}
Central (Salt Lake City+Provo)	1.44×10^{22}	2.39×10^{24}
South (Nephi+Levan)	3.45×10^{22}	3.42×10^{24}

Table 1. Average moment release rate from earthquakes and GPS measurements. Earthquakes represent seismic slip on a fault; GPS data represent total moment release rates from all sources.

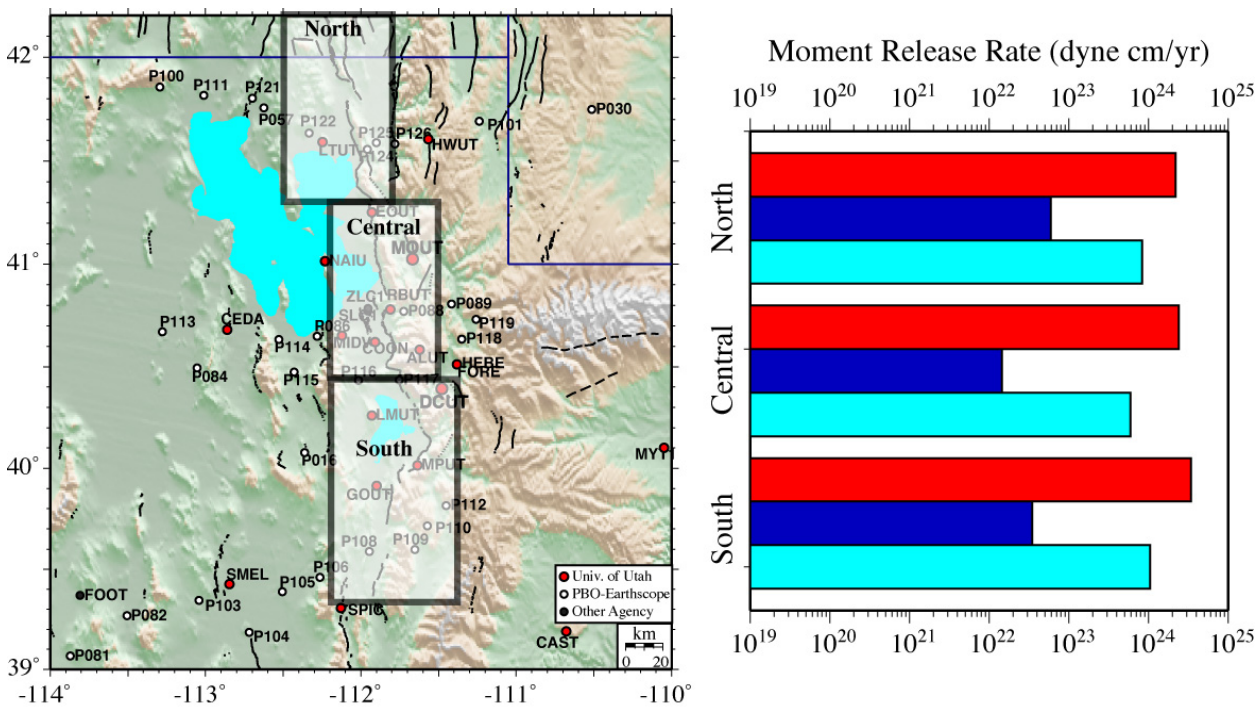

Figure 5. Average moment release from GPS measurements (red), seismicity (dark blue), and L. Quater. fault slip rates (light blue). Earthquakes represent seismic slip on a fault and are averaged over the period 1975-2009; GPS data represent the observation of the total moment release rates from all sources and are averaged over the period 1992-2009. GPS strain rates were obtained from kinematic modeling of western U.S. deformation.

Modeling of Western U.S. Deformation

A University of Utah postdoctoral fellow Christine Puskas has modeled the GPS-derived kinematics and dynamics of the western U.S. focusing on the Intermountain region (Puskas and Smith, 2009), including Utah and the Wasatch fault (Fig. 6). This science aspect of the project is

funded by sources external to the USGS grant, but for which we have employed the data from the USGS Wasatch fault study area. That study compiled more than 2,500 GPS-resolved velocity vectors converted to a common reference frame.

To evaluate the western U.S. GPS deformation data, two modeling approaches are employed: 1) a microplate tectonic deformation model, and 2) a continuum model. Horizontal components of the GPS velocities were combined with Late Quaternary fault slip data and focal mechanisms of M>6 earthquakes to model the deformation of the western U.S. interior. The microplate model divided the study area into blocks of homogeneous strain bounded by faults based on geologic history, faulting style, and seismic zones. The model resolved block rotations, velocities, and internal strain rates. A key result of this study was the identification of a general clockwise rotation of deformation of the western U.S interior resolved by the GPS data (Fig. 7, 8).

The general deformation pattern consists of westward extension, with a high gradient at the Wasatch fault, that continues across the Basin-Range tectonic province, transitioning to northwest-directed strike-slip motion in the western Basin-Range and California. Contraction and eastward motion was observed in Oregon and Washington while the Yellowstone-Snake River Plain volcanic province moved to the southwest, accommodating plate extension and SW flow from the Yellowstone hotspot high geopotential. High strain rates are associated with microplate boundaries, i.e. the zones of concentrated seismicity and thus earthquake hazard.

In this study we have incorporated the Wasatch Front GPS data in large-scale analyses of contemporary deformation of the Basin-Range and evaluated how it fits into the total deformation of the western U.S. In Fig. 9 we have determined the principal axes of the strain rate tensor derived from all available GPS data of the region. Notably the highest strain gradients are on the Wasatch fault with the highest rates in the southern segments. How these data can be used to augment the seismic hazard is a key problem of incorporating GPS with seismic and other data for probabilistic seismic hazard analysis.

Another key observation from these GPS data is the close correspondence in magnitude of intraplate deformation compared to pattern of historic seismicity and to the earthquake hazard. Fig. 10 shows the strain magnitude (derived by the second invariant of the strain tensor) compared to locations of larger earthquakes of the western U.S. and the new 2008 USGS PGA earthquake hazard map. The close correspondence of these highest strain rates with zones of highest seismicity and thus of highest hazard thus suggests the clear possibility that GPS data are a good proxy for earthquake-related plate deformation and fault loading. This is very important observation especially in areas of sparse data on fault slip and demonstrates the need to integrate GPS observations with USGS Earthquake Hazard assessments. From this comparison it is clear that there is a close correspondence in magnitude of intraplate deformation compared to the pattern of historic seismicity and to the earthquake hazard. This suggests that the GPS data can be used as a proxy for areas of relatively low seismicity and unknown fault slip rates in the USGS NEHRP hazard evaluations.

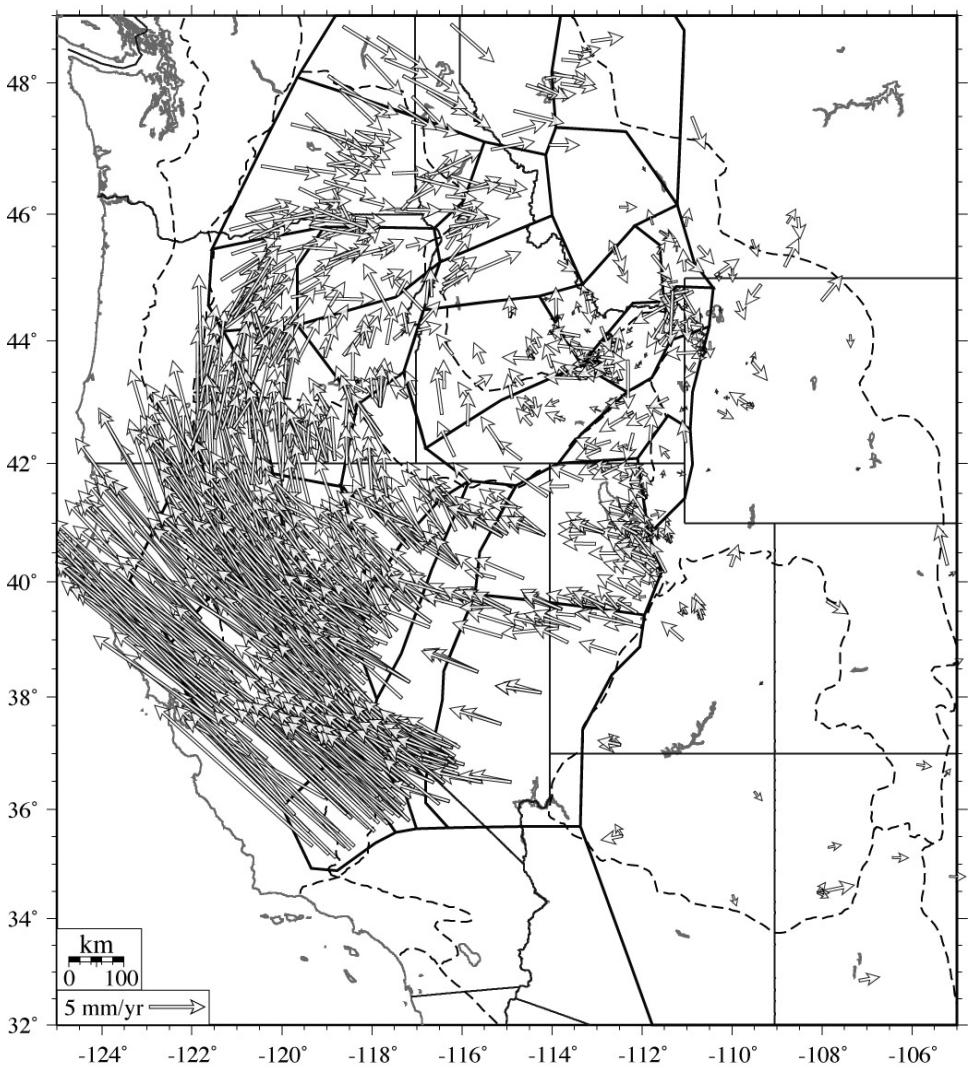

Figure 6. Western U.S. GPS velocities used to constrain block modeling. Data have been transformed into model reference frame (North America-fixed) through a Helmert transform. Velocities have been corrected for post-seismic effects following large, M>7 earthquakes.

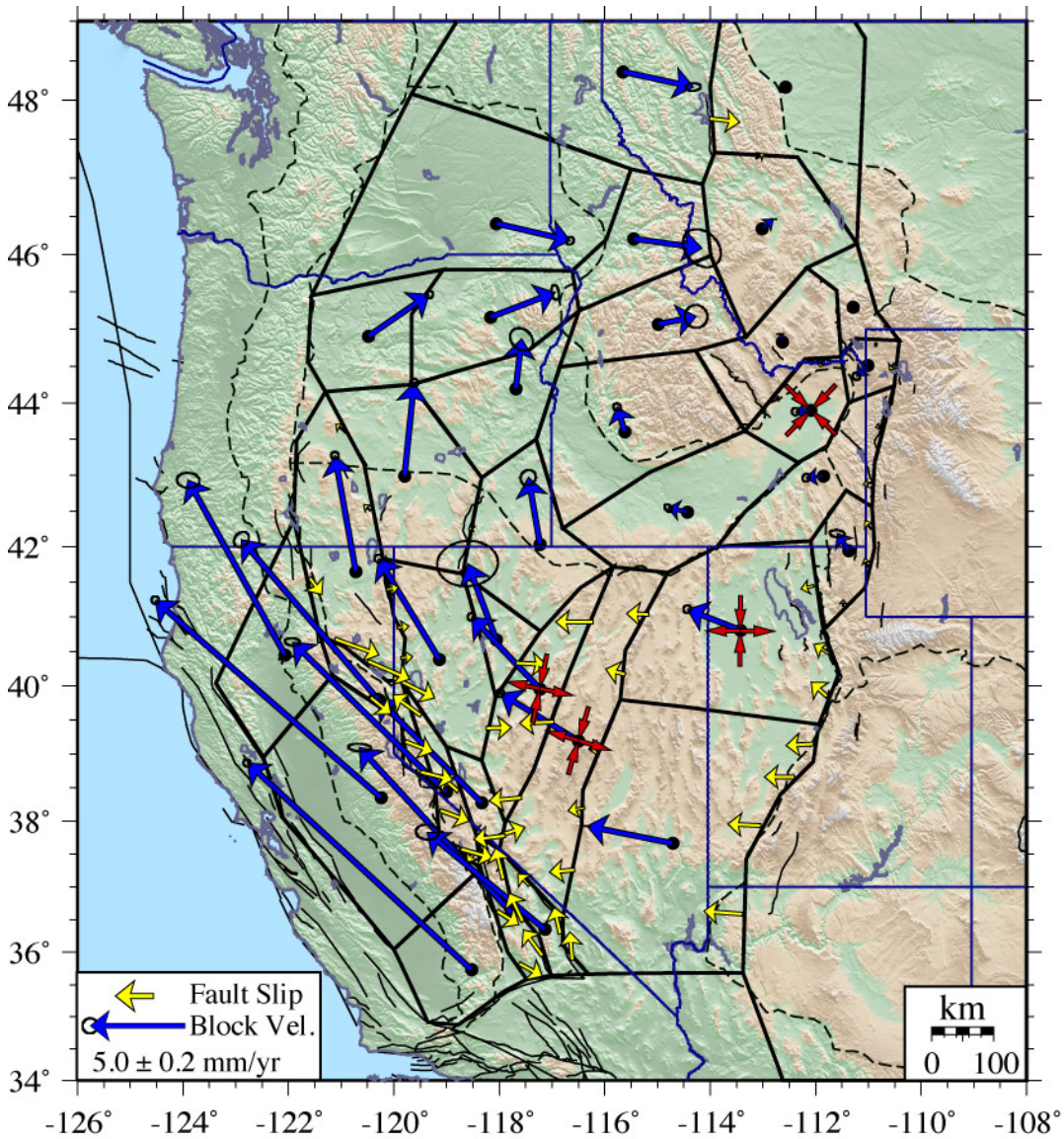

Figure 7. Block modeling results showing block velocities (blue) and fault slip rates at selected block boundaries (yellow). Modeled fault slip rates represent relative motion between blocks. Red crosses denote internal strain within blocks and are not to scale.

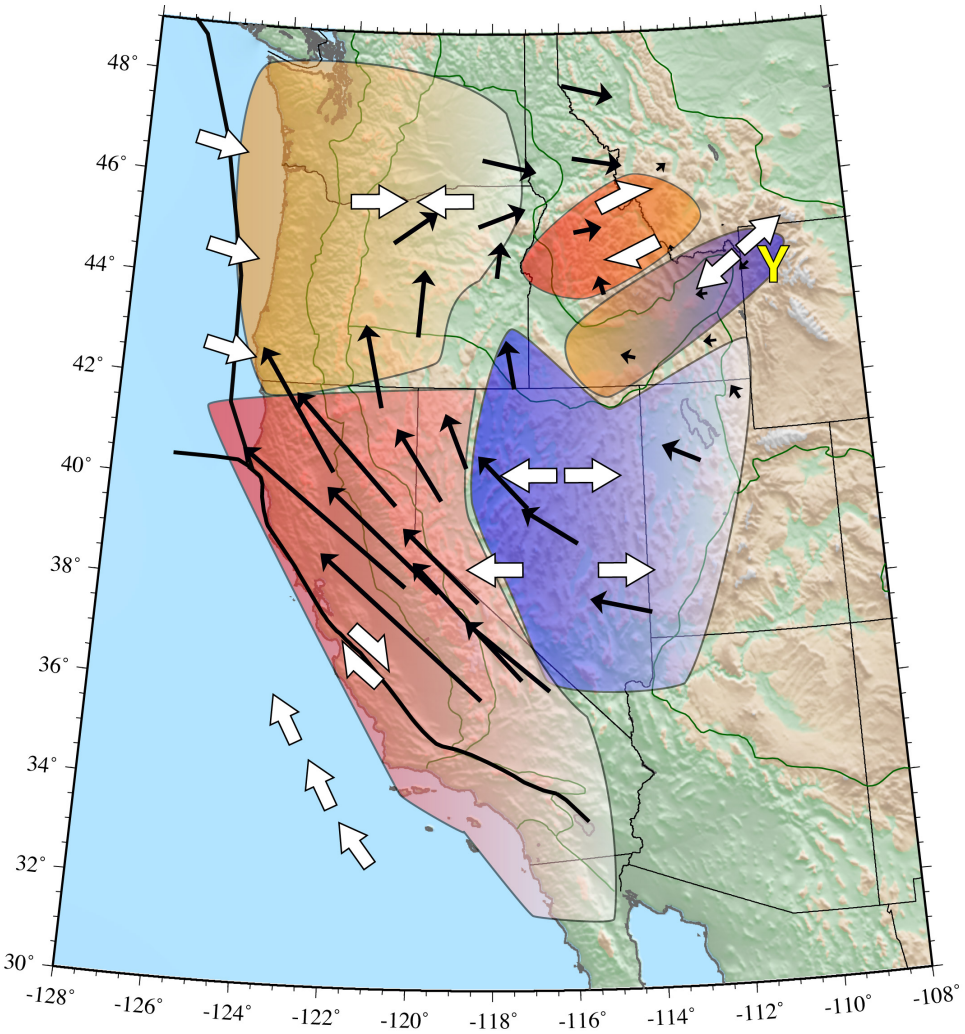

Figure 8. Summary of western U.S. contemporary deformation based on tectonic block modeling. Black arrows represent block velocities, while white arrows represent regional deformation styles. Colored regions different deformation regimes: blue=extension, red=shear, and orange=contraction (Puskas and Smith, 2009).

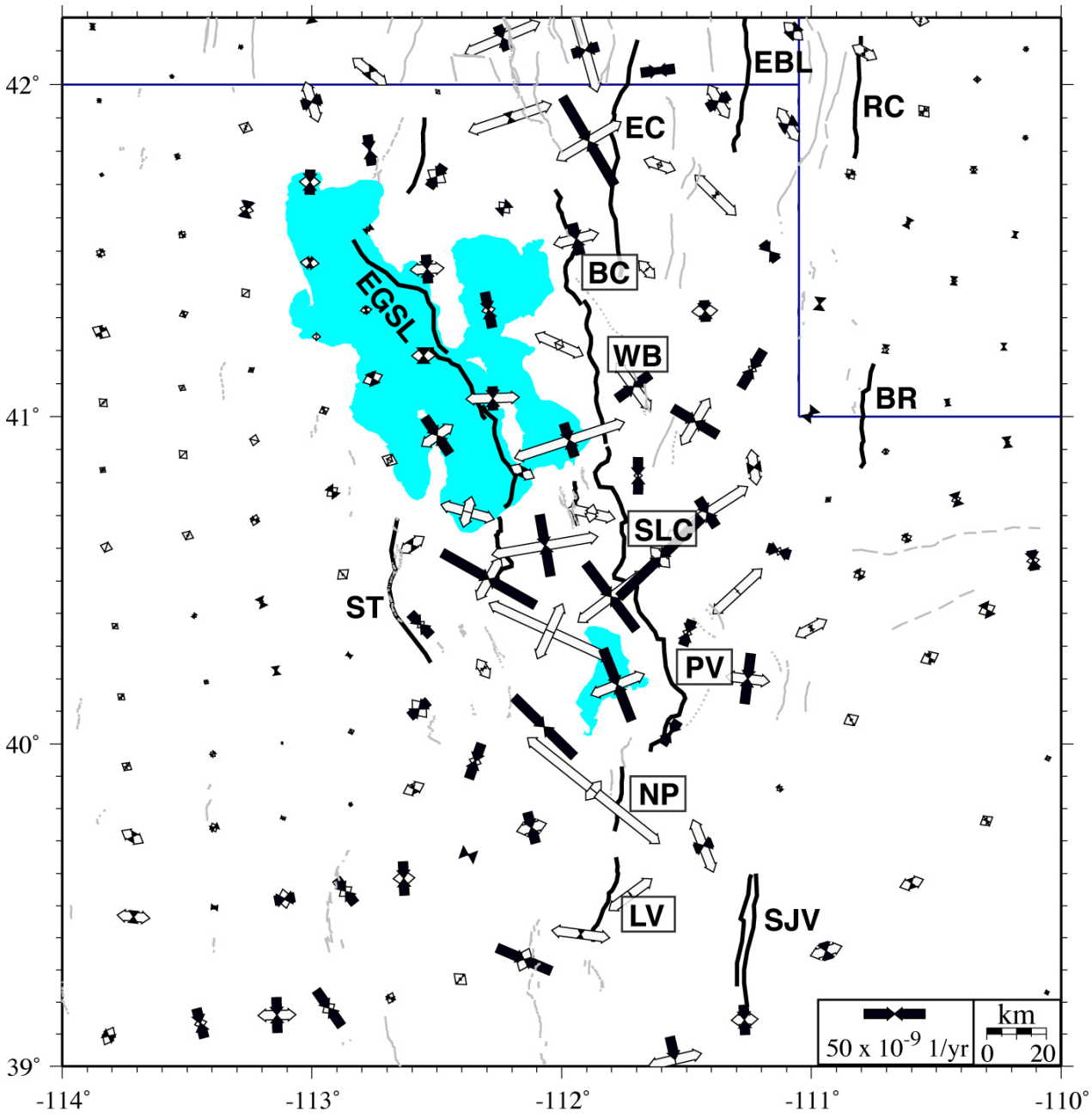

Figure 9. Principal horizontal strain rates of the Wasatch Front from kinematic modeling of western U.S. deformation. Black arrows represent contraction and white arrows represent extension. The main segments of the Wasatch fault are labeled with boxes: BC=Brigham City, WB=Weber, SLC=Salt Lake City, PV=Provo, NP=Nephi, LV=Levan. Other major Late Quaternary faults are marked with heavy lines and labeled: EBL=East Bear Lake, RC=Rock Creek, EC=East Cache, BR=Bear River, SJV=Southern Joes Valley, EGSL=East Great Salt Lake, ST=Stansbury.

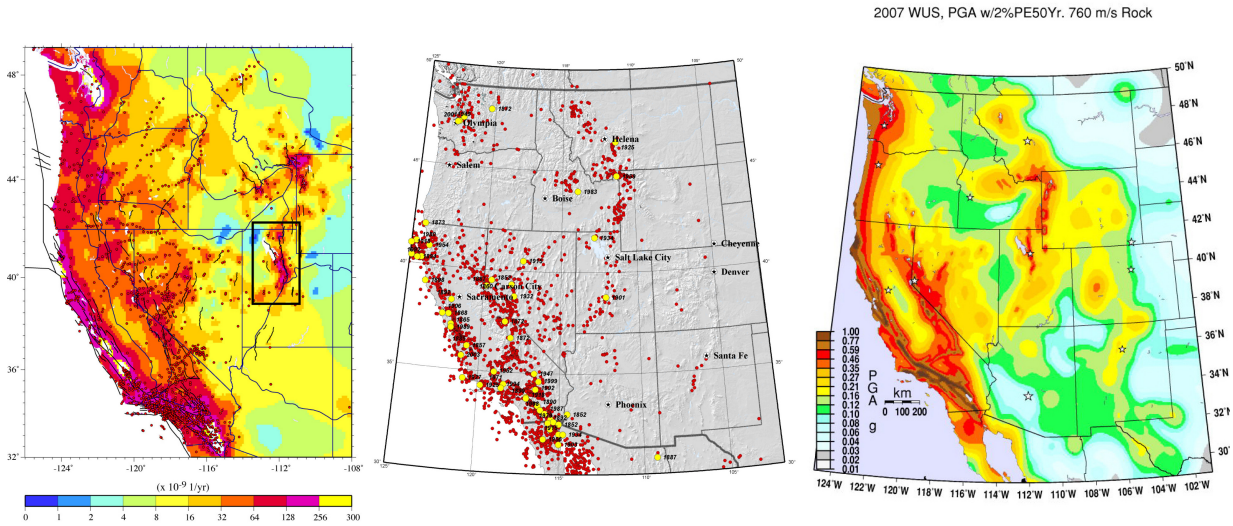

Figure 10. Comparison of GPS-derived strain data, seismicity and earthquake hazard showing that regions of high strain rates correspond to the active seismic zones and higher expected peak ground accelerations: a) GPS-derived strain rates, b) western U.S. historic earthquake distribution, and c) USGS 2007 Peak Ground Acceleration earthquake hazard map. *Black box is the Wasatch Front, Utah, GPS-earthquake study area*.

Collaboration

A key aspect of our Wasatch fault project is our collaborative efforts in GPS and earthquake hazards research. Moreover, we have worked closely with the EarthScope Plate Boundary Observatory management who have installed ~40 stations on the Wasatch fault, valued at ~$2.5M, funds that are clearly not available from the NEHRP program. Robert B. Smith was instrumental in recommending the station locations to encompass the expected regional crustal extension from which the physics of normal-fault processes can be derived. The research group is also working with colleagues of the USGS including Fred Pollitz to implement data from the University of Utah in studies of the western U.S. post-seismic deformation field.

Published Papers, Presentation Abstracts, and Meeting Reports of Research Related to this Project

Chang, W. L., and R. B. Smith, 2009, Rheological properties of extensional lithosphere from postseismic relaxation of the 1959 M=7.5 Hebgen Lake Montana earthquake, J. Geoph. Res., (in revision).

Chang, W., and R. B. Smith, 2009, Postseismic Deformation of the large 1959 Hebgen Lake, MT, and 1983 Borah Peak, ID, earthquakes, with implications for lithospheric rheology, Eos Tran. AGU, 90(52), Fall Meet. Suppl., Abstract U52A-04.

Chang, W., and R. B. Smith, 2009, Elastic and viscoelastic finite-element models of crustal motion across the Wasatch fault, II. Models, J. Geophys. Res. (in preparation).

Pollitz, F. F., McCory, P., Wilson, D., Svarc, J., Puskas, C. and Smith, R.B., 2010, Viscoelastic-cycle model of interseismic deformation in the northwestern United Statess, J. Geophys. Res., (in press).

Puskas, C. M., 2009, Contemporary deformation, kinematics, and dynamics of the Yellowstone hotspot and western U.S. interior from GPS, fault slip rates and earthquake data, PhD thesis, University of Utah, Salt Lake City, Utah, 238 pp.

Puskas, C. M., and R. B. Smith, 2009, Intraplate deformation and microplate tectonics of the Yellowstone hotspot and surrounding western U.S. interior, J. Geophys. Res., 114, B04410, doi:10.1029/2008JB005940.

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Puskas, C. M., and R. B. Smith, 2009, The Yellowstone Hotspot: Effects on intraplate stress and deformation of the western U.S., Eos Tran. AGU, 90(52), Fall Meet. Suppl., Abstract U52A-06.

Puskas, C. M., L. M. Flesch, R. B. Smith, K. Settles, 2008, Effects of the Yellowstone hotspot on the geodynamics of the western U.S. iInterior, UNAVCO 2008 Science Workshop, Boulder, CO.

Puskas, C. M., R. B. Smith, and W. L. Chang, 2009, Kinematics and geodynamics of the Intermountain Region: Wasatch fault to the Yellowstone Plateau, Geol. Soc. Am. Abstracts with Programs, 41(6), 16.

Smith, R. B., and C. M. Puskas, 2009, Contemporary deformation and kinematics of the Yellowstone Hotspot and its effect on the western U.S. from GPS, slip rates, and earthquakes, Geol. Soc. Am. Abstracts with Programs, 41(6), 16.