GPS Measurements, Fault Modeling and Integrated Earthquake Hazard Assessment of the Wasatch Front, Utah

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Investigations Undertaken

The above research project focused on investigations evaluating the earthquake hazard of the Wasatch fault, Utah, by integration of various types of seismic sources: paleoearthquake slip rates, historic seismicity and geodetic data. High precision crustal deformation data were acquired by six continuous GPS stations and a 40-station campaign GPS survey of the southern Wasatch fault area. Fault dislocation modeling was used to invert horizontal velocity field derived from the GPS measurements for the 3D geometry and loading rate of the Wasatch fault. In addition we evaluated the time-dependent post-seismic effects of the larger historic earthquake, M>5, and prehistoric earthquakes deduced from trenching, by viscoelastic modeling for specific sources on the Wasatch fault.

Our main field project during the report period has included the operation of six continuous GPS stations, installation of a new CGPS station, and conducting routine data processing of nine CGPS stations (including five from the Harvard/CalTech northern Basin-Range CGPS array). Use of the data involved investigations of how the earthquake hazard of the Wasatch Front is affected by the GPS-deduced contemporary loading rates on the Wasatch fault (Fig. 1).

We completed the statistical analysis of the Wasatch Front paleoearthquake data obtained from trenching studies and developed paleoearthquake time- and slip-rate history for single to multiple event sources that we believe are the best geological realizable models. These data were then employed in probability calculations to analyze the integrated effect of employing all types of data (prehistoric fault slip rates, historic seismicity and GPS deduced fault slip rates) on earthquake hazard of the Wasatch Front.

In addition, our CGPS data are sent daily automatically to the UNAVCO GPS data archive where they are web accessible to any interested user and the public.

Results (October 1, 2002 to September 30, 2003)

General Accomplishments -- Under this project the University of Utah received support to assess earthquake hazard on the Wasatch Front, Utah using continous and campaign high precision GPS measurements and investigating relevant models of normal fault behavior applied to the Wasatch fault. Because of reduced funding from our proposed project, tasks were reduced to three elements: 1) building and installing one new continuous-GPS (CGPS) sites in the northern and southern Wasatch fault; 2) maintenance of six CGPS sites on the Wasatch Front, and incorporation of data from five Harvard Smithsonian-Cal Tech Basin-Range CGPS stations in the eastern Basin Range, for a total of 9 stations in our processing scheme; and 3) research on understanding time-varying behavior of the Wasatch normal fault incorporating GPS-derived motions and viscoelastic modeling (Fig. 1).

We also published a paper on research from the GPS monitoring and related earthquake hazards of the Wasatch fault in the Bulletin, Seismological Society of America (Chang and Smith, 2002).

Specific efforts included:

- Permitting and completed installing one continuous GPS (CGPS) stations at Little Mountain, in the northern and southern Wasatch Front, respectively to provide additional deformation baselines across the Wasatch fault.

- Planned for installation of a GPS station at the USGS ANSS broadband seismic station at Hardware Ranch in northern Utah.

- Conducted the 2003 GPS campaign reoccupying 31 sites along the central and southern Wasatch fault

- Operating six CGPS stations of the Wasatch Front to provide the multiple baseline crossings of the Wasatch fault for measuring ground deformation.

- Incorporation of data from five ancillary GPS stations of the Northern Basin and Range (BARGEN) array operated by Harvard-Smithsonian and Caltech into our processing scheme.

- Providing daily downloads of our CGPS data to the UNAVCO data archive for web access to any interested user at: http:// http://archive.unavco.org/query/pss.

- Development of viscoelastic models of normal faults to evaluate the time-dependent effect of past earthquakes on the contemporary deformation field.

- Modeling the GPS data using non-linear inverse methods to determine the geometry and rates of causative faults especially incorporating the 3D geometry of the Wasatch fault.

- Completed initial development of a prototype integrated probabilistic seismic hazard assessment incorporating the corrected late Quaternary slip rates, GPS and historic earthquake data. Our results were published by Bulletin, Seismological Soc. America, June, 2002.

- Organized an effort to include the Wasatch fault as a major element of the Plate Boundary Observatory. This component will provide three profiles of CGPS stations across the Wasatch fault at ~15 km intervals complimentary to the USGS funded stations. The research objective is to focus on the physics of earthquakes as well as an example of GPS monitoring of an active fault with major societal impact.

Wasatch Front CGPS Operations

The Wasatch Front CGPS network has been operating for nearly seven years (1997-present). Currently, six GPS stations are operating and telemetering data to the University of Utah (Fig. 1). We employ the Bernese Processing Engine (BPE) to daily process the RINEX data from the four Wasatch Front stations together with data from seven stations of the International Geodetic Service, five from BARGEN, and six from the Yellowstone and Snake River Plain (YSRP) network.

Along with our six CGPS and the five BARGEN stations, these 11 stations (Fig. 1) form multiple baselines that cross the Wasatch and Oquirrh-Great Salt Lake and subsidiary faults, and are important for estimating the overall crustal deformation of the Wasatch Front.

This effort included the installation of two new CGPS stations and drilled-steel monuments (on bedrock), at Little Mountain (LTUT) and Maple Canyon (MPUT) sites near the northern and southern Wasatch fault, respectively (Fig. 1). Both stations were finished and started to collect data.

We collaborated with the Brigham Young University during the summer of 2003 on resurveying 31 campaign GPS sites across the central (Salt Lake City segment) and southern (Provo and Nephi segments) Wasatch fault. This experiment increases the total time span of our campaign surveys to 11 years (1992-2003) and gives more confident estimations on the local velocity fields. The data processing of the 2003 campaign GPS data is currently being done.

We procured a new GPS receiver for a site planned east the Wasatch fault in northern Utah at the USGS ANSS Hardware Ranch seismograph station. This site will provide key data on the footwall of the East Cache and Wasatch faults. Moreover it can be economically operated as it will use the USGS VSAT telemetry to the National Earthquake Information Center then relayed via the Internet to the University of Utah and to the UNAVCO GPS archive. We specifically note that because of logistical problems and early winter, we were unable to install this station in 2003, and plan on installing it in 2004.

CGPS Array Operation – Our continuous GPS sites are designed to operate in high mountainous, cold weather conditions planned for unattended operation. The instrumentation includes photovoltaic power (except for Lake Mountain) and digital spread-spectrum radios for telemetry between the sites and the University of Utah GPS recording laboratory. Choke-ring antennas are attached to 2-inch stainless steel rods set in four-foot long boreholes drilled into bedrock.

All previous stations are equipped with Trimble SSi dual-frequency GPS receivers (*acquired at no cost to the project by a grant to the University of Utah from the National Science Foundation*). Our two new stations use Ashtech Micro Z dual frequency receivers.

Spread spectrum digital radio links to the University of Utah campus transmit the GPS data which are then recorded on a Sun UltraSparc computer. Data are sampled at a 30-second rate.

Problems Encountered -- No major logistical problems were encountered during the report period.

Research Results

Contemporary crustal deformation of the 370 km-long Wasatch fault, Utah, has been measured by continuous and campaign GPS measurements. These data were then modeled for the effects of normal fault loading employing elastic and viscoelastic models. GPS campaign surveys of 90+ sites begun in 1992 and re-observed in 1993, 1994, 1995, 1999, 2000 and 2003 reveal a principal E-W horizontal strain rates of 28 to 44 nstrain/yr (Fig. 2). This corresponds to a general E-W extension of 1.8 to 2.2 mm/yr across a 60 km-wide survey area spanning the northern and southern Wasatch fault.

Beginning in 1997, the University of Utah began installing continuous GPS (CGPS) stations with baselines spanning the fault that by 2003 totaled six. Data from these sites and five additional stations of the BARGEN network in Utah are routinely processed. The CGPS results show that the strain rate is negligible east of the fault, but sharply increases to west across the fault to 40 nstrain/yr, essentially the same as that measured by the campaign GPS results.

Fault Geometry Inversion Using GPS Measurement -- Because of the confirmation of the relatively high strain rates for an intraplate normal fault, and the need to understand the implication of loading the Wasatch and other faults, we initiated a study of the relationship between fault slip and the crustal deformation measured by GPS using elastic dislocation modeling.

The relationship between the deformation field and fault geometry can be expressed as a classical, non-linear inversion problem. To accomplish this goal, we have collaborated with Peter Cervelli, USGS, Hawaii Volcano Observatory who has developed a non-linear inversion scheme. Among different methodologies, we are investigating the use of Monte Carlo optimization techniques, including simulated annealing and the random cost methods, to the inversion of deformation data for source geometry.

Using the horizontal deformation results from the CGPS and the campaign GPS surveys, we have run nonlinear inversions on fault geometry and loading rates. Before doing this, we first estimated and removed the background tectonic motion, namely the extension of the eastern Basin and Range, from our observed velocities to obtain the motion caused only by the loading of the Wasatch fault. Moreover, the fault length was fixed to 350 km, approximately the total length of the Wasatch fault, which is long enough to avoid the dislocation edge effect. Results for the Wasatch fault suggest a best fit to the GPS data by a fault plane with a width of 23 km, a strike of N4ºW, a dip of 27º, a locking depth of 9 km, and a fault loading rate of 7 mm/yr (Fig. 3) that is notably higher than the rate derived from the paleoseismic data (~ 1-2 mm/yr).

To consider along-strike variations of the fault behavior, we split the study area into the northern and southern parts at approximately the boundary between the Salt Lake and Provo segments (Fig. 2). Note that most of the campaign GPS data from the northern Wasatch have better quality due to more frequent observations, so we removed sites from inversion that were occupied less than three surveys. For a better lateral constrain on fault geometry, however, we kept the sites HOWE and V175 that were surveyed only twice but the only two observations between the Salt Lake valley and CEDA. The tectonic motion of EBAR discussed above was also removed. Figure 3 shows the best-fit model of the northern Wasatch fault, with inverted fault plane steeper (34º) and slip faster (9 mm/yr) compared with the result in Fig. 3.

The best-fit fault plane for the southern Wasatch in Fig. 5 locates closer to the surface trace of the Wasatch fault and strikes more northwest-southeast (N9ºW) that is similar to the trend of the fault trace north of the bend of the Provo segment. Its much narrower width (13 km) and significantly higher slip rate (14 mm/yr) compared with models in Figures 2 and 3 are needed to mimic the rapid change of E-W velocities from the footwall to the west part of the hanging wall (Fig. 5). This result, however, is questionable because there are no observations in between to support the modeled increasing and decreasing of velocity east of the fault, and the credibility of the southern Wasatch model in Fig. 5 needs to be justified with more reliable data, for example, from spatially denser network or more site re-occupations to collaborate velocity estimations. Including our newly collected 2003 campaign GPS results of this area can give more reliable velocity estimations.

Post Seismic, Viscoelastic Fault Modeling -- The effects of long-term viscoelastic loading and relaxation of the Earth's lithosphere and asthenosphere should be included to better model the complete earthquake cycle. To do this, viscoelastic relaxation of prehistoric (M>7) and historic (M>4) earthquakes are being evaluated to examine time-dependent effects of past earthquakes on the contemporary strain field. For this part of the project we have begun to work with Fred Pollitz of the USGS Menlo Park.

To investigate lithospheric rheology beneath the Wasatch fault zone where no large historic earthquake has been recorded, we first studied the change of surface deformation after the 1959 Ms = 7.5 Hebgen Lake, Montana, earthquake, measured by trilateration and GPS from 1973 to 2000 and the only postseismic observations of large normal-faulting earthquake in the Basin-Range. Time-dependent changes of baseline length across the fault were used to optimize rheological models beneath the Hebgen Lake fault zone. We have applied a Monte Carlo method to search a range of plausible rheological models that best fit these geodetic observations. A set of 20,000 two-layered models was randomly generated, and four rheological parameters were estimated: the depths of the two layers and the viscosities of the lower crust and upper mantle. The results of this study were presented in the fall AGU meeting of 2003.

Our optimized rheological models for the Hebgen Lake area are similar to that of the eastern-Basin-Range lithosphere implied by the long-term deformation of the lacustrine shoreline caused by the Lake Bonneville rebound. Based on these results, we then estimated combined postseismic responses caused by the most recent paleoearthquakes on the Wasatch and East Great Salt Lake faults and some Wasatch Front large ($M > 5.5$) historic earthquakes. Half-space and layered rheological models were used. Results show that the post-seismic velocity field due to five Wasatch fault paleoearthquakes and three northern-Wasatch historic earthquakes are 10~20 times lower than the contemporary velocity observed by GPS. This result implies that the post-seismic response does not significantly contribute to the contemporary deformation of the Wasatch fault (Fig. 6).

Non-Technical Summary

Under this research project, the University of Utah conducts studied the contemporary time-varying behavior of ground motion around the Wasatch fault. This was done by precise measurements of points on the ground using continuous-recording and temporary field occupations of GPS (Global Positioning Systems) satellite receivers. The continuous recording GPS antennas are mounted in bedrock and transmit data to the University of Utah in real-time via radio links for recording and processing. Our project is a follow-up to GPS measurements from a 1992-1995 along the Wasatch fault that revealed unexpectedly high deformation rates of 2 to 3 times faster loading of the fault than deduced from geologic determinations. The new Wasatch Front continuous GPS network incorporates data from a collaborative network of GPS stations in western Utah operated by the Harvard Smithsonian-CalTech research groups as well as cooperative efforts with Dr. Ron Harris of Brigham Young University for GPS surveys on the southern Wasatch Front. Results of the surveys confirm the high deformation rates determined in our 1992-1995 surveys and are much larger than those inferred by geology studies. They imply a higher earthquake hazard than before. Because of this discrepancy the GPS measurements have a greater implication for earthquake hazard than heretofore considered. Note that our CGPS position data are provided on the web and specifically to the local surveying community for high accuracy reference surveying.

Meeting Participation – We presented invited and contributed papers on our research at the: 1) 2002 Fall Meetings of the American Geophysical Union; 2) the UNAVCO annual meeting in Colorado Spring, CO, March, 2002; and 3) an invited presentation of earthquake hazard assessment of the Wasatch fault given at the Spring 2002 European Geophysical Society meetings, Nice, France.

Collaborative Efforts – We continue to work with Professor Ron Harris of Brigham Young University, Provo Utah for campaign GPS measurements. Dr. Harris has four Trimble GPS receivers that he loans to us when needed. Moreover, he supervises a team of undergraduate students that conduct campaign GPS surveys of the Wasatch fault in 2003 to our specifications costing us only their salaries and travel. This cooperative effort has materially contributed to this project.

In addition we are working with Dr. Fred Pollitz of the USGS Menlo Park on viscoelastic effects of normal faults applied to the Wasatch fault GPS data.

Papers and Presentations Related To Project (2000-2003)

Chang, W. L., R. B. Smith, and C. M. Puskas, 2003, Rheology of Extending Lithosphere From Postseismic Deformation of Large Basin-Range Normal-Faulting Earthquakes, *Eos. Trans. AGU* **84**, F1033, 2003.

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Smith, R. B., C. M. Meertens, W. Chang, G. Waite, C. Puskas, and A. Lowry, 2001, What's Moving the Basin-Range? Hotspots, Earthquakes and Lithosphere, Program for "The Lithosphere of Western North America, and Its Geophysical Characterization", The George Thompson Symposium, Sponsored by the School of Earth Sciences, Stanford University, Dec. 8-9, 2001, p. 12, (invited paper).

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Smith, R.B., W. Chang, and C. M. Meertens, 2001, Comments Relevant to Earthquake Hazard Analysis in the Intermountain Seismic Belt (other than GPS), USGS National Earthquake Hazard Program Workshop on the Intermountain region, March 28-30, 2001.

Smith, R. B., W. Chang, J. Braun, and C. Meertens and R. Harris, 2001, Integrated ground shaking and fault displacement hazards of the Wasatch Front, Utah, from paleoearthquakes, GPS observations, and historic seismicity, Program With Abstracts, Geologic Hazards in Utah: Practical Information for Geologists and Engineers, Amer. Soc. Civil Engineers, Salt Lake City, Utah, April 12-13. p. 7-8, (invited paper).

Smith, R. B., W. Thatcher, and C. Meertens, 2000, Kinematics and Earthquake Physics of the Wasatch Fault: An Eastern Plate Boundary Fault, Plate Boundary II Workshop, Palm Springs, Abst. p. 50.

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Smith, R. B., C. Meertens, W. Chang, G. Waite, C. Puskas and A. Lowry, 2002, What's moving the Basin-Range, Annual Meeting of the European Geophysical Society Meetings, Nice France.

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Availability of Data

All Wasatch Front continuous GPS data are available to the interested user and to the public in near real-time via the web. The data are downloaded daily and archived in Rinex format the UNAVCO (University NAVSTAR consortium) data management center, Boulder, Colorado at http://www.unavco.org/query/pss

In addition hourly data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network that are accessible by ftp at ftp://cors.ngs.noaa.gov/coord. The cooperative component of our research project provides the local surveying community with local base stations.

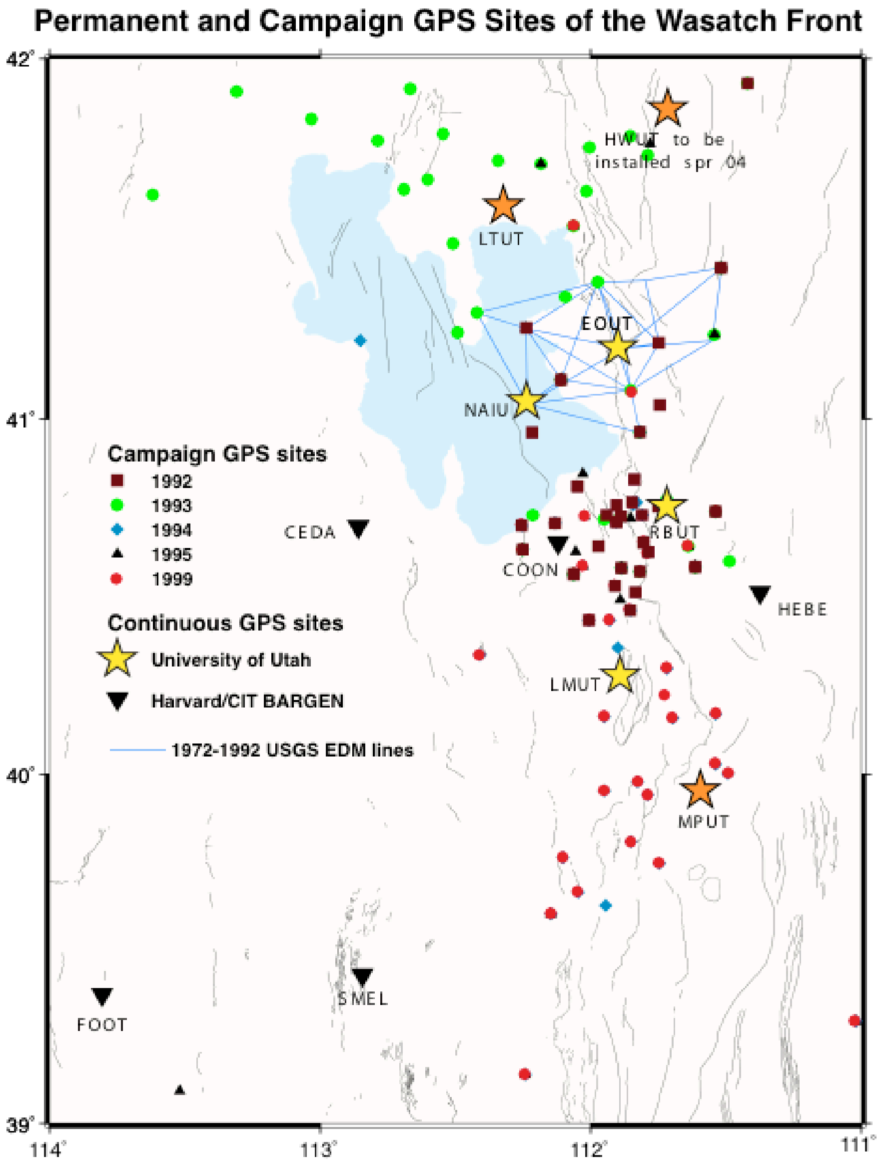

Figure 1. Map showing continuous and campaign GPS sites on the Wasatch Front. Black lines indicate Late Quaternary

faults.

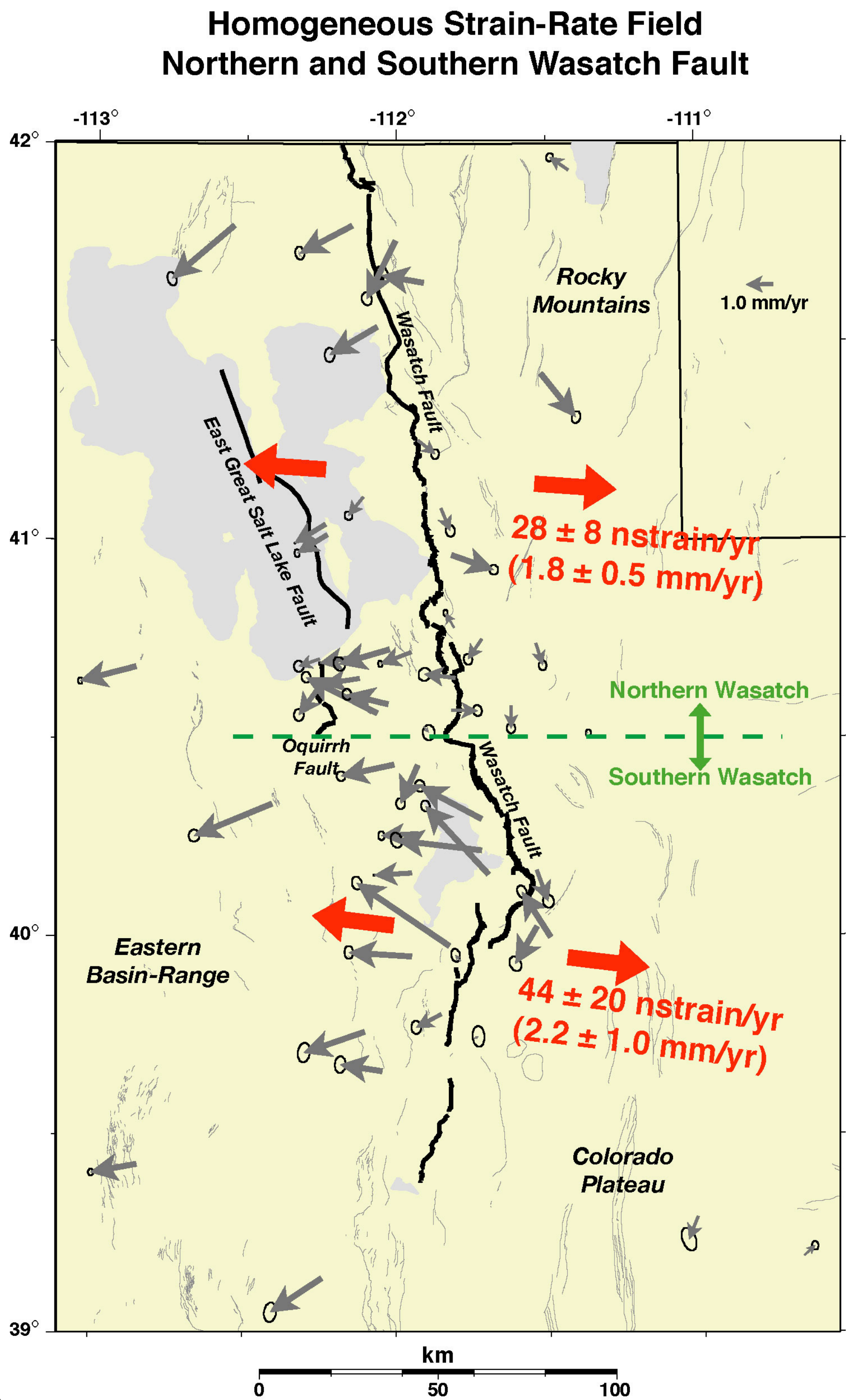

Fig. 2. Wasatch Front strain rates estimated from GPS data using the program, DYNAP. The northern and southern Wasatch (divided by the dashed line) are assumed to have homogeneous strain fields. Gray arrows represent horizontal velocity vectors.

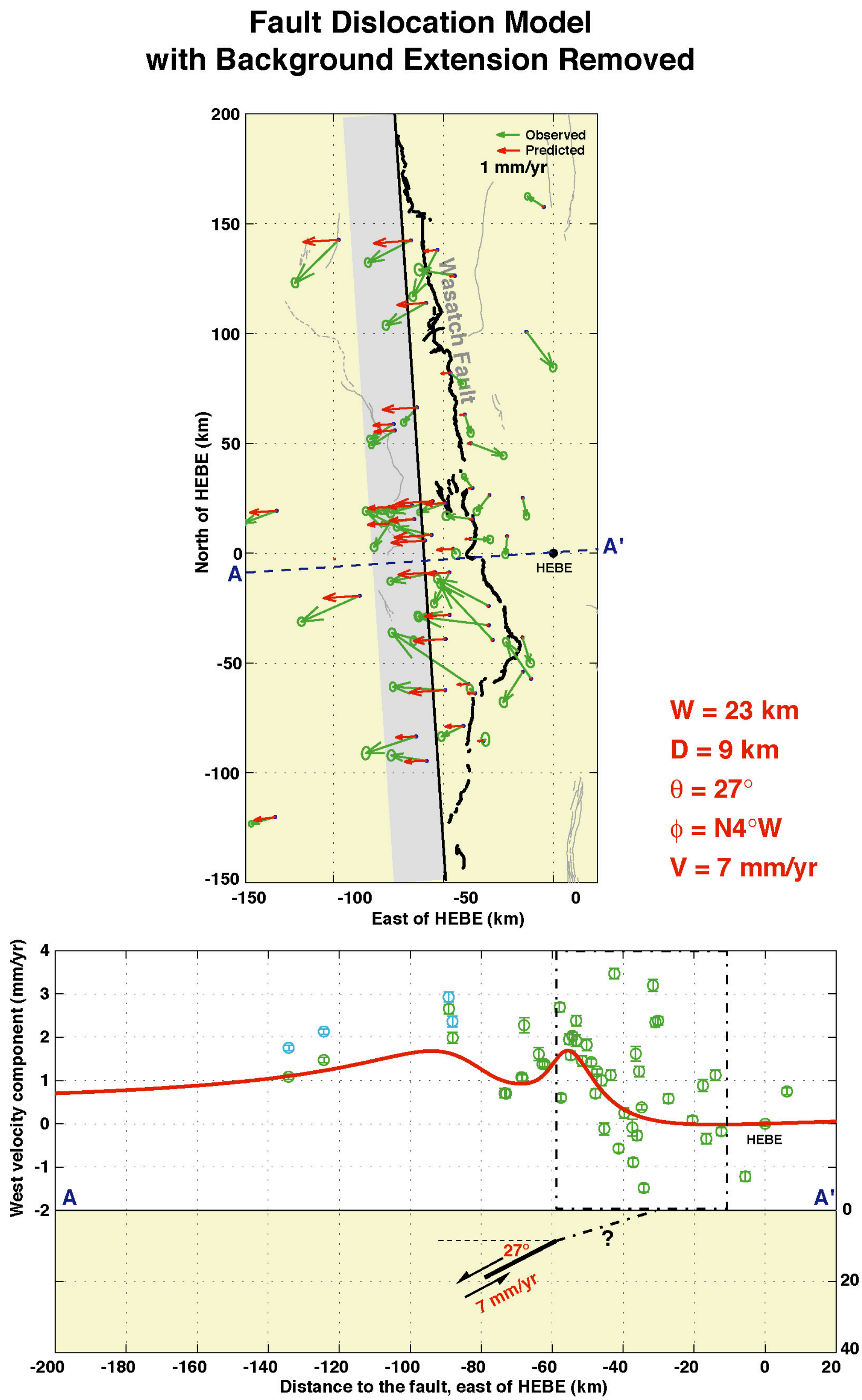

Fig. 3. The map-view (top) and vertical profile (bottom) of a dislocation model for the Wasatch fault. The parameters of the dislocation are: W=the width; D=the locking depth; q=the dip angle, f=the strike; V=the loading rate.

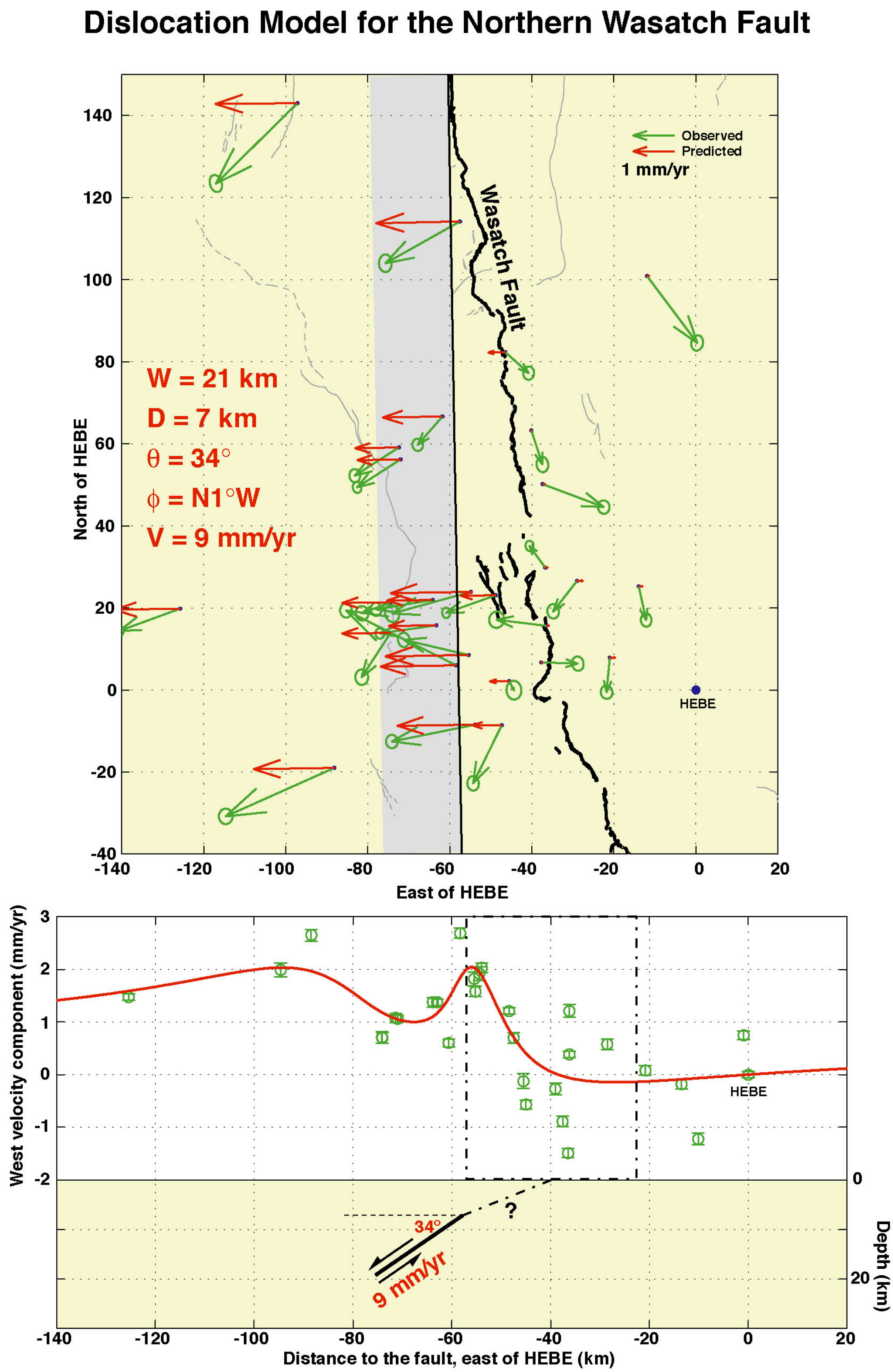

Fig. 4. A dislocation model best fits the northern Wasatch velocity vectors.

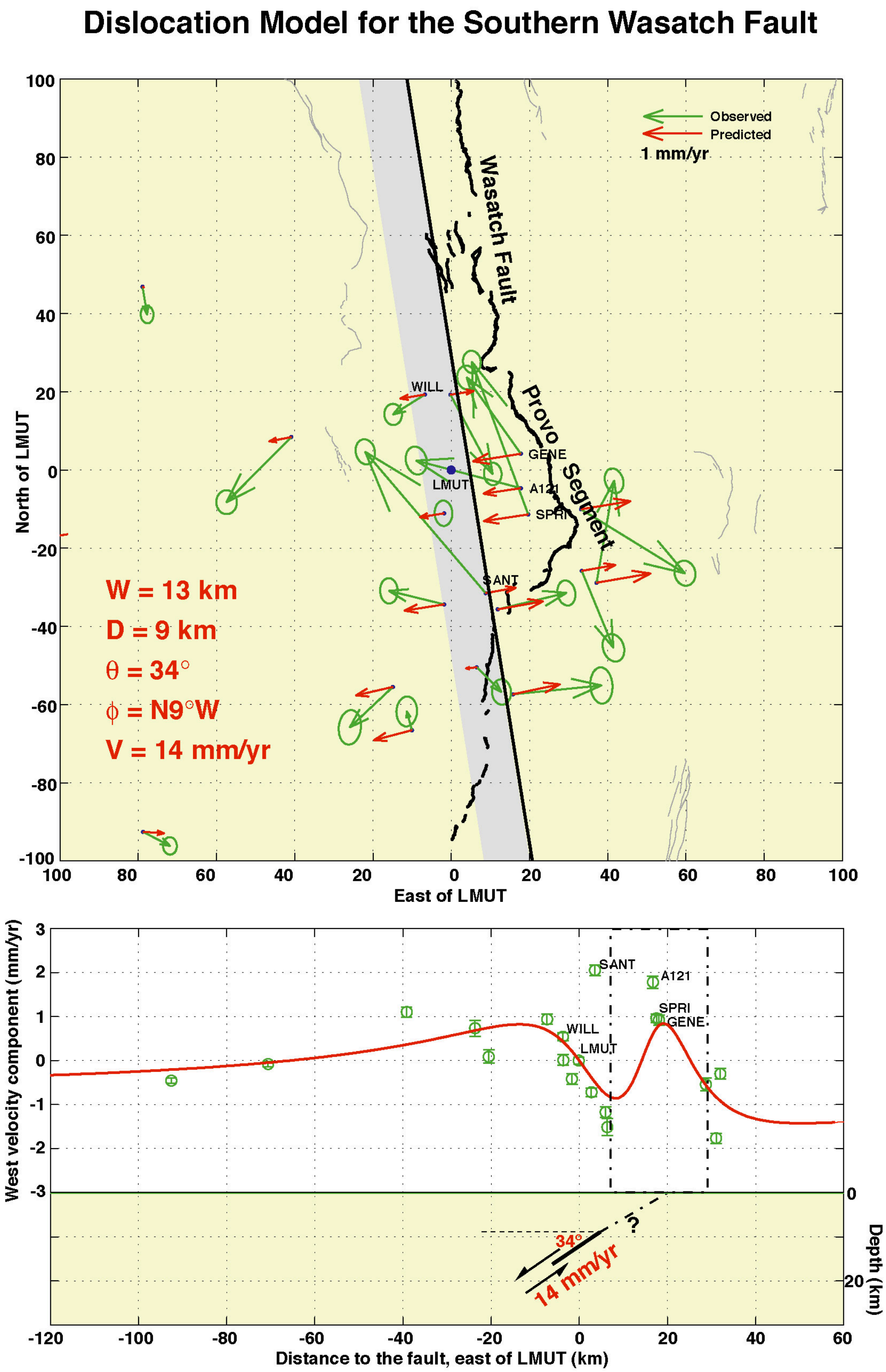

Fig. 5. A dislocation model best fits the southern Wasatch velocity vectors.

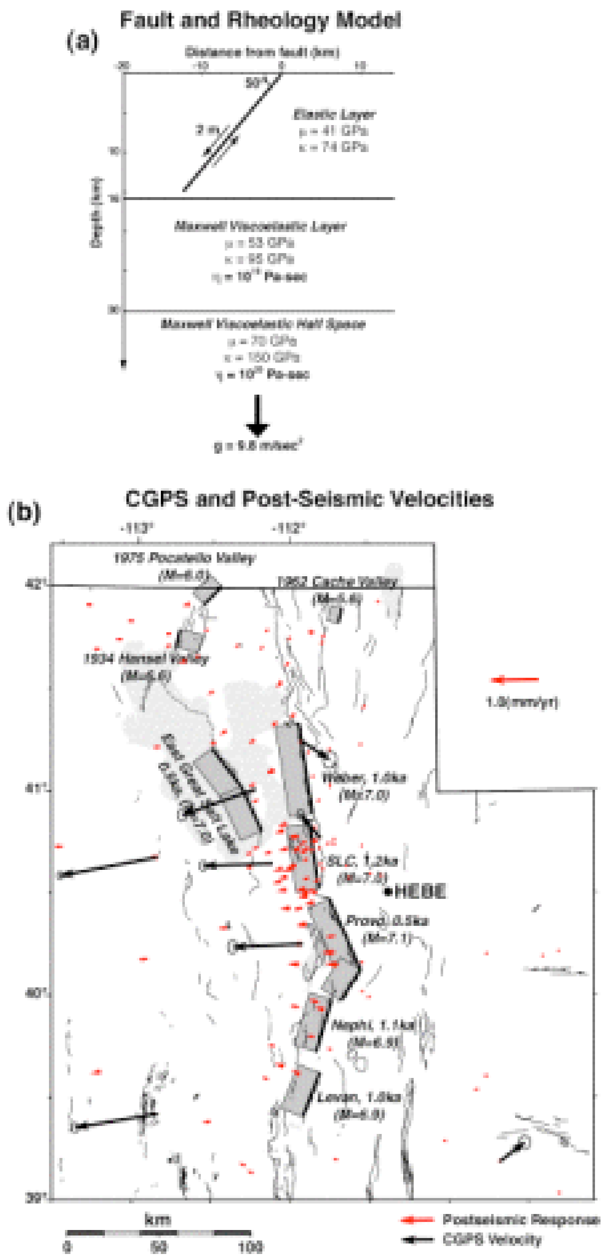

Fig. 6 (a) Fault and rheological model used for post-seismic visco-elastic modeling. (b) Post-seismic velocity field produced by five scenario Wasatch fault paleoearthquakes and the thee largest historic Wasatch Front earthquakes (M>5.5).