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

Progress Report for Period
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R.B. Smith, C. M. Meertens and WuLung Chang
Department of Geology and Geophysics
135 South 1460 East, Room 702 WBB
University of Utah
Salt Lake City, UT 84112
Tel: (801) 581-7129, Fax: (801) 585-5585
E-mail: rbsmith@mines.utah.edu
URL: www.mines.utah.edu/~rbsmith/research.html

Data URL: http://www.unavco.ucar.edu/data_support/data/data.html

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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 geodetic data were acquired by seven continuous stations and a 40-station campaign GPS survey of the southern Wasatch fault area. Fault stress modeling was used to evaluate horizontal velocity data derived from the 2001 and all previous GPS measurements. In addition we began evaluating 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 four University of Utah continuous GPS stations, installation of two new CGPS stations, and developing routing 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.

We completed the statistical analysis of the Wasatch Front paleoearthquake data obtained from trenching studies and developed a more geologically realizable paleoearthquake time- and slip-rate history for single to multiple event sources that we believe are more geological realizable. 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. Wasatch fault.

Results (October 1, 2001 to September 30, 2002)

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 two new continuous-GPS (CGPS) sites in the northern and southern Wasatch fault; 2) maintenance of four 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. We also finalized and published a professional paper on the Wasatch Front seismic hazard analyses that was published in the Bulletin, Seismological Society of America (Chang and Smith, 2002).

Specific efforts included:

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

- Operating four CGPS stations to provide the multiple baseline crossings of the Wasatch fault for monitoring ground deformation.

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

- Provide daily downloads of CGPS data to the UNAVCO data archive for web access to any interested user at http://archive.unavco.ucar.edu/cgi-bin/dmg/pss

- Continue analytic modeling the GPS data using non-linear inverse methods to determine the geometry and rates of causative faults.

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

- Complete development of integrated probabilistic seismic hazard curves 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 focus three profiles of CGPS stations across the Wasatch fault at ~15 km intervals. 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 five years (1997-present). Currently, four stations are operating and telemetering data to the University of Utah. 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 four CGPS and the five BARGEN stations, these 9 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.

Moreover, we are constructing 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). The former station was finished and started to collect data, whereas the installation of the latter one is in progress.

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 and 2000 reveal a principal E-W horizontal strain rates of 28 to 44 nstrain/yr (Fig. 1). This corresponds to a general E-W extension of 2.1 to 3.3 mm/yr across a 75 km-wide survey area spanning the central and southern Wasatch fault.

Beginning in 1997, the University of Utah began installing continuous GPS (CGPS) stations with baselines spanning the fault that by 2002 totaled five. 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 measurements.

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 method, to the inversion of deformation data for source geometry.

Using the strain and deformation results from the CGPS and the campaign GPS surveys, we have run nonlinear inversions on fault geometry and loading rates. Results for the northern Wasatch fault suggest a best fit to the GPS data by a fault plane with a length of 300 km, a width of 39 km, a strike of N10ºW, a dip of 31º, a locking depth of 15 km, and a fault loading rate of 7.9 mm/yr (Fig. 2) that is notably higher than the rate derived from the paleoseismic data (~ 1-2 mm/yr). For the southern Wasatch fault, a length of 150 km, a strike of N0ºW, a dip of 10º, a locking depth of 15 km, and a fault loading rate of 6.5 mm/yr best fit the GPS observations (Fig. 2).

Post Seismic, Viscoelastic Fault Modeling -- In addition, 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.

Our initial work has been evaluating simple rheological models that include two layers, a 16-km thick elastic layer on the top of a 14-km thick viscoelastic layer, and a viscoelastic half space to the Wasatch fault zone. 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 (Figs. 3, 4).

In order to investigate viscoelastic behaviors associated with large normal-faulting earthquakes, we are investigating the post-seismic deformation field recorded by geodetic measurements across the aftershock and fault zone of the M7.5 Hebgen Lake MT earthquake. We note that to our knowledge this is only large earthquake for which such precise post-seismic data exist and will help provide a rheological model for normal faulting earthquakes.

Horizontal deformation rates from 1973 to 2001 were measured by EDM and GPS methods and form multiple baselines that reveal significant post seismic horizontal slip up to 4 mm/yr, N-S.. 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 will be estimated: the depths of the two layers and the viscosities of the lower crust and upper mantle. This study will examine the time-dependent postseismic deformation effected by rheological properties that provide an insight into understanding the cycle of large earthquakes in extensional stress regime.

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) 2001 Fall Meetings of the American Geophysical Union; 2) the UNAVCO annual meeting in Colorado Spring, CO, March, 2002, 3) Assoc. of Civil Engineers, meeting on earthquake engineering, Salt Lake City, Utah, Spring, 2001; and 4) 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 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

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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://archive.unavco.ucar.edu/cgi-bin/dmg/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.

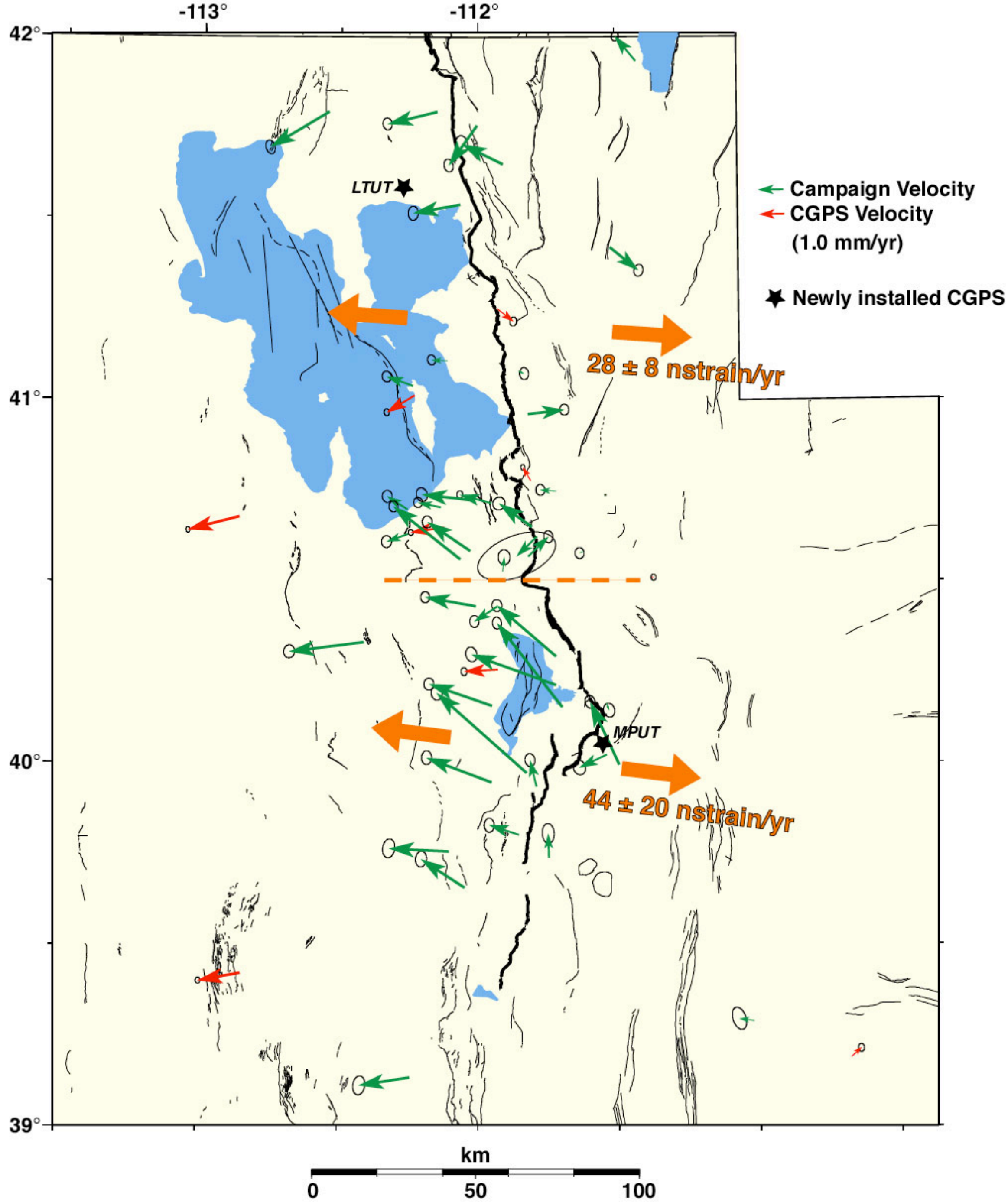

Fig 1. Velocities and strain rates estimated from GPS observations. Two black stars show newly installed CGPS stations.

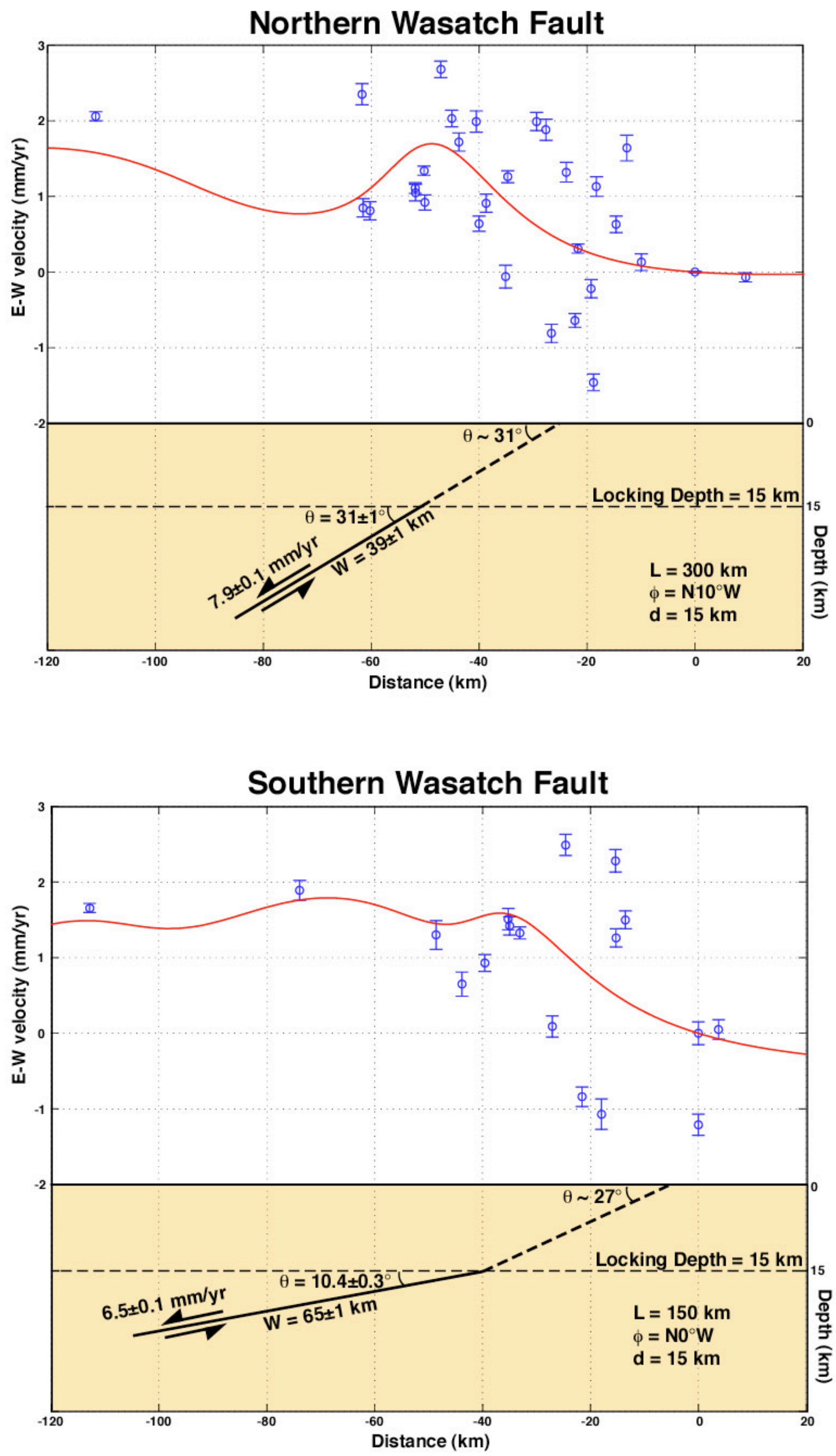

Fig 2. Inverted models for fault geometries and slip rates that match the GPS observations (blue circles with 2-σ error bars), for the northern and southern Wasatch fault. θ, dip angle,; W, fault width; L, fault length; ϕ, fault strike.

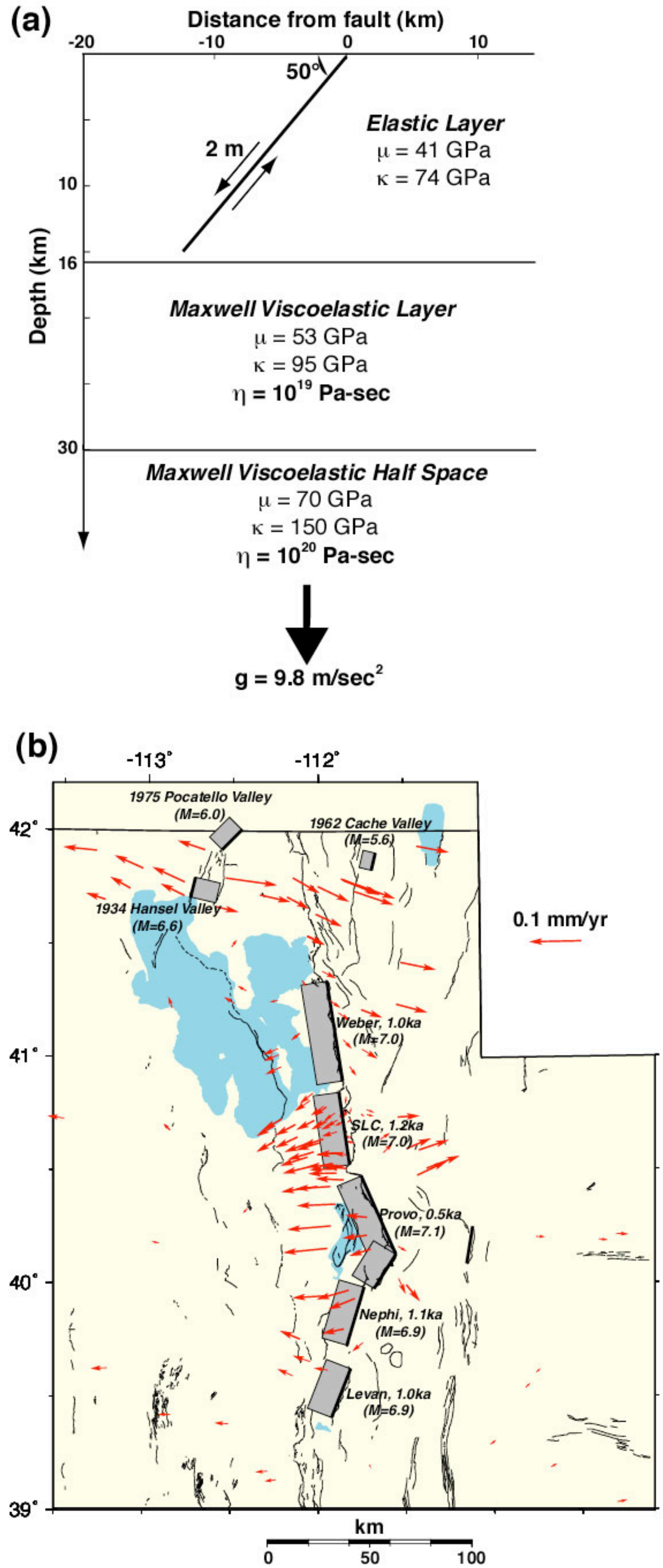

Fig 3. (a) Rheological model for the Wasatch Front area. (b) Postseismic velocity field due to viscoelastic response from five scenario Wasatch-fault paleoearthquakes and three M>5.5 Wasatch Front historic earthquakes. Note that the velocity scale is one tenth of that in Fig. 1.

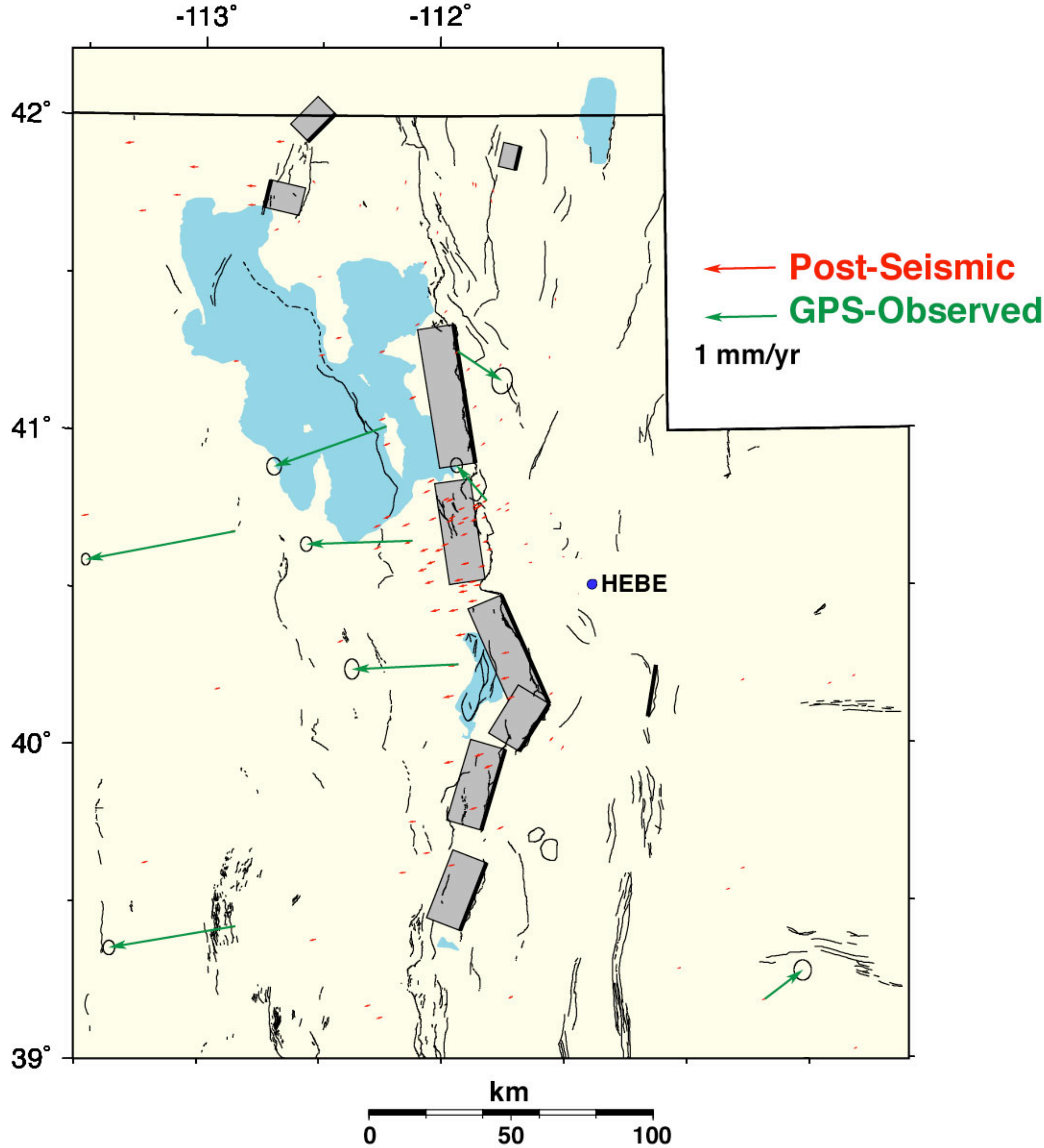

Fig. 4. Post-seismic (red arrows) and CGPS-observed (green arrows) velocities, with station HEBE fixed. The result implies that viscoelastic post-seismic response may not significantly contribute to the current deformation of the Wasatch Front area.