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Final Report

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Title of Award

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

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Disclaimer

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TABLE OF CONTENTS

NON-TECHNICAL REPORT SUMMARY

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

Under this USGS National Earthquake Hazard Program project, the University of Utah conducted research focused on evaluating the earthquake hazard of the Wasatch fault, Utah, by integration of various types of earthquake source data: paleoearthquake fault-slip rates, historic seismicity, and high resolution GPS data. The GPS data were acquired by seven continuous GPS stations and from field campaign GPS surveys of ~ 60 stations on the Wasatch Front, Utah. Our results indicate that the Wasatch fault is an area of notably higher ground deformation than expected from geologic data and is interpreted to related to fault-loading processes of the Wasatch fault and surrounding structures. This increases the earthquake hazard from previous estimates. The University of Utah GPS data are automatically sent to the University Navigation Consortium (UNAVCO) archive on a daily basis and accessible to any user over the Internet in near-real time.

FINAL REPORT SUMMARY

Earthquake hazards related to the Wasatch fault are of great concern because 80% of Utah's population of two million+ live within 50 km of it. Geological studies reveal evidence of at least 17 paleoearthquakes, 6.8<M<7.1 on the fault in the past 5,600 years, which implies a high likelihood of large earthquakes in the future.

This research project focused on an evaluation of the earthquake hazard of the Wasatch fault, Utah, by integration of various types of seismic sources contributing to earthquake hazard: paleoearthquake slip rates, historic seismicity and geodetic data. Seven continuous stations and campaign GPS measurements of the Wasatch Front acquired the geodetic data. Fault-stress modeling was used to evaluate horizontal velocity data derived from all of the GPS measurements. In addition evaluated the time-dependent effects of past earthquakes by viscoelastic modeling of fault-specific sources on the Wasatch fault. The project was conducted within the framework of the USGS National Earthquake Hazards Reduction Program.

During the period of the award, efforts were devoted to investigations outlined and described in the paper and report summaries that are attached, as well as in our reports and national meeting presentations and in a thesis partially supported by this grant. The summaries are updated and expanded versions of those submitted for inclusion in the National Earthquake Hazards Reduction Program Summaries of Technical Reports.

As directed by the USGS National/International review panel, funding from that proposed by the University of Utah, the budget was reduced from that requested and our efforts were focussed primarily on the task of measuring deformation of the Wasatch fault from CGPS (Continuous Global Positioning System) measurements. Our main field project included operation of five University of Utah continuous GPS stations and a GPS campaign field surveys of the central and southern Wasatch fault.

We continued developing routine data processing of ten collaborative CGPS stations in the Wasatch Front study area (including five from the Harvard/CalTech northern Basin-Range CGPS array). Our CGPS data are sent daily to the UNAVCO archive are web accessible to any user.

In addition we also evaluated the time-dependent effects of interseismic loading by employing viscoelastic models of paleoearthquakes and the larger, M>5, historic earthquakes of the Wasatch Front region.

University of Utah CGPS Data Availability -- We note that the USGS NEHRP review panel specifically addressed the need to incorporate data from regional CGPS stations of the Harvard-Smithsonian/CalTech Basin-Range GPS network with our data. We have addressed this task by cooperative sharing of data from public access from the UNAVCO permanent GPS station web site. As a result of this collaborative effort, all Wasatch Front and surrounding area continuous GPS data are archived (in Rinex format) at the UNAVCO data management center, Boulder, Colorado and are accessible to anyone via the Internet at: http://archive.unavco.org/query/pss.

Moreover, hourly data from the University of Utah stations RBUT, BLWY, GTRG and MAWY GPS stations are provided to the surveying and research community via the National Geodetic Survey and the CORS on-line network that are accessible at: http://www.ngs.noaa.gov/CORS/

In addition to this report, scientific results in total or in part from research reported by this award are summarized in the following papers, abstracts and theses.

Papers Published in National Journals

Chang, W. L. and R. B. Smith, 2002, Integrated earthquake hazard analysis of the Wasatch Front, Utah, Bull. Seismological Soc. Amer., v. 92, n. 2, 1904 – 1922.

Abstracts of Presentations At National Meetings

Chang, W., Puskas, C M, Waite, G P, R. B. Smith and C.M. Meertens, 2001, Rheological properties of lithospheric extension from postseismic GPS observations of the 1959 M=7.5 Hebgen Lake, Montana, earthquake, Eos Transactions Amer. Geoph. Un., v. 82 (47), Fall Meeting. Suppl. Abstract, F 267.

Chang, W., R. B. Smith and C. M. Meertens, 2002, Rheologic properties of an extending lithosphere from inversion of postseismic deformation (EDM and GPS) from the 1959 M 7.5 Hebgen Lake, Yellowstone earthquake, Eos Transactions Amer. Geoph. Un. Fall Meeting. Suppl. Abstract, NG62A-0934.

Chang, W.L., R.B. Smith, R. B., C. M. Meertens and R. Harris, 2001, Crustal deformation of the Wasatch Front, Utah from GPS measurements, paleoseismicity and elastic-viscoelastic modeling, Seismol. Res. Letters., v. 72, n. 2, p. 281.

Meertens, C.M., R.B. Smith, C. Puskas, and W. Chang, 2002, Contemporary deformation of the Yellowstone caldera from GPS, 1st Annual Science Workshop, Yellowstone Volcano Observatory, Salt Lake City, Utah, Abs. Program, April 4, 2002.

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).

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.

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 talk.

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, C. Meertens, C. Puskas and R. Harris, R., 2001, Earthquake hazards of the Intermountain Seismic Belt using GPS, paleoseismology and modeling with emphasis on the Wasatch Fault, USGS National Earthquake Hazard Program Workshop on the Intermountain region, March 28-30, 2001.

Smith, R.B., W.L. Chang, C. Puskas, C.M. Meertens and A. Sylvester, 2001, Crustal deformation and seismic cycle of the of the northern Basin-Range based on geodetic, historic seismicity and Quaternary fault data, Seismol. Res. Letters. v. 72, n. 2, p. 281.

Web Site of Ancillary Earthquake Hazard Information (contributed with expertise derived from the Wasatch Front GPS earthquake hazard project)

Ward, P., R. Smith, L. Cahn, C. Dahl, and K. Watts. 2001, Natural Hazards That Could Affect the Schools of Teton County, Wyoming, online web document: http://www.tetonsafety.com/natural_disaster_risks_in_teton_county_schools.htm

PhD Thesis In Completion

Chang, W.L., 2004, GPS studies of the Wasatch fault zone, Utah, with implications for fault behavior and earthquake hazard, Ph.D. dissertation.

DISTRIBUTION OF FINAL REPORT

Name	No. of Copies
Dr. John Unger Project Officer Extramural Program U.S. Geological Survey National Earthquake Hazards Program Mail Stop 905 12201 Sunrise Valley Drive Reston, Virginia, 20192	1 unbound original, 5 bound copies, 1 CD report in PDF and 3 reprints
Dr. Robert B. Smith Principal Investigator	1
Dr. Charles M. Meertens Co-Principal Investigator	1
WuLung Chang Graduate Research Assistant	1
File Copies University of Utah Seismograph Stations University of Utah Office of Sponsored Projects	1

ATTACHMENT NO. A

Published paper on our research on GPS and earthquake hazards on the Wasatch fault. Three reprints of this paper are included in this report.

Chang, W. L. and R. B. Smith, 2002, Integrated earthquake hazard analysis of the Wasatch Front, Utah, Bull. Seismological Soc. Amer., v. 92, n. 2, 1904 – 1922.

ATTACHMENT NO. B

Research on Continuous and Campaign GPS Monitoring of the Wasatch Fault, Utah

General Accomplishments -- Under this project the University of Utah received support to assess earthquake hazard on the Wasatch Front, Utah using continuous and campaign GPS measurements and incorporating models of normal fault behavior. Because of reduced funding from our requested amount, tasks were reduced to: 1) conducting one limited GPS surveys in 2001 to extend the time span of Wasatch campaign data up to nine years for the purpose of reducing errors on the estimation of station velocities; and 2) operating, archiving, and processing the data of the University of Utah's 4 permanent GPS stations, along with 5 stations of the Harvard/CalTech regional Basin-Range network and 7 stations of the International Geodetic Survey (IGS) provide a stable baseline network.

In addition we addressed research on understanding the time-varying behavior of ground deformation on the Wasatch normal fault, including the inversion of GPS results for elastic dislocation modeling and the time-dependent effects of viscoelastic processes on surface deformation.

Specific efforts included:

- One GPS campaign surveys were conducted in the summer of 2001, that extends the time span of the Wasatch campaigns (started in 1992) up to nine years. This longer time interval increases the quality of estimated velocities by a factor of four compared with our previous 1992-1995 results. These surveys were materially enhanced by the contribution, at little cost to the project, by the use of four GPS receivers and trained undergraduate students under the supervision of Professor Ron Harris of Brigham Young University.

- Operating and maintaining five permanent GPS stations. Note that we have obtained three additional years of CGPS data (1999 to 2002) that will increase the quality of velocity estimations by a factor of five.

- Continued design of permanent GPS stations and digital telemetry to withstand rugged, mountainous terrain in cold weather climate.

- Installation of a UPS for reliable CGPS recording and the addition of extended memory for the UltraSparc recording computer.

- Daily data processing of 19 CGPS stations in the Intermountain region.

- Presented invited and contributed papers on our research at the following scientific meetings: 1) the 2000 and 2001 Annual Meetings of the Seismological Society of American; 2) the 2000, and 2001 Fall Meetings of the American Geophysical Union; and 3) the 2001 USGS sponsored probabilistic earthquake hazards workshop in Salt Lake City, Utah.

Campaign GPS Surveys – GPS campaign survey provide denser and broader station spacing and materially add new information to the 3-D velocity field obtained by CGPS. During the fall of 1999, the University of Utah, in cooperation with Brigham Young University, conducted a GPS field campaign along the central Wasatch fault. We had re-occupied 43 sites whose baselines cross the Weber, Salt Lake City, Provo, and Nephi segments of the fault. In the summer of 2001, six more sites were re-surveyed along the Brigham City segment to the north that provides the spatial coverage of the Wasatch fault geodetic investigation more complete.

The above data were jointly processed with that from previous Wasatch campaigns (1992, 1993, 1994, and 1995) using the new Bernese 4.2 software. With time span up to nine years, we expect to get more evident deformation rate with lower error on most of the stations. These results will provide necessary data for kinematic analyses of the Wasatch fault, as well as contemporary information on its aseismic nature as input of its earthquake hazard assessments.

CGPS Data Processing -- Daily processing of the Wasatch Front CGPS network uses the Bernese Engine GPS processing software. Included in the processing are five permanent GPS station of the central Wasatch Front array, five northern Basin Range stations, and seven International Geodetic Service stations across North America. These stations provide essential reference frame constraints and baseline ties to stable North America. By constraining rather than fixing the coordinates and velocities at the IGS sites to the ITRF96 frame, solutions SINEX files can rigorously be combined with solutions for regional stations determined by other institutions that use other processing software.

Results -- Initial results revealed a non-uniform 2-D velocity field with respect to the stable North America reference frame, ITRF96. Strain is negligible east of the Wasatch fault, but increases rapidly west of the fault to E-W extension at ~ 0.030 ± 0.008 μstrain/yr. This rate is comparable to that from the earlier campaign survey, which showed a regional horizontal strain rate of 0.049 ± 0.023 μstrain/yr. - corresponding to a velocity of 2.7 ± 1.3 mm/yr. across 55-km wide area spanning the Wasatch fault (Martinez et al., 1998). Baselines that cross the fault also show an increase of strain from south to north, corresponding to a change of 1.8 to 2.6 mm/yr. These spatial variations imply that local tectonic strain is heterogeneous in both NS and EW directions.

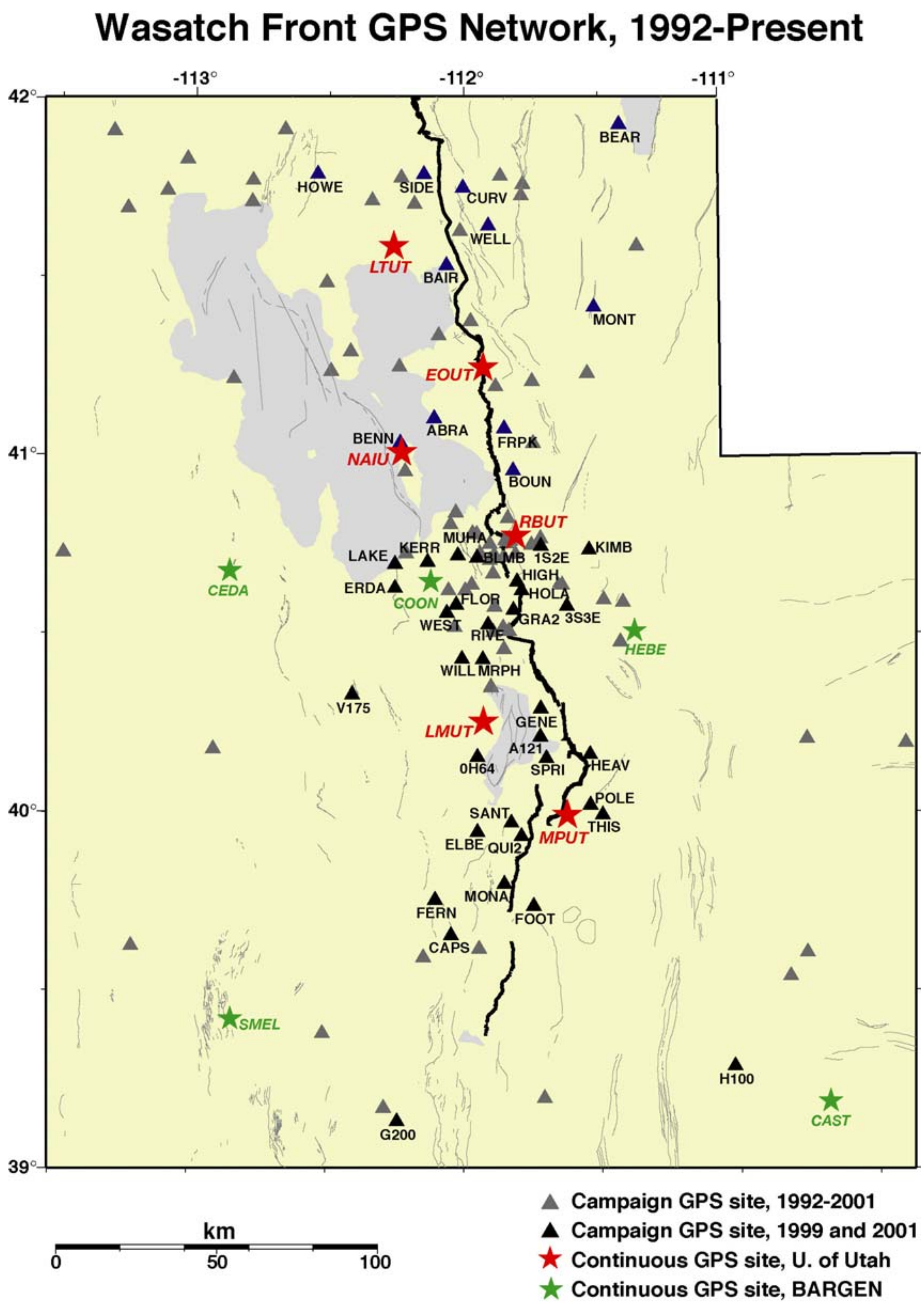

Figure 1. GPS stations of Wasatch Front, Utah. Continuous (starts) and campaign (triangles) stations are shown. Thick black lines highlight the Wasatch fault.

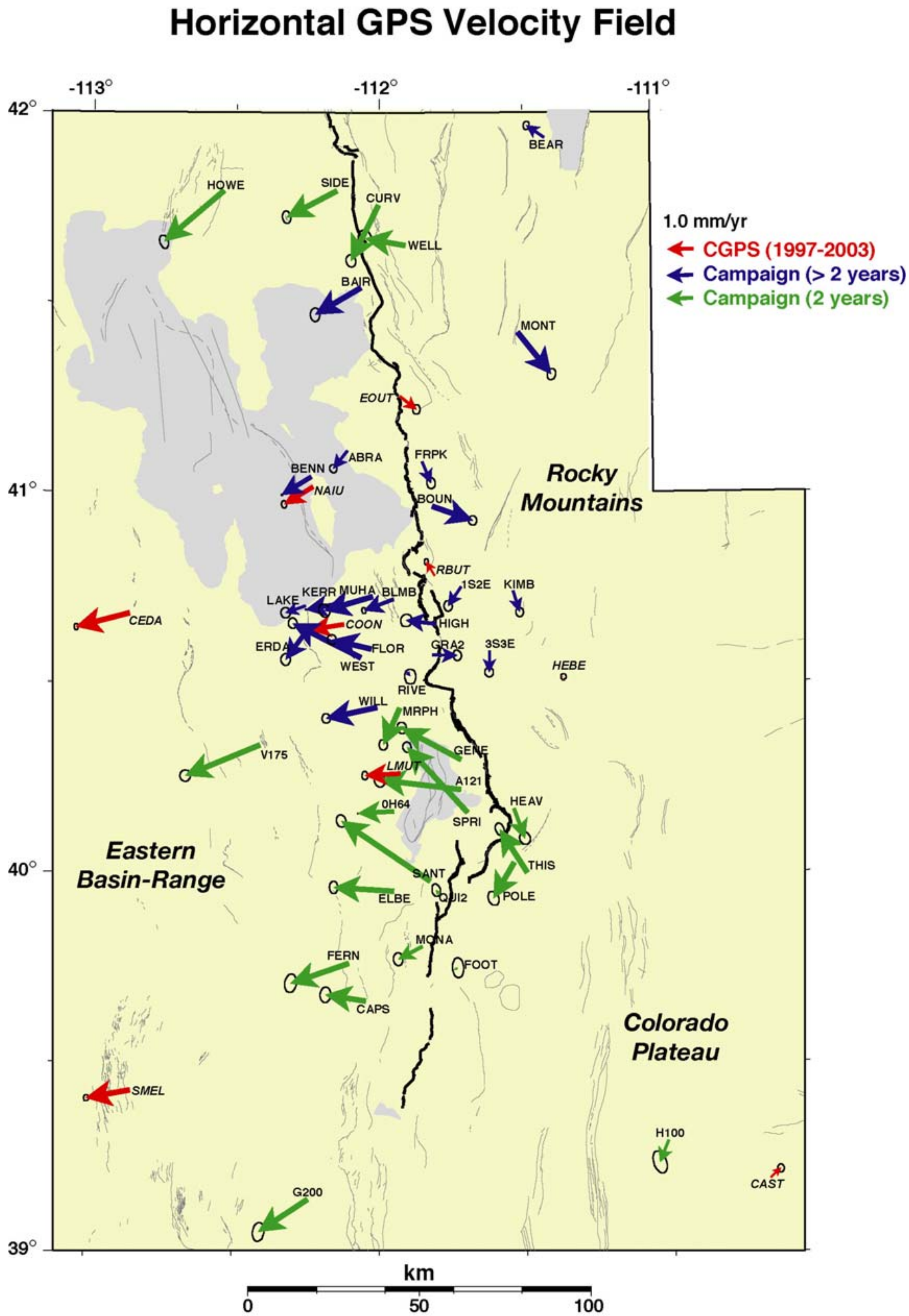

Figure 2. Wasatch Front GPS horizontal velocity vectors (1997-2002). Red vectors are from continuous recording stations, where blue and green vectors are from campaign sites.

ATTACHMENT NO. C

Research on Elastic and Viscoelastic Modeling of the Wasatch Fault, Utah

Viscoelastic, Post-Seismic Deformation Modeling -- For the Wasatch Front postseismic modeling, we employed a program package, VISCO1D (Pollitz, 1997) that is designed to describe the response of a spherically stratified elastic-viscoelastic medium to the stresses generated by an earthquake occurring in one of the elastic layers. The program allows the determination of time-dependent postseismic deformation and velocity fields, corresponding to specific rheological model and shear dislocations on a fault plane.

Rheological parameters, mainly the viscosity, for the crust and upper mantle are important factors for the modeling. Various studies derived the effective viscosity of the Wasatch Front area according to the isostatic deformation of Lake Bonneville (Crittenden, 1963; Bills et al., 1994).

Figure 3 shows a postseismic response caused by three paleoearthquakes (M>7.0) and three historic earthquakes (M>5.5), corresponding to a rheology model shown in the figure. The ruptures on the Weber and Provo segments are the two youngest paleo-earthquakes of the Wasatch fault (<1.0 ka), where the historic earthquakes were selected because postseismic response for M<5.5 event is considered to be relatively small. We also include a rupture on the East Great Salt Lake fault in 0.5 ka although its paleoseismic history is not well known. Results show that the postseismic velocities are about few tenths of the observed velocities (Fig. 2), which suggests that large paleo- and historic earthquakes on the Wasatch Front do not appear to contribute significantly to the contemporary GPS-measured velocity.

Elastic Dislocation Modeling -- Next we modeled the continuous and campaign velocity data using an elastic, non-linear inversion scheme (Cervelli et al., 2001) solving for slip-rate, locking depth and fault geometry. Results show that the data are best fit by a single N 4° W., 23-km wide dislocation that corresponds to a west dipping 27° normal fault extending eastward toward the surface expression of the Wasatch fault (Fig. 4). It has a locking depth of 9 km with an unexpectedly high loading rate of ~ 7 mm per year.

References:

Bills, B. G., D. R. Currey, and G. A. Marshall, Viscosity estimates for the crust and upper mantle from patterns of lacustrine shoreline deformation in the Eastern Great Basin, *J. Geophys. Res.*, *99*, 22,059-22,086, 1994.

Cervelli, P., M. H. Murray, P. Segall, Y. Aoki, and T. Kato, (2001). Estimating source parameters from deformation data, with an application to the March 1997 earthquake swarm off the Izu Peninsula, Japan, *J. Geophys. Res.*, **106**, 11217-11237.

Crittenden, M.D., (1963). Effective viscosity of the Earth derived from isostatic loading of Pleistocene Lake Bonneville, *J. Geophys. Res.*, **68**, 5517-5530.

Pollitz, F.F., (1997). Gravitational-viscoelastic postseismic relaxation on a layered spherical Earth, *J. Geophys. Res.*, **102**, 17921-17941.

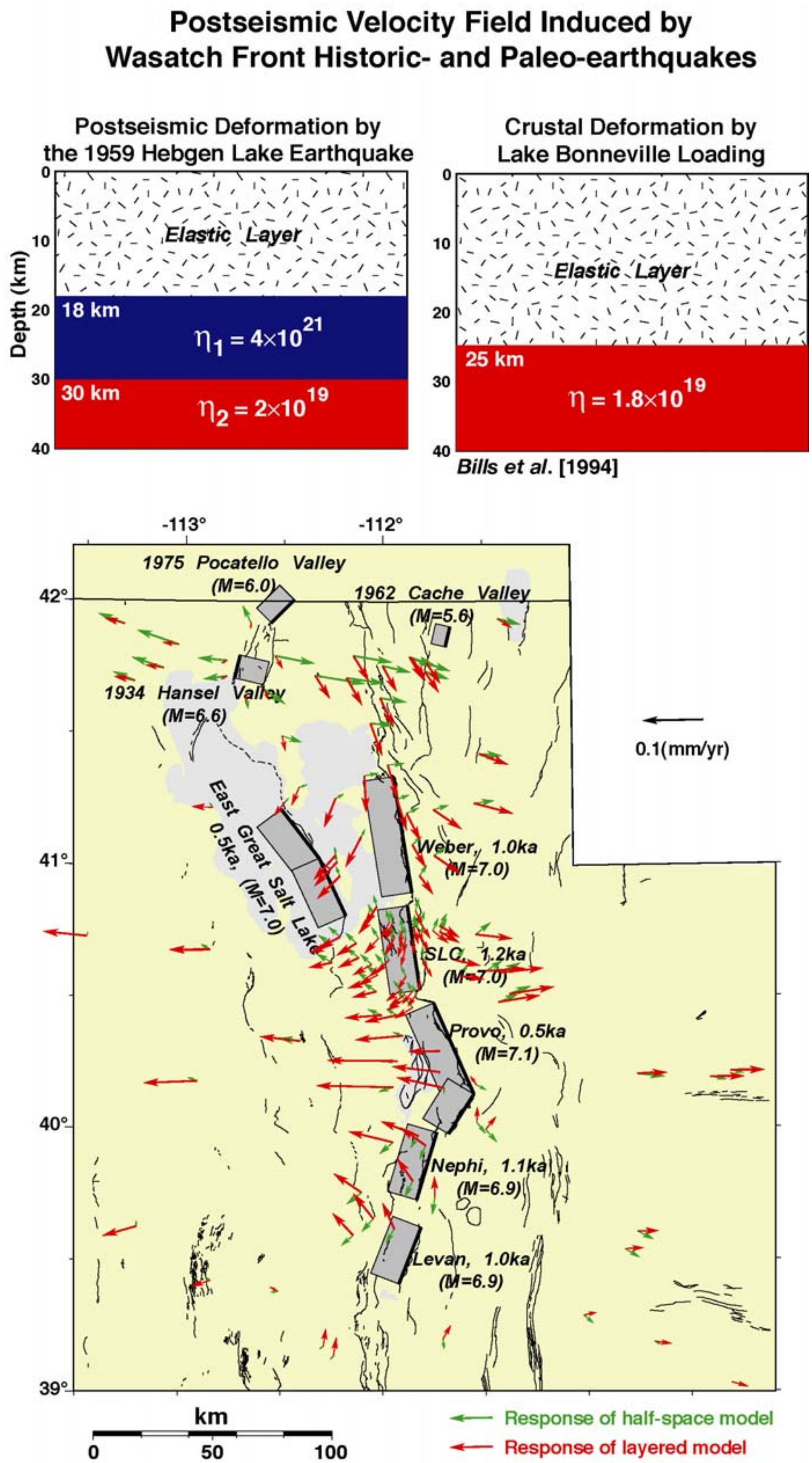

Figure 3. (a) Rheological models used for the postseismic viscoelastic modeling. (b) Postseismic velocity fields induced by five Wasatch-fault paleoearthquakes and the three M>5.5 Wasatch Front historic earthquakes.

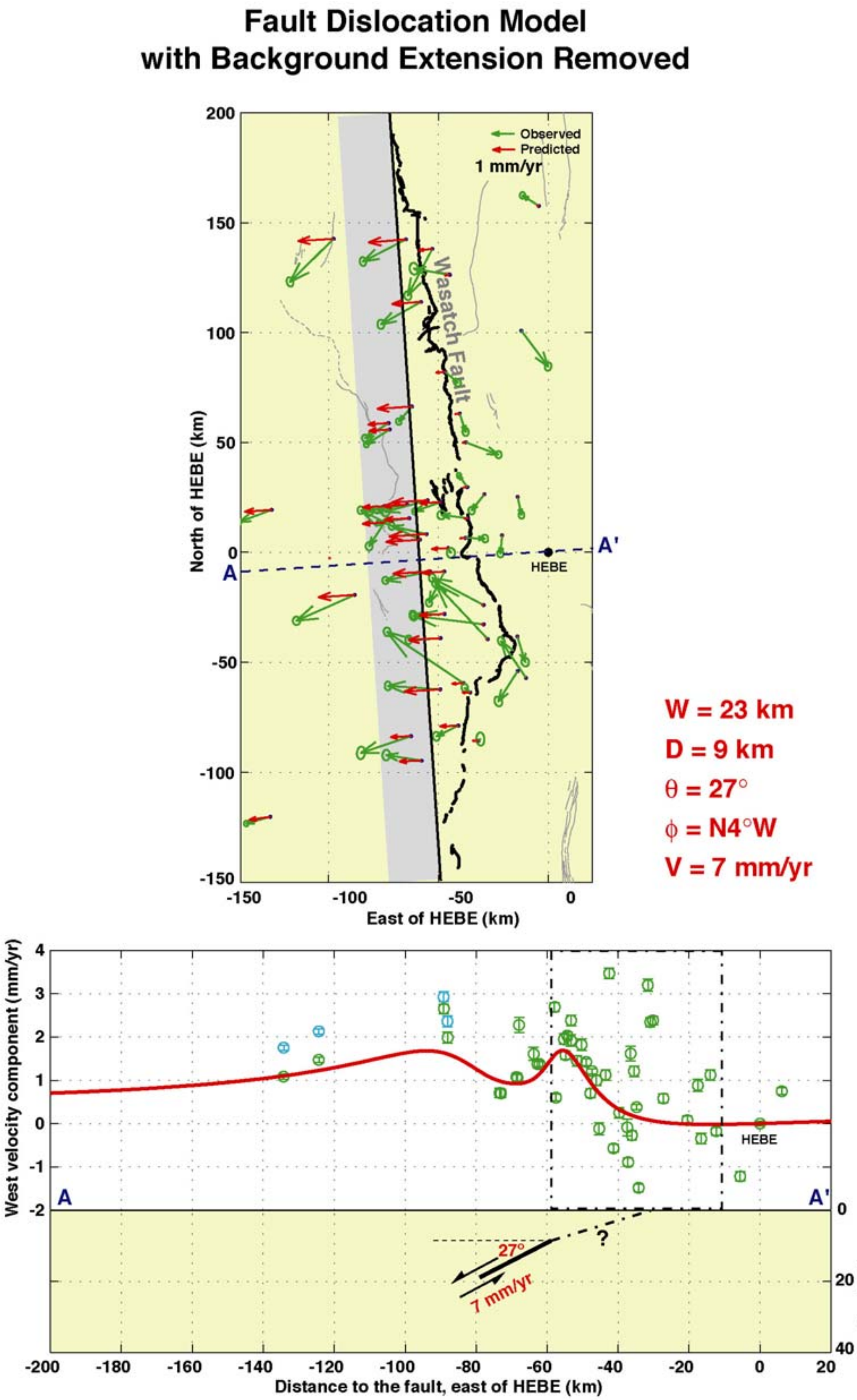

Figure 4. (a) Observed (green) and modeled (red) horizontal velocities. (b) An inverted model of the Wasatch fault that best fits the E-W velocity components (green circles with error bars).