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

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Investigations Undertaken

The above research project focused on investigations of the Wasatch fault, Utah, using continuous and campaign GPS measurements to assess the contemporary state of strain and its contribution to earthquake hazard. Fault stress modeling incorporated a new inverse fault modeling scheme employing horizontal velocity data derived from seven CGPS stations and Holocene slip rate information from paleoseismic studies. Ancillary studies included fault stress interaction to understand the relationships for earthquake triggering of multiple segments on the Wasatch fault. As well as a Probabilistic Displacement Hazard Assessment.

Our main field project includes operation of four University of Utah continuous GPS stations and data processing of nine ancillary CGPS stations (including five from the Harvard/CalTech northern Basin-Range CGPS array). Our CGPS data are set up to automatically be sent daily to the UNAVCO archive are web accessible. We also analyzed the paleoearthquake data obtained by trenching on the Wasatch fault and developed a more geologically realizable paleoearthquake time history that is not restricted by the preconceived notion of independent segments that are not affected by rupture on adjacent segments.

Results (October 1, 1998 to December 31, 1999)

General Accomplishments -- Under this project the University of Utah received support to assess earthquake hazard on the Wasatch Front, Utah using continous GPS measurements and investigating relevant models of normal fault behavior. Because of reduced funding from our proposed project, tasks were reduced to three elements:1) maintenance of four continuous recording GPS sites on the Wasatch Front, Utah, 2) 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, the paleoseismic record and fault stress interactions.

Specific efforts included:

- Operating four GPS 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.
- Continued design of continuous GPS (CGPS) stations and digital telemetry to withstand rugged, mountainous terrain in cold weather climate.
- Provide daily downloads of CGPS data to the UNAVCO data archive for web access to any interested user at: unavco.ucar.edu/data.
- Began an error analysis of the paleoearthquake data for the Wasatch Front as input to earthquake hazard models.
- Began analytic modeling the GPS data using non-linear inverse methods to determine the geometry and rates of causative faults.
- Began development of probabilistic seismic hazard curves incorporating the corrected late Quaternary slip rates, GPS and historic earthquake data.
- Presented invited and contributed papers on our research at the 1999 Fall Meetings of the American Geophysical Union and participated in a SCEC science workshop on fault stress interaction.
- In an important aspect of Wasatch Front earthquake hazards, we also began a project to analyze the Probabilistic Displacement Hazard Assessment of the Wasatch fault in an independently funded but closely related project to that our USGS funded work.

Wasatch Front CGPS Operations

The Wasatch Front CGPS network has been operating for three years (1997-1999). Currently, four stations (RBUT, LMUT, NAIU, and EOUT) are operating and telemetering data to the University of Utah. We operated an additional station at a county surveyors site in the middle of the Salt Lake Valley, mounted on alluvial fill in the early part of the project, however following a 1.5 year occupation, we removed the site because of a large, – 2.5 cm secular deformation signal due to variations in the annual ground water level.

We currently employ the Y2K compatible Bernese Processing Engine (BPE) to daily process the RINEX data from the four Wasatch Front stations together with data from seven stations from the International Geodetic Service, five from BARGEN, and six from the Yellowstone and Snake River Plain (YSRP) network.

We note that the BARGEN stations were not included in our daily processing until 1999. For this reason, we combined and reprocessed all of our data and that of the eastern BARGEN network for 1997 and 1998, and combined the results with that of 1999 to calculate station velocities over a three-year time period.

Along with our four CGPS and the five BARGEN stations, these 9 stations 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 (Fig. 1).

1999 Wasatch Front GPS Campaign Survey -- GPS campaign surveys, on the other hand, provide a denser and broader station spacing and will materially add information to the three-dimensional velocity field, especially in areas of multiple fault hangingwall/footwall coverage. During the fall of 1999, the University of Utah, in cooperation with Brigham Young University (at not cost to the project), conducted a GPS field campaign of 43 sites around the Weber, Salt Lake City, Provo, and Nephi segments of the Wasatch fault. These data will be jointly processed with that from previous Wasatch campaigns (1992, 1993, 1994, and 1995) as well as with our CGPS station data. With a time history up to seven years from these surveys, we expect to get much better time and spatial distributed deformation data with lower errors. These results will provide the necessary data for kinematic analyses of the Wasatch fault, including the necessary detail for assessing fault geometry, as well as contemporary information on its aseismic nature. These are critical input for earthquake hazard assessments.

CGPS Array Operation — Our continuous GPS sites are designed to operate in high mountainous, cold weather conditions planned for unattended operation. The instrumentation includes photo voltaic 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 Invar rods set in four to six foot long boreholes drilled into bedrock. All 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). Spread spectrum digital radio links to the University of Utah campus provide the GPS data which are then linked to a Sun UltraSparc computer (acquired by the University of Utah at no cost to the project.) Data are sampled at 30-second rates..

Problems Encountered -- This year we have not encountered any major logistical problems.

Research Results

Results (Fig. 1) from our initial CGPS processing, including four University of Utah and five BARGEN stations, revealed an unusually fast, non-uniform velocity field across the Wasatch fault with respect to the stable North America reference frame. Strain is low east of the Wasatch fault, but notably increases west of the fault to E-W extension at ~ 0.050 – 0.020 µstrain/yr. This corroborates the high strain rates from our earlier campaign surveys (Martinez et al., 1998) as well as that of determined by the USGS for the northern Wasatch fault from EDM surveys, 1972-1985 (Savage et al., 1992. The earlier surveys revealed a regional horizontal strain rate of 0.049 – 0.023 µstrain/yr. corresponding to an E-W velocity of 2.7 – 1.3 mm/yr. across 55-km wide area spanning the Wasatch fault. CGPS fault crossing baselines not only revealed the high strain rate, but a significant increase of strain from south to north, corresponding to a change of 1.7 to 2.6 mm/yr from the Provo segment to the Weber segment. These spatial variations imply that local tectonic strain is heterogeneous in both NS and EW directions.

Notably the rates of ~2 mm/yr EW correspond to a fault loading rate of 5-6 mm/yr on a 60¡ west dipping Wasatch fault plane. These rates are 4 to 6 times higher than those from determined from paleoseismic information which form the basis for the earthquake hazard assessment in the U.S. National Hazard maps.

Fault Geometry Inversion Using GPS Measurement -- Because of the confirmation of the high strain rates 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 begun collaboration with Mr. Peter Cervelli, a Ph.D. student at Stanford University who has developed a non-linear inversion scheme. Among different methodologies, we are investigating are 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 these codes, we have made initial estimates of the geometry of the causative fault responsible for the observed Wasatch fault velocity field. Preliminary modeling suggests a N-S striking, 40… W. dipping fault with a locking depth of 15 km and 15 km west of the surface exposure of the Wasatch fault The calculate fault slip rate is ~ 6 mm/yr, notably 4-5 times larger than the rate determined from paleoseismology. We are just beginning this analysis and will include the results from our recent GPS campaign data, that we expect to provide more realistic models including other surrounding potential faults such as the Oquirrh, Great Salt Lake, and Cache Valley faults.

Analysis of Paleoseismic Slip Data -- After reviewing the paleoseismic data for the Wasatch fault we concluded that is was highly variable in quality and lacked a quantitative analysis of errors. We collaborated with Dr. Jim McCalpin who has worked extensively in paleoearthquake studies of normal faults and who did the first quantitative analysis of earthquake hazard of the Wasatch fault (McCalpin and Nishenko, 1995). To do this we worked with Dr. McCalpin to sort out the highest quality fault slip rates from the existing 16 trench suite of data.

We then developed multiple-segment fault slip models (Fig. 2) of Late Quaternary fault ages and measured displacements from sixteen trench sites along the Wasatch fault independently fitting ellipsoidal displacement surfaces to the age and displacement data. These data, reveal that as many as 13 M7+ earthquakes have occurred in the 5,600 paleoearthquake record with slip rates varying from 0.94 to 2.1 mm/yr but with notable standard errors as large as 1.2 mm/yr (Table 1) indicating that these data can not be used with an understanding of their errors, how they may or may not fit into stochastic vs. spatial-clustering models, and whether the characteristic earthquake model, routinely used by the paleseismological community, is valid. Using our model we then developed space-time scenarios of 17 scarp-forming, paleoearthquakes, M7+, in the past 5,600 years, including as many as eight, multiple-segment ruptures, that extended across segment boundaries.

TABLE 2
Slip Rate Of Individual Segment Of The Wasatch Fault, Based On The Modeled Maximum Displacement Of Each Paleoevent

Fault Segment	Inter-event Slip Rate (mm /yr)				Average Slip Rate (– 1σ)
Events[***]	W - X	X - Y	Y - Z	Z - present	
Brigham City		0.97	0.92		0.94 – 0.04
				0.94[*]	0.94 – 0.03[**]
Weber		2.24	0.93		1.58 – 0.93
				1.97	1.71 – 0.69
Salt Lake City	0.69	1.80	1.81		1.44 – 0.64
				1.63	1.48 – 0.53
Provo		1.10	1.21		1.16 – 0.08
				3.24	2.17 – 1.20
Nephi		2.67	0.81		1.74 – 1.32
				1.74	1.74 – 0.93

- Present slip rates in gray cells are defined as 2m/(age of the most recent event).
- [**] Average slip rates in gray cells include the present slip rates.
- [***] Event names are based designated Wasatch fault segements.

Using the reanalyzed paleoearthquake data, the occurrence rate of large, Mw > 6.6 earthquakes on the Wasatch fault is about four times higher than that predicted by the historic seismicity of the Wasatch fault, but lower than that predicted by the 1960-1995 geodetically determined strain rate of the Wasatch Front, Utah. This suggests that aseismic moment due to fault creep, interevent fault-loading or advective westward extension may be important mechanisms that affect earthquake loading on the Wasatch Front.

Non-Technical Summary

Under this research project, the University of Utah conducts research on time-varying behavior of the Wasatch fault by precise measurements of ground motion using continuous-recording GPS (Global Positioning Systems) satellite receivers. The GPS antennas are mounted in bedrock and transmit data to the University of Utah via radio links for recording and processing. The project is a follow-up to confirm measurements from a 1992-1995 temporarily deployment of GPS receivers 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 across western Utah and northern Nevada. Initial results confirm the high deformation rates determined in our earlier surveys and are much larger than those inferred by geologists. Because of this discrepancy they have a much more important implication for earthquake hazard than heretofore considered. We also note that our CGPS data are provided to the local surveying community for high accuracy reference surveying.

Papers, Theses and Presentations Related To Project

Braun, J., 1999, Probabilistic displacement hazard assessment of the Wasatch and surrounding faults, Wasatch Front, Utah, 151 pp.

Chang, W. L. and R. B. Smith, 1999, Stress analyses and earthquake history of large historic and paleoearthquakes of the Intermountain region, 1999 Abstracts with Programs, Rocky Mountain Section, Geological Soc. America, v. 31, n. 4, A-7.

Chang, W. L. and R. B. Smith, 1999, Stress analyses of historic and paleoearthquakes in the Intermountain region, 1999 Ann. Meeting and Exposition, Geological Soc. America, A-376-377.

Chang, W. L., and R.B. Smith, 1999, Normal-fault stress interaction and its effects on probabilistic seismic hazard analysis, Program with Abstracts, 43 Ann. Meeting, Association of Engineering Geologists, p. 61.

Chang, W.L. and R. B. Smith, 1999, Stress contagion by large normal-faulting earthquakes and its effects on seismic hazard estimations, Eos, Trans. Amer. Geophys. Un. 80, 46, F1009.

Smith, R. B., C. M. Meertens, K. Lynch, A.R. Lowry, and R. Palmer, 1999, Active tectonics of the northern Basin-Range and Yellowstone hotspot, 1999 Abstracts with Programs, Rocky Mountain Section, Geological Soc. America, v. 31, n. 4, A-56.

Chang, W. L. and R.B. Smith, 2000, Stress contagion, paleoseismicty and seismic hazard assessment of the Wasatch Front, Utah, Seis. Soc. Am. Bulletin, (in preparation).

Availability of Data

All Wasatch Front campaign and continuous GPS data are archived in Rinex format the UNAVCO (University NAVSTAR consortium) data management center, Boulder, Colorado at unavco.ucar.edu/data. Hourly data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network which are accessible by ftp at ftp://cors.ngs.noaa.gov/coord. This component of our research project provides the local surveying community with local base stations. As soon as a reliable automated processing scheme is completed all of our data along with the Northern Basin Range array data will be available on-line.

Horizontal Velocity Field of the Wasatch Fault and Surrounding Area from CGPS data (1997-1999)

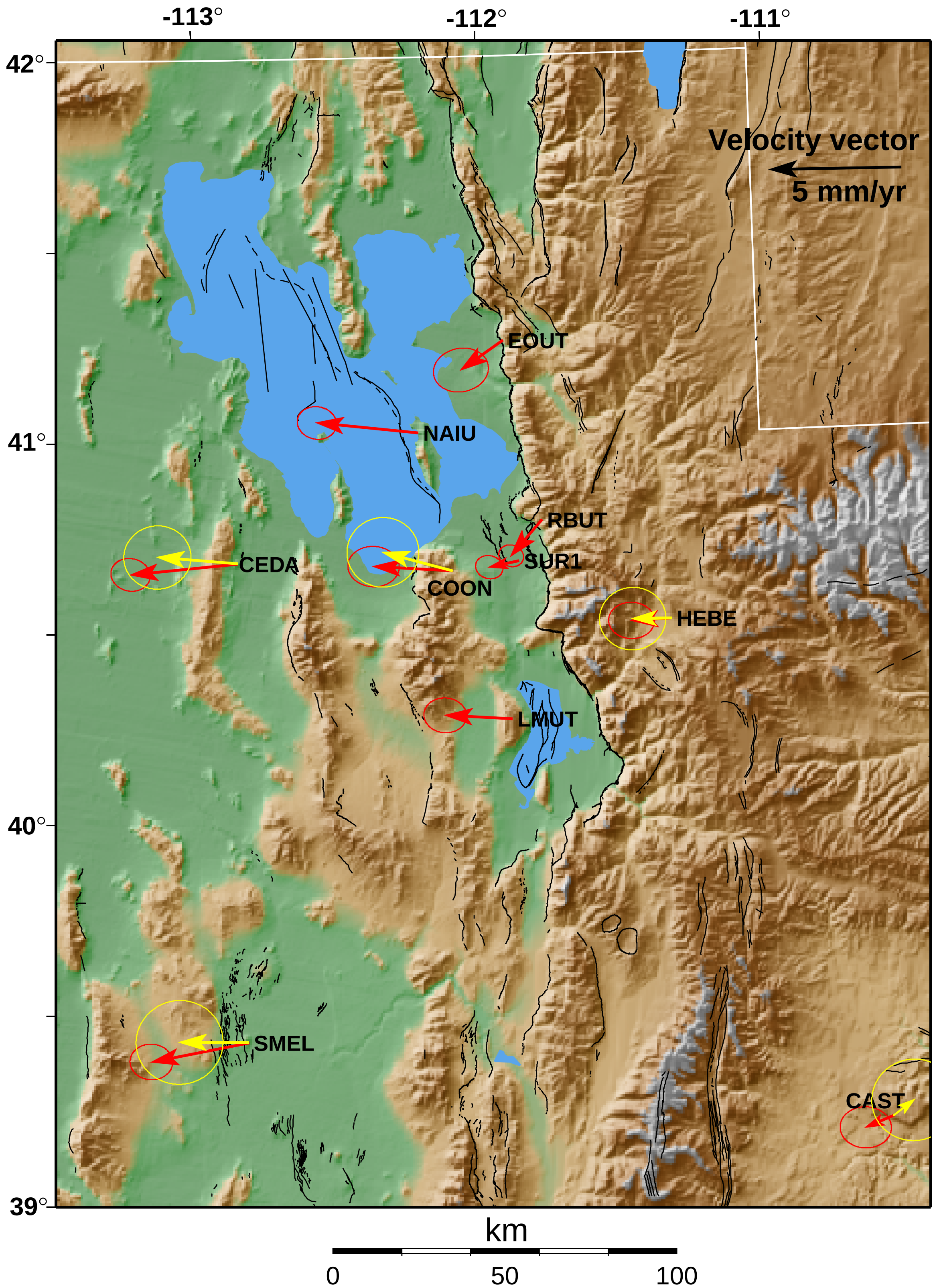

Figure 1. Combined processing of CGPS data from University of Utah and Harvard-Smithsonian-Caltech stations holding 4 N. American stable stations fixed and in a ITRF96 Reference frame (Red = University of Utah, Yellow = HSC).

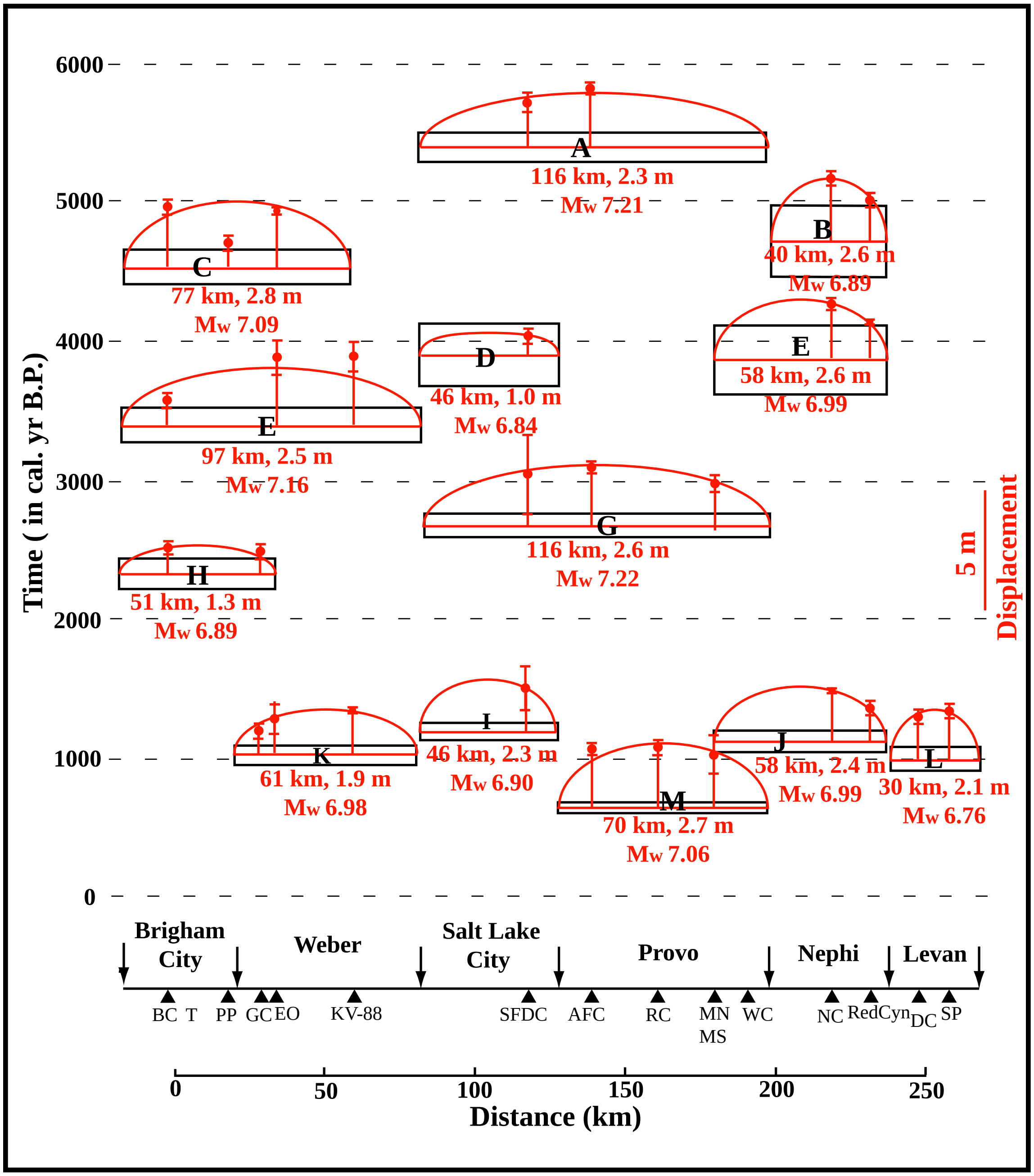

Figure 2. Distributions of fault slip on paleoearthquakes (lettered box) of the Wasatch fault, based on the multisegment scenario. Red bars show earthquake displacements measured from trenches, with average values and error ranges. Elliptical envelopes (red curves) fit the displacement data of each event. The rupture length (in km), the maximum displacement (in m), and the moment magnitude (Mw) are shown under each event. The magnitudes are estimated according to the maximum displacements and rupture lengths.