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Rapid deformation rates along the Wasatch fault zone, Utah, from first GPS measurements with implications for earthquake hazard

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Abstract. Anomalously high rates of crustal deformation have been measured at the Basin-Range transition to the Rocky Mountains along the Wasatch fault zone, Utah, by repeated Global Positioning System (GPS) measurements. Four GPS field campaigns (1992-1995) and comparisons with older (1962-1991) geodetic data have revealed east-west extensional strain at a rate of 0.05 ± 0.02 μstrain/yr, corresponding to a 2.7 ± 1.3 mm/yr rate of horizontal displacement across a 55-km wide area. This rate is more than 20% of the total ~12 mm/yr extension rate across of the ~800-km wide Basin and Range province. It is also two to three times larger than the average Late Quaternary fault slip rate on the Wasatch fault and tens of times larger than the displacement rates inferred from the cumulative seismic moments of historic earthquakes. While we do not yet know the source of this unexpected contemporary deformation, possible mechanisms include homogeneous crustal extension, loading of the Wasatch and adjacent faults, and pressure solution creep. If the Wasatch fault is being loaded by this high strain rate, it increases the expected peak ground acceleration significantly from standard values. These new findings demonstrate the importance of GPS in earthquake hazard assessment.

Introduction

The 750-km wide northern Basin and Range Province is characterized by parallel north-south trending mountains, most bounded by range-front normal faults that have been active in Quaternary time (Figure 1). The 350-km long Wasatch fault zone, the focus of our investigation, marks the easternmost edge of the province. Very Long Baseline Interferometric (VLBI) results [*Dixon, et al.*, 1995] have provided constraints on the broad deformation pattern of the Basin-Range (Figure 1) showing an integrated Basin-Range motion of 12.1 ± 1.2 (1σ) mm/yr from OVRO in a north-northwest direction with respect to stable North America. A rate of 4.9 ± 1.3 mm/yr of westward motion of Ely, Nevada, in the central Basin-Range, was also determined from VLBI observations [*Dixon, et al.*, 1995]. Initial results from a regional 18 station permanent GPS network across the entire northern Basin-Range, with an average station spacing of 100 km, are consistent with the VLBI results [*Bennett et al.*, 1998].

The Wasatch fault zone, Utah, is part of the Basin-Range transition to the Rocky Mountains. It has been surveyed by ground-based trilateration methods across part of the Weber segment [*Savage, et al.*, 1992] and by our GPS surveys (Figures 2 and 3). The Wasatch Front GPS network spans the trilateration network and, in addition, covers the populated Salt Lake fault segment to the south and the Brigham segment to the north. In this work, we present first deformation measurements from repeated GPS surveys observed in a three year period, supplemented by comparisons with trilateration and triangulation observations made up to 30 years ago. The results indicate that half of the regional strain rate between Vernal, UT, and Ely, NV, (Figure 1) is occurring in the ~55 km wide GPS survey area, encompassing the Wasatch fault.

The Wasatch fault is the longest, spatially continuous Quaternary normal fault in the western United States and in the last 6000 years has experienced at least ten 6.8>M>7.3 scarp-forming paleoearthquakes, on average every 400 years [*McCalpin and Nishenko*, 1996]. Although the Wasatch fault has had significant Late Quaternary movement, it has exhibited relatively low seismicity in historic time. Our GPS measurements suggest, however, that it is part of an actively deforming crustal block and we point out that these data can contribute to earthquake risk assessment.

Wasatch Fault GPS Surveys

Collaborative GPS surveys were initiated by the University of Utah in 1992 to determine the state of strain on the Wasatch fault. A total of 93 GPS sites (Figures 2 and 3), with an average spacing of ~15 km, were occupied in the 1992 (Salt Lake City segment), 1993 (Weber-Brigham City segment), 1994 (Provo-Nephi segments), and 1995 (combined) surveys. The GPS results were compared with geodetic data, dating back to 1962, collected by the National Geodetic Survey (NGS) [*Snay, et al.*, 1984] and the U.S. Geological Survey (USGS) [*Savage, et al.*, 1992].

The Wasatch Front GPS data were processed with Bernese software [*Rothacher and Mervart*, 1996] using precise post-fit orbits from the NGS and the International GPS Service. For our data, the weighted coordinate (1σ) uncertainties based on day-to-day solution repeatabilities averaged 2-3 mm for the N-S, 3-4 mm for the E-W, and 8-9 mm for the vertical baseline components. The uncertainties were twice as large for the baselines used to position the Utah network in a global coordinate reference frame and precluded determination of precise velocities with respect to the stable North American continent.

Between 1992 and 1995, twenty-six of the GPS sites, primarily along the Salt Lake and Weber segments, were surveyed twice or more permitting estimation of individual station velocities and network strain rates. Analysis of the Wasatch data was performed using inner-coordinate solutions [e.g. *Savage et al.*, 1992]. With

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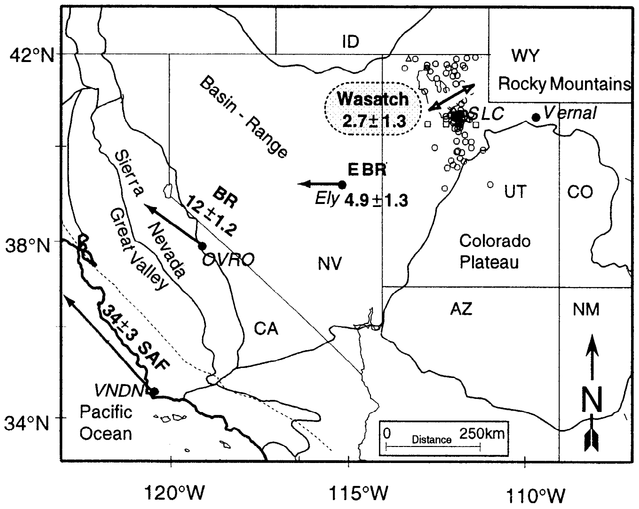

Figure 1. Regional tectonic provinces of the western United States showing horizontal displacement rates (mm/yr.) for various regions from VLBI (single headed arrows) and GPS measurements (double headed arrow). SAF = motion along the San Andreas fault; BR = total Basin-Range rate (Vernal, UT, to OVRO, CA), and EBR = eastern Basin-Range rate Vernal to Ely, NV, [*Dixon et al.*, 1995]. Wasatch = Wasatch Front GPS network (circles).

this method, network translations are determined by minimizing coordinate differences from year-to-year and then applied to the coordinates to give station velocities relative to the local centroid of the network (Figure 3). Though showing some scatter in direction, there is a consistent sense of east to northeast extension that is more apparent in the strain analysis results.

Strain Analyses

For strain analysis, we used a weighted least squares adjustment program, DYNAP, that simultaneously estimates the strain rate tensors and positional coordinates [*Snay, et al.*, 1984]. As opposed to velocity estimates, where two velocity parameters are estimated per station (direction and magnitude), the strain rate determinations use all the coordinate differences to estimate as few as three independent parameters (e.g. magnitude and orientation of the two horizontal principal axes of strain in the two-dimensional case).

The assumption of spatial and temporal homogeneous strain was shown to be appropriate by *Martinez* [1996] who found no significant spatial variations in the data that would warrant a higher-order strain model. Since the noise level of the vertical component of GPS data is several times larger, we only considered the horizontal component of deformation in this study. The strain rates estimated from the GPS and combined geodetic data are summarized in Table 1 along with published earthquake, geodetically, and geologically derived strain and displacement rates for the Wasatch fault zone.

GPS Results--Strain rate estimates were made for the central portion of the Wasatch fault zone using the GPS data acquired from 1992 to 1995 from 57 baseline vectors (one vector per station per campaign). They yielded a strain rate of 0.049 ± 0.023 (1σ) µstrain/yr (extension positive) at an azimuth of 59° ± 15°. The orthogonal strain rate component was smaller and contractional at -0.033 ± 0.020 µstrain/yr. A horizontal displacement rate of 2.7 ± 1.3 mm/yr of extension across the 55 km width of the GPS network is thus inferred from our strain rate determination.

Combined GPS and Trilateration--On the Weber segment of the Wasatch fault, eight of the GPS sites were co-located at USGS trilateration sites that had been observed between 1972 and 1990 using Geodolite laser distance measurement instruments [*Savage, et al.*, 1992]. The trilateration method has a length precision of 5 to 8 mm (1σ) over baseline lengths of 20 to 40 km. However, *Savage et al.* [1994] has shown that it also yields distances systematically larger than GPS measurements by 0.44 ppm. The strain rate determined by adjustment of the GPS and corrected trilateration observations reveals extension at a rate of 0.054 ± 0.014 µstrain/yr at an azimuth of 74° ± 8° with minor contraction in the perpendicular direction.

Combined GPS-Trilateration-Triangulation--The GPS data were also combined with data from the triangulation and trilateration surveys by the NGS on the Weber and Salt Lake segments of the Wasatch fault [*Snay, et al.*, 1984]. NGS data from 40 triangulation measurements from 1962-1963, and 1412 triangulation and 76 trilateration measurements done between 1973 and 1974, had a standard error of 4 µradians in direction and 20 mm in distance. The strain rate estimated using the combined data is predominantly extension at a rate of 0.051 ± 0.010 µstrain/yr at an azimuth of 73° ± 7°.

Comparison with other strain indicators

The regional displacement rate of the 350 km wide eastern Basin-Range transition to the stable North American plate is 4.9 ± 1.3 mm/yr (Figure 1) as determined from VLBI measurements [*Dixon, et al.*, 1995]. Our GPS determined rate indicates that at

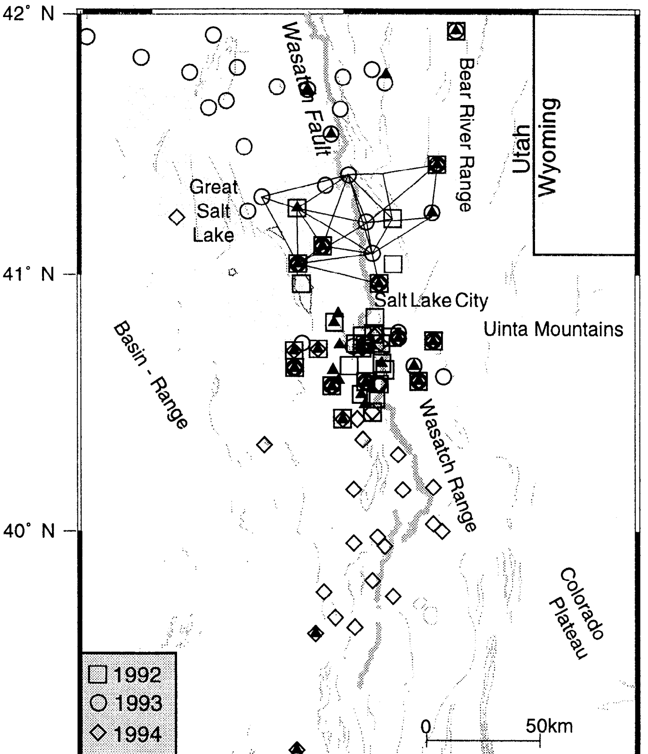

Figure 2. Map of Wasatch Front GPS survey points by year of occupation observed by the University of Utah. Late Quaternary faults are highlighted. Baselines of USGS EDM network near Odgen are shown.

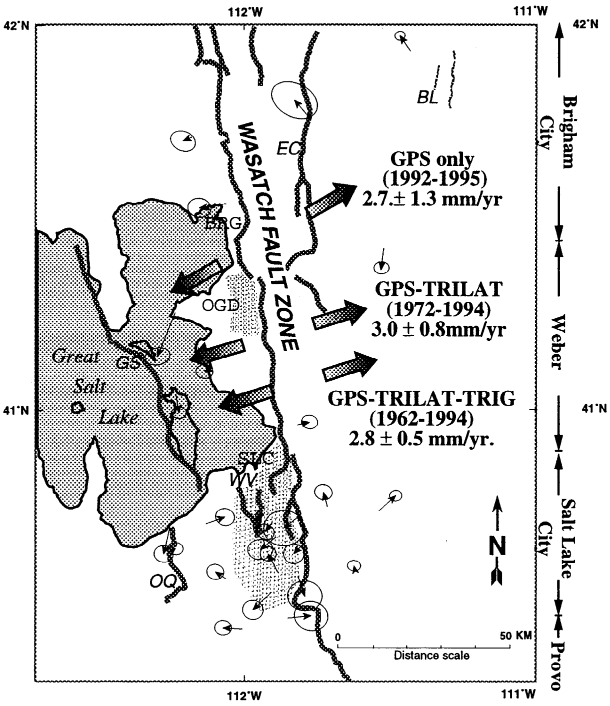

Figure 3. Wasatch Front GPS velocities and derived average strain and velocities from various data (mm/yr) with 1σ error ellipses. Late Quaternary faults and named segments are highlighted. Offset of arrows separates results only. Faults: BL = Bear Lake, EC = East Cache, WV = West Valley, OQ = Oquirrh and GS = Great Salt Lake. Cities: BRG = Brigham City, OGD = Ogden, and SLC = Salt Lake City.

least half of the extension is occurring across the 55 km width of the central Wasatch fault zone. In addition, initial results from the three easternmost Basin-Range permanent regional GPS stations of *Bennett et al.* [1998], show 2 ± 2 (1σ) mm/yr across a 150 km-wide area spanning the Wasatch fault zone and are consistent with our results within the current uncertainties.

Wasatch fault slip rates determined from trenching studies yield recurrence intervals of Late Quaternary paleoearthquakes, 6,000 - 450 year before present, of 0.4 to 2.0 mm/yr. [*McCalpin and Nishenko*, 1996]. These rates, however, were made by measuring offsets in near-vertical fault scarps in unconsolidated rocks. Assuming a 60° west dip of the Wasatch fault at seismogenic depths, the corresponding horizontal rates are 0.15 to 1 mm/yr. The measured GPS and combined GPS-geodetic determined rates are about three times larger, although within 2 σ they are similar to the geologic rates.

An estimate of brittle strain release can also be made from cumulative moments of historic earthquakes. Although Basin-Range seismicity is concentrated in the western and eastern margins of the province, the absence of large events on the Wasatch fault in historic time corresponds to low earthquake moment strain rates. The rates are 0.004 μstrain/yr oriented NW-SE for the northern part and 0.001 μstrain/yr for the southern parts of the Wasatch fault [*Eddington, et al.*, 1987]. Though in the same direction of extension, these rates are over an order of magnitude smaller than the geodetically determined strain rates.

Implications of high strain rates

The strain rates determined in this study and the results of *Savage, et al.* [1992], summarized in Table 1, are consistent and indicate ~2.8 mm/yr of east-northeast extension across the Wasatch Fault zone. The uncertainties range from 0.5 to 1.3 mm/yr (1σ) with more precise rate estimates reflecting longer time intervals.

To examine possible sources of the GPS measured horizontal deformation field, *Martinez* [1996] constructed simple dislocation models for plausible geometries of the Wasatch and nearby faults similar to those of *Savage, et al.* [1992]. Within the observed measurement uncertainties, the results were found to be consistent with: 1) approximately 4 to 5 mm/yr of localized slip on a buried fault plane dipping 60° west, or 2) uniform east-west strain of a homogeneous crustal block. It is not yet possible to distinguish between these two end-member models because of the lack of broader GPS coverage and the limitations of the current resolution of the GPS measurements.

Other possibilities for the anomalous strain rate include unrecoverable permanent deformation associated with such mechanisms as pressure solution creep [*Spiers et al.*, 1990], unidentified footwall faulting, loading of buried and unidentified faults or loading of faults beyond the study area. Nonetheless, if the source of the deformation extends beyond the 55 km wide GPS network, the VLBI constraints limit the relatively high strain rates to a few tens of kilometers beyond our network.

Another important aspect of the GPS determined rates are implications for earthquake risk. In the absence of significant historical earthquake activity along the Wasatch fault zone, earthquake probability estimates have relied primarily upon Late Quaternary fault slip rates. These data suggest that the probability of a large earthquake occurring on any one segment of the Wasatch fault is 25% in the next 100 years [*McCalpin and Nishenko*, 1996]. However, this estimate is only a part of the information needed to assess earthquake hazards. The U.S.G.S. 1996 National Earthquake Hazard Maps [*Frankel et al.*, 1996] give a more complete

Table 1. Wasatch Front Strain Rates from Geodetic, Seismic and Geologic determinations

Method	Source	Least (Top) and Greatest Principal Strain Rate (μstrain/yr)	Horizontal Displacement or Fault Slip Rate (mm/yr)	Orientation of Least Principal Strain Rate
Geodetic	This study: GPS only [1992-1995]	0.049 ± 0.023 -0.033 ± 0.020	2.7 ± 1.3 (55 km)	59° ± 15°
	This study: GPS- Trilateration [1970-1994]	0.054 ± 0.014 -0.017 ± 0.012	3.0 ± 0.8 (55 km)	74° ± 8°
	This study: GPS-Triangulation-Trilateration [1962-1994]	0.051 ± 0.009 0.005 ± 0.008	2.8 ± 0.5 (55 km)	73° ± 7°
	Trilateration [*Savage, et al.* 1992]	0.047 ± 0.011	2.6 ± 0.6 (55 km)	91° ± 5°
Late Quaternary Slip Rates	Summarized by *McCalpin and Nishenko* [1996]		0.35-2.0 (in fault plane; dependent on fault segment)	E-W (perpendicular to fault strike)
Seismic Moments	*Eddington, et al.* [1987]	0.0041 (northern Wasatch) 0.0012 (southern Wasatch)	0.13 0.04	78° 76°

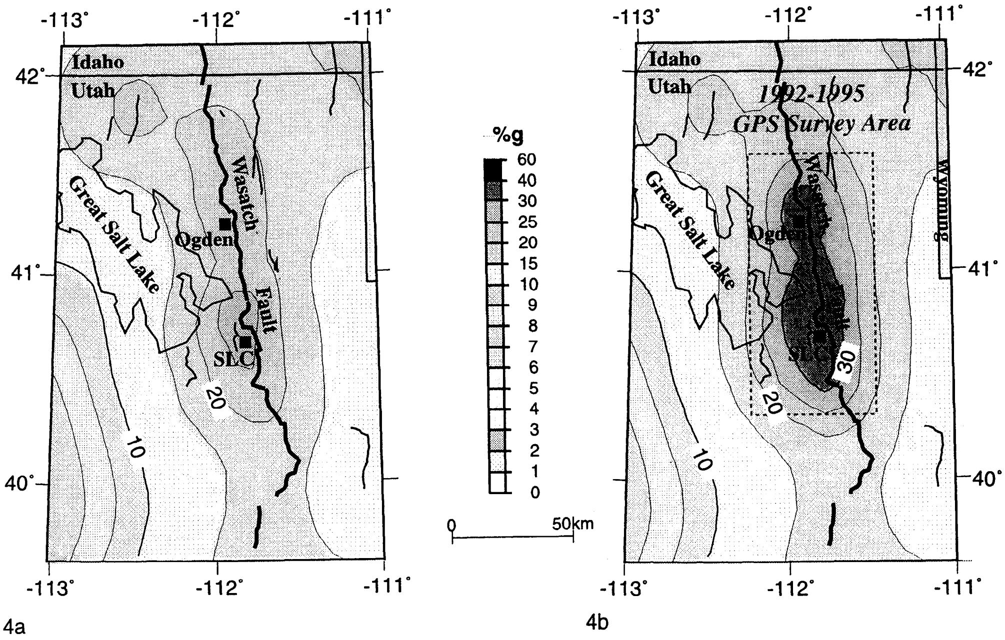

Figure 4. Earthquake hazard estimates for the middle to northern Wasatch Front, Utah; (a) Peak ground accelerations for 10% probability of exceedance in 50 years using fault and historical seismicity data [*from Frankel et al.*, 1996]; and (b) Peak ground accelerations with same parameters as in (a), but assuming a contribution of fault slip inferred from the GPS measured deformation in the 110 km by 55 km survey area (*Arthur D. Frankel, pers. comm.*, 1997). Note that the Bear Lake fault was not included in the calculations.

hazard assessment in terms of the estimated annual exceedance rates of peak ground acceleration (PGA) using Late Quaternary fault slip rates and historical earthquake rates for a range of plausible magnitudes, 5.0 < M < 7.2 (Figure 4a).

The impact of including the excess deformation rates from our new GPS measurements into the Wasatch Front hazard scenario is shown in Figure 4b. For the middle segments of the Wasatch fault, *Frankel et al.* [1996] employed rates of 1.0 to 2.0 mm/yr of fault slip derived from *McCalpin and Nishenko* [1996]. An additional 2 mm/yr of fault slip was added to model the lower bound of the GPS measured deformation. Using the summed rate, the total seismic moment rate for the GPS survey box was calculated. The new a-value that would produce this total moment rate with the b-value from the historic earthquake data was used to determine the PGA values for a 10% probability of exceedance in 50 years. The PGA values of 0.2 to 0.25 g (Figure 4a) [*Frankel et al.*, 1996] were raised to 0.3 to 0.35 g (Figure 4b) in the vicinity of the Wasatch fault, a significant increase in expected ground accelerations. Using the upper bound of the observed GPS deformation, the largest values of PGA could increase to over 0.40 g.

The new Wasatch fault GPS results suggest that if the excess strain is loading the faults, the earthquake risk on the populated Wasatch Front, Utah, may be underestimated. These findings emphasize the need for a broader distribution of GPS stations recording for longer periods of time to improve data precision, better constrain models of normal faulting, assess inter- and post-seismic deformation stress loading, and evaluate how geodetic data can be incorporated in earthquake hazards assessments.

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