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IS THERE SLOW SLIP ON THE WASATCH FAULT?

by

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Thesis submitted in partial fulfillment
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IS THERE SLOW SLIP ON THE WASATCH FAULT?

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ABSTRACT

To accurately determine the earthquake hazard posed by a fault, we need to understand both strain accumulation and release along the fault. Strain accumulates during aseismic periods but it is released during fault slip events that can be either seismic or aseismic. Aseismic slow slip events are motions similar to earthquakes but they occur over much longer timescales. Slow slip is not felt at the Earth's surface but it can be recorded in GPS time series. A deformation modeling tool that was applied in Guerrero, Mexico by Lowry et. al. (2001) fits a hyperbolic tangent function to GPS time series and can be used to distinguish slow slip events from noise in the data and from non-tectonic deformation. Time series from the Plate Boundary Observatory, Wasatch Front GPS Network, and Basin and Range Geodetic Network were analyzed for transient deformation during the period encompassing 2004 to 2008. Data suggests several transient motions including a possible slow slip event beginning in mid-2008 and continuing into 2009. Both seismic and aseismic slip influence the earthquake cycle, and slow fault slip events offer a window into frictional properties on fault surfaces that will rupture in future earthquakes. Consequently, as we increase our understanding of aseismic slip and why it occurs, we eventually may expect to develop predictive models of fault slip through time by combining measurements of aseismic and seismic slip in models that reflect the physics of frictional slip on faults.

ACKNOWLEDGEMENTS

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I extend my thanks and appreciation to my advisor, Tony Lowry, for all he has taught me about geophysics. His advice, patience, and encouragement have been a great help in class, research projects, and other aspects of my undergraduate life. I would also like to thank my departmental honors advisors, Pete Kolesar and Joel Pederson, for all their patience and help with setting up honors contracts and arranging class schedules.

In addition, I would like to thank my family and friends whose support and example has motivated me to work hard and helped me get through the stressful times. I would especially like to thank my parents for teaching me that it is alright to step off the traditional path because that is when the journey of discovery begins.

> “Every day I remind myself that my inner and outer life are based on the labors
> of other people, living and dead, and that I must exert myself in order to give
> in the same measure as I have received and am still receiving.”
> Albert Einstein

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1 INTRODUCTION

To accurately determine the earthquake hazard posed by a fault, we need to understand both strain accumulation and release along the fault. Strain accumulates during aseismic periods but it can be released during seismic and aseismic periods. Seismic release of strain results in earthquakes. Aseismic strain release is commonly known as aseismic or slow slip and it occurs over a long time period. It is expected that aseismic moment release will be a little smaller that seismic release because the amount of slip that occurs during an aseismic event is generally two or more orders of magnitude smaller that the slip that occurs during an earthquake, even though the area activated during an aseismic event many be larger.

Previously, slow slip events have been identified on plate boundaries in Mexico (Larson et. al., 2004; Lowry et al, 2001; Lowry et. al., submitted), Cascadia (Brudzinski and Allen, 2007; Dragert et. al., 2001), New Zealand (Douglas et. al., 2005), Japan (Hirose et. al., 1999; Ozawa et. al., 2001: Obara et. al., 2004), Alaska (Freymueller et. al., 2003), and Costa Rica (Protti et. al., 2005) using continuous GPS network observations. These locations correspond to subduction margins but slow slip has also been seen within the continental interior on a large-scale normal detachment in western Nevada (Davis et. al., 2006).

The purpose of this study is to determine if slow slip is occurring along the Wasatch Fault by examining GPS measurements from stations near the fault. Currently, there are two main hypothesized mechanisms for the occurrence of slow slip events. It could be a frictional rheological response (Liu & Rice, 2005) or a fluid-related process (Julian, 2002; Melbourne & Webb, 2003). If slow slip events are seen on both large subduction thrust faults and smaller normal faults in continental interiors, then it would add to growing evidence that slow slip is a frictional rheological response common to all types of faults and not a fluid-related process requiring special conditions.

2 THE WASATCH FAULT

The Wasatch fault is an active, west dipping (~33°) normal fault, which forms the eastern boundary of the Basin and Range province (Bruhn et. al., 2005; Machette et. al., 1991; Malservisi et. al., 2003). The 370-km-long fault extends from southern Idaho into Utah. It is divided into ten segments, which are 30 to 60 km in length; each segment is capable of generating magnitude 7+ earthquakes. The central segments (Brigham City to Nephi) have recurrence intervals of 1300 to 2500 years, resulting in an average recurrence interval of three to five hundred years for the entire fault. Faulting may have started in the central portion of the Wasatch fault 17 million years ago and it was almost certainly underway 10 to 12 million years ago (Bruhn et. al., 2005). The average horizontal displacement for the Wasatch Fault over the last 5600 years is 3.0-4.5 mm/yr (Malservisi et. al., 2003) and the vertical displacement is approximately 1 mm/year (Bruhn et.al., 2005; Hetzel and Hampel, 2006).

3 METHODS

Processed continuous GPS coordinate time series were obtained from the University Navstar Consortium (UNAVCO) archive (http://facility.unavco.org/data/gnss/perm_sta.php). These times series came from stations in Utah that are part of three GPS Networks in North America. The Plate Boundary Observatory (PBO) is part of the Earthscope program and consists of 852 GPS stations at various locations in western North America. The Basin and Range Geodetic Network (BARGEN) consists of 69 GPS stations in the Basin and Range province and the Wasatch Front GPS network consists of 118 stations, only 11 of which are permanent, spanning a 100-km area surrounding the Wasatch fault. While some stations in these networks have been in operation since mid-1996, only the period from 2004 to 2008 was examined in this study, as that is the time period for which precise coordinate data are available in the UNAVCO archive.

To estimate transient displacements in the GPS data the coordinate time series are fit with a hyperbolic tangent function (HTF) of the form:

$$\vec{x}(t) = \vec{x_0} + \vec{V}t + \sum_{i=1}^{n} \frac{\vec{U_i}}{2}\left[\tanh\left(\frac{t-T_{0i}}{\tau_i}\right) - 1\right] \qquad (1)$$

in which $\vec{x}(t)$ are GPS site coordinates at time t, $\vec{x_0}$ are coordinates at a reference time, $\vec{V}$ is a background velocity, $\vec{U_i}$ is anomalous displacement during the i^{th} of n slow slip events, T_{0i} is the median time of the i^{th} event, and τ is a timescale parameter roughly corresponding to one-fourth of the total duration of the event. The time series data were fitted with the HTF using a linear inversion algorithm to estimate the steady-state velocity and transient displacement and a grid-search algorithm to optimize the time parameters T_{0i} and τ (Lowry, 2001). The results can be used to distinguish slow slip events from correlated noise and non-tectonic deformation signals. For this study the HTF was applied to GPS time series from 13 stations located between latitudes 37° N and 42° N (Figure 1). The data used in this study are from the period January 2004 to February 2009. The algorithm to estimate transient displacement is freely available at http://anquetil.colorado.edu/~arlowry/code_release.html.

Once the transient displacements have been estimated via the HTF analysis, slow slip events can be distinguished from noise and non-tectonic deformation signals that otherwise might be mistaken for slow slip. A transient in the data from the Wasatch front might be a slow slip event if 1) the displacement is dominantly in the east-west component,i.e., permendicular to the fault, 2) the transient is seen at several neighboring sites, and 3) the total displacement is significantly greater than the 95% confidence interval of the estimate at each of the sites. If displacement is dominantly in the vertical component, the transient is more likely to be non-tectonic deformation due to mass loading at the surface, and if the displacement is smaller than the confidence interval it probably reflects correlated noise in the data. The horizontal displacement does not need to be universally larger than the vertical, as a fault slip event on a normal fault geometry might reasonably be expected to produce a larger vertical than horizontal signal at some locations. However, elastic loading almost always produces a vertical response many times greater than the horizontal, so a transient that consistently shows vertical greater than the horizontal is not a slow slip event.

4 RESULTS

The GPS data show evidence of several transient displacements. During the January 2004 to February 2009 interval considered here there are four main transients seen in most of the stations. Some of these transients may be slow slip events while others indicate non-tectonic deformation or station noise. The average root mean squared (RMS) residual is 1.141 mm; this is the average amount by which the magnitude of the GPS measurement differs from the trend line. Time series from four of the stations are shown in figure 2. Location information and calculated results for individual stations are given in appendix A.

Station P057

Only measurements from September 2004 to February 2009 were available for the P057 station. Three transients were identified during this interval. The first transient has a mid-time of 2006.09 and occurs over a period of approximately one month. Displacement is mostly downward. The second transient has a mid-time of 2007.19 and a period of 2.06 years. This transient is mostly upward (~11.8 mm) although there is more displacement eastward (~3.1 mm) for this transient then was present in the 2006 transient. The third transient has a mid-time of 2008.50 and a period of about one year. This transient shows the majority of displacement is westward with minor displacement upwards. The 2006 and 2008 events have a northward displacement of approximately 1 mm. In 2007 the displacement has roughly the same magnitude but it is to the south.

Station P122

Data were available for the P122 station from June 2004 to February 2009, with a gap from mid-July to November 2005. Two transients were found in the available data. The first has a mid-time of 2007.03 and occurs over 3.37 years. The displacement for this event is greater than what was seen in the 2007 event at P057, approximately 3.9 mm eastward and 17.6 mm upward. The magnitude of the north displacement is 3.7 mm to the south, approximately equal to the magnitude of the east component. The second transient has a mid-time of 2008.52 and occurs over a period of slightly less than one year. The east displacement for this event is equal to the magnitude of the vertical displacement, with motion to the west and upwards, and a smaller component of motion to the north.

Station LTUT

GPS measurements at LTUT are from the full time interval considered in this study (January 2004 to February 2009). However, prior to April 19, 2008 the north coordinates oscillate, forming a sinusoidal wave, which masks any transients occurring before April 2008. The cause of these oscillations is not known but could be due to instrument error, a monumentation problem, or positioning of the station near a fracture, which would allow the back and forth motion seen in the coordinate time series. The end of these oscillations coincides with the date of the last visit to the station on April 18. Using only GPS measurements taken after April 18, 2008 we calculated a transient displacement with a mid-time of 2008.51 and a period of approximately seven days. This event might have had a longer period but the earlier portion of the event is cut-off. Displacement is largely westward with smaller displacements to the north and downwards.

Station P124

The P124 station was established in 2007 so only data from March 2007 to February 2009 are available for this site. Only one transient displacement was calculated for this station, as the addition of more events did not improve the fit of the HTF to the data. This transient has a mid-time of 2008.47 and a period of 1.02 years. The displacement is westward and about 0.7 mm greater than the downward component of displacement.

Station HWUT

Only data from February 2006 to February 2009 is available in the UNAVCO archive for HWUT even though the station was established in October 2004. However, there are not many measurements recorded prior to mid-2007. Similar to P124, only one transient displacement was calculated for HWUT. This transient has a mid-time of 2008.46 and a period of approximately eight months. While the westward displacement for this transient is fairly large (~5 mm) the downward component is greater (~7 mm).

Station EOUT

Four transient displacements were calculated from the EOUT data. The first transient has a mid-time of 2005.37 and occurs over an eight month period. Motion is dominantly to the west. The second transient has a mid-time of 2006.41 and a period of 13 days. For this transient the displacement is also dominantly westward. The third transient has a mid-time of 2007.36 and 1.86-year period. Here the vertical component has the greatest magnitude displacement upward. The final event seen at this station has a mid-time of 2008.51 and period of approximately six months. For this event the largest magnitude displacement is the east component although the displacement in the vertical component is only slightly less and motion is to the west and downwards.

Station COON

At COON four transients were calculated. The first of these transients has a mid-time of 2005.39 and occurred over four days. Displacement is primarily eastward. The second transient is located close to the first, with regard to time. The mid-time of this event is 2005.89 and it has a period of approximately three months. For this transient, displacement is mostly downward. The third transient has a mid-time of 2007.06 and occurs over a 1.85-year period. Like the second transient, the majority of displacement is downward. The fourth transient has a mid-time of 2008.76 and occurs over approximately two months. Here the displacement is mainly westward.

Station CEDA

Three transient displacements were identified in the time series. The first has a mid-time of 2005.60 and period of three months. The dominant displacement is westward. The second transient is at 2007.06 and occurs over a period of 2.18 years. For this event the vertical displacement is approximately 20 mm upward, significantly greater than the east component of displacement (~0.04 cm, westward). A transient in mid-2008 is also seen at CEDA. This transient has a period of 6 months. Here, again, we see the majority of displacement occurring in the east component with motion to the west and only minor motion downward.

Station P117

GPS measurements at P117 began in mid-2006 so the May 2006 to February 2009 time interval was examined and three transients were found (Figure 2). An event at 2006.91 has a period of approximately three months. The displacement is mostly in the vertical component (~3 mm) with movement upwards and displacement to the west and south slightly greater than 1 mm. Another event at 2007.53 occurs over a 2 month period. For this event an upward displacement of approximately 8 mm was calculated. The southward and westward displacements are less than 1 mm. Similar to stations discussed previously, the final event seen at P117 occurred in mid-2008. The vertical and east displacements have very similar magnitudes, ~6.0 mm, downward, and ~5.7 mm, westward. There is a very small (~0.3 mm) northward displacement.

Station LMUT

Data for LMUT is available for May through June 2006 and April 2007 to February 2009. One transient found in the LMUT data has a mid-time of 2007.49 and period of 2.40 years. This event has a upward displacement of 34.6 mm whereas magnitudes of the east and north displacements are 8.2 mm, eastward, and 1.2 mm, southward. Another transient occurs over four days and has a mid-time of 2008.69. The vertical displacement is only 7 mm, upward, but it is still greater than either the east or north components. The magnitude of the east displacement is actually less than the 95% confidence interval of the estimation and motion is to the east.

Station FOOT

We have continuous GPS measurements for the FOOT station from January 2004 to February 2009, but only two transient displacements were found in the data. The first event has a mid-time of 2007.09 and a period of 2.72 years. The eastward and southward displacements are much less than the approximately 2 cm upward displacement. The second event has a mid-time of 2008.55 and a period of approximately two months. For this event displacement is dominantly westward with minor motion to the south and downwards.

Station P012

P012 was established in March 2006 and we only found one transient displacement in the data. This transient has a mid-time of 2007.37 and occurs over 2.30 years. The eastward displacement is fairly large (~8 mm) but it is still less than the upward motion in the vertical component (~11.4 mm).

Station P009

P009 was established at the end of January 2006. We examined measurements from the time the station was established until February 2009 and found three transient displacements. The first event was seen at 2006.20 and has a period of approximately 19 days. The magnitude of the displacement, eastward, is 1 mm greater than the magnitude of the upward displacement. The second event is at 2007.43 and occurs over about seven months. For this transient, the eastward and upward motions have about the same magnitudes but the vertical component is slightly greater. The third transient has a mid-time of 2008.06 and a period of approximately 8 months. The north component has slightly more motion northward than the east component has to the east but both are greater than the upward, vertical displacement.

5 DISCUSSION

Most of the stations show transients in late 2005 to early 2006, mid-2007, and/or mid-2008. The 2005/2006 event is seen at only five of the stations and four of those stations show motion dominantly in the east component. For all of these stations the displacement is greater than the 95% confidence interval indicating that this transient is not correlated noise. This event may be a slow slip event but we would like to see it at more of the stations. However, these five stations are the only ones with usable measurements from this time period. In order to determine if this event is in fact a slow slip event we will need to examine more stations with measurements available for the mid-2005 to early 2006 time period. Davis et. al. (2006) examined the COON and CEDA sites over the earlier part of the time period we studied and concluded that the displacements seen were probably due to changing lake levels and hydrological loading.

A displacement in 2007 is seen at all stations. For the majority of stations the event occurs in mid-2007. Displacement for the mid-2007 event is dominantly in the vertical component and at EOUT the magnitude of the east displacement is less than the confidence interval. At eight of the stations the 2007 event has a period greater than 1.8 years, ranging up to approximately 3.4 years. The long period, dominantly vertical displacement, and large variations in the mid-time of the event indicate that the mid-2007 event likely is not due to slow slip. The motion may reflect interannual variations in surface mass loading.

The mid-2008 event is seen at 12 of the 13 examined stations. At nine of these stations the magnitude of the east component is greater than or equal to the magnitude of the vertical component. Of the other three stations which show the event, HWUT and P117 show fairly significant displacement in the east component. The displacement at LMUT is very small and may be perturbed by noise. The only station that does not show the mid-2008 event is P012 which is located some distance south and east of the trace of the Wasatch fault and may give us some indication that the transient motion decreases to zero before it reaches this station. While there is some variability in the mid-times of the 2008 event, it is less than what was seen for the 2007 event. These small variations in the mid-time are consistent with what we would expect to see for a slow slip event. Overall, the mid-2008 event appears to be a slow slip event.

A vector plot of the horizontal motion for the 2008 event shows dominantly northwest motion with slight southwest motion at some of the sites (Figure 3). The LMUT station is the only one with significant variation from this trend. This indicates that the signal we see at LMUT does not have the same causes as the signals we see at other stations. The anomalous direction and short period of the 2008 event found at LMUT indicate that it is probably surface mass loading or correlated noise. Examination of the vector plot shows that the largest displacements occur at the stations closest to the fault with smaller displacements to the west. Further inspection of variations in the mid-times of the 2008 event shows that, in general, the event occurs earliest near the fault and then at progressively later times as we move to the west.

Adding the vertical component to the vector plot provides further information about the mid-2008 event (Figure 4). The vertical component tends to be noisy as it is superposed by large loading signals that cannot be easily separated from signals of tectonic deformations. However, the vector plot suggests that the vertical is small at sites west of the Wasatch fault but tends to have large subsidence at stations along the fault and to the east. The exception to this trend is LMUT which exhibits anomalously large uplift near the fault. This provides further evidence that the signal at LMUT is not a slow slip event.

6 CONCLUSIONS

While many transient displacements are seen in the GPS measurements, several lines of evidence point towards the mid-2008 transient being a slow slip event. This event is seen at almost all of the examined GPS stations and the stations have a consistent motion to the northwest for this event. Displacement at the majority of sites where we see the mid-2008 event is greater than the 95% confidence interval for the estimation and it is dominantly in the east component. The presence of slow slip on faults in the continental interior, like the Wasatch fault, indicates slow slip is a frictional rheological response instead of a fluid-related process.

Further work will involve analysis of all GPS sites in the region to determine how widespread the 2008 event is and where the transient motion decreases to zero. Analysis of GPS measurement over a time period earlier than what was examined in this study could be used to determine the recurrence interval of slow slip events on the Wasatch fault. Another important step is to model slip on the Wasatch fault, and possibly on detachments projected from the base of the Wasatch, which would enable us to characterize the source location of the deformation.

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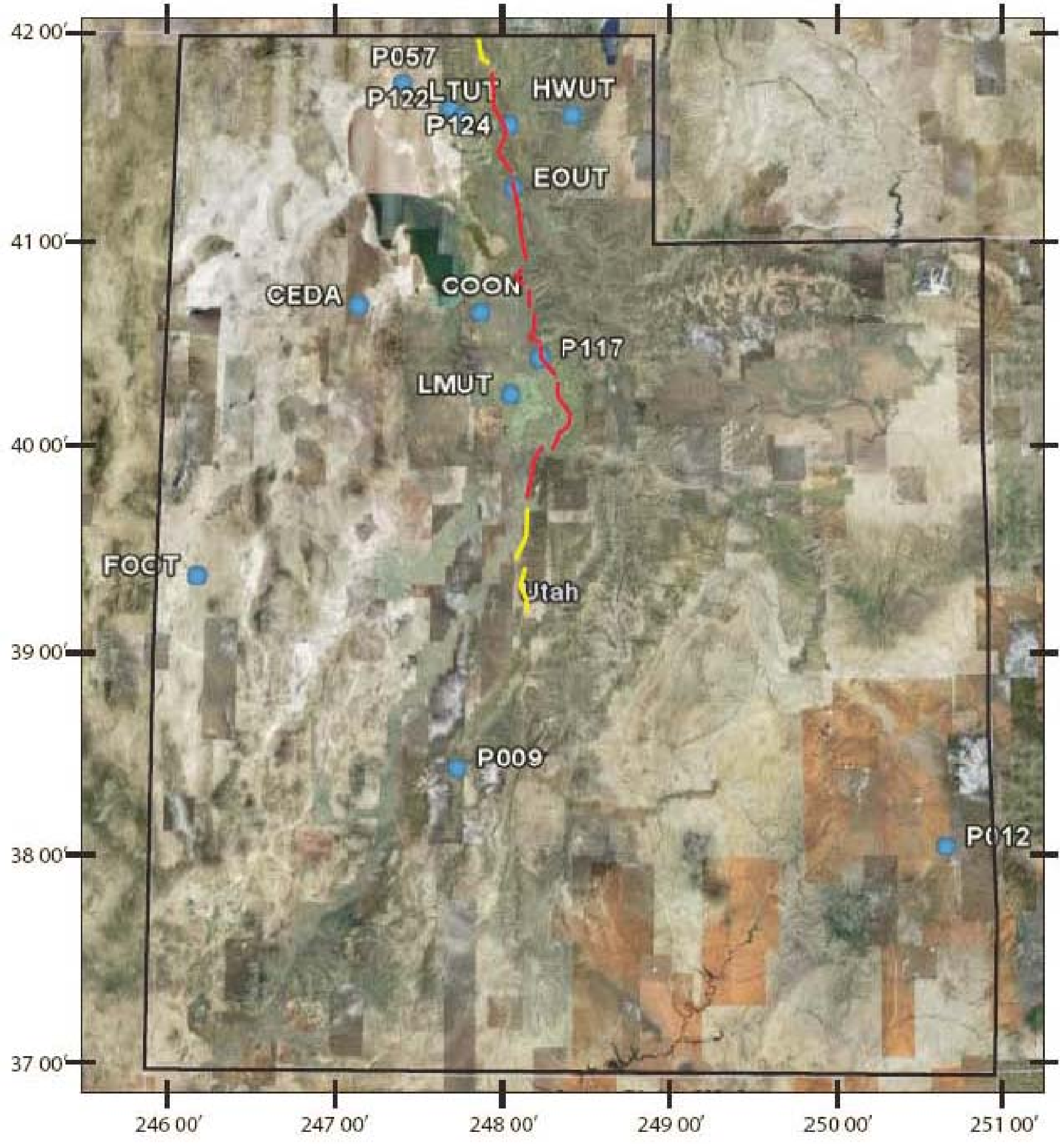
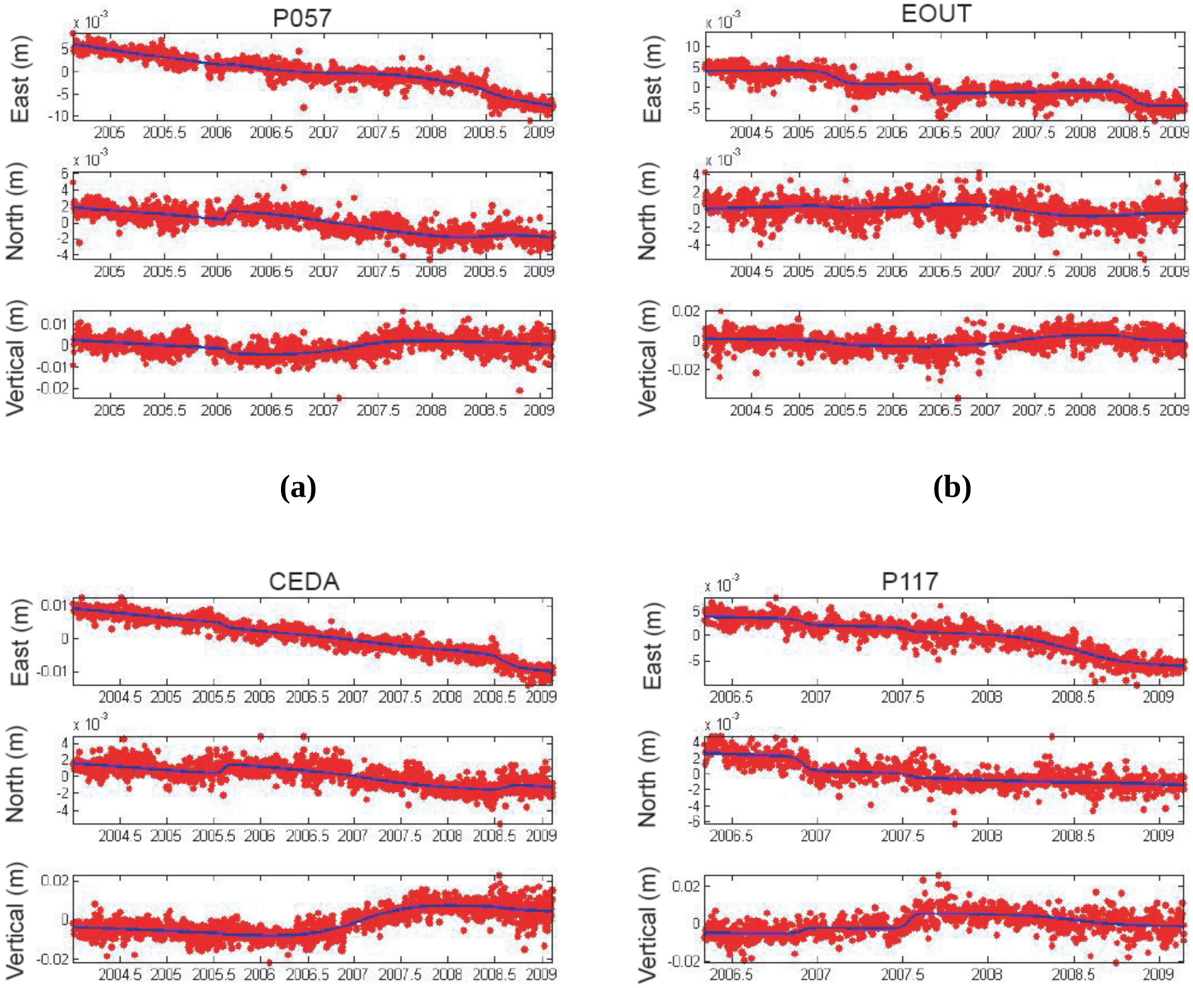


Figure 1. Map of GPS sites. Map shows locations of the GPS sites (circles) from the Plate Boundary Observatory, the Basin and Range Geodetic Network, and the Wasatch Front GPS network that were used in this study. The trace of the central (red) and distal (yellow) segments of the Wasatch fault are also shown.



(a) (b)

(c) (d)

Figure 2. Representative time series, Time series from **(a)** P057, **(b)** EOUT, **(c)** CEDA, and **(d)** P117. Filled red circles are measured daily coordinates and blue lines are the best-fit functions of the form given by equation (1).

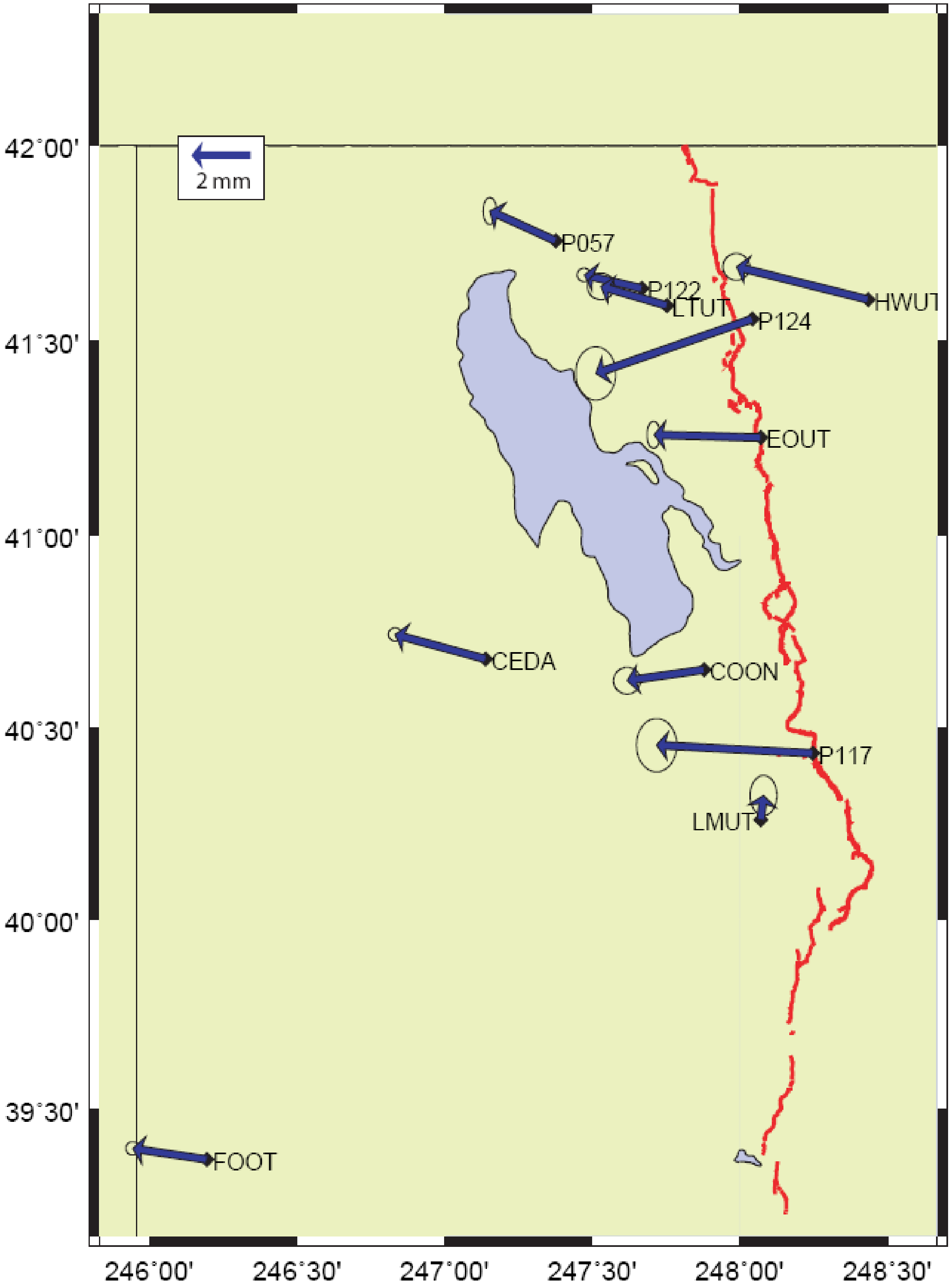


Figure 3. Measured anomalous horizontal displacement during the 2008 slow slip event. Thick blue vectors, with 95% confidence ellipse, represent the horizontal transient displacement from equation (1). The trace of the Wasatch fault is shown in red.

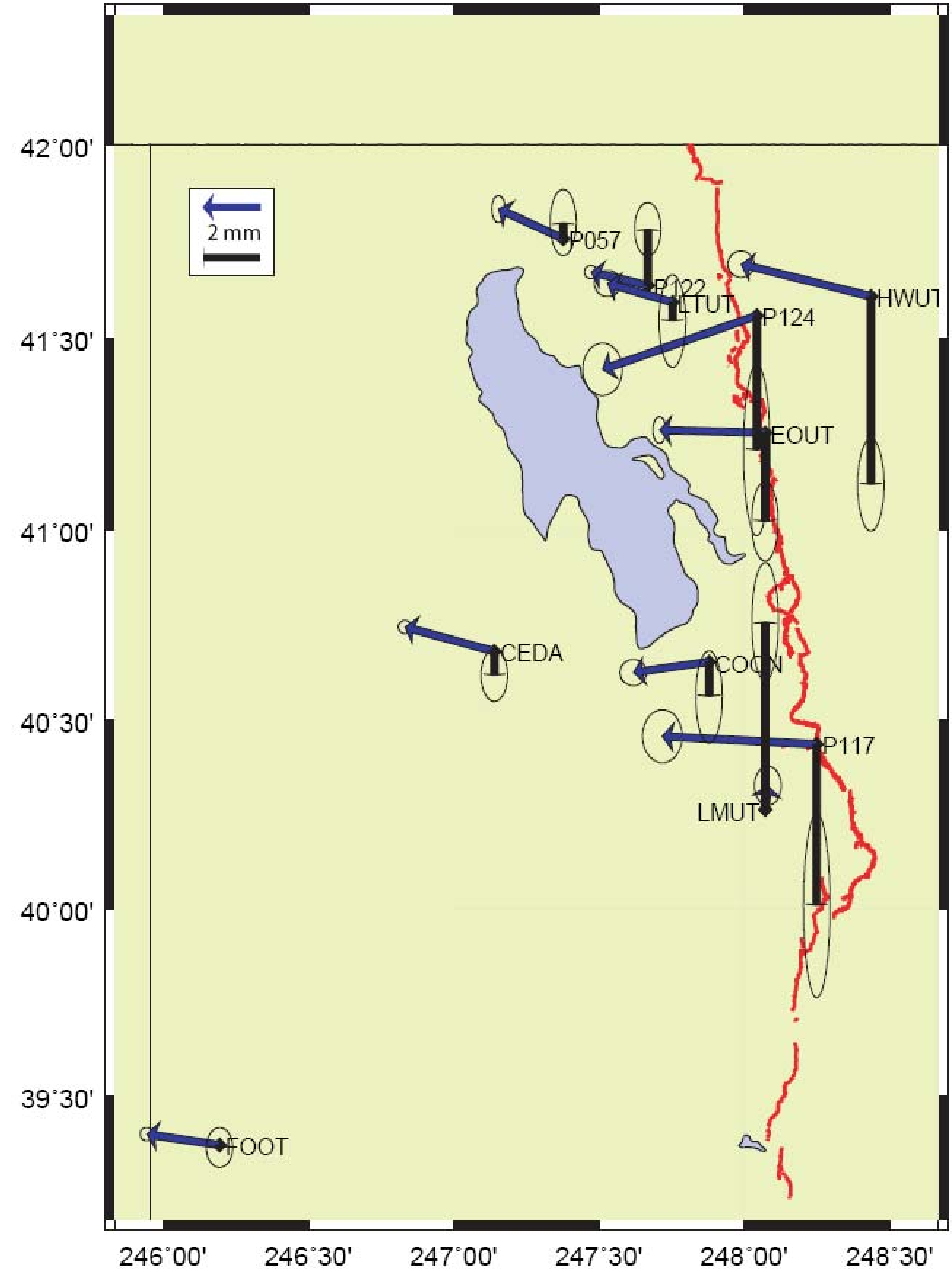


Figure 4. Measured anomalous horizontal and vertical displacement during the 2008 slow slip event. Thick blue vectors, with 95% confidence ellipse, represent the horizontal transient displacement and thick black vectors, with 95% confidence ellipse, represent the vertical transient displacement, both from equation (1). The trace of the Wasatch fault is shown in red.

APPENDIX A
Information on GPS Stations

Station	Velocity (cm/yr)			Mid-time	Period (years)	Tau	Displacement (cm)			RMS	Latitude	Longitude
	East	North	Vertical				East	North	Vertical			
EOUT	0.02 +/- 0.01	0.03 +/- 0.01	-0.11 +/- 0.06	2005.37	0.658	0.1645	-0.37 +/- 0.02	-0.05 +/- 0.02	-0.25 +/- 0.09	0.1341	41.2530	-111.9290
				2006.406	0.036	0.0090	-0.25 +/- 0.01	0.02 +/- 0.01	0.08 +/- 0.06			
				2007.362	1.864	0.4660	0.03 +/- 0.02	-0.20 +/- 0.02	0.94 +/- 0.10			
				2008.513	0.468	0.1170	-0.39 +/- 0.01	0.01 +/- 0.02	-0.33 +/- 0.06			
COON	-0.26 +/- 0.01	-0.01 +/- 0.01	-0.07 +/- 0.06	2005.393	0.011	0.0028	0.15 +/- 0.01	0.12 +/- 0.02	-0.09 +/- 0.07	0.1677	40.6526	-112.1210
				2005.887	0.209	0.0523	-0.18 +/- 0.01	-0.10 +/- 0.02	-0.24 +/- 0.07			
				2007.062	1.854	0.4635	0.12 +/- 0.02	-0.14 +/- 0.03	-0.13 +/- 0.07			
				2008.764	0.099	0.0248	-0.28 +/- 0.02	-0.04 +/- 0.02	-0.13 +/- 0.07			
CEDA	-0.27 +/- 0.01	-0.08 +/- 0.01	-0.21 +/- 0.03	2005.601	0.209	0.0523	-0.12 +/- 0.01	0.12 +/- 0.01	-0.05 +/- 0.05	0.1200	40.6807	-112.8605
				2007.062	2.181	0.5453	-0.04 +/- 0.02	-0.10 +/- 0.02	2.05 +/- 0.07			
				2008.6	0.453	0.1133	-0.33 +/- 0.01	0.09 +/- 0.01	-0.09 +/- 0.04			
FOOT	-0.35 +/- 0.00	-0.00 +/- 0.01	-0.37 +/- 0.02	2007.094	2.723	0.6808	0.05 +/- 0.02	-0.22 +/- 0.02	2.21 +/- 0.06	0.1170	39.3690	-113.8050
				2008.545	0.178	0.0445	-0.27 +/- 0.01	0.04 +/- 0.01	-0.01+/- 0.03			
P009	-0.69 +/- 0.02	-0.20 +/- 0.02	-0.44 +/- 0.07	2006.201	0.054	0.0135	0.46 +/- 0.03	0.03 +/- 0.03	0.36 +/- 0.11	0.1888	38.4800	-112.2230
				2007.431	0.557	0.1393	0.50 +/- 0.02	-0.07 +/- 0.02	0.57 +/- 0.08			
				2008.059	0.691	0.1728	0.23 +/- 0.02	0.27 +/- 0.03	0.18 +/- 0.09			
P012	-0.49 +/- 0.01	0.03 +/- 0.02	-0.61 +/- 0.05	2007.366	2.302	0.5755	0.83 +/- 0.03	-0.19 +/- 0.03	1.14 +/- 0.11	0.1300	38.0970	-109.3340
P057	-0.33 +/- 0.01	-0.11 +/- 0.01	-0.27 +/- 0.04	2006.086	0.102	0.0255	0.05 +/- 0.01	0.12 +/- 0.01	-0.25 +/- 0.05	0.1103	41.7570	-112.6230
				2007.193	2.064	0.5160	0.31 +/- 0.02	-0.11 +/- 0.02	1.18 +/- 0.07			
				2008.518	1.000	0.2500	-0.24 +/- 0.01	0.11 +/- 0.02	0.06 +/- 0.05			
P124	0.11 +/- 0.02	0.25 +/- 0.03	0.03 +/- 0.09	2008.472	1.020	0.2550	-0.57 +/- 0.03	-0.20 +/- 0.04	-0.50 +/- 0.13	0.1700	41.5576	-111.9574
LTUT	-0.29 +/- 0.03	-0.09 +/- 0.04	-0.08 +/- 0.11	2008.514	0.020	0.0050	-0.24 +/- 0.02	0.07 +/- 0.02	-0.07 +/- 0.07	0.1237	41.5921	-112.2468
P122	-0.29 +/- 0.01	-0.02 +/- 0.01	-0.54 +/- 0.03	2007.031	3.365	0.8413	0.39 +/- 0.02	-0.37 +/- 0.03	1.76 +/- 0.10	0.1223	41.6354	-112.3319
				2008.52	0.960	0.2400	-0.21 +/- 0.01	0.05 +/- 0.01	0.21 +/- 0.04			
HWUT	0.08 +/- 0.01	-0.10 +/- 0.01	0.30 +/- 0.05	2008.461	0.667	0.1668	-0.48 +/- 0.02	0.12 +/- 0.02	-0.70 +/- 0.07	0.1500	41.6072	-111.5651
LMUT	-0.68 +/- 0.04	-0.03 +/- 0.04	-1.59 +/- 0.14	2007.479	2.402	0.6005	0.82 +/- 0.08	-0.12 +/- 0.09	3.46 +/- 0.30	0.1481	40.2614	-111.9283
				2008.689	0.011	0.0028	0.01 +/- 0.02	0.09 +/- 0.03	0.70 +/- 0.09			
P117	-0.09 +/- 0.03	-0.07 +/- 0.03	-0.06 +/- 0.11	2006.909	0.181	0.0453	-0.13 +/- 0.02	-0.17 +/- 0.02	0.30 +/- 0.09	0.1398	40.4352	-111.7514
				2007.533	0.154	0.0385	-0.08 +/- 0.02	-0.05 +/- 0.02	0.81 +/- 0.09			
				2008.501	1.318	0.3295	-0.57 +/- 0.03	0.03 +/- 0.04	-0.60 +/- 0.14			

AUTHOR’S BIOGRAPHY

Tamara Jeppson, raised in Tremonton, Utah, graduated in 2005 from Bear River High School as valedictorian. She entered Utah State University (USU) that autumn as a presidential scholar and dual geology and physics major. During the fall of 2006 Tamara began a research project with Dr. Jim Evans, studying the San Andreas Fault. In fall 2008 she started to look for slow slip on the Wasatch fault with Dr. Anthony Lowry. Tamara has also participated in a summer internship at the Pacific Northwest National Lab working with George Last. While at USU, Tamara received the Eccles Undergraduate Research Fellowship, College of Science mini-grant, Society of Exploration Geophysicists undergraduate scholarship, and Barry M. Goldwater scholarship. She has supplemented her school work as an Undergraduate Teaching Fellow for the Geology Department, the Sigma Pi Sigma physics honors society vice president, and, at various times, a public relations officer, treasurer, and president in the Institute Women’s Association.

After she graduates in May 2009, Tamara plans to serve a mission for the LDS Church in the Spokane, Washington area. In the autumn of 2011 she will begin earning her graduate degree in geophysics at the University of Wisconsin-Madison.

“The most beautiful thing we can experience is the mysterious. It is the source of all true art and all science. He to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, is as good as dead: his eyes are closed.”

Albert Einstein