FINAL TECHNICAL REPORT

ACTIVE UPLIFT AND THRUST-FAULT STRAIN ACCUMULATION RATES FROM PS-INSAR AND GPS DATA

National Earthquake Hazard Reduction Program

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Technical abstract:

Range-change rates determined with the permanent scatterer InSAR method are combined with horizontal velocities measured at 200 GPS sites in order to resolve vertical motions in the San Francisco Bay Area at sub-mm/yr precision. In this report we focus on deformation in the epicentral region of the 1989 Loma Prieta earthquake that suggest transient subsidence and contraction due to postseismic relaxation. To isolate vertical tectonic rates, we use only those InSAR measurements made on material that was not Quaternary substrate, which is potentially susceptible to large non-tectonic and seasonally varying ground motions. Modeling of the observed deformation patterns after removing a model of interseismic motions in the area suggest that postseismic viscous relaxation could still be resolved a decade after the event, implying an upper mantle viscosity of $\sim 5 \times 10^{18}$ Pa s. These results provide valuable constraints on the rheology of the lithosphere in northern California. Comparison with other postseismic studies suggests that much of the western US is underlain by weak, asthenospheric mantle.

Non-technical abstract:

Space-based InSAR measurements of surface deformation are combined with horizontal velocities measured at GPS sites in order to resolve tectonic motions in the San Francisco Bay Area at great precision. We focus on deformation in the epicentral region of the 1989 Loma Prieta earthquake that suggest transient subsidence and contraction due to post-earthquake relaxation. To isolate vertical tectonic rates, we use only those InSAR measurements made on young soils, which are potentially susceptible to large non-tectonic ground motions. Modeling of the observed deformation patterns after removing a model of interseismic motions in the area suggest that viscous flow below the Earth's crust could still be resolved a decade after the event. These results provide valuable constraints on the rheology of the lithosphere in northern California. Comparison with other postseismic studies suggests that much of the western US is underlain by weak, asthenospheric mantle.

Active Uplift and Thrust-fault Strain Accumulation Rates from PS-InSAR and GPS data

1. INTRODUCTION

1.1 Project components

The primary objective of this project is to evaluate our ability to resolve the spatial distribution and rates of vertical tectonic motions in the San Francisco Bay Area. A combination of Permanent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) and Global Positioning System (GPS) data allow us to map out in great detail, and at high precision, the surface deformation occurring in the region. The data have complementary strengths and sensitivities – PS-InSAR data are spatially dense and widely distributed, and are particularly sensitive to vertical motions; GPS data, on the other hand, offer precise measurements of horizontal displacements, and as such, give strong constraints on the regional strain field due to strike-slip faulting. By utilizing this property of the GPS data, we can effectively characterize, and remove, the effects of this horizontal deformation from the InSAR data; any remaining deformation signal must therefore be vertical. Here we focus on deformation in the epicentral region of the Loma Prieta earthquake that suggest transient subsidence in the aftermath of the M_w 6.9 event.

2. OBSERVATIONS

2.1 PS-InSAR data

InSAR provides a one-dimensional measurement of change in distance along the look direction of the radar spacecraft. Given the orientation of the track direction of polar, sun-synchronous satellites, this measurement is affected by deformation in both horizontal components and, particularly, in the vertical. We have had significant success in the recent past in applying conventional InSAR to both the horizontal and the vertical surface deformation in the San Francisco Bay Area, revealing cm-level uplift and subsidence patterns related to the seasonal drawdown and recharge of the Santa Clara valley aquifer (Schmidt and Bürgmann, 2003); rapid motions of deep-seated landslides (Hilley et al., 2004); a possible sub-mm/yr contribution of an east-side-up, dip-slip component to the range change offset across the creeping northern

Hayward fault (Hilley et al., 2004; Schmidt et al., 2005); and allowing the estimation of the distribution of fault creep on the Hayward fault, and therefore the extent of the part of that fault that remains locked (Schmidt et al., 2005).

Conventional InSAR relies to a large extent on the connectivity of coherent portions of the interferogram in order to distinguish signal from noise. In areas of high relief, or heavy vegetation, such as the East Bay Hills or Santa Cruz Mountains in the Bay Area, this can be a great challenge; consequently studies that have relied on the interpretation of one or a stack of several interferograms have had little or no data coverage in those areas. Another problem with conventional InSAR is the effect of atmospheric water vapor in adding an unknown additional phase delay to the radar signal, which can add significant uncertainties to the measurements. In order to mitigate these effects, which can dramatically affect the effectiveness of InSAR as a geodetic tool in the Bay Area, we use a new InSAR processing technique, the Permanent Scatterer (PS-InSAR) method (Colesanti et al., 2003; Ferretti et al., 2000, 2001). This allows for the identification and integration of individual radar-bright and radar-phase-stable points (outcrops, buildings, utility poles, etc.) in >15 SAR images. The phase data from these permanent scatterers are then used to separate time-dependent surface motions, atmospheric delays, and elevation-error components of the range-change measurement (Colesanti et al., 2003).

We incorporate 49 European Remote Sensing satellite (ERS-1 and 2) acquisitions collected from 1992 to 2000 of our Bay Area target scene (track 70, frame 2853) (Figure 1). Points whose displacements vary in a highly non-linear fashion, such as a large area of rapid seasonal uplift and subsidence in the Santa Clara Valley (Colesanti et al., 2003; Schmidt and Bürgmann, 2003) are excluded from the final data set. The PS-InSAR data provide range-change rates at 115,487 points including targets in vegetated or mountainous areas that are unsuitable for standard InSAR. In addition, this dataset contains a time-series of displacement, which allows us to identify regions in which there is a significant time-varying, often seasonal component to the deformation field.

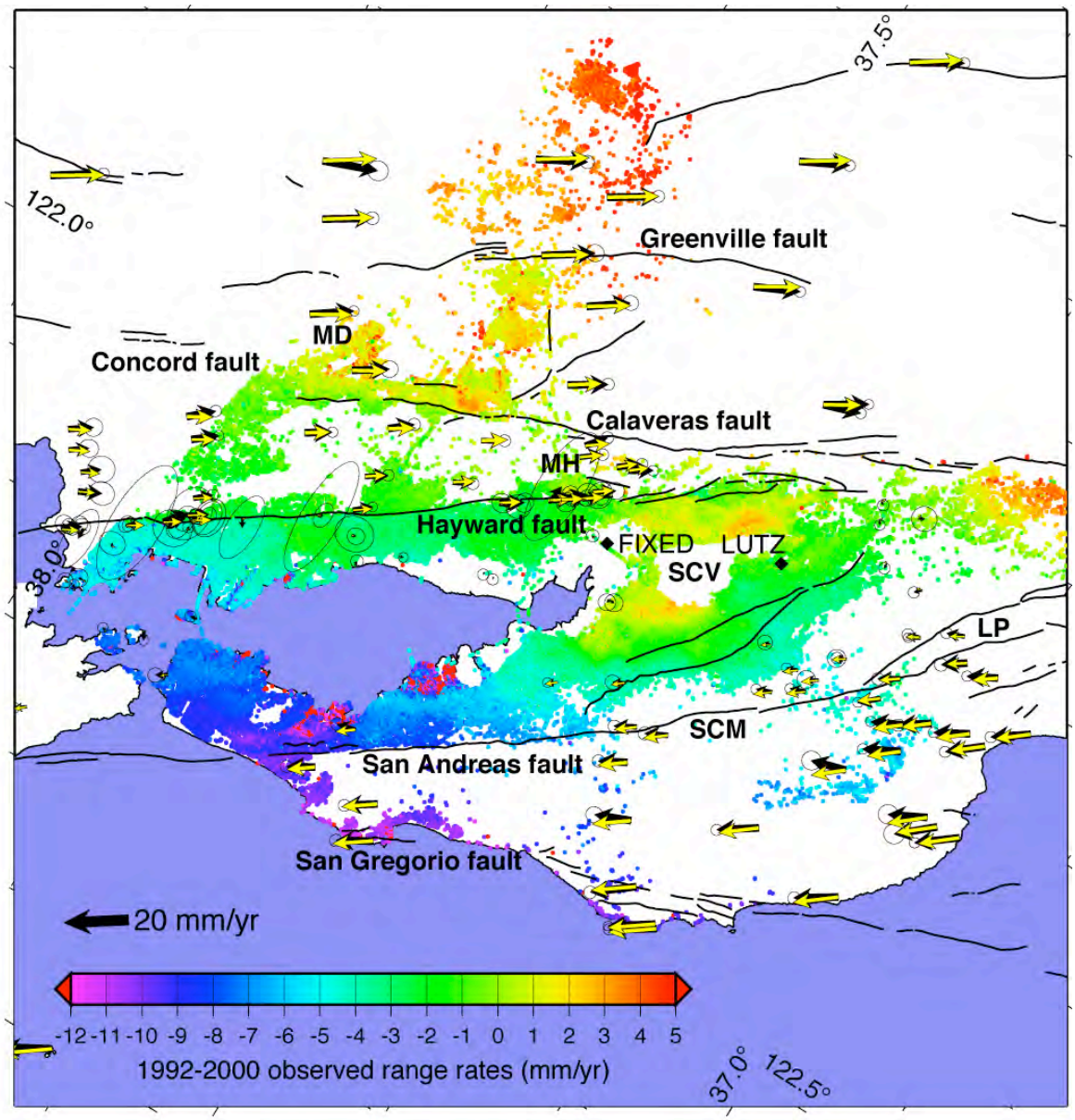

Figure 1: Surface deformation rate data used in this study. Each colored dot on land indicates the location of a permanent scatterer on the ground; red colors indicate points where the distance, or range, between the satellite and the ground increases with successive satellite passes (i.e. movement away from the satellite), blue colors indicate movement towards the satellite. Black arrows are horizontal velocities from the BAVU compilation of GPS data (d'Alessio et al., 2005) with 2σ error ellipses, relative to the fixed station LUTZ; yellow arrows are modeled horizontal velocities assuming that the deformation in the region can be described as the motions of a series of subparallel rigid blocks. (SCM – Santa Cruz Mountains, LP – Loma Prieta, MD – Mount Diablo, MH – Mission Hills)

When interpreted in terms of vertical motions, the residual range-change rate field of bedrock target points includes three larger areas of subsidence and three regions of uplift at 0.5-1.5 mm/yr rates (Figure 2). One area of apparent subsidence is located east of the Greenville fault and we have no obvious explanation for this feature. The second area of subsidence at rates of up to ~2 mm/yr appears localized about the epicentral region of the 1989, $M_w = 6.9$ Loma Prieta earthquake and coincides with the region of horizontal contraction evident in the residual GPS velocities. A third zone of slow (~0.5 mm/yr) subsidence along the northern San Francisco peninsula may be related to an extensional bend in the SAF and/or interaction with the offshore San Gregorio fault zone. Uplifted regions along the East Bay Hills, the Santa Cruz Mountains to the northeast of the SAF near Black Mountain and in the southern foothills of Mt. Diablo appear to reflect tectonic uplift along restraining discontinuities of Bay Area strike-slip faults (Bürgmann et al., 2006).

2.1 GPS data

Over 10 years of GPS data have now been collected in the San Francisco Bay Area, providing high precision measurements of horizontal surface velocities across the whole plate boundary zone. In this study, we use velocities from the BAVU (Bay Area Velocity Unification) compilation of continuous GPS data from the BARD network and campaign data collected by UC Berkeley and the US Geological Survey since 1994. Velocities from 200 BAVU sites were used in this study (Figure 1). A full description of the GPS data analysis, collection and processing is given by d'Alessio et al. (2005); recent data products are available at http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/index.html .

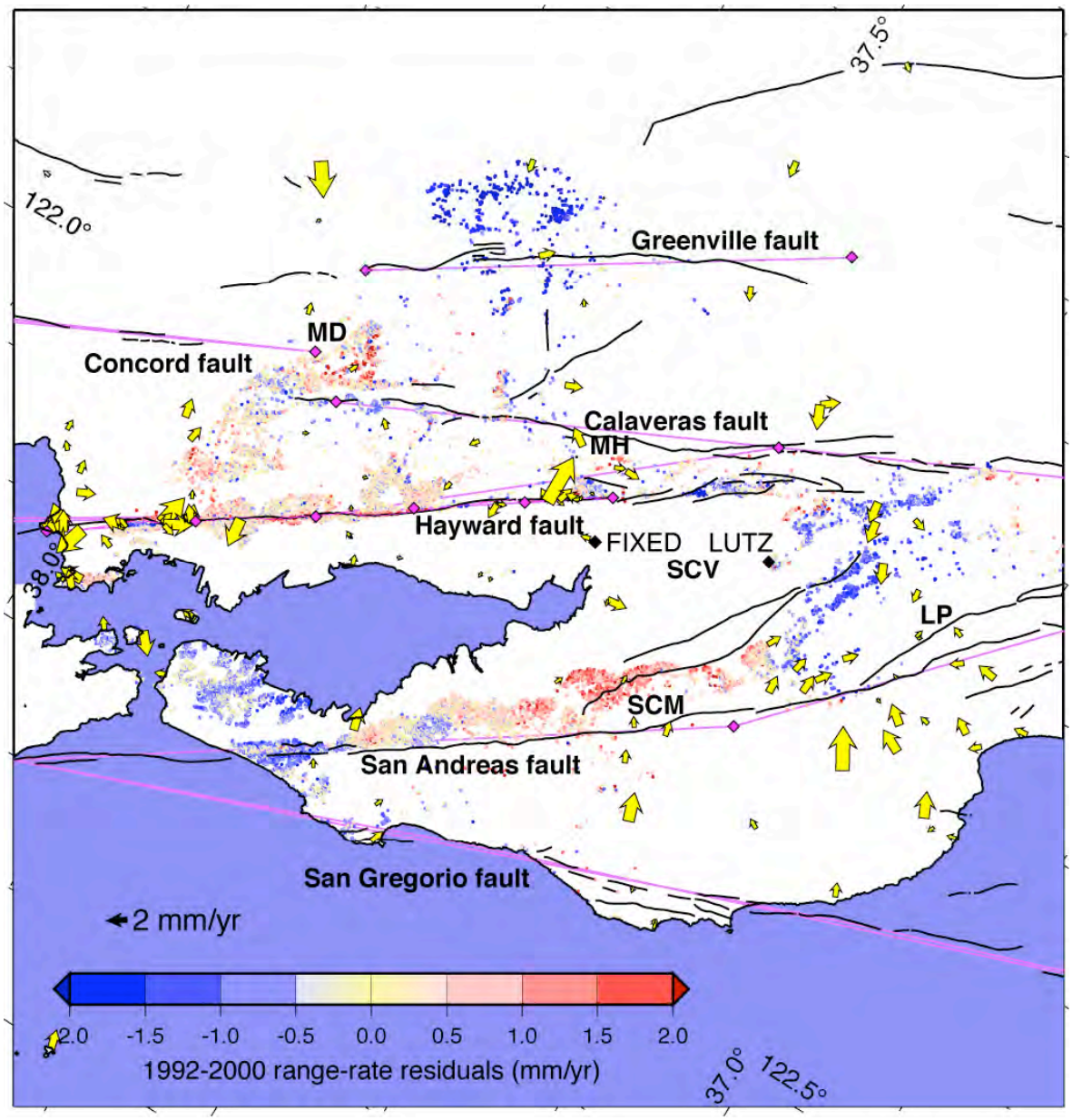

Figure 2: Residual surface velocities after correction for the horizontal strain field due to strike-slip faulting. Only PS points located on bedrock are shown, to ensure that non-tectonic signals related to the behavior of Quaternary substrate are removed. Areas of red here indicate uplifiting zones; conversely, blue areas indicate subsidence. Yellow arrows are the residuals of the fit of the dislocation model to the GPS data. Note the uplift signals associated with Mount Diablo (MD), the Santa Cruz Mountains (SCM) and the Mission Hills (MH), and the subsidence seen at Loma Prieta (LP). Purple lines are the surface projections of the shallow and/or deep dislocations used to model the horizontal strain field.

3. POSTSEISMIC DEFORMATION FOLLOWING LOMA PRIETA EARTHQUAKE

3.1 Introduction

Periods of accelerated postseismic deformation following large earthquakes reflect the response of the Earth's crust to sudden coseismic stress changes. Thus, detailed geodetic measurements of postseismic relaxation effectively probe the rheology at depth (Bürgmann and Dresen, 2008). Transient post-earthquake relaxation includes contributions from (1) fault afterslip above (Bürgmann et al., 1997; Johnson et al., 2006; Marone et al., 1991) and below (Bürgmann et al., 2002; Tse and Rice, 1986) the base of the seismogenic zone, (2) viscous flow in the lower crust and upper mantle (Pollitz et al., 2000), and (3) poroelastic rebound in the upper crust due to fluid flow in response to coseismic pressure changes (Jónsson et al., 2003; Peltzer et al., 1996). For relatively small earthquakes, shallow afterslip and poroelastic relaxation dominate the observed postseismic transients and contributions from below the seismogenic zone are difficult to resolve (Jónsson et al., 2003; Pollitz et al., 1998). Larger events are likely to lead to transient deformation in the lower crust and upper mantle, that lead to measurable surface displacements.

Of particular interest is distinguishing the deformation resulting from localized afterslip on a narrow aseismic shear zone below a large earthquake rupture from surface strain resulting from distributed viscous flow at depth (Thatcher, 1983). For an infinitely long (2D) strike-slip fault earthquake cycle, these two end-member models can produce equivalent surface deformation (Savage, 1990). However, this inherent ambiguity in identifying the contributions of either relaxation process does not apply when considering postseismic deformation about finite strike-slip ruptures (Pollitz et al., 2000) or events with a significant dip-slip component (Gourmelen and Amelung, 2005; Hsu et al., 2002; Pollitz et al., 1998). Highly precise measurements of postseismic horizontal and vertical motions can reveal the source mechanics of the transient deformation and allow for determining the appropriate constitutive properties of the relaxing lithosphere.

Much of our knowledge of the earthquake cycle and the rheology of the deep SAF system in central California is based on interpretation of geodetic measurements collected in the decades following the 1906 San Francisco earthquake that ruptured a ~400-km-long section of the SAF (Kenner and Segall, 2003; Thatcher, 1983). Kenner and Segall (2003) consider data collected between 1906 and 1995 in a systematic evaluation of various first-order models of lower-crustal structure and rheology. They find that models incorporating vertical viscous shear zones in the lower crust provide a good fit to the geodetic data and are consistent with seismic studies that suggest that narrow fault zones extend through the entire crust. The occurrence of the $M_w = 6.9$

Loma Prieta earthquake provides the first opportunity since 1906 to study postseismic relaxation processes and estimate rheological parameters in the region with modern space geodetic tools.

The deformation measured with GPS immediately following the Loma Prieta earthquake revealed significant postseismic contraction and right-lateral shear across the southern Santa Cruz Mountains northeast of the SAF (Bürgmann et al., 1997; Savage et al., 1994). The localized nature of the transient displacement field indicates relatively shallow deformation sources. The measurements of the first five years can be interpreted to be due to aseismic right-oblique fault slip on or near the coseismic rupture, as well as thrusting up-dip of the rupture within the Foothills thrust belt (Bürgmann et al., 1997). Analysis of the time-varying nature of the deformation signal suggests that the shallow transient thrusting ceased in 1992 while resolvable oblique shear at seismogenic depths may have persisted through 1994 (Segall et al., 2000). The total moment of the modeled 1989-1994 afterslip on the two sources was ~5 x 10^{18} Nm, about 15 % of the coseismic moment release (Segall et al., 2000). Analysis of the GPS measurements did not resolve a significant contribution of lower-crustal, or upper-mantle relaxation processes during the first 5 years following the event (Pollitz et al., 1998). Surface displacement measurements using GPS and InSAR help us resolve continued transient strain accumulation in the region, since 1993.

3.2 Data and Approach

We rely on the residuals of surface deformation measurements from InSAR and GPS measurements following the removal of a modeled interseismic velocity field. d'Alessio et al. (2005) carried out a comprehensive analysis of 1993-2004 GPS velocities and developed a mechanical block model of the deformation. As Meade and Hager (2005) point out, the ability to fit interseismic deformation data to such models of steady strain accumulation about locked upper-crustal faults suggests that contributions from time-dependent deformation processes tend to be minor throughout California. We focus on a 200-station, greater Bay Area subset of the regional GPS velocity field to constrain a mechanical model of the horizontal velocity field (Bürgmann et al., 2006). In the model, uniform-slip dislocations in an elastic, homogenous, and isotropic half-space (Okada, 1985) reproduce the surface motions about the Bay Area faults, including the contribution of shallow aseismic creep on several faults in the region. A relatively simple 17-element dislocation model can explain much of the observed horizontal velocity field. The summed misfit to the GPS-velocities, the weighted residual sum of squares (WRSS) of this model is 1173, and the reduced misfit statistic $\sqrt{WRSS/(n-p)}$ is 3.1, where n and p are the number of data (199 north and east velocities relative to reference station) and model parameters (strike slip on 17 dislocations), respectively. The Loma Prieta region exhibits a systematic misfit

pattern in the residual GPS velocities, where a zone of apparent residual contraction and right-lateral shear of ≤ 5 mm/yr is observed that is not explained by our model. The remaining large-misfit sites are located along the creeping portions of the San Andreas and Hayward faults (Figure 2), where more complex, distributed slip-models are warranted (Johanson and Bürgmann, 2005; Schmidt et al., 2005). We utilize the residual GPS velocities of sites located within a distance of ≤ ~ 30 km of the epicenter.

We use permanent scatterer InSAR (PS-InSAR) (Colesanti et al., 2003; Ferretti et al., 2000, 2001) data to add a large number of additional point-displacement measurements and constrain vertical motions in the area (Bürgmann et al., 2006). InSAR provides measurements of change in distance along the look direction of the radar spacecraft and is highly sensitive to vertical motion due to its steep (20-26° off-vertical) look angle (Bürgmann et al., 2000). We use results presented in Bürgmann et al. (2006) relying on 49 European Remote Sensing satellite (ERS-1 and 2) acquisitions of frame 2853 along track 70 collected from 1992 to 2000 (Figure 1). As motions of points on Quaternary substrate are often impacted by hydrological processes (Schmidt and Bürgmann, 2003), we only include points located on pre-Quaternary bedrock units based on the map of Knudsen et al. (2000). After removing the contribution of background deformation as defined by the GPS-derived dislocation model, residual PS-InSAR rates reveal an area of range increase at rates of up to ~2 mm/yr localized about the epicentral region of the Loma Prieta earthquake, which roughly coincides with the region of horizontal contraction evident in the residual GPS velocities (Figure 3) (Bürgmann et al., 2006). The horizontal residual motions indicated by the GPS measurements project to < 0.5 mm/yr of range change; thus, this range-change rate anomaly is dominantly due to subsidence at ~ 2 mm/yr in this region. Here we evaluate if this zone of contraction, right-lateral shear and subsidence is related to late-stage postseismic relaxation from the oblique-reverse earthquake (Pollitz et al., 1998).

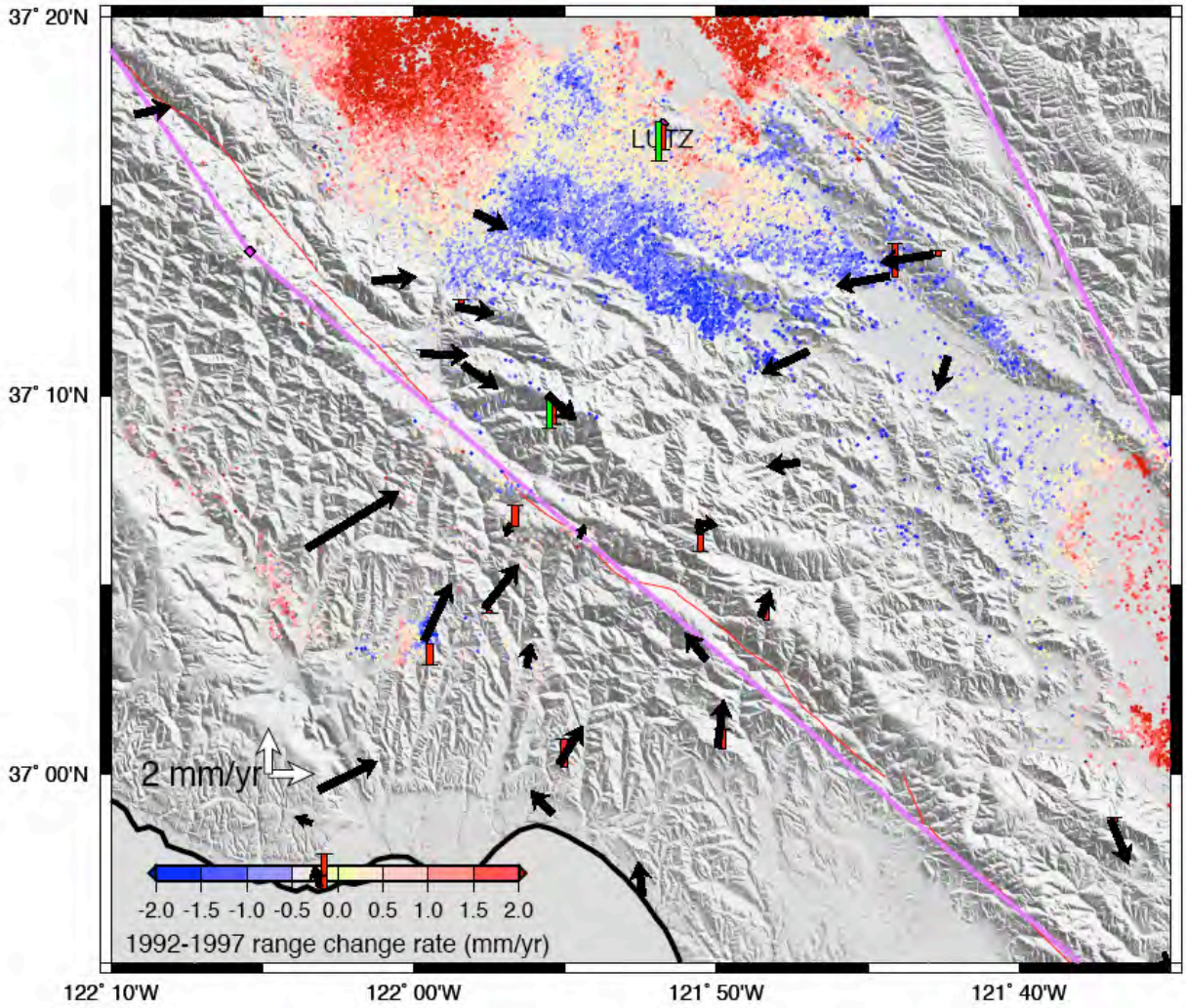

Figure 3. Residual range change rates and residual horizontal GPS velocities in Loma Prieta region following removal of an interseismic deformation model. This view includes data on Quaternary and bedrock substrate; however, for the model inversions we remove data on Quaternary substrate to avoid contributions from non-tectonic deformation processes (Bürgmann et al., 2006). Vertical rates for sites with 1-sigma uncertainties estimated at < 2 mm/yr (red bars) and independent SOPAC estimate for CGPS BARD sites (green bars) are shown as well.

3.3 Models of Postseismic Relaxation

We consider simple models of postseismic relaxation in a layered visco-elastic representation of the Earth's lithosphere. The model consists of an elastic upper crust (to 15 km depth) underlain by a Maxwell visco-elastic lower crustal layer and visco-elastic mantle half-space. The calculations are carried out using the VISCO1D program (Pollitz et al., 1997) to calculate deformation using spheroidal and toroidal motion modes of the spherically stratified elastic-viscoelastic medium. The model is parameterized by specifying the coseismic fault geometry and slip of the source event and the depth dependent elastic and viscous parameters.

We also consider the possibility of localized afterslip down-dip of the Loma Prieta rupture as an alternate mechanism of continued postseismic deformation. We evaluate simple models of uniform slip on a 70° SW-dipping dislocation plane adjoining the coseismic rupture below 17-km depth.

3.4 Results

As a starting point, we examine a model developed by *Pollitz and Nyst* (2005), which incorporates viscoelastic relaxation from the Loma Prieta earthquake in a layered, spherical Earth in a study of interseismic strain in the Bay region. We adopt the coseismic fault model of *Marshall et al.* (1991) to drive the viscous relaxation. The model lithosphere consists of an elastic upper crust of thickness 15 km, a Maxwell viscoelastic lower crust of thickness 15 km and viscosity η_c, and a Maxwell viscoelastic upper mantle of viscosity η_m, following a model developed by *Pollitz et al.* (1998). The model is characterized by a relatively strong crust and weak mantle with $\eta_c/\eta_m = 3.3$. Figures 4 and 5 show the predicted average horizontal velocities and range-change rates during the observation time period assuming relaxation in a mantle with viscosity of 1.2×10^{19} Pa s and 5×10^{18} Pa s. The first-order pattern of predicted deformation from these models matches the InSAR observations well. The modeled horizontal deformation produces much of the observed fault-normal contraction, but does not do a good job in reproducing the amount and distribution of fault parallel motions. This may be due to limitations in our ability to separate and remove "background" interseismic motions from the observed deformation using the deep-slip dislocation model we employ. Figure 6 shows the misfit of residual 1992-2000 range change rates and viscous relaxation model as a function of viscosity of the upper mantle. The lower crust is assumed to have viscosity of three times that applied to the upper mantle layer. A viscosity of 5×10^{18} Pa s produces the best fit to the observed range change pattern.

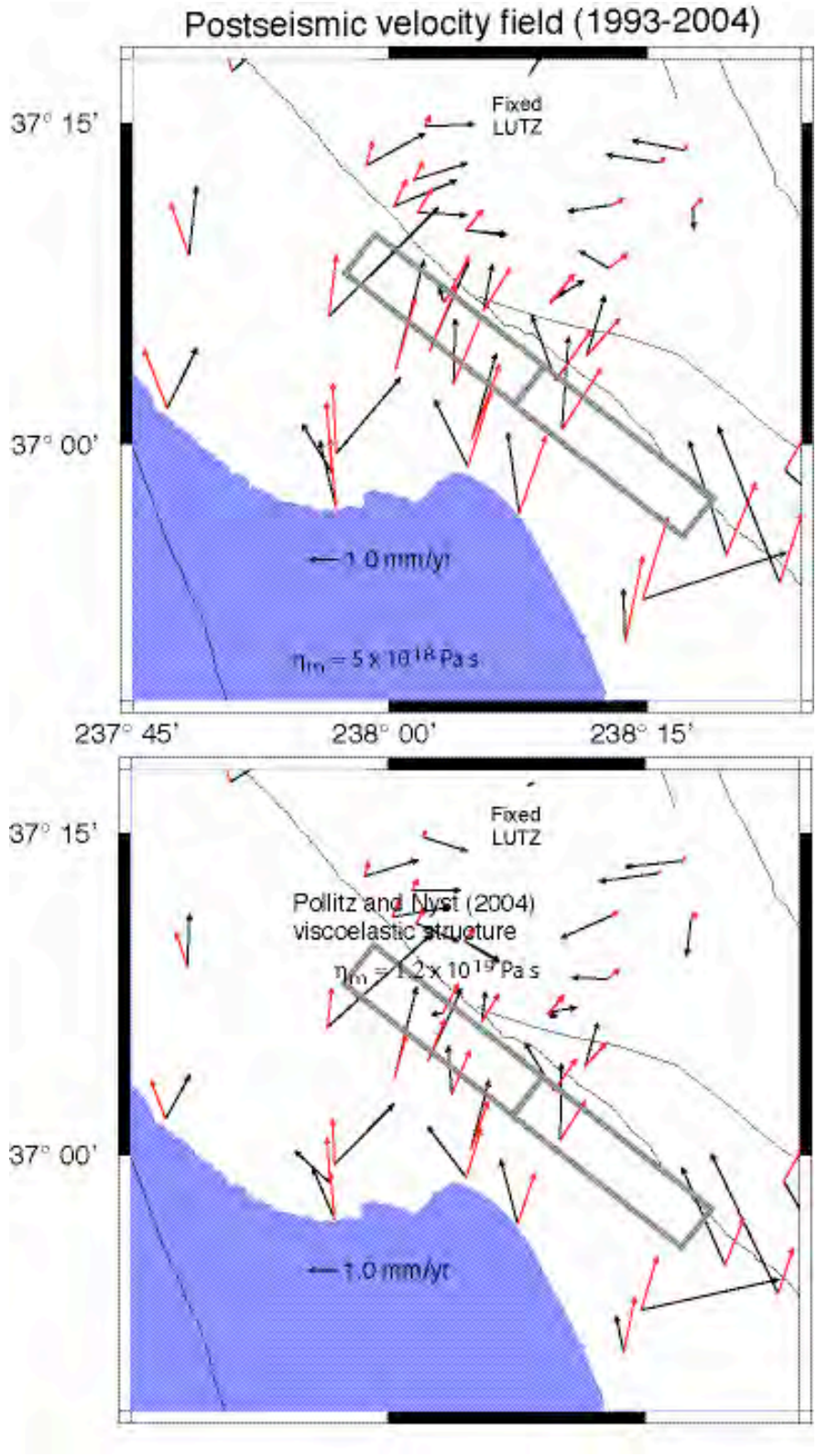

Figure 4. Observed GPS residual rates following removal of an interseismic model (black arrows) shown with predicted horizontal motions from models of viscoelastic relaxation in the upper mantle and lower crust (red arrows). See text for model description.

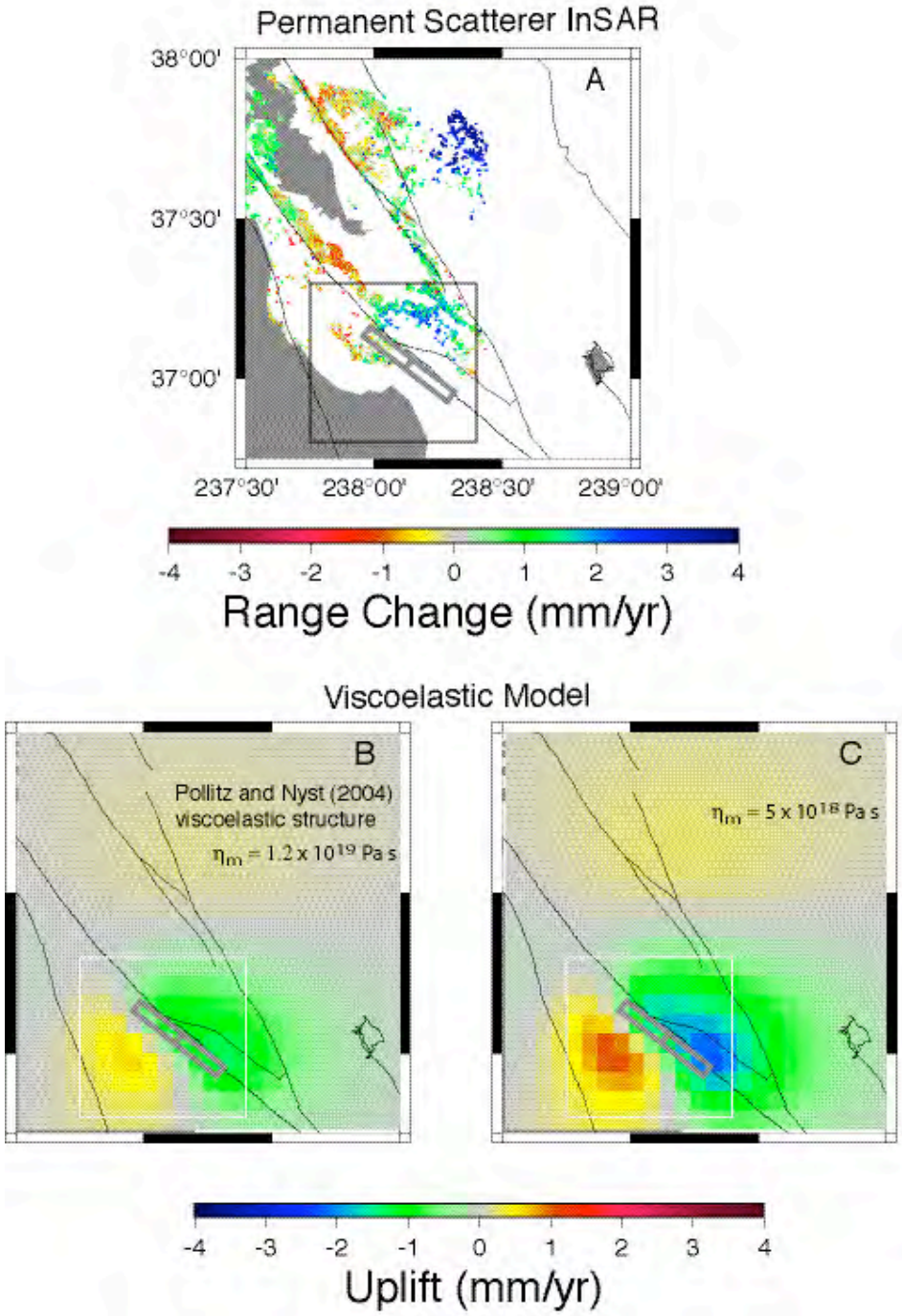

Figure 5. (a) Observed range-rate residuals and modeled rates due to viscous relaxation at depth (b, c).

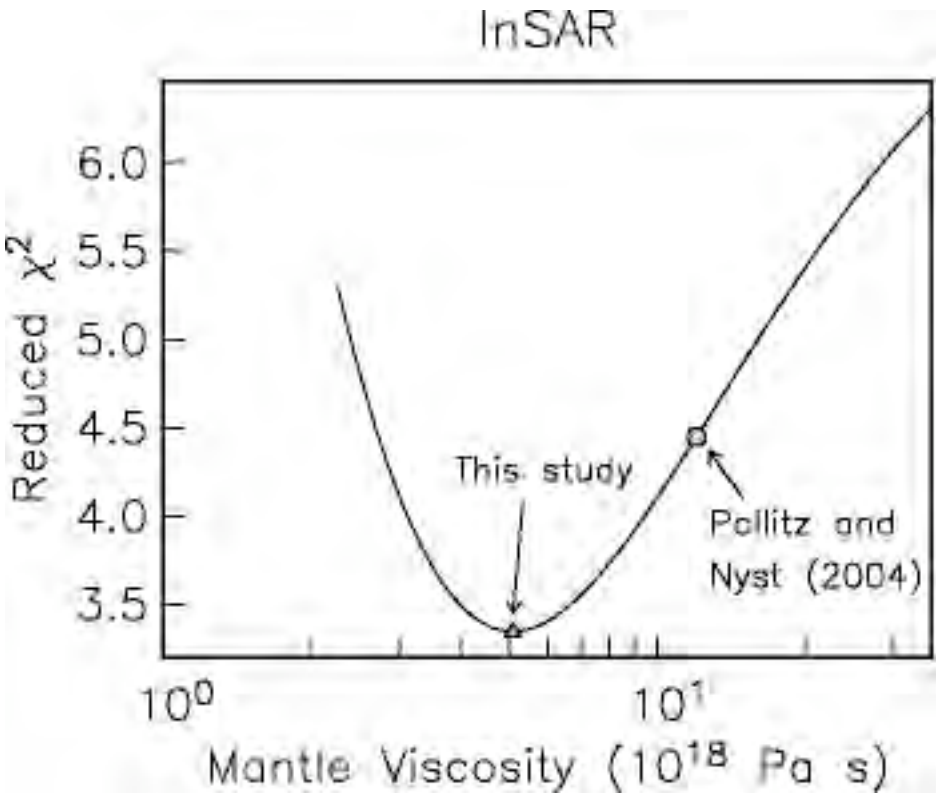

Figure 6. Misfit of residual 1992-2000 range change rates and viscous relaxation model as a function of viscosity of the upper mantle. The lower crust is assumed to have viscosity of three times that applied to the upper mantle layer. A viscosity of 5 x 10^{18} Pa s produces the best fit to the observed range change pattern.

3.5 Discussion

Assumptions made/problems. Our determination of a transient post-Loma-Prieta deformation is based on a displacement signal of small magnitude; that is, about 20 mm subsidence and residual contraction during a decade-long observation period. Lacking pre-earthquake measurements of sufficient precision, the residuals we rely on are with respect to a regional GPS-derived interseismic model, rather than an actually observed pre-Loma Prieta deformation pattern (Bürgmann et al., 1997). However, the anomalous nature of the observed deformation residuals, in particular the rapid subsidence along the restraining bend of the SAF near Loma Prieta makes us confident that this is in fact part of a transient, Loma Prieta related deformation feature. We can make predictions about the deformation in the next decade that will allow us to test our result.

Time dependence of deformation. We examine the InSAR time series for evidence of

decaying rates of subsidence by calculating range-change rates for the 1992-1996.5 and 1996.5 – 2001 periods, respectively. We do not find a resolvable change in range-change rate (Figure 7). This is; however, consistent with the degree of time dependency predicted by the viscous relaxation model. We find that within their uncertainties the estimates are indistinguishable from one another, or the predicted transient rates during the observation period. Rates should decrease by ~1 mm/yr over the next decade, which should be measurable by future observations.

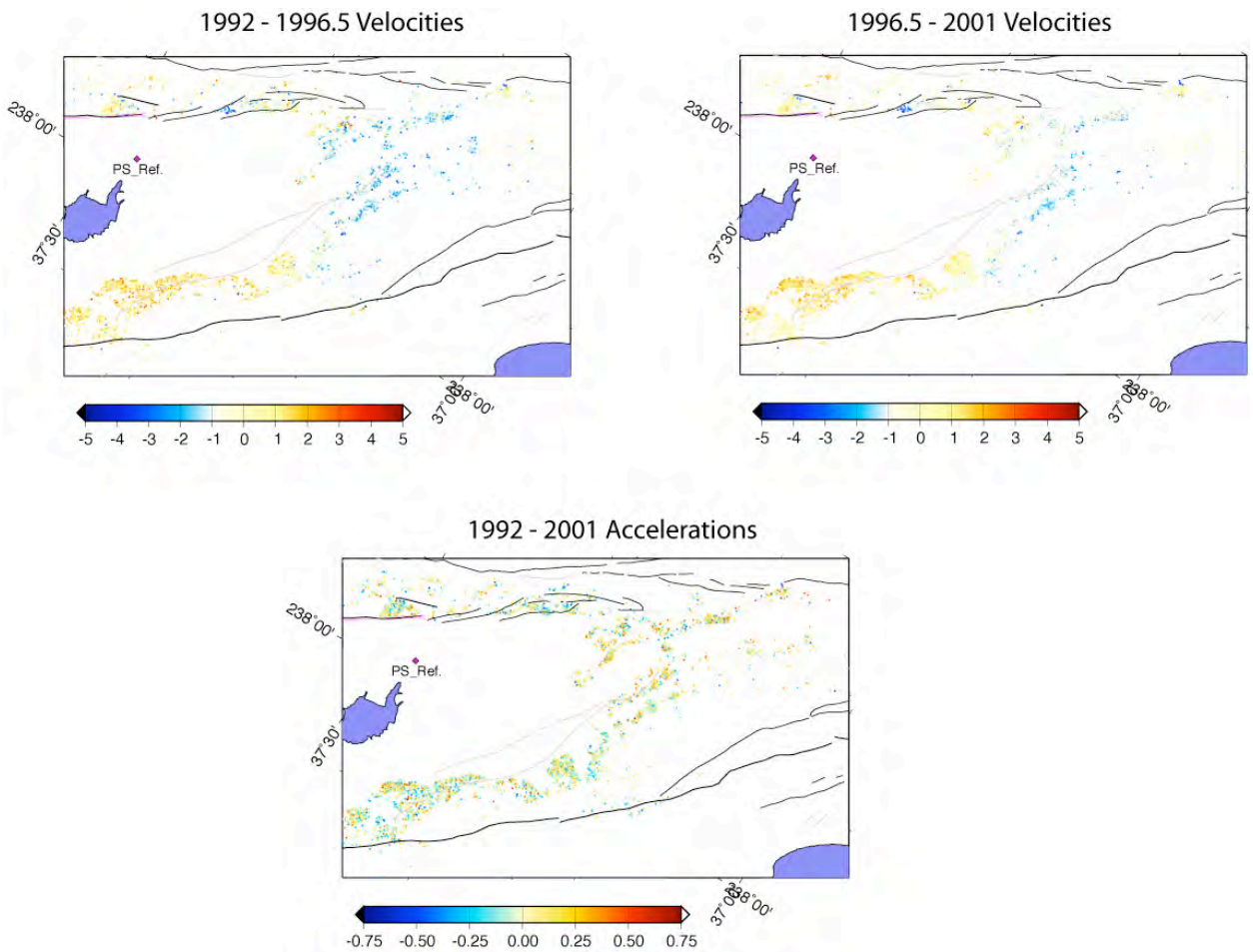

Figure 7. Stability of range change rate of bedrock points during 1992 – 2001 PS InSAR observation period. We see no significant rate changes during this time period.

4. DATA AVAILABILITY

Data from GPS campaigns are publicly available from the UNAVCO Campaign Data Holdings Archive. Both raw GPS data and accompanying metadata are included and freely accessible at http://facility.unavco.org/data/gnss/campaign.php

Data collected by our group for this project are archived under the PI Name (Burgmann) for campaigns named "Calaveras Fault", "Hayward Fault", "Central San Andreas" and "Loma Prieta."

Please see http://www.unavco.ucar.edu/data_support/data/general.html for policies regarding the use of these freely available data. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

Processed GPS solutions, including the BAVU velocity field, time series and GAMIT-format solution files (h-files) are available via the BAVU web pages at:

http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/

http://seismo.berkeley.edu/~dalessio/BAVU/FILES/gamit.html

For more information regarding data availability, contact:

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