Contemporary uplift of the Sierra Nevada, western United States, from GPS and InSAR measurements

William C. Hammond[1]*, Geoffrey Blewitt[1], Zhenhong Li[2], Hans-Peter Plag[1], and Corné Kreemer[1]
[1]Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, and Nevada Seismological Laboratory, University of Nevada, Reno, Nevada 89557, USA
[2]Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET+), School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, UK

ABSTRACT

Modern space geodesy has recently enabled the direct observation of slow geological processes that move and shape Earth's surface, including plate tectonics and crustal strain accumulation that leads to earthquakes. More elusive has been the direct observation of active mountain growth, because geodetic measurements have larger uncertainties in the vertical direction, while mountain growth is typically very slow. For the Sierra Nevada of California and Nevada, western United States, the history of elevation is complex, exhibiting features of both ancient (40–60 Ma) and relatively young (<3 Ma) elevation. Here we exploit the complementary strengths of high-precision three-component point positions from the GPS and blanket coverage line-of-sight measurements from interferometric synthetic aperture radar (InSAR) to show that contemporary vertical motion of the Sierra Nevada is between 1 and 2 mm/yr. The motion is upward with respect to Earth's center of mass and with respect to a relatively stable eastern Nevada, indicating generation of relief and uplift against gravity. Uplift is distributed along the entire length of the range, between latitude 35°N and 40°N, and is not focused near localized, seismically imaged mantle downwellings. These results indicate that the modern episode of Sierra Nevada uplift is still active and could have generated the entire modern range in <3 m.y.

INTRODUCTION

The Sierra Nevada is an ~600-km-long mountain range that is part of the Sierra Nevada–Great Valley (SNGV) microplate in the western United States (Fig. 1) that moves subparallel to the motion of the Pacific plate relative to North America (Argus and Gordon, 1991). It is bounded on the west by the San Andreas fault system, and on the east by the faults in the Great Basin. Away from these bounding faults, rigidity of the microplate interior is inferred from a dearth of significant faults and internal seismicity (Goter et al., 1994), direct geodetic measurements (Dixon et al., 2000; McCaffrey, 2005), long-wavelength patterns in topography, and structure (Christensen, 1966; Unruh, 1991; Saleeby et al., 2009).

Some investigations using various stratigraphic, isotopic, and thermochronologic dating techniques conclude that the Sierra Nevada experienced a pulse of late Cenozoic uplift and tilting that is responsible for much of the modern elevation (e.g., Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001; Stock et al., 2004). These uplift rates are broadly consistent with normal fault slip rates on the Sierra Nevada eastern range front, 0.3–1.1 mm/yr (Jayko, 2009), and imply young modern topography (<3 Ma). On the other hand, studies using (U-Th)/He thermochronometry and hydrogen isotope paleoelevation estimates conclude that the west slope of the Sierra Nevada was high between 28 and 60 Ma (e.g., House et al., 1998; Mulch et al., 2006; Cassel et al., 2009), and thus that pre–3 Ma elevation was substantial.

GPS DATA AND ANALYSIS

High-precision GPS networks now span the SNGV and Great Basin, and can resolve the contemporary motion in three dimensions (Fig. 1A). In particular, the EarthScope Plate Boundary Observatory has provided hundreds of new stations in California and Nevada, including about a dozen on the west slope of the Sierra Nevada. We processed all available GPS data to obtain station height time series, and fit them with a six-parameter empirical model including an epoch position, a velocity, and an amplitude and phase of annual and semiannual harmonic constituents (to model seasonal effects). To enhance the signal-to-noise ratio, we used GPS vertical velocities based on over 3 yr of data with 1σ rate uncertainties ≤ 1.0 mm/yr, and required that the empirical model adequately fit the data (Fig. 2). The processing and analysis details are included in the GSA Data Repository[1].

Our results show that almost all GPS vertical velocities are between −2 and 2 mm/yr (Fig. 1). A transect from the Sierra Nevada to eastern Nevada shows the signal relative to rate uncertainties (Fig. 1C). Sierra Nevada west slope stations move upward with an average rate of 1.1 ± 0.4 mm/yr, while eastern Nevada stations move −0.3 ± 0.3 mm/yr (uncertainties represent the standard deviation of rates to quantify data scatter). Great Valley rates have a large variance, indicating that those signals are largely nontectonic in origin owing to soft sediments and irrigation, so we exclude them from consideration. In general, the correlation between elevation and vertical velocity is poor except in some long-wavelength components—e.g., upward motion of the Sierra Nevada (consistent with Bennett et al., 2009). However, there is a strong correlation between vertical rate and geologic province, as seen in the interpolation of vertical velocity estimated using kriging on a regular 0.2° × 0.2° grid (Hansen, 2004) (Fig. 1B).

Several factors suggest that these GPS vertical velocities predominantly represent solid Earth motion, rather than noise or processing artifacts. The most compelling evidence comes from the Central Nevada Seismic Belt (CNSB), which today slowly responds to a sequence of large twentieth-century earthquakes. Our results show that the CNSB domes upward at a rate of 1.9 ± 0.5 mm/yr (station GOLM) in a feature spanning multiple mountain ranges. Models of transient viscoelastic postseismic relaxation of the mantle predict this feature (Gourmelen and Amelung, 2005) (Fig. DR4 in the Data Repository). Thus, GPS appears to be sensitive enough to resolve signals near 2 mm/yr, and postseismic relaxation models do not predict the Sierra Nevada uplift. Secondly, the transect shows that vertical velocities within the westernmost Great Basin have greater variance, consistent with strain rates an order of magnitude larger than eastern Nevada (Thatcher et al., 1999).

If the Sierra Nevada bedrock moves upward with respect to Earth's center of mass, then its gravitational potential energy is likely increasing, having important geodynamic implications (Jones et al., 1996). Our vertical velocities are aligned to the International Terrestrial Reference Frame (ITRF2005), whose origin is Earth's center of mass, to within ~0.5 mm/yr (Altamimi et al., 2007). Generally, relative station velocities have smaller uncertainties than geocentric velocities because noise common to multiple stations does not affect trends in relative location (Wdowinski et al.,

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*E-mail: whammond@unr.edu.

[1] GSA Data Repository item 2012167, supplementary figures, methods, and table, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, doi:10.1130/G32968.1; 3 figures; Data Repository item 2012167.

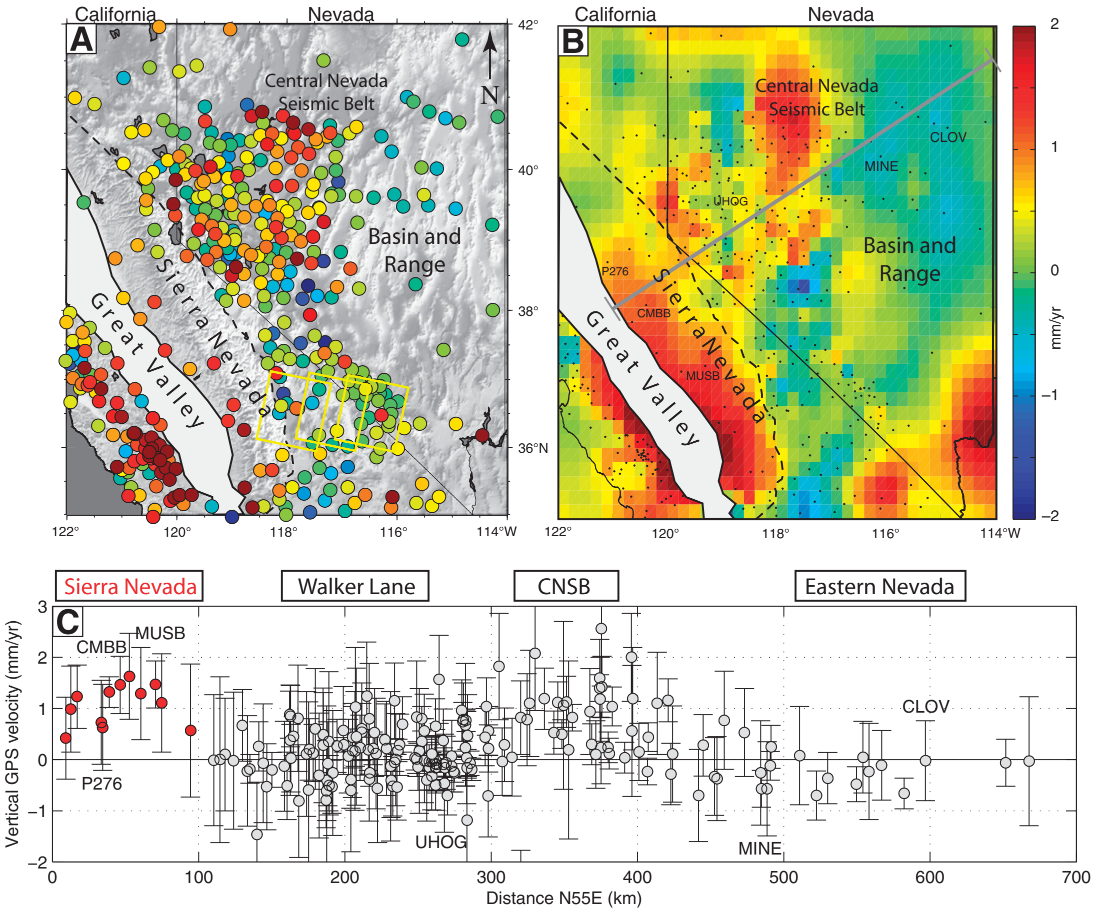

Figure 1. Vertical GPS velocity across California and Nevada. A: Color represents upward rate. Dashes outline the Sierra Nevada. Great Valley stations are unreliable and omitted. Yellow boxes indicate radar scene boundaries (close-up shown in Fig. 3A). B: Interpolated vertical velocity and GPS stations (dots). Gray bar is profile in C. C: Vertical velocity transect from Sierra Nevada to eastern Nevada. The profile trends N55E and includes all sites east of 121°W and north of 36°N. Vertical bars indicate 2σ uncertainty. Acronyms are selected station names. CNSB—Central Nevada Seismic Belt.

1997). Thus, geocentric velocities require longer time series to achieve the same precision. The longest-running Sierra Nevada stations (e.g., sites MUSB, CMBB, LIND, ORVB) have 9.8–15.5 yr of data, and move upward with respect to Earth's center of mass (mean 1.2 ± 0.5 mm/yr), suggesting increasing gravitational potential energy.

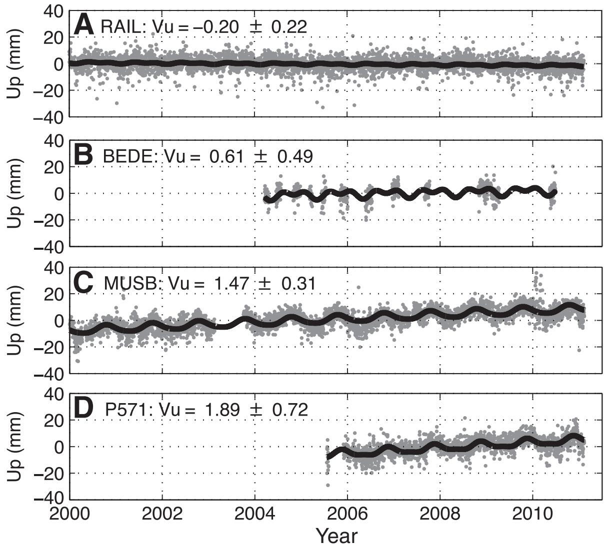

Figure 2. Vertical GPS position time series examples. Stations in the Great Basin (A and B) have vertical rates near zero. Sierra Nevada west slope stations move upward (C and D). Black line indicates best-fitting model. Vu—upward velocity.

INSAR DATA AND ANALYSIS

Complementary to GPS point measurements, interferometric synthetic aperture radar (InSAR) can provide blanket coverage of long-term motion of Earth's crust in the radar line-of-sight (LOS) direction. The radar beam is inclined ~23° from vertical, implying strong sensitivity to vertical motion. We use 18 yr of European Remote Sensing satellite (ERS-1 and ERS-2) and Envisat data from descending tracks 442, 170, and 399 with overlapping scene boundaries to form a transect between the Sierra Nevada and Yucca Mountain (Fig. 3). In total, we used 271 scenes to form 1943 interferograms with good coherence. The degree of internal consistency between GPS and InSAR, after alignment, is 0.7 mm/yr, which characterizes the precision of the LOS rate map.

We separate vertical from horizontal signals in the InSAR LOS using a strain-rate map derived from horizontal GPS velocities. On the east side of the transect, there is very close agreement between rates for (1) InSAR LOS, (2) three-component GPS projected onto LOS, and (3) horizontal-only strain-rate map projected into LOS, indicating that vertical motion is very small (Fig. 3). West of Owens Valley, in the Sierra Nevada (west of kilometer 75, Fig. 3B), the mean vertical rate is 1.6 ± 0.7 mm/yr, indicating that vertical motion contributes to the signal. This agrees with GPS rates on the Sierra Nevada and shows that the east edge of the uplift coincides with the SNGV east boundary.

Several factors suggest that the signals seen in the vertical rate map are from solid Earth motion, and not noise associated with data processing artifacts. First, internal consistency between InSAR and GPS suggest that they measure a common surface displacement signal. For example, subsidence at the Coso, California, geothermal area (Fialko and Simons, 2000) is the same in InSAR and GPS (–4 mm/yr at COSO site, Fig. 3A), suggesting accurate alignment. Second, while InSAR results can be sensitive to

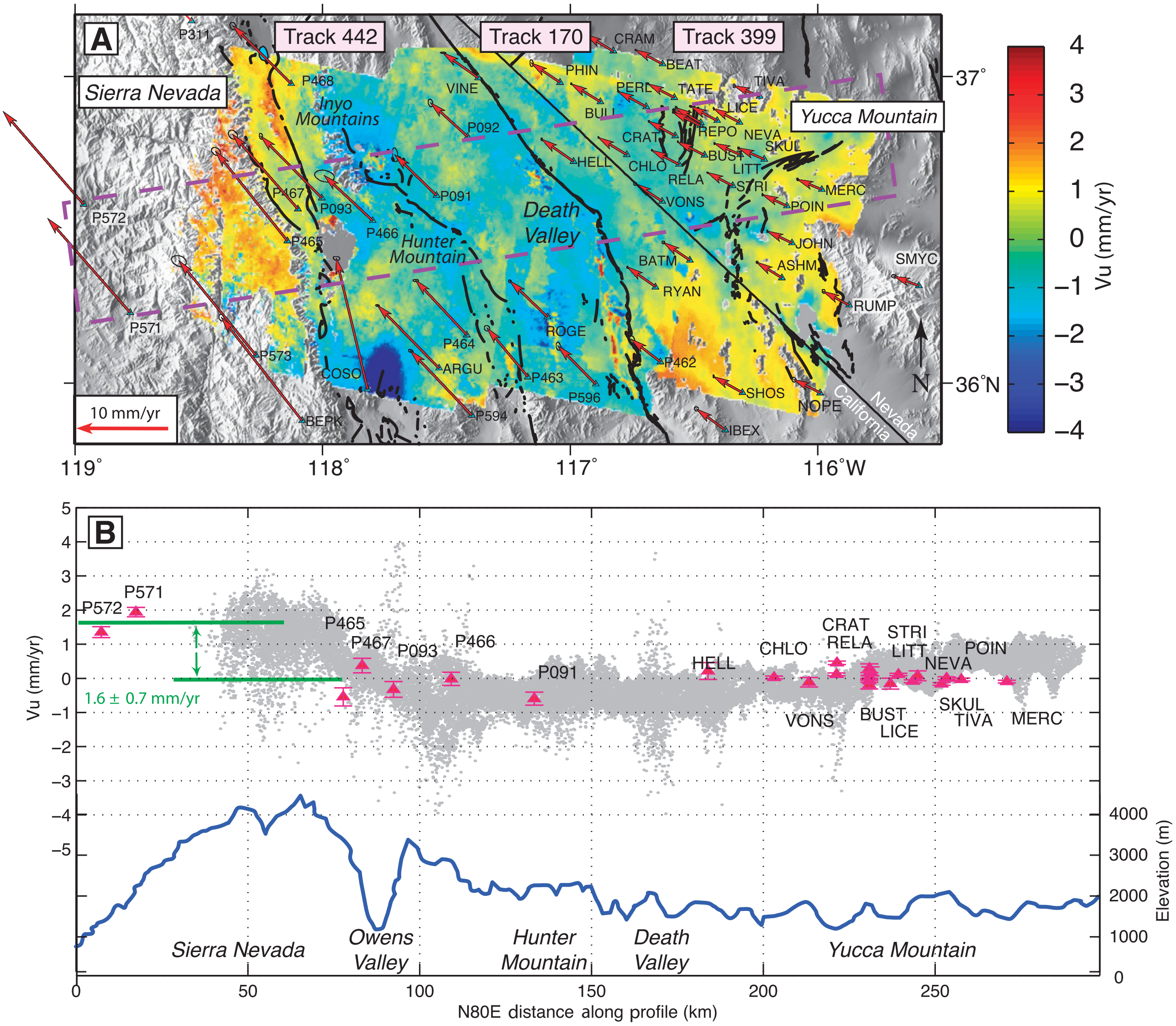

Figure 3. Upward velocity (Vu) from interferometric synthetic aperture radar (InSAR). A: Red vectors with site names show horizontal GPS velocity with respect to North America (with 95% confidence ellipses). Black lines are major faults. Dashed box indicates location of profile. B: Profile of upward rate derived from InSAR (gray) and GPS (magenta). Uncertainty bars are 2σ. Blue line indicates topography across profile. Green bars highlight mean uplift rate from InSAR. Acronyms are selected station names.

topography when relief is high, our results do not show close correlation to topography. Only the Sierra Nevada exhibits coherent uplift in both InSAR and GPS measurements, while other prominent ranges (e.g., Inyo and Panamint) do not. Third, while a lack of GPS stations in the Sierra Nevada high-country wilderness precludes direct confirmation, the InSAR is in agreement with vertical rates for stations P571 (1.9 ± 0.7 mm/yr) and P572 (1.3 ± 0.8 mm/yr), which lie immediately west of our InSAR tracks, and are corroborative because they were not used in the alignment between GPS and InSAR (Fig. 3B).

DISCUSSION AND CONCLUSIONS

Geodesy can constrain the initiation time of uplift if it measures an average motion of the solid rock valid over long periods of geologic time, adjusted for the rate of erosion (England and Molnar, 1990). An average uplift rate of 1–2 mm/yr is enough to generate ~3000 m of elevation in 1.5–3.0 m.y., assuming that erosion is negligible and that surface elevation was initially near zero. Independent estimates of Sierra Nevada erosion rates vary in space and time, between <0.01 and 0.6 mm/yr depending on whether summit bedrock or fluvial canyon incision rates are considered (Small et al., 1997; Riebe et al., 2000; Wakabayashi and Sawyer, 2001). However, geographically distributed rock uplift rates should be compared with landscape-averaged erosion rates that are likely ≤0.1 mm/yr. Thus geodetic uplift rates are much faster than erosion, indicating net uplift. If geodesy measures a recent, more rapid episode of uplift that initiated since 3.5 Ma (Clark et al., 2005), then some proportion of contemporary elevation may be ancient and could reconcile geodetic rates and data that indicate an older range.

Postglacial rebound (PGR) following the Last Glacial Maximum could also add motion unrepresentative of long-term uplift. Rates attributable to unloading following the melting of Sierra Nevada alpine glaciers are not available, but the viscoelastic rebound time scale of the adjacent Great Basin may be ~300 yr (Adams et al., 1999), implying that PGR following removal of local glaciers is complete, though the Sierra Nevada lithosphere may be stiffer, requiring more time to adjust. More recent ice loads (e.g., of the "Little Ice Age") were not thick enough to cause contemporary rebound rates of 1 mm/yr. Contributions from continental ice sheets have horizontal wavelengths of >1000 km and would not predict an uplift pattern matching the SNGV outline as we observe (Fig. 1B). Hence PGR cannot explain a significant fraction of the observed uplift. Rates attributable to decade-scale climatic changes in the atmosphere or terrestrial hydrosphere are not known, but could have nonlinear effects with nonzero trends that add to vertical motion. However, the linearity of our time series argues that these effects are minor.

Contemporary uplift is not confined to be near the Sierra Nevada crest or range front faults (Fig. 1.), and is distributed along the length of the SNGV microplate between latitude 35°N and 40°N. Uplift is not focused near localized, seismically imaged mantle downwellings (e.g., Zandt et al., 2004; Jones et al., 2004), as might be expected if basal unloading is the driving force. However, range-wide uplift could be driven by foundering of anomalously dense lower lithosphere if the microplate responds rigidly, or if delamination is more pervasive than realized. Because of the complexity of signals in the Great Valley, our ability to distinguish between upward-only motion of the Sierra Nevada and down-to-the-southwest tilting is presently limited. Thus these data cannot rule out a contribution from erosional mass transfer (Small and Anderson, 1995) that helps drive tilting. In either case, the long wavelength of the signal suggests that it is a range-wide response to vertical forces, and indicates that contemporary Sierra Nevada uplift is a fundamental part of the active evolution of the Pacific–North America plate boundary.

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