Magnitude and duration of surface uplift above the Socorro magma body

2009

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ABSTRACT

We use interferometric synthetic aperture radar and geomorphic data to constrain the magnitude and duration of uplift driven by the magma body beneath Socorro, New Mexico, United States. Interferometry spanning 1992–2006 confirms uplift of the Socorro magma body at a rate of ~2.5 mm/yr. However, we find no clear evidence for volcanic uplift after an examination of three rivers (Rio Salado, Rio Puerco, Rio Grande), and two terraces (Llano de Manzano, Llano de Albuquerque) crossing the Socorro magma body. Our geomorphic measurements permit at most 25–50 m of cumulative surface uplift above the Socorro magma body since the middle Pleistocene, but require no long-term uplift. Given previously articulated thermal arguments for the Socorro magma body, we therefore suggest either a recent (within the last few centuries) initiation of uplift at Socorro, or that long-term uplift and subsidence have been essentially equal.

INTRODUCTION

Melt in the mid-crust (e.g., Sanford et al., 1977), enhanced seismicity (e.g., Balch et al., 1997), and surface uplift around Socorro, New Mexico, United States (e.g., Larsen et al., 1986), indicate the presence of an actively inflating 19-km-deep, ~150-m-thick horizontal magma body (Ake and Sanford, 1988; Fig. 1). Violent eruptions of the nearby Valles caldera (e.g., Smith and Bailey, 1966) and the large size of the Socorro magma body (Balch et al., 1997) motivate work to constrain the duration of current volcanic unrest at Socorro. However, because the Socorro magma body has no eruptive record, nor a seismic or geodetic record prior to the early twentieth century, constraints on its evolution beyond decadal time scales are sparse.

Results from two geomorphic studies (Bachman and Mehnert, 1978; Ouchi, 1985) imply between 5 and 43 k.y. of cumulative volcanic uplift at Socorro, assuming surface uplift rates of ~2 mm/yr (Fialko and Simons, 2001). However, Fialko and Simons (2001) noted that a 150-m-thick magma body would freeze in a few centuries. Thus, if surface uplift is truly continuous for millennia, there is a thermal paradox. With the aim of reconciling the thermal paradox articulated by Fialko and Simons (2001), we seek to improve constraints on the duration and magnitude of volcanic uplift at Socorro using interferometric synthetic aperture radar (InSAR) and quantitative geomorphology.

GEODETIC CONSTRAINTS ON THE RATE AND EXTENT OF SURFACE UPLIFT AT SOCORRO

To quantify surface uplift over Socorro, we used 180 interferograms created from 36 European Space Agency European Remote Sensing satellite (ERS-1 and ERS-2) synthetic aperture radar (SAR) acquisitions for the period 1992–2006 (Table DR1 in the GSA Data Repository[1]), representing an order of magnitude more interferograms and twice the number of SAR acquisitions used in the Fialko and Simons (2001) analysis of Socorro uplift from 1992 to 2000. We apply a least squares inversion to the 1992–2006 interferograms to solve for the deformation history (see the Data Repository). Figure 1B shows rates of surface velocity generated from the 1992–2006 inversion along the satellite line-of-sight (LOS) direction. Figure 1C shows the predicted surface velocity from the opening of a 21-km-radius, 19-km-deep, horizontal, circular, penny-shaped tensile crack in an elastic half-space (Fialko et al., 2001). The model residuals (Fig. 1D) indicate that this source geometry adequately captures measured deformation over Socorro. The time series inversion over the Socorro magma body (Fig. 1E) shows that surface elevation, though quite variable over 1–2 yr time intervals, appears to increase at an average rate of 2.5 mm/yr between 1992 and 2006.

The maximum 1992–2006 average surface velocity we compute (~2.5 mm/yr) is similar to the results of Fialko and Simons (2001) for 1992–2000, and to those of Larsen et al. (1986) for 1912–1951, suggesting that surface uplift at Socorro has occurred steadily since at least 1912 to the present. However, whereas Fialko and Simons (2001) advocated for the superposition of two circular cracks at depth to explain deformation at Socorro, we model the deformation at Socorro with a simpler geometry.

GEOMORPHIC CONSTRAINTS ON THE DURATION OF SURFACE UPLIFT AT SOCORRO

The Llano de Manzano surface (Fig. 1A) comprises west-sloping fan deposits that override ancestral Rio Grande deposits containing 1.2 Ma ash and clasts derived from the Bandelier Tuff (older than 1.2 Ma) (Connell et al., 2000). The Rio Grande has been incising its ancestral deposits in the Albuquerque basin since the early to middle Pleistocene, and the Llano de Manzano (Fig. 1A) is thought to be graded to a base-level elevation set by the position of the Rio Grande when incision commenced 0.6–1.2 Ma (Connell et al., 2007). Because it crosses from a region with no measured volcanic uplift into the region near the apex of volcanic deformation over Socorro (Fig. 2A), the Llano de Manzano is well positioned to record volcanic uplift (Figs. 1A and 1B; see the Data Repository). Figure 2A shows that the inside edge of the Llano de Manzano has a smooth, concave-up morphology characteristic of an alluvial channel long profile (e.g., Mackin, 1948). Volcanic uplift is therefore not required to explain the shape of the Llano de Manzano. Nevertheless, some surface deformation could still be absorbed by the terrace without changing the concave appearance of the terrace. Figure 2B

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[1] GSA Data Repository item 2009062, geodetic and geomorphic data and methods, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, March 2009; v. 37; no. 3; p. 231–234; doi: 10.1130/G25132A.1; 3 figures; Data Repository item 2009062.

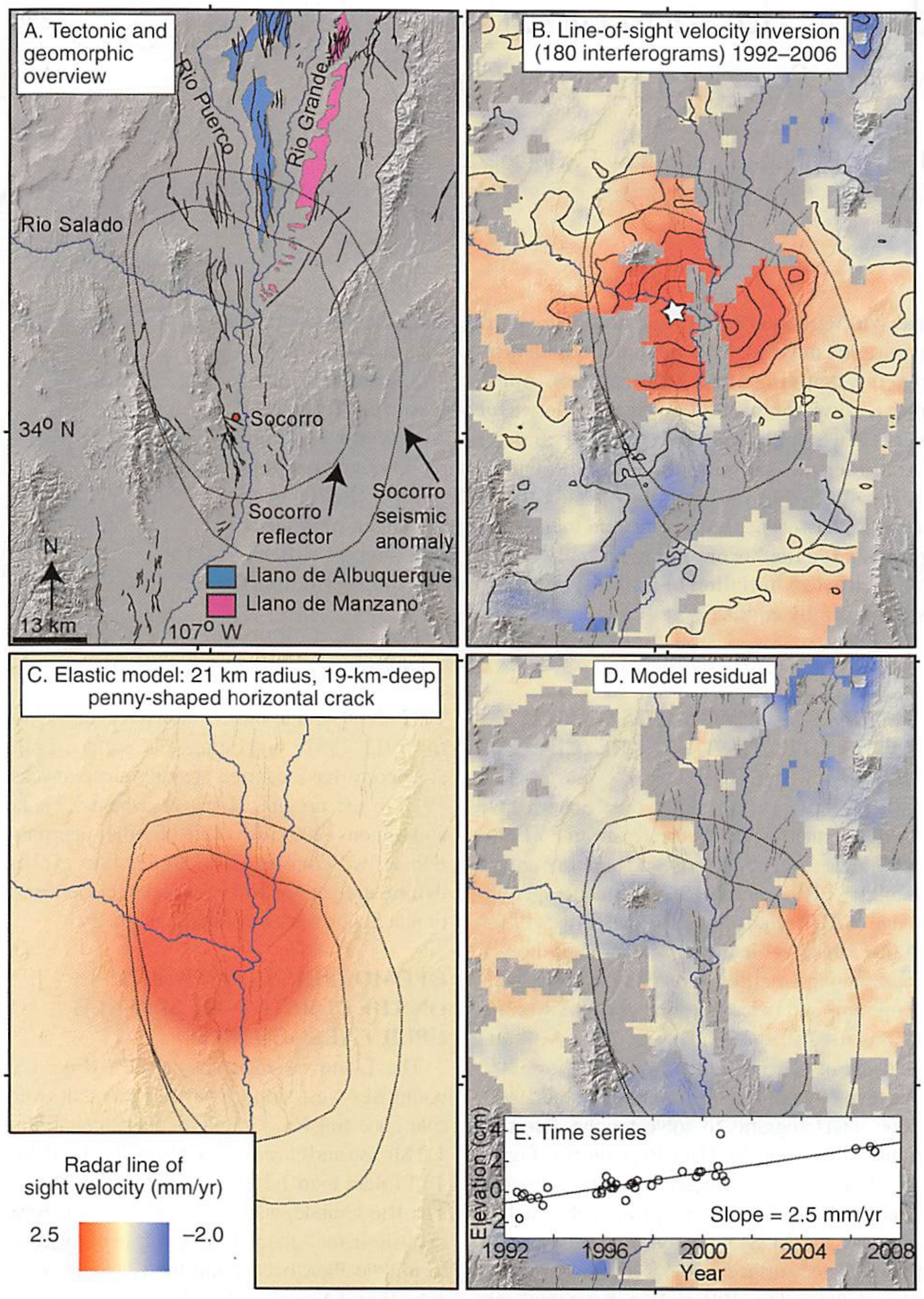

Figure 1. A: Shaded relief map showing terraces, rivers, Socorro seismic anomaly, Socorro reflector (Balch et al., 1997), and mapped faults (U.S. Geological Survey and New Mexico Bureau of Mines and Mineral Resources, 2006). B: Line-of-sight surface velocity from inversion of 180 European Remote Sensing satellite interferograms, 1992–2006; contour interval is 0.5 mm/yr. White star indicates location of time series shown in E. C: Model of surface velocity driven by opening of 21-km-radius, 19-km-deep, circular, penny-shaped, horizontal crack in an elastic half-space. D: Residual surface velocity after subtracting C from B. Outlines of Socorro seismic anomaly (outer line) and Socorro reflector (inner line) are also plotted in B–D. E: Surface elevation as function of time from the time series inversion over the center of the magma body (star in B).

shows profiles of the Llano de Manzano after subtracting varying amounts of cumulative volcanic deformation. With more than 10 k.y. of cumulative volcanic uplift at modern rates (i.e., ~25 m at the center of uplift), the initial profile of the Llano de Manzano would have been weakly convex, not concave. The concave-up shape of fluvial elevation profiles is widely recognized (e.g., Mackin, 1948). Therefore, to the extent that concavity is a robust feature of alluvial channels, the Llano de Manzano records no more than 10 k.y. (<25 m) of net volcanic uplift over the past 0.6–1.2 m.y. at current geodetic rates (Fig. 2B).

Figure 2B also shows the profile of the Llano de Manzano after 20 k.y. of cumulative volcanic uplift have been removed. With 20 k.y. of uplift, the top of the Llano de Manzano would have been both convex and at the elevation of the modern Rio Grande. Thus, if more than 20 k.y. of net volcanic uplift (at modern rates) is recorded by the Llano de Manzano, its surface should show signs of occupation by the Rio Grande in the vicinity of Socorro. Although there are no direct constraints on the age of the Llano de Manzano over the Socorro magma body, the heavily dissected morphology of the surface at the southern end of the Albuquerque basin (Fig. 1), combined with the 0.6–1.2 Ma abandonment age for the Llano de Manzano at other locales (Connell et al., 2007), suggests that over the past 20 k.y. the surface has been above the elevation of the active Rio Grande. Therefore, more than 20 k.y. (i.e., ~50 m at the center of uplift) of cumulative volcanic uplift over the past 0.6–1.2 m.y. is unlikely.

REVISITING THE GEOMORPHIC EVIDENCE FOR SURFACE UPLIFT AT SOCORRO: PLIOCENE FLUVIAL DEPOSITS

Bachman and Mehnert (1978) suggested that a southward-dipping Pliocene fluvial deposit on the south side of the Socorro magma body records as much as 85 m of volcanic uplift, assuming a depositional slope comparable to the modern Rio Grande. Along with the Rio Grande and the Llano de Manzano, we therefore plot the profile of this Pliocene deposit in Figure 2A; we also plot the Llano de Albuquerque, which is older than the Llano de Manzano and probably reflects filling of the Albuquerque basin by a through-going Rio Grande during the early Pleistocene or Pliocene (Connell et al., 2007). Figure 2A shows that terraces near Socorro tilt southward relative to the modern Rio Grande. However, whereas the tilting of the Pliocene fluvial deposit is consistent with deformation from magma intrusion at Socorro, the tilting of the Llano de Albuquerque and the Llano de Manzano would not be expected from magma intrusion alone.

There are two alternative explanations for the southward tilt of the terraces in the vicinity of Socorro. First, Larsen et al. (1986) documented a regional long-wavelength 5–10 cm southward tilt across the Socorro magma body in leveling data from 1912 to 1951. Larsen et al. (1986) attributed this tilt either to a systematic surveying error or to regional tectonics. If the latter scenario is true, the steep orientation of mapped terraces relative to the Rio Grande throughout the study area might record this tilting. However, as no southward tilting is apparent in continuous global positioning system (GPS) data from the Rio Grande Rift at present (see

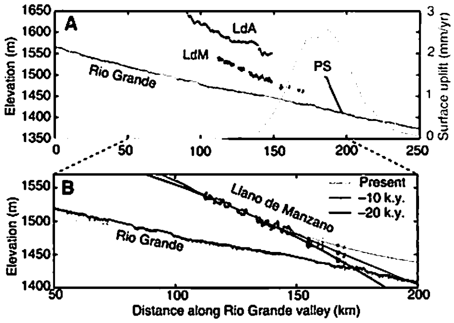

Figure 2. A: Elevation long profiles of Rio Grande, Llano de Albuquerque (LdA), Llano de Manzano (LdM), and Pliocene sediments (PS) (Bachman and Mehnert, 1978) through the study area. Surface uplift profile is from the model in C. B: Llano de Manzano after subtracting varying amounts of cumulative volcanic uplift.

the Data Repository), any tectonic mechanism responsible for terrace tilting must be inactive currently or below detection in the noisy vertical GPS component.

Alternatively, if Pliocene–Pleistocene sediment supplies were larger or coarser, or river discharges lower than at present, steeper depositional slopes along the Rio Grande relative to the present would be expected. A more recent increase in river discharge or a decrease in sediment supply or caliber would drive the Rio Grande to attain a lower gradient profile. This scenario would result in a relatively lower gradient Rio Grande inset within its steeper deposits, as is currently observed, and indicates that the tilt of the unit described by Bachman and Mehnert (1978) could have a sedimentary component.

REVISITING THE GEOMORPHIC EVIDENCE FOR SURFACE UPLIFT AT SOCORRO: RIO GRANDE CONVEXITY

Happ (1948) documented an ~10-m-amplitude convexity in the elevation long profile of the Rio Grande in central New Mexico. Based on the position of the convexity relative to the Socorro magma body, Ouchi (1985) argued that the river records uplift of the Socorro magma body; however, Ouchi also noted that the apex of this convexity is spatially coincident with the tributary junction of the Rio Puerco and the Rio Grande (Figs. 1A and 3C), and therefore could be of a sedimentary origin (as suggested by Happ, 1948). Tributary junction convexities are commonly observed where a river with a high sediment load joins another, driving gradient shallowing upstream of the sediment supply perturbation and gradient steepening downstream (e.g., Ferguson et al., 2006). The Rio Puerco is thought to provide >70% of the Rio Grande's sediment supply (Gellis et al., 2004). Therefore, it is essential to rule out sedimentary processes due to the extremely large sediment load of the Rio Puerco as an explanation for the Rio Grande's convexity.

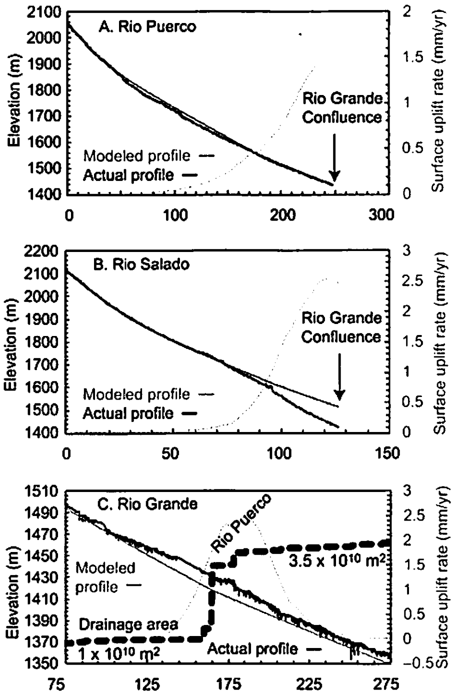

Figure 3. Modeled (dark gray) and measured (black) fluvial elevation long profiles over the Socorro magma body. A: Rio Puerco. B: Rio Salado. C: Rio Grande. In A–C, light gray line shows surface uplift from Figure 1C. In C, heavy dashed black line shows drainage area of Rio Grande as it passes over the Socorro magma body.

A test of the origin of the Rio Grande convexity is provided by the Rio Puerco and the Rio Salado (Figs. 1A, 3A, and 3B), which also cross the Socorro uplift, but do not have major tributary junctions in the vicinity of the uplift. If the convexity on the Rio Grande is volcanic in origin, we anticipate the same response (aggradation and profile shallowing upstream of the uplift) recorded by the Rio Salado and the Rio Puerco where they encounter the volcanic uplift. Alternatively, if the convexity on the Rio Grande is sedimentary, we expect to see no evidence for aggradation on the Salado or the Puerco as these rivers lack tributary junctions near Socorro.

In Figures 3A–3C we show the elevation long profiles of the Rio Grande, Rio Puerco, and Rio Salado where they cross the Socorro magma body; we also plot surface uplift rate profiles from Figure 1C, and modeled river profiles. To compute the latter, we project the elevation profile of each alluvial river across the Socorro magma body based on the measured concavity outside of the region of volcanic uplift (see the Data Repository). As anticipated, Figure 3C shows a clear convexity on the Rio Grande over the Socorro magma body relative to the expected profile. However, examination of the Rio Salado profile (Fig. 3B) shows the opposite sense of profile deflection relative to the volcanic uplift. In addition, the Rio Puerco (Fig. 3A), though only a few kilometers from the Rio Grande, shows no departure in its profile from the expected profile over the Socorro magma body. The river profile data thus show no consistent fluvial response to the uplift of the Socorro magma body.

The strongly extensional fabric of the topography near Socorro (Fig. 1A) is not obviously interrupted by swelling over the magma body. This suggests that relative to active normal faulting, the Socorro magma body is insignificant to the development of regional topography. Indeed, the Rio Salado steepens where it encounters the Socorro magma body near the river's confluence with the Rio Grande (Fig. 3B), indicating that base-level fall of the Rio Grande relative to the Rio Salado, rather than volcanic uplift, is the primary control on the development of the Rio Salado's long profile.

DISCUSSION AND CONCLUSIONS

We find no clear evidence for uplift of the Socorro magma body recorded in regional topography. The 0.6–1.2 Ma Llano de Manzano is not obviously deflected where it crosses over the actively inflating magma body (Fig. 2B). On the contrary, the elevation profile of the terrace is consistent with a graded alluvial channel. In addition, neither the Rio Puerco nor the Rio Salado, which both cross the Socorro magma body, display evidence of warping or aggradation due to the magma body (Figs. 3A–3C). This observation, combined with the striking spatial coincidence of the Rio Puerco tributary junction with the apex of the convexity on the Rio Grande (Fig. 3C), suggests that sedimentary processes, not volcanic uplift, are responsible for the widely recognized convexity on the Rio Grande near Socorro. All of the preserved terraces in the vicinity of Socorro, regardless of position relative to the magma chamber, tilt to the south. This tilt is consistent with either regional southward tectonic tilting or simply from steeper Pliocene–Pleistocene depositional slopes, but is not easily explained by volcanic deformation.

We therefore question the two lines of geomorphic evidence for uplift of the Socorro magma body over geologic time scales: (1) the convexity of the Rio Grande (Ouchi, 1985); and (2) the relative tilting of Pliocene sediments (Bachman and Mehnert, 1978). Although our geomorphic measurements permit at most 25–50 m of cumulative uplift of the Socorro magma since the middle Pleistocene, we emphasize that no deformation is required by our measurements and observations. Combined with previously articulated thermal arguments for the Socorro magma body (Fialko and Simons, 2001), the geomorphic data thus point to a recent (within the past few centuries) initiation of uplift at Socorro. Alternatively, long-term uplift and subsidence could have been equal to such an extent that surface deformation is unrecognizable in the landscape. At Yellowstone Caldera, in Yellowstone National Park, United States, temporal fluctuations of surface uplift and subsidence are recorded by Yellowstone Lake shoreline levels (Pierce et al., 2002).

ACKNOWLEDGMENTS

We thank George Hilley and two anonymous reviewers for helpful suggestions that clarified our arguments and presentation. Detailed comments on an earlier draft from Dave Love greatly aided in our interpretation of the regional topography and its relationship to the tectonic and geomorphic history of the Rio Grande Rift. We also thank Chris Andronicos and Frank Pazzaglia for helpful discussions about the geology of central New Mexico. Interferometric synthetic aperture radar (InSAR) data were acquired by the Western North America InSAR (WInSAR) consortium.

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Manuscript received 15 May 2008
Revised manuscript received 22 October 2008
Manuscript accepted 25 October 2008

Printed in USA