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# Evidence for on-going inflation of the Socorro magma body, New Mexico, from Interferometric Synthetic Aperture Radar imaging

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**Abstract.** Interferometric synthetic aperture radar (InSAR) imaging of the central Rio Grande rift (New Mexico, USA) during 1992-1999 reveals a crustal uplift of several centimeters that spatially coincides with the seismologically determined outline of the Socorro magma body, one of the largest currently active magma intrusions in the Earth's continental crust. Modeling of interferograms shows that the observed deformation may be due to elastic opening of a sill-like intrusion at a rate of a few millimeters per year. Despite an apparent constancy of the geodetically determined uplift rate, thermodynamic arguments suggest that it is unlikely that the Socorro magma body has formed via steady state elastic inflation.

## Introduction

The area of Socorro, central New Mexico, is a geophysically unusual segment of the Rio Grande rift, as expressed by high seismicity (the so-called Socorro Seismic Anomaly) [*Sanford et al.*, 1973; *Balch et al.*, 1997], high electric conductivity in the mid-to-lower crust [*Hermance and Neumann*, 1991], and a long-term surface uplift [*Reilinger and Oliver*, 1976; *Larsen et al.*, 1986]. Studies of local microearthquakes, and deep seismic sounding using active sources have revealed a strong seismic reflector having a characteristic horizontal dimension of 50-70 km, and depth of about 19 km; this reflector has been interpreted as indicating the presence of melt [*Brown et al.*, 1987; *Ake and Sanford*, 1988]. Taken together, these data suggest that the anomalous object beneath Socorro is one of the largest currently active magma bodies in the Earth's continental crust. Geophysical observations of the Socorro magma body may therefore be important for understanding the mechanics and thermodynamics of large crustal intrusions, and magmatic underplating.

Three leveling surveys conducted in the Socorro area in 1911, 1951, and 1980-1981 have measured average uplift rates of a few millimeters per year [*Larsen et al.*, 1986]. Interpretations of geomorphologic data suggest that the crustal uplift above the Socorro magma body may have occurred at a similar rate for the last several tens of thousands of years [*Bachman and Mehnert*, 1978; *Ouchi*, 1983; *Schlue et al.*, 1996]. These results imply an essentially steady state build-up in the excess magma pressure in the Socorro magma body, presumably due to melt supply from a deep source. However, measurements of relative horizontal displacements of the Earth's surface using a local trilateration network did not detect any systematic strain accumulation in the Socorro area between 1972 and 1984 [*Savage et al.*, 1985]. One interpretation of the trilateration measurements is that no magma-induced deformation occurred during the period 1972-1984, implying that the melt supply into the Socorro magma body may be episodic on timescales less than a few tens of years, as commonly observed elsewhere [e.g., *Fialko et al.*, 2001b]. Unfortunately, no measurements of vertical displacements were performed in the Socorro area between 1972 and 1984. Recent seismic mapping of the Socorro magma body [*Balch et al.*, 1997] shows that the extent of the mid-crustal reflector may be somewhat different from that suggested by the earlier seismic studies [*Sanford et al.*, 1973; *Brown et al.*, 1987] (see Figure 1). While some of the differences in the spatial extent of the seismic reflector (that presumably delineates the roof of the magma body) may be due to the seismic station coverage [*Balch et al.*, 1997], the inferred differences might also manifest temporal evolution of the Socorro magma body on a timescale of the order of ten years.

## InSAR data and modeling

We use the interferometric synthetic aperture radar (InSAR) data to study the recent history and spatial extent of deformation due to the Socorro magma body. The Socorro area has been imaged by the European Space Agency radar satellites ERS-1 and ERS-2 since 1992. Figure 1 shows the area illuminated by the ERS satellite radar from a descending orbit (track 98, frames 2907 and 2925). We have generated and analyzed nine long-term interferograms from the descending orbit covering the time period between 1992 and 1999 (Figure 2a). Effects of local topography have been removed from the interferograms using a mosaic of 209 USGS digital elevation maps (DEM) with 30 m postings. While there is some indication of uplift in the area of the Socorro magma body in most of the interferograms (Figure 2a), each individual interferogram is dominated by the essentially random variations in the satellite line of sight (LOS) displacements of the order of a few centimeters, most likely due to variability in atmospheric conditions. Because atmospheric fluctuations are expected to be uncorrelated between the radar acquisitions, one may reduce the atmospheric noise and amplify the tectonic signal by summation of independent interferometric pairs. Figure 2b shows a stack of nine interferograms having a cumulative time span of about 29 years (i.e., having a measurement redundancy of about a fac-

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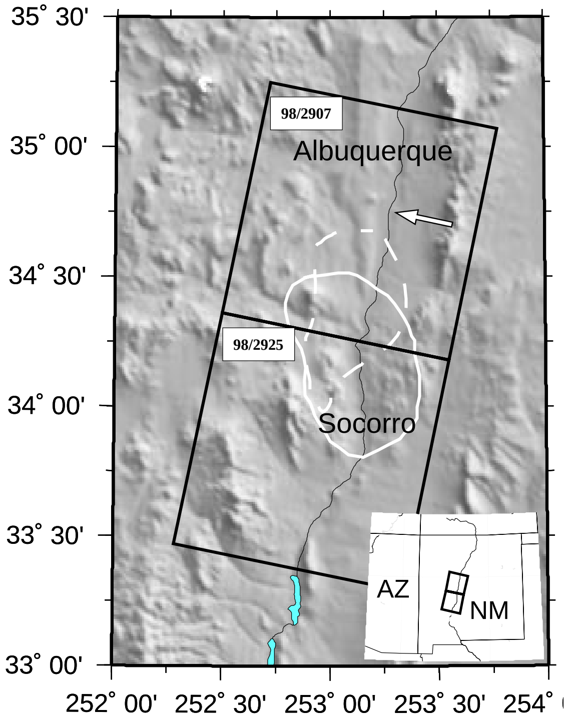

**Figure 1.** Digital elevation map of the Socorro area. White contours outline the lateral extent of a mid-crustal reflector, as inferred from seismic data by *Sanford et al.* [1973] (dashed line), and *Balch et al.* [1997] (solid line). Black squares denote ERS radar scenes for the descending orbit (track 98, frames 2907 and 2925). White arrow indicate the look direction of the satellite radar.

tor of four). Shown in color in Figure 2b are relative LOS displacements between the satellite and the Earth's surface. White areas in Figure 2b denote regions of poor radar phase coherence (e.g., due to changes in the reflective properties of the ground with time), and radar lay-overs due to steep topography.

The stacking procedure involves a loss of data over an area representing a union of all decorrelation areas in the original interferograms. Fortunately, the radar phase coherence is preserved in the area of the Socorro magma body. The stacked InSAR data clearly show the LOS displacements toward the satellite over an area that spatially coincides with the location of the mid-crustal reflector beneath Socorro. We interpret the observed radar LOS displacements as indicating the crustal uplift above the Socorro magma body. Assuming a constant rate of deformation, the inferred uplift amplitude of 8 to 10 centimeters over 29.3 years spanned by the stacked interferograms suggests an average uplift rate of 2-3 mm/yr during seven years of InSAR observations (i.e., between 1992 and 1999). This estimate is similar to those deduced from the leveling data (representing an average uplift rate over a few tens of years) [*Reilinger and Oliver*, 1976; *Larsen et al.*, 1986]. Therefore it appears that the inflation of the Socorro magma body has continued at a long-term steady state rate between 1992 and 1999.

The leveling surveys also revealed narrow subsidence areas at the northern and southern edges of the seismic reflector, with amplitude comparable to the central uplift. *Larsen et al.* [1986] proposed that these subsidence areasare due to magma withdrawal from spheroidal chambers at the periphery of the Socorro sill [*Larsen et al.*, 1986]. The InSAR data do not confirm existence of a large-amplitude localized subsidence at the southern tip of the intrusion (unfortunately, no data are available at the North due to decorrelation). Instead, there is an indication of a peripheral subsidence at the western margin of the Socorro anomaly (Figures 2b, d), and perhaps a small-amplitude subsidence "moat" surrounding the central uplift (Figures 2d,e). Subsidence to the west of of the Socorro magma body is also seen in the leveling data [*Larsen et al.*, 1986]. Observations shown in Figure 2 argue against a hypothesis of isolated deflation sources at the edge of the Socorro sill [*Larsen et al.*, 1986], but may be consistent with subsidence being due to peripheral inelastic deformation (e.g., ring faulting) associated with magma withdrawal from a deep source feeding the mid-crustal magma body [*Guterman et al.*, 1996; *Fialko et al.*, 2001b]. A combination of inflation and subsidence sources may be responsible for the absence of a measurable horizontal strain accumulation across the Socorro trilateration network during 1972-1984 [*Savage et al.*, 1985]. A broad subsidence area in the northern part of the interferogram is likely to be due to ground water withdrawal near Albuquerque [*Larsen et al.*, 1986].

While measurements of only one component of surface displacement field do not allow robust inferences about the depth and geometry of a magma chamber [*Fialko et al.*, 2001b], we can test whether the central uplift around Socorro is consistent with a build-up in the excess magma pres-

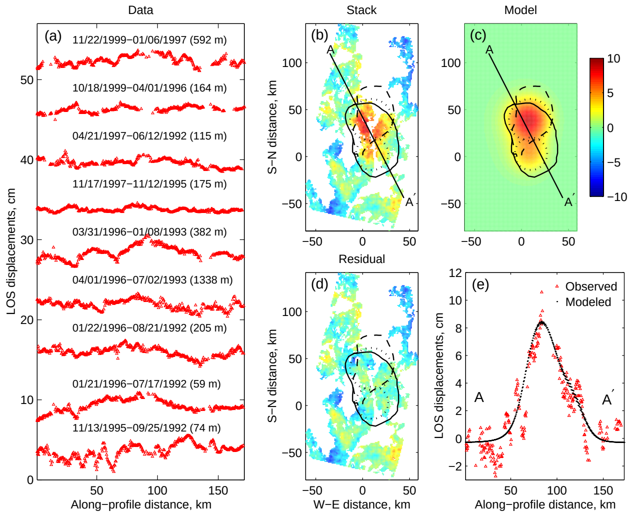

**Figure 2.** (a) Observed LOS displacements in the Socorro area for nine interferograms used in this study. Data are plotted along the profile AA′. Also shown are the InSAR acquisition dates for each pair (month/day/year), and the corresponding height of ambiguity (DEM error necessary to produce 2.8 cm of spurious LOS displacement). (b) A stack of radar interferograms listed in Figure 2a. Coordinates denote the West-East (horizontal axis) and North-South (vertical axis) distance in kilometers, with origin at 107°W, 34°N. Positive LOS displacements denote motion toward the satellite. Solid and dashed contours show the extent of the crustal reflector, as in Figure 1. (c) Best-fitting model of the Socorro uplift. Dotted circles denote two horizontal penny-shaped cracks used to approximate the Socorro magma body. The assumed crack depth is 19 km. (d) Residual after subtracting the model (c) from the data (b). (e) Stacked InSAR data and model predictions along the profile AA′. Triangles are the observed, and dots are the modeled LOS displacements from a 3 km-wide swath along the profile.

sure in the mid-crustal sill imaged by seismic studies. We model the observed LOS displacements using semi-analytic solutions for a horizontal circular tensile crack in an elastic half-space [*Fialko et al.*, 2001a]. Because both the seismic and InSAR data suggest that the Socorro sill may be elongated in the north-south direction, we approximate the sill by a superposition of two cracks at the seismically determined depth of 19 km. The crack radii, horizontal coordinates, and the excess magma pressure that best explain the InSAR observations are found through a constrained non-linear least square minimization [*Fialko and Simons*, 2000]. We do not model marginal subsidence because (i) only limited data is available on the intrusion periphery due to decorrelation of the radar images, and (ii) the nature of the observed subsidence is not well understood (in particular, an assumption of elastic deformation of the Earth's crust may not hold) [*Larsen et al.*, 1986; *Fialko et al.*, 2001b]. The calculated LOS displacements are shown in Figure 2c along with the outlines of the seismic reflector (solid and dashed contours), and horizontal circular cracks corresponding to the best fitting solution (dotted circles). Figure 2d shows a residual after subtracting the best fitting model from the data, and Figure 2e shows a NW-SE profile (AA′) across the Socorro anomaly with the observed and modeled LOS displacements. As one can see from Figure 2, locations of deformation sources obtained from our inversion are in good agreement with the mid-crustal reflector mapped by a recent seismic study [*Balch et al.*, 1997]. Therefore we conclude that the elastic inflation of the Socorro magma body is a likely cause of uplift imaged by the InSAR.

## Discussion

Interpretations of seismic data suggest that the current volume of the Socorro magma body is of the order of $10^2 - 10^3$ cubic kilometers [*Ake and Sanford*, 1988; *Balch et al.*, 1997]. Our modeling of the InSAR data suggest that the volume of the Socorro magma body increases at a rate of $6 - 8 \times 10^{-3}$ km$^3$/yr. A similar inflation rate is inferred form interpretation of the leveling data corresponding to a deformation period between 1911 and 1981 [*Fialko et al.*, 2001b]. Thus, the current volume of the Socorro magma body might have been produced by a steady state inflation over $10^4 - 10^5$ years. A general agreement between the total uplift amplitude of the order of 100 m [*Bachman and Mehnert*, 1978; *Ouchi*, 1983], and the seismically inferred present thickness of the Socorro sill [*Ake and Sanford*, 1988], on one hand, and the apparent constancy of the uplift rate deduced from the geodetic data, on the other hand, have prompted suggestions that the magma body has been formed in the result of magma injection at a nearly constant rate since late Pleistocene [*Larsen et al.*, 1986; *Schlue et al.*, 1996]. These observations present something of a paradox, as a sheet intrusion having thickness of the order of 100 m is not thermally viable over a time period of the order of $10^4$ years. In particular, sill intrusion into sub-solidus rocks implies magma freezing at an average rate of the order of $\kappa/w$, where $w$ is the intrusion thickness, and $\kappa$ is the thermal diffusivity of the host rocks, provided that magma loses heat by conduction alone [e.g., *Fialko and Rubin*, 1999]. For $w = 100$ m and $\kappa = 10^{-6}$ m$^2$/s, the corresponding freezing rate is of the order of a few tens of centimeters per year, greatly exceeding the observed uplift rate. The average freezing rate is larger for thinner intrusions, and/or in the presence of convection within the magma body. The above estimate of the freezing rate is not significantly perturbed even if the host rock temperature is near the solidus (e.g., if rocks have been "pre-heated" by previous magma injections), provided that the magma solidus is higher still (as is likely the case for basalts intruding the middle continental crust). One may expect that the near-solidus host rocks have viscous-like long-term response to stress perturbations due to the intrusion emplacement. Finite element modeling of a sill intrusion in a rheologically stratified half-space (unpublished results by the authors) indicates that visco-elastic relaxation is unlikely to explain the observed deformation, as viscous flow in the mid-to-lower crust gives rise to an uplift pattern that is too broad compared to the observed one, for a reasonable range of the crust and mantle rheologies. Thermal arguments therefore suggest that the emplacement of the Socorro sill may have occurred relatively recently (e.g., within the last several hundreds of years or so). In this case, the geodetically documented uplift over the last ~90 years may result from either a continued magma supply, or thermodynamic effects (in particular, volume changes associated with the in situ crustal melting) due to heat advected by the intrusion of mafic (presumably, mantle) melts [*Fialko et al.*, 2001b]. We note that an apparent variability in the extent of the crustal reflector suggested by seismic studies (Figure 1) is correlated to changes in the extent of the surface uplift, as determined from a comparison between the leveling data [*Larsen et al.*, 1986; *Fialko et al.*, 2001b] and InSAR observations (Figure 2). This variability may indicate temporal (e.g., thermal) evolution of the Socorro magma body on a timescale of a few tens of years.

Alternatively, if magma-induced deformation is quasi steady state, the total thickness of the magma sill intruded in the middle crust beneath Socorro may be significantly greater than the estimated current thickness of the order of $10^2$ m. Assuming conductive cooling, and a nearly constant melt injection rate, a sustained presence of melt over a time period of several tens of thousands of years requires injection of a magma sheet having cumulative thickness of several kilometers. In this case, one has to assume an essentially isostatic accommodation of the Socorro magma body, to satisfy the constraint of the long-term uplift of ~100 m deduced from the geomorphologic data [*Bachman and Mehnert*, 1978; *Ouchi*, 1983]. A piston-like subsidence of a lower crustal block in response to magma withdrawal from a deep source might be a mechanism that created space for the bulk of the intrusion (e.g., similar to the results of physical analog experiments of *Guterman et al* [1996a]). Thus, a good agreement between the observed uplift, and that predicted using an elastic model (Figure 2) may not be indicative of an elastic accommodation of the entire magma body. The latter conclusion also stems from the fact that average strains associated with a sheet intrusion having thickness of the order of $10^2$-$10^3$ m, and characteristic in-plane dimension of several tens of kilometers, are of the order of $10^{-2}$ or greater, i.e., likely in excess of the elastic limit. Further theoretical studies are required to explore consequences and implications of the observed "instantaneous" elastic deformation, and the inferred long-term inelastic deformation associated with the emplacement of the Socorro magma body. More accurate constraints on the long-term history and spatial extent of the paleo uplift in the Socorro area (e.g., from detailed geomorphologic studies) would greatly help to discriminate the proposed scenarios of formation of the Socorro magma body.

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