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SURFACE UPLIFT DUE TO THERMAL EXPANSION AROUND THE SOCORRO MAGMA BODY: PRELIMINARY RESULTS

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Abstract—The Socorro magma body is the second largest known magma body on Earth: a partially molten sill with a thickness of ~130 m and a surface area of ~3400 km^2 that lies at ~19 km depth below central New Mexico. The largest known magma body is a similar sill of ~1 km thickness and ~5000 km^2 area in South America. Both cause active surface uplift. Understanding the emplacement and deformation histories of these large magma bodies is significant for understanding neotectonics, volcanic hazards and mid-crustal magma processes. We report the results of two-dimensional elastic crustal models (200 km wide by 30 km thick) of surface uplift due solely to conductive heat loss from a sill (60 km wide, 100 m thick, 19 km depth) and attendant thermal expansion of the surrounding host rocks, allowing us to separate surface uplift due to thermal expansion from uplift due to other causes, such as sill inflation, volume loss caused by crystallization of the sill, volume gain or loss due to melting or recrystallization of the host rocks, or isostatic adjustments. The sill is heated linearly in time from ambient temperature to 1200°C over 100 years. Net surface uplift during this heating stage is domical, somewhat wider than 140 km in diameter and ~3.5 m in amplitude, and accumulates at a nearly constant rate of ~30 mm/yr in the center. When heating ceases at 100 yr, the central uplift rate drops dramatically to <1 mm/yr and continues to decline until ~100,000 years have passed. The magnitude and rate of uplift across ~140 km of the dome remain above noise levels of repeated geodetic surveys (~1 mm/yr) for >100 yr but are well below noise levels after 1000 yr. As the uplift rate falls below the geodetic noise level, the diameter of the measurably uplifting dome decreases, an effect that is consistent with the Socorro magma body being about as wide as the zone of measurable surface uplift and intruded >100 yr ago.

INTRODUCTION: THE SOCORRO MAGMA BODY

Rift opening in continental crust is accommodated by typically normal faulting in the upper crust, ductile deformation in the deeper crustal and upper mantle layers, and magmatic intrusions and volcanism. When rift opening slows down, tectonic and magmatic activity are expected to slow down as well. The Rio Grande rift in Colorado and New Mexico has experienced a decreasing opening rate since the Miocene (e.g., as recorded by sedimentation rates: Chapin and Cather, 1994; Gragg et al., 2015; and by GPS surveys: Kreemer et al., 2010; Berglund et al., 2012), but is still magmatically active today (e.g., Baldridge et al., 1995; Baldridge, 2004; Dunbar, 2005).

The Socorro magma body in the central Rio Grande rift (Fig. 1) is an example of this recent magmatic activity. Micro-earthquakes in the Socorro seismic anomaly (Fig. 1) were among the first observations that led to the documentation of the Socorro magma body (Sanford and Long, 1965; Sanford et al., 1973; Sanford et al., 1977). The Socorro seismic anomaly (~5,000 km^2) is a high-seismicity area, accounting for about 40% of the seismicity in New Mexico above magnitude of 2.5 (Balch et al., 1997). Sanford et al. (1973) interpreted two strong phases, arriving after direct S-waves, as reflections from the top of a low-rigidity, subhorizontal crustal layer approximately 19 km depth below Socorro. This reflector has subsequently been interpreted as the top of a sill-like magma body (Sanford et al., 1977; Brown et al., 1980; Ake and Sanford, 1988; Hartse, 1991; Balch et al., 1997) with a thin feeder system below (Schlue et al. 1996). The magma body is currently mapped as a N-S elongate ellipse of area ~3,400 km^2 (Balch et

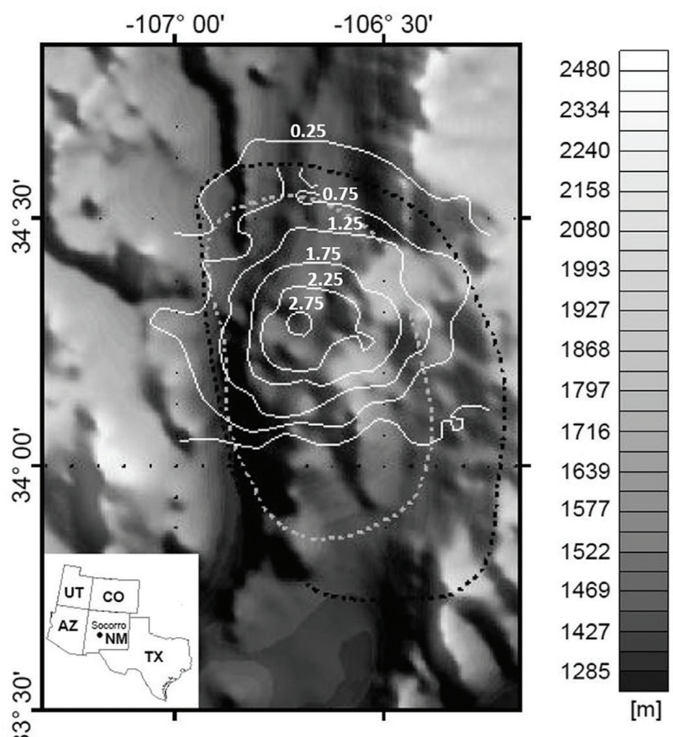

FIGURE 1. Outlines of the Socorro Magma Body (thick black line) and the Socorro Seismic Anomaly (dotted black line). The measured uplift rates in mm/year are shown in dotted white line (after Finnegan and Pritchard, 2009).

al., 1997) with an estimated thickness of ~0.13 km (Ake and Sanford, 1988; about 70 m of molten material above about 60 m of crystal mush), thus yielding a volume of ~440 km^3 (Ake and Sanford, 1988).

The Socorro seismic anomaly is also elliptical but larger than the magma body (Fig. 1). The north-south and east-west dimensions of the Socorro magma body are estimated to be ~80 km and ~50 km, respectively (Balch et al., 1997). Earthquakes and earthquake swarms above in the Socorro seismic anomaly occur at shallower depth (~2-15 km) than the magma body (Balch et al., 1997), and presumably reflect fluid circulation and tectonic stress release above the magma body (Sanford et al., 2006; Stankova et al., 2008; Morton and Bilek, 2014). Some geologic evidence has been interpreted as reflecting longer-term uplift above the magma body (Bachman and Mehnert, 1978; Ouchi, 1983; Sion et al., 2016, this guidebook).

Leveling studies performed near Socorro showed surface uplift of this section of the Rio Grande rift (Reilinger and Oliver, 1976; Reilinger et al., 1980; Larsen et al., 1986). More recent InSAR results verify this uplift, but show somewhat different patterns of uplift, (Fialko and Simons, 2001; Finnegan and Pritchard, 2009; Pearce and Fialko, 2010) and results suggest that long-term uplift rates of ~2 mm/yr have been relatively constant since ~100 years ago. A recent preliminary analysis of InSAR and GPS data concludes, however, that uplift may have ended between 2006 and 2010 (Havazli et al., 2015). The uplifting region is roughly circular in map view with a diameter several kilometers larger than the E-W breadth of the magma body (Finnegan and Pritchard, 2009; Pearse and Fialko, 2010), with a maximum central uplift of about 20-30 cm located above the northern two-thirds of the magma body (Fig. 1).

Fialko and Simons (2001; Fialko et al., 2001a) showed a two-lobed InSAR uplift pattern that they modeled with inflation of two oblate spheroids (see Fialko et al., 2001a; 2001b) of about 45- and 35-km diameter intruded into an elastic halfspace, and concluded that surface volume increase equals magma body inflation of 6–8 10^{-3} km^3/year. This implies that the current volume of the Socorro magma body has been accumulating over tens to hundreds of thousands of years, which is inconsistent with and much slower than the rate at which a thin sill of magma is expected to crystallize (Fialko and Simons, 2001), presenting a “thermo-mechanical paradox”. Finnegan and Pritchard (2009) fit their roughly circular InSAR uplift pattern using a 42-km diameter penny-shaped crack in an elastic halfspace and concluded that the magma body is relatively young (~100 yrs) or that longer-term uplift has been balanced by subsidence episodes. Pearse and Fialko (2010) also modeled a circular InSAR uplift pattern with a penny-shaped crack in a visco-elastic model. They found that surface uplift rates are reduced because the elastic upper crust acts as a strong lid and forces subsidence below the magma sill. They also found that power-law creep with stress exponent n = 3.5 fit the uplift pattern better than Maxwell viscosity (n = 1) and that it is likely that the imaged magma body is composed of a partial melt of rocks initially surrounding a basaltic intrusion. Reiter et al. (2010) argued that the magma body must be intruded in <20-30 yr in order for intrusion to keep pace with crystallization, at a rate much higher than that yielded from models of the uplift (e.g., Fialko and Simons, 2001), but consistent with known effusion rates for two nearby, young basaltic flows. They also concluded that conductive heat flow from the magma body would take 1-3 Ma to reach the surface and that heat flow and seismic shear-wave velocities are consistent with an addition of heat into the rift equal to that carried by 4-8 similar magma bodies (>600 m of basaltic intrusions).

We present numerical model results of uplift above the Socorro magma body that can be expected as a result of thermal expansion of the crust during and after sill heating, a phenomenon that was not considered in previous models. Several physical phenomena can cause surface deformation above magma bodies, including inflation, deflation, isostatic adjustments, contraction of the magma body due to crystallization, and expansion (followed by contraction) of surrounding host rocks due to either (or both) a passing thermal pulse or melting and recrystallization. The Socorro magma body is the second largest known magma body in the world: the largest is a similar, but larger, sill in South America (Chmielowski et al. 1999; Zandt et al. 2003) so models of the Socorro magma body have wider application. Model results presented here form part of an ongoing multidiscisplinary study of the magma body being undertaken by New Mexico Tech personnel (e.g., Sion et al., 2016, this guidebook).

A general-purpose engineering finite-element software package, Abaqus (http://www.3ds.com/products-services/simulia/products/abaqus/) was used to develop an elastic two-dimensional coupled thermal-displacement model of crustal deformation due to sill emplacement. Elastic deformation models can adequately represent surface deformation due to thermal expansion on our timescale of interest (50,000 years), but we will briefly discuss the effect of visco-elasticity. Because surface deformation above a crustal magma body may result from different processes, it is useful to understand their relative contributions. Here we report solely on thermal expansion related to sill heating. Thermal conduction from the hot sill into the surrounding crust results in heating of the crust, thermal expansion, and surface deformation.

MAGMATIC PROCESSES AND SURFACE UPLIFT

Magmatic intrusions in Earth’s crust cause surface deformation. The density anomaly of the intrusive body after cooling, and inflation or deflation of the magma chambers commonly are suggested to be the main cause of surface uplift (Fernández and Rundle, 1994). Surface subsidence may occur during the cooling phase. Most studies of surface deformation due to subsurface magmatic activity reflect upper crustal magma chambers or magma movements inside of active volcanic complexes (e.g., Fournier et al., 2010, many others). The relation between surface deformation and magmatic intrusions and bodies within the middle crust is not well understood, and it is impossible to observe directly the magmatic processes at depth that cause the observed surface deformation. Most modeling studies used Mogi’s magma intrusion model (a spherical “point” source within a homogenous isotropic elastic half-space) to simulate deformation (Mogi, 1958). In our study the magma body is not a point source, but a finite volume in the shape of a rectangular box.

Often, surface deformation due to magmatic activity in the crust is associated with uplift and subsidence of calderas preceding and following eruptions (e.g., Campi Flegrei, southern Italy; Dvorak and Mastrolorenzo, 1991; Lundgren et al., 2001; Beauducel et al., 2004). The major magmatic processes that cause surface inflation and deflation are the pressurization and de-pressurization of a magma chamber, and the continuous movement and crystallization of the magma itself (Wicks et al., 2006; Chang et al., 2007). Surface uplift may also result from crustal heating and hence thermal expansion.

BRIEF OVERVIEW OF EXISTING NUMERICAL MODELS OF MAGMA INTRUSION

Numerical models have been developed to understand the link between observed deformation on Earth's surface and the inaccessible deformation source of magma at depth (Masterlark, 2007). Mogi (1958) published the first magma intrusion model to predict surface deformation of volcanoes using a spherical expansion source inside a homogenous isotropic elastic half-space (Mogi, 1958). Mogi (1958) presented a quantitative interpretation of observed surface deformation for volcanoes in Japan and Hawaii. He computed displacements for a small source of inflation (or deflation) in an elastic half space (Mogi, 1958; Dietrich and Decker, 1975). Subsequent models have improved or modified the geometry and pressure distribution of the magma chamber to compare to surface deformation patterns (Yokoyama, 1971; Dietrich and Decker, 1975; Yang et al., 1988; Fialko and Simons, 2001; Fialko et al., 2001a; 2001b). Dieterich and Decker (1975) used finite element models of a magma reservoir, represented as a cavity in an elastic body, to assess predicted sensitivities to various magma chamber geometries in a homogeneous, isotropic, elastic half-space. They showed that different source geometries can produce similar vertical deformation patterns, but the horizontal components of deformation are much more sensitive to the source geometry (Dietrich and Decker, 1975; Masterlark, 2007). Fialko and Simons (2001) reported that they were able to fit a model for the Socorro magma body with a sill at 19 km depth and with magma intruded at a rate of ~$6 \cdot 10^{-3}$ km^3/year for a uniformly pressurized penny-shaped crack in an elastic half-space (Fialko et al., 2001).

In this study, we use an isotropic elastic model of crustal deformation in a coupled thermal-displacement finite element analysis of the Socorro magma body (Fig. 2). An elastic model is assumed to be a good first-order approximation of crustal rheology, since the bulk of the crust behaves essentially elastically on a time scale of an intrusion event (Fialko et al, 2001), but we will also briefly discuss visco-elastic models of sill heating.

CRUSTAL MODELS OF THERMAL EXPANSION AND SILL HEATING

Model setup and parameters

We developed two-dimensional numerical models of crustal deformation and surface uplift due to heating of the Socorro magma body with the general finite element package ABAQUS (http://www.3ds.com/products-services/simulia/, accessed 4/11/2016). The model domain (Fig. 2) consists of a 30 km thick, 200 km wide crustal block. In the crust, a sill is included at the depth of 19 km (as inferred by seismic data; Balch et al., 1997). We used a maximum mesh size of 0.5 km. Since we study here the effects caused by thermal expansion, there is no inflation of the magma sill itself and the sill is prescribed a constant thickness of 100 m to approximate seismic results (Ake and Sanford, 1988). The crust has an elastic rheology in all the results presented here. The sides and the bottom of our model are fixed, and the surface of the domain is a free-surface. We choose a fixed base to represent the strong uppermost mantle.

Thermal boundary conditions include a surface temperature of 10°C, a temperature of 600°C at 30 km depth (Ranalli, 1987, Moho temperature in between "hot" and "cold" continental lithosphere; we note that model results are not strongly dependent upon the geothermal gradient), and zero heat flow through the left and right side of the model domain. The sill

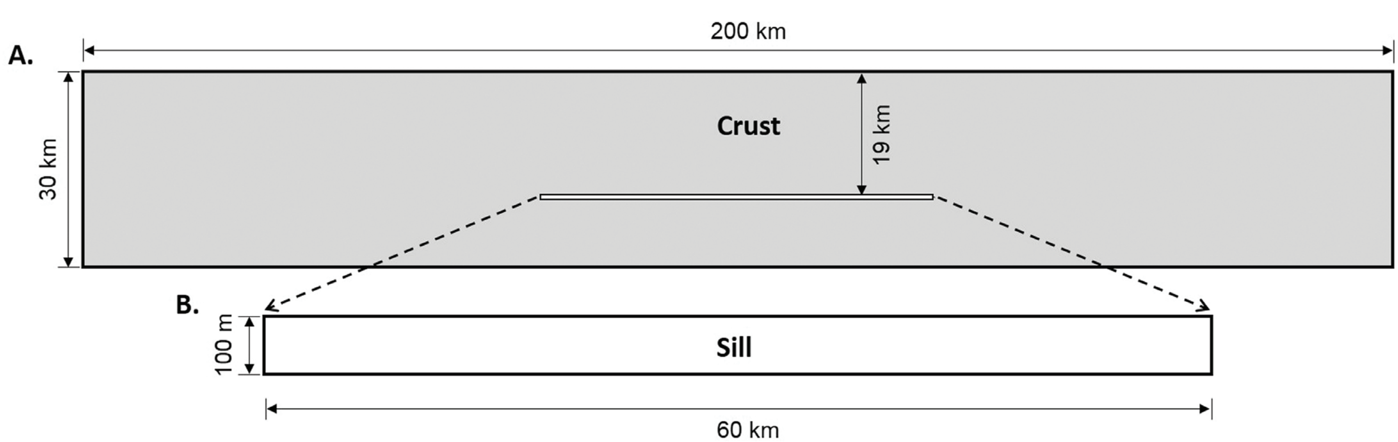

FIGURE 2. Schematic diagram showing the model setup. **A**) Dimensions of the crust, and **B**) dimensions of the sill (not to scale).

at 19 km depth reaches a maximum temperature of 1200°C; the surrounding host rock at that depth is initially at 380°C. The thermal expansion coefficient of the crust is set at 10^{-5} K^{-1} (other material parameters are in Table 1), but for the sill is set at zero so that its thickness remains constant. Results from tests with larger and smaller crustal expansion coefficients ($5 \cdot 10^{-5}$ K^{-1} and 10^{-6} K^{-1}) are discussed but not shown.

The simulations consist of two steps: (1) a sill "heating" phase of 100 years, followed by (2) the "cooling" phase (1000 years). During the "heating" phase, the temperature of the magma body increases linearly from the ambient temperature (380°C) to 1200°C at 100 years, in order to simulate heat added during a constant inflation rate, but without the effects of inflation. During the subsequent "cooling phase", heat input to the "sill" stops (equivalent to end of addition of new magma and heat) and the sill cools conductively. We show results of a 50,000-years cooling phase.

RESULTS

During the sill heating phase, the crust around the sill heats up. This results in thermal expansion of the crust, and surface uplift at nearly constant. At the beginning of the cooling phase, uplift rate drops dramatically, but the sill is still warmer than its surroundings, which continue to be heated and expanded. After ~100,000 years the sill has thermally equilibrated with its surroundings, and the surface uplift ends. The crust then slowly cools toward its original thermal gradient, and the surface above the sill subsides (not shown in Figures 3 and 4).

The total model surface rises ~3.5 m at a nearly constant rate during the heating phase (Fig. 3B), then continues to rise but at a much lower rate during the cooling phase, when the sill is still warmer than its surroundings. Maximum uplift is about 4.5 m after 100,000 years. The linear "heating" phase prevents an unreasonable instantaneous expansion of the host rocks right after the sill "emplacement" begins.

The predicted maximum surface uplift rate within the first 100 years (more than 30 mm/yr) is ten times higher than present uplift rate suggested by geodetic data (~2.0 mm/yr). Assuming that the sill was emplaced in 100 years, we can conclude that the sill is not currently inflating, as this would add the physical inflation to the thermal expansion effect and result in even larger syn-emplacement uplift rates. Immediately after the "cooling" phase begins, the uplift rate drops rapidly to ~0.1 mm/year in a few tens of years. However, the positive surface uplift rate during the "cooling" phase indicates heat is still being conducted to the rest of crust. Figure 4 reveals that the surface uplift pattern is much broader than the dimension of the sill itself.

Tests with larger and smaller thermal expansion coefficients ($5 \cdot 10^{-5}$ K^{-1} and 10^{-6} K^{-1}) gave similar patterns of uplift (rate); the amplitude of the uplift (rate) however changed proportionally (i.e., a thermal expansion that is half the shown thermal expansion results in half the surface amplitude and uplift rate). During the 100,000 years duration of these tests, the thermal

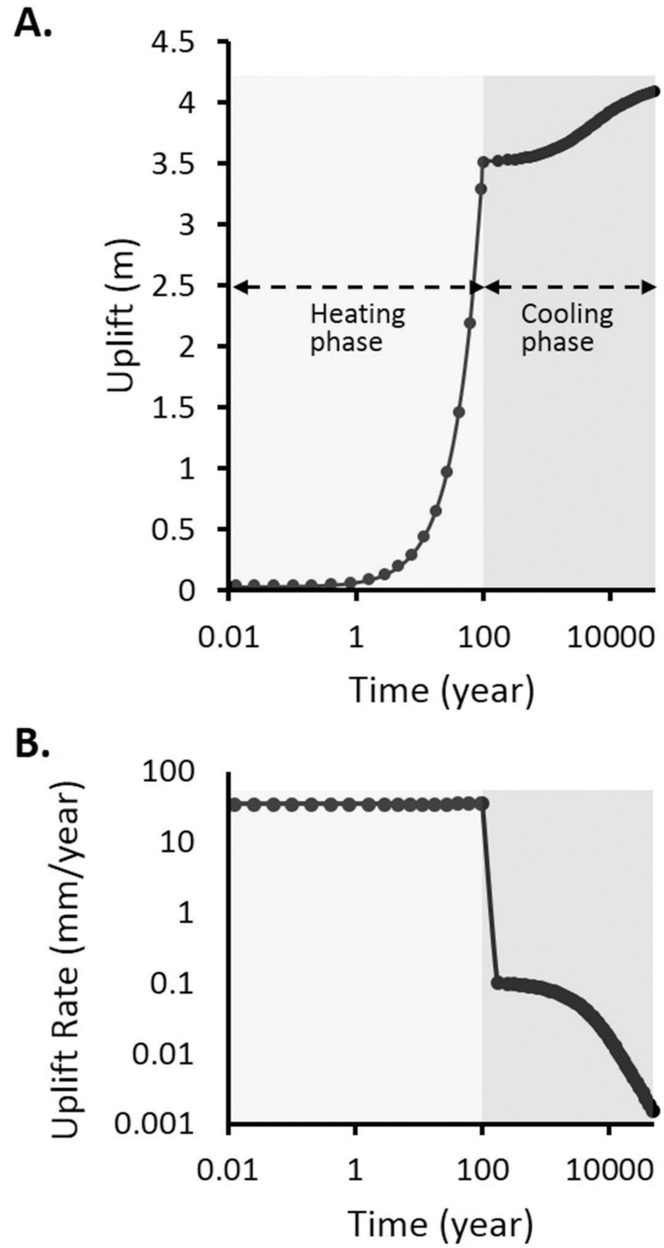

FIGURE 3. Modeling results for a point above the center of the sill: **A**) surface uplift vs. time, and **B**) the surface uplift rate vs. time.

Table 1. List of parameters used in the simulations. *Annen and Sparks (2002)

Parameter	Value
Conductivity (crust)	2.6 W/m/K
Conductivity (sill)	2.7 W/m/K
Density (crust)	2750 kg/m^3
Density (sill)	2800 kg/m^3
Young's modulus	$7 \cdot 10^{10}$ Pa
Poisson's ratio	0.25
Specific heat (crust)	1380 J/kg·K*
Specific heat (magma)	1480 J/kg·K*

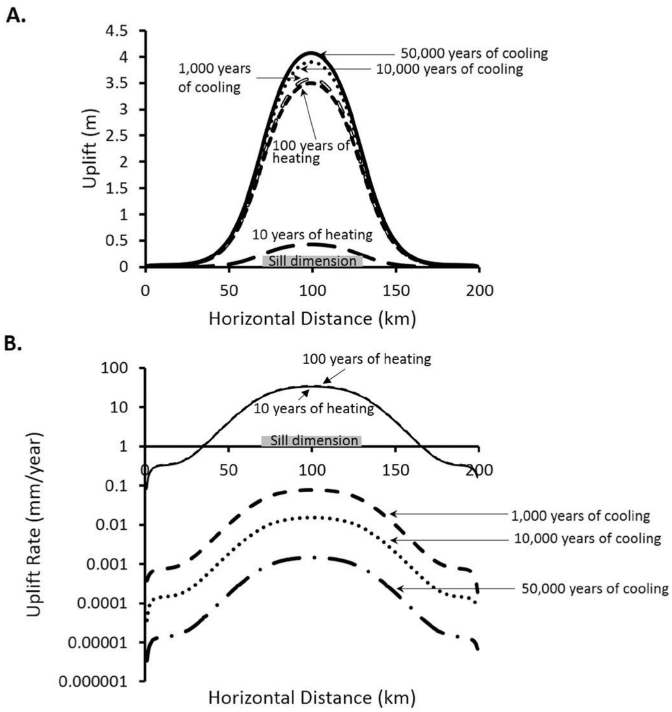

FIGURE 4. Graphs showing **A**) temporal evolution of surface uplift above the sill (indicated by the grey bar) and **B**) temporal evolution of uplift rate above the sill. The horizontal line that indicates 1 mm/yr surface uplift rate is the detection limit of many current geodetic methods.

pulse does not travel toward the surface, and surface heat flow values do not increase.

DISCUSSION: IMPLICATIONS FOR THE SOCORRO MAGMA BODY

Maximum surface uplift rates as a result of thermal expansion are very high (~35 mm/yr) but constant throughout the heating phase. Surface uplift continues in the cooling phase, but at a rate (<1 mm/yr) that is not discernable with current geodetic methods. The amplitude of uplift scales with the thermal expansion coefficient: larger values than we used ($5 \cdot 10^{-5}$ K^{-1}) increase the predicted maximum surface uplift (~17.5 m), and smaller values (10^{-6} K^{-1}) reduce the predicted surface uplift (<0.5 m). However, the spatial patterns of uplift, subsidence and uplift rates are not affected by the choice of this parameter.

We also tested models with sill heating phases of 1,000 years and 10,000 years. These tests suggest that the heating period does not affect patterns of surface deformation, but it does affect the absolute amplitude of surface uplift (more heat enters the crust in 1,000 and 10,000 years than in 100 years). In all models, the surface uplift rate decreases dramatically once the heating phase ends. Assuming that the uplift rate of the Socorro magma body in the last 100 years was 1–3 mm/year, and surface uplift is solely the result of thermal expansion, we would currently be in the cooling phase, i.e., after magma injection.

As shown in Figure 4A, the surface uplift after 10 years of sill heating is broad (~100 km), which is about two times wider than the E-W dimension of the sill. As deformation progresses through the heating and cooling phases, the uplift maintains a domical shape but the width grows to about 140 km, which is wider than currently measurable uplift. This may imply that the area that is currently uplifting (Fig. 1) is surrounded by a region that experiences an uplift rate below the geodetically detectable limit: the uplift rate curve (Fig. 4B) moves down vertically along the amplitude axis over time, and at some point in time only a portion is above the detectable rate, while the surrounding areas are below the detectable rate. This result should hold even for heat added during inflation of the sill, which we do not model (magnitude of uplift and uplift rates should be higher than our model if inflation is added).

As shown in Figure 4, the model predicted surface uplift (and rate) is symmetrical above the sill. This is in contrast with the measured surface uplift rate above the Socorro magma body (Fig. 1). This suggests that other factors affect the measured uplift pattern, including, for example, other shallow intrusions located off-center above the magma body (see Fialko and Pearse, 2012), an asymmetrically expanding magma body (Reilinger et al., 1980), an asymmetrically shaped or heated magma sill, or asymmetric or lateral advection of heat by groundwater flow. These mechanisms may also explain the observed small area of recent surface uplift.

We performed several tests of a crust with visco-elastic rheology, and found that the differences in the results are negligible: although ductile flow can occur due to magma intrusion and heating adjacent to the magma body, the time scale in our study (50,000 to 100,000 years) is too short for significant viscous relaxation. We will continue to explore this aspect of crustal behavior in future studies.

SUMMARY

We developed two-dimensional elastic numerical models to understand the effects of thermal expansion on surface uplift as a result of heating of the Socorro magma body. The results suggest that the uplift rate during heating due to sill emplacement is constant, dictated mainly by the thermal expansion properties of the host rock surrounding the magma body. Uplift rates decrease drastically once the active heating of the sill ends.

The uplifted surface area has a broad, domical shape during the initial stages of sill heating, then broadens and increases in amplitude. The modeled surface uplift area is 20-40 km wider than the dimensions of the seismically imaged sill. The detectable size of surface uplift is smaller than the model-predicted area of uplift. However, this area shrinks over time, and therefore the current small area of active, measurable surface uplift can simply be the effect of the shrinking area in which uplift is measurable. In general, detectable rates of uplift, either through leveling or InSAR, are achieved above the magma body only during the sill heating phase or within a few hundred years after the cooling phase began.

This study has focused only on the thermal component of surface uplift due to magma injections in the crust. Future studies will integrate this thermal component with actual inflation of magma bodies and more carefully interrogate the effects of visco-elastic deformation.

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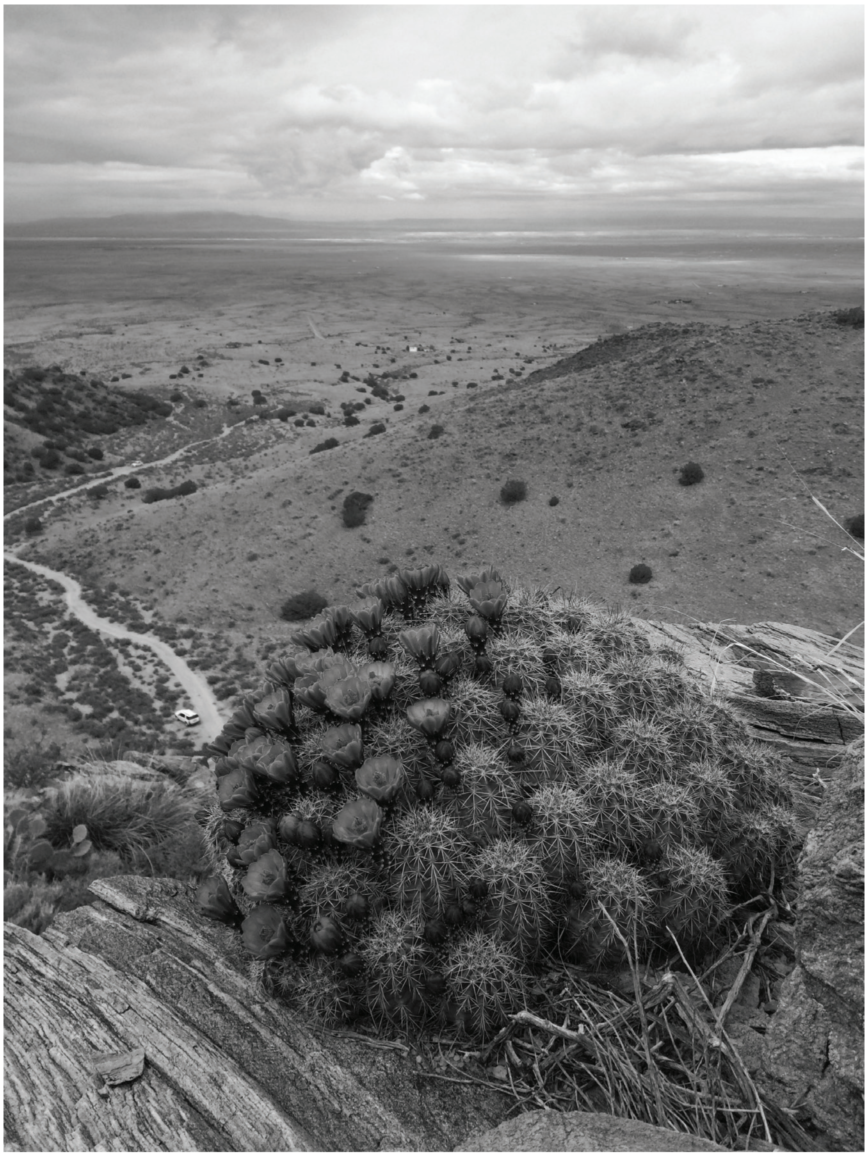

View from Estadio Canyon. Photo courtesy of Bonnie Frey.