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SUMMARY OF INTERPETATIONS OF SIX YEARS OF TILTMETER MOTIONS ABOVE THE FLANKS OF THE SOCORRO MAGMA BODY, CENTRAL RIO GRANDE RIFT

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Abstract—Tiltmeters installed on the flanks of the uplift above the Socorro magma body (February 2002 through February 2008) show 1) twice-daily earth-tide cycles of 10ths of µrad; 2) effects of seasonal changes in temperature at 3-4 m depths; 3) 10-14-month variations perhaps related to seasonal lags in temperatures at depth; 4) effects of surface waves from distant earthquakes; 5) effects of large amounts of rainfall; 6) a few abrupt excursions of uncertain origin; and 7) multi-year, long-term changes in average tilts, both in direction and magnitude. Several of these effects create an intractable problem of resolving tilts at less than 12-month averages. We have yet to determine whether the overall trends in tilt are real or whether they might be due to instrument drift. Data so far do not show consistent tilts away from surface uplift above the magma body.

INTRODUCTION

The elliptical pancake-shaped Socorro magma body (SMB; Fig. 1) is inferred to extend over 3,400 km^2 at a depth of ~ 19 km with an estimated thickness of 0.1 km: thus yielding a volume of about 340 km^3 (Balch et al., 1997; Schlue et al. 1996). Since 1909 the rate of historic uplift near the center of the SMB at San Acacia has been between 1.8 mm/yr and 4 mm/yr (Larsen et al., 1986; Fialko and Simons, 2001; Finnegan and Pritchard, 2009). Using vertical uplift rates from previously published studies, we calculate average tilt rates on the flanks of the uplift to be ~0.12 microradians (µrad) per year (~1^o in 145 ka; 100 µrad of tilt corresponds to ~ 10 cm of vertical displacement over a horizontal distance of 1 km). Above the SMB, fault blocks of the Rio Grande rift are numerous, strongly extended, and variably tilted. However, the long axis of the SMB is approximately coincident with the active axis of the rift as defined by Quaternary normal faults that outline the southern end of the Belen Basin and the much narrower graben of the Socorro Basin (Fig. 1). The southern limit of the SMB appears to coincide with the westward stepover of Quaternary faults to the Palomas-Milligan Gulch Basin south of the Magdalena Mountains. Uplift at the surface of SMB has been modeled using two penny-shaped sills at 19 km, a single penny-shaped sill, or a shallower, small, spherical magma body (Fialko and Simons, 2001; Finnegan and Pritchard, 2009; Newman et al., 2004).

We selected tiltmeter locations to the north (Sevilleta 1; SEV; Fig. 1) and south (Tech 1; TECH) that were away from Quaternary scarps and within graben blocks in order to minimize rift-related block rotation. The western station (Silver Creek 1; SC), however, is on a large, active, west-tilting half graben (La Jencia Basin) where tectonic tilt and magmatic tilt should be additive. The tiltmeters have been gathering data since the winter of 2002.

The tiltmeters used in this study (Applied Geomechanics model 722) measure tilt along two orthogonal axes, and are deployed with the two axes (X and Y) oriented east-west and north-south, respectively. Available equipment limited the installation to depths of 3-4 m in alluvium. The tiltmeters are set at high-gain resolution of ± 0.1 µrad over a range of ± 800 µrad (output range of ± 2500 mV). Readings of North-South and East-West tilts, as well as air and soil temperatures are taken every 30 seconds and the average recorded every 20 minutes, resulting in a sampling of 72 measurements per day. The SC datalogger also records local 20-minute precipitation accumulations.

SUMMARY OF RESULTS

Figure 2 shows the daily averages of orientations of all three of the tiltmeters and the temperatures and precipitation data for Silver Creek. Figure 3 shows the cumulative changes in tilts at the three stations. It has become clear that influences of subsurface temperature, precipitation, earth tides, and perhaps instrument drift create an intractable problem of resolving long-term tilts at less than 12-month averages. It is troubling that we can not say for sure whether the overall trends in tilt are real or simply reflect long-term instrument drift.

In detail the tiltmeter records show: 1) earth-tide cycles of 10ths of µrad on the order of two per day (Figs. 4, 5); 2) tiltmeters at depths of 3-4 m are affected by seasonal changes in temperature (Fig. 6); 10-14 month wave-like variations are perhaps related to lagging seasonal temperature gradients at depth of burial (Fig. 2, SC; Fig. 6, TECH); 3) surface waves of distant moderate-to-large earthquakes affect tilt averages over 20-40 minutes (Fig. 7); quakes as small as 5.1 (upstate New York and Baja California) produce noticeable spikes on all three tiltmeters; the M 7.9 Denali quake moved all three tiltmeters off-scale until the next 20-minute average; 4) Large precipitation events can affect short-term trends in tiltmeter orientations (10- to 20-day abrupt excursions), but not in a consistent and predictable way (Fig. 8); 5) a few abrupt excursions of uncertain origin (Fig. 2, SEV 2004; SC 2006), and 6) multi-year long-term changes in average tilts, both in direction and magnitude (Fig. 3). These longer-term trends of

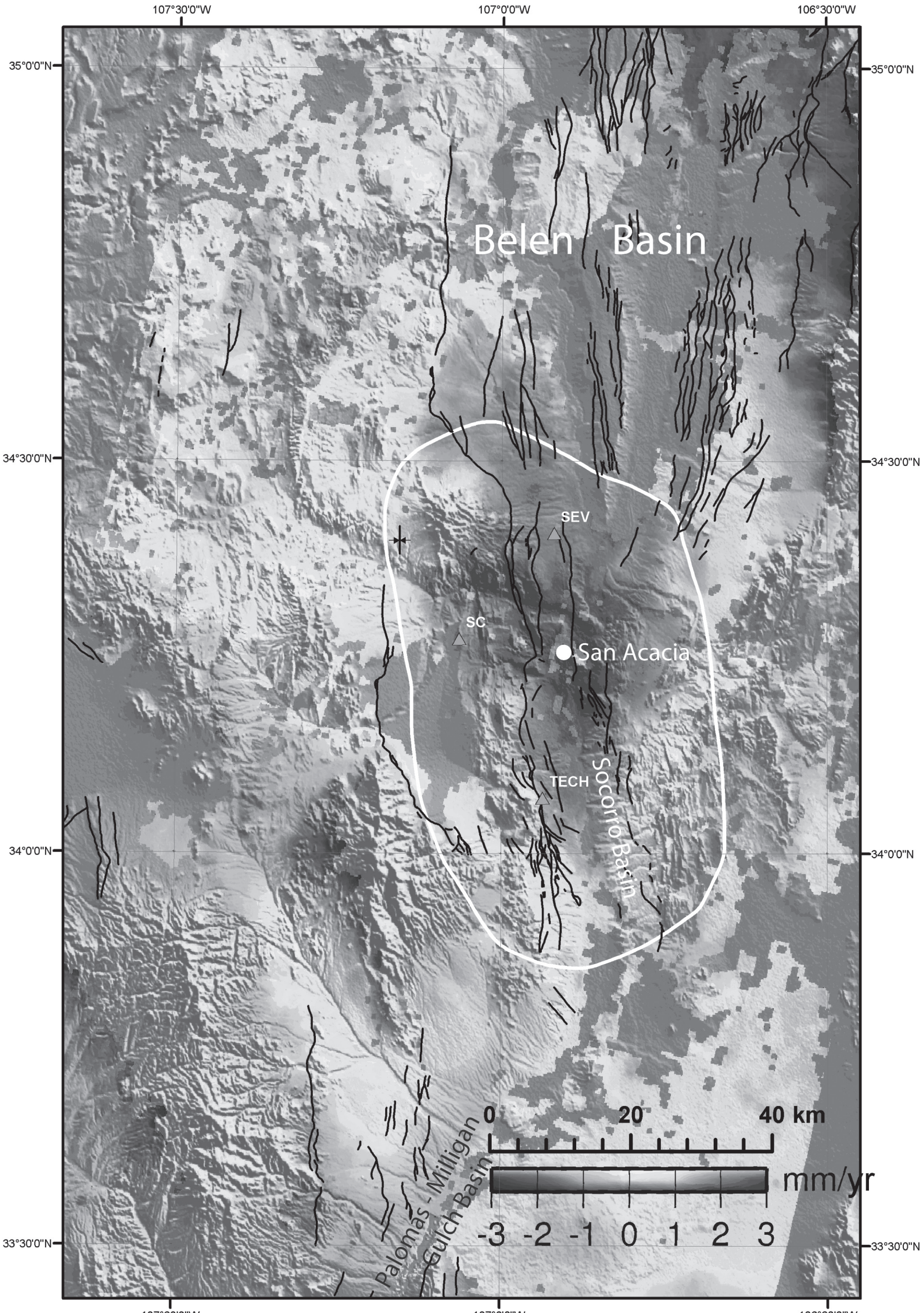

FIGURE 1. Shaded relief map showing tiltmeter locations with respect to InSAR-interpreted uplift rates (mm/yr; Interferometric Synthetic Aperture Radar, courtesy Yuri Fialko, http://sioviz.ucsd.edu/~fialko/), Quaternary faults (in black, modified from USGS and NM Bureau of Geology and Mineral Resources, 2006; Chamberlin, unpublished data; and Olig and Zachariasen, 2008), and Socorro magma body (in white, Balch et al., 1997). Note that the Socorro magma body parallels the active faults of the Socorro basin; its southern limit coincides with the westward step-over of rift-related active faults into the San Marcial basin. See Plate 6 for a color version of this figure.

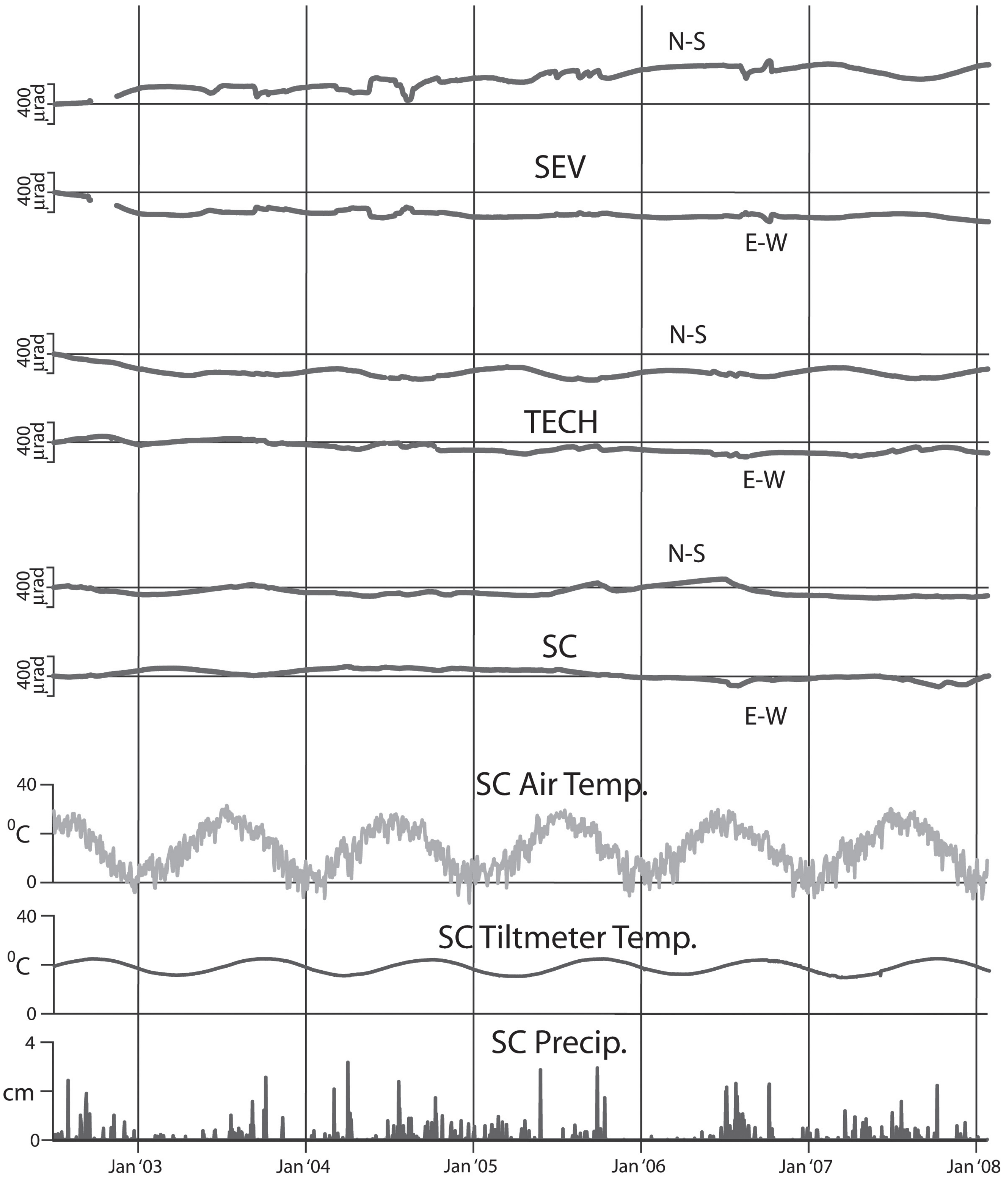

FIGURE 2. Time series of tilt measurements from shallow-borehole tiltmeters deployed above the margins of the Socorro magma body at localities SC, SEV, and TECH. Plotted data are daily averages of the raw 20-minute data. Also shown are the Silver Creek air and tiltmeter temperatures and local precipitation.

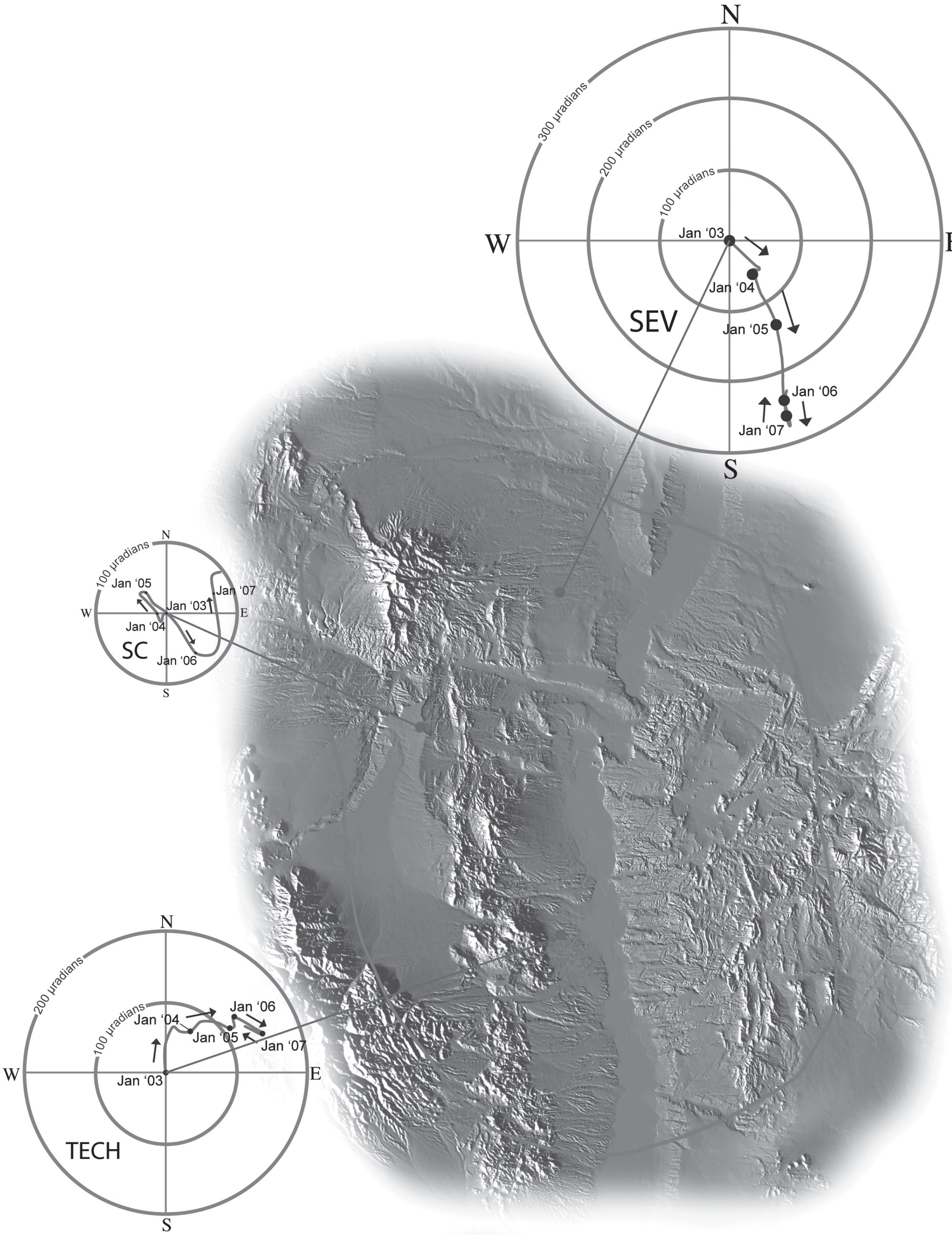

FIGURE 3. Long-term cumulative changes in tilt at the three localities being monitored in this study. The vector sums (east-west and north-south tilt axes) plotted here are 12-month running averages of the raw data. These trends could be real or could be related to drift in instrument electronics. Reversals or other changes in the latter half of 2007 may be real or they may be artifacts of using 12-month running means and the problems of temperature, precipitation, and other irresolvable seasonal drift.

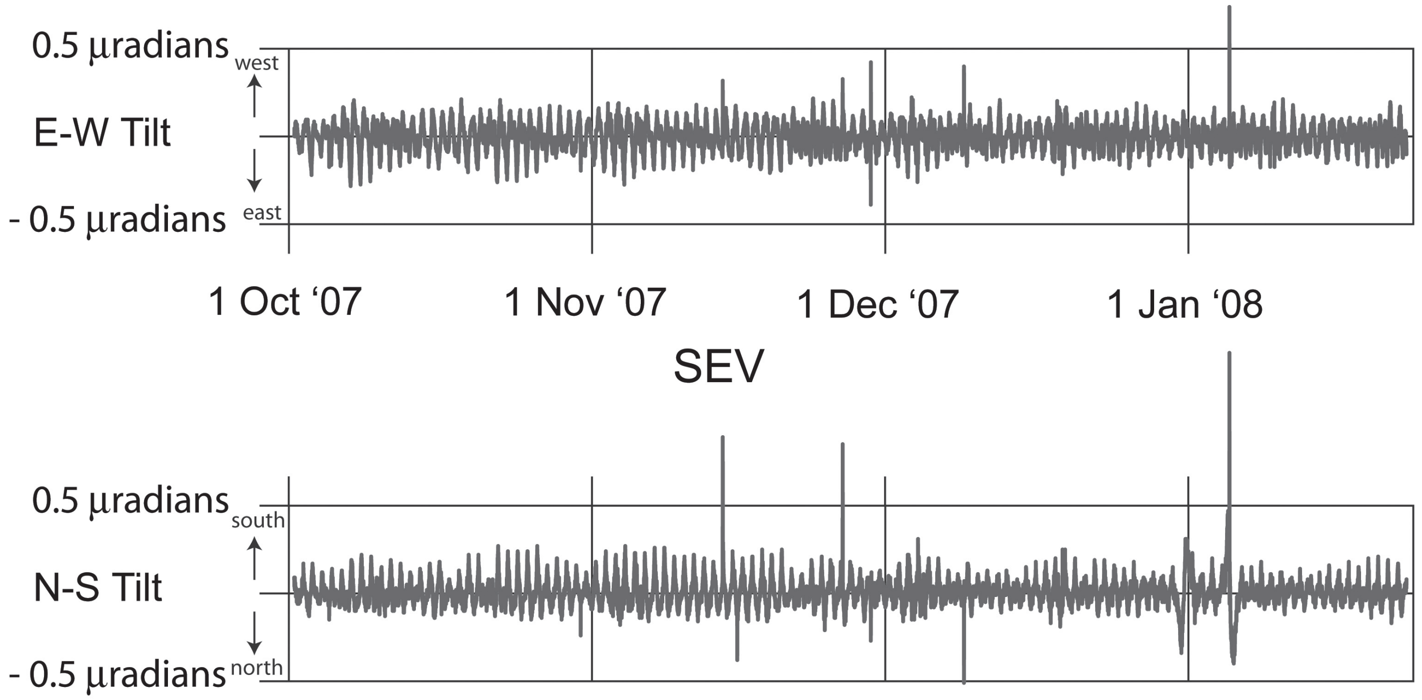

FIGURE 4. Tilt measurements from locality SEV, 1 October 2007 to 28 January 2008, showing short-term fluctuations likely due in part to earth tides (periodic fluctuations) and seismic events (spikes in the data). In this plot, raw data were detrended using a 24-hour running mean in order to remove longer-term changes in tilt measurements.

tens to hundreds of µrad show various amounts of multi-directional changes in orientation and reversals.

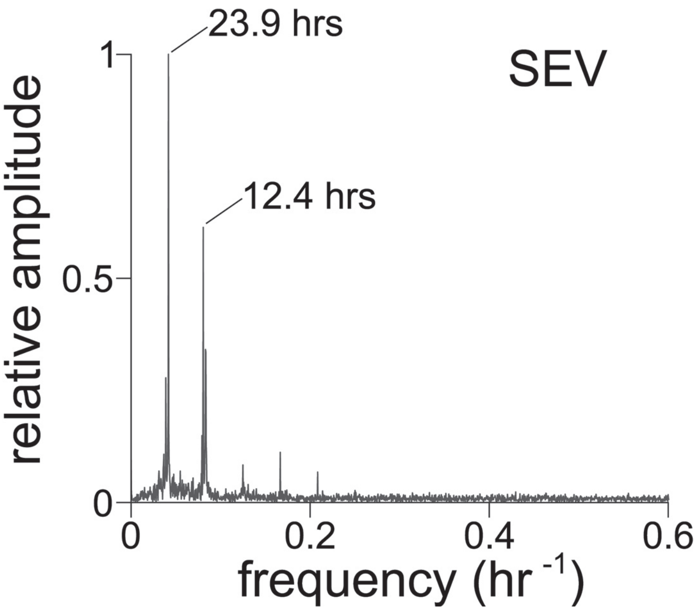

FIGURE 5. Fourier spectrum of detrended E-W-axis tilt (as plotted in Fig. 3A) from locality SEV, 1 October 2007 to 28 January 2008. Spectral peaks corresponding to periodicities of 23.9 hours and 12.4 hours are consistent with the expected timing of displacements due to earth body tides.

The largest and most consistent trend is the south-southeast to north-northwest trend at SEV. Its magnitude appears to be contrary to expectations based on campaign GPS measurements by Newman et al. (2004), who recorded 2 cm of uplift south of San Acacia from 2003 to 2004, and 1 cm of subsidence from 2004 to 2005. TECH shows an intermediate amount of wandering in an eastward trend, and also reverses course. SC, which was expected to exhibit cumulative tilt to the west, exhibits the most erratic wandering, but within 100 µrads of its initial position. The movement of SC may correlate with the uplift between 2003 and 2004 and subsidence between 2004 and 2005, but the other tiltmeters do not respond in smiliar ways. If these long-term changes in tilts are real (not instrumental drift), they may reflect "breathing" of a hypothesized shallow, small magma body as interpreted by Newman et al. (2004) or these tilts may reflect local adjustments on small fault blocks at the surface within the Rio Grande rift. When viewed together in a relative and qualitative sense, averaged tiltmeter data for stations north and west of San Acacia suggest a period of magmatic uplift (inflation) was occurring from the fall of 2002 to the summer of 2004. Tilting dominantly toward San Acacia from the summer of 2004 to the fall of 2006 may represent a period of magmatic deflation. Inflation may be ongoing since 2006 (A. Newman, written commun., 2009).

The apparent motions of local fault blocks are clearly not unidirectional and when viewed in an absolute sense some patterns seem counterintuitive. Clearly, longer-term records of tilt and perhaps more tiltmeters are warranted. Tiltmeter data may

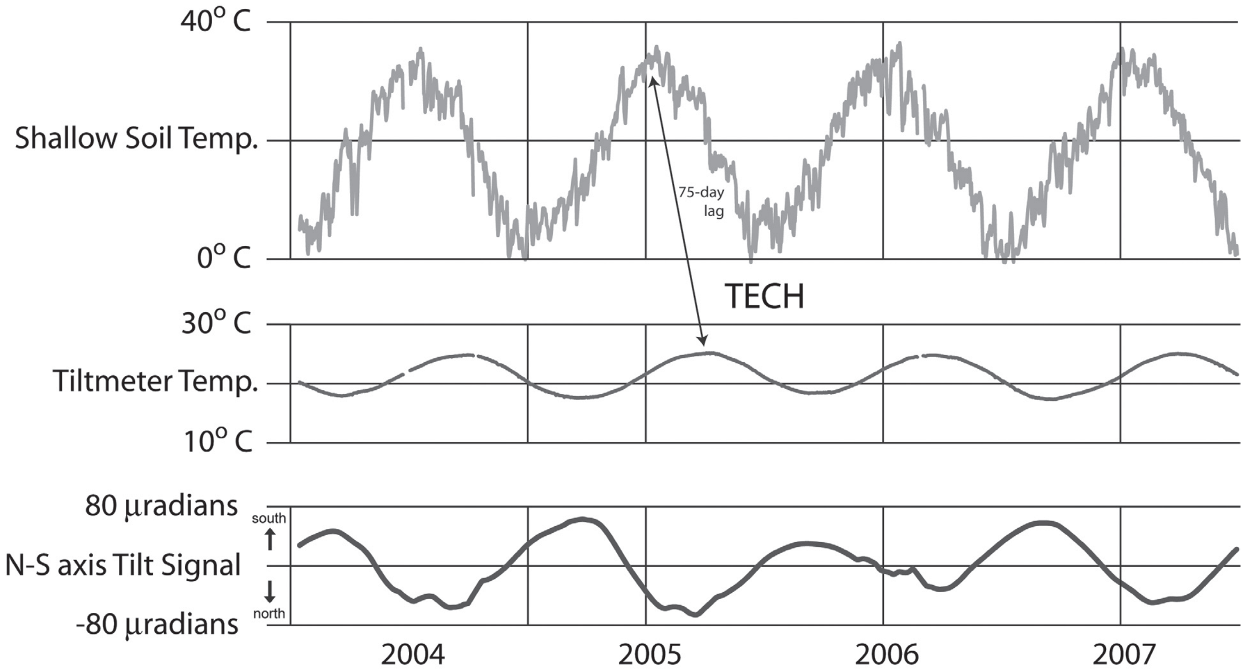

FIGURE 6. Daily average shallow soil temperature (6 cm depth), tiltmeter temperature (3 m depth) and 30-day running mean of north-south axis tilt measurements at locality TECH, 2004 through 2007, illustrating annual fluctuation in tilt measurements and an approximately 75-day lag in peak temperatures at depth. General correspondence in phase between the tilt signal and tiltmeter temperature suggests a temperature coefficient for this particular sensor of ~13 µrad / °C. This is much larger than the nominal, ~1.5 µrad / °C temperature coefficient reported by the manufacturer of the tiltmeter, suggesting 1) that some component of the apparent annual variation reflects real changes in tilt, 2) the temperature dependence of these instruments may be significantly larger than the value suggested by the manufacturer, or 3) some combination of the two.

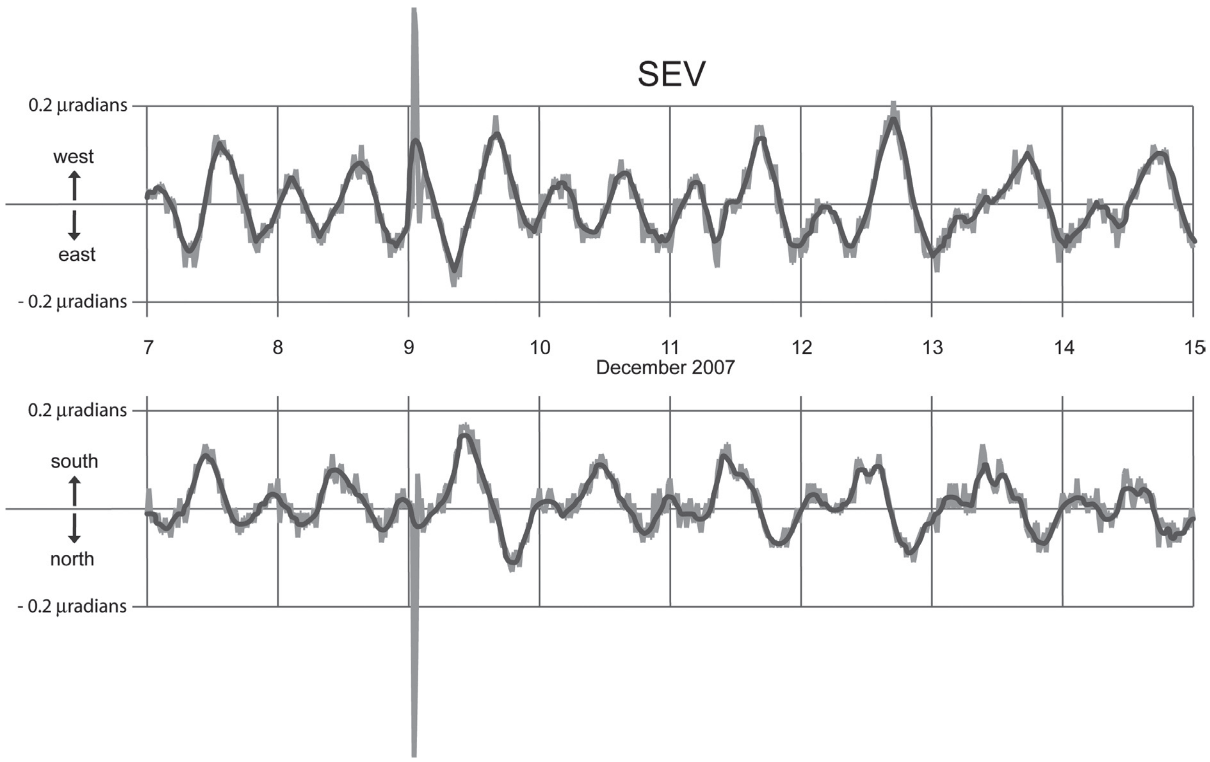

FIGURE 7. Detrended tilt measurements from locality SEV, December 7th through the 14th, 2007, showing diurnal and semi-diurnal changes in tilt. Plotted data are the raw 20-minute averages (blue-gray), and the 7-day running mean (violet-black). The spike in the raw data on 9 December may reflect a response to the magnitude 7.8 earthquake that occurred south of the Fiji Islands (26° South, 177.51° West; confirmed on local seismometers by Dr. Susan Bilek).

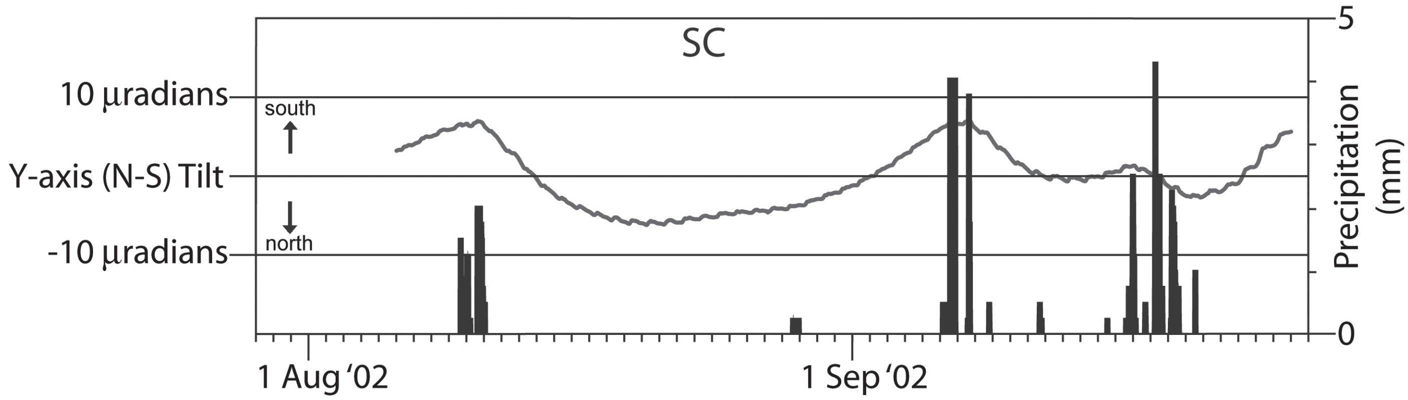

FIGURE 8. North-south axis tilt measurements (raw 20-minute data, detrended to remove longer-term variations) and 20-minute precipitation totals at locality SC, 6 August through 25 September (2002), illustrating changes in apparent tilt following rainfall events. Similar responses to rainfall events (deflections in tilt signals followed by gradual recovery) are present in all three tiltmeter records, suggesting that some component of these deflections reflect real ground deformations in the vicinity of the tiltmeters due to wetting and drying of the soil. Specific responses to individual rainfall events are generally inconsistent and unpredictable, however.

ultimately be temporally correlated to surface motions currently being measured by nearby continuous GPS stations and new InSAR data.

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