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PROGRESS REPORT ON TRACKING RIO GRANDE TERRACES ACROSS THE UPLIFT OF THE SOCORRO MAGMA BODY

D.W. LOVE [1], D. J. MCCRAW [1], R. M. CHAMBERLIN[1], M. REITER[1], S. D.CONNELL[1], S. M. CATHER [1], AND L. MAJKOWSKI[2]
[1]NM Bureau of Geology & Mineral Resources, NM Institute of Mining & Technology, 801 Leroy Place, Socorro, NM 87801, dave@gis.nmt.edu
[2]Earth & Environmental Science, New Mexico Institute of Mining & Technology, Socorro, NM 87801

Abstract—Although the ground surface above the Socorro magma body (SMB) is rising at rates as high as 3 mm per year historically, three discontinuous early- to middle-Pleistocene terrace deposits, local late-Pleistocene terrace deposits, and top(s) of early-Pleistocene fluvial basin fill (upper Santa Fe Group) show no major uplift of terrace treads from the southern Albuquerque basin across the northern part of SMB uplift. These terraces and basin fill surfaces can be traced along the Rio Grande from 34.50° N (Veguita) to 33.75 ° N (south of San Antonio) across the southern Albuquerque Basin, the Socorro magma body, and the relatively narrow Socorro Basin. Complications of interpreting surfaces include: 1) original maximum fluvial aggradational elevations may be preserved only locally, especially compared to the southern Albuquerque Basin and the northern Palomas-Jornada Basin; 2) commonly some lesser elevation of fluvial deposits is preserved by interfingering with less erodible coarse-grained valley-border alluvium; 3) coarse sediments as terraces from the Rio Salado have affected the course of the Rio Grande and partially buried Rio Grande terrace deposits over several square km; 4) if the historic SMB uplift rate were constant (2-4 mm/yr), a 100,000 year-old terrace tread should be about 200-400 m higher than its present elevation, and older treads should have undergone even more uplift—they have not; 5) Multiple north-trending rift-related faults in the Socorro Basin south of San Acacia significantly affect the elevations of Bandelier ashes preserved in axial fluvial deposits (20 m displacement locally confirmed), making estimates of maximum aggradation or stream gradients uncertain; 6) Short-term elastic uplift is generally viewed as domelike, but longer-term uplift could cause sufficient extension to trigger longitudinal collapse of keystone grabens, so terrace heights might not be affected or terraces might subside in places; and 7) The upper crust may be uplifted over short time episodes, but over longer periods, the mid crust may deform ductilely so that the ground surface returns to equilibrated elevations. Implications for the processes of the SMB are A) current uplift may be too recent to be recorded in the terrace succession, or B) current uplift is at a maximum rate, or C) this reach is affected by both subsidence and uplift of the SMB, or D) long-term uplift is matched by episodic subsidence of the surface. Within the Socorro Basin above the SMB, however, ample evidence of fault-bounded uplift, subsidence, and extensive valley-border erosion contrasts with the basins to the north and south within the rift, suggesting that this local area is more active both tectonically and erosionally than the adjacent broad basins. These observations affect not only interpretations of the duration of uplift, but also hypotheses of a possible smaller shallow magma body and geologically reasonable rates of magma injection into the SMB.

INTRODUCTION

The Socorro magma body (SMB) is interpreted to be a large, pancake-shaped body of magma that is uplifting the ground surface in the Socorro region of New Mexico (Sanford and Long, 1965; Reilinger and Oliver, 1976; Reilinger et al., 1980; Reinhart and Sanford, 1981; Larsen et al., 1986; Ake and Sanford, 1988; Schlue et al., 1996; Balch et al., 1997; Fialko and Simons, 2001; http://www.ees.nmt.edu/Geop/magma.html; Finnegan and Pritchard, 2009). This body extends over an area of 3,400 km^2 at a depth of 18.75 km (Figures 1, and 2), and is estimated to be 100-150 m thick. The rate of inflation at the center of the uplift near San Acacia has been estimated using conventional geodetic surveys and resurveys yielding an uplift value of 1.8 mm/yr (Larsen et al., 1986) and using Interferometric Synthetic Aperture Radar (InSAR) from satellites yielding a value of 2.5-4 mm/yr (Fialko and Simons, 2001; http://igpp.ucsd.edu/~fialko/research5-6.html; Finnegan and Pritchard, 2009). A recent GPS survey (Newman et al., 2004) indicated short-term uplift of 20 mm/yr, a possible small, shallow magma body, and the possibility of magmatic "breathing." The region surrounding the magma body appears to be subsiding. Uplift is accompanied by increased seismic activity known as the Socorro Seismic Anomaly (Sandford et al., 1995; 2002).

Bachman and Menhert (1978) suggested that uplift by the SMB had affected the attitude of Pliocene lava flows and sediments on the east side of the Rio Grande between San Acacia and Socorro. Ouchi (1983, 1985) investigated the effects of uplift on stream behavior and interpreted the gradient of the Rio Grande and its adjacent Pleistocene terraces to show that the SMB is affecting the present stream gradient. He suggested that uplift has continued for some time and has warped a least one of the terraces. Ouchi adopted the terrace nomenclature of Denny (1941) and mapped some surfaces along the Rio Grande from La Joya to San Acacia, New Mexico. He interpreted uplift of one terrace as much as 36 m in the reach he studied. Ouchi's conclusions have been used for the past 25 years in discussions of magma body age and emplacement behavior.

The area including the SMB has a complex geologic history and several on-going and interrelated geologic processes that should be considered under multiple working hypotheses as partial explanations for the attitudes and elevations of terraces. Tectonic, erosional, and sedimentologic processes may play roles. Not only is this area undergoing uplift, it is also being extended and broken into multiple tilted blocks of the Rio Grande rift where the Southern Albuquerque structural basin merges with the Socorro and La Jencia basins, and the northern Jornada Basin (Fig. 2). Older tectonic fabrics such as the Socorro accommodation zone continue to influence local tectonics.

Two major tributary streams join the Rio Grande in this area, the Rio Puerco (the most sediment-laden stream in the US) and

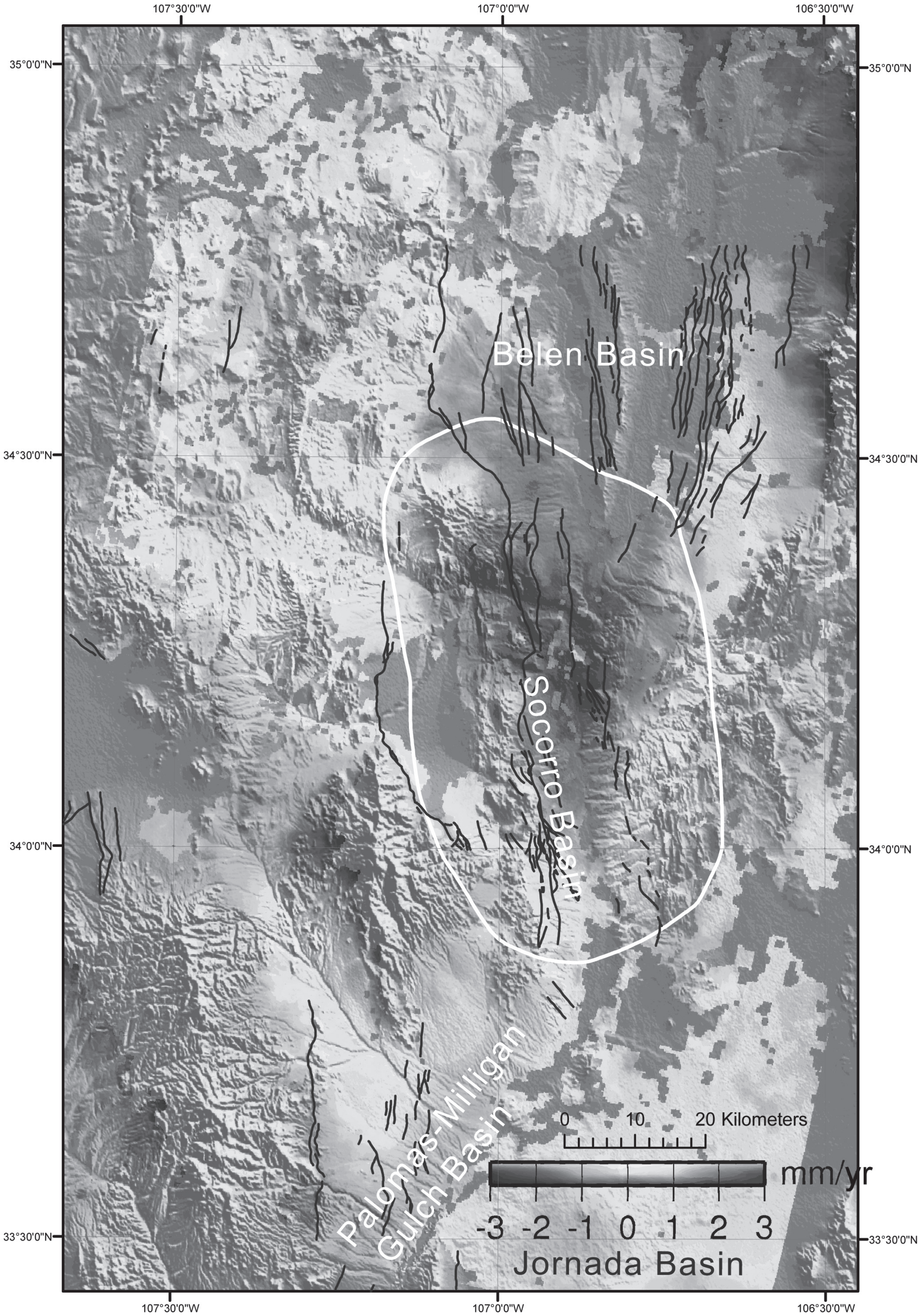

FIGURE 1. Shaded relief map of the greater Socorro area with rates of uplift of the Socorro magma body in color (courtesy of Yuri Fialko), outline of the Socorro magma body (white; from Balch et al. 1997), and Quaternary faults (black) from U.S. Geological Survey and New Mexico Bureau of Geology and Mineral Resources (2006), Olig and Zachariasen (2008), and unpublished data. See Plate XX, page XXX for a color version of this figure.

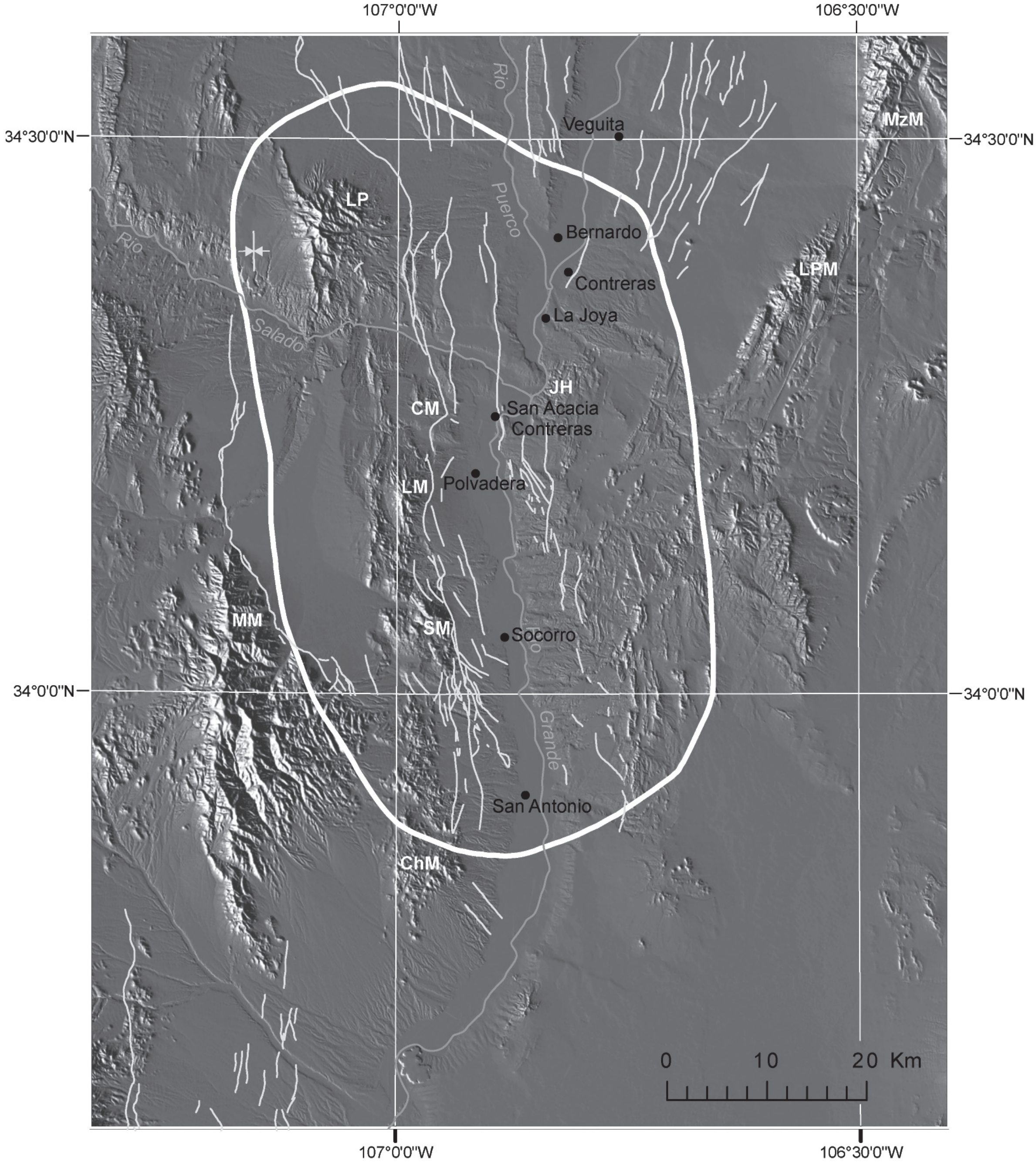

FIGURE 2. Shaded relief map of the Socorro area with outline of Socorro magma body, Quaternary faults and folds, river courses, and towns. Labeled uplifts are Manzano Mountains (MzM), Los Pinos Mountains (LPM), Joyita Hills (JH), Ladron Mountains (LP), Cerritos de las Minas (CM), Lemitar Mountains (LM), Socorro Mountains (SM), Magdalena Mountains (MM), and Chupadera Mountains (ChM).

the Rio Salado. In this reach at least ten large ephemeral tributaries from the east and at least eight large tributaries from the west deliver sediment to the Rio Grande valley and affect the sediment storage and transport capacity of the river These deliver large quantities of sediment to the Rio Grande valley and affect the sediment storage and transport capacity of the river. The tributaries have affected both the erosional and depositional geomorphology of the valley borders for at least the past million years.

Processes and questions concerning the Socorro magma body

Balch et al. (1997) and Schlue et al. (1996) determined the extent, thickness, and attitude of the SMB and the location of a possible feeder conduit below it at one location. Among the many questions about the magma body are: 1) is it continuing to inflate and/or rise toward the surface? 2) Is there a smaller magma body closer to the surface that may be "breathing?" 3) How old is the magma body? Heat-loss models suggest that if it is basaltic and holds its present geometry, it can not remain molten for more than 500 years, and regional heat flow suggests it can be no older than 3 Ma, even if it is episodically replenished. So (4) is it very recent geologically speaking, or has it been inflating for hundreds of thousands of years? 5) What is its composition? Is it one composition (basaltic) from the mantle to the sill; if it is older, should it be intermediate to silicic and might it evolve a more felsic melt in the mid crust? 6) is the rise of the magma from the mantle a plume-like diapir or a dike—is it viscosity-driven (density) or pressure- and overburden- driven? 7) Why is it spreading out in the mid-crust? Is its sill shape due to buoyant forces, crustal inhomogeneities, or a rheological boundary at 19 km (c.f. Parsons et al., 1992), where the crust above is too ductile to allow it to move upward? 8) Given the presence of molten rock in the subsurface, why has the Socorro area not had any eruptions in the past 3.7 million years? Related to these questions is whether the sill is being fed at a rate similar to other basaltic fields across New Mexico with independent small batches of basaltic magma or whether it is being fed at a rate similar to or larger than mid-ocean rise basalts. If the body is young, one might expect that terraces at the surface would not be deformed much, and the rate of magma injection would necessarily be large. If the magma body has been active for a longer period of time, why has it not cooled in the mid crust, and why is it difficult to see geomorphologic evidence of long-term uplift? Is the magma body too deep to affect the behavior of rift-related fault blocks? Or are they moving in response to the magma body as well as rift extension? Is this magma body just the most recent manifestation of a large number of similar bodies beneath the Rio Grande rift that are ephemeral and quickly cooled bodies in the crust? Are surface uplifts such as the horst and graben system at Cerritos de las Minas (Fig. 2) underlain by a shallow intrusion derived from the magma body?

Terrace interpretations and complications

Although terrace treads appear to be simple surfaces marking the top of aggradation of former river channels, such interpretations would be oversimplified along the Rio Grande, particularly in the Socorro basin. Connell et al. (2007) reviewed the definition of terraces, their internal sedimentary makeup, the variety of contacts with older valley-border substrates, and processes modifying their treads (Fig. 3). Some of the issues that make terraces complicated include, 1) where they are located with respect to the valley border or the valley center, 2) how they are preserved (commonly buried and protected from erosion by valley-border alluvium), 3) whether the tops and sides are eroded, 4) how the terrace treads have developed soils, and 5) whether the terrace treads are maintained in a state of quasi-equilibrium by additions, subtractions, and movement within soils. Of particular concern where only discontinuous remnants of terraces occur along the margins of river valleys is whether the preserved deposits delineate the maximum level of aggradation or whether the degree of preservation just reflects where they are preserved by burial. It is conceivable that aggradation in the valley centers was higher than along other portions of a known terrace deposit, but not preserved when downcutting resumed. The terraces in this reach of the Rio Grande have been faulted, affecting their original elevation and gradient regardless of their location relative to valley centers or borders. All these complications imply that use of the elevations of terrace treads by themselves has an inherent amount of uncertainty of at least several meters vertically. Similarly the bases of terraces probably are not so much horizontal straths, but have considerable vertical and lateral relief ranging from 2 or 3 meters at the outcrop scale to perhaps several more locally, as slopes of the valley margins reflect lateral advances by the river as it aggrades (Fig. 3, left side illustrations).

METHODS

Standard geological investigations and mapping were done on most of the quadrangles along the Rio Grande, and the Abeytas and La Joya quadrangles in particular. We used 1:12,000 color stereo aerial photographs and U.S. Geological Survey 7.5 minute quadrangles with 20-foot contour intervals to estimate the elevations of terrace treads and straths. We refer readers to the Bureau of Geology and Mineral Resources web site where most of the maps are open-filed and available on-line.

RESULTS

The top of the ancestral Rio Grande basin fill (upper Santa Fe Group) and flights of three terraces were traced from Veguita southward to La Joya and spot-checked to Polvadera. South of Polvadera, four terrace levels were mapped discontinuously to Bosque Del Apache, and their present tops or strath bases were identified where possible. At Contreras, McCraw et al. (2006; Fig. 4) described three terraces and the Rio-Grande-related basin fill. The most prominent terrace deposit in that area is longitudinally nearly continuous and about 27 to 30 m thick from the elevation of the present floodplain to the top of the modified terrace tread. This deposit is offset by a north-trending fault with a scarp of 2-3 m and larger offset of deposits within the terrace. Much of this deposit is pebbly to cobbly sand, intertonguing with fine-grained floodplain deposits and valley-border alluvium from the east. The fine-grained floodplain deposits at the top of the terrace are preserved beneath prograding valley-border deposits from tributaries. Near Contreras a strath terrace may be inset into these deposits, but this feature may also be due to later erosive stripping to resistant gravelly layers within the thick terrace fill.

East of Contreras, a thin (3 m) basal strath-terrace deposit about 38 m above the floodplain overlies Pliocene (?) cemented ancestral Rio Grande facies of Santa Fe Group basin fill, and is in turn truncated by erosion preceding deposition of the valley-border alluvium that also overlies the lower terrace (Fig. 4). This thin strath is pebbly to cobbly sand. No fine-grained slackwater or floodplain deposits are preserved at this locality.

The basal strath of the highest terrace is 50 m above the floodplain and the fill body is as much as 15 m thick west of its bluff line. This is a coarse-grained deposit with cross-bedded pebble-

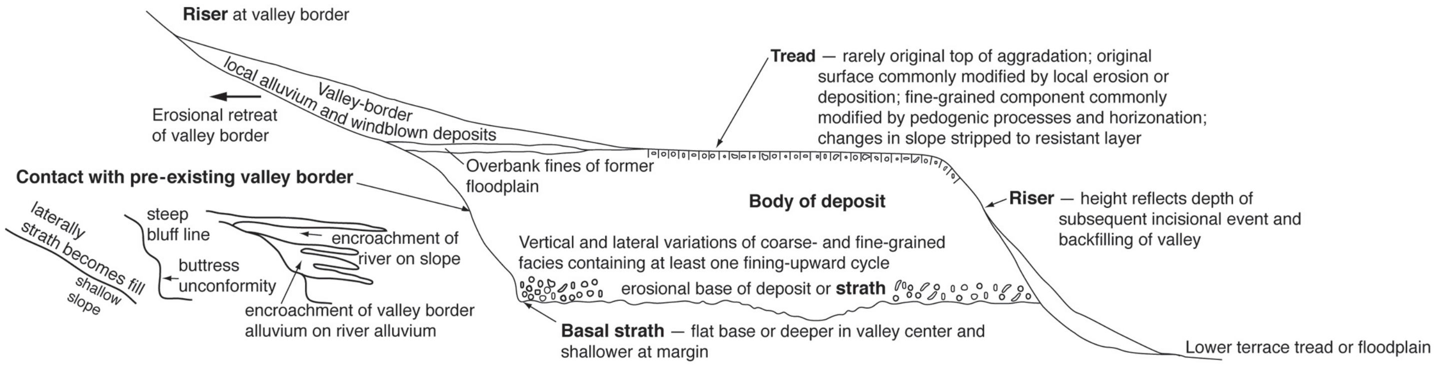

FIGURE 3. Generalized cross section illustrating terrace bodies, tops, and contacts with valley border (from Connell et al., 2007).

to-cobble gravel and sand in sets more than 1 m thick as well as finer-grained overbank deposits. A similar tread level exists west of the Rio Grande along the Rio Puerco (Fig. 4). It appears to be a much thinner body of alluvium and is regarded as a preserved basal strath.

The 50-m (base; 65-m top) terrace may be identified from near Veguita south to San Acacia. It appears to be thicker on the bluffs east of the junction of the Rio Salado (Fig. 5). The 39-m strath terrace is difficult to identify (and may not be preserved) in most reaches and is not shown on Figure 5. The extent of the 27-30 m terrace, however, is very traceable along the reach. As described below, low strath terraces are prominent north of the Rio Salado confluence and are locally present south of San Acacia.

Beyond the terraces to the east of Contreras, the upper part of the Albuquerque Basin fill (Sierra Ladrones Formation of Machette, 1978a and b) consists of ancestral Rio Grande gravelly sand at least 44 m thick. It interfingers with and is overlain by coarse piedmont alluvium derived from the Los Pinos Mountains to the east (Treadwell, 1996; McCraw et al., 2006). The top of the Rio Grande deposits is about 94 m above the floodplain. Pebbles of Rabbit Mountain obsidian (eroded from a rhyolite dome in the Jemez Mountains; 1.428 ± 0.007 Ma, Peters and McIntosh, NMGRL-IR-353) are present from its base to its top so the whole deposit is younger than 1.43 Ma. The base and top of deposits of Rio Grande basin fill may be traced northward beyond 34°30' north and south to 34°15' near San Acacia (Fig. 5). Where the top of the basin fill is exposed, the top is about 94-97 m above the floodplain. Where the top of the Rio Grande basin fill is overlain by tributary alluvium, the Rio Grande fill is preserved at slightly higher levels.

On the west side of the Rio Grande from at least 34°30' N south to San Acacia, the top of the basin fill and terraces reflect the tops of tributary alluvium, particularly from the Rio Puerco and Rio Salado (Fig. 6). Faults have offset the basin fill (mostly deposited by the ancestral Rio Puerco; Ceja Formation of Connell, 2008) on the Llano de Albuquerque and along the Cliff fault between the Rio Puerco and Rio Salado (Fig. 6). The 50-m terrace along the Rio Puerco is similar in elevation to the base of the 50-m terrace on the east side of the Rio Grande, whereas the top of the 50-70- m terrace along the Rio Salado is similar to the top of the Rio Grande terrace on the east side of the river (Fig.

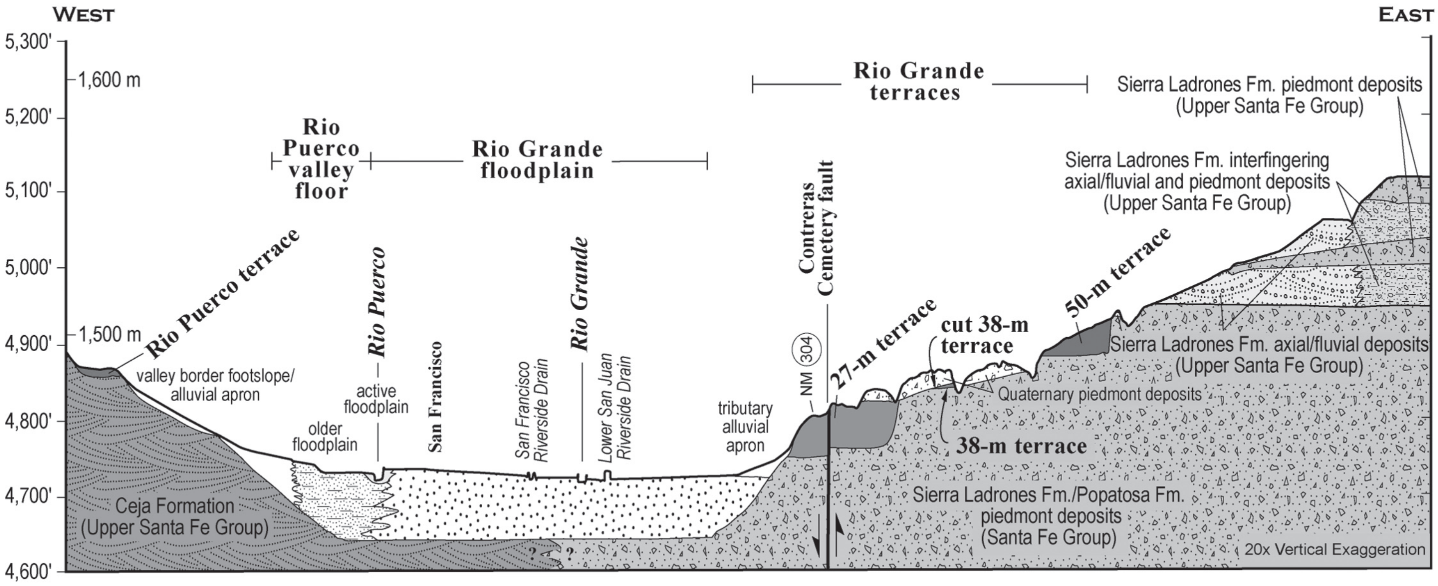

FIGURE 4. Geologic cross-section across Rio Grande at Contreras illustrating terrace deposits at three heights above the modern floodplain (modified from McCraw et al., 2006).

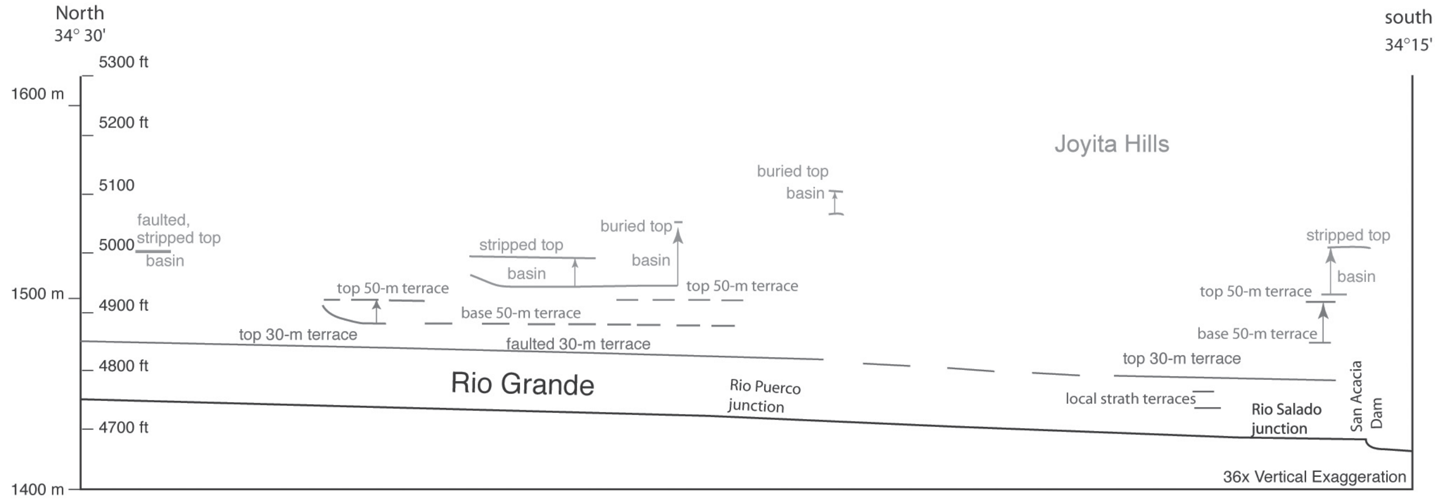

FIGURE 5. N-S profile of east-side terraces of the Rio Grande from Veguita to San Acacia. Higher levels are paler shades of gray to reflect their poorer preservation and distance from the valley. Palest are the bases and tops of Rio Grande deposits that comprise part of the basin fill (upper Santa Fe Group).

6; cf. Machette, 1978a, 1978b). The 30-m terrace is not seen in this reach of the lower Rio Puerco, but a terrace tread at a similar elevation is found along the Rio Salado (Majkowski, 2009). Coarse gravel deposits from the Rio Salado have buried the 30-m terrace of the Rio Grande both upstream and downstream from the present confluence of the two rivers.

Near the mouth of the Rio Salado three minor strath terraces capped by coarse cobbly gravel derived from the Rio Salado and tributaries from the Joyita Hills are found 7 to 12 m above the Rio Grande floodplain. These straths appear to reflect local high-discharge events rather than more regional climatic or tectonic episodes.

Upstream along the south side of Rio Salado, four very discontinuous terrace treads are preserved from 6 to 32 m above the stream channel (Majkowski, 2009). Each terrace tread appears to increase in height above the channel downstream, and the higher terrace treads increase more than the lower terraces. For example, terrace treads Qt7 and Qt8 rise from 10 and 6 m to 12.4 and 8.5 m above the channel. Qt6 rises from 11.8 to 17.2 m and Qt5 rises from 14 to 32.2 m. Majkowski estimates a range in ages for the terraces based on total-mass carbonate accumulation within the soil profile: Qt7, 16-59 kyr; Qt6, 154-181 kyr; and Qt5, 213-244 kyr.

An east-west cross-valley profile and simplified section is shown in Figure 7 to illustrate the terrace levels immediately north of San Acacia. The terraces are shown on the east side of the Rio Grande along the edge of the Joyita Hills and on the west side of the Rio Grande to the west of Indian Hill. The 30-m terrace is exposed between Indian Hill and Loma Blanca and the 38-m strath terrace may also underlie the Rio Salado alluvium there, but exposures are absent. The 30-m terrace appears to have a west-facing fault scarp along strike of the Cliff fault west of Indian Hill. Partially cemented piedmont alluvium south of Loma Blanca is graded toward the Rio Grande valley at the level of the 38 or 30-m terraces and is not faulted (Machette, 1978a)

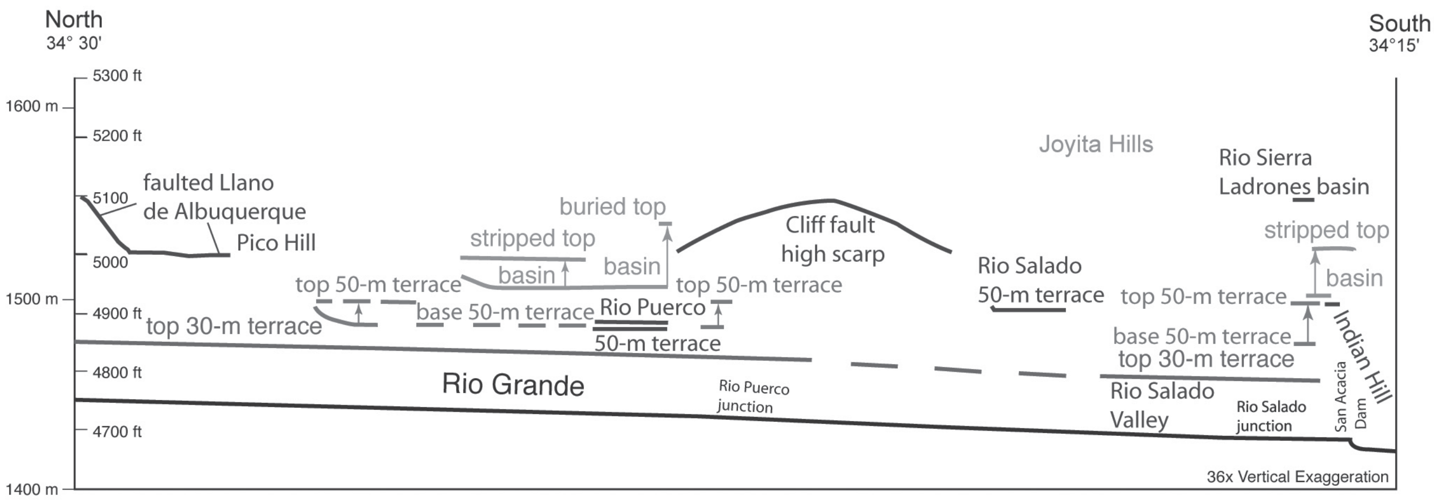

FIGURE 6. N-S profile of west-side terraces from Veguita to San Acacia. Gray features are those from the east side of the Rio Grande for comparison.

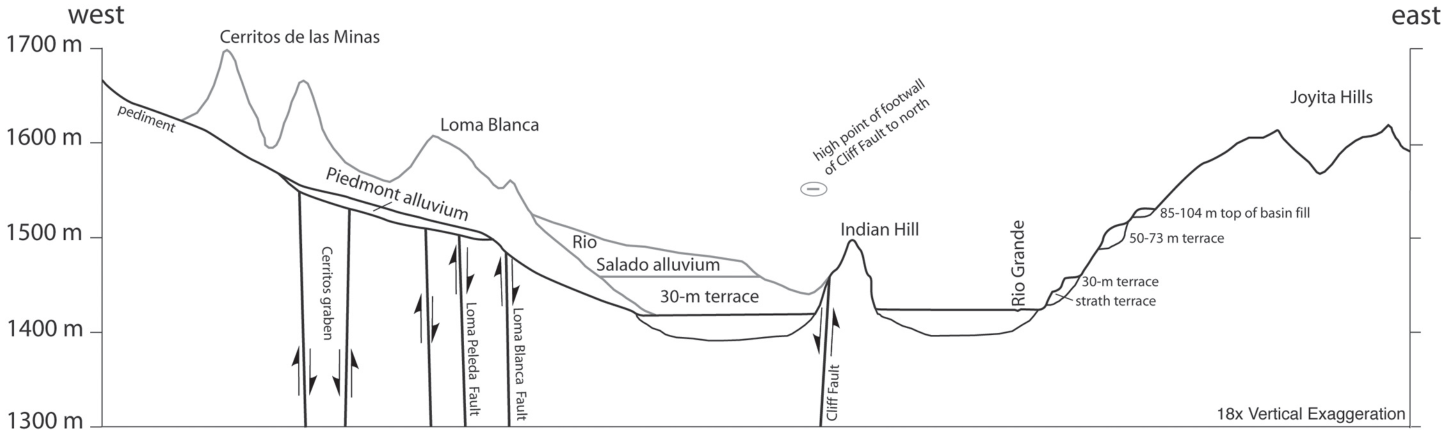

FIGURE 7. W-E profile and cross section across Indian Hill near San Acacia showing terraces, piedmont alluvium, and uplifted Loma Blanca and Cerritos de las Minas. Gray lines indicate features north of profile.

or uplifted by the magma body. In contrast, older river deposits (Miocene [?] or Pliocene ancestral Rio Grande[?]) are exposed at least 185 m above the Rio Grande floodplain at Loma Blanca and Early Miocene lavas of Cerritos de las Minas indicate that hundreds to thousands of meters of uplift have taken place within this part of the Rio Grande rift. This large amount of uplift at the surface is almost directly at above the center of the uplift of the SMB and is unlike any area to the north in the Albuquerque Basin or to the south in the Socorro or Jornada-Palomas basins.

Compared with the broad, more uniformly aggraded rift basins to the north and south (Albuquerque-Belen and Palomas basins), the Socorro Basin exhibits several narrow uplifts that expose pre-rift rocks, early-rift volcanic rocks, older basin fill, and younger Rio Grande fluvial deposits. The uplifted blocks have undergone extensive erosion within and beyond the margins of the basin. Quaternary faults commonly cut both Rio Grande deposits and intertongued piedmont deposits (Figs. 2 and 8). Wide-spread erosion of the valley borders has removed many Rio Grande deposits from several levels, making the geologic history of the Rio Grande difficult to interpret in these areas. Deposition of large alluvial fans with debris derived from the Magdalena Mountains to the west, however, have buried and preserved Rio Grande deposits at the mouths of Nogal, Socorro, and other canyons.

Dunbar et al. (1996) document several localities with Quaternary ashes and pumices deposited within ancestral Rio Grande sediments in the Socorro Basin. Although these ashes and pumices are in stratigraphic order within each structural block of the Socorro Basin, they are at different elevations on different blocks and no longer reveal unambiguous information about river gradients nor original elevations. With further investigations, however, it may be possible to tie some of these localities together in terms of elevations of tops of basin-fill.

Figure 8 shows where we have tentatively identified the tops and bases of Rio Grande basin fill and terraces from San Acacia southward to San Antonio and the orientation of Quaternary faults in the Socorro Basin. Many of the faults are parallel to the Rio Grande valley; some offset terrace deposits and the top of the basin fill locally. With the exception of the 79-m top of basin fill in a graben northwest of Socorro, most of the tops of Rio Grande basin fill are between 93 and 97 m above the floodplain. Oddly, the thick terrace deposit from 50-70 m above the floodplain in the Contreras area (Figs. 4 and 5) has yet to be observed in the Socorro area. The base of a 35-m terrace (perhaps the 38-m strath farther north) is found south of San Acacia on the east side of the valley. The 30-m terrace top is common along the west side of the valley and inset strath terraces are also found. Additional mapping is required to delineate these levels in more detail.

DISCUSSION

Gradient of the Rio Grande

Ouchi (1983) interpreted multi-year measurements of the gradient of the Rio Grande from San Felipe to San Marcial to show a bulge between Belen and Socorro and attributed the bulge to the SMB. The largest deflection, however was along the profile measured in 1936-1938. The bulge in general and the late 1930s deflection, however can be explained in this reach by the addition of sediments from several large tributary drainages—Abo Arroyo, Rio Puerco, Salas Arroyo, Arroyo los Alamos, and Rio Salado. The Rio Puerco and Rio Salado contributed large volumes of sediment to the Rio Grande during two floods in 1929, again in 1935, and 1936 (Heath, 1983). The other tributaries are ungaged, but might be expected to contribute large volumes of sediments at the same time if storm events were regional (as they were in 1929). Finnegan and Pritchard (2009) addressed the gradients of the Rio Grande, Rio Puerco, and Rio Salado and did not find consistent deflections in the gradients of the streams. They attributed the bulge in the gradient of the Rio Grande to sediment contributions by the Rio Puerco.

Other interpretations of terrace and basin-fill bulge

Bachman and Mehnert (1978) interpreted 85 m of uplift along the east side of the Rio Grande between Socorro and San Acacia. The southern part of the area (~6.5 km NE of Socorro, Arroyo de la Parida) is where Needham (1936) found Pliocene fossils in ancestral Rio Grande deposits only a few meters above the level of the modern Rio Grande floodplain. Lucas and Morgan (2001) and Morgan et al. (2008) collected more fossils in the area and

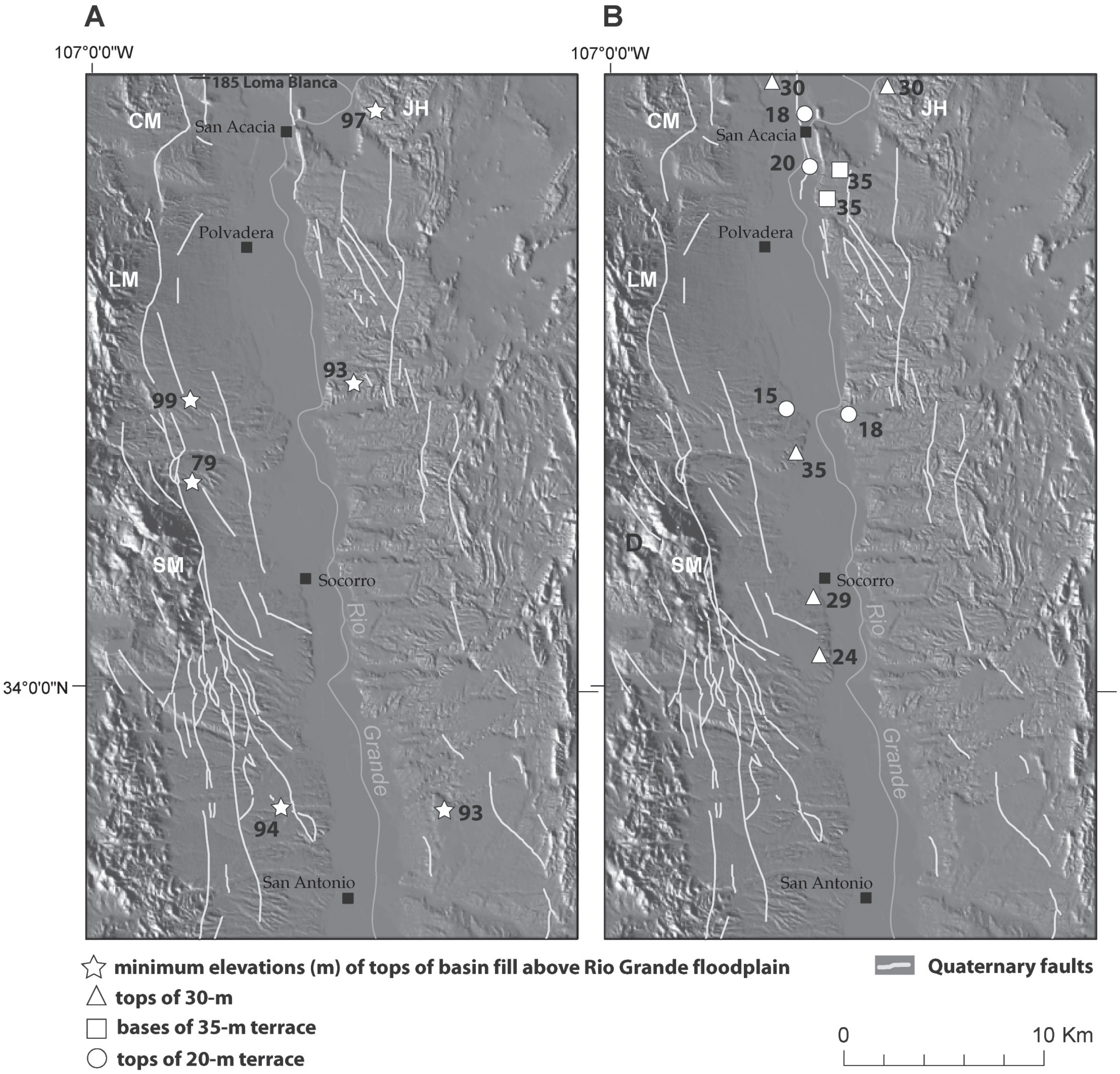

FIGURE 8. Shaded relief maps with Quaternary faults in the Socorro Basin showing localities with tops of basin fill, tops of the 30-m terrace, bases of a 35-m terrace, and tops of a 20-m terrace. A. Tops of Rio Grande deposits in basin fill (Santa Fe Group); B. inset terraces along the Rio Grande Valley.

estimate that the fossils are medial Blancan in age (2.7-3.6 Ma). The Pliocene ancestral Rio Grande deposits here are at least 70 m thick, with the base not exposed and the maximum aggradation elevation above the floodplain at ~ 93 m (on the hanging wall of the Socorro Basin). According to Bachman and Mehnert (1978), 11 km to the north, similar Rio Grande deposits are 85 m higher, resting on top of the 4.9 Ma lava flow southeast of San Acacia, but the Pliocene age-equivalency of the overlying river deposits was not established. The top of the lava flow slopes southward along a footwall block within the rift. Maximum known elevation of ancestral Rio Grande basin fill northeast of the lava flow is 85-104 m above the modern floodplain but that deposit has clasts of lower Pleistocene (1.43-1.25 Ma) volcanic rocks from the Jemez Mountains so it does not correlate with the older Pliocene beds. Therefore a steeper tectonic slope of Pliocene Rio-Grande fluvial basin fill remains to be documented.

Another issue is that the valley margins and paleo-valley margins are discontinuously preserved and probably record a complicated history of where the river was and where the valley margins were during the past 5 million years. Deposits and their contacts with underlying valley borders commonly are at oblique angles to the modern valley, so exposures of the “base” of ancestral Rio Grande deposits may trend diagonally upward within the same paleo-valley fill (Fig. 3 left edge).

Ouchi (1983) presented a map of the La Joya-San Acacia area with three terraces using Denny's (1941) terminology. The Loma Parda surface corresponds to the top of our 27-30 m terrace tread. However, Ouchi's down-Rio profile of the Loma Parda surface (his figure 2-100.6) inexplicably ignores his map and interprets the surface to rise to 36 m above the Rio Grande. He also includes a 12-m tread (tributary arroyo (?); not shown on his map) near La Joya to interpret that the bulge begins north of there. As mapped, the Loma Parda or 30-m terrace tread is discontinuous from the Rio Salado down to San Acacia at more-or-less the same height above the river. Ouchi's 36-m elevation (on his illustrated profile) appears to be either a remnant of our 39-m strath terrace or the top of a tributary fan resting on the Loma Parda surface.

Ouchi (1983) also assumed that the Loma Parda surface was only 20,000 years old, based on the idea that the terrace formed during the last glacial maximum (a reasonable assumption at the time). However, work by Phillips et al. (2003) and Connell et al. (2007) show that this terrace tread is about 130,000 years old. This age makes the apparent lack of deformation all the more pertinent to the age of the SMB.

Terraces of the Rio Salado with respect to Rio Grande and the magma body

Majkowski (2009) correlated discontinuous terrace treads along the south side of Rio Salado at or below the level of the 30-m terrace and interpreted progressively more uplift downstream for older terraces. However, further examination of the location of the terraces and the mass-carbonate accumulation in soil profiles suggest possible problems with correlation and mis-tracing of the highest preserved terrace tread near the east end of her transect. The lower reaches of the Rio Salado terraces are also in the area of influence of Rio Grande terraces, so past gradients of the Salado may have flattened close to the main river, and preserved terrace remnants might reflect complicated lateral and longitudinal shifts in the confluence between the two rivers. Nonetheless, the apparent rise in the elevation of the terraces could indicate short-term response to uplift, while over longer time periods the older main-stem terraces have returned to near their original elevations as the mid crust has undergone extension and relaxation.

Implications for dynamics of the Socorro magma body and overlying crust

The lack of all but possibly minor terrace deformation across the historic uplift of the SMB suggests consideration of several possible processes for injection of the magma and behavior of the overlying crust. First, the 340 km^3 SMB may have arrived recently (< 10^3 yr) under a very high rate of injection into the middle crust. This amount of magma in a short period of time suggests at least an order of magnitude greater injection rate than known for other volcanic fields in New Mexico (except perhaps for magma stored and episodically erupted in the Jemez Mountains; Goff and Gardner, 2004). A high rate of magma injection implies that the mantle beneath the rift is capable of generating similar amounts of magma as the mantle beneath mid-ocean ridges. Rates of sea floor spreading are easily two orders of magnitude faster than the spreading rate of the Rio Grande rift so the following comparison may not be valid. Sigurdsson (2000) estimated that average magma upwelling along 59,200 km of mid-ocean rises and ridges is about 18 km^3 per year. If the 100-km long axis of the SMB received a proportional amount of magma (~0.03 km^3 per year), the 340 km^3 of magma would take more than 11,000 years to be emplaced, and the rate of cooling would have to be offset by replenishment of fresh magma at a significantly greater rate. Other volcanic fields in New Mexico show great variability in the rates of eruption of lavas over time, so variable rates of intrusion of the SMB should probably be expected.

Second, it is possible that magma injection has been accelerating during the past century or possibly during the past few centuries. A third alternative is that the historic doming is due to a shallower, smaller magma body, as suggested by Newman et al. (2004). A fourth alternative is that at least some of the SMB is older and that episodic doming, extension, ductile relaxation within the mid crust, and/or down-dropping along rift-related normal faults keep relative terrace elevations close to their original positions.

The ductile behavior of the mid crust may explain both the upper limit of magma injection and the long-term elevation of terraces at the surface. Parsons et al. (1992) show that the rheological strength of the crust and contrast in ductility of the mid crust may lead to horizontal intrusions of magma to form sills. While the brittle upper crust may be uplifted over short time periods due to magma injection, the ductile mid crust may relax and extend laterally over longer time periods so that uplifted upper crust is adjusted back to near initial elevations.

CONCLUSIONS

This article is a progress report. We have not finished identifying and tracing terrace deposits between San Acacia and Bosque del Apache. We recognize several inherently cautionary reasons for uncertainty in identifying and tracing terrace treads. It remains possible that the Socorro magma body is responsible for some deformation of terraces.

"Tops" of terraces commonly are preserved along valley margins, where deposition, aggradation, and erosion are complicated, and deformation due to local structures may be more common. The terrace treads we have examined so far reflect quasi-equilibrium of subtractions, additions, and stabilizing processes.

In the reach between Veguita and San Acacia, deformation of Rio Grande terraces is not apparent. Within the Socorro Basin above the Socorro magma body, fault-bounded uplift, subsidence, and extensive valley-border erosion contrast with reaches to the north and south. Older fluvial deposits (terrace treads not preserved?) are more eroded and more overprinted with Pleistocene tectonic and climatic events than younger terraces, producing more uncertainty in using such deposits to trace river positions through time.

The implications of minor terrace deformation for processes of injection (or plume displacement) of the SMB are either 1) the 340 km^3 SMB arrived recently (< 10^3 yr) under a high rate of injection into the middle crust, or 2) magma injection is accelerating recently, or 3) historic doming is due to a shallower, smaller magma body, or 4) at least some of the SMB is older; episodic doming, extension, relaxation of ductile crust, and/or down-dropping along rift-related normal faults keep relative terrace elevations unnoticeably close enough to their original positions.

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