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GEOMORPHIC SURFACES OF THE RIO GRANDE VALLEY IN THE VICINITY OF SOCORRO, NEW MEXICO

FRED M. PHILLIPS[1] AND BRAD D. SION[2]

[1]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 810 Leroy Place, Socorro, NM 87801; Fred.Phillips@nmt.edu
[2]Division of Earth and Ecosystem Sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512

Abstract—The sides of the Rio Grande Valley north and south of Socorro, New Mexico, exhibit readily apparent, sloped, quasi-planar surfaces ("terraces"). These have only recently been systematically mapped, characterized, and dated. The dating confirms that the terraces decrease in age with decreasing height above the Rio Grande. The highest terrace, the Las Cañas surface, represents the land surface at the time of maximal aggradation of the Rio Grande, at about 800 ka. At this time, the top of the basin fill was about 100 m higher than the modern Rio Grande. The surface about 20 m below it, the Tio Bartolo, stabilized at ca. 610 ka, near the 621 ka termination (Lisiecki and Raymo, 2005) of a very intense global glaciation (MIS 16). Forty meters below it, the Valle de la Parida surface formed ca. 135 ka, also at the end of an exceptionally intense glacial interval. Below the Valle de la Parida are three more terraces, two of which formed due to fluvial incision at the start of a glacial paleoclimate and the youngest within an interglacial. This pattern supports a model originally advanced by John Hawley, which proposed glacial/interglacial transitions as a control on terrace formation. The Rio Grande rift in the vicinity of Socorro is currently undergoing uplift as a result of injection of magma into a mid-crustal sill. A longitudinal profile of the terraces along the river shows two features that may be related to earlier magma injections. The first is an apparent 'bulge' of about 50 m in the two highest terraces, near San Acacia, the current area of most rapid uplift. The second is a more subtle rise in terrace elevations, amounting to 10 m, across the southern boundary of the current magma body. These both suggest that magma injections in the geological past may have produced upward topographic deflections, but additional data and examination of alternative explanations are needed before they can be considered solid evidence of such events.

INTRODUCTION

Successively higher levels of terraced landscape are readily apparent when viewing the valley of the Rio Grande from any high vantage point in the vicinity of Socorro. What are the origins of these striking features? What can they tell us about the geologic and geomorphic history of the Rio Grande? Do they give clues to the tectonics of the Rio Grande rift?

These questions have stimulated generations of geologists, including legendary figures such as Kirk Bryan and John Hawley. In this paper, we will recount some of the interpretations of these previous workers, provide a comprehensive map of geomorphic surfaces in the Socorro area, review the chronology of terrace formation, and evaluate the significance of the terraces in the context of new data and modern understanding of geomorphological processes.

The term "terrace" is used in a very broad sense in this paper. Geomorphologists often restrict "terrace" to an alluvial deposit formed by the result of direct fluvial action (aggradation or lateral planation), the former typically possessing a basal strath cut into older deposits, and both exhibiting relatively flat surfaces (or treads) that are quasi-parallel above axial drainages (see Connell et al., 2007, for a detailed treatment in the context of the Rio Grande Valley). A large percentage of the Rio Grande "terraces" in the Socorro area in the classical literature of Bryan and contemporaries are instead smooth and sloping surfaces on the piedmonts flanking the Rio Grande, often formed on thick terrace alluvium whose straths are buried below modern grade, and formed either by aggradation of coalescing alluvial fans during periods of base-level rise or by pedimentation associated with relatively uniform stripping of piedmont slopes during episodes of base-level fall. Here, we use "terrace" to describe both the axial Rio Grande fluvial surfaces and alluvial-fan/pedimentation surfaces in piedmont areas.

PREVIOUS STUDIES

Although the terraces of the Rio Grande have been features of interest since the beginning of the 20th century, rather remarkably those in the vicinity of Socorro had no comprehensive study published until well into the 21st century (Sion, 2018; Sion et al., 2020). Kirk Bryan evidently started mapping the terraces of the Socorro area (Bryan, 1932), but his map was never published and now is apparently lost. His student, Charles Denny, did utilize enough of Bryan's mapping in his study of the northern end of the Socorro Basin (Denny, 1941) to enable us to understand Bryan's classification of the terraces.

The geomorphic surfaces corresponding to Bryan's 'terraces' were comprehensively mapped on the east side of the Rio Grande in the Socorro Basin by de Moor et al. (2005), and on the west side by Machette (1978a), Chamberlin et al. (2001, 2002), Chamberlin (1999), and Chamberlin and Cikoski (2010). Terrace correlations along the Socorro Basin were explored by Love et al. (2009). Most of the findings described here are based on Sion (2018) and Sion et al. (2020). They combined: (a) high-resolution mapping of selected terrace treads using 5 m resolution (1 m vertical) digital terrain models and a moving window smoothing algorithm to facilitate

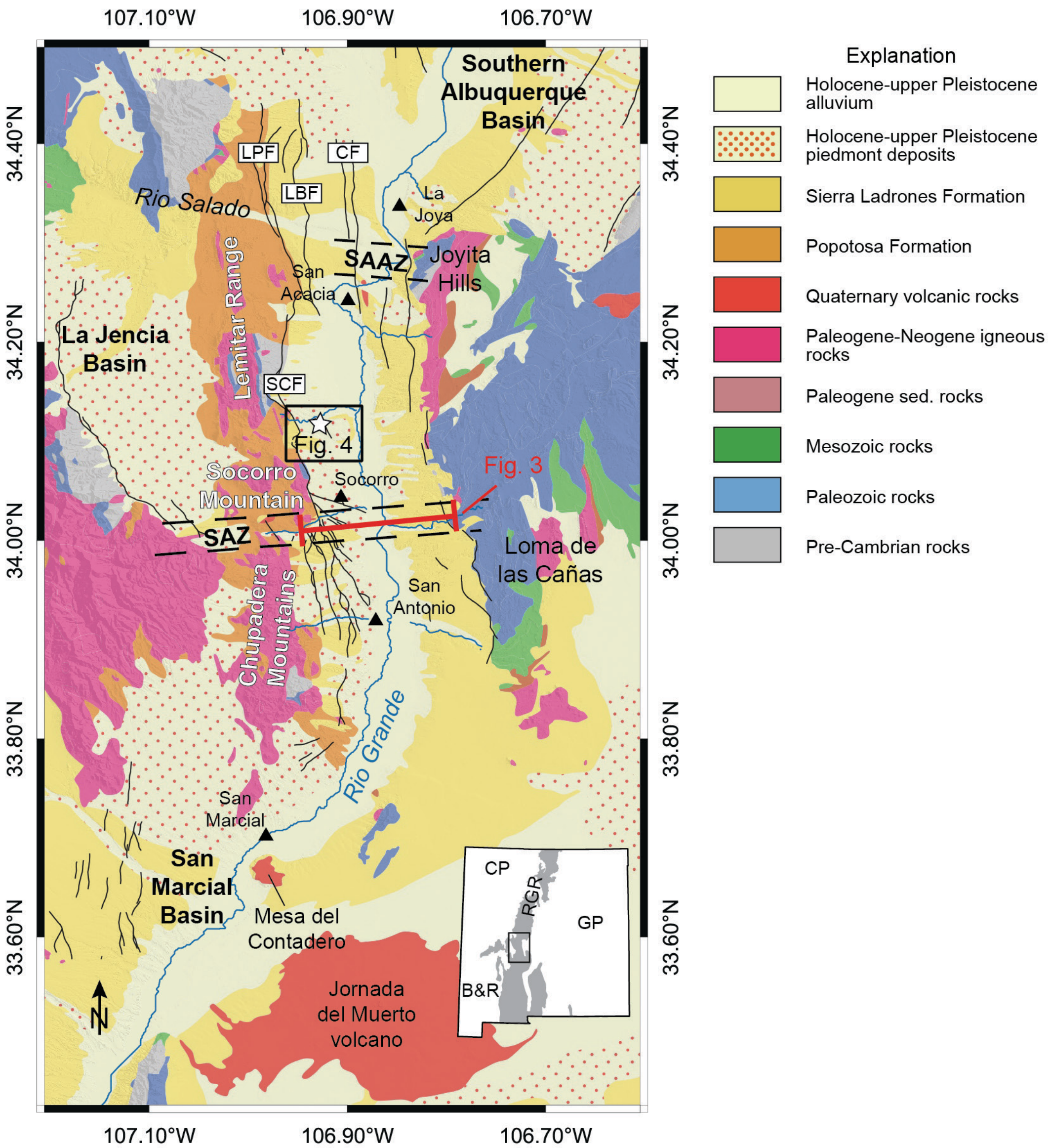

FIGURE 1. Simplified geologic map of the Socorro area. Location of Figure 4 is shown with rectangle and the star marks Stop 1 (Day 1 Road Log). Abbreviations: LPF – Loma Pelada fault, LBF – Loma Blanca fault, CF – Cliff fault, SCF – Socorro Canyon fault, SAAZ – San Acacia accommodation zone, SAZ – Socorro accommodation zone, CP – Colorado Plateau, B&R – Basin and Range, GP – Great Plains. Black lines are Quaternary faults. Geologic units are from New Mexico Bureau of Geology and Mineral Resources Geologic Map of New Mexico. Modified from figure 1 in Sion et al. (2020).

comparison of longitudinal terrace profiles with other surfaces up and down the Rio Grande Valley; (b) soil profile and stratigraphic column characterization on comparative surfaces; and (c) radiometrically determined surface ages to document the occurrence and spatiotemporal distribution of geomorphic surfaces in the Socorro area. For additional details regarding other prior studies in the area, see Sion et al. (2020).

We note that the terraces adjacent to the Rio Grande in select reaches north and south of the Socorro stretch have previously been thoroughly studied. Connell et al. (2007) mapped and dated terraces in the Albuquerque Basin. Gile et al. (1981) have provided a geochronological framework for the terraces in the Las Cruces area. In general, the chronologies provided by these studies are in good agreement with that in the Socorro Basin from Sion et al. (2020).

REGIONAL SETTING

The Rio Grande flows southward through the Rio Grande rift (Fig. 1). The rift extends continuously from central Colorado to Mexico. It began to open about 25 Ma and was highly active until about 10 Ma (Ricketts et al., 2016). Since then, extension has continued, but at a slower rate. South of the Albuquerque Basin, the rift was originally composed of a string of topographically closed basins. The drainage of the Rio Grande integrated mainly from north to south (i.e., downstream) from the Socorro area beginning at about 4.8 Ma, reaching the Gulf of Mexico at about 800 ka (Connell et al., 2005; Galloway, 2005; Galloway et al., 2011; Repasch et al., 2017). Subsequent to integration with the Rio Grande, sedimentation in the Socorro Basin and other rift basins in central and southern New

Mexico shifted from closed-basin facies to through-going fluvial deposition flanked by piedmont deposition (Chapin and Cather, 1994; Connell et al., 2013; Sion et al., 2020). Early closed-basin deposits of the Santa Fe Group in the Socorro area are called the Popotosa Formation (Denny, 1941; Bruning, 1973; Chapin and Cather, 1994). Santa Fe Group clastic deposits synchronous with, and subsequent to, establishment of the axial river (4.8–0.8 Ma) is called the Sierra Ladrones Formation (Machette, 1978a).

The narrow Socorro Basin has two parts separated by the Socorro lineament (Koning et al., this volume). The northern part is an asymmetric half-graben (Sanford, 1968), with the bounding normal fault, the Socorro Canyon fault, on the west side (Fig. 1). The southern part may possibly be more symmetrical and appears to have the largest-displacement faults on its eastern side (Koning et al., this volume). The northern Socorro Basin is bounded on the north by the San Acacia accommodation zone, a relative structural high where a complex array of structures transfer extensional strain from the southern Albuquerque Basin. The accommodation zone exhibits a wide distribution of normal faults (Grauch and Connell, 2013), which transitions to fewer faults of the northern Socorro Basin, the most prominent being the Socorro Canyon fault on the west side of the basin (Fig. 1; Love et al., this volume). On the south, the Socorro Basin merges into the San Marcial Basin. The mountain ranges on the west side of the Socorro Basin, in the footwall of the bounding fault, are generally steep and formed of Proterozoic, Paleozoic sedimentary, and Tertiary volcanic-to-sedimentary rocks. The east side, with limited late Quaternary faulting, has much gentler topography.

TERRACE CHARACTERISTICS

The mapped extent of the terraces in the Socorro Basin is shown in Figure 2, and the terrace characteristics are listed in Table 1. Sion et al. (2020) delineated both terrace-fill formations (allostratigraphic units) and geomorphic surfaces that top the fill units. Type localities and stratigraphic and soil descriptions are given in Sion et al. (2020), Sion (2018), and Sion et al. (2021), and the descriptions below are drawn from those sources. The units were dated using ^{36}Cl, ^{40}Ar/^{36}Ar, and radiocarbon. The relations of the terraces to each other and the topography of the Rio Grande Valley near Socorro is illustrated in a cross section transverse to the river in Figure 3.

The Las Cañas surface constitutes the remains of the land surface at the time of maximum basin aggradation, at 820–770 ka and occurs about 100 m above the current Rio Grande. This age range was determined by dating a capping, 818.3±10.6 ka basalt in the San Marcial Basin (Sion et al., 2020) and the Brunhes/Matuyama magnetic polarity boundary interpreted several meters below correlative surfaces in the Albuquerque Basin (Connell et al., 2013) and near Rincon-Hatch (Mack et al., 1993, 1998).

The Las Cañas surface covers large areas at the central and southern part of the Socorro Basin, east of the Rio Grande and west of the Rio Grande near San Antonio. In these areas, the Las Cañas surface is preserved on the distal hanging wall ramp (east side of central Socorro Basin) or on the footwall of major faults (southern Socorro Basin). It is underlain by the Sierra Ladrones Formation. The Las Cañas has been stripped away by erosion over most of the rest of the basin.

The controls on the timing of incision into the Las Cañas surface, and other correlative surfaces up and down the Rio Grande, have not been demonstrated, but the most commonly cited cause is the switch from low-amplitude to high-amplitude glacial cycles at about 0.8 Ma (e.g., Connell et al., 2005).

Twenty meters lower than the Las Cañas surface, the Tio Bartolo surface is found either widely scattered over the uplands east of the Rio Grande or on the remnants of alluvial fans immediately downstream of where the major drainages from the west incised through the bounding mountain ranges. This distribution suggests that the Tio Bartolo originally formed as a pediment over wide areas on the valley piedmont or as constructional surfaces in tributary valleys. On the east side of the river, the Tio Bartolo is generally underlain by thin pediment or veneer deposits of the La Joyita Formation. On the west side of the Rio Grande, for example at Kelly Canyon (Figs. 1 and 4), the La Joyita Formation is often composed of thick alluvial-fan deposits. The surface has been dated to ca. 610 ka using ^{10}Be accumulation in quartzite boulders on a surface remnant near the Sierra Ladrones (Ramírez-Torres, 2017).

These characteristics are consistent with the Tio Bartolo being formed through several hundred thousand years of slow incision by the Rio Grande, allowing denudation of the upland piedmont to keep pace with base-level lowering. In localities with abundant sediment supply, constructional surfaces were created, but it appears that over most of the basin the dominant process was slow pedimentation, with the fill terraces being the result of a pulse of aggradation at the end of the largely

TABLE 1. Ages, height above the Rio Grande, and carbonate stage development of terraces near Socorro. All ages are from Sion et al. (2020) except for the Tio Bartolo, which is from Ramírez-Torres (2017). Terrace heights are from fig. 8B (Socorro area) in Sion et al. (2020), which is the same as our Figure 3.

Surface/fill unit	Age (ka)	Method	Height (m)	Carbonate Stage*
Las Cañas/Sierra Ladrones	820–780	^{40}Ar/^{39}Ar, paleomagnetism	100	IV
Tio Bartolo/La Joyita	ca. 610	^{10}Be surface exposure	80	III+
V de la Parida/Bowling Green	ca. 135	^{36}Cl depth profile	40	III
Loma Parda/Matanza	70–64	^{36}Cl profile, ^{40}Ar/^{39}Ar	30	II+ to III
Cañada Mariana/Jaral Largo	29–27	^{36}Cl profile	14	II
Chamizal/Polvadera	ca. 3	Radiocarbon	5	trace

*Machette (1985)

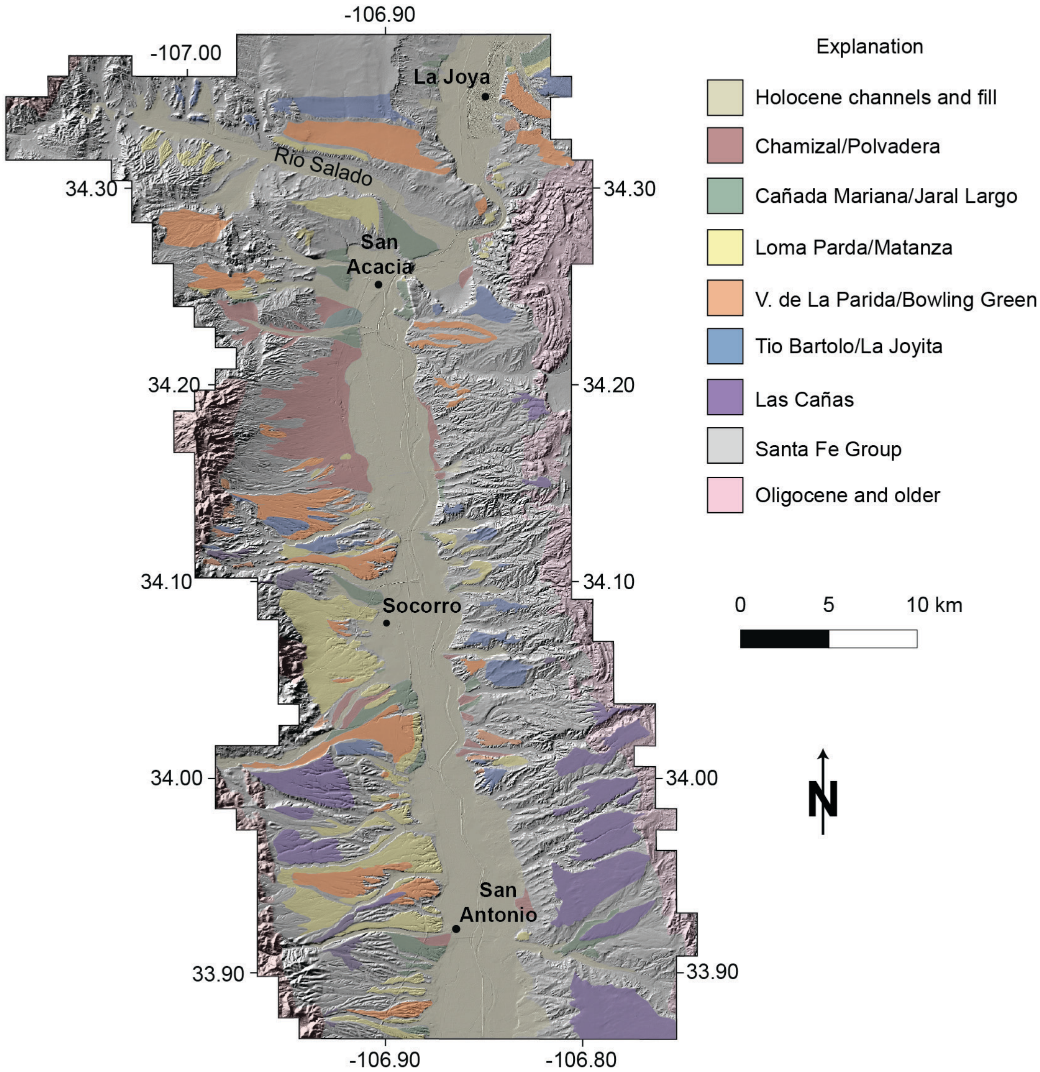

FIGURE 2. Generalized geomorphic surface map, compiled in large part from previous studies. Mapping on this figure for the west side of the Rio Grande was compiled from Sion et al. (2020), Machette (1978a), Chamberlin (1999), Chamberlin et al. (2001, 2002), and Chamberlin and Cikoski (2010). Mapping on the east side of the Rio Grande was largely from this study, Cather (2002), and de Moor et al. (2005). In some cases, we have modified previously mapped units based on our observations. In areas characterized by common small-scale variability, we have generalized unit boundaries. Figure adapted from Sion et al. (2020).

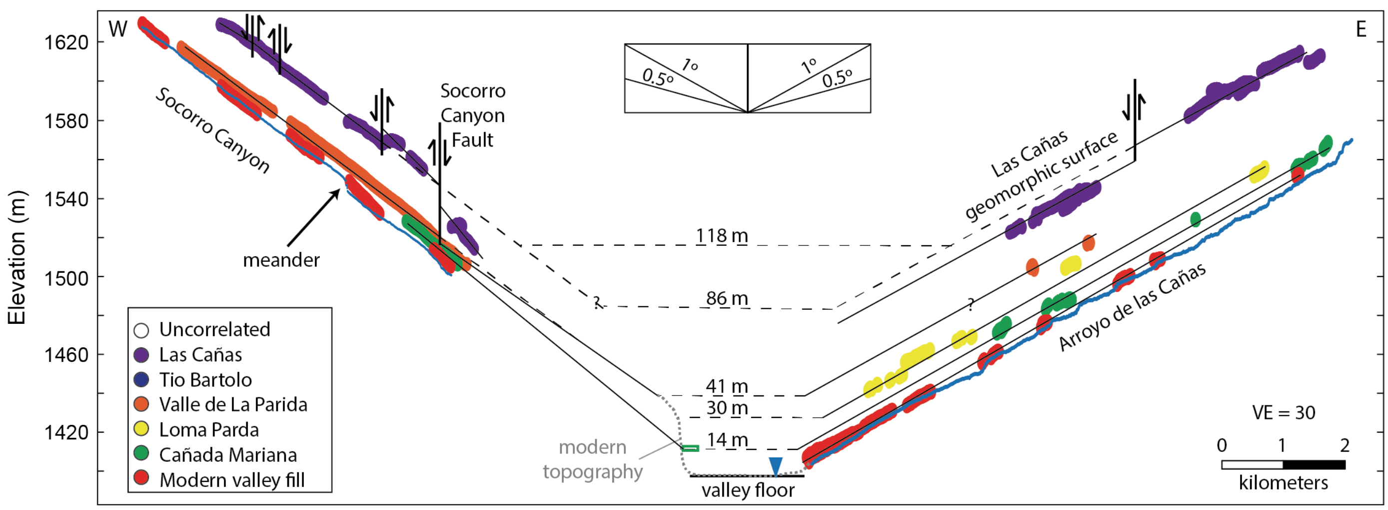

FIGURE 3. East-west profile transverse to the Rio Grande at Socorro approximately from Socorro Canyon on the west to Arroyo de las Cañas on the east. The location of the profile is shown in Figure 1. Dashed horizontal lines show projected heights above the Rio Grande Valley. Modern topography shown in gray dotted lines to indicate modern valley margins. Modified from Sion et al. (2020).

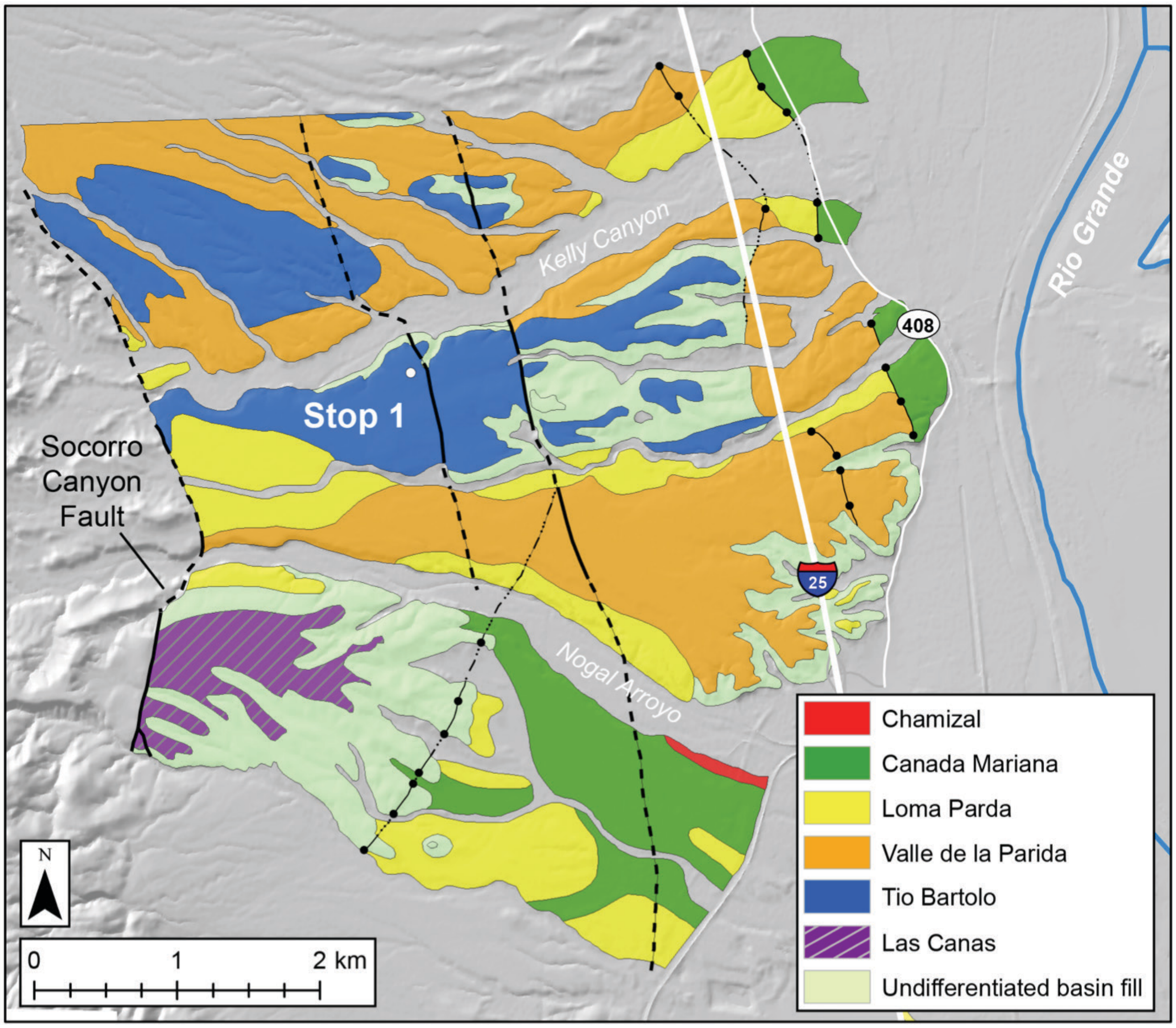

FIGURE 4. Terrace surface map in the vicinity of Stop 1. The heavy solid black lines represent fault traces (certain), heavy dashed black lines represent inferred or buried fault traces, thin black lines with dots represent facies boundaries (certain), and thin dashed black lines with dots represent inferred or buried facies boundaries. Mapping based on Chamberlin (1999) and Chamberlin et al. (2001).

erosional period. The timing of this pulse, at ca. 610 ka, is during the Marine Isotope Stage 15 (MIS 15) interglaciation that immediately followed MIS 16, one of the three globally most intense glaciations of the entire Pleistocene (Lisiecki and Raymo, 2005). High fill terraces dating to the same time interval are found widely across the western United States, including upstream and downstream along the Rio Grande (Dethier, 2001). The timing of the Tio Bartolo aggradation thus appears to be climatically controlled. Achieving maximum aggradation during an interglacial period is consistent with the model of Hawley and Kottlowski (1969) and Hawley et al. (1976), which theorized fluvial incision during glacial stades with high discharge and low local sediment supply under a well-vegetated landscape, and fluvial aggradation during interglacials with reduced discharge and high local sediment supply from a devegetated landscape.

The next surface, the Valle de la Parida, and its associated fill unit, the Bowling Green Formation, is found about 40 m above the modern Rio Grande. It has been dated to ca. 135 ka by the ^{36}Cl-profile method. Similar to the Tio Bartolo, it includes both large areas of pedimentation high on the piedmont slopes and extensive fill terraces, but the area of pediments is less than the Tio Bartolo and the area of fill is greater. This suggests that the rate of uniform denudation had difficulty keeping pace with base-level lowering due to Rio Grande incision. The timing is at the termination of MIS 6, another large global glaciation. Most of the glaciations intervening between MIS 16 and MIS 6 were significantly smaller than the ones that produced the Tio Bartolo and the Valle de la Parida (Lisiecki and Raymo, 2005).

The surfaces below the Valle de la Parida, with corresponding fill units, heights above the current Rio Grande, and ages are as follows: Loma Parda/Matanza Formation at 30 m and ca. 70 ka, Cañada Mariana/Jaral Largo Formation at 14 m and 29–27 ka, and the Chamizal/Polvadera Formation at ~5 m and ~3 ka. Unlike the older surfaces, these consist almost entirely of fill terraces, and they are largely restricted to the interior valley of the Rio Grande and its tributaries.

Most of the classic studies on the Rio Grande terraces, such as those of Kirk Bryan, attributed the formation of distinct terrace levels to changes in the sediment-carrying capacity of the river, but were exceedingly vague regarding the causes of these changes. Hawley and Kottlowski (1969) addressed this issue by proposing that episodes of terrace formation and incision were controlled by global glacial/interglacial cycles, as originally put forward by Kottlowski (1958). However, at least in the Socorro Basin, the terrace chronology has not been sufficiently precise to test this hypothesis. The terrace chronology of Sion et al. (2020), reviewed here, offers the opportunity to perform this test.

Hawley and Kottlowski (1969) proposed that the glacial/interglacial fluvial geomorphology model of Schumm (1965) applied to the Rio Grande. That model specified the following fluvial responses to portions of the glacial cycle: the transition from interglacial into glacial and the early glacial leads to incision, the late glacial and transition to interglacial leads to aggradation, and interglacials are periods of semistability. In general, it is the termination of episodes of aggradation that will be recorded by surface-exposure dating methods. This may or may not correspond with the beginning of the next major incision episode, which is expected at the interglacial/glacial boundary. The Holocene provides a good example of this. Hawley and Kottlowski (1969) have detailed the alluvial history of the Rio Grande Valley near Las Cruces. Early in the most recent glacial cycle the valley was incised about 25 m. The river then relatively rapidly aggraded at the beginning of the glacial/interglacial transition, to near-modern elevations by ~10 ka. This surface was then mildly incised and refilled to its maximal level shortly after 3 ka. Our current interglacial is approaching the typical length of those since the middle Pleistocene, 10 ky (Lisiecki and Raymo, 2005), and were a glaciation and fluvial incision (per the Hawley model) to be initiated within the next few thousand years, the age of the stranded terrace would be substantially younger than the 14 ka glacial/interglacial transition, but somewhat older than the incision event (depending on the complex late Holocene terrace pattern characterizing the modern floodplain; e.g., Pearce and Kelson, 2003). The "stability" invoked by Schumm (1965) is thus relative. Minor incision during an interglacial would yield a terrace age relatively close to the glacial/interglacial transition. Minor aggradation would yield a terrace age closer to the next interglacial/glacial transition.

Viewed in this perspective, the cycles of incision and aggradation in the Socorro Basin, at least since MIS 6, do seem to be modulated by glacial cycles. The 135 ka age of the Valle de la Parida surface corresponds to the MIS 6/5 glacial/interglacial transition, which is expected to be an aggradational event. This surface was presumably incised at the MIS 5c/5b boundary (start of significant glaciation) and aggraded at the 5b/5a boundary, with continued minor aggradation through 5a. The 70 ka age of the Loma Parda surface records the termination of this slow aggradation and the beginning of incision at the start of a major glacial episode. The subsequent terrace, the Cañada Mariana, dates to 29 ka, at the end of the mild interglacial MIS 3, indicating minor aggradation during this interglacial before the beginning of MIS 2. Radiocarbon data indicate that the valley refilled at the MIS 2/1 glacial/interglacial transition, but continued to slowly aggrade throughout most of the Holocene (Sion et al., 2020). Thus, these timings are consistent with the hypothesis of Hawley and Kottlowski (1969), if the model includes a small degree of aggradation or incision during interglacial intervals.

Erosion has accelerated since the formation of the Valle de la Parida surface. Between 800 ka and 600 ka the incision rate was 60 m/my, between 600 ka and 135 ka it was 80 m/my, and following 135 ka it has averaged 300 m/my. A much larger number of data from the wider region compiled by Dethier (2001) shows the same pattern. The shorter time intervals and faster incision rates since MIS 6 have not allowed widespread pedimentation, so the most recent terraces are all fill units occupying accommodation space created close to the Rio Grande by its incision.

The reason that the cycles of erosion and incision since ~135 ka (MIS 6) have been so much more pronounced than those prior to this time, and that net incision rates have increased, are not clear. Dethier (2001) observed a very similar pattern across the western U.S. of enhanced erosion rates since the beginning of MIS 6, which he explained as follows: "The trend toward increasing incision rates in the late Pleistocene suggests that some aspect of climate, locally including drainage integration, altered the balance of stream capacity and local sediment budgets."

Kelly Canyon Terraces

Kelly Canyon provides an excellent overview of the Rio Grande Valley terraces (Fig. 4). Field Trip Stop 1, Day 1, is on the south side of the canyon, about 2 km east of the Socorro Canyon fault, the rift-bounding fault on the west side, opposite a gap between the Lemitar Mountains and the Socorro Mountains. Nogal Arroyo flows through this gap, draining much of the La Jencia Basin and the eastern flank of the Magdalena Mountains, 25 km to the west. During periods in the past before the Rio Grande had incised, flow from this drainage deposited a large alluvial fan (hereafter Nogal fan) that graded to the level of the Rio Grande at that time. In the areas both north and south of the Nogal fan, sediment-poor runoff from the erosionally resistant Socorro Mountain and Lemitar Range has stripped away most of the alluvial fill older than the Loma Parda surface/Matanza Formation (Sion et al., 2020). Focused runoff from Nogal Arroyo, however, eroded a low geomorphic surface south of the alluvial fan complex and left the latter standing high—preserving the ancient alluvial surfaces and fills. These have been mapped locally by Chamberlin (1999) and Chamberlin et al. (2001), and Figure 4 is based on that mapping. We describe the surfaces using the terminology of Sion et al. (2020) with Chamberlin's designations in parentheses.

Stop 1 is on the Tio Bartolo surface (Qvo1). To the southwest, about 2 km distant, the high, relatively linear feature defining the south edge of Nogal Arroyo is the Las Cañas surface (Qlc), which has been preserved on the hanging wall of the Socorro Canyon fault (Fig. 4). A small portion of the Las Cañas surface is also preserved on the footwall of the Socorro Canyon fault, and the surface is offset 25 m where it crosses the fault, indicating an average vertical displacement rate of about 3 cm/ka over the past 800 ka.

The Tio Bartolo surface (Qvo1) is preserved along the ridgetops on both sides of Kelly Canyon and is about 20 m lower in elevation than the corresponding Las Cañas surface. At Stop 1, there is a good exposure of the soil at the top of the La Joyita Formation. These are typically characterized by carbonate-stage morphology III+ to IV (Sion et al., 2021), using the classification of Machette (1985). The Tio Bartolo forms the high, smooth surface on the otherwise eroded topography about 1.4 km to the northwest. Another, lower surface can be discerned on the same line of sight, directly above the floor of Kelly Canyon. This is the Valle de la Parida surface (Qvo2). It covers the largest proportion of the Nogal Arroyo fan complex and forms the longest stretch of relatively flat land along the route of Interstate 25 over the fan. The surface lies about 20 m below the Tio Bartolo.

Looking slightly north of east, down Kelly Canyon, one can see a low terrace on the north side of the canyon, just this side of Interstate 25. This is the Loma Parda surface (Qvo3). At Kelly Canyon, the Loma Parda surface is only about 8 m above the modern arroyo channel, whereas it is commonly found about 25 m above modern grade elsewhere in the Socorro Basin, and the Valle de la Parida surface is about 15 m above the channel rather than the usual 40 m. In contrast, the relative heights of these surfaces above Nogal Arroyo, a short distance to the south, is close to the typical heights. The anomalous heights over Kelly Canyon may be partly due to a large sediment supply from erodible Popotosa Formation playa deposits in the headwaters of Kelly Canyon. Additionally, just south of the point where the Kelly Canyon drainage joins the Rio Grande, the paleo-fan of Nogal Arroyo and a modern fan from Arroyo de la Parida on the east side of the river constrict the Rio Grande Valley. This may retard sediment transport through the constriction and result in accumulation of sediment on the upstream side. This hypothesis is supported by an elevation profile down the Rio Grande, which shows a nearly flat gradient above the constriction and a distinct steepening through it. Neither the Cañada Mariana (Qvo4) nor the Chamizal (Qvo5) surfaces are found in Kelly Canyon, and this is probably related to the high local base level here. These terraces may have formed and subsequently been buried beneath the channel alluvium.

TECTONIC IMPLICATIONS

The Rio Grande rift continues to be a tectonically active province. As described above, normal faulting at the base of the western bounding ranges has produced about 25 m of downward displacement of the west side of the valley since the early Pleistocene. The Socorro Basin is bounded on the north by the San Acacia accommodation zone, which is a structural high (de Moor et al., 2005; Grauch and Connell, 2013). Standard geomorphic methods give little evidence of active faulting there, but it is possible that there are other strain features that have not been evaluated. Finally, the northern Socorro Basin is underlain at 19 km depth by the Socorro Magma Body, which is currently bulging up the Earth's surface at rates up to ~2.5 mm/yr, with its center close to the Rio Grande (Fialko and Simons, 2001; Reilinger and Oliver, 1976). If tectonic deformation has been ongoing or episodic over the past ~800 ka, then it may be recorded in deflections of terrace profiles.

Previous Studies

Ouchi (1983) showed that the bed of the modern Rio Grande in the vicinity of the Rio Salado confluence "bulges" 6 to 8 m higher than would be expected based on the relatively linear gradient observed in the region, and he claimed that the Loma Parda terrace between the Rio Puerco and Lemitar exhibited a corresponding bulge amounting to about 37 m (his figure 2-100.6b). He attributed both deviations to current and prehistoric inflation of the Socorro Magma Body. However, Love et al. (2009) traced out terraces from well north to well south of the Rio Salado confluence and did not find evidence for significant vertical deflections. Finnegan and Pritchard (2009) utilized what they claimed was the Llano de Manzano surface in the southern Albuquerque Basin as a marker and did not detect vertical deflection. They also modeled the sediment balance of this stretch of the Rio Grande and concluded that the bulge in the Rio Grande bed was due to sediment inputs from the Rios Puerco and Salado, rather than magma inflation. One limitation of these previous studies is that the maximum uplift rate over the Socorro Magma Body along the river is approximately coincident with the confluence with the Rio Salado within the San Acacia accommodation zone, at a distinct narrowing of the Rio Grande Valley, and here terraces higher than the Loma Parda have been removed by erosion. In this paper we will revisit this issue with a broader database.

Sion et al. (2016) described the terraces of the lower Rio Salado. They documented that the Cañada Mariana surface is distinctly bulged upward relative to the modern channel (see Sion et al., 2020, Fig. 8) by about 7 m. The pattern of arching is similar to that of the modern uplift over the Socorro Magma Body, and they attributed it to a previous inflation event. Based on updated terrace ages from Sion et al. (2020), the arching would have occurred between about 3 ka and 30 ka.

Reevaluation of Longitudinal Rio Grande Terrace Profile

Figure 5 shows a longitudinal profile of terrace heights down the Rio Grande from Albuquerque to south of Mesa del Contadero. The figure combines data from Finnegan and Pritchard (2009), Love et al. (2009), and Sion et al. (2020) with new data for additional surfaces included in this study. The new data were acquired to help address the lack of surfaces older than the Loma Parda close to the Rio Grande in the 'narrows' area between the confluences with the Rios Salado and Puerco. These are essentially reconnaissance data. The procedure was that portions of geomorphic surfaces distal from the river were identified and cross sections constructed. These cross sections allow projection of the surfaces to the eastern edge of the current river valley to obtain heights above the modern river. The eastern edge was used because the maps of de Moor et al. (2005) and Rinehart et al. (2014) show axial ancestral Rio Grande gravels at the level of the highest fluvial deposits on the east side of the basin, indicating that the river then occupied an easterly course. This procedure entailed identifying and profiling surfaces that were not included in the systematic characterizations of Sion (2018) and Sion et al. (2020). The heights above the Rio Grande from this method are shown in Figure 5 as solid lines with triangular data points. A file with the profiled surfaces delineated is included in Appendix 1.

Figure 5 also includes data from Sion (2018) and Sion et al. (2020), indicated as filled circles. These were from carefully studied terrace remnants. As described above, the sTable terrace treads (i.e., avoiding terrace edges) were mapped and then elevation data was extracted from high-density point clouds (5 m spacing) within the mapped treads, using a 5 m resolution NEXTMap digital elevation model purchased from Intermap Technologies, Inc. Those points were projected onto planes perpendicular to the river, and then along these planes

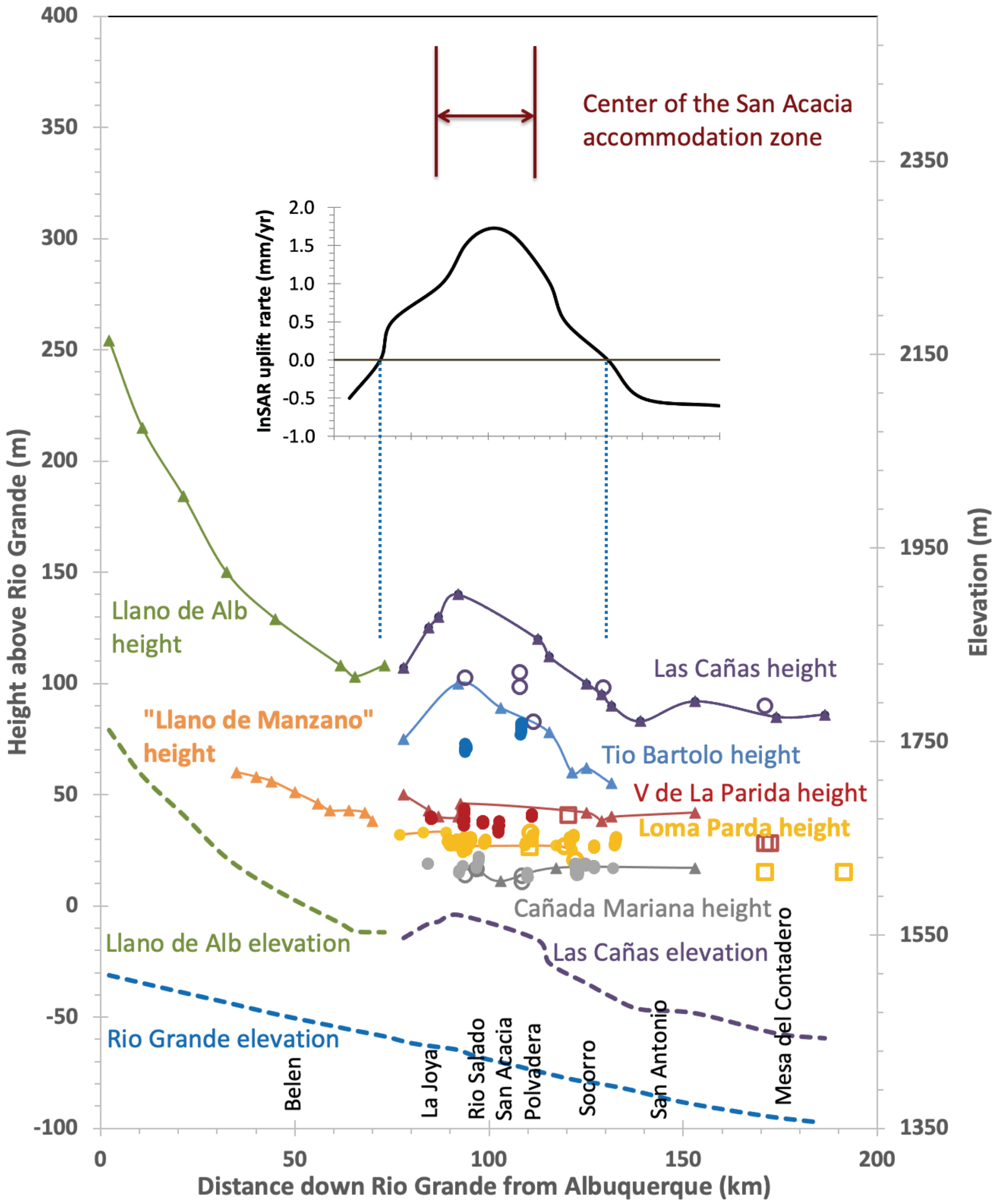

FIGURE 5. Longitudinal terrace profile along the Rio Grande from Albuquerque (I-40 bridge) to south of Mesa del Contadero, showing height above the Rio Grande and, for selected features, elevation. Elevation profiles are dashed. Dashed lines and filled triangles connected by solid lines are from this study, open squares are previously unpublished data from B. Sion using methods similar to Sion et al. (2020), filled circles without lines are from Sion et al. (2020), open circles are from Love et al. (2009), Llano de Manzano data (orange filled triangles connected by solid line) are from Finnegan and Pritchard (2009), and uplift-rate data are from Fialko and Simons (2001).

projected to the eastern edge of the current inner valley, and the projected heights were averaged using a moving window algorithm. Finally, the stream elevations were differenced from those eastern-edge points to obtain the relative terrace heights.

The open circles on Figure 5 are data points from Love et al. (2009). These were generated using “standard geological investigations and mapping.” The Llano de Manzano data points are from Finnegan and Pritchard (2009). They stated, “For the northern ~2/3 of the study area, we define the Llano de Manzano based on Connell et al.’s (2007) map. South of Connell et al.’s (2007) map, we extend the location of the Llano de Manzano via a combination of Google Earth imagery and SRTM 1 arc-sec digital elevation data (Fig. 1A). We trace the elevation of the Llano de Manzano along the inside edge of the terrace, thereby obtaining terrace elevations as close to the modern Rio Grande as possible.”

The open squares are data collected by B. Sion using methods similar to Sion et al. (2020), but not previously published. The data points for the Loma Parda terrace at 171 km and 191 km are of particular interest, since they are lower in height than Loma Parda data to the north. The point at 191 m is well constrained in both height and age, because the surface there is covered by the Jornada del Muerto basalt flow, which is dated by $^{40}Ar/^{39}Ar$ to 78.1±3.2 ka (Sion et al., 2020). There is no evidence of alluvium being deposited on the top of the flow. The alluvial surface beneath the basalt at that location is 6 m above the current elevation of the Rio Grande. However, there was quite significant aggradation in this area in the early 20th century, due both to human-induced flow and sediment changes in the Rio Grande and to the closure of Elephant Butte Dam, downstream, in 1915. The amount of deposition since 1915 can be quantified using repeat hydrographic surveys conducted by the Bureau of Reclamation (Ferrari, 2008), and that between the late 19th century and 1915 using records kept by the U.S. Soil Conservation Service and published by Happ (1948). These show 1.2 m aggradation prior to 1915 and 8 m subsequent to it, yielding 9 m of infill since the late 19th century. Adding to this, the 6 m height of the surface beneath the basalt flow yields a height of the Loma Parda terrace of 15 m above the historic Rio Grande.

The data from three essentially independent studies generally show quite good agreement with regard to terrace height, lending confidence to the reconstructed terrace positions. A few exceptions are worthy of note. One is the solid circle point for the Tio Bartolo terrace (medium blue) at 94 km, which is much lower than the corresponding solid blue line. Sion (2018) noted that this locality had been down-faulted. Another is the open Las Cañas circles (purple) at 94 km and 108 km, which are also below the corresponding purple solid line. These were obtained from the heights of the highest Rio Grande gravels close to the river in the ‘narrows’ section, but constructional landforms were not preserved there, and thus these may be erosional surfaces and represent minimum values for the height of the Las Cañas surface.

Based on an interpretation of Connell et al. (2007), Finnegan and Pritchard (2009) estimated the age for the Llano de Manzano surface to be 1.2 to 0.6 Ma. However, we note that at least the southern part of the area they indicate as Llano de Manzano is excluded from the original map of that surface in Machette (1978b). In Figure 5, based on height above the Rio Grande, their Llano de Manzano would appear to correlate with our Loma Parda surface (~70 ka), although correlation with the Valle de la Parida surface (~135 ka) is not out of the question. These correlations are quite inconsistent with the 1.2–0.6 Ma age estimate of Finnegan and Pritchard (2009). See below for a more detailed discussion of the age and significance of the Llano de Manzano. In any case, as noted by Finnegan and Prichard (2009), the profile they measured does not provide any evidence for vertical deflections in that portion of the profile.

One interesting feature is that the profiles for both the Cañada Mariana and Valle de la Parida surfaces show a distinct low at 102 km. The intervening Loma Parda surface lacks data at that point, thus it is unclear whether it shares this feature. This low point is just below the confluence of the Rio Grande with the Rio Salado, which is the high point of the river-profile bulge identified by Ouchi (1983). Finnegan and Prichard (2009) attributed this bulge to unusual sediment deposition due to high-sediment-load tributaries joining with the Rio Grande here. The magnitude of the low in the terrace profiles is approximately the same as the river-profile high, ~8 m. It seems likely therefore that these apparent drops in the terrace heights result from subtracting anomalously high elevations of the modern Rio Grande within the sediment ‘bulge’ from a fairly linear increase in terrace elevation. This argues against a tectonic origin for the river-profile bulge, as Ouchi proposed, since that would have lifted the riverbed and the terraces equally, resulting in no terrace anomaly.

The most secure tectonic inference is that none of the data presented support the Loma Parda profile reconstruction of Ouchi (1983), which showed ~37 m of upward deflection centered at 95 km distance on Figure 5. All three sources of data for the Loma Parda in Figure 5 indicate an essentially flat profile height across this reach. This is also consistent with the conclusions of Finnegan and Pritchard (2009).

The most striking feature of Figure 5 is the strong upward deflections of both the Tio Bartolo and Las Cañas profiles from this study, centered at about 100 km distance. The magnitude of the deflection, measured as the difference in terrace height between San Acacia and San Antonio, is about 50 m. As described above, these apparent deflections are not matched by obvious deflections in the lower terraces. The correspondence between the spatial pattern of the Las Cañas and Tio Bartolo upward deflections and the distribution of modern upward velocity from the InSAR measurements of Fialko and Simons (2001) is strong. This pattern would be consistent with an episode of prolonged magma-body injection by a precursor Socorro Magma Body between the formation of the Tio Bartolo and the Valle de la Parida terraces (i.e., between ca. 800 ka and ca. 130 ka).

Another feature of possible tectonic significance is the upward trend in terrace heights moving northward from the southern end of our profile. Near Mesa del Contadero, the height of the Loma Parda terrace is about 15 m (this is the locality where it is overlain by the Jornada del Muerto basalt flow), whereas near the Rio Salado it is as high as 28 m. Over the same stretch, the Valle de la Parida terrace rises from about 28 m to about 40 m. Correspondingly, the frequency with which the Cañada Mariana surface is observed south of San Antonio is significantly less than between there and La Joya. The portion of the transect above the current magma body appears to contain terraces that are systematically higher than those beyond its boundaries. Although there is no pronounced bulge where current geodetically determined upward deflection is largest, this pattern is consistent with the general 'pancake' shape of a mid-crustal sill. If the height difference can be attributed to magmatic inflation, it would presumably have to be between Loma Parda time (~70 ka) and the present. This timing is compatible with the 30–3 ka uplift postulated by Sion et al. (2016) for the bulge in the Rio Salado profile, although alternative explanations for this bulge are possible.

Is the Llano de Manzano a 'Mythical' surface?

The Llano de Manzano should presumably play an important role in any attempt to evaluate contemporary vertical tectonic movement in the vicinity of the San Acacia accommodation zone/Socorro Magma Body. Its significance has been succinctly stated by Finnegan and Pritchard (2009): "The Llano de Manzano surface (Fig. 1A) comprises west-sloping fan deposits that over-ride 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." In contrast, Love et al. (2016) stated that the components of the Llano de Manzano have multiple ages and refer to it as a "mythical" surface. Given its significance for this issue, and its importance in the geomorphological literature on the southern Albuquerque Basin, it is worthwhile to reevaluate this putative geomorphic surface.

The Llano de Manzano was named by Bachman and Machette (1977), who introduced the term without explanation and cited Machette (1978b) as the source. Machette (1978b) contains a map that shows the Llano de Manzano to consist of the Rio Grande Valley east of the river, extending between the foothills of the Manzano Mountains and the bluffs above the modern river valley, but offered no explanation of its significance (i.e., age, formation processes, identifying characteristics). Machette (1978b) cited Bachman and Machette (1977) as the explanation for the term.

In summary, although subsequent investigators (Connell et al., 2000, 2007) have attempted to informally impose a meaning on the term, it has never been satisfactorily defined. Furthermore, as noted by several publications (Connell et al., 2000, 2001; Love et al., 2016; Rinehart et al., 2014), the 'surface' is clearly highly diachronous. Olig et al. (2011) described it as "an early to late Pleistocene alluvial surface." All maps purporting to show the boundaries of the surface differ significantly, in some cases being mutually exclusive (Connell et al., 2007; Finnegan and Pritchard, 2009; Machette, 1978b; Olig et al., 2011).

Wysocki et al. (2012) defined geomorphic surfaces as follows: "Geomorphic surface is a definable land surface area that forms during a given time under a common set of erosional and depositional processes. A geomorphic surface may include multiple landforms, but it is a mappable spatial area based upon geomorphic techniques and field observations that has specific and identifiable borders (Ruhe, 1975)." The Llano de Manzano clearly fails on all counts to meet the criteria for a valid geomorphic surface.

Under the current circumstances, continuation of the term serves no useful purpose and continuing to employ it only sows confusion. We suggest three possible courses of action, in decreasing order of desirability: (1) Formally publish a description of the surface, including its significance in the geomorphic history of the basin, a reasonably narrow age range, features of the surface that can be used to identify it in the field, and a corresponding map of its extent. The very brief statement in Connell et al. (2007) could provide a starting point for such a definition. (2) Explicitly acknowledge that it is diachronous and refer to it as the 'Llano de Manzano surface complex' (Connell et al., 2001). Although helping to avoid confusion, the new term would have little practical utility. (3) Drop 'Llano de Manzano surface' entirely and retain 'Llano de Manzano' as simply a geographical designation for the area delineated on the original map of Machette (1978b).

Discussion

Data presented here suggest two possible types of surface deformation related to past magmatic inflation. The first would require a large amount of magmatic injection that produced a pattern of doming similar to the contemporary injection event, between ca. 800 ka and 130 ka. The second would have produced a much smaller amount of surface uplift (~10 m) in a pancake-like geometry rather than a dome, between 70 ka and the present.

While the evidence we have presented is suggestive, we caution that it currently should not be viewed as more than that. Additional data are needed to make a solid case for either scenario. With regard to the 'doming' scenario, the additional high surfaces that were profiled to produce the reconstructions of the Tio Bartolo and Las Cañas surfaces have not been investigated in any detail. Field investigations, soil descriptions, and if possible, direct dating are needed to establish the origins and ages of these surfaces and to provide secure correlation with the established terrace chronology. An additional consideration is that the large distance of these surfaces from the Rio Grande means that the heights based on the surface projections could be in error if the position of the Rio Grande then was farther west than it is today.

The data are more secure for the 'pancake' scenario, with the correlations southward to Mesa del Contadero supported by the fact that the 78.1±3.2 ka Jornada basalt overlies a fill terrace whose surface is correlated to the Loma Parda geomorphic surface. Assuming these correlations are correct, the interpretation of the data is open to question. While the difference in terrace heights over and outside of the current magma body seem clear, they are not terribly large. Spatial patterns in sediment supply and transport, for example, could provide an alternative explanation. A thorough examination and testing of the alternatives is needed. Geodynamic modeling of the long-term effects of magma injection (e.g., van Wijk et al., 2016) and how it might interact with fluvial processes would be very desirable.

CONCLUSIONS

The geologic and geomorphic features of the Rio Grande Valley have been studied for well over 100 years, but the area north and south of Socorro has remained something of a blank spot on the geomorphic map. A variety of investigations in the past decade have enabled us to systematically delineate the various geomorphic surfaces and their associated stratigraphic units, to adequately describe them, and to assign to them a chronology.

These results have both confirmed and clarified the speculations of earlier investigators. They have confirmed Kirk Bryan's perspective that decreasing terrace height is associated with decreasing surface age and that large parts of the terrace system were formed by erosion of the basin fill. They have also supported and provided additional Rio Grande Valley examples of John Hawley's premise that global glacial/interglacial cycles have largely driven both incision events and subsequent aggradation and terrace formation along the Rio Grande. With newly dated geomorphic surfaces, we can now identify specific climate events that played a role in the formation of specific terraces.

A combination of new work reported here with data from previous studies suggests that the oldest surfaces, the Las Cañas and Tio Bartolo, are deflected upward by as much as 50 m over the current center of uplift due to injection of the Socorro Magma Body, whereas younger terraces are not. But we also have found suggestions that the younger terraces are systematically about 10 m higher over the current magma body than south of its margins. Both of these observations might be explained by previous emplacement of crustal sills in the vicinity of the current magma body. But we caution that such interpretations are speculative and that additional evidence is needed to ensure that the data are being correctly interpreted before these observations can be accepted as more than suggestive of such events. It is our hope that this paper will help to stimulate further study.

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Appendices can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2022009

Loading chute for cattle 13 miles southeast of the town of San Antonio. Photo by Scott Elrick.