TERRACE STRATIGRAPHY AND SOIL CHRONOSEQUENCE OF CAÑADA ALAMOSA, SIERRA AND SOCORRO COUNTIES, NEW MEXICO

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ABSTRACT—A total of six major terraces of probable climatic origin incised into the Palomas Formation of the Santa Fe Group make up the terrace stratigraphic framework for Cañada Alamosa. The tread heights of these terraces extend from 9-16 m to 76-83 m above the modern floodplain and thicknesses range from 4.7 m to 18 m or more. Quaternary tectonism along the Cuchillo Negro fault zone has offset or warped the oldest four terraces and created two localized terraces, suggesting relative age of movement along faults from ~0.55 to ~0.32 Ma. Minor structural perturbations and/or complex response of transport/depositional systems are responsible for additional local terrace surfaces along the lower four terrace levels. A total of eleven terraces were mapped.The effects of intercanyon and intraterrace spatial soil variations somewhat diminished the effectiveness of the soil chronosequence developed in this study. Soil profile CA3 shows the maximum amount of development, more so than the oldest profile, CA1. Nevertheless, soils generally exhibit increases in pedogenic fines (silt + clay percentages increasing from 7.5 to 26.4 %) and carbonate development (stages I to III) with age. Soil Development Indices reflect this as well and correlate ($r^2 = 0.776$) with values derived from the Desert Project soils with known ages, indicating that Cañada Alamosa terraces fall within the established southern New Mexico alluvial morphostratigraphy.The data obtained in this study permit a relative age chronology to be suggested, with ages based upon the rate of incision, degree of pedogenesis, and the timing of glacial cycles recorded in the marine oxygen isotope record of the equatorial Pacific. Rio Grande downcutting into the Cuchillo surface at the top of Palomas Formation aggradation began ~0.8 Ma and has progressed some 90-100 m. Cañada Alamosa terraces Qt1-Qt6 likely formed at ~0.67-0.63, ~0.58-0.56, ~0.45-0.43, ~0.38-0.32, ~0.15-0.12 Ma, and 17 to 15 ka.

INTRODUCTION

The geographic place name "Cañada Alamosa" is used synonymously by those living in its vicinity for both the stream and the canyon the stream carved in northern Sierra and southern Socorro Counties, New Mexico. This name even appears on a highway sign above the stream crossing on Interstate 25. On many maps, however, including U.S. Geological Survey topographic maps, these features are labeled as "Alamosa Creek" and "Monticello Canyon." Following McLemore (2010), the local name is used in this study.

Cañada Alamosa (Fig. 1) is a large tributary of the Rio Grande, whose mouth is now inundated near the top of Elephant Butte Reservoir, some 25 km upstream of Truth or Consequences, New Mexico. The stream is divided into three primary reaches. The lower reach occupies and drains much of the Engle basin, an upper Oligocene half-graben (Mack et al., 1984; Seager et al., 1984), and is cut into the Plio-Pleistocene Palomas Formation of the Santa Fe Group (~5-0.8 Ma) (Mack et al., 1993, 2006). A middle mountainous reach flows through the Monticello graben of early Miocene age (McLemore, 2010) from the Monticello Box down to the town of Monticello. The stream is sandwiched between Plio-Pleistocene Santa Fe Group sediments and Tertiary (42-24 Ma) andesites and ignimbrites of the Mogollon-Datil volcanic field (Chapin et al., 2004), commonly flowing on bedrock in this reach. An upper headwaters reach drains the Alamosa Creek basin (upstream of Monticello Box), where Santa Fe Group sediments filling the northern Winston graben (or the Cuchillo Negro graben of Myers et al., 1994) of late Miocene age are also flanked

Supplemental data for this paper can be accessed at:
http://nmgs.nmt.edu/repository/index.cfm?rid=2012xxx

by Mogollon-Datil volcanics. This study focuses on the terraces developed primarily in the lower reach (0-27.2 km; Elephant Butte Reservoir to Monticello) (Fig. 2), although terrace-surface (tread) heights are traced up canyon to tie into those mapped by McLemore (2010, 2012) on the Montoya Butte 1:24,000-scale quadrangle, which contains the Monticello Box at the top of the middle reach (57 km upstream).

As summarized in McCraw and Love (2012, this guidebook), the Cuchillo geomorphic surface was formed at the termination of Palomas Formation aggradational deposition throughout the coalescing Engle and Palomas basins, around 0.8 Ma ago. Since then, Cañada Alamosa and other nearby Rio Grande tributaries have abandoned the Cuchillo surface, entrenching some 90 to 100 m into the Palomas Formation in response to Rio Grande downcutting. This has occurred in a climatically-driven, alternating fashion, oscillating between episodes of incision punctuated by periods of partial backfilling (Mack et al., 2006, 2012, this guidebook). During wetter, cooler glacial periods of higher precipitation and runoff, larger ratios of water discharge to sediment load occur, stream power exceeds resisting forces, and streams actively incise, producing abandoned aggradation surfaces or terrace treads (Bull, 1990, 1991). In contrast, during interglacial episodes with diminished, insufficient stream discharges to effectively transport bedload, subsequent partial backfilling occurs. The net result in this simple model is a stepped sequence or flight of climatic fill terraces with parallel treads formed above their basal straths which step down basinward (Lozinsky, 1986; Mack et al., 2006).

One cannot discount the role of tectonism, the other main external process of terrace formation, especially in strath development, nor that of autocyclic complex-response mechanisms
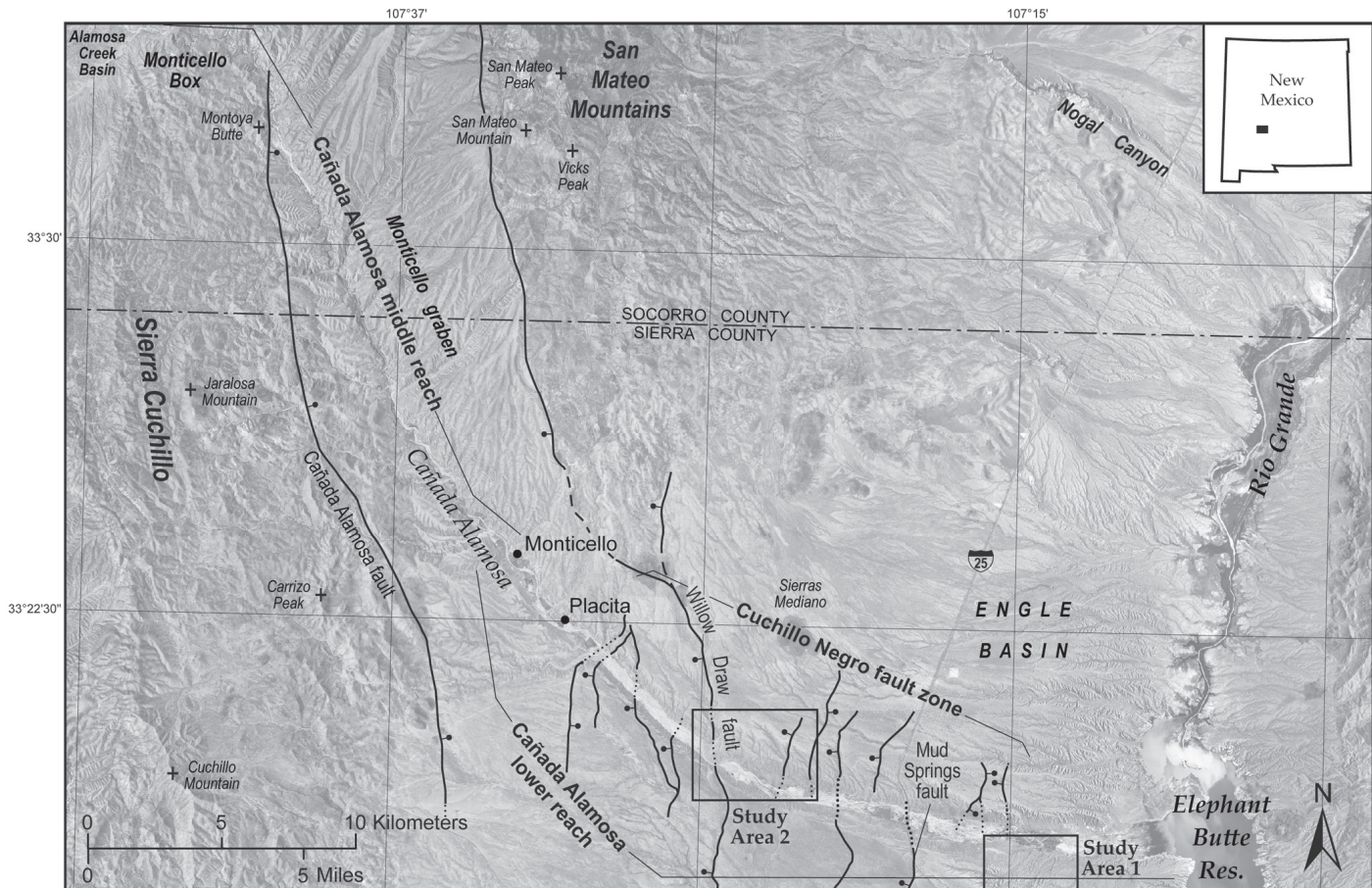
FIGURE 1. Location of Cañada Alamosa in northern Sierra and southern Socorro Counties. Only the stream's lower reach in the Engle basin and the middle reach in the Monticello graben are shown. The upper reach in the Alamosa Creek basin begins beyond the Monticello Box in the upper left. The location of terrace study areas 1 and 2 as well as the Quaternary faults most directly impacting Cañada Alamosa in the lower two reaches (particularly those of the northernmost Cuchillo Negro fault zone of Machette, 1987) are shown.

(Schumm, 1973), however. Quaternary movement along faults has been active in the Engle and Palomas basins, particularly in the middle Pleistocene, on both basin-bounding faults (Cañada Alamosa fault, Palomas fault, Hot Springs fault, Caballo fault), and intrabasin faults (Mud Springs and the numerous small faults of the Cuchillo Negro fault zone) (Machette, 1987). Many of these intrabasin faults cut directly across Cañada Alamosa, clearly complicating matters. Along the Willow Draw fault, which is the east-bounding fault of the Monticello graben before crossing Cañada Alamosa to become an intrabasin fault to the south, a total of 21 m of down-to-the-west Quaternary offset is evident. Nevertheless, other Cuchillo Negro fault scarps are commonly less than a few meters high, so the amount of change in slope for a drainage the size of Cañada Alamosa would be slight.

While flights of three to five terraces flanking Rio Grande tributaries in the Engle and Palomas basins have been mapped by several workers (Fig. 3), none have been dated. In Cañada Alamosa, Heyl et al. (1983) map four terraces on a 6.8 km reach flowing through the Priest Tank 1:24,000-scale quadrangle while McLemore (2010, 2012) describes "at least four levels of stream terraces" on the Montoya Butte 1:24,000-scale quadrangle. Both Maxwell and Oakman (1990) and Lozinsky (1986) map five terraces in the Cuchillo Negro drainage immediately south of

Cañada Alamosa, but Lozinsky, who only mapped the first 9.5 km, did not encounter the highest terrace (Qt1) of Maxwell and Oakman (1990). Farther south, Seager and Mack (1991, 2005) describe three terraces and "younger valley-fill alluvium" comprising "deposits of arroyo floors, terraces and alluvial fans" along tributaries flowing across the Caballo and Garfield 1:24,000-scale quadrangles.

Seager and Mack (1991), Lozinsky (1986), and McLemore (2010) all correlate these terraces to the sequence of Rio Grande morphostratigraphic units (terraces and geomorphic-surface bound, valley-fill and piedmont alluvial deposits) in the Las Cruces area some 100 km to the south. Hawley and Kottlowski (1969) first established approximate ages for these units and Hawley (1965) was able to recognize them as far north as the Rincon Valley, immediately below the Palomas basin. This was expanded upon with extensive soils work and ^{14}C dating by the "Desert Project" (Gile et al., 1981, 1995), establishing firm chronologic control for the lowest (youngest) two surfaces. Since the Desert Project (DP), better tephrachronology (Seager et al., 1984), magnetostratigraphy (Mack et al., 1993), and the discovery of both the Bishop (0.75 Ma) and Lava Creek B (0.64 Ma) ashes in the Jornada I unit, have allowed Mack et al. (1998, 2006) to greatly refine the chronology of Rio Grande Quaternary
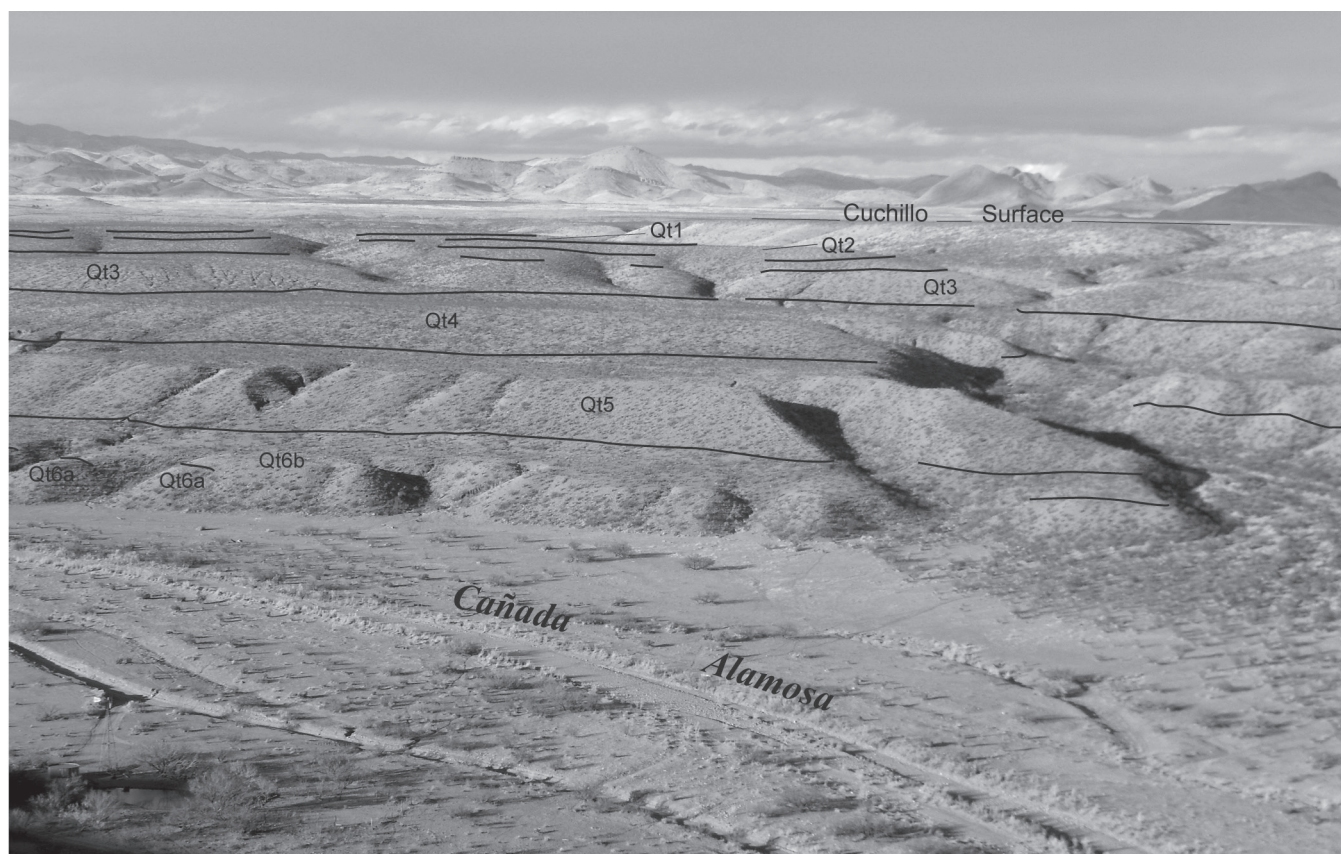
FIGURE 2. North-northeast-looking view of the six major terraces of Cañada Alamosa, located about 0.5 km west of Questa Blanca Canyon (see Fig. 8) in the lower reach.

deposits and landforms throughout the southern Rio Grande rift, in southern New Mexico.

Soils and soil chronosequences are popular tools for correlation and relative age determination of associated deposits, particularly in the American Southwest where airborne dust influx causes pedogenic carbonate accumulation over time (Gile et al., 1981; Machette, 1985). When investigating a succession of Quaternary landforms, soil chronosequences are especially effective (Birkeland, 1990). Like pedogenic silt and clay accumulating in the solum over time, soil properties predictably alter with time, reflecting their degree of pedogenesis, although their spatial variability can certainly complicate matters (Harrison et al., 1990). Harden (1982) developed the Soil Development Index (SDI) to quantify degree of pedogenic development. For any given soil, properties of soil horizons (e.g., color, consistence, texture) are described in the field and quantitatively ranked. These values are then normalized by subtracting the minimum value obtained for each property (usually derived from the parent material) and divided by the maximum value recorded for the property. The normalized SDI products are then summed for each horizon, divided by the total number of properties measured, and compiled into a Profile Development Index (PDI) by multiplying the values obtained for each horizon by their horizon thickness

and summing throughout the profile. This PDI value can then be compared to others calculated from soils developed on older or younger landforms which comprise the chronosequence. Assuming some of these landforms have some form of chronologic control, age estimates of others can be obtained using their PDI values.

The SDI was applied to the DP soils by Harden and Taylor (1983). They were testing the applicability of the SDI to soils developed in different climates. The extensive DP chronosequence dataset with its established chronology proved to be an invaluable source for SDI application to aridisols. Their DP SDI data (Harden and Taylor, 1983, appendix IV, p. 358) thus provides an excellent opportunity to evaluate our proposed correlation of Cañada Alamosa terraces with DP morphostratigraphic units.

There were, therefore, four main objectives of this present study. A) All terraces in the lower reach were mapped to establish the terrace stratigraphy of the canyon. B) Terrace soils have been characterized to develop a soil chronsequence. C) SDI values have been calculated and compared to the DP analysis of Harden and Taylor (1983) to test the overall suitability of terrace correlation. D) Finally, the suitability of the soil chronosequence for inferring relative age ranges has been evaluated and applied to the Cañada Alamosa terraces.
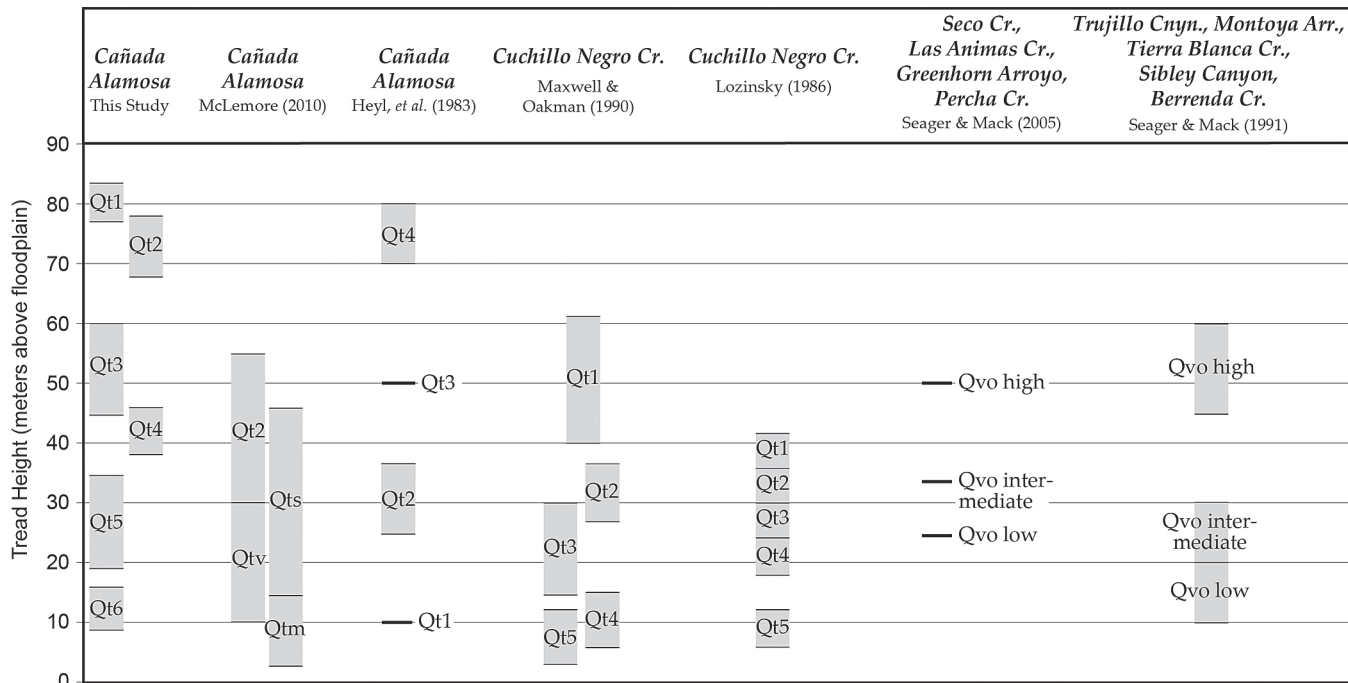
FIGURE 3. Comparison of Cañada Alamosa terrace tread elevations mapped in this study with those of McLemore (2010) in the Montoya Butte quadrangle below the Monticello Box, Heyl, et al. (1983) in the Priest Tank quadrangle, and with terrace heights of other Rio Grande tributaries to the south.

METHODS

Terraces in the lower reach of Cañada Alamosa are best preserved in two areas: on the south canyon wall from ~0.5 to 4 km upstream from Elephant Butte Reservoir, and on the north canyon wall from 12 to 22 km upstream. These areas were selected for detailed study (study areas 1 and 2, see Fig. 1). The two areas were mapped at a scale of 1:6,000 and compiled in ArcGIS v. 10.2 utilizing 2009 NAIP four band ortho imagery, stereo imagery, and terrain (DEM, hillshade) data, with a resolution of 1 meter ground sample distance rectified to a horizontal accuracy of ±5 meters. A total of 31 topographic profiles derived from DEM data extending from the floodplain up to the Cuchillo surface in the Engle basin and up to bedrock above Quaternary terraces in the Monticello graben were generated for both canyon sides (14 on the south and 17 on the north) to compare terrace tread elevations both from side to side as well as up canyon and down.

Roadcuts, gully cuts, and tributary stream cuts were utilized to examine soil profiles where possible. Five terrace soils were characterized from excavations cleaned back ~0.5 m from the original cut exposure. Two additional soil pits were excavated within 30 m of soil profiles CA3 and CA6 to capture data for the tops of these profiles since erosion of the surfaces of these gully cuts has occurred. Profiles CA1 and CA3-6 were measured and described on terraces Qt1 and Qt3-6. Soils were characterized using the profile nomenclature revised from the 1981 USDA Soil Survey Manual by Birkeland (1984), and each horizon was sampled for grain size. The soil parent material was also sampled for the SDI calculation. Attempts were made to collect parent materials directly beneath each profile and beneath the level of illuvial carbonate accumulation, although this was not possible for profiles CA 3-5. The parent material immediately beneath profile CA4 was inaccessible and had to be collected at the base of the terrace in an arroyo cut about 120 m to the west of the profile. For terraces Qt3 and Qt5, depth of carbonate precipitation exceeded terrace thicknesses.

Samples were collected and passed through a 20 mm sieve to remove cobbles and large gravel. In the laboratory, all samples were dried at 105°C and weighed. Gravels ≥2 mm were segregated and soaked, agitated, and washed to collect as much adhering fine grained sediment as possible. Samples were then dry sieved using 2 mm, 1 mm, 500 micron, 125 micron, and 63 micron sieves on a Tyler Ro-Tap shaker, wet sieved, and dried at 105°C.

TERRACE STRATIGRAPHY

A total of six major fill or fill-cut terraces formed on straths cut into the Palomas Formation were mapped (Table 1). They possess treads with parallel longitudinal profiles indicative of climatic terrace formation (Bull, 1990, 1991); these were plotted throughout the lower two reaches utilizing the topographic profiles (Fig. 4). The highest and oldest, Qt1, has a tread elevation of 76-83 m above the floodplain, inset 9-15 m below the Cuchillo surface. The elevations of the younger terraces (Qt2-Qt6) have grades above the floodplain of: 68-78 m; 45-60 m; 38-46 m; 19-34 m; and 9-16 m. Within the lower reach, terraces are located primarily on the north side of the canyon, with only small scattered remnants seen on the south side. A sizeable exception to this occurs near the mouth of the drainage (study area 1). Heyl et al. (1983) noted this preferred northern preservation and suggested either a
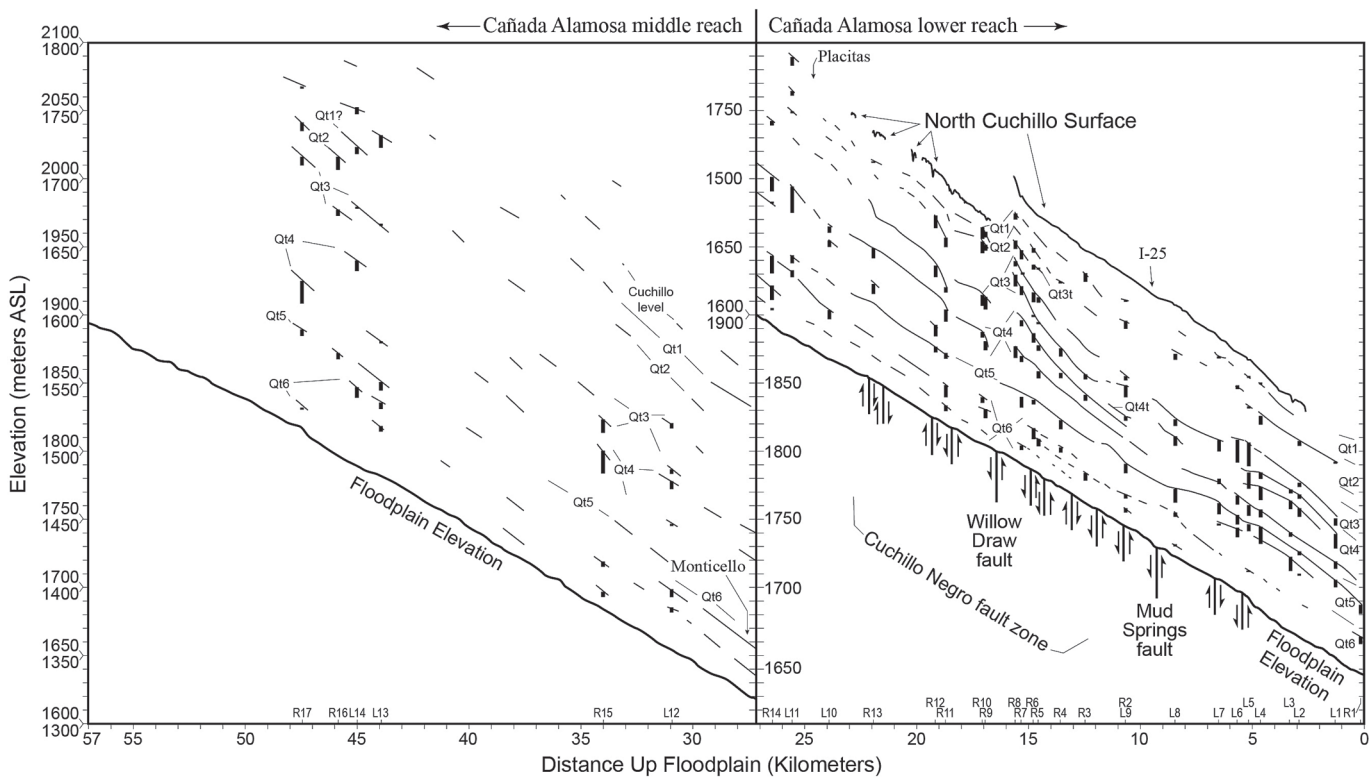
FIGURE 4. Location and distribution of Cañada Alamosa terrace treads above the floodplain for the lower and middle reaches. The profiles of the northern Cuchillo surface and the floodplain were derived from 2009 1-m NAIP DEM terrain data. The vertical boxes show ranges of tread heights measured from 31 DEM-based topographic profiles on both north canyon (right) and south canyon (left) walls. Estimated extents of treads are indicated by lines running roughly parallel to the floodplain. Tectonic-induced tread offsets and warping are evident in the older terrace treads Qt1-Qt4.

buried fault beneath the canyon axis or larger discharges of water and sediment from the northeast side, pushing Cañada Alamosa to the south.

This phenomenon of preferential north-side terrace preservation also occurs on most other Palomas Basin tributaries to the south, as Seager and Mack (1991, 2005) document. This may imply a regional tilting of the Palomas and western Engle basins to the south or southeast. Yet neither Mack and Seager (1990) or Mack and Leeder (1999) mention a southern vector to the east tilting half-graben structure of the basin.

Flexure of regional structure could likewise account for the south side terrace complex near the mouth of Cañada Alamosa, as

well as the reversal from north-side terraces along Cuchillo Negro Creek west of the Mud Springs Mountains to the predominance of south-side terraces east of this small intrabasin fault-block range (Maxwell and Oakman, 1990). These areas are located close to the uplifted structural high of the Cutter Sag (Lozinsky, 1986), located south southeast of the Engle basin and Elephant Butte Reservoir, where the eastern margin of the Rio Grande rift steps over from the Caballo fault-bounded Caballo Mountain uplift to the Hot Springs and Walnut Canyon fault-bounded uplift of the Fra Cristobal Range (Mack, 2004). If late Cenozoic epeirogenic uplift has continued in the Cutter Sag, this could account for a northern deflection of easternmost Cañada Alamosa and preservation of terraces on the south side of the drainage.

Basal strath elevations of terraces and terrace fill thicknesses were commonly difficult to ascertain due to nearly identical lithologies of both the terraces and the underlying Palomas Formation (QTp), and erosion surfaces were often covered with colluvium. QTp deposits in the area consist primarily of purplish gray to reddish brown, grain-supported, granule to cobble conglomerate, comprised of rhyolitic, andesitic, and basaltic clasts derived from the San Mateo Mountains and the Sierra Cuchillo, interbedded with pebbly sands (the volcanic-clast conglomeratic facies assemblage of Mack et al., 2012, this guidebook). They are often partially indurated and both induration and redness (at least in study area 2) increases with depth to the bottom of the canyon.

TABLE 1. Terrace Characteristics.

Terrace	Elevation above Floodplain (m)	Elevation below Cuchillo surface (m)	Thickness (m)
Qt1	76-83	9-15	18
Qt2	68-78	19-23	≥5
Qt3	45-60	49-57	≥15
Qt4	38-46	69-73	14.7
Qt5	19-34	69-73	15.8
Qt6	9-16	77-81	≥16

The base of Qt1 is exposed in the cutbank of Questa Blanca Canyon below soil profile CA1 (UTM 279194E 3691630N – coordinates listed herein are relative to the NAD1927 horizontal datum), 18 m below the terrace tread. Terrace Qt2 appears to be ≤ 5 m thick and is probably a fill-cut terrace, incised into both QTp and Qt1. The thickness of Qt3 is unknown; its terrace riser (exposed side) has a thickness of 7 to 15 m above the tread of Qt4, where these two are seen juxtaposed. Palomas Formation axial Rio Grande sands are exposed beneath terrace Qt4 in an arroyo about 110 m west of soil profile CA4 (UTM 292639E 3684616N), 14.7 m below the tread. Axial sands are also exposed in the Cañada Alamosa cutbank of terrace Qt5 at 15.8 m below the terrace top, 40 m east of soil profile CA5 (UTM 290015E 3687047N) (Fig. 5). The depth of the basal strath of Qt6 is unknown, its terrace riser is 9-16 m above the floodplain.

A comparison of Cañada Alamosa terrace tread elevations with those described from other Rio Grande tributaries in the Engle and Palomas basins reveals a relatively good correlation of the lowest four terraces (Fig. 3), further strengthening the climatic origin hypothesis for these terraces. In addition to attempting to correlate Cañada Alamosa terraces to intrabasinal Rio Grande tributaries and to the southern New Mexico alluvial mor-

FIGURE 5. Basal strath of the 15.8 m thick Qt5 terrace cut into Rio Grande axial sands of the Palomas Formation (QTpa) located 40 m east of soil profile CA5. Note clast imbrication of cobbles and boulders at the base of Qt5, which record an average paleoflow of N 26° E.

phostratigraphy, it is tempting to correlate these with Rio Grande terraces to the north. McCraw et al. (2006) and Love et al. (2009) map three Rio Grande terraces in the southernmost Albuquerque basin. The lowest, rising from the floodplain some 27-30 m, has a modified tread but might possibly correlate with Qt5, which grades out into a Rio Grande terrace 24-27 m above the reservoir-inundated floodplain. They also map a 3-m thick terrace with a strath elevation of 38 m above the floodplain and a high terrace with a strath of 50 m and a top at 65 m. Could Qt4 and Qt3 possibly correlate with these? Love et al. (2009) describe numerous complications that arise in making terrace correlation interpretations and McCraw and Love (2012, this guidebook) defer to even extend the Cuchillo surface north beyond the Engle basin due to possible differences in base level changes, perhaps reflecting differing Rio Grande river behavior north of a shallow bedrock sill. In the Socorro basin, the effects of the shallow Socorro magma body (Love et al., 2009) could certainly also affect any upstream correlation of terraces.

Within Cañada Alamosa, the terraces mapped in this study correlate well with those of Heyl et al. (1983), located near the top of the lower reach, and with McLemore's (2010, 2012) terraces upstream near the Monticello Box. There are numerous, isolated high terraces in the middle reach; one of the lowest of which correlates with the Cuchillo geomorphic surface at ~91-98 m above the floodplain. The terrace immediately above that (~114-128 m) appears to grade to an unnamed geomorphic surface occurring above Roque Ramos Canyon and Bernal Chavez Canyon drainages (both combining to form Cañada de la Cruz, a southern tributary of Cañada Alamosa) at the eastern base of the Sierra Cuchillo. There is no clear evidence for these middle reach higher terraces being either paired or climatic in origin. There are also numerous strath terraces cut into bedrock. The complex terrace stratigraphy of the middle reach is beyond the scope of this current study.

A closer examination of the terraces of the Cañada Alamosa lower reach reveals its own set of complexities. There are multiple terrace surface levels observed on the four lowest terraces in places. These are further described in the discussion of the two study areas below.

Study Area 1

The terrace stratigraphy of study area 1 as well as locations of outcropping Palomas Formation sediments (QTp) and Palomas Formation axial sand facies (QTpa) are depicted in Fig. 6 and in two selected profiles (Fig. 7). Both terraces Qt4 and Qt5 have two distinct levels located to the west of topographic profile L4. Terraces Qt5a and Qt5b have elevational ranges of 20-26 m and 24-36 m above the floodplain while treads of Qt4a and Qt4b range from 40 to 45 m and 44 to 50 m. These variations reflect the basinward down-stepping of these terrace surfaces towards the mouth of Cañada Alamosa. At topographic profiles L1 and L2, the lower two surfaces (Qt4a and Qt5a) no longer remain. Terrace Qt5 has a tread height of 26-28 m here while the surface of Qt4 is restricted to 33-36 m above the floodplain.

FIGURE 6. Map of Cañada Alamosa terraces (Qt map units) developed in the Palomas Formation (map unit QTp) or in its axial Rio Grande facies (QTpa) of study area 1. Locations of soil profiles CA3-5 and topographic profiles L2-L5 are shown. Note how terraces Qt4b and Qt5b step down from the west to form a single lower terrace surface to the east of the drainage immediately left of profile L4.

Study Area 2

The Cañada Alamosa terrace stratigraphy of study area 2 is considerably more complex than that of study area 1 (Fig. 8). Neotectonism has warped terraces, offset older terraces, and is responsible for two localized terrace surfaces that cannot be correlated elsewhere upcanyon or down. Of all the faults in the Cuchillo Negro fault zone, the down-to-the-west Willow Draw normal fault has had the greatest impact on terraces. Both the Cuchillo surface and terrace Qt1 are offset 21 m across the fault, on either side of Questa Blanca Canyon (Fig. 9).

East of the fault, terrace treads are offset and warped upward from 3 to 21 m, reflected in topographic profiles R4 to R8. Terraces Qt1 and Qt2 exhibit the largest amount of offset (from tread heights of 77-78 m to 96-98 m; 73-75 m to 88-90 m) while terraces Qt5 and Qt6 have no offset. Based upon morphometry of scarps on the Cuchillo surface, Machette (1987) concluded that movement on all Cuchillo Negro faults was middle Pleistocene in age. Onset of movement of the Willow Draw fault can be refined here to between Qt2 and Qt3 time, likely close to the time of early Qt3 formation, as a unique terrace level, Qt3t at 63-65 m, likely formed during rupture(s). This terrace surface level can only be traced about a kilometer east of the fault. Small warping reflected in Qt3a and Qt4b treads (~3-5 m) suggest additional younger movement.

A second tectonic terrace formed later between Qt4a and Qt4b time on the horst block 3 km east of the Willow Draw fault. This terrace (Qt4t, with a tread height of 42-43 m, sandwiched between Qt4a, 38-40 m, and Qt4b, 45- 48 m) likely formed by movement along an unnamed fault to its east (farthest right fault in Fig. 8). It can only be traced up canyon for ~500 m.

Movement on additional faults farther east has also warped Cañada Alamosa terraces. The northern end of the Mud Springs fault, located at the Interstate 25 crossing of Cañada Alamosa, has offset the Cuchillo surface 6-10 m south of the canyon. This fault bounds the Mud Springs Mountains fault block south of Cuchillo Negro Creek and extends beyond these mountains to the southeast, where it most likely joins the Williamsburg fault east of the Rio Grande (Machette, 1987). Holocene movement has occurred on the Williamsburg fault (Seager and Mack, 2003). The offset seen in the DEM-derived floodplain elevation of Cañada Alamosa depicted in Fig. 4, suggests recent movement at its northern end as well.

The direct effect of neotectonics alone cannot explain the number of terrace surfaces mapped in study area 2. Including the tectonic terraces described above, a total of eleven surfaces are clearly discernible within a 4 km reach of Cañada Alamosa. These levels, on the order of 2 to 5 m apart, are superimposed on the climatic and tectonic terraces, having most likely been
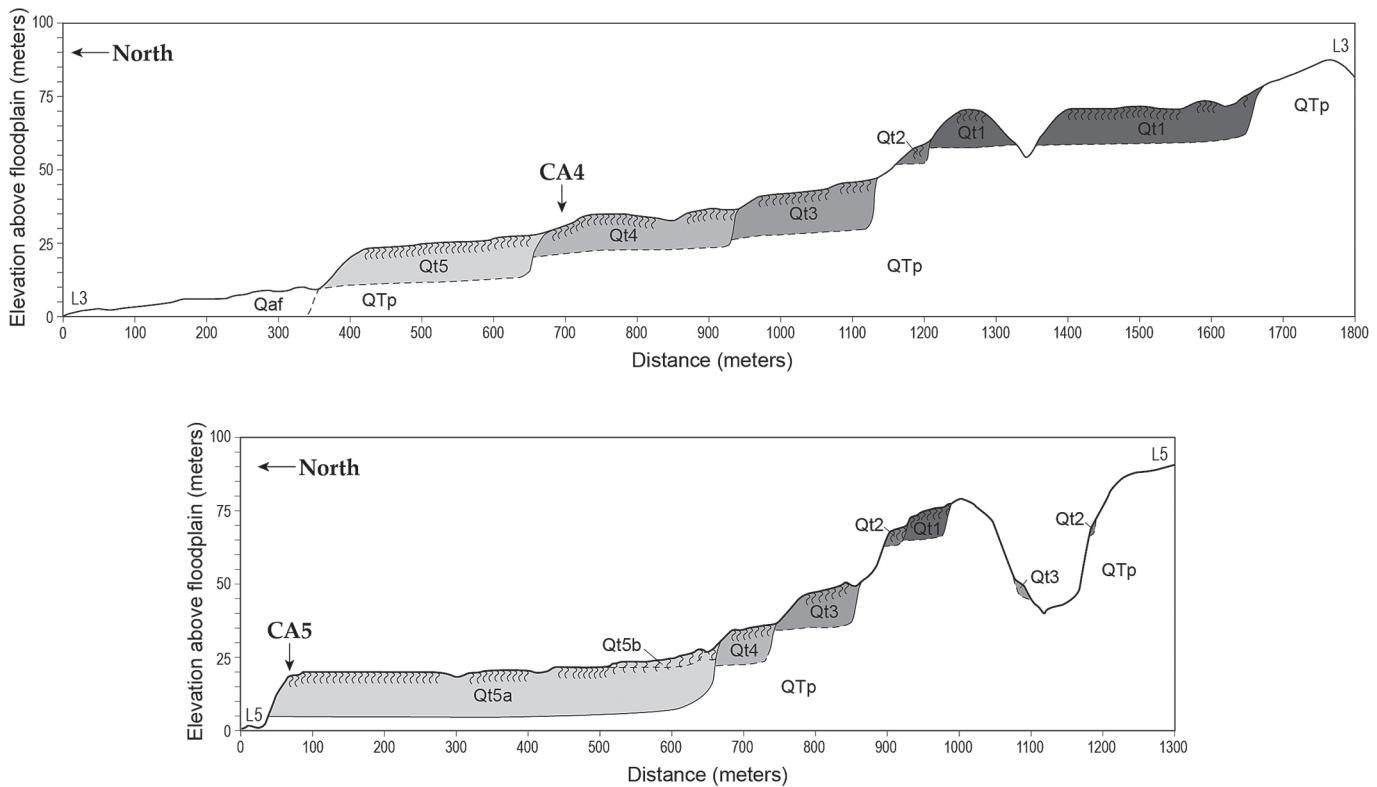
FIGURE 7. Selected topographic profiles (L3 and L5) illustrate the terrace stratigraphy and soils of study area 1.

formed by complex response (Bull, 1990, 1991; Schumm, 1973). Following a perturbation in a downstream reach in this model, a minor aggradation event occurs within the overall climatic down-cutting cycle as a nickzone passes through the reach to the head-waters. The terraces formed from complex response cannot be traced throughout the drainage, and vary in length from several kilometers, such as Qt3b and Qt4b, or can be highly localized (Qt6b, Qt6c). Here again, neotectonism is a likely culprit for the initial disruptive perturbation, and the active Mud Springs fault a likely player.

SOIL CHRONOSEQUENCE OF
CAÑADA ALAMOSA TERRACES

Characteristics of field properties of the five soil profiles (CA1 and CA3-6; Fig. 10) examined are listed in Table 2 (data supple-ment). The soils are all developed in gravelly to very gravelly medium-grained sand and are typical of arid soil chronose-quences, showing an increase in production of pedogenic clay and accumulation of pedogenic carbonate with increasing age. The grain size data collected from samples taken from each soil horizon are given in Table 3.

Profile Development Trends

Increases in pedogenic clay, approximated by the percent silt+clay (Fig. 11), start at 7.5 and 12.3% in the Bt horizons of CA6 and CA5 (excluding the 17.4% in CA6a) and increase to 26.4 and 22.4% of CA3 and CA1 Bt horizons. The anomalous

high value of CA6a is probably due to a high silt accumulation on the fine-grained terrace surface, perhaps either washed in from adjacent, higher Qt6 surfaces or the result of eolian accumulation winnowed from the floodplain. A similar increase from 6-10% to 12-16% occurs in the underlying Bk horizons although there is a distinct lag through CA4. Gile et al. (1981) found that clay accumulation occurred rapidly in DP soils and young entisols commonly approached 10% clay concentrations due to the large influx of atmospheric dust.

Carbonate increases are similar to pedogenic clay, passing from stage I to III from CA6 to CA3 and CA1, whose petrocalcic K and upper Ck horizons reach >1 m in thickness. Overall depth of carbonate throughout these profiles varies little (>3-5 m), how-ever, with the exception of CA6, where it is seen only in the Bk horizons, up to ~50 cm thick. Both dry and moist consistencies, like the carbonate and due in part to the accumulation of carbon-ate, typically become harder and firmer with time, although again with the notable exception of the hard CA6.

In addition to finer soil textures, increases in pedogenic car-bonate, and harder, firmer consistencies, soil colors change with age through rubification (redder hues and chromas) and meliza-tion (darkening due to accumulation of organic matter) (Harden, 1982). Color-paling and color-lightening, the opposite progres-sion to these two respective processes, typify color trends in carbonate-accumulating aridisols after ~100 ka as soils progress from stage II to III (Harden and Taylor, 1983). While CA1 and to some extent CA3 soils have both paled and lightened consider-ably, no apparent soil color change pattern emerges from the data presented in Table 2 for the youngest three soils. Both profiles
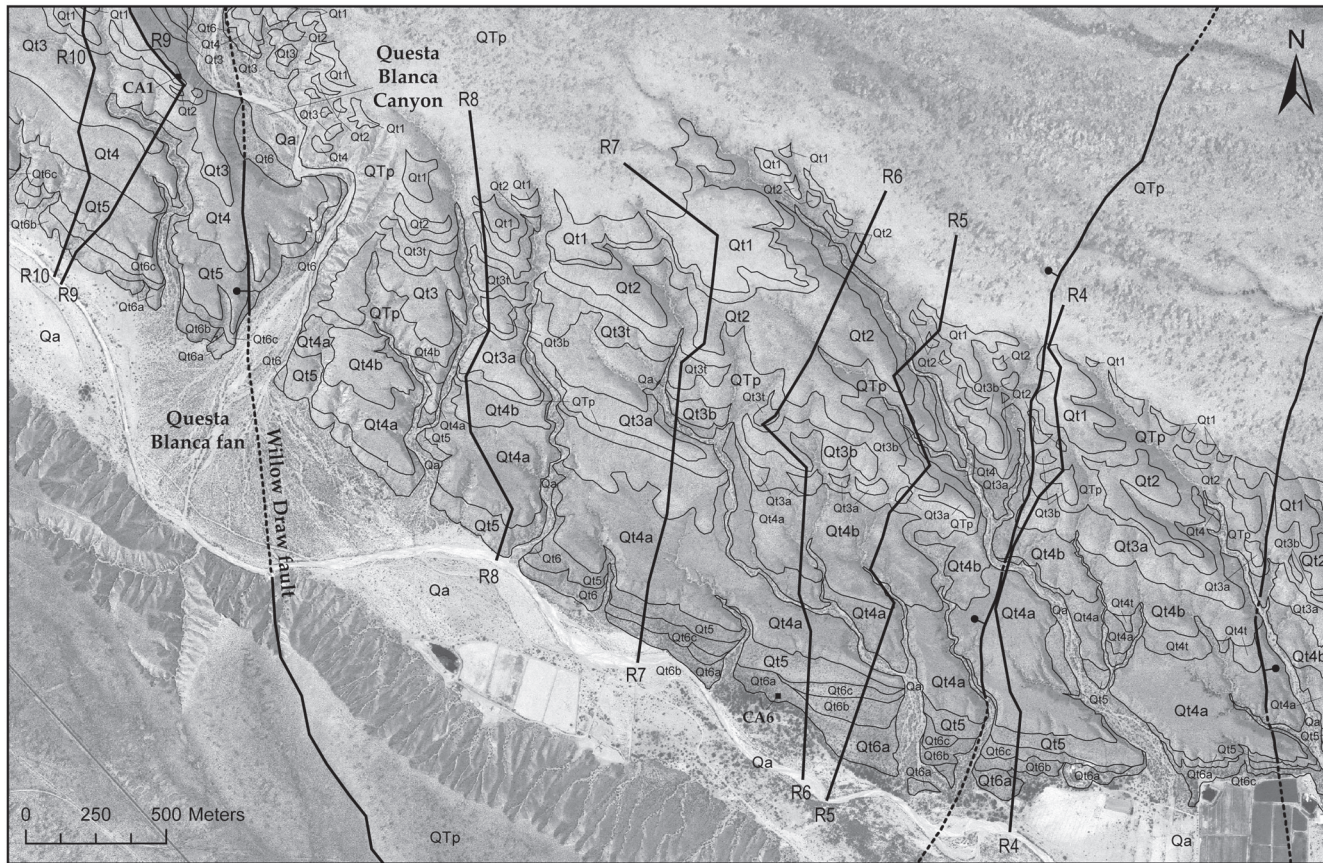
FIGURE 8. Map of Cañada Alamosa terraces (Qt map units) developed in the Palomas Formation (map unit QTp) of study area 2, showing three faults of the Cuchillo Negro fault zone cutting the Cuchillo surface and the inset terraces. Location of soil profiles CA1 and CA6 as well as topographic profiles R4-R10 are shown. Younger terraces Qt3-Qt6 exhibit multiple terrace surface levels either due to complex response or neotectonism, as is the case for the tectonic terraces Qt3t and Qt4t. The photograph in Figure 2 was taken from the top of the southern escarpment on the far left, looking up the small drainage immediately west of Questa Blanca Canyon (north-northeast).

CA6 and CA4 are much redder (2.5 YR - 5YR) than the other soils and CA5 is much darker (10YR).

The effects of spatial soil variability, as discussed by Harrison et al. (1990), have clearly complicated the straightforward inter-pretation of the soil chronosequence described in this study. For example, the soil properties exhibited by profile end members, CA5-6 and CA3-1, were somewhat unexpected. The uncom-monly hard and red CA6 (which correlates to terraces in the other
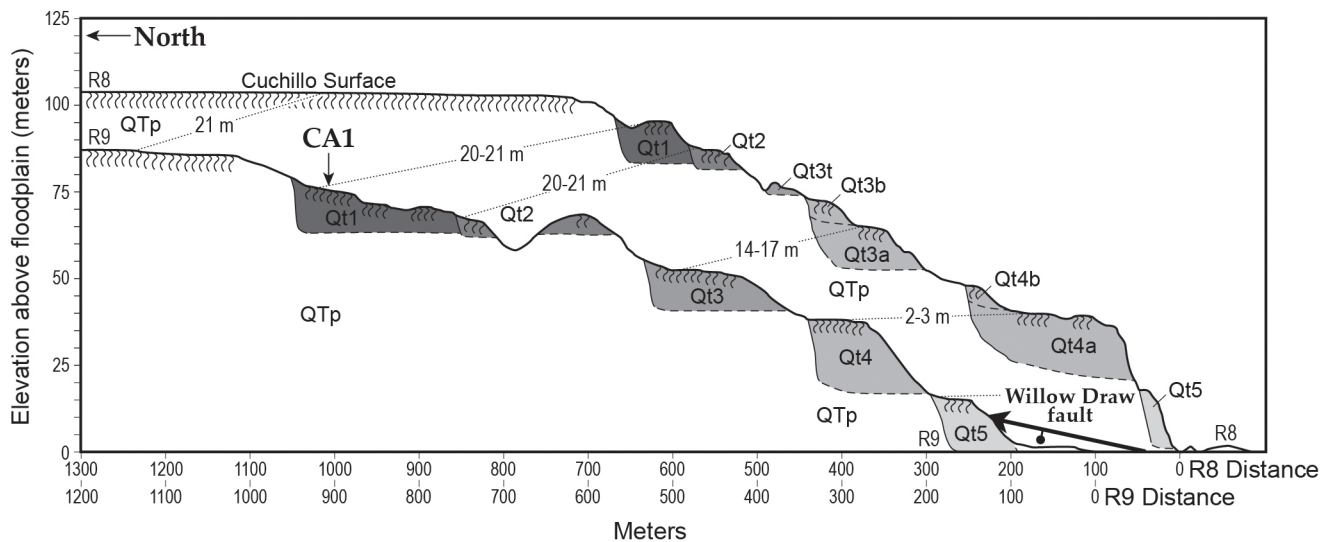

FIGURE 9. Topographic profiles R8 and R9, illustrating the amount of terrace tread offset on either side of the Willow Draw fault. Profile R8 shows the tectonic terrace Qt3t, which resulted from rupture(s) between Qt2 and Qt3 time. Profile R9 passes through soil profile CA1 locality.
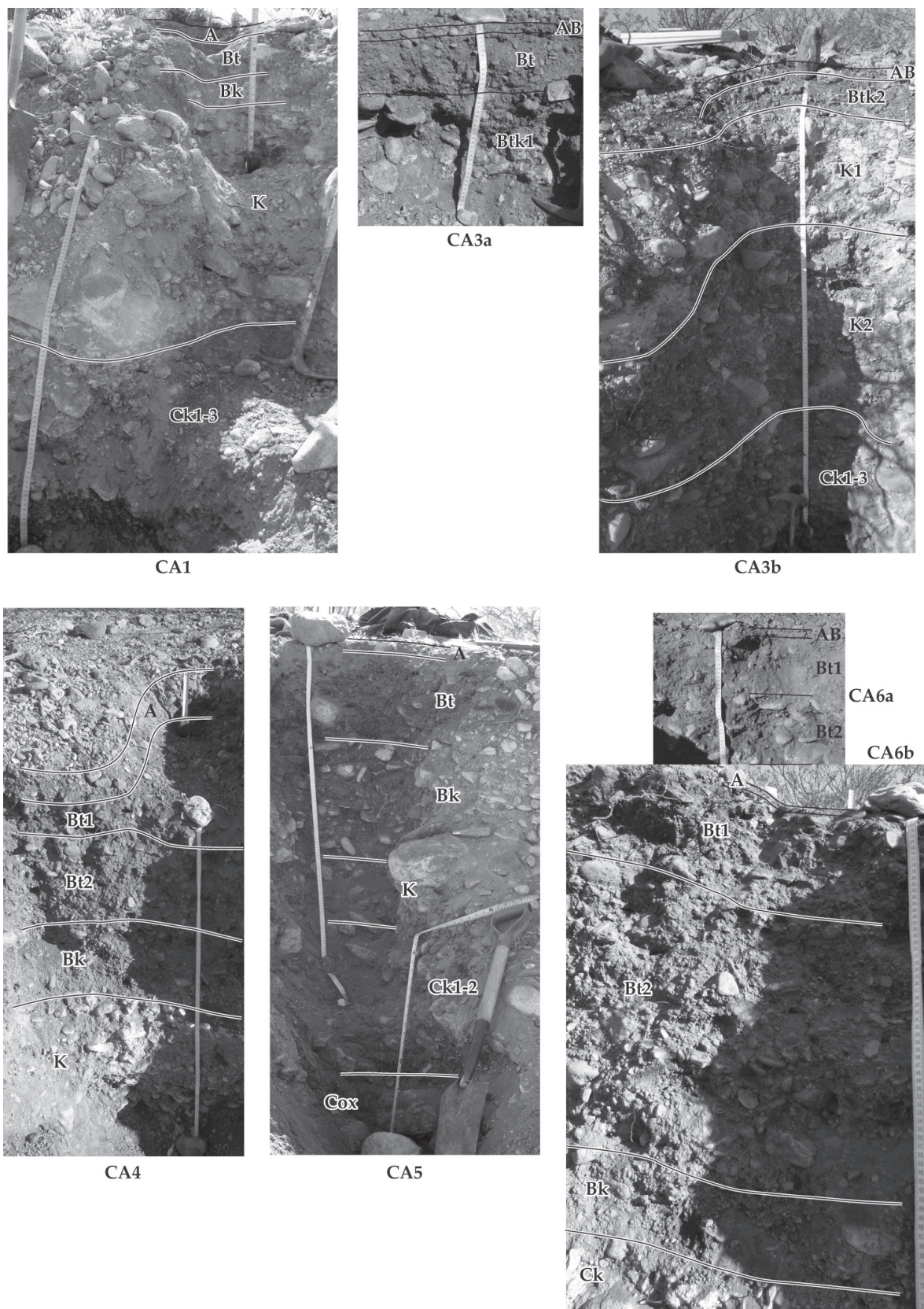
FIGURE 10. View of soil profiles CA1, CA3a and CA3b, CA4, CA5, and CA6a and CA6b. Profiles CA6a-b, CA4, and CA3a-b exhibit red hues and increasing pedogenic carbonate content. Profile CA5 has dark brown Bt and Bk horizons and only stage I carbonate. Profile CA1 exhibits strong color-paling and color-lightening associated with its strong stage III petrocalcic K horizon.
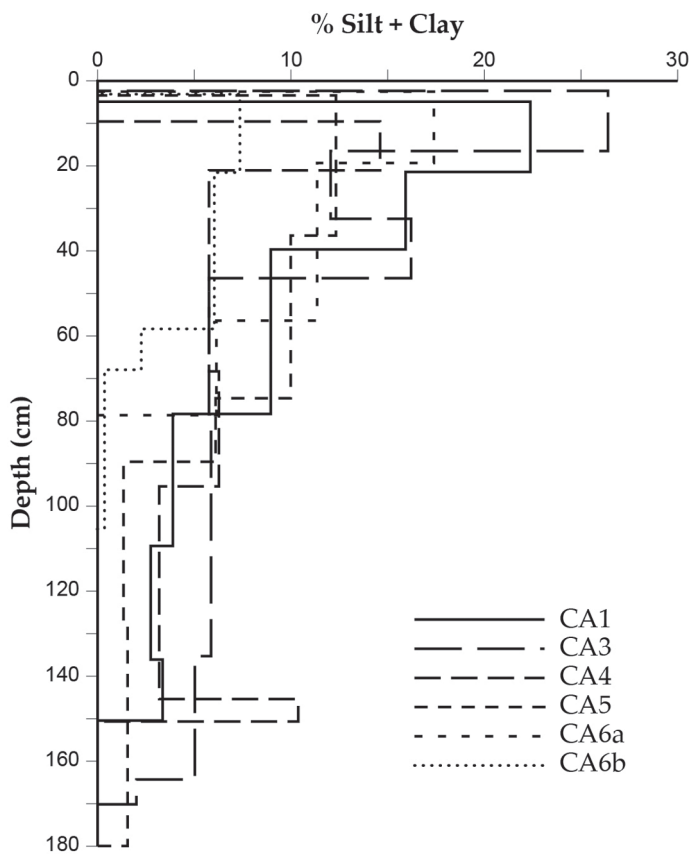
FIGURE 11. Percentage of the silt + clay grain size fraction with depth for soil profiles CA1; CA3-6a-b.

studies depicted in Figure 3 that are described as Holocene in age) reflects the properties of its parent material. The section of QTp exposed at the base of the canyon in study area 2 into which Qt6 soils developed, has a greater degree of induration and an oxidized, redder color than the upper canyon section, as previously noted. This is not the case for QTp in study area 1, which is either comprised of axial river sands or the finest-grained of the distal-most piedmont sediments. The CA5 soil, with its thicker, finer-grained, melanized B horizons, likely derives these characteristics from the underlying QTpa sands.

Another example is soil profile CA3, which is either as well developed or further developed than the higher and presumably older profile CA1. However, although CA1 only reaches a stage III K horizon, stage IV horizons are apparent in nearby locations. McCraw (2012, this guidebook) documents the same degree of variation in Cuchillo surface soils approximately 5 km to the east.

In short, further soils work is necessary. The effects of spatial variability on the chronosequence reported here have been observed both locally as well as on an intracanyon level (between the two study areas). Additional soil profiles should be characterized for each study area to obtain two complete soil chronosequences, thereby eliminating this latter source of variation.

Soil Development Index

The SDI was calculated on the following field properties: rubification (that combines both the dry and moist color properties of hue and chroma, and increases from initial conditions), melanization (derived from increased color value of the combined dry and moist measurements), color-paling (those properties measured in rubification which show decreases), color-lightening (decreasing color values), structure, dry consistence, moist consistence, total texture (which incorporates wet consistence properties of stickiness and plasticity to better reflect pedogenic clay production), and the carbonate index (CI). This latter property, added by Harden et al. (1991), is derived from the sum of a horizon's color-paling and color-lightening values, multiplied by the soil's carbonate stage, and divided by the maximum value obtained. Thus, a total of nine soil development properties were used to calculate the SDI in this study.

The SDI data derived from the Cañada Alamosa terrace soil chronosequence yields the following PDI values for profiles CA6-3, and CA1: 25.53, 26.52, 22.21, 48.51, and 47.96. Of the SDI properties utilized, dry and moist consistence yielded the most inconsistent results, comparing poorly with DP values. Commonly, parent materials of aridisols are loose, lacking any consistence, as is the case for the alluvial sediments underlying the DP soils. With the exception of CA5, however, Cañada Alamosa sediments posessed some measure of hardness prior to pedogenesis, limiting the utility of their derived normalized consistence values.

At first glance, the PDI data appear to reflect the spatial variability problems described above. Profile CA6 seems too strongly developed for its young (Holocene?) age, especially when compared with the DP values obtained by Harden and Taylor (1983) on Fillmore surface soils with ^{14}C ages of around 4 ka (25.53 vs. 4.62-7.85 – Table 4). Also, the PDI of profile CA3 seems relatively high, exceeding that of CA1.

The Desert Project data presented in Table 4 are not directly comparable with the results obtained from this study. Harden and Taylor (1983) used 8 properties in their SDI calculations, including clay films and pH-lowering, which were not analyzed here. This study included color-paling and color-lightening, as well as the CI, which was developed after the Desert Project analysis, for a total of 9 properties. Nevertheless, data comparison of the profile's maximum normalized property used in both studies listed in Table 4, as well as the PDI index values calculated show good agreement between the datasets. Both SDI analyses effectively document increasing soil development with logarithmic age (reflecting diminishing rates of property development, especially beyond 100 ka, which have been well documented in many settings) through their respective chronosequences in the same manner. Furthermore, there is a good correlation between the two datasets if the ages of DP morphostratigraphic units are applied to corresponding Cañada Alamosa terraces (r^2=0.776 – Fig. 12).

A similar correlation is achieved when looking at the carbonate index. Harden and Taylor's (1983) "normalized property
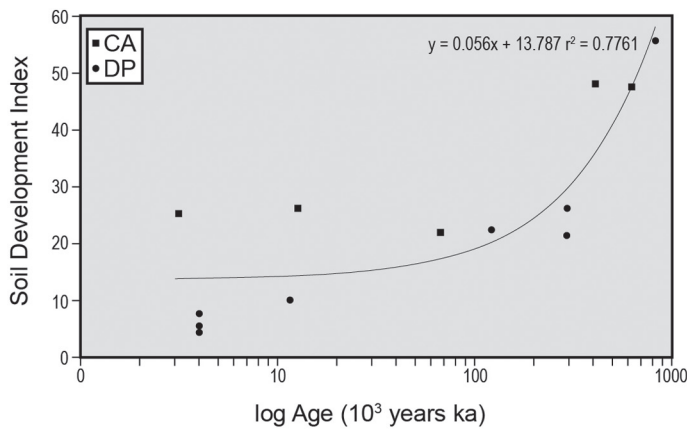
FIGURE 12. Comparison of the soil development indices calculated from PDI values for the Cañada Alamosa (CA) soil chronosequence with those of Harden and Taylor (1983) from the Desert Project (DP) soils.

maximum of profile" values for color-paling and color-lightening were used to back calculate to original values by multiplying by their maximum values (60 and 80, respectively) and these values were used in the CI calculation. A new maximum value of 560 derived from an Upper La Mesa soil was encountered in calculating the index, so other CI calculations utilized this maximum. By comparing the resulting DP CI values with the presumably correlative Cañada Alamosa CI data against log age, the correlation is r^2=0.755 (Fig. 13).

DISCUSSION

Although the soil chronosequence developed on terraces in Cañada Alamosa was affected by localized spatial variability, its ability to support the regional correlation of relative ages within southern New Mexico alluvial morphostratigraphy is both encouraging and useful. The fact that the degree of pedogenesis of both Cañada Alamosa terraces and DP morphostratigraphic units are directly comparable and that DP apparent formation ages occurred predominantly during glacial periods of the middle to late Pleistocene is significant. The observations and data presented here suggest that we can add degree of soil development on terrace chronosequences as another line of evidence to support the climatic hypothesis of terrace formation in Cañada Alamosa, in addition to terrace form (parallel treads) and regional-wide similarity of tributary terrace tread height.

As previously mentioned, the climatic model proposes that terrace creation occurs during glacial epochs, with the abandonment of aggradation surfaces brought on by increases in stream power and the ratio of water discharge to sediment load. Gile et al. (1981) proposed that this occurred in three stages: a) incision of both the axial valley (i.e., the Rio Grande) and its tributaries, at least in their lower reaches, during both waxing and full-glacial conditions; b) deposition during waning and early interglacial times; and c) relative stability for the remainder of the interglacial. Glacial climate conditions would have also increased rates of pedogenesis in southern New Mexico. Increased effective soil moisture availability would bring about increased leaching,

increased clay production and translocation, increased chemical and physical weathering, and decreased pH. While the rate of carbonate accumulation would likely decrease with a presumably lower dust influx due to greater ground cover, there would be additional Ca^{2+} available in the increased amount of precipitation. Gile et al. (1981) found that Ca^{2+} dissolved in rainwater accounted for greater than one-half the total source of calcium in pedogenic carbonate. Thus, it is reasonable to expect calcium carbonate would penetrate deeper through the solum and into the regolith during glacial conditions.

We suggest that the orbitally driven, ~100 ka glacial-interglacial cycles of the middle to late Pleistocene offer both a causal mechanism of periodic terrace flight formation and a conceptual framework for assessing the degree of pedogenesis occurring on each chronosequential terrace through time. In addition to terrace soil development, Mack et al. (2006) calculated an incision rate of the Rio Grande into the Palomas Formation of ~13-19 cm / 1000 yr, so an "incision age" can also be calculated from tread height if a constant rate of incision is assumed. Thus, relative terrace age refinement may be possible when the combination of morphostratigraphic correlation and the degree of soil development is coupled with incision age. Finally, we suggest that these data may be further "calibrated" with the correlation of the climate cyclicity that has occurred for the last 0.8 Ma as expressed in the marine oxygen isotope record from the equatorial Pacific, which would likely be an enhanced glacial period moisture source region for southern New Mexico.

Figure 14 presents a suggested chronology of Cañada Alamosa terraces within the southern New Mexico morphostratigraphic framework (adapted from Mack et al., 2006, fig. 13, p. 159) in light of the climate record recorded in the equatorial Pacific Ocean oxygen isotope curve from ODP site 846 (Cande and Kent, 1995). Six major glacial periods (even numbered peaks 16, 12 10, 8, 6, 2) have occurred since the time of entrenchment of Cañada Alamosa into QTp ~0.8 Ma ago. Mack et al. (2006) acknowledge that the ages of units older than Leasburg are poorly constrained although both the Bishop and Lava Creek B ashes have
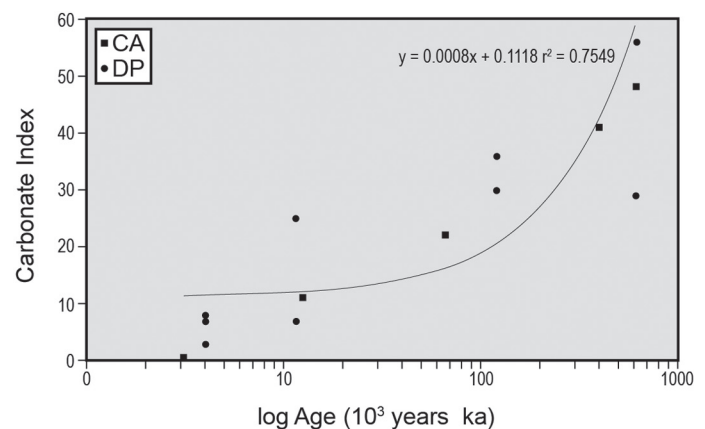

FIGURE 13. Comparison of the carbonate indices calculated from the carbonate stage and SDI color-paling and color-lightening values for the CA soil chronosequence with those of Harden and Taylor (1983) from the DP soils.

been found in Jornada I sediments, firmly securing it with marine isotope stage (MIS) 16. The morphostratigraphic units younger than Jornada I do not have an exact correlation with the timing of glacial periods, with the exception of Leasburg, which formed during the Wisconsinan glacial. The mean age of Tortugas centers on the interglacial MIS 11, although its age range brackets both glacial MIS 12 and 10. Picacho formed during glacial MIS 8 but could likely have continued well beyond. The Butterfield range in age extends from glacial MIS 6 through the interglacial 5e, to the increasingly glacial waxing progression from MIS 5e to 3, so its formation can still be explained within the model promoted by the Desert Project, albeit over an entire cycle spanning two glaciations. Fillmore, with its ^{14}C chronology of 7-0.1 ka (Gile et al., 1981) however, appears contraindicative of the model.

Relative Ages of Cañada Alamosa Terraces

Terrace Qt1 is strongly correlated with the Jornada I surface in light of its soil chronosequence data and elevation above the floodplain. The SDI data supports this correlation (CA1 = 47.96; Jornada I = 56.15; La Mesa I = 45.20) as does the incision age. If the age of glacial MIS 16 (0.63-0.67 Ma) is assumed for Qt1 formation, about 15 m of incision into the Cuchillo surface is calculated, which accurately describes the elevation of Qt1 beneath the Cuchillo.

Terrace Qt2, although not included in the soil chronosequence study, has a tread elevation of only 5-6 m below that of Qt1. It appears in places to have cut into at least the base of Qt1 fill deposits. If it is assumed that Qt2 formation occurred during MIS

14 at ~0.54 Ma the amount of incision required (~31 m) with a constant incision rate is too great. The "correct" amount of incision to reach the tread elevation of Qt2 is ~26 m, which would place it on the oxygen isotope curve at about 0.58 Ma. This age is used in Figure 14 as an earliest tentative age, placing Qt2 within the estimate range of Jornada I, which is consistent with the fact that it cuts Qt1. But Qt2 may also be correlative with early Tortugas.

Both the amount of incision (~40-45 m) and its well developed soil (40 cm thick combined Bt and Btk horizons, Bt silt+clay content of 26.42%, stages II to III pedogenic carbonate K horizons 89 cm thick, PDI = 48.51) indicate that terrace Qt3 is Tortugas equivalent. Actually, the CA3 profile data suggests its possible correlation with Jornada I, but field observations indicate that soil development occurring in this profile is likely stronger than the majority of Qt3 soils. The age derived from the incision rate for the Qt3a tread elevation of 48 m above the floodplain, which is the average tread height of all Qt3 surfaces encountered in the 31 topographic profiles is ~0.44 Ma, suggesting tread abandonment occurred during MIS 12.

The soil chronosequence data for terrace Qt4 is problematic. The PDI value suggests a probable correlation with Picacho or Jornada II surface soils (Table 3) while the Qt4 tread elevation (42 m above the floodplain) suggests an incision age of ~0.36 Ma, equivalent to MIS 10 and late Tortugas time. While the pedogenic carbonate in the profile only reached stage II in the CA4 soil property calculations, there were pockets of stage III within the stage II K horizon, also suggesting greater antiquity. When comparing Qt4 with the terraces mapped in the tributaries to the south, its high elevation implies an equivalency to the terraces that Lozinsky (1986) and Seager and Mack (1991) correlated to Tortugas, not Picacho.

There may be no Picacho equivalent terrace in Cañada Alamosa. The incision rate-derived age for the Qt5a tread height of 20-24 m in study area 1, as well as that of Qt5 up canyon, puts it squarely within glacial MIS 6 at about 0.15 Ma, at the beginning of the Butterfield. The incision age derived from the tread height of Qt5b (averaging 26-28 m) implies a Picacho age for tread abandonment, coinciding with glacial MIS 8 at ~0.27 Ma. However, the distribution of Qt5b is limited to the first 5 km of the stream valley and it merges with Qt5a to the east near the mouth, suggesting a non-climatic origin.

The soil described in profile CA5 also supports correlation with MIS 6. The degree of pedogenesis required to reach CA5 properties in these terrace soils, with its 71 cm thick B (33 cm Bt), melanized top 89 cm with 10YR hues and dark (3) chromas indicative of high organic matter content, would most likely require greater than 100,000 years of development. The last interglacial (MIS 5e) is thought to be warmer and drier than the present interglacial climate and global sea levels were higher than present (Muhs et al., 2011). This was followed by an overall long glacial waxing trend lasting 100 ka or so, spanning practically the entire late Pleistocene, passing through 2 minor interglacials (5c and 5a) as well as glacial MIS 4. Given the intensity in which soil forming factors have worked during this period, the PDI of 26.52 is less surprising than originally thought.
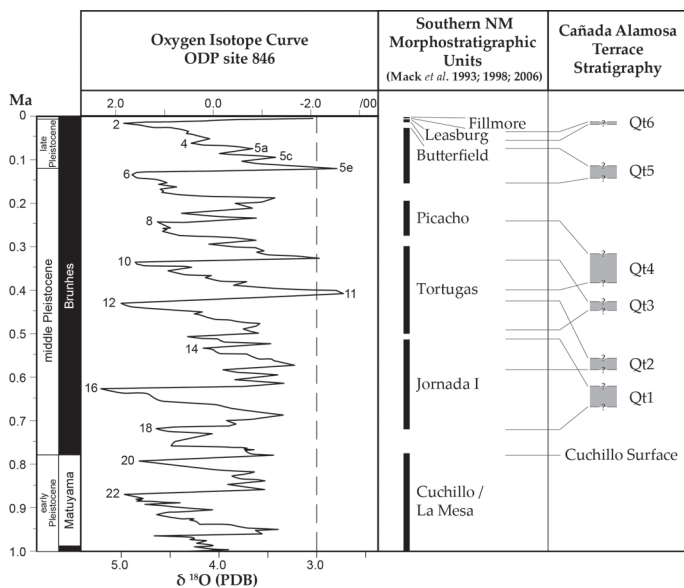

FIGURE 14. Relative ages suggested for the Cañada Alamosa terrace stratigraphy constrained within the southern New Mexico morphostratigraphy (from Mack et al., 2006, fig. 13, p. 159) and calibrated against the marine oxygen isotope curve for the equatorial Pacific ODP site 846 (Cande and Kent, 1995). Numbers adjacent to the isotope curve refer to marine isotope stages, odd numbers correspond to interglacials, even numbers to glacial periods.

Terrace Qt6 was believed to be early Holocene in age by Heyl et al. (1983) (but bear in mind that they assign Holocene ages to the lowest three terraces). Lozinsky (1986) correlated his Qt5 in Cuchillo Negro Creek with Fillmore, and Maxwell and Oakman (1990) suggested that "one of the two lowest is Wisconsinan," presumably their Qt4. The CA6a and CA6b profiles examined in this study contain 36 and 55 cm thick rubified Bt horizons, 6.47 to 17.35 % silt+clay content, and increased stickiness and plasticity in the clay content, implying that they are too well developed to be Holocene in age. CA6 is classified as an aridisol (Ustollic Haplargids) in the Sierra County soil survey (Neher, 1984), while Fillmore soils described in the Desert Project are young entisols. Given that the soil appears to be too well developed, further reflected in its unusually high PDI of 25.53, and that the terrace tread height yields an incision age of 16.5 ka, suggests that Qt6 tread abandonment occurred during full-glacial Wisconsinan conditions. Therefore, Qt6 is correlated here with the Leasburg morphostratigraphic unit, not Fillmore.

CONCLUSIONS

The terrace stratigraphy of Cañada Alamosa is comprised of six major terraces which are incised into the Plio-Pleistocene Palomas Formation. The parallel form of their treads and the correlation of their tread heights with terraces flanking other Rio Grande tributaries in the region are indicative of a primary climatic origin. The effects of Quaternary climatic cycles are recorded in the terraces, by varying degree of pedogenesis. Upon this climatic terrace framework, the effects of neotectonics and complex response have locally altered and complicated the stratigraphy. The four oldest terraces are warped and offset, reflecting tectonic movement since sometime between ~0.55 and 0.44 Ma, presumably closer to the latter. Two minor terraces of probable tectonic formation (Qt3t and Qt4t), most likely the result of ruptures occurring slightly before Qt3 and during Qt4 times, are locally preserved. Additionally, climatic terraces Qt3-6 are locally imprinted upon with minor terraces (surface levels) formed from complex response, recording minor pauses in degradation as the stream adjusted to downstream perturbations, most likely tectonic in nature. In study area 2, eleven total terrace surfaces were mapped.

Soils were examined on five of the six major terraces; their profiles were characterized and their horizons sampled for grain size and soil development analyses. The resulting soil chronosequence, though complicated by spatial soil variability, document both the decreasing age progression of terrace formation linked with stream incision and the effects of Quaternary climate change. The degree of pedogenesis quantified by PDI values show a good correlation with values derived from the Desert Project soils. This has permitted the development of a relative age chronology of Cañada Alamosa terraces based upon the established framework of southern New Mexico alluvial morphostratigraphy, with ages based upon rate of incision, degree of pedogenesis, and the timing of glacial cycles recorded in the oxygen isotopic record of the equatorial Pacific.

Cañada Alamosa began downcutting into the Palomas Forma-

tion in response to Rio Grande degradation, which formed the Cuchillo geomorphic surface at ~0.8 Ma. A period of renewed incision occurred during glacial conditions associated with MIS 16, ~0.67-0.63 Ma, forming Qt1 with a surface ~9-15 m below the Cuchillo surface. This terrace was partially cut into by the Qt2 terrace, ~5-6 m lower in elevation, probably sometime after 0.58 Ma. The next (Qt3) terrace-forming downcutting event was probably associated with MIS 12, ~0.45-0.43 Ma, leaving a tread 48-54 m below the Cuchillo. A period of active tectonism in the Cuchillo Negro fault zone ensued from ~0.55 to perhaps 0.32 Ma.

Renewed active downcutting associated with MIS 10 from about 0.38 to 0.32 Ma brought about one of the most prominent of Cañada Alamosa's modern terraces, Qt4. Little evidence of terrace formation exists for the period between 0.30 and 0.19 Ma, including a Picacho equivalent terrace which could have formed during MIS 8. It was not until MIS 6 about 150 ka, that the next major incision event occurred, causing the stream to abandon the Qt5 surface, inset some 69-73 m below the Cuchillo and 13-16 m beneath Qt4. A sixth final climatic terrace, equivalent with the Leasburg morphostratigraphic unit, was formed during the Wisconsinan full glacial from about 17 to 15 ka. It presently sits 9 to 16 m above the modern floodplain, inset some 79-82 m beneath the long abandoned top of Quaternary aggradation, the Cuchillo surface.

REFERENCES

Birkeland, P. W., 1984, Soils and geomorphology: Oxford University Press, 372 p.

Birkeland, P. W., 1990, Soil-geomorphic research: a selective overview: Geomorphology, v. 3, p. 207-224.

Bull, W. B., 1990, Stream terrace genesis: implications for soil development: Geomorphology, v. 3, p. 351-367.

Bull, W. B., 1991, Geomorphic responses to climatic change: Oxford University Press, Inc., 326 p.

Cande, S. C., and Kent, D. V., 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research Solid Earth, v. 100, p. 6093-6095.

Chapin, C. E., Wilks, M., and McIntosh, W. C., 2004, Space-time patterns of Late Cretaceous to present magnetism in New Mexico; comparison with Andean volcanism and potential for future volcanism: *in* Tectonics, geochronology, and volcanism in the southern Rocky Mountains and Rio Grande rift, New Mexico, Bureau of Geology and Mineral Resources, Bulletin 160, p. 13-40.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico: Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Gile, L. H., Hawley, J. W., Grossman, R. B., Monger, H. C., Montoya, C. E., and Mack, G. H., 1995, Supplement to the Desert Project Guidebook, with emphasis on soil micromorphology: New Mexico Bureau of Mines and

Mineral Resources, Bulletin 142, 96 p.

Harden, J. W., 1982, A quantitative index of soil development from field descriptions: examples from a chronosequence in central California: Geoderma, v. 28, p. 1-28.

Harden, J. W., and Taylor, E. M., 1983, A quantitative comparison of soil development in four climatic regimes: Quaternary Research, v. 20, p. 342-359.

Harden, J. W., Taylor, E. M., McFadden, L. D., Hill, C., Mark, R. K., Reheis, M. C., Sowers, J. M., Wells, S. G., 1991, A comparison of four chronosequences in the southern Great Basin: rate of soil development and implications for soil chronology: Quaternary Research, v. 35, p. 383-399.

Harrison, J. B. J., McFadden, L. D., and Weldon III, R. J., 1990, Spatial soil variability in the Cajon Pass chronosequence: implications for the use of soils as a geochronological tool: Geomorphology, v. 3, p. 399-416.

Hawley, J. W., 1965, Geomorphic surfaces along the Rio Grande valley from El Paso, Texas to Caballo Reservoir, New Mexico: New Mexico Geological Society, 16th Field Conference Guidebook, p.188-198.

Hawley, J. W., and Kotlowski, F. E., 1969, Quaternary geology of the south-central New Mexico border region: *in* Kottlowski, F. E., and LeMone, D. V., *eds*., Border Stratigraphy Symposium, New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 89-115.

Heyl, A. V., Maxwell, C. H., and Davis, L. L., 1983, Geology and mineral deposits of the Priest Tank quadrangle, Sierra County New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1665, scale 1:24,000.

Lozinsky, R. P., 1986, Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 187, 40 p.

Love, D. W., McCraw, D. J., Chamberlin, R. M., Reiter, M., Connell, S. D., Cather, S.M., and Majkowski, L., 2009, Progress report on tracking Rio Grande terraces across the uplift of the Socorro magma body: New Mexico Geological Society, 60th Field Conference Guidebook, p. 415-424.

Machette, M. M., 1985, Calcic soils of the southwestern United States: Geological Society of America, Special Paper, v. 203, p. 1-61.

Machette, M. M., 1987, Preliminary assessment of Quaternary faulting near Truth or Consequences, New Mexico: U.S. Geological Survey, Open-file Report 87-652, 38 p.

Mack, G. H., 2004, Middle and late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande rift, Basin and Range, and southern transition zone of southwestern New Mexico: *in* Mack, G. H. and Giles, K. A., *eds*., The geology of New Mexico, a geologic history, New Mexico Geological Society, Special Publication 11, p. 389-406.

Mack, G. H., Foster, R., and Tabor, N. J., 2012, Basin architecture of Pliocene-lower Pleistocene alluvial-fan and axial-fluvial strata adjacent to the Mud Springs and Caballo Mountains, Palomas half-graben, southern Rio Grande rift: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.

Mack, G. H., and Leeder, M. R., 1998, Channel shifting of the Rio Grande, southern Rio Grande rift: implications for alluvial stratigraphic models: Sedimentary Geology, v. 117, p. 207-219.

Mack, G. H., and Leeder, M. R., 1999, Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half-graben, southern Rio Grande rift: Journal of Sedimentary Research, v. 69, p. 635-652.

Mack, G. H., Salyards, S. L., and James, W. C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49-77.

Mack, G. H., Salyards, S. L., McIntosh, W. C., and Leeder, M. R., 1998, Reversal magnetostratigraphy and radioisotopic geochronology of the Plio-Pleisto-

cene Camp Rice and Palomas Formations, southern Rio Grande rift: New Mexico Geological Society, 49th Field Conference Guidebook, p. 229-236.

Mack, G. H., and Seager, W. R., 1990, Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Plio-Pleistocene) in the southern Rio Grande rift: Geological Society of America Bulletin, v. 102, p. 45-53.

Mack, G. H., Seager, W. R., Leeder, M. R., Perez-Arlucea, M., and Salyards, S. L., 2006, Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA: Earth-Science Reviews, v. 79, p. 141-162.

Mack, G. H., Seager, W. R., and Kieling, J., 1984, Late Oligocene and Miocene faulting and sedimentation, and evolution of the southern Rio Grande rift, New Mexico, USA: Sedimentary Geology, v. 92, p. 79-96.

Maxwell, C. H., and Oakman, M. R., 1990, Geologic map of the Cuchillo quadrangle, Sierra County, New Mexico: U.S. Geological Survey, Geological Quadrangle Map GQ-1686, scale 1:24,000.

McCraw, D. J., 2012, Cuchillo surface overview and soils: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.

McCraw, D. J., Love, D. W., and Connell, S. D., 2006, Preliminary geologic map of the Abeytas quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resource:, Open-file Geologic Map OF-GM 121, scale 1:24,000.

McCraw, D. J., and Love, D. W., 2012, An overview and delineation of the Cuchillo geomorphic surface, Engle and Palomas basins, New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.

McLemore, V. T., 2010, Geology, mineral resources, and geoarchaeology of the Montoya Butte quadrangle, including the Ojo Caliente No. 2, mining district, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report OF-535, 106 p.

McLemore, V. T., 2012, Preliminary geologic map of the Montoya Butte quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources: Open-file Geologic Map OF-GM 69, 1:24,000.

Muhs, D. R., Simmons, K. R., Schumann, R. R., and Halley, R. B., 2011, Sea-level history of the past two interglacial periods: new evidence from U-series dating of reef corals from south Florida: Quaternary Science Reviews, v. 30, p. 570-590.

Myers, R. G., Everheart, J. T., and Wilson, C. A., 1994, Geohydrology of the San Agustin basin, Alamosa Creek basin upstream from Monticello Box, and upper Gila basin in parts of Catron, Socorro, and Sierra Counties, New Mexico: U.S. Geological Survey, Water Resources Investigations Report 94-4125, 33 p.

Neher, R. M., 1984, Soil survey of Sierra County area, New Mexico: U.S. Department of Agriculture, Soil Conservation Service, Washington, D. C., 214 p.

Schumm, S. A., 1973, Geomorphic thresholds and complex response of drainage systems: *in* Morisawa, M., *ed*., Fluvial Geomorphology,: State University of New York Binghamton Publications in Geomorphology, 4th Annual Meeting, p. 299-310.

Seager, W. R., and Mack, G. H., 1991, Geology of Garfield quadrangle, Sierra and Doña Ana Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 128, 24 p.

Seager, W. R., and Mack, G. H., 2003, Geology of the Caballo Mountains: New Mexico Bureau of Geology and Mineral Resources, Memoir 49, 136p.

Seager, W. R., and Mack, G. H., 2005, Geology of Caballo and Apache Gap quadrangles, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 74, scale 1:24,000.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87-99.