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# QUATERNARY STRATIGRAPHY, SOILS AND GEOMORPHOLOGY OF THE NORTHERN RIO GRANDE RIFT

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**Abstract**—The Quaternary stratigraphy and geomorphology of the eastern flank of the San Luis basin in New Mexico can be characterized by middle Pleistocene-Holocene alluvial fan, fluvial terrace and pediment deposits overlying the Pliocene–middle Pleistocene Lama formation basin-fill sequence. These deposits are distributed among four major physiographic regions: (1) the dissected piedmont; (2) undissected piedmont; (3) incised river valleys; and (4) Guadalupe Mountain. A soil chronosequence coupled with stratigraphic and sedimentologic analyses has demonstrated that Quaternary deposits are morphologically similar and temporally correlative across the different landscape regions. Regional changes in base level and climatic conditions are recorded in specific elements of the northern Rio Grande rift landscape. Middle Pleistocene strath fluvial terraces and pediment deposits record the initiation of incision of major Rio Grande tributaries into the Lama formation following regional base level fall. Late-middle Pleistocene-Holocene alluvial fans and aggradational terraces record depositional episodes temporally correlative to periods of glaciation during the late Quaternary. The alluvial fan units demonstrate the complex interaction between available moisture and vegetative cover associated with climatic changes accompanying glacial and neoglacial events. The relative sensitivity of Quaternary stratigraphy to climatic and base-level change is scale dependent, with the younger deposits reflecting the smaller-scale climatic fluctuations and older deposits reflecting the larger-scale base-level changes.

## INTRODUCTION

A diverse suite of landforms and Quaternary deposits along the west-facing mountain front and piedmont of the Sangre de Cristo Mountains (Taos Range) between Taos and Costilla, New Mexico help constrain the geomorphic and structural development of the northern Rio Grande rift. The stratigraphy and soil morphology of deposits and landforms plays a critical role in evaluating: (1) the amount, style and location of Quaternary tectonism (Menges, 1988, 1990); (2) the processes of drainage integration within an active rift system (Wells et al., 1987); (3) the role of lithology and drainage basin hydrology on landform genesis (Kelson, 1986; Kelson and Wells, 1989); and (4) the relative roles of climatic versus tectonic processes on landform evolution (Pazzaglia, 1989). The goal of this paper is to assess the genesis and evolution of Quaternary stratigraphy and landforms in a portion of the northern Rio Grande rift. Specifically this paper will: (1) define the spatial distribution, sedimentologic, soil morphologic and geomorphic characteristics of Neogene-Quaternary depositional units; (2) establish relative and absolute age-control for the regional correlation of depositional units; and (3) suggest a relationship between regional climatic change and stratigraphy.

## PHYSIOGRAPHIC, GEOLOGIC AND GEOMORPHIC SETTING

The eastern flank of the northern Rio Grande rift in New Mexico is situated along the Southern Rocky Mountain and Basin and Range Physiographic Province structural boundary (Fig. 1). This boundary is defined by a segmented, north-south-oriented normal fault (Menges, 1990) that juxtaposes the Taos Range of the Sangre de Cristo uplift to the east with the San Luis basin of the northern Rio Grande rift to the west. Late Pleistocene to Holocene ruptures along this and adjacent fault systems (Machette and Personius, 1984; Menges, 1987a, b, 1988, 1990) are indicative of neotectonic activity. The Taos Range is composed of Proterozoic metamorphic rocks and late Paleozoic sedimentary rocks which are intruded by Tertiary plutons and partially mantled by Tertiary volcanic rocks (Reed et al., 1983; Reed, 1984; Lipman and Reed, 1989). The San Luis basin is one of four major axial basins composing the Rio Grande rift between Socorro, New Mexico and

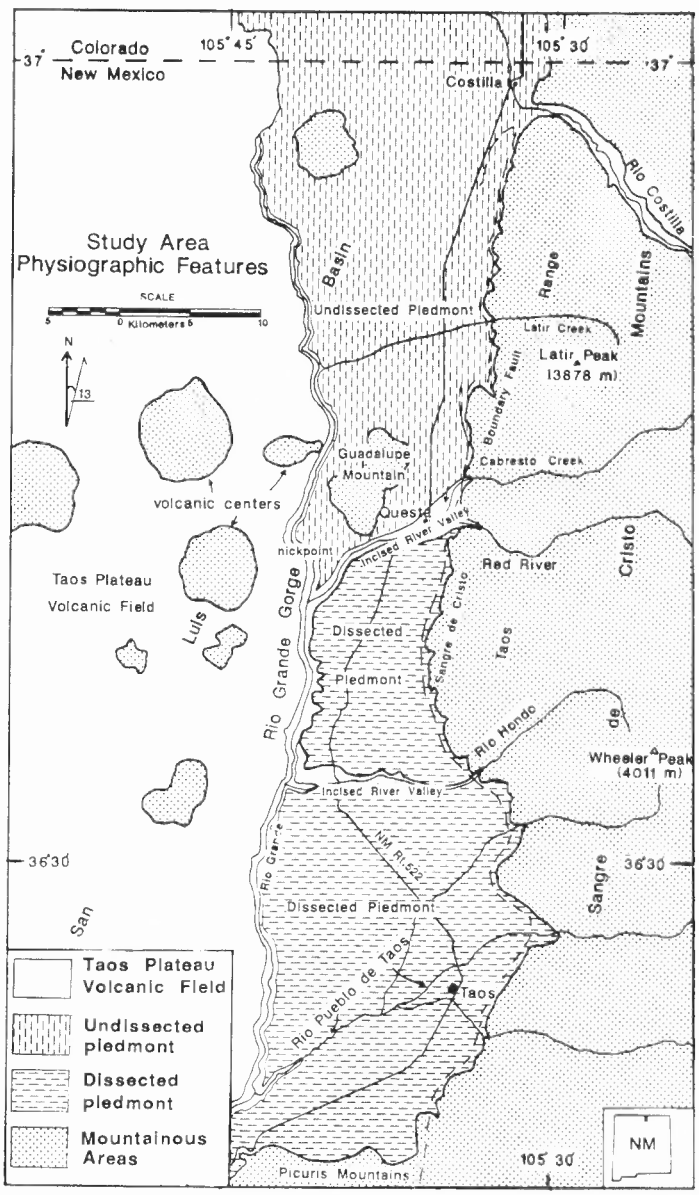



FIGURE 1. Location map and physiographic features of the study area. Note the undissected piedmont located north of Questa, the dissected piedmont located south of Questa, the three major incised river valleys (Red River, Rio Hondo, Rio Pueblo de Taos) and Guadalupe Mountain, part of the Taos Plateau volcanic field.

Leadville, Colorado aligned in a right-stepping en-echelon pattern between uplifted and outward-tilted shoulders. Rifting in northern New Mexico is generally believed to have begun in the Miocene and continues to the present (Chapin, 1988).

Partially consolidated volcaniclastics, conglomerates, sands, silts and minor clay of the Santa Fe Group (Baltz, 1978) comprise a Miocene rift-fill sequence 1000–3000 m thick. The Santa Fe Group is overlain by Pliocene to Pleistocene sedimentary basin fill along the eastern flank of the San Luis basin and Servilleta Formation olivine tholeiite basalt flows of the Taos Plateau Volcanic Field (TPVF) (Lipman and Mehnert, 1975; Dungan et al., 1984) in the center of the basin.

A piedmont slopes westward from the Sangre de Cristo Mountains into the San Luis basin and is subdivided into an undissected portion north of Questa, New Mexico, and a heavily dissected portion south of Questa. The Rio Grande, which flows from north to south along the center of the San Luis basin, is relatively unincised north of the New Mexico–Colorado border but has cut a gorge up to 245 m deep through the basalts of the TPVF. A prominent nickpoint in the Rio Grande, present near Questa, is concident with the dissected-undissected piedmont boundary. The main tributaries of the Rio Grande in this region include the westward-flowing Rio Costilla, Red River, Rio Hondo and Rio Pueblo de Taos (Fig. 1).

## METHODOLOGY

Analysis of stratigraphic relationships among Quaternary depositional units is based primarily upon sedimentologic and soil morphologic characteristics, and to a lesser extent, relative topographic position. Soil profile characteristics, described in accordance with the Soil Conservation Service (1975) and Birkeland (1984) are used to develop a soil chronosequence (Jenny, 1941; Birkeland, 1984). Soil chronosequences presuppose that the effects of all soil forming factors (Jenny, 1941; parent material, slope position, vegetation, climate, time) are both unidirectional and cumulative resulting in soil morphologic characteristics that are predominantly a function of the duration of pedogenic processes acting upon a given surface. Specific morphologic characteristics of the soil profiles such as calcium-carbonate accumulation (Gile et al., 1966; Machette, 1985) and overall argillic horizon development (McFadden et al., 1986; McFadden and Weldon, 1987) have been shown to be largely time dependent. The soils developed in Quaternary deposits therefore reflect the relative ages of the surfaces associated with these deposits. A calibrated age can then be established for some deposits by combining relative age relations with absolute radiocarbon dates obtained from charcoal and charcoal-rich sediments.

## QUATERNARY GEOLOGY

### Landscapes, basin fill and Quaternary deposits

Four major landscapes have been identified, each distinguished by a characteristic suite or assemblage of landforms and deposits. These four landscapes are: (1) large river valleys; (2) a dissected piedmont region located south of Questa between the Rio Hondo and Red River; (3) an undissected piedmont located north of Red River; and (4) Guadalupe Mountain, an eroded Tertiary volcanic center in the TPVF (Fig. 2). With the exception of Guadalupe Mountain, these landscapes are underlain by a Pliocene to Pleistocene rift-fill sequence defined as unit Q1 and informally named the Lama formation (Wells et al., 1990). This unit is composed of poorly sorted alluvial fan and axial stream (Rio Grande) sands and gravels. The Lama formation is interbedded with the 4.3–2.0 Ma Servilleta Basalts at its base and with 1.1–1.2 Ma Jemez volcanic ash (Izett et al., 1981) near the top of the sequence (Kelson, 1986; Wells et al., 1987).

Three major Quaternary deposits overlie the Lama formation. These deposits are: (1) pediment gravels; (2) fluvial terrace sands and gravels; and (3) alluvial fan sands, silts and gravels. The deposits are not ubiquitous across the region, rather they tend to be closely associated with one of the four landscapes. For example, pediment gravels occur almost exclusively with pediment surfaces in the dissected piedmont region whereas fluvial terrace sands and gravels are restricted to the large river valleys. Major alluvial fan deposits occur predominantly in the undissected piedmont region along the mountain front but smaller fans also exist in the Guadalupe Mountains, large river valley and dissected piedmont regions.

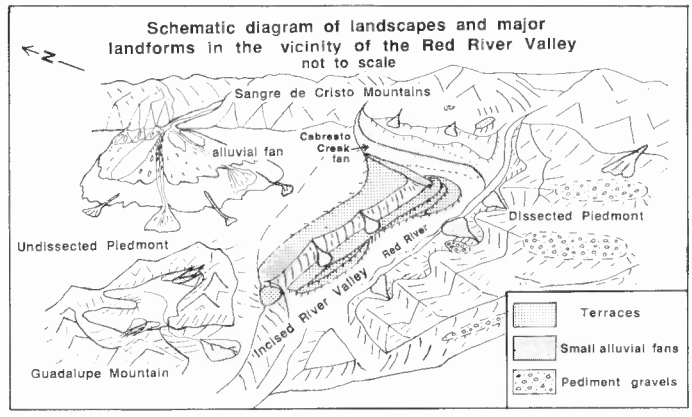



FIGURE 2. Major landforms of the study area. Alluvial fans and fluvial terraces comprise the dominant landforms and deposits in the incised river valleys, pediment gravels are found predominantly in the dissected piedmont region, and alluvial fans are the dominant deposits on the undissected piedmont as well as on Guadalupe Mountain.

### Incised river valley landscape

The Red River and Rio Hondo have incised long (~15 km), linear river valleys 1–2 km wide and 80–90 m deep through the piedmont and TPVF on the northern and southern flanks of the dissected piedmont respectively. The Rio Pueblo de Taos and San Cristobal Creek valleys (Fig. 1) are morphologically similar to the Red River and Rio Hondo but smaller in size. Longitudinal profiles of the Red River and Rio Hondo are straight to slightly concave-up along the length of the piedmont and slightly to moderately convex near their confluence with the Rio Grande (Wells et al., 1987).

The dominant landforms in the river valleys are fluvial terraces. Fluvial terrace deposits are composed of weakly imbricated and cross-stratified, poorly to moderately well-sorted, medium to thickly bedded, gray, sandy, gravel and gravelly sand. Gravel clasts are subangular to well-rounded and range from 10–50 cm in diameter (b-axis). Eolian loess units of variable thickness (0.25–1.5 m) commonly overlie the fluvial sands and gravels.

The Red River contains nine terraces, the Rio Hondo contains six and the Rio Pueblo de Taos contains four indicating that terrace deposition is not synchronous between the major incised river valleys (Kelson and Wells, 1987; Pazzaglia, 1989). The highest terrace surface (Qt1) is defined as the top of the Lama formation along the Rio Grande axis (Wells et al., 1987) and is not present within the river valleys. Terrace surfaces Qt2–Qt10 compose a flight of terrace surfaces inset into the Lama formation and subdivided into two major groups: (1) an upper sequence of strath terraces (Qt2–Qt4 for Red River valley; Qt2–Qt5 in Rio Hondo and Rio Pueblo de Taos valleys) emplaced directly on the Lama formation along valley margins, and (2) a lower sequence of aggradational terraces (Qt5–Qt10 in Red River valley; Qt6–Qt7 in Rio Hondo and Rio Pueblo de Taos valleys) along the valley axis (Fig. 3; Table 1). The depth at which the Lama formation underlies those fluvial deposits in the valley axis is not known.

Upper terrace sequence deposits such as unit Qt2 exhibit a 1–2 m thick mantle of post-fluvial colluvium and eolian material that overlies the fluvial gravels. This mantle is characterized by one or more buried soils and erosional contacts indicative of multiple phases of surface stability, soil formation and subsequent erosional stripping (Fig. 4a). The uppermost horizons are weakly developed, dark (10 YR), eolian silty-loam A/Ck and loamy cambic B horizons 5–20 cm thick (Table 1). These surface horizons contain a small amount of disseminated calcium carbonate. The underlying horizons comprise a well-developed buried profile characterized by a pale pink (5 YR) loamy 1–2 m thick K horizon with carbonate morphology stage III–IV and remnants of a

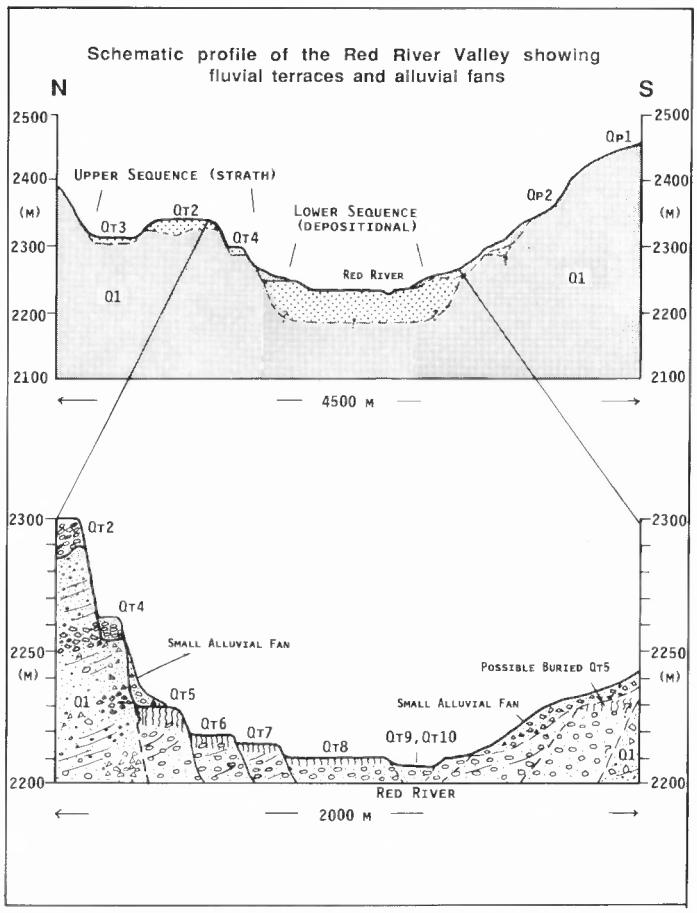



FIGURE 3. Profile of Red River valley terraces. This schematic profile demonstrates the inset relationship between terrace deposits and the Pliocene-Pleistocene Lama formation basin fill. Upper terrace sequence deposits are strath, while the lower terrace sequence are cut-and-fill deposits. Late-middle Pleistocene-Holocene small alluvial fan deposits mantle portions of the lower terrace sequence.

TABLE 1. Summary of soil morphologic characteristics.

| Location | Deposit | Profile thickness (cm) | Argillic thickness (cm) | Argillic horizon color | Calcic thickness (cm) | Calcic horizon stage | Height above base level 1 (m) |
|---|---|---|---|---|---|---|---|
| Red River Valley | upper Qt2 | 250+ | 10 - 50 truncated | 7.5 YR | 70-150 | III+ IV | 85 |
| | upper Qt3 | - | not prs. truncated | - | 50-100 | III-III+ | 65 |
| | upper Qt4 | 218+ | 22 truncated | 7.5 YR | 150 | III-II+ | 40 |
| | lower Qt5 | 114+ | 88 | 7.5 YR | 50-100 | II-II+ | 25 |
| | lower Qt6 | 85+ | 77 | 8.75 YR | 40 | I+ | 15 |
| | lower Qt7 | 52+ | 41 | 10 YR | - | - | 5 - 10 |
| | lower Qt8 | 85+ | 42 | 10 YR | - | - | 1 - 5 |
| Rio Hondo and Rio Pueblo de Taos Valleys | Qp1 | 128 | 29 | 8.25 YR | 86 | IV | 88 |
| | upper Qt2 | 200 | 84 | 7.5 YR-10 YR | 54 | III-IV | ~70? |
| | upper Qt3[2] | 90+ | 27 | 7.5 YR | 48 | III | 58 |
| | upper Qt4 | 90+ | 51 | 8.25 YR-10 YR | 38 | II+ -III | 44 |
| | upper Qt5[2] | 70+ | 60 | 10 YR | 80-150[3] | II-III | 32 |
| | lower Qt6 | 60+ | 30 | 7.5 YR-10 YR | 40-100[3] | II | 27 |
| | lower Qt7[2] | 50+ | - | - | - | - | 9 |
| Piedmont and Small Alluvial Fans | Qf1 | 50+ | 40+ | 7.5 YR | 80-140 | I+ -II+ | C-14 detes |
| | Qgm1 | 50+ | 50 | 7.5 YR | 50 | II-III | |
| | Qf2 | 250 | 115 | 8.75 YR-10 YR | 90 | I - I+ | 8590+150[4] |
| | Qgm2 | 90 | 90 | 7.5 YR-10 YR | 25 | I | |
| | Qf3 | 80 | - | 10 YR | - | - | 4850+140[4] 3500+240[5] 3600+130[5] |
| | Qgm3 | 30 | - | 10 YR | - | - | |

Horizontal lines in deposit column denote the break between upper and lower terrace sequence.
1 = height above local base level determined for approximate valley axis midline
2 = terrace deposit not present in Rio Pueblo de Taos valley.
3 = estimated from Kelson (1986)
4 = dates from Pazzaglia (1989)
5 = date from Wells et al. (1987)

red (7.5 YR) loamy argillic B horizon 10–50 cm thick. The argillic horizons exhibit moderate, medium prismatic, separating to moderate, fine subangular blocky structure and continuous, moderately thick to thick clay films. Calcium carbonate accumulation often extends through this profile for 2+ m into the underlying fluvial gravels as thin to thick coatings on the undersides of clasts.

Lower terrace sequence deposits such as Red River unit Qt5 exhibit a 1–2 m thick loess mantle that, unlike the upper terrace sequence deposits, generally lacks erosional contacts and multiple buried soils. A typical profile exhibits a thin A horizon overlying an argillic and occasionally calcic B which overlies a C horizon developed in the fluvial gravels (Fig. 4b). The epipedon is a 20 cm thick, dark brown (10 YR), loamy Ap horizon. The Ap horizon is underlain by a 40–100 cm thick, red (7.5 YR), reddish-brown (8.75 YR) and brown (10 YR), argillic horizon (Table 1). Carbonate accumulation for the topographically higher terrace deposits is stage II to II+. This accumulation diminishes to stage I for intermediate-level terraces and is completely absent in the lowest terrace near the modern stream.

Terrace surfaces, especially those near the valley margins, are often mantled by small (<0.1 km$^2$) alluvial fans derived from either higher terrace surfaces or the adjacent piedmont regions (Fig. 3). The small

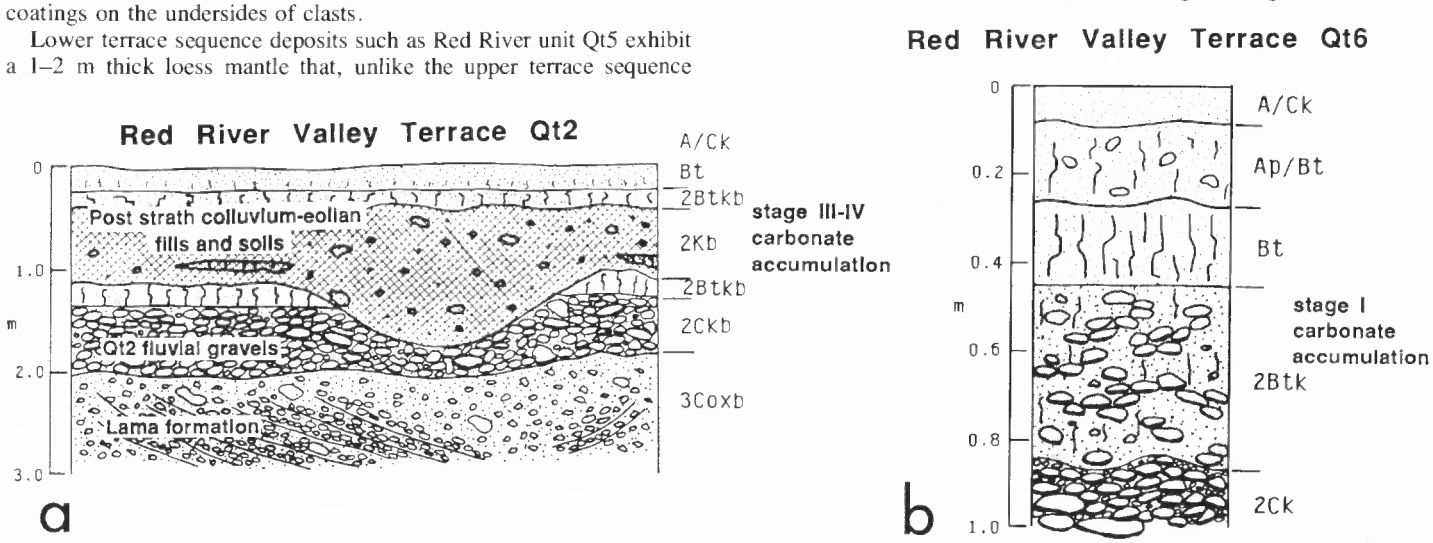



FIGURE 4. Soil stratigraphic columns of terrace deposits. Note the large differences in calcic horizon development and multiple buried soils vs. a single profile for the upper terrace sequence deposit (Fig. 4a) and lower terrace sequence deposit (Fig. 4b).

alluvial fans are composed of three units, Qf1, Qf2 and Qf3. Fan units are gray to yellow-brown, predominantly poorly sorted, angular to subrounded gravelly sand, sandy gravel and matrix-supported boulder sandy silt (Fig. 5a). The form and poorly sorted nature of these units, particularly of unit Qf3, suggest that they are debris flow deposits (Fig. 5b). Soil stratigraphy of a typical small alluvial fan deposit consists of dark (10 YR), organic rich surface horizons 10–30 cm thick (unit Qf3) above a weak, slightly reddened (8.75 YR), argillic horizon and relatively unaltered sand and gravel (unit Qf2) with stage I calcium carbonate accumulation. The base of the deposit is a red (7.5 YR) well-developed, silt-loam argillic horizon (unit Qf1). Lack of exposure prevented direct observation of the lower portion of the Qf1 soil and parent material; however, 0.5 m of a gravelly silty sand with many carbonate nodules was observed at one location.

Charcoal collected from a B horizon in a Qf2 unit (Lab # Beta-30143) and from the base of a stratified zone, overlying a debris flow bed in unit Qf3 (Lab # Beta-28621) in the Red River valley, were radiocarbon dated at $8590 \pm 140$ years and $4850 \pm 150$ years respectively. Another Qf3-type deposit in an arroyo-fill south of Taos has been dated at $3600 \pm 130$ years (Wells et al., 1987), which compares favorably with the Red River valley unit Qf3 date.

### Dissected piedmont landscape

The dissected piemont is located south of the Red River valley (Fig. 2) and is characterized by mostly ephemeral streams originating from small mountain front basins that have incised narrow, V-shaped canyons up to 75 m deep through the weakly consolidated Lama formation (silty-gravelly facies of Lambert, 1966). Typical longitudinal profiles of streams in this region are concave-up along the length of the piedmont but strongly convex near their confluence with the Rio Grande (Kelson, 1986; Wells et al., 1987). Few terraces are developed along the streams, although all are flanked by three well-developed pediment surfaces and deposits (Qp1, Qp2 and Qp3).

Pediment-gravel deposits are generally less than 5 m thick and composed of brown to yellowish-orange, poorly sorted, angular to subrounded, reworked Lama formation sediments. Soils developed in these deposits generally exhibit truncated profiles containing two to four buried calcic horizons with stage III–IV carbonate accumulation, and remnants of reddened (7.5 YR) argillic horizons separated by erosional, often channel-scoured contacts. These soil characteristics are indicative of periods of prolonged surface stability, probably associated with a stable base level that favored soil formation interspersed with periods of surface degradation probably associated with base-level fall. Pediment surface Qp1 occupies the highest broad, relatively flat interfluve regions and represents the reworked, post-depositional surface of the Lama formation prior to incision of the Rio Grande and its major tributaries. The topographic equivalent to pediment Qp1 in the axial portion of the basin is terrace Qt1 (Wells et al., 1987). Pediment surfaces Qp2 and Qp3 occupy narrow, relatively flat surfaces paralleling major drainages and are graded to and laterally correlative with the topographic elevation of fluvial terraces Qt2 and Qt3 in the Red River valley.

Interfluve areas near the mountain front–piedmont junction are generally mantled by small ($<0.1$ km$^2$), steep (0–15% slope) alluvial fans. The fans are derived from steep, first- or second-order (Strahler numbering) mountain-front-drainage basins and composed predominantly of a dark brown, poorly sorted, bouldery, sandy, mud with little to no soil profile development. The form, location and sedimentology of these fans suggest that they are relatively recent (middle-late Holocene) debris flow deposits.

### Undissected piedmont landscape

The undissected piedmont is located north of the Red River (Fig. 2) and the conspicuous nickpoint on the Rio Grande. Streams in this region are ephemeral, exhibit an approximately 100-m-high nickpoint at their confluence with the Rio Grande and are unincised along the length of the piedmont. Discharge and sediment from these streams rarely reach the Rio Grande, rather large alluvial fans have been deposited at the piedmont-mountain front junction (Fig. 2). Fans vary in size and shape ranging from small (0.2–5 km$^2$), steep ($>5°$ slope), elongate forms to large (5–14 km$^2$), gentle-sloped ($<5°$ slope), equant forms.

The fans are composed of three major depositional units, Qf1, Qf2 and Qf3. These units are composed of poorly sorted, angular to subrounded sandy gravel and gravelly sand (10–50 cm b-axis) interbedded with sand and silt. In the proximal fan areas, unit Qf3 is inset into unit Qf2 which in turn is inset into unit Qf1. Thus, the topographically higher surfaces are associated with the oldest deposits (unit Qf1) and are not undergoing active deposition. The topographically lower surfaces are associated with younger deposits (unit Qf3) and constitute the modern active fan depositional lobes.

Fan units Qf1 and Qf2 are 1–10 m+ thick and are composed of a brownish-red to yellowish brown, moderately well-sorted, weakly stratified, subangular gravelly sand, sandy gravel and gravelly sandy silt. These coarse-grained gravelly units are commonly overlain by reddish-brown, silt and sandy silt loess mantles. The moderate sorting and stratification in these units suggests they were deposited mainly by fluvial and possibly hyperconcentrated-flow processes (Wells and Harvey, 1987).

Soil development in unit Qf1 is characterized by a 1.5+-m-thick silt loam red (7.5 YR) argillic horizon with well-developed, coarse to medium, angular and subangular, blocky to fine prismatic structure (Fig. 6a; Table 1). Accumulation of calcium carbonate ranges from stage I+ to II+ and extends from the argillic horizon into underlying, typically coarser-grained material. Unit Qf2 soils exhibit a dark (10 YR), loamy, organic-rich A horizon 10–30 cm thick above a meter-thick slightly reddish (10 YR to 8.75 YR) silt loam or loamy sand argillic horizon with stage I carbonate accumulation (Fig. 6b; Table 1).

Unit Qf3 is a 1–10 m thick, dark, charcoal-rich, very poorly sorted, predominantly unstratified, subangular bouldery gravelly sand to bouldery mud deposit (Fig. 6c). This unit is found as short, steep fans at the mountain front piedmont junction, as sinuous, elongate, inset terraces along active channels and as debris fans at the termini of discontinuous arroyo channels. The large amount of fine-grained material, poor sorting and stratification, and deposit form, suggest that this unit was deposited largely by hyperconcentrated-flow and debris flow processes. Soils are very weakly developed or are non-existent in unit Qf3 deposits. The profiles are non-calcareous and are characterized by a dark (10 YR) loamy A horizon that overlies a dark (10 YR) cambic B horizon (Fig. 6c; Table 1). Charcoal from the B horizon of unit Qf3 has been dated at $3500 \pm 240$ years (Beta #30142).

### Guadalupe Mountain landscape

Guadalupe Mountain is a rhyodacite and olivine-andesite volcanic center composed of two peaks astride a broad saddle referred to as the central valley (Fig. 2). Small ephemeral drainages have deposited small alluvial fans (0.1–1 km$^2$) along the interior flanks of the mountain surrounding the central valley, and along the exterior flanks surrounded by the undissected piedmont (Fig. 2).

There are three major Quaternary deposits on Guadalupe Mountain, Qgm1, Qgm2 and Qgm3, and their soil morphologic characteristics closely resemble those of units Qf1, Qf2 and Qf3 in the large river valleys and in the undissected piedmont region. Sediments of the central valley and alluvial fans of Guadalupe Mountain are composed predominantly of volcanic detritus derived from hillslopes and eolian silt to fine-grained sand.

The soil stratigraphy of Guadalupe Mountain fan deposits is characterized by a silt and fine-grained sand (0–5 cm thick), vesicular A horizon (underlying a poorly developed desert pavement) overlain by a dark, organic-rich, silty loam A horizon (5.0–30.0 cm thick) (unit Qgm3). The argillic horizon is a black and dark brown to red and brownish-yellow clay loam with maximum stage I calcium carbonate accumulation (Qgm2). The base of the profile is a red (7.5 YR) clay-loam argillic horizon and gravelly sand with a 40+ cm thick stage II to II+ calcium carbonate accumulation. Archaeological artifacts ranging in age from 3000–1000 years were confined to the upper 20–30 cm of the surface indicating a mid- to late Holocene age for unit Qf3 (Pazzaglia, 1990) (Fig. 7; Table 1).

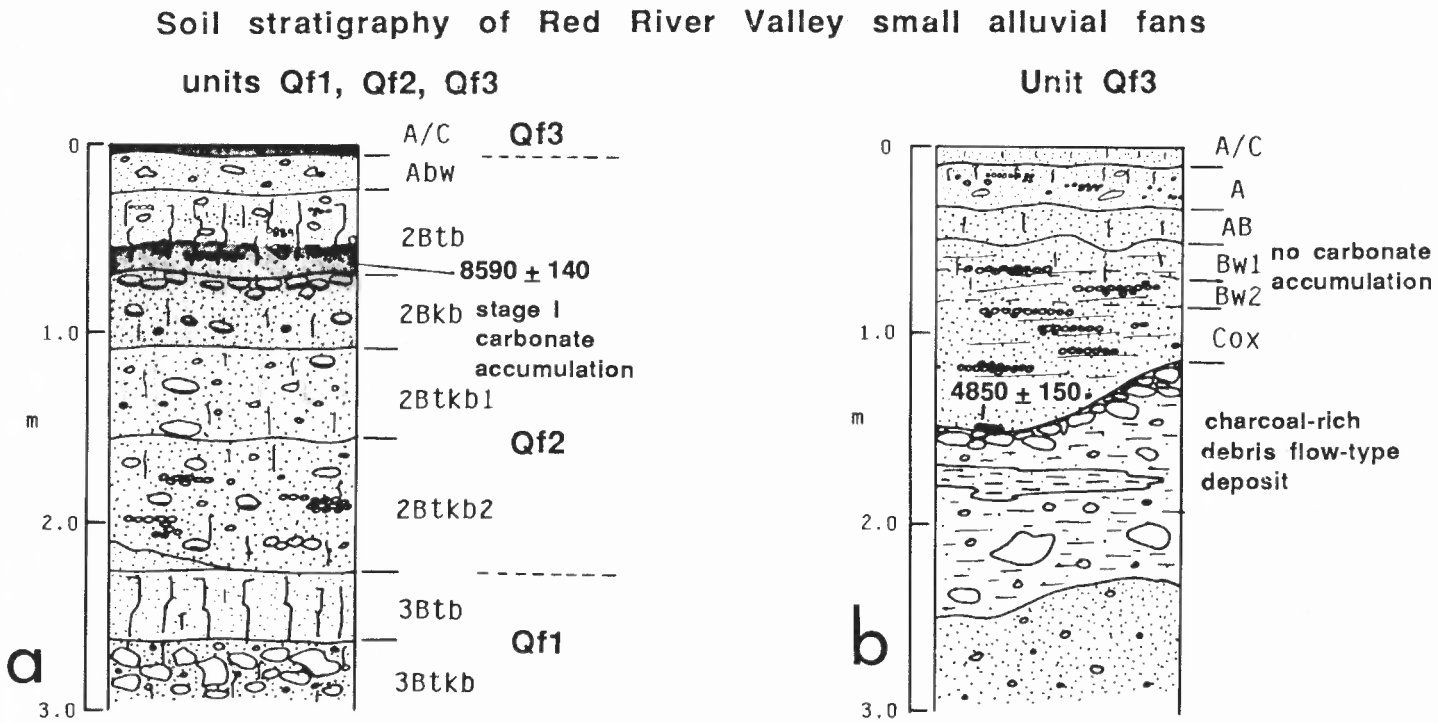



FIGURE 5. Soil stratigraphic columns of small alluvial fan deposits. Individual fan deposits (Qf1, Qf2, Qf3) are distinguished by stacked, buried soil deposits illustrated in Figure 5a. Radiocarbon dates help calibrate the ages of these units indicating a latest Pleistocene–early Holocene age for unit Qf2 and a mid-Holocene age for unit Qf3.

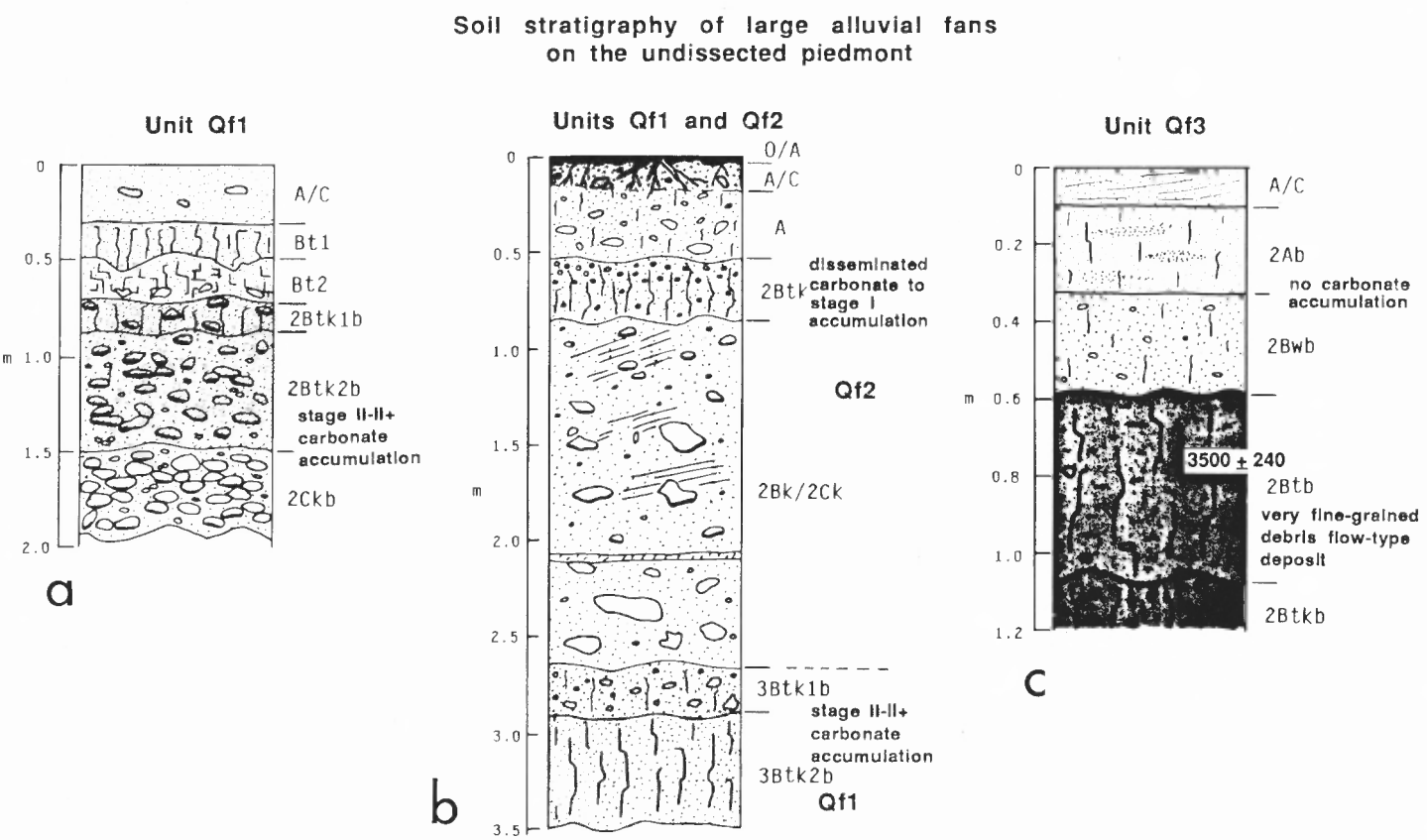



FIGURE 6. Soil stratigraphic columns of large alluvial fans on the undissected piedmont. The three fan units, Qf1, Qf2 and Qf3, exhibit a systematic decrease in the thickness and reddening of their argillic horizons and a decrease in calcium-carbonate accumulation. A radiocarbon date from unit Qf3 yields a mid-Holocene age.

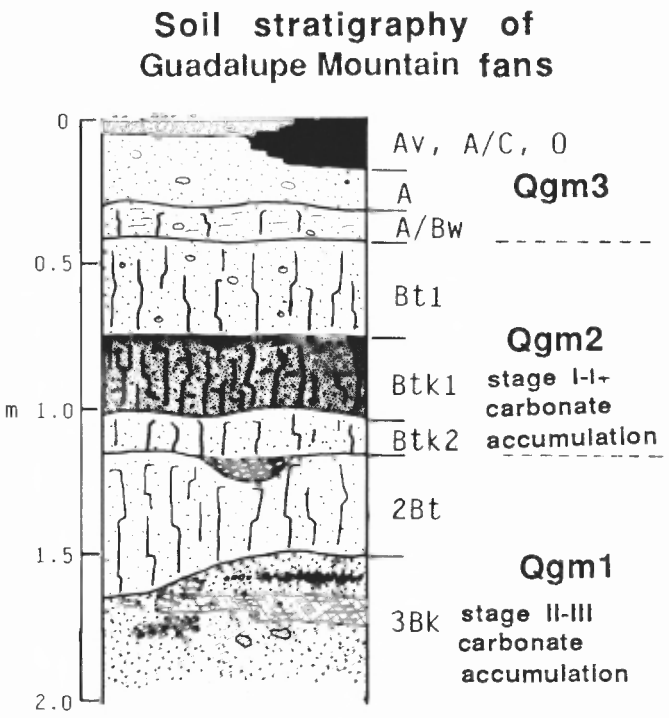



FIGURE 7. Soil stratigraphy of Guadalupe Mountain fans. Fan units are distinguished by stacked, buried soil profiles which are morphologically similar to small fan units in the incised river valleys and on the undissected piedmont.

TABLE 2. Relative age of Quaternary deposits and their correlation to adjacent areas.

| Red River Valley | Rio Hondo | Rio Pueblo | Small Fans | Piedmont fans | Guadalupe Mountain | Wesling (1988) | McCalpin (1983) | Aga Ka ** | Time Div. |
|---|---|---|---|---|---|---|---|---|---|
| Qt9 Qt10 | modern flood-plain | modern flood-plain | Qf3 3600±130 4850±150 | Qf3 3500±240 | Qgm3 | Three periods of talus deposition | Late / Neo-glacial | -3- | Holocene |
| | | | | | | Early Neoglacial 3570±140 | Early | | |
| Qt8 | | | | | | | Altithermal | -5- | |
| Qt7 | Qt7 | | 8590±140 Qf2 | Qf2 | Qgm2 | early Holocene-latest Pleistocene | Post Pinedale alluvium | -10- | |
| | | | | | | late / Pinedale | late / Pinedale | | late Pleistocene |
| Qt6 | | | | | | early / Till | early / Till | | |
| | | | | | | Interglacial | Intarglecial | | |
| Qt5 | Qt6 | Qt6 | Qf1 | Qf1 | Qgm1 | Bull Lake Till two morainas | Bull Lake Till | -2B- | late middle |
| Qt4 | | | | | | | | -86- | |
| | Qt5 | | | | | | pre-Bull Lake | | middle Pleistocene |
| Qt3 Qp3 | Qt4 | Qt4 | | | | | alluvium | | |
| | Qt3 | | | Lama formation | | | | | |
| Qt2 Qp2 | Qt2 | Qt2 | | | | | | -620- | early Pleistocene |
| Qp1 | Qp1 | Qp1 | | | | | | | |
| Qt1 | Qt1 | Qt1 | | | | | - Bishop Ash - 740 Ka | -736- | early Pleistocene |
| Lama formation | | | | | | | | | |
| ----- Jemez ash 1.1 ma * ----- | | | | | | | | | |

* = Jemez ash cropsout in two locations of the dissected piedmont area. One is 1 km south of the Red River Valley in a road cut on route 522. The second is opposite the Steak-out ranch road, 10 km south of Taos on NM route 522.

** = Quaternary aga assignments adopted from Richmond (1986) and Imbrie et al. (1984).

## CORRELATION OF QUATERNARY UNITS

Systematic changes in soil morphologic characteristics developed on fluvial terrace and alluvial fan deposits are used to construct a soil chronosequence (Table 1). In general, the older and topographically higher deposits such as the upper terrace sequence and pediment deposits exhibit multiple phases of soil development, thick, reddened argillic horizons and stage III to IV calcium carbonate accumulation. The lower and younger deposits represented by the lower terrace sequence and alluvial fan units exhibit a single phase of soil development with thinner, brownish-red argillic horizons and stage II+ to no carbonate accumulation. Calibrated ages for all Quaternary deposits (Table 2) are established by: (1) use of absolute radiocarbon dates; and (2) comparing relative soil development to a soil chronosequence constructed for Quaternary deposits of the northern San Luis basin (McCalpin, 1983) which is physically tied into the standard Rocky Mountain glacial stratigraphy (Richmond, 1962, 1986). Time divisions for the Quaternary are adapted from Imbrie et al. (1984) and Richmond (1986). The Holocene ranges from 0–10 Ka, the late Pleistocene ranges from 10–128 Ka, the middle Pleistocene ranges from 128–736 Ka, and the early Pleistocene ranges from 0.736–1.67 Ma (Table 2).

In general, relative soil development strongly suggests that deposition of the three major fan units on the undissected piedmont, in the incised river valleys and on Guadalupe Mountain was both episodic and temporally correlative. These episodes of fan deposition are also temporally correlative to deposition of the lower terrace sequence. A comparison to the soil chronosequence of McCalpin (1983) indicates that alluvial fan units and lower sequence terraces are late middle Pleistocene-Holocene in age. Red River terrace Qt5, Rio Hondo terrace Qt6 and alluvial fan unit Qf1 are interpreted to be correlative with Bull Lake glaciation. Red River terraces Qt6 and Qt7, Rio Hondo terrace Qt7 and alluvial fan unit Qf2 are interpreted to be latest Pleistocene to early Holocene in age, which is supported by the 8590 ± 140 years radiocarbon date, and correlative to late Pinedale glaciation. Alluvial fan unit Qf3 and all lower terraces are interpred to be mid- to late Holocene in age, which is strongly supported by the three radiocarbon dates of 3500 ± 240, 4850 ± 150 and 3600 ± 130 years (Table 2).

The upper terrace sequence and pediment deposits exhibit surficial and soil morphologic properties indicating that they are significantly older than the lower terrace sequence and fan deposits. Deposition of the Lama formation continued through the early Pleistocene along the entire piedmont until at least 1.1 Ma as indicated by the Jemez ash. Deposition of the Lama formation ceased in favor of upper terrace sequence and pediment deposits in the dissected piedmont region following incision of the major river valleys in response to Rio Grande base-level fall. Regional base-level lowering is probably related to Rio Grande drainage integration and thought to have occurred between 1.1 and 0.6 Ma (Wells et al., 1987). McCalpin (1983) describes a bed of reworked Bishop ash (740 Ka) within a pre–Bull Lake fan deposit with soil characteristics similar to those observed in pediments Qp1 and Qp2 and terrace Qt2. Pediments and upper terrace sequence deposits are inferred to be correlative with McCalpin's pre–Bull Lake deposits and therefore were deposited in the middle Pleistocene. Periods of Lama formation deposition interspersed with relative surface stability continued on the undissected portion of the piedmont (Pazzaglia, 1989) until the deposition of fan unit Qf1 in the late-middle Pleistocene.

## CLIMATIC INFLUENCES ON DEPOSITION OF QUATERNARY UNITS

The results of the stratigraphic and soil morphologic study have demonstrated the Quaternary deposits associated with different landforms and located in different landscape regions such as undissected and dissected piedmont are temporally correlative. The stratigraphy and relative soil development of fan and terrace deposits are similar to the Quaternary stratigraphy in the northern San Luis basin where piedmont deposits can be physically traced eastward to glacial deposits in the Sangre de Cristo Mountains (McCalpin, 1983; Richmond, 1962, 1986). These results suggest that fan and terrace deposition may be related to glacial events and that Quaternary climatic changes have played an important role in the development of the observed stratigraphy.

The results obtained from Guadalupe Mountain strongly support this hypothesis. All other landscapes identified in this paper are subject to Rio Grande base-level rise or fall, tectonic uplift, drainage basin hydrology and lithologic variations in addition to regional climatic fluctuations. Due to its location, uniform lithology and isolated drainage system, the sole remaining geomorphic driving force that could affect the Guadalupe Mountain landscape is climatic change. Since Guadalupe Mountain stratigraphy and geomorphology is virtually identical to late middle Pleistocene-Holocene deposits observed in other landscape regions, late Quaternary climatic change, manifest as glacial and interglacial periods, is hypothesized to have strongly influenced the Quaternary stratigraphy.

Unit Qf3 is also of particular interest in terms of establishing a relationship between climatic change and Quaternary stratigraphy. The abundance of charcoal in alluvial fan unit Qf3 suggests that its deposition may be related to rapid devegetation and destabilization of hillslopes following large forest fires. Large fires have probably occurred throughout the Holocene, yet most Qf3-type deposits appear to be temporally restricted to the mid-Holocene (5000–3000 years). Wesling (1988) has identified neoglacial moraines in the Sangre de Cristo Mountains. Charcoal from a moraine has been dated at $3570 \pm 140$ years (Wesling, 1988). It is hypothesized that climatic conditions associated with this neoglaciation during the mid-Holocene, coupled with destabilization of the hillslopes induced by large forest fires, produced conditions promoting the delivery of sediment from the basin to the piedmont via debris flow processes. Climate change from warmer, drier conditions present in the early Holocene to cooler, more moist conditions featuring a summer monsoon circulation pattern (Van Devander and Spaulding, 1979; Spaulding et al., 1983; Van Devander et al., 1987) and/or a more southerly winter storm track (Enzel et al., 1989) may have introduced enough moisture causing drainage basins to shed sediment following devegetation by forest fires. Analogously, deposition of older alluvial fan units Qf2 and Qf1 might be expected to occur in response to the complex interactions of available moisture and change in vegetative cover introduced by climatic fluctuations of cool-moist to warm-dry and vice versa associated with Pinedale and Bull Lake glaciations.

Other late-middle Pleistocene-Holocene deposits such as the lower terrace sequence (Qt5–Qt10) may also be related to deglaciation and associated outwash events. However it should be noted that despite the similarities in soil morphology and the ability to establish fairly well-constrained correlations, there are different numbers of terrace surfaces in the Red River, Rio Hondo and Rio Pueblo de Taos valleys. This is most likely the result of complex basin response to variable size, shape, lithology and hydrology to a regional climatic change. For example, Kelson (1986) suggests that no significant aggradation occurred in the Rio Hondo valley during deglaciation of the Rio Hondo drainage basin. It is hypothesized that the Rio Hondo maintained relatively high stream power due to basin lithology and hydrology (Kelson and Wells, 1987, 1989) during glacial and deglaciation episodes such that glacially derived sediment was transported completely out of the basin. This does not appear to be the case for the Red River valley. The lower terrace sequence is actually a thin fill deposit overlying the Lama formation. The broad alluvial fan developed along the present Cabresto Creek drainage (Figs. 1, 2), which joins with the Red River in the Red River valley, attests to that stream's inability to transport sediment effectively across the piedmont region resulting in an aggradational wedge of sediment near its confluence with the Red River (Fig. 2).

## CONCLUSIONS

The geomorphology of the eastern flank of the San Luis basin in New Mexico can be characterized by middle Pleistocene-Holocene alluvial fan, fluvial terrace and pediment deposits overlying the Pliocene–middle Pleistocene Lama formation basin-fill sequence. These deposits are distributed among four major physiographic landscapes: (1) the dissected piedmont; (2) undissected piedmont; (3) incised river valleys; and (4) Guadalupe Mountain. These landscape regions and their predominant landforms owe their morphologic expression to tectonic and drainage integration processes (Menges, 1988, 1990; Wells et al., 1987). However, stratigraphic, sedimentologic and soil morphologic investigations have demonstrated that Quaternary deposits are morphologically similar and temporally correlative across the different landscape regions.

Deposition of Lama formation basin fill proceeded from the Pliocene through the early Pleistocene. Lama formation deposition ceased, and deposition of the upper terrace sequence and pediment deposits began in response to incision of the Rio Grande and its larger tributaries such as the Red River and Rio Hondo. Initiation of the incision is related to a base-level fall following Rio Grande drainage integration during the late early-to-middle Pleistocene based in part on estimated ages of the upper terrace sequence deposits. Deposition of the Lama formation interspersed with periods of relative surface stability favoring soil development proceed on the undissected piedmont until the late middle Pleistocene.

The late-middle Pleistocene-Holocene is characterized by the genesis of large alluvial fans on the undissected piedmont and a sequence of cut and fill terraces in the incised river valleys. The late-middle Pleistocene-Holocene fan and terrace deposits are separated by soils indicating that periods of relative surface stability existed between periods of deposition. Relative ages for these deposits, derived from a soil chronosequence, suggests that the depositional episodes are correlative to major periods of glaciation in the late Quaternary. Analysis of the youngest fan deposit, unit Qf3, demonstrates the complex interaction between available moisture and vegetative cover associated with climatic fluctuations of a neoglacial event on the deposition of this Holocene unit.

It is proposed that at least since the late-middle Pleistocene, the stratigraphy of landforms along the southeastern flank of the San Luis basin has been strongly influenced by climatic fluctuations associated with glacial and interglacial events. The effect of climatic change on deposits older than late-middle Pleistocene, however, is not clearly evident in the stratigraphy of these units. Middle Pleistocene strath terraces and pediment deposits are more sensitive to and record the larger scale changes in base level rather than climatic fluctuations.

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