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1996, pp. 335-345. https://doi.org/10.56577/FFC-47.335

in:

Jemez Mountains Region, Goff, F.; Kues, B. S.; Rogers, M. A.; McFadden, L. S.; Gardner, J. N.; [eds.], New Mexico Geological Society 47th Annual Fall Field Conference Guidebook, 484 p. https://doi.org/10.56577/FFC-47

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QUATERNARY STRATIGRAPHY, TECTONIC GEOMORPHOLOGY AND LONG-TERM LANDSCAPE EVOLUTION OF THE SOUTHERN SIERRA NACIMIENTO

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Abstract—The geomorphic expression of the Sierra Nacimiento-Colorado Plateau margin in northern New Mexico is consistent with an active tectonic landscape. In light of recent studies that have documented a protracted period of deformation, we investigate the relative roles of active tectonism and erosional exhumation in shaping the landscape of the Sierra Nacimiento. We mapped the southern Sierra Nacimiento from Arroyo Peñasco in the west, around the southern portion of the range, and east to the town of Cañones in the Jemez River drainage basin. Based on correlation of post-Bandelier Tuff terrace deposits in the Jemez River drainage basin, we establish a Quaternary stratigraphy with relative ages for surficial deposits based on limited ^{14}C radiometric ages, the occurrence of Lava Creek B ash, dated at approximately 620 ka, and soil stratigraphy and morphology. In the Arroyo Peñasco drainage basin, three mapped units, including the youngest Holocene terrace, are offset by faults that generally exhibit down-to-the-west, normal components of slip and stratigraphic separations ranging from 1.2 to 4.2 m. Two of these Quaternary faults are coincident with the Nacimiento range-bounding fault. In the Jemez River drainage basin, Quaternary faults offset the oldest terrace deposit dated at approximately 620 ka, based on a single bed of Lava Creek B ash that occurs within the Qt1 terrace deposit. All faults in this basin display down-to-the-southeast, normal components of slip with stratigraphic separations ranging from 1 to 8.2 m. We suggest that the Quaternary landscape of the southern Sierra Nacimiento has responded to neotectonism related to extensional deformation of the adjacent Rio Grande rift. Neotectonic deformation has reactivated pre-existing structures, increased local relief and played a partial, but important role in fluctuations in local base level. Variations in local base level destabilized surficial deposits and accelerated the process of erosional exhumation. Relatively high incision rates, (0.16 m/1000 yrs), since approximately 600 ka, and low average rates of Quaternary fault offset (0.03 m/1000 yrs) indicate that the long-term evolution of the southern Sierra Nacimiento is predominantly one of erosional exhumation rather than tectonic uplift.

INTRODUCTION

The Sierra Nacimiento lies at the tectonic boundary between the eastern margin of the Colorado Plateau and the western margin of the Rio Grande rift (Fig. 1). Previous investigators have speculated on the Laramide and post-Laramide deformational history of the eastern margin of the Colorado Plateau, proposing from 5 to 60 km of dextral strike-slip movement along the Nacimiento range-bounding fault (Baltz, 1967; Chapin and Cather, 1981; Woodward, 1987; Karlstrom and Daniel, 1993). Proponents for both low and high estimates of strike-slip movement base their reasoning on a spectrum of geologic and geophysical evidence, including the remarkably linear map trace of the range-bounding fault (Fig. 1).

The geomorphic expression of the Sierra Nacimiento is consistent with an active tectonic landscape based on the premise that recent uplift straightens and steepens mountain fronts (Bull and McFadden, 1977). However, the Nacimiento fault juxtaposes resistant Proterozoic crystalline rocks against less resistant Paleozoic and Mesozoic sedimentary rocks. It remains unclear what component of contemporary topographic relief can be attributed to rock type alone. In this paper, we use detailed Quaternary mapping and tectonic geomorphologic analyses to investigate the relative roles of post-Laramide tectonism versus erosional exhumation in shaping the landscape of this portion of the Colorado Plateau-Rio Grande rift margin. We focus our field work in the southern Sierra Nacimiento because it lies at the critical juncture of the Colorado Plateau-Rio Grande rift margin.

Several investigators have examined Quaternary stratigraphy throughout Colorado and New Mexico with the purpose of deciphering the geologic evolution of the Rio Grande rift (e.g., Bryan and McCann, 1936; Bryan, 1938; Wright, 1946; Ruhe, 1967; Lambert, 1968; Bachman and Mehnert, 1978; Hawley, 1978; Wells, et al., 1987; Dethier et al.,1988; Gonzalez and Dethier, 1991; Connell, 1995; Reneau et al., this volume). Previous studies, including Gonzalez and Dethier (1991), Gonzalez, (1993), and Rogers and Smartt (this volume), have laid the groundwork for understanding the Quaternary stratigraphy of the southern Sierra Nacimiento. This paper represents work in progress; we are still in the preliminary stages of correlating the Quaternary stratigraphy from Arroyo Peñasco in the west, around the southern Sierra Nacimiento, including the Rio Salado drainage basin north of NM-44, to the town of Cañones in the Jemez River drainage basin (Fig. 1). Detailed mapping (1:24,000 scale) of neotectonic features associated with this stratigraphy, and soil stratigraphic analyses allow us to address the processes of landscape evolution specifically in terms of active tectonism versus erosional exhumation.

PHYSIOGRAPHIC, GEOLOGIC AND GEOMORPHIC SETTING

The southern Sierra Nacimiento lies at the juxtaposition of the Colorado Plateau, the southern Rocky Mountains, the Rio Grande rift, and the Jemez volcanic field. Sierra Nacimiento is a basement-cored, Laramide uplift located within the southern Rocky Mountain physiographic province. The study area lies in the southern portion of the Sierra Nacimiento (Fig. 1).

The Quaternary landscape of this region reflects a long and diverse history of tectonic events, including a structural fabric inherited from Proterozoic orogenesis (Karlstrom and Daniel, 1993) and fault-block uplifts associated with late Paleozoic ancestral Rocky Mountain deformation (Woodward, 1987). The Late Cretaceous to Eocene Laramide orogeny redefined the western structural boundary of the Sierra Nacimiento as a segmented, north-trending, oblique-slip, reverse fault that juxtaposes Cretaceous and early Tertiary sedimentary rocks of the San Juan Basin to the west against uplifted Proterozoic basement rocks to the east (Woodward, 1987) (Fig.1).

Late Cenozoic deformation associated with the evolution of the Rio Grande rift is superimposed along the southern terminus of the Sierra Nacimiento. Local rift-margin faults including the San Ysidro, Sierrita and Jemez fault zones (Fig. 1) delineate the westernmost boundary of the Rio Grande rift and the northeastward extension of the Rio Puerco fault zone (Slack and Campbell, 1976). Neotectonism is also manifest, in part, by microseismicity along the western margin of the range (Fig. 2).

Total relief for the Sierra Nacimiento is about 1600 m, with the highest elevation reaching 3400 m at San Pedro Peaks. The steep western escarpment of the mountain range has a topographic relief of approximately 915 m, but relief diminishes to the south and is approximately 500 m in the study area.

QUATERNARY STRATIGRAPHY

Jemez River drainage basin

Fluvial stratigraphy in the Jemez River drainage basin consists (Table 1) of a flight of four inset Pleistocene fill terraces (Qt1-Qt4), three pied-

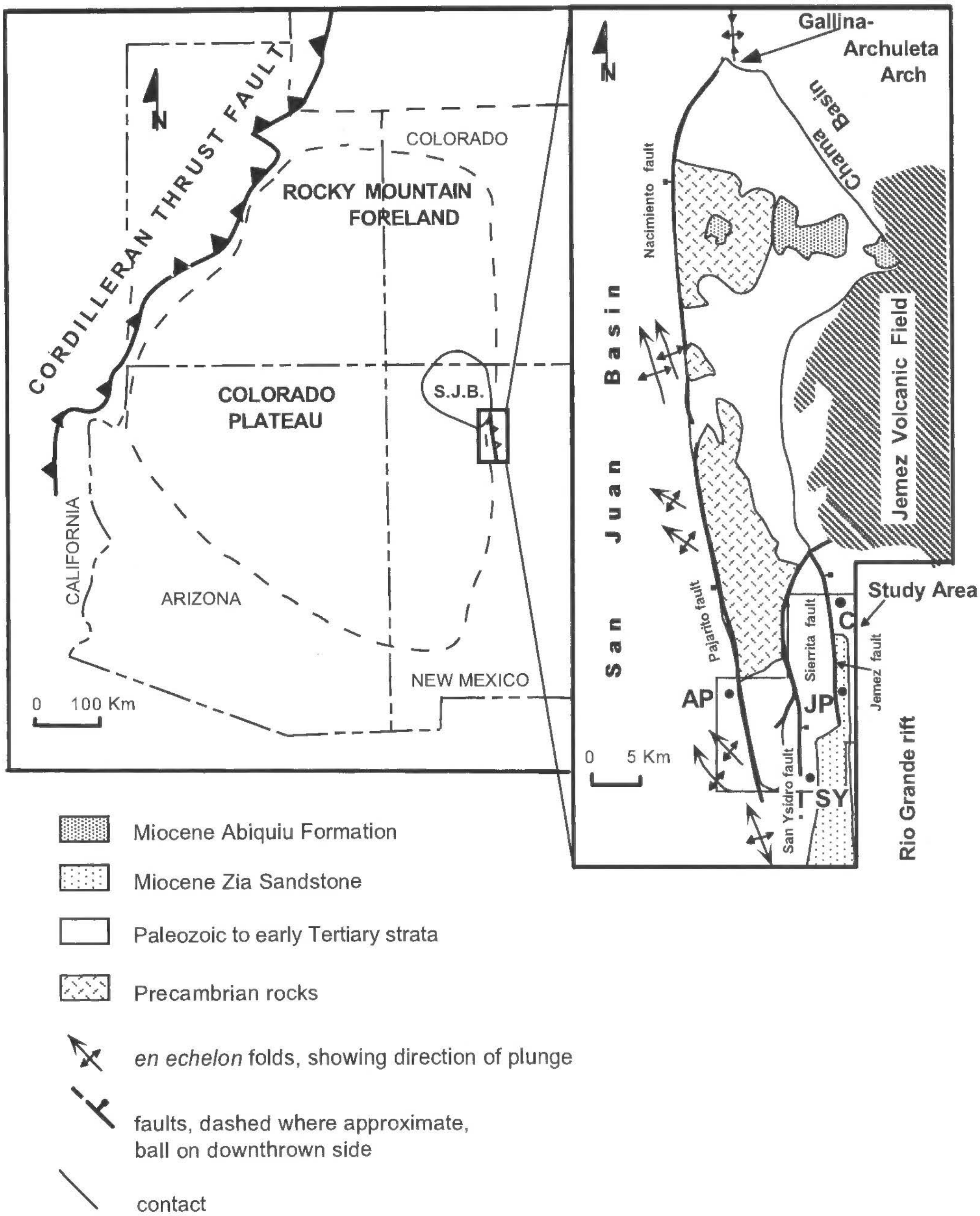


FIGURE 1. Location and schematic regional tectonic map of the Sierra Nacimiento. AP=Arroyo Peñasco; SY=SanYsidro; C=Cañones; JP=Jemez Pueblo. After Woodward (1987) and Miller (1992).

mont alluvial deposits (Qp1, Qp2, Qp4), and two Holocene fill-cut terraces (Qt5, Qt6). The highest terrace surface (Qt1) is underlain by 14 m of alluvium. Terrace deposits consist of a gray, coarse sandy-gravel base (3 m thick), with a fine-grained sandy-silt unit (approximately 9 m thick) that is overlain by a coarse sand and gravel unit (2.85 m thick). The strath has up to 1 m of local relief and lies from 91 to 110 m above the modern channel. Terrace gravel clasts consist of 23% Precambrian granite, 27% Pennsylvanian Madera Formation, and 27% Bandelier Tuff, with minor amounts of quartzite, chert and Permian-Triassic sandstones. Lava Creek B ash (Rogers, this volume) dated at 0.60 ± 0.15 Ma (Naeser et al., 1973) is found within the fine-grained sand unit, approximately 10 m below the terrace tread.

Terrace deposits Qt2 and Qt4 exhibit a similar stratigraphy; basal gravels cemented with calcium carbonate, overlain by fine-grained sands and silts, capped by an upper gravel bed defining the terrace tread (Table 2). Terrace deposit Qt3 consists of approximately 10 m of rounded gravels and lacks fine-grained sandy-silt deposits.

Holocene fill-cut terrace surfaces (Qt5 and Qt6) are underlain by red to tan, fine-grained sands and silts. The straths lie 8 and 2 m, respectively, above the modern channel. Charcoal from about 1 m below the surface of Qt5 yielded a date of 1660 ± 70 radiocarbon years BP (Beta #85445). Subsurface data, including well data (B. White, personal commun.), and 2-D seismic imaging, record up to 33 m of channel alluvium buried beneath the modern channel (J.C.Witcher, unpubl. report for Southwest Technology Development Institute, 1990).

Piedmont alluvial deposits (Qp1, Qp2, Qp4) are commonly red, locally stratified, angular coarse gravels and sand, that are locally cemented with calcium carbonate and range from 0.5 to 6 m in thickness. Clast composition consists predominantly of Precambrian granite, Pennsylvanian Madera limestone and Permian-Triassic sandstones. Recognition of piedmont deposits is facilitated by the lack of axial stream gravel rock types, including the Bandelier Tuff. Piedmont deposits Qp1 and Qp2 occupy narrow, relatively flat interfluves that locally bury fluvial terraces Qt1 and Qt2 (Figs. 3, 4).

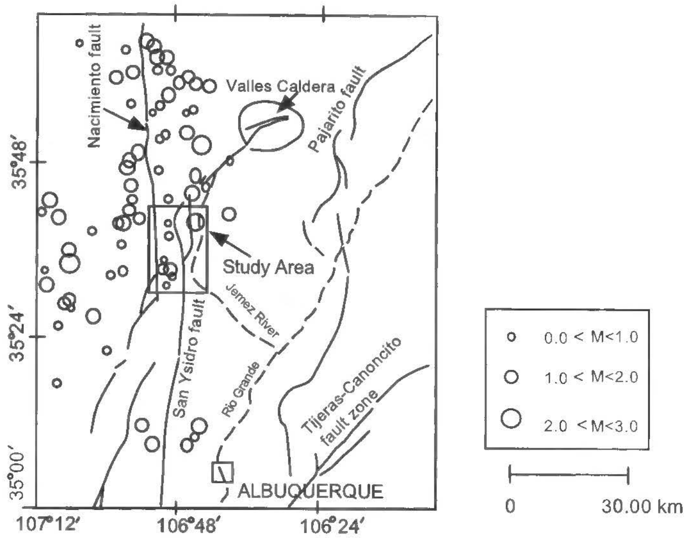


FIGURE 2. Selected major faults (solid lines) and well located earthquakes along the Sierra Nacimiento front between December 1973 and August 1994. Symbol size is proportional to earthquake magnitude. Dashed lines indicate major drainages, Rio Grande and Jemez River. After House and Hartse (1995).

Arroyo Peñasco drainage basin

Arroyo Peñasco flows south from Pajarito Peak, trends parallel to the mountain front and joins the Rio Salado near the southwest corner of Sierra Nacimiento (Fig. 5). Five major Quaternary deposits comprise the piedmont portion of the Arroyo Peñasco drainage basin: pediment-fan deposits (Qpf1.P), terrace deposits (Qt2.P, Qt4.P) (Table 1), travertine mounds (Qtrm) and travertine deposits (Qtr) (Fig. 5). Quaternary pediment-fan complexes are relatively narrow, proximal alluvial fan and pediment deposits restricted to interfluves. The deposits are of variable thickness ranging from a thin gravel lag to approximately 6 m of red, subangular, poorly-sorted and weakly stratified gravels and boulders in a silty-sand matrix. The base of the pediment-fan complex is concave-up, has 1 m of local relief and lies from 15-20 m (in the distal fan) to 100 m (in the proximal fan) above the modern Arroyo Peñasco channel. Gravel-boulder clasts are composed of locally derived Precambrian granite and Permian-Triassic rocks.

Fill terrace (Qt2.P) is underlain by alluvium ranging from 3 to 25 m thick. The terrace deposit consists of gravels in a red, pebbly-sand matrix that are locally intercalated with laminated travertine deposits up to 5 m thick. The strath exhibits up to 1 m of local relief, ranges from 13 to 25 m above the modern channel, and lies unconformably on Triassic bedrock. Terrace gravels are cemented with calcium carbonate and consist of 56% Precambrian granite and 26% Permo-Triassic rocks with minor amounts of Pennsylvanian Madera limestone and Jurassic Entrada sandstone.

Holocene terrace (Qt4.P) is underlain by alluvium ranging from 3 to 8 m thick. The deposit consists of red, pebbly sands and silts with a bioturbated yellow-gray, organic-rich clay and silt layer. The strath exhibits less than 1 m of local relief, lies about 3 m above the modern channel, and gradually slopes into the active floodplain, downstream of the study area. Charcoal from three locations, approximately 1 m below the Qt4.P terrace tread, yield dates of 2170±40 radiocarbon years BP in the upper reach (Beta #85446); 960±60 radocarbon years BP in the middle reach (Beta #85443); and 2290±70 radiocarbon years BP in the lower reach (Beta #85444) of the study area.

At least 18 active and non-active mounds occur in the Arroyo Peñasco drainage basin (Fig. 5). Quaternary travertine mounds surround constructional, circular springs that protrude up to 25 m above the adjacent landscape. The mounds can have diameters up to 15 m (Fig. 6). In general, mounds found closer to the mountain front have circular vents or "pipes" that are at least 20 m deep. Mounds that are close to the modern channel, in both elevation and location, have vents that are typically 10+ m deep. For data on water chemistry of these springs, see Gardner et al. (this volume). Quaternary travertine consists of light tan, thick- to thin-bedded sheet deposits that occur up to 15 m thick.

Soil stratigraphy

Eleven soil pits were dug and described (following Birkeland, 1984) throughout the study area. Soil pits were located on piedmont and fluvial terrace treads, throughout the Jemez drainage basin (Qt1-Qt5 and Qp2); on Quaternary fans (Qf.RS) and alluvium (Qal.RS) along the Rio Salado; and on a Quaternary pediment-fan deposit (Qpf1.P) along Arroyo Peñasco. Soil stratigraphy and morphology is complex and generally characterized by stripped surface horizons overlying one or more buried soils. Episodic erosion and/or burial of surface remnants results in soil development that may not always reflect deposit age.

In general, the soils described throughout the study area consist of soil profiles that are approximately 1 m thick, have thin AC horizons that contain minor amounts of disseminated calcium carbonate, and overlie well-developed Bk and K horizons with stage I to III+ calcium carbonate stage morphology (Gile et al., 1966). In all but two cases, (Qp2 and Qt5

TABLE 1. Relative ages for Quaternary deposits of the Jemez River and Arroyo Peñasco drainage basins.

Jemez River Drainage Basin			**Arroyo Peñasco Drainage Basin**		
UNIT	AGE	SOURCE	UNIT	AGE	SOURCE
Qt6 Qt5	1660±70*	Beta #85445 standard			
			Qt4.P	2170±40*(upper reach) 960±60*(mid-reach) 2290±70*(lower reach)	Beta #85446 AMS Beta #85443 standard Beta #85444 standard
Qp4	150ka ± 50,000***	This report	Qt3.P	150ka ± 100,000(?)***	This report
Qt4	150ka ± 50,000**	This report	Qt2.P	200ka ± 100,000(?)***	This report
Qt3	300ka ± 100,000**	This report	Qpf1.P	300ka ± 100,000**	This report
Qp2	400ka ± 100,000**	This report			
Qt2	400ka ± 100,000**	This report			
Qp1	0.6 ± 0.15 Ma	Naeser et al.,1973			
Qt1	0.6 ± 0.15 Ma	Naeser et al.,1973			

Notes:
* = all ages in radiocarbon years B.P.
** = estimated from soil stratigraphy, regional correlation and landscape-topographic position.
***= estimated from landscape-topographic position.

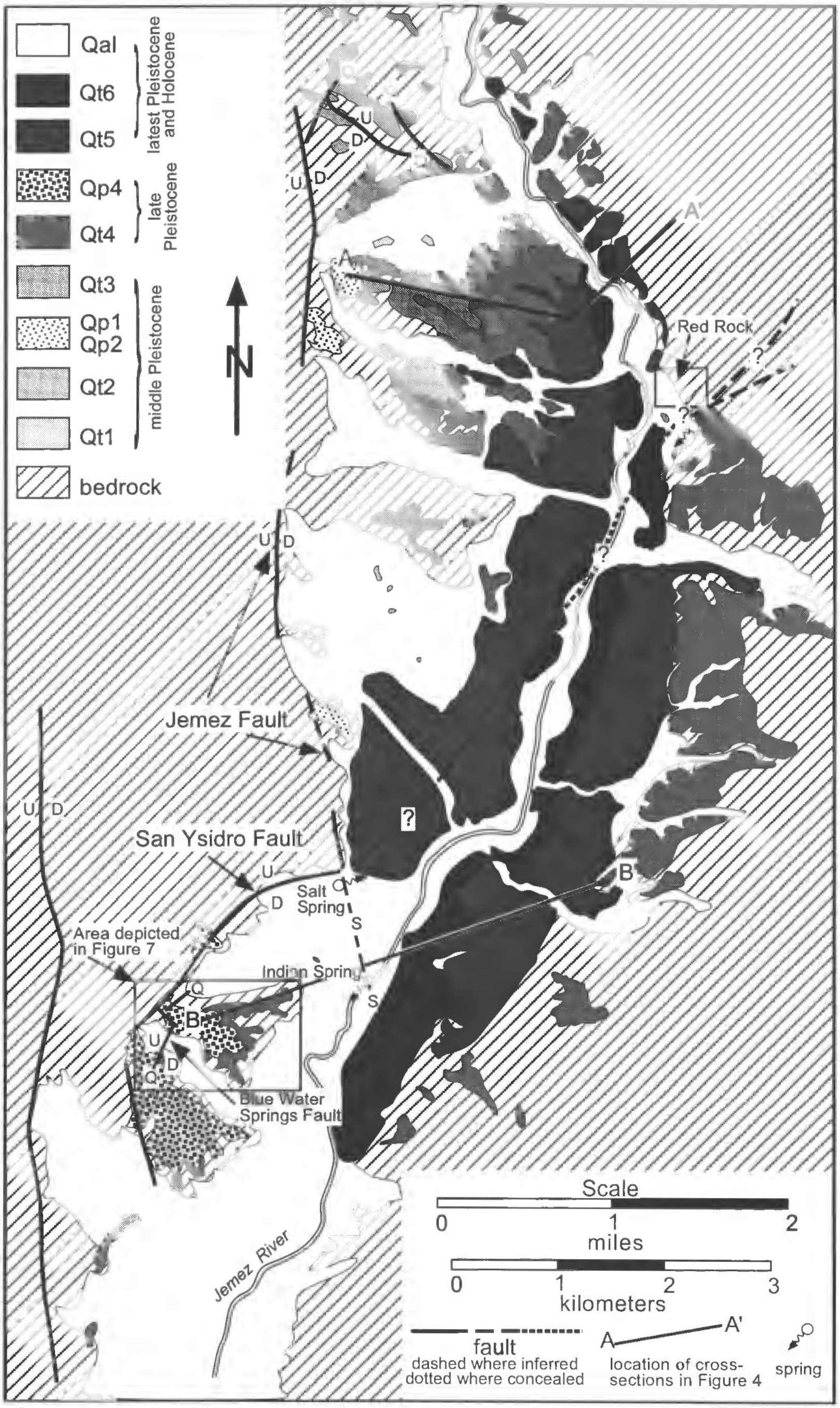


FIGURE 3. Quaternary map showing the lower reach of the Jemez drainage basin with surficial deposits and associated Quaternary faults, denoted by Q. Faults interpreted from seismic lines are denoted with S (J. C. Witcher, unpubl. report for Southwest Technology Development Institute, 1990). Cross sections A-A, and B-B are shown on Figure 4.

TABLE 2. Representative section of Jemez River drainage basin inset terrace stratigraphy.

units	Measured Stratigraphic Section (Qt1 - Jemez River drainage basin) lithology	Top of Section thickness (m)
13	Colluvial mantle; orange and grey; loose gravels and grus; predominantly Precambrian granite and Pennsylvanian Madera limestone.	not measured
12	Gravels and Boulders; grey; rounded; poorly-sorted; cemented with calcium carbonate; (maximum clast size: 42 cm); pebbly-sand matrix; clast-supported; rock types: granite, limestone, Tertiary volcanics, Bandelier Tuff, Permo-Triassic sandstones, Pedernal chert.	2.85
11	Siltstone; buff; sub-rounded and mod.-poorly sorted; lenses of granitic pebbles; fines upward.	1.50
10	Mudstone; dark-brown; bioturbated with abundant rootlets.	0.04
9	Pebbly-sandstone; buff-grey; well-rounded, moderately-sorted; weak planar cross-beds; fines upward.	1.00
8	Siltstone; buff; planar-laminated.	0.20
7	Pebbly-siltstone; buff-pink; granitic sands interbedded with lenses of massive silt; calcareous; locally cemented.	2.56
6	Siltstone; buff; ripple laminated; calcareous.	0.86
5	Siltstone; red-pink; with Lava Creek B ash; cemented with calcium carbonate; forms a ledge.	0.65
4	Lava Creek B ash reworked with buff sands and silts; cemented with calcium carbonate; forms a ledge.	0.55
3	Mudstone; yellow-buff to dark brown colored; with abundant rootlets; calcareous nodules.	0.70
2	Siltstone; red; with abundant rootlets; calcareous nodules.	0.05
1	Gravels; grey; rounded; moderately sorted; cemented gravels and boulders (maximum clast size: 34 cm) with pebbly sandy matrix; clast-supported; rock types: granite, limestone, Tertiary volcanics, Bandelier Tuff, Permo-Triassic sandstones, Pedernal chert. Planar, unconformable contact with Permo-Triassic bedrock.	2.28
		base of section

have weakly developed Bt horizons) soil profiles lack clay accumulation.

The soil stratigraphy of the Qt4 terrace deposit on the west side of the Jemez River drainage basin is atypical. Here, soil development is characterized by a weakly developed desert pavement that overlies a 2 cm-thick, dark (7.5 YR), vesicular A horizon with platy structure and an erosional lower contact. The underlying horizons consist of three buried Bk horizons with silty loam textures and maximum stage I carbonate accumulation. Below these horizons, is parent material, a 29 cm-thick Ck horizon, with planar cross-beds. The Ck horizon contains calcium-carbonate cemented silt rip-ups, approximately 10-30 cm in diameter,

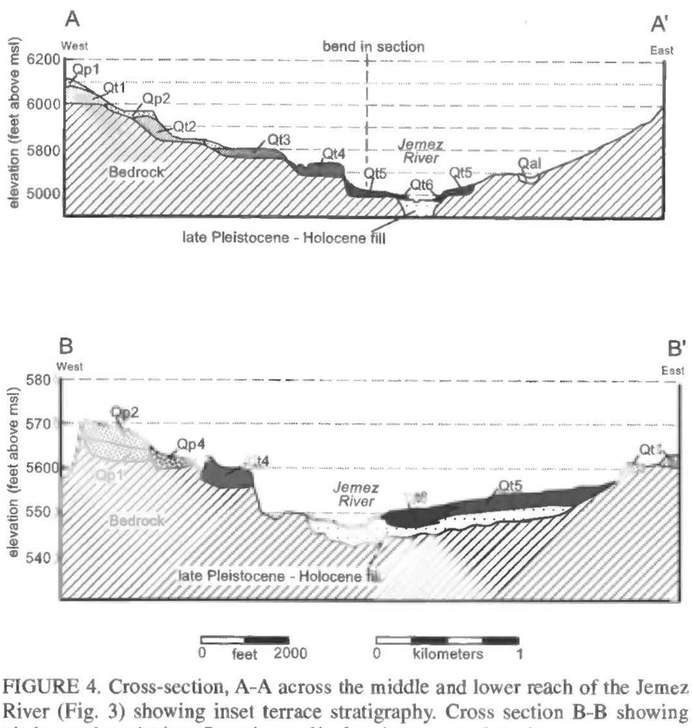


FIGURE 4. Cross-section, A-A across the middle and lower reach of the Jemez River (Fig. 3) showing inset terrace stratigraphy. Cross section B-B showing piedmont deposits interfingering and/or burying terrace deposits.

reworked from upland piedmont soils. Below the Ck horizon, this same pattern of buried calcic horizons overlying parent material is repeated. The second suite of buried horizons consists of a 32 cm-thick Bk horizon that is variegated with red (7.5 YR) and pale pink (5 YR) colors, and stage II carbonate accumulation. Below this horizon, is a 20 cm-thick C horizon that occurs at the base of the soil pit (120 cm). This horizon is preferentially cemented with calcium carbonate.

SOIL-LANDSCAPE RELATIONSHIPS

The complex soil stratigraphy throughout the southern Sierra Nacimiento does not lend itself to the construction of a chronosequence; however, the soils do help reconstruct important landscape processes. For example, relative height above local base level for correlating piedmont stratigraphy is misleading. In the Blue Water Spring region, soil-morphologic characteristics demonstrate that Qp2 buries Qp1, whereas Qp4 deposits are typically reworked from Qp2 deposits upslope (Figs. 3, 7).

In addition, field relationships and soil stratigraphy suggest that weakly developed surface soil horizons of Qt4 are younger than the underlying, buried horizons that are perhaps more representative of deposit age. This interpretation is verified in the Blue Water Spring region, where Qt4 is partially buried by Qp4 and inset below Qp2 (Fig. 4, cross section B-B′).

Soils developed on surface remnants that are contiguous with the mountain piedmont are differentiated by a complex superimposition of soil horizons. In contrast, soils developed on surface remnants that are topographically isolated in the landscape tend to be stripped and exhibit well-developed, gravelly Bk or K horizons at the surface. Soil-landscape relationships suggest that surfaces contiguous with mountain piedmonts undergo a more dynamic history of surface modification, perhaps related to increased surface runoff and sediment supply from adjacent hillslopes. Soils developed on isolated surface remnants are cut off from aggradational inputs from hillslope systems and are predominantly modified by eolian processes and rainsplash erosion.

CORRELATION OF QUATERNARY STRATIGRAPHY

We develop a relative age-control framework for our mapped surficial deposits (Table 1) based on (1) the elevation of the deposit strath above local base level; (2) limited ^{14}C radiometric ages; (3) the occurrence of Lava Creek B ash bed; and (4) soil stratigraphy and morphology.

Age control for fluvial stratigraphy in the Jemez River drainage basin proposed by Rogers and Smartt (this volume) used gastropod amino acid

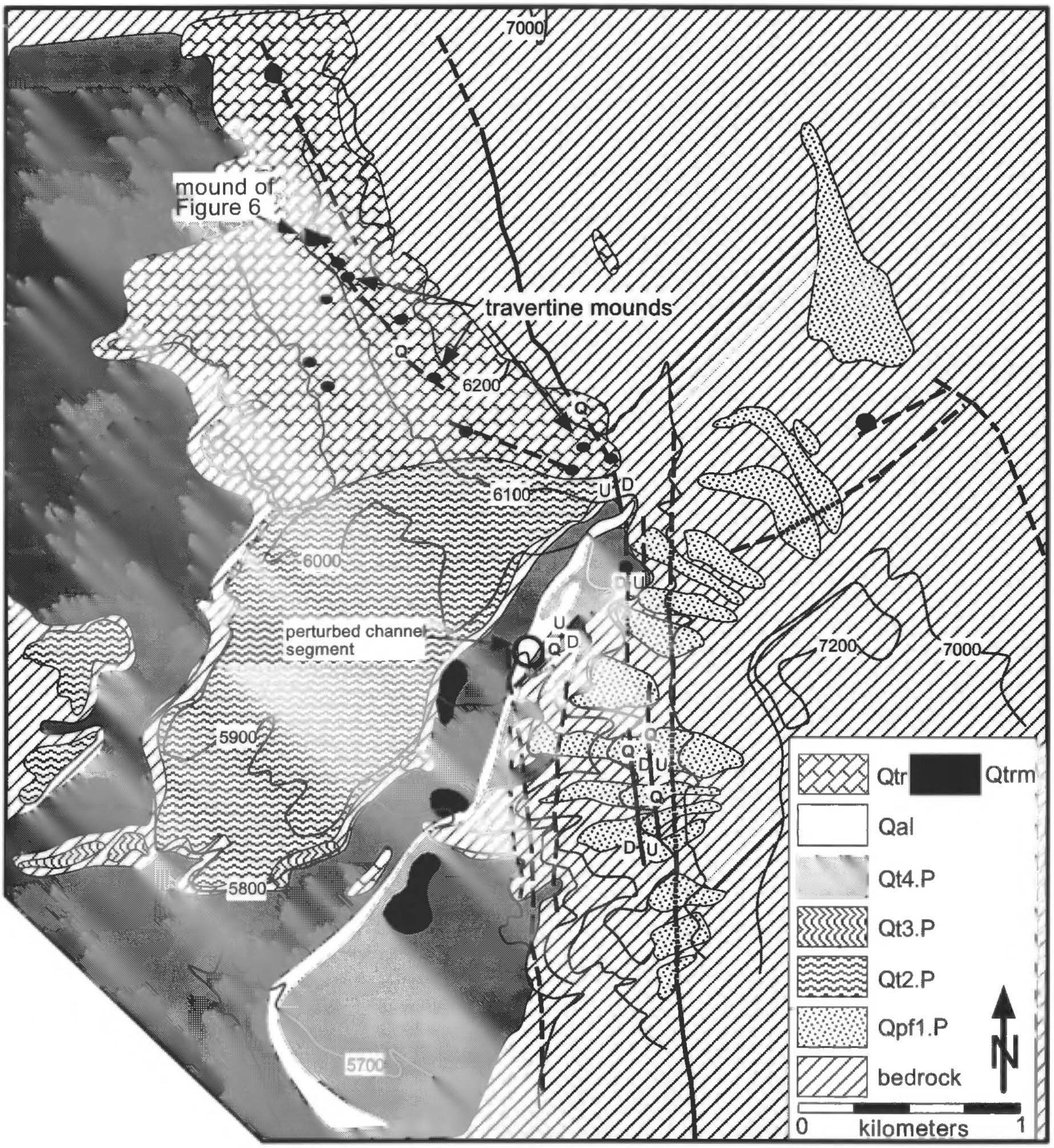


FIGURE 5. Quaternary map of the Arroyo Peñasco drainage showing stratigraphy and associated Quaternary faults (Q). Note the northwest alignment of travertine mounds.

racemization dates and regional correlation to previous aminostratigraphic work in the northern Española Basin (Dethier and McCoy, 1993). In addition, Rogers and Smartt found Lava Creek B ash, dated at 0.6 ± 0.15 Ma (Naeser, et al., 1973) within the Qt1 terrace deposit.

We, therefore, anchor the correlation of our Quaternary stratigraphy with two numerical dates, the Lava Creek B ash (about 620 ka), and ages for the youngest terrace deposit (Qt5, 1660±70 radiocarbon years BP). At this stage of the research, we do not correlate Jemez River stratigraphy to Arroyo Peñasco stratigraphy; that is, the Qt4 terrace deposit in the Jemez River drainage basin is not necessarily the same age as the Qt4.P terrace in Arroyo Peñasco. Refer to Table 1 for our best age estimates.

Soil relative ages

The state factor approach of Jenny (1941) is used by most soil geomorphologists to estimate age of soil profiles through comparison with regional chronosequences that have numerical age determinations. Soil-morphologic characteristics such as pedogenic calcium carbonate and clay accumulation are used to estimate soil-profile age because these characteristics typically increase in monotonic, time-dependent functions (Birkeland, 1984). The stripped and/or polygenetic character of the soils in the Jemez River drainage basin make it difficult to construct a rigorous soil chronosequence. However, soil profiles developed on fluvial and piedmont deposits show an overall pattern of increasing carbonate accumulation with increased landscape-topographic position along a given reach. This data, when calibrated with numerical ages from the youngest and the oldest terrace deposits enabled us to establish age control for Jemez River terrace deposits Qt2-Qt4 with the following caveats. Carbonate stage morphology seemingly increased with age of the deposit; however, variable local inputs of travertine springs may strongly influence the rate of carbonate accumulation on a particular surface. In addition, variable travertine input on a given geomorphic surface may result in unpredictable spatial and temporal variability in secondary carbonate input. Hillslope and fluvial terrace deposits are distinguished by parent material and grain size distinctions. Hillslope deposits are generally finer

FIGURE 6. Travertine mound in the Arroyo Peñasco drainage basin.

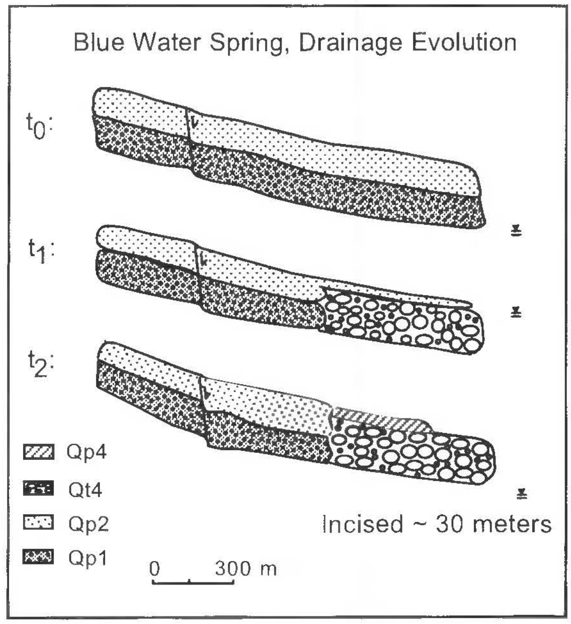


FIGURE 7. Schematic figure for landscape evolution of the Blue Water Spring tributary drainage located in the lower reach of the Jemez River drainage basin (Fig. 3); t_0: deposition and faulting of Qp1 deposit, followed by deposition of Qp2 and subsequent base level fall and incision. t_1: between Qt2 and Qt4 time, the lower valley was excavated, allowing the Qt4 aggradational event to backfill against the older Qp1 and Qp2 piedmont deposits. t_2: concomitant with Qt4 axial stream aggradation, piedmont deposits (Qp4) prograded from the west, in part reworking the older Qp2 deposits. These Qp4 deposits both interfinger with and overlie Qt4. Progradation of the Qp4 deposits ceased when local tributaries incised, exposing the Qt4 valley fill as a terrace.

grained and are dominated by granite and limestone rock types. Younger hillslope deposits are mantled by significant grus and eolian constituents. In contrast, terrace deposits generally consist of granite, limestone and a significant amount (typically one-third) of Tertiary volcanics. And finally, clay accumulation, where present, is not consistent with the degree of calcium carbonate accumulation found on the present terrace tread (Gile, 1966). This may indicate a process in which impermeable soil horizons increase runoff and promote surface stripping, leaving the more resistant, gravelly Bk or K horizons at the surface (Wells, 1983; Dohrenwend, 1987).

In summary, we are aware of the climatic, lithologic and complex geomorphic processes that can influence the accumulation of pedogenic carbonate, particularly with respect to the study area. Given the mentioned caveats, we use landscape-topographic positions, including inset relationships, sedimentology, and stage morphology of carbonate accumulation to place the terrace deposits within a relative age framework within the Pleistocene, with large errors of a maximum of ± 100 ka where numeric age control is lacking (Table 1).

We are in the preliminary stages of calibrating the Quaternary stratigraphy in Arroyo Peñasco. In terms of mean elevation above base level, Qpf1.P occupies a similar landscape position as the Rito Leche and/or La Jara pediments of Bryan and McCann (1936). We have not correlated these surfaces beyond the Arroyo Peñasco drainage basin; therefore, any relation to pediments of earlier workers is speculative. Nevertheless, on the basis of landscape position (the Rito Leche and the La Jara pediments are 23 and 55 m above local base level) and degree of soil development (stage I overlying a buried stage II), we assign Qpf1.P a late-middle Pleistocene age.

Qt2.P is capped by voluminous travertine deposits that may have issued from springs (Fig. 6) that were more active during periods of higher effective moisture. The best age estimate for Qt2.P, based on volume of travertine deposition, elevation above the modern channel and the character of the degraded surface, is middle to late-middle Pleistocene age.

NEOTECTONIC FEATURES

There is evidence for neotectonism throughout the southern Sierra Nacimiento. In the Arroyo Peñasco drainage basin, three of the four mapped allostratigraphic units are offset by Quaternary faults. We use the term Quaternary faults to indicate those bedrock faults with demonstrated Quaternary offset. In cases where field relationships of Quaternary faults are poorly constrained, we use three lines of evidence to surmise offset: (1) bedrock faults that trend into Quaternary faults, (2) changes in stream morphology that strongly reflect the effect of neotectonic faults, and (3) mass-movement processes that are promoted by fault offset.

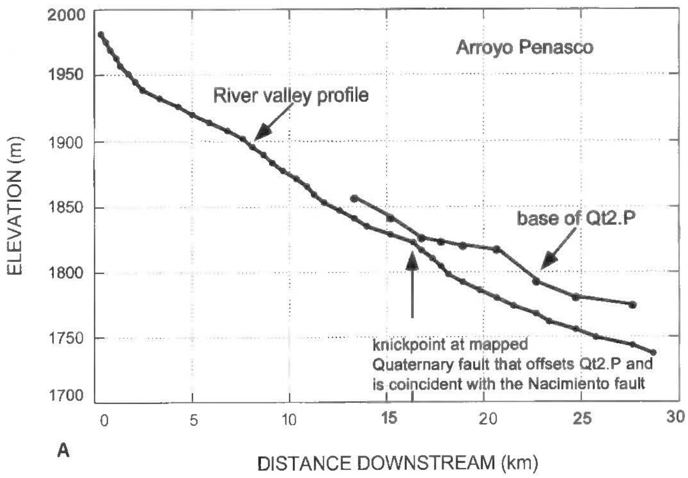
In all cases we have been unable to calculate a slip rate because we have not located a piercing point for well-dated strata. Slickenline data were calculated for bedrock faults that trend into Quaternary faults, with the supposition that older, bedrock faults may have been reactivated. However, slickenline data were not found in the Quaternary gravelly fluvial or piedmont deposits.

Arroyo Peñasco Quaternary faults

The range-bounding fault of the Sierra Nacimiento is mapped as two discontinuous fault segments (Fig. 1), the Nacimiento fault in the north and the Pajarito fault in the south (Woodward, 1976). The Arroyo Peñasco drainage basin is bounded on the east by the Pajarito fault. However, to avoid confusion with the Pajarito fault in the Española basin, we will refer to both the Nacimiento fault segment and the Pajarito fault segment (as mapped by Woodward, 1976) simply as the Nacimiento fault.

Vertical displacement along the Nacimiento fault increases to the north. Maximum stratigraphic separation on the northern and southern segment of the range-bounding fault is 1200 m with approximately 750 m of thrust component of slip (Woodward, 1987). The Nacimiento fault is a Laramide feature (Woodward, 1987) that can be traced in incised drainages close to the mountain front and as a low topographic scarp buried by pediment-fan deposits Qpf1.P (Fig. 5). The subtle scarp on the Qpf1.P surface suggests the fault may have been reactivated since Laramide time. Farther north and east, the Nacimiento fault is buried by modern Arroyo Peñasco stream channel alluvium, but resurfaces on the north side of the drainage where it truncates the Pennsylvanian Madera and Permian Abo Formations, and the Qt2.P terrace gravels. At this locality, the fault displays a predominantly down-to-the-west, normal component of slip; however when the fault offsets Quaternary terrace gravels (Qt2.P), it exhibits an opposite sense of movement (down-to-the-east, normal component of slip) with 4.2 m of stratigraphic separation. The fault scarp in the Qt2.P terrace deposit has been preserved and buried by travertine deposition from a constructional mound upslope. In addition, a knickpoint has developed at the trend of the fault (Fig. 8A). The spatial arrangement of the bedrock and Qt2.P fault suggests either reactivation of the Nacimiento fault or the development of an antithetic splay (Fig. 5).

A few meters west of the Nacimiento fault, on the Qpf1.P surface, a 17-m high topographic scarp parallels the trace of the Nacimiento fault for approximately 2 km (Fig. 5). The fault zone offsets a calcic horizon formed in pediment-fan gravels on the Qpf1.P surface and continues into the bedrock. Mass-movement processes have increased the height of the scarp, thereby making it difficult to determine the exact amount of stratigraphic separation. Given the fact that the pediment-fan gravels overlie



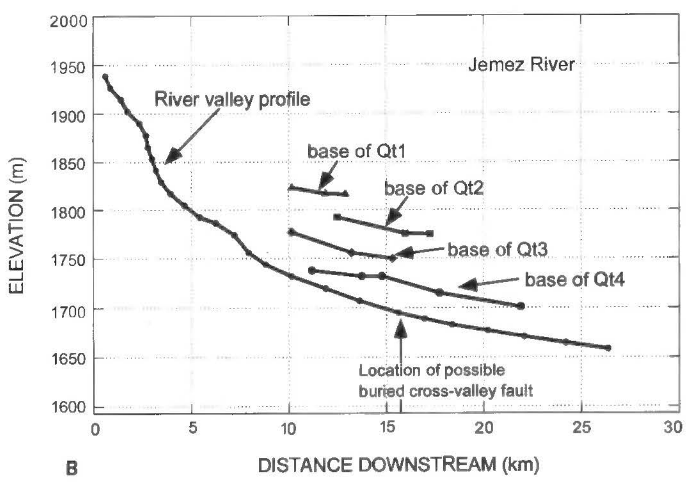


FIGURE 8. A, Modern valley longitudinal profile of Arroyo Peñasco showing knickpoint at location of Quaternary fault offset. Note the longitudinal profile of the Qt2.P strath flattens at the knickpoint. B, Modern valley longitudinal profiles of the Jemez River and longitudinal profiles of the base of the fluvial terraces. Note how the terrace profiles flatten and diverge at the location of the projected cross valley fault.

landslide-prone shale and mudstone bedrock (Triassic Petrified Forest Formation of the Chinle Group), we have considered the possibility that the scarps on the Qpf1.P surface are not tectonic, but rather are landslide head scarps. Nevertheless, the scarp is linear and laterally continuous along the mountain front for approximately 2 km; therefore, we favor some component of Quaternary fault offset. Further surface degradation is enhanced through slump block and landslide processes.

North of Arroyo Peñasco drainage, in the proximal piedmont region, constructional travertine mounds trend northwest and are aligned in a right-stepping, en-echelon pattern (Fig. 5). In addition, an approximately 2-m-thick, buff-colored horizon in the pipe of one the mounds appears to be offset with west-side-down, oblique-slip sense of movement. The kinematic similarity of the orientation of travertine mounds and northwest-trending folds that broadly deform the eastern margin of the San Juan Basin suggest structural control for the alignment of the travertine mounds (Fig. 5).

Quaternary fault offset throughout Arroyo Peñasco drainage basin can be subtle, particularly with regard to offset of terrace deposit Qt4.P. Responses in channel morphology seem to indicate fault offset; however, we recognize that the causal mechanisms responsible for changes in channel patterns in alluvial streams are complicated (Schumm et al., 1987; Bull, 1991).

Evidence consistent with fault offset of terrace Qt4.P include variations in stream grade and morphology. Upstream of the fault, the stream bifurcates into several anastomosing channels, consistent with a local change in channel gradient. It is important to note that the channel is in alluvium throughout this reach, so we discount the importance of a change in rock type in controlling channel pattern. In one of the anastomosing channels, tamarisk-lined springs with sustained flow are on trend with a projected fault (Fig. 5). In the lower reach, several faults, including an oblique-slip fault cutting the Triassic Petrified Forest Formation of the Chinle Group, trend into the breached area of an abandoned meander loop in the stream. Horizontal slickenline data collected in bedrock faults indicate a dextral component of slip. A 2-3 m-thick layer of silt and clay, interpreted as cienga deposits, forms a stratigraphic marker that is offset approximately 0.5 m, down-to-the south. Cienga deposits are locally drag folded, west-side-up, mimicking the drag folds of the bedrock fault that trends into the breached portion of the meander loop. Charcoal sampled from cienga deposits in this area yield a date of 2290±70 radiocarbon years BP (Beta #85444).

Jemez River drainage basin Quaternary faults

The Bandelier Tuff (1.13 ± 0.01 Ma, Spell et al., 1989) is offset 12 m, down-to-the-southeast, along the Sierrita fault (Woodward, 1987). The oldest terrace, Qt1 (about 620 ka) is offset in an unnamed tributary drainage on the west side of the Jemez River, 1.5 km north of the Jemez Pueblo boundary and northwest of Jemez Valley high school (Fig. 3). In the westernmost region of the tributary, two faults offset Qp1 and truncate Qt1 to form a graben with approximately 3 m of stratigraphic separation. Near the outlet to the Jemez River, Qt1 is offset with 3.1 m of stratigraphic separation with a normal component of slip, down-to-the-east (Fig. 3).

In the Blue Water Spring drainage (Figs. 3, 7), two faults offset the strath of Qp1, with a total of 8.2 and 1.8 m of stratigraphic separation. A 1-m high topographic scarp on the surface is partially buried by Qp2.

Finally, apparent offset in the Qt4 terrace strath near Red Rock (Fig. 3) strongly suggests a previously unmapped northeast trending fault on the east side of Jemez River. We believe, based on several lines of evidence, that this fault zone lines up with the continuation of San Ysidro fault on the west side of the Jemez River (Fig. 3). For example, the Miocene Zia Sandstone and the Qt4 terrace strath onlap the south-dipping, highly jointed and fractured Permian bedrock, suggesting either the occurrence of a fault or broader flexural deformation of Permian rocks. In addition, terrace profiles flatten and diverge at the same point and at the projected location of the fault (Fig. 8B). The only terrace preserved below the projected fault is the thickest fill terrace, Qt4 (Fig. 3).

Geophysical evidence and well data also indicate that there are buried faults in the lower Jemez River drainage basin. Subsurface seismic imaging exhibits evidence for two faults buried beneath the modern strath in channel alluvium. Seismic data suggests the continuation of the northwest-trending Jemez fault buried under 33 m of Quaternary alluvium, approximately 0.6 km east of Indian Springs (Fig. 3). Well data demonstrates that the flow and salinity of the Jemez River increases between Jemez Pueblo and San Ysidro (J.C.Witcher, unpubl. report for Southwest Technology Development Institute,1990).

LONG-TERM LANDSCAPE EVOLUTION

Long-term landscape evolution for the southern Sierra Nacimiento is based on our surficial geologic map, landscape-topographic position, and numeric dates. We recognize the possible far-reaching effects of Rio Grande modulated regional base-level fall, but our data does not allow us to resolve these effects. Future studies that incorporate detailed mapping of Quaternary deposits in the region linking the Jemez River drainage basin and the northern Albuquerque basin may address this issue. Here, we focus on the lower Jemez River drainage basin, particularly the relationship between the piedmont deposits and the axial stream gravel deposits. We use these relationships to understand the relative roles that active tectonism versus erosional exhumation play in shaping the southern Sierra Nacimiento landscape.

Following deposition of the upper Bandelier Tuff (about 1.1 Ma), the Jemez River began a long period of incision, punctuated by several episodes of aggradation now preserved as the six major terrace deposits (Qt1 through Qt6; Fig. 8B). Given that the age of Qt1 is about 620 ka (Rogers and Smartt, this volume), the long term, average rate of incision since the middle Pleistocene is 0.16 m/1000 yrs (Figs. 8B, 9A). This rate is similar to long term rates of incision (Table 3), in the western Española basin (Dethier, et al., 1988) and the Grants-Laguna region (Drake et al., 1991). In both areas, rates of incision have dramatically increased since approximately 500 ka (Table 3). We are working to establish numeric age control in order to address increased rates of incision in the southern Sierra Nacimiento; however, based on the estimated age for the Qt4 terrace (150±50 ka), a short-term incision rate that encompasses this age range is approximately 0.15 m/1000 yrs to 0.3 m/1000 yrs. The upper end of this range is consistent with short-term incision rates of regional studies (Dethier et al., 1988; Drake et al., 1991) that exhibit increasing rates of incision between 500 ka to 100 ka (Table 3). In contrast, the average, long-term rate of fault offset in our study area is approximately 0.03 m/1000 yrs (Fig. 9B). This rate is an order of magnitude less than the long-term rate of incision suggested by the inset fluvial terraces. In addition, regional rates of denudation (2.6 Ma to present) of approximately 0.5m/1000 yrs (Hallet, 1994) indicate that the major control on landscape evolution is one of exhumation (Table 3). This process of erosional exhumation is best observed in the Jemez River drainage basin.

In the upper Jemez River drainage basin, all terraces and piedmont deposits are inset, stepping down towards the modern channel (Fig. 4, cross-section A-A; Fig. 8B). In contrast, in the lower Jemez River drainage basin, we find evidence for burial of older Quaternary units as well as Quaternary deposits that exhibit an inset relationship (Fig. 4, cross-section B-B). Here, the oldest aggradational event, Qp1, is represented by a fine-grained sand and gravel unit composed predominantly of grus. The base of the deposit unconfomably overlies the Miocene Zia Sandstone. Qp1 is unconformably overlain by Qp2 (Fig. 3), a carbonate ce-

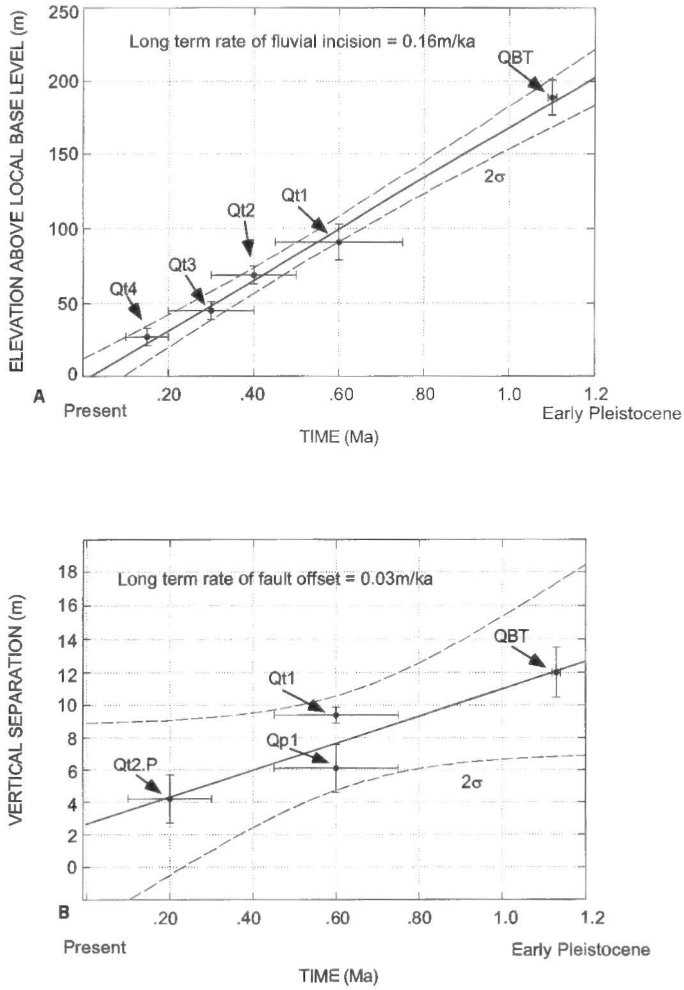


FIGURE 9. A, Fluvial incision in the Jemez River valley. Data points represent the elevation of straths above local base level. The errors on the time axis are described above where numeric age control is available. For terrace deposits with no numeric age control, errors are based on landscape topographic positions, inset relationships and soil stratigraphy and morphology. Estimated ages are assumed to have an error of ±100,000 yrs, except for Qt4, where the estimated error for deposit age is ±50,000 yrs. The estimated error for elevation above modern base level is based on standard error of ±1 contour interval (±20 or ±40 ft). Note that the rate of fluvial incision is based on Jemez River terrace deposits only. At this time we do not know rates of fluvial incision for the Arroyo Peñasco because of a lack of well-constrained age control. B, Fault offset in the Jemez and Arroyo Peñasco drainage basins. Age errors compiled from the Bandelier Tuff (QBT) 1.13±0.01 Ma, (Spell et al., 1989); the Lava Creek B (LCB) ash 0.60±0.15 Ma, (Naeser et al., 1973) and estimated at ±100,000 yrs for Qp1 and Qt1 (Table 3). Offset errors reflect ±1.5 m altimeter precision. Also note that the 2б reported on both figures is associated with the best fit regression line and does not reflect the standard errors of any individual data point, which we show as error bars.

TABLE 3. Regional summary of incision and denudation rates.

STUDY	TIME INTERVAL	RATES OF INCISION	RATES OF DENUDATION
This report	~620 ka to present	0.16m/ka	----
Diether, et al., 1988	net rate since 2.8 Ma to present rate since 500 ka	0.1m/ka 0.38m/ka	0.05 to 0.50m/ka
Drake et. al, 1991	average rate since 2.5-3.0 Ma to present between ca. 2.5-2.4±0.18 my, 0.8-.5 my	0.07-0.12m/ka 0.3-0.7m/ka	---
Hallet, 1994	between 3.0-2.5 Ma from 2.6 Ma to present	---	~0.44m/ka ~0.59m/ka

mented, coarse-grained gravel and boulder deposit composed of angular granite clasts. No soil is preserved at the contact between Qp1 and Qp2, but that contact is planar (Fig. 7), and areally extensive throughout the map area. Through Qp2/Qt2 time, the upper valley (portion north of Red Rock; Fig. 3) was producing an inset terrace stratigraphy, while the lower valley (portion south of Red Rock; Fig. 3) was alternating between valley aggradation and regional strath beveling.

Between Qt2 and Qt4 time, the lower valley was excavated, allowing the Qt4 aggradational event to backfill against the older Qp1 and Qp2 piedmont deposits (Fig. 7). Concomitant with Qt4 axial stream aggradation, piedmont deposits (Qp4) prograded from the west, in part reworking the older Qp2 deposits. These Qp4 deposits both interfinger with and overlie Qt4. Progradation of the Qp4 deposits ceased when local tributaries incised, exposing the Qt4 valley fill as a terrace (Fig. 7).

Incision in the lower Jemez valley may be driven in part by local tectonic deformation (Fig. 3). In the Blue Water Spring region (Figs. 3, 7), the unconformity between Qp1 and the Miocene Zia Sandstone is offset by at least 8 m (Fig. 7); however, a subdued scarp offsets Qp2 no more than 1 to 2 m. We use this data to infer that most of the offset on this Quaternary fault occurred in post-Qp1 time, which is consistent with the observation that the lower valley was still aggrading. Incision following deposition of Qp2 is consistent with our stratigraphic control constraining movement on the Blue Water Spring fault. But can we attribute most Quaternary base level fall and subsequent incision to tectonic movements such as those documented for the Blue Water Springs fault? Average rates of fault offset for the entire southern Nacimiento region (Fig. 9B) suggest that locally, such as in the lower Jemez River valley, Quaternary faults may be important in lowering base level, driving fluvial incision, and increasing relief in the landscape. Additional evidence for fluctuations in base level due to fault control is suggested by divergence of long profiles of the major terraces (Fig. 8B). Pre-Qt4 terraces are not preserved south of the projected trace of the San Ysidro fault (Fig. 3). The base of the Qt4 strath is locally warped by this projected cross valley fault (Fig. 8B). Nevertheless, we cannot reconcile the large disparity in measured rates of fluvial incision and fault offset (Table 3; Fig. 8). In addition, preliminary results show no evidence for significant Quaternary dextral offset along the Nacimiento range-bounding fault. Therefore, this suggests that neotectonism does not play the dominant role in shaping the geomorphic expression of the Sierra Nacimiento. We conclude that the exhumation of rock-types of variable resistance has played the dominant role in defining the characteristic relief and geomorphic expression of the southern Sierra Nacimiento.

ACKNOWLEDGMENTS

This paper summarizes a portion of ongoing research for an M.S. thesis by Formento-Trigilio at the University of New Mexico. Funding for this research was generously provided by the Geological Society of America, New Mexico Geological Society, the Colorado Scientific Society and the Department of Earth and Planetary Sciences, University of New Mexico. The authors express appreciation to D. Love and S. Connell for reviews of this manuscript. Thanks are extended to L. McFadden, M. Elrick, A. Kuhle and A. Ellwein for insightful discussion and helpful suggestions. Special thanks are also extended to Chris Toya, for assistance in the field, and the people of Jemez Pueblo and Zia Pueblo for their hospitality and access to the field area.

REFERENCES

Bachman, G. O. and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan basin, New Mexico: U.S. Geological Survey, Professional Paper 552, 101 p.

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

Bryan, K., 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico; *in* U.S. National Resources Planning Board, The Rio Grande Joint Investigation in the Upper Rio Grande basin: U.S. Government Printing Office, v. 1(2), p. 197-225.

Bryan, K. and McCann, F. T., 1936, Sucessive pediments and terraces of the upper Rio Puerco in New Mexico: Journal of Geology, v. 44, p. 145-172.

Bull, W. B. and McFadden, L. D., 1977, Tectonic geomorphology north and south of the Garlock Fault, California; *in* Doehring, D. O., ed., Geomorphology in arid regions. Proceedings of the Eighth Annual Geomorphology Symposium, State University of New York, Binghamton, p. 115-138.

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

Chapin, C. E. and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau Rocky Mountain area: Arizona Geological Society Digest, v. 14, p. 173-198.

Connell, S. D., 1995, Quaternary geology and geomorphology of the Sandia Mountains piedmont, Bernalillo and Sandoval Counties, central New Mexico [M.S. thesis]: Riverside, University of California, 390 p.

Dethier, D. P, Harrington, C. D. and Aldrich, M. J., 1988, Late Cenozoic rates of erosion in the western Española basin, New Mexico: evidence from geologic dating of erosion surfaces: Geological Society of America Bulletin, v. 100, p. 928-937.

Dethier, D. P. and McCoy, W, D., 1993, Aminostratigraphic relations and age of Quaternary deposits, northern Española Basin, New Mexico: Quaternary Research, v. 39, p. 222-230.

Dohrenwend, J. C., 1987, Basin and range; *in* Graff, W.L., ed., Geomorphic systems of North America: Geological Society of America Centennial Special Volume 2, p. 303-342.

Drake, P. G., Harrington, C. D., Wells, S. G., Perry, F. V. and Laughlin, A. W., 1991, Late Cenozoic geomorphic and tectonic evolution of the Rio San Jose and tributary drainages within the Basin and Range/Colorado Plateau transition zone in west-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 149-157.

Gardner, R. D., Crossey, L. J., Groffman, A. and Sterling, J., 1996, Travertine mound springs along the eastern boundary of the San Juan basin, Sandoval County, New Mexico: New Mexico Geological Society, Guidebook 47.

Gile, L. H., Peterson, F. F. and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Gonzalez, M.A., 1993, Geomorphic and neotectonic analysis along a margin of the Colorado Plateau and Rio Grande rift, northern New Mexico [Ph.D. thesis]: Albuquerque, University of New Mexico, 302 p.

Gonzalez, M. A. and Dethier, D. P., 1991, Geomorphic and neotectonic evolution along the margin of the Colorado Plateau and Rio Grande rift, northern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 29-45.

Hallet, R. B., 1994, Volcanic geology, paleomagnetism, geochronology and geochemistry of the Rio Puerco necks, west-central New Mexico, [Ph.D. thesis]: Socorro, New Mexico Institute of Mining and Technology, 340 p.

Hawley, J.W. ed., 1978, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 p.

House, L. and Hartse, H., 1995, Seismicity and faults in northern New Mexico: New Mexico Geological Society, Guidebook 46, p. 135-137.

Jenny, H., 1941, Factors of soil formation: New York, McGraw-Hill.

Karlstrom, K. E. and Daniel, C. G., 1993, Restoration of Laramide right-lateral strike slip in northern New Mexico by using Proterozoic piercing points: tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21 p. 1139-1142.

Lambert, P. W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: [Ph.D. thesis]: Albuquerque, University of New Mexico, 329 p.

Miller, D. M., Nilsen, T. H. and Bilodeau, W. L., 1992, Late Cretaceous to early Eocene geologic evolution of the U.S. Cordillera; *in* Burchfield, B. C., Lipman, P. W. and Zoback, M. L., eds., The Cordilleran orogen: conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 205-260.

Naeser, C.W., Izett, G. A. and Wilcox, R. E., 1973, Zircon fission-track ages of pearlette family ash beds in Meade County, Kansas: Geology, v. 1, p. 187-189.

Reneau, S. L., McDonald, E. V., Gardner, J. N., Kolbe, T. R., Carney, J. S., Watt, P. M. and Longmire, P. A., 1996, Erosion and deposition on the Pajarito Plateau, New Mexico and implications for geomorphic responses to late Quaternary climatic changes: New Mexico Geological Society, Guidebook 47.

Rogers, J. B. and Smartt, R. A., 1996, Climatic influences on Quaternary alluvial stratigraphy and terrace formation in the Jemez River valley, New Mexico: New Mexico Geological Society, Guidebook 47.

Ruhe, R. V., 1967, Geomorphic surfaces and surficial deposits in southern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 18, p. 1-66.

Schumm, S. A., Mosley, M. P. and Weaver, W. E., 1987, Experimental fluvial geomorphology: New York, John Wiley, 413 p.

Slack, P. B. and Campbell, J. A., 1976, Structural geology of the Rio Puerco fault zone and its relationship to central New Mexico tectonics: New Mexico Geological Society, Special Publication 6, p. 46-52.

Spell, T. L., Harrison, T. M. and Wolff, J. A., 1989, $^{40}Ar/^{39}Ar$ dating of the Bandelier Tuffs and associated ignimbrites: constraints of evolution of the Bandelier magma system: EOS, American Geophysical Union, Transactions, v. 70(43), p. 1413.

Wells, S. G., 1983, Regional badland development and models of late Quaternary evolution of badland watersheds, San Juan Basin, New Mexico; *in* Wells, S. G., Love D. W. and Gardner, T. W., eds., Chaco Canyon country: Fieldtrip Guidebook, 1983 Field Conference American Geomorphological Field Group, p. 121-132.

Wells, S. G., Kelson, K. I. and Menges, C. M., 1987, Quaternary evolution of fluvial systems in the northern Rio Grande rift, New Mexico and Colorado: implications for entrenchment and integration of drainage systems; *in* Menges, C.M., ed., Quaternary tectonics, landform evolution, soil chronologies and glacial deposits - northern Rio Grande rift of New Mexico: Friends of the Pleistocene, Field-trip Guidebook, Albuquerque, New Mexico, p. 55-69.

Wright, H. E., Jr., 1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geological Society of America Bulletin, v. 57, p. 383-456.

Woodward, L. A., 1976, Geology of San Ysidro quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 37, scale 1:24,000.

Woodward, L. A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 42, 84 p.