

New Mexico Geological Society

Downloaded from: <https://nmgs.nmt.edu/publications/guidebooks/35>



Erosional history and soil development on Quaternary surfaces, northwest Espanola Basin, New Mexico

David P. Dethier and Karen A. Demsey
1984, pp. 227-233. <https://doi.org/10.56577/FFC-35.227>

in:

Rio Grande Rift (Northern New Mexico), Baldridge, W. S.; Dickerson, P. W.; Riecker, R. E.; Zidek, J.; [eds.], New Mexico Geological Society 35th Annual Fall Field Conference Guidebook, 379 p. <https://doi.org/10.56577/FFC-35>

This is one of many related papers that were included in the 1984 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs, mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

EROSIONAL HISTORY AND SOIL DEVELOPMENT ON QUATERNARY SURFACES, NORTHWEST ESPANOLA BASIN, NEW MEXICO

DAVID P. DETHIER and KAREN A. DEMSEY

Department of Geology, Williams College, Williamstown, Massachusetts 01267

INTRODUCTION

Extensive late Cenozoic fans and pediments form surfaces that flank the Rio Grande River along much of its course in New Mexico. The surfaces record pauses during general downcutting by the Rio Grande, as well as episodes of aggradation. Surface formation is likely linked with tectonic control of base level, but climate change may also be important. Where ages can be determined for pediments and fans, these features can be used to help constrain local uplift and denudation histories. However, easily dated material is uncommon in the arid and semiarid regions of the West, and radiometrically dated Quaternary sequences are rare.

Arid and semiarid basins with axial drainage display a general sequence of landforms outward from flanking mountain ranges: mountain front, pediment or fan, coalescing pediments or fans, and stepped alluvial terraces along the major drainage. In most semiarid regions, pediments and adjacent alluvial fans have similar gradients and transport similar material by flow in one or more channels (Moss, 1977). Surfaces are more likely to be erosional near the mountain front and depositional near the axial drainage, but any surface may display evidence for contemporaneous erosion and deposition. Grain size in many active alluvial fans decreases away from the mountains (Bull, 1964), and preservation of stratigraphic relations and soils is more likely downslope. However, once a surface is abandoned by base-level lowering, lateral erosion may proceed more rapidly in downslope areas where surfaces are covered by finer material. Preservation of a complete stratigraphic record is thus unlikely at any point, but comparison of morphostratigraphic and soil relations on several surfaces aids in reconstruction of geomorphic history.

Soil Development

Available water and organic matter are sparse and rates of chemical weathering are slow in arid regions. Carbonate accumulates in dry soils because eolian sources, precipitation, and slow weathering of soil minerals result in high concentrations of calcium (or magnesium) carbonate in evaporating soil solutions. Dry fallout and precipitation constitute most of the calcium carbonate, which accumulates in arid soils at rates of 0.2-0.5 g cm⁻²/1,000 years (Machette, 1982). The zone of carbonate precipitation is usually below the depth of minor erosional events that affect upper soil horizons. Thick accumulations of carbonate resist erosional stripping by rainsplash or sheetflow and tend to preserve surfaces. Total soil carbonate is thus likely to increase regularly with time, allowing soil ages to be estimated where there is some radiometric control (Bachman and Machette, 1977; Machette, 1978).

Carbonate accumulation in soils follows a regular sequence, first described by Gile and others (1966), who proposed a field classification for carbonate development. Stage I is marked by discontinuous grain coatings and suggests an age of several thousand years; stage II is characterized by thicker coatings, nodule development, and formation of minor cement in soils as young as 10-15,000 years (ka); in stage III cement is widespread as a slowly permeable, CaCO₃-rich K horizon develops in soils of late Pleistocene age; stage-IV morphology consists of laminar carbonate overlying a strongly cemented carbonate layer and is developed in soils over about 250 ka old. Careful field study of carbonate horizons can thus be used to provide age estimates for surfaces.

As arid soils increase in age, B horizons become increasingly clay-rich, and color hues become redder and chromas darker. The clay and iron content begin to provide some cementation in perhaps 10-20 ka,

affording additional protection for underlying carbonate horizons. Argillic horizons have formed in southern New Mexico on soils of early Holocene age (Gile and others, 1981). However, surface erosion, limited flocculation due to concentrated soil solutions, and mechanical disruption by carbonate crystals make argillic horizons unstable in most older surface soils. Texture of the B horizon is thus a guide to the age of upper Pleistocene and Holocene soils, but systematic increases in fine material are less common with increasing age.

Regional Geology

The central part of the Rio Grande rift consists of three en-echelon basins (Albuquerque, Espanola, and San Luis) flanked by mountain ranges and drained by the Rio Grande (Fig. 1). In Miocene through mid-Pliocene time the Espanola Basin was probably internally drained and accumulated sediment of the Santa Fe Group on fans constructed from upland areas to the west, north, and northeast of the basin (Manley, 1979). The Rio Grande—Rio Chama system first became integrated through the Espanola Basin in Pliocene time, probably between about 2.8 and 4.0 m.y. ago, and followed a course through the center of the Velarde graben. Santa Fe deposition ended about 3 m.y. ago, and the event is marked by an erosional unconformity and a layer of resistant cobble gravel in areas near the Rio Grande, and by erosion surfaces near the Sangre de Cristo Range and Ortiz Mountains (Manley, 1979). Kelley (1979) correlated all high-level pediments in the Espanola Basin with Bryan's (1938) Ortiz surface. Basin deposition near the Rio Grande resumed after cutting of the Ortiz pediment, covering that surface with the Ancha Formation east of the Rio Grande, and with the Puye Formation west of the river. General basin aggradation apparently continued until after the Puye fanglomerate was covered by local basalt flows and the Bandelier Tuff. Regional erosion resumed sometime after deposition of the youngest member of the Bandelier Tuff, some 1.1 m.y. ago, and a series of cut and fill surfaces formed as the Rio Grande eroded down to present levels (Fig. 2).

Surfaces of pediments, fans, and terraces cut during Quaternary time are prominent landforms of the northern Espanola Basin, particularly in the area along the east flank of the NE Jemez Mountains. Because the area includes active faults and major climatic shifts have marked the past million years, erosion and depositional episodes may represent a response to these two forces, as well as to regional base-level control by the Rio Grande. In this paper we report the results of detailed geomorphic mapping and soil sampling near the Rio del Oso, and reconnaissance studies elsewhere in the northern Espanola Basin.

SETTING

Topography and Climate

The Espanola Basin comprises a dissected lowland bounded by the volcanic Jemez Mountains to the west, the Sangre de Cristo Range to the north and northwest, the Brazos—Tusas Ranges to the northwest, and low volcanic plateaus to the north and south. Local relief in the badlands and dissected surfaces is generally 100-250 m, but reaches 300 m near the Picuris Mountains. The Rio Chama and Rio Grande are the main perennial drainages in the area of interest; numerous tributaries such as the Ojo Caliente, Santa Cruz, and Pojoaque Rivers, Santa Clara Creek, and Rio Embudo and Rio del Oso have some flow during most of the year.

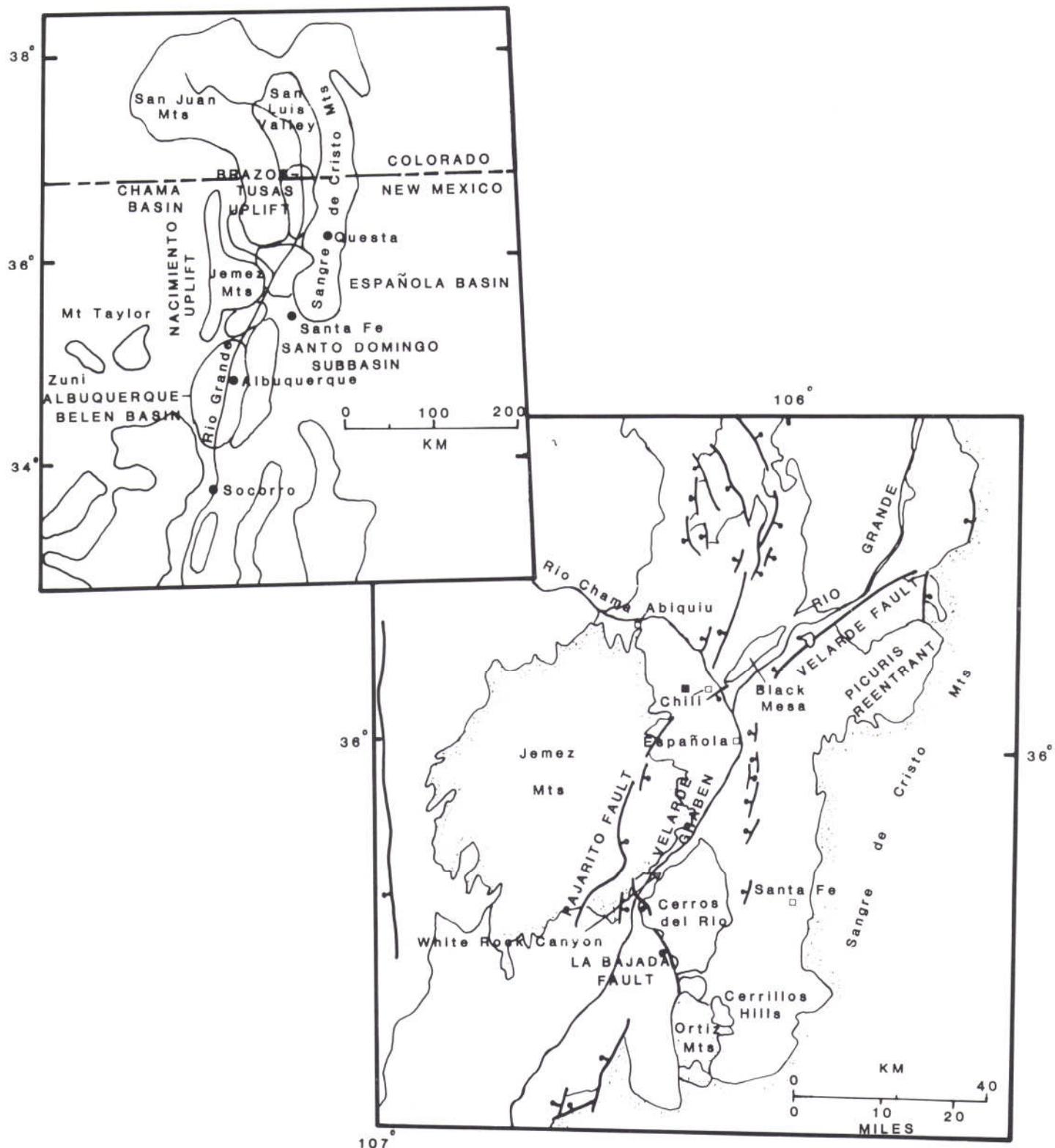


FIGURE 1. Map showing location of the Rio Grande rift and geographic features of the *Española* Basin (after Manley, 1979). Field area is shown as a square near Chili.

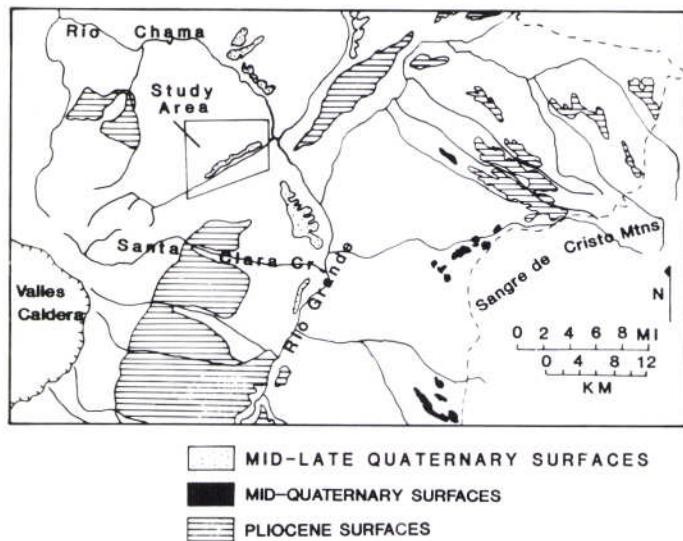


FIGURE 2. Map showing distribution of Pliocene and Quaternary erosion surfaces in the northern Espanola Basin (after Kelley, 1979).

Climate in most of the Espanola Basin is semiarid. Mean annual precipitation averages 25 cm at Espanola, 36 cm at Santa Fe (Spiegel and Baldwin, 1963), and 46 cm at Los Alamos (Griggs, 1964). Significant understory vegetation and soil organic matter are present only above 2,200 m. Detailed information about paleoclimate in the Espanola Basin is sparse, but general inferences about Quaternary climates can be drawn from studies in nearby areas (Van Devender and Spaulding, 1979). Full "glacial" climates in northern New Mexico were probably expressed by greater effective moisture. Cirque and small valley glaciers formed in the Sangre de Cristo Range and vegetative cover likely increased in lowland parts of the Espanola Basin. Interglacial climates, by analogy to the Holocene, were warmer and drier than glacial climates and the change to interglacial climates likely resulted in landscape instability, erosion, and sedimentation. Holocene climate was initially warm and dry (Martin and Mehringer, 1965), but in the past 4,000 years has become more variable (Leopold, 1951).

Pliocene and Quaternary Geology

High pediments correlative with the Ortiz are preserved in the Penasco embayment and slope WNW toward the top of Black Mesa. The lowest of the high pediments (Truchas surface of Manley, 1976) predates deposition of the lower Bandelier Tuff (1.4 m.y.), which is preserved on a surface cut about 35 m below the Truchas level. A basalt flow that caps Black Mesa was dated at 2.8 m.y. (Manley, 1979); it overlies cobble gravel deposited by the ancestral Rio Grande, giving a close approximation for base level above the present channels at 3 m.y. ago. A lower surface, termed the Santa Cruz (Manley, 1976), is preserved as isolated remnants in the eastern Espanola Basin. Kelley (1979) suggested that the surface is a pediment near the mountains and a fan down-gradient. Manley (1976) noted upper Pleistocene terrace deposits at two levels as much as 50 m above present channels.

Surface remnants west and northwest of Espanola cannot be traced laterally to surfaces east of the Rio Grande. However, basal Puye Formation is a channel gravel deposited by the Rio Grande at grade with the Ortiz surface about 3 m.y. ago (Manley, 1979). Base level rose from 3 to 2 m.y. ago and probably 1.4 m.y. ago as the Puye, flows and maar deposits from the Cerros del Rio volcanic field, and finally the lower Bandelier Tuff periodically dammed the Rio Grande at White Rock Canyon. Base level lay about 180 m above the present level when a basalt flow entered an extensive lake in Los Alamos Canyon some 2 m.y. ago (Manley, 1979). We know of little specific evidence for relative base-level changes between 1.4 and 1.1 m.y. ago. Smith, Bailey, and Ross (1970) noted that deep canyons were cut into the lower Bandelier and filled by upper Bandelier Tuff, but published maps and reconnaissance fieldwork suggest that much of the distal upper Bandelier covered

a surface of low relief. Upper Bandelier Tuff exposed at similar elevation east and west of White Rock Canyon strongly suggests that base level did not change dramatically until after 1.1 m.y. ago.

Late Quaternary base-level changes on the axial drainage must have been controlled by relative motion between the Santo Domingo Basin and the Espanola Basin along the La Bajada fault, and by resistance to erosion provided by the basalt flows and tuff in the 10 km upstream from the fault. After the volcanic rocks were removed, headward erosion doubtless occurred rapidly in the poorly consolidated Santa Fe Group. We also recognize the importance of deformation along late Quaternary faults to individual drainages, but concentrate here on the influence of Rio Grande base level.

METHOD

We mapped surfaces and deposits along Rio del Oso in detail, and described and sampled soils in this area from surfaces south of the Rio del Oso and from one exposure in the Santa Cruz surface. All soil samples were analyzed for bulk density (Chleborad and others, 1975), carbonate content, and gravel/sand ratios. We performed complete granulometric analyses on selected samples and determined extractable iron (Jackson, 1973) for all **B** horizons and for selected samples of parent material. Our carbonate analyses followed a CO₂ generation technique using Chittick apparatus as proposed by Dreimanis (1962) and modified by Machette (written comm. 1982). Precision of carbonate analyses was $\pm 6\%$, whereas replicate analyses for bulk density and extractable iron gave a precision of about $\pm 8\%$.

We calculated total carbonate content for each horizon (c_i) using methods suggested by Machette (1982). Initial carbonate content was estimated using parent material beneath soil profiles, or assuming an initial carbonate value of 1% (Gile and others, 1981) where unaltered parent material was absent. We calculated total secondary carbonate in a soil profile (c_S) by summing c_i values for all horizons. For undisturbed soils and constant accumulation rates, c_S should be directly related to age. Machette and others (1982) suggested that carbonate-accumulation rates have averaged 0.5 gm cm⁻² ka⁻¹ for the past 50 ka and 0.25 gm cm⁻² ka⁻¹ prior to 50 ka.

Two samples were submitted to Beta Analytic, Inc., for ¹⁴C analyses. Sample KD-29 consisted of charcoal fragments disseminated in silty sand beneath an alluvial surface some 3 m above the modern Rio del Oso. The second sample (KD-8) consisted of an overthickened A horizon buried by some 5 m of alluvium and colluvium and overlying a poorly developed soil. The surface above the buried soil lies some 26 m above the Rio del Oso in an erosional zone dissected by many small gullies.

RESULTS

Surfaces and Deposits Along the Rio del Oso

Five surfaces could be consistently distinguished above the active channel of the Rio del Oso and in adjacent areas along the Arroyo del Palacio (Fig. 3). The highest surface, designated Q 1, is exposed as isolated remnants in the western part of the Chili and eastern part of the Vallecitos quadrangles. The surface is generally cut into a stratigraphic sequence consisting of Santa Fe Group truncated and overlain by Puye deposits which underlie the lower Bandelier Tuff. Overlying the tuff are deposits of basaltic cobble and boulder gravel that display stripped stage-IV soils overlain by stage-III soils. The Q2 surface is more widely exposed at lower elevations and is cut across basaltic cobble and boulder gravel that fills channels in Santa Fe sediment near the mountain front. Deposits beneath the Q2 surface are finer and soils are better preserved east of the Vallecitos quadrangle. Surfaces Q3 and Q4 overlie arkosic sand and basaltic gravel from one to more than 20 m thick that fill channels cut into the Ojo Caliente Sandstone. The Q3 surface truncates an aggradational sequence near the Rio Chama. Deposits beneath the Q3 surface contain buried soils at a number of locations and surface-boulder cover is minimal. Deposits beneath the Q4 surface contain less gravel than those beneath the Q3 surface. Qal represents low, alluvial terraces near modern channels.

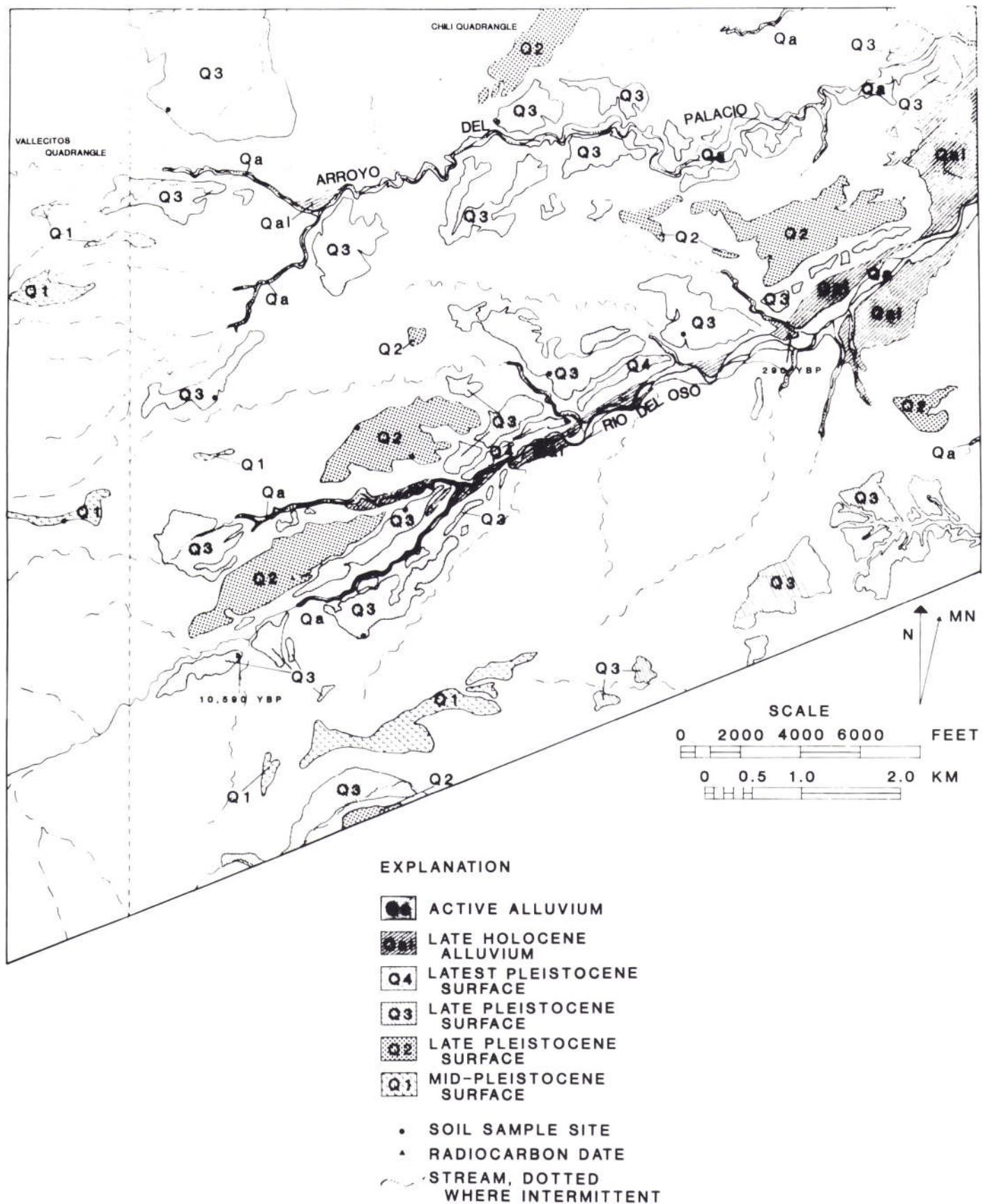


FIGURE 3. Map showing surfaces of the Rio del Oso area, northeast Jemez Mountains.

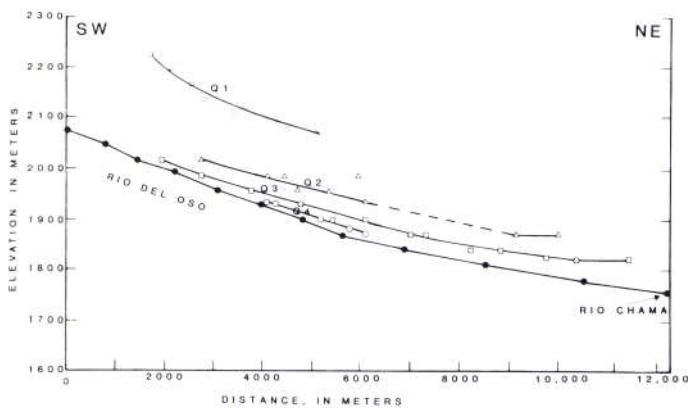


FIGURE 4. Gradients of surfaces in the Rio del Oso area. Distances measured from the west border of Figure 3.

Gradients on surface remnants along Rio del Oso (Fig. 4) are similar to the river with the exception of Q1, which appears to steepen toward the mountain front. Easterly segments of Q1 project to an elevation of -2,000 m at the Rio Chama. The present channel of the Rio Chama at Black Mesa lies at an elevation of 1,735 m, whereas the Pliocene gravels beneath the capping flow on Black Mesa crop out at about 2,010 m.

Soils

Laboratory analyses of carbonate in 21 soil profiles generally support field descriptions of soils (Demsey, unpubl. data 1983) and clearly show the influence of erosion on the accumulation of soil carbonate. Soil ages calculated from carbonate content give minimum age for surface stabilization ranging from about 200 to 20 ka (Table 1). Bulk densities ranged from 1.2 to 2.1 g cm⁻³, whereas dithionite-extractable iron ranged from 0.4 to 1.04% in B horizons and from 0.16 to 0.28% in parent material, but the data show no clear trend related to surface position or inferred age.

Carbonate content of typical profiles on each surface ranges from a

TABLE 1. Selected analyses and calculated ages for soils developed along the Rio del Oso and in nearby areas.

Surface	Carbonate stage	Soil carbonate in gm cm ⁻²	Age ¹ of best developed soil on surface in ka	Iron content ² in percent
Q-1	IV	59		0.24
Q-1 ³	IV	78	200	0.84
Q-2	Strong III	52	160	0.64
Q-3 ⁴	III	28	51	0.40
Q-5 ⁵	III	21		0.87
Q-3	I	2		0.6
	III	13		0.26
	I	~1		0.60
	III	23		0.67
	III	12		0.52
Q-4	II	17	35	0.39
Santa Cruz	Strong III	--		1.0

1 Calculated from carbonate accumulation rates listed by Machette, 1982.

2 Dithionite extractable in strongest B horizon.

3 Colluvial slope adjacent to Q-1 surface, Vallecitos Quadrangle.

4 Surface south of Arroyo del Palacio, Chili Quadrangle.

5 Surface north of Arroyo de la Plaza Larga, San Juan Pueblo Quadrangle.

maximum of 60% (Q1) to about 25% for a stage-II soil on the Q4 surface (Fig. 5). The strongest K horizon on the Q1 surface displays stage-IV morphology, and several soils elsewhere on the surface expose two or more stripped and buried K horizons of at least stage-III development. Maximum carbonate content of the Q2 soils is about 40%, typical of "strong" stage-III field descriptions. Soils on several Q2 surfaces expose weak Holocene B horizons overlying stronger argillic or carbonate-cemented buried B horizons. Soils on Q3 and Q4 surfaces along the Rio del Oso are more poorly developed than those on adjacent higher surfaces.

Approximate minimum ages for Rio del Oso surfaces were estimated using the soil-carbonate stage (tile and others, 1981) and values listed in Table 1. Soils on the Q1 and Q2 surfaces have carbonate contents that suggest ages of about 150-250 ka. However, the stripped stage-IV carbonate which underlies stage-III soils on the Q1 surface probably took at least 200 ka to develop, and the surface probably formed at least 400-500 ka ago. Comparable stages of surface soils on the Q1 and Q2 surfaces suggest that both stabilized at about 200 ka. Maximum profile stage suggests Q3 soils are slightly older than Q4 soils, but the surfaces are of broadly similar age. A buried A horizon beneath an eroding, low Q3 surface gave a radiocarbon date of $10,590 \pm 150$ yrs B.P. (Beta-8359), and soil development and carbonate content suggest it was about 5 ka when it was buried. This evidence shows that at least portions of the Q3 surface were active at about 15 ka, implying complex erosional and depositional events in latest Pleistocene time. Tree-ring counts on the Qa 1 surface suggest it was abandoned at least 100 yrs ago; soil development is modern. Charcoal in deposits beneath the surface gave a date of 280 ± 90 yrs B.P. (Beta-7821).

DISCUSSION

Rio del Oso Surfaces

Our data and those of Manley (1976, 1979) indicate that the late Pliocene and Quaternary landscape northwest of Espaⁱola was generally stable until after deposition of the upper Bandelier Tuff, and downcutting which isolated Q1 surfaces did not occur until mid- to late Pleistocene time. Once erosion began, denudation of areas east of Lobato Mesa occurred rapidly, dropping local arroyo levels at least 150 m and average landscape elevation more than 80 m. No evidence is preserved for periods of significant aggradation between at least 200 and 50 ka before present. Deposits beneath the Q3 surface near the Rio Chama record

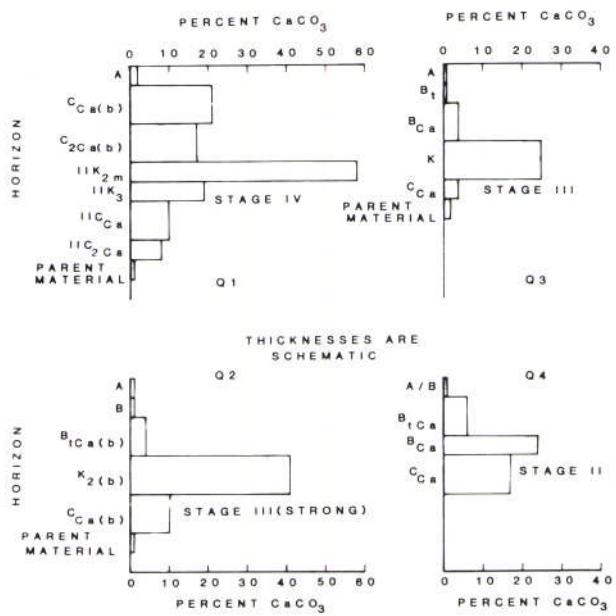


FIGURE 5. Carbonate content and stage of the best preserved soils on surfaces of the Rio del Oso area.

at least 10-20 m of net deposition during latest Pleistocene time. Soil carbonate gives reasonable minimum-age estimates for surfaces, but profiles that closely match surface age are fairly uncommon on Q4 and Q4 surfaces, rare on Q2 surfaces, and have not been observed on Q1 surfaces. Erosion rates in the study area were influenced by Rio Grande/Rio Chama base-level control that depended on downcutting rates at White Rock Canyon and regional uplift. Similar flights of surfaces are present south of the Rio del Oso (Fig. 2), but their history was also influenced by the great thickness of Puye cover, and by late Pleistocene deformation (C. Harrington, written comm. 1984).

Surfaces along the Rio del Oso and in nearby areas stabilized between about 250 and 500 ka before present. The surface of pediment Q1 was an aggradational area until after 1.4 m.y. ago, and probably until after 1.1 m.y. ago, assuming surfaces are similar to those exposed 8 km to the south of Rio del Oso. Carbonate stage and total-profile carbonate suggest that colluvium which slopes from Q1 surfaces has been stable for more than 200 ka. After erosion removed most of the Q1 surface and cut through into underlying Miocene sediment, the Q2 surface formed some 40 m lower and was abandoned at about 200 ka. Although the Q1 surface formed more than 400 ka ago, soil development implies that erosion slowed on the Q1 and Q2 surfaces at similar times. Total soil carbonate suggests that parts of the Q3 surface stabilized at 25-40 ka, carbonate stage indicates latest Pleistocene, and a single radiocarbon date demonstrates that portions of the surface were active at about 10 ka. Carbonate stage on Q4 soils suggests that they are slightly younger than Q3 soils, and cS values and absolute elevations of the surfaces overlap. Both surfaces must have been abandoned in latest Pleistocene or earliest Holocene. Periods of aggradation and erosion probably characterized much of Holocene time, but the Rio del Oso area records evidence only for 3-5 m of aggradation followed by erosion in historical time.

For most of their length, surfaces in the study area are pediments carved by streams during high-energy, episodic transport in systems of shallow channels that sloped toward Black Mesa. Dethier and Martin (this guidebook) mapped a north-trending fault at the west edge of the Chili sheet that displays at least 5 m of Quaternary motion. Activity of this fault and others along the mountain front could have influenced deposits beneath the Q1 surface and local stream gradients, but our field studies give no positive evidence. None of the younger surfaces show gradient changes or offsets that can be attributed to faulting.

The depositional nature of the distal Q3 surface and latest Pleistocene aggradation along major rivers in northern New Mexico was probably a response to latest Pleistocene climatic changes or to slowing of regional uplift. Aggradation in Q3 time along the Arroyo del Palacio, Rio del Oso, and Arroyo de la Presa produced terraces at the mouths of these drainages and other terraces along the west side of the Rio Grande. Local evidence is not sufficient to decide whether the Rio Grande produced aggradation by decreasing gradients or whether the tributaries aggraded in response to excessive loads from their catch-

ments.

Surfaces of the Northern Espanola Basin

Late Quaternary dissection is most complete and surfaces youngest in the northwest Espanola Basin. South of Espanola, canyons are narrow and steep-walled, and dissection of the surface cut across the Bandelier Tuff (the Pajarito Plateau) has apparently occurred more slowly than in the Rio del Oso area because unconsolidated Miocene sediment is covered with tuff and thick Puye gravels. Gradients for the high pediments (Q1) and lower surfaces are comparable north and south of Espanola (Fig. 6). However, lower surfaces are principally terrace deposits near the Rio Grande, and there are no low pediments parallel to stream channels. The high surfaces of Manley (1976) probably correlate with the Ortiz pediment and have gradients similar to that plotted in Figure 6. The late Pliocene surface that corresponds to the Ortiz is buried beneath the Puye Formation west of the Rio Grande and is displaced by north- and northeast-trending faults.

Our reconnaissance investigations and analyses of soils developed on the Santa Cruz surface are not sufficient to establish its age. Soil carbonate is at least stage III, and clay and iron accumulation are greater than in any of the soils we examined in the Rio del Oso area. Kelley's (1979) reconstruction of the surface from isolated remnants (see Fig. 6) shows that it is much lower than the Ortiz and grades toward a Rio Grande level close to, or lower than, the present level. Because soil development suggests that the Santa Cruz formed prior to latest Pleistocene time, and its gradients suggest modern base levels, the Santa Cruz event does not correlate with surfaces preserved in the northwest Espanola Basin.

We believe evolution of surfaces in the northwest Espanola Basin resulted primarily from base-level control by the Rio Grande, but apparent west-to-east asymmetry suggests at least some local tectonic influence. Once White Rock Canyon was cut through the resistant volcanic rocks into unconsolidated sediment, river grade probably responded to regional erosion and deposition controlled by tectonism and climatic change. We have sketched base-level changes from late Pleistocene to the present for an area near Espanola, assuming minimal tectonic influence over short intervals (Fig. 7). The graph shows inferred, relative local changes and should be used as a guide for discussion. Integration of the Rio Grande in late Pliocene resulted in cutting of widespread erosion surfaces graded to a base level some 35 m higher than the present level about 2 m.y. ago. Afterwards the base level in the NW Espanola Basin rose as a result of damming and aggradation by Jemez Mountain rocks, reaching levels some 350 m above the present level about 1 m.y. ago. Erosion followed, lowering the base level 200 m by at least 200 ka and perhaps by as much as 400 ka.

Bachman and Mehnert (1978) suggest that slowing of regional-uplift rates caused cutting of the Llano de Albuquerque surface at about 500 ka ago, and formation of the Llano de Manzano by coalescing fans some 200 or 300 ka ago. Surfaces Q1 and Q2 may broadly correlate

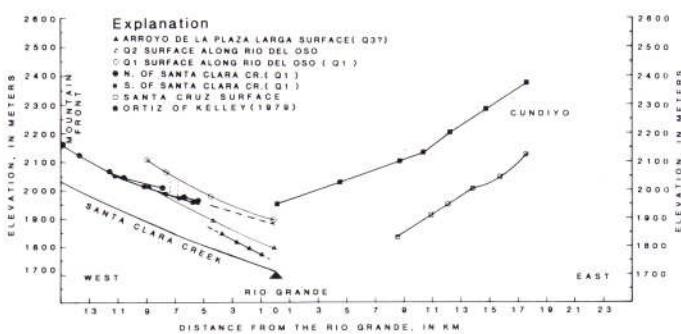


FIGURE 6. Gradients of the Ortiz, Santa Cruz, and mid- to late Pleistocene surfaces near Espanola, New Mexico. Vertical dashes are faults mapped along Santa Clara Creek.

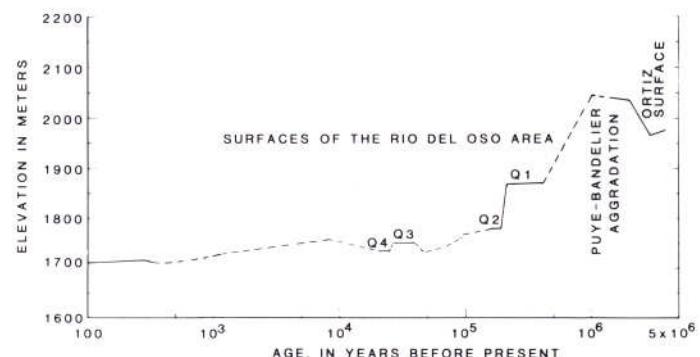


FIGURE 7. Schematic illustration of changes in base level near Espanola from late Pliocene to present.

with these Albuquerque Basin surfaces, which would imply regional base level during most of the 3-1 m.y.B.P. interval was controlled locally. The upper Pliocene to mid-Quaternary deposits in White Rock Canyon provided local-base level, and understanding their evolution is a key to advancing our knowledge of Quaternary geomorphic evolution of the Espanola Basin.

ACKNOWLEDGMENTS

Portions of this work were supported by Los Alamos National Laboratory and the Bronfman Science Center at Williams College. Chuck Harrington provided encouragement in the field and a thorough review of an earlier version of this manuscript, and John Hawley made a number of helpful suggestions.

REFERENCES

- Bachman, G. O., and Machette, M. N., 1977, Calcic soils and calcretes in the southwestern United States: U.S. Geological Survey, Open-file Report 77-794, 163 pp.
- , 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, pp. 283-292.
- Bryan, K., 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico; *in* Rio Grande joint investigation in the upper Rio Grande basin in Colorado, New Mexico, and Texas: National Resources Committee, Regional Planning, pt. 6, pp. 197-225.
- Bull, W. B., 1964, Geomorphology of segmented alluvial fans, western Fresno County, California: U.S. Geological Survey, Professional Paper 352-E, pp. 89-128.
- Chleborad, A. F., Powers, P. S., and Farrow, R. A., 1975, A technique for measuring bulk volume of rock materials: Association of Engineering Geologists, Bulletin, v. 12, no. 4, pp. 317-322.
- Dethier, D. P., and Manley, K., 1984, Geology of the Chili quadrangle, Rio Arriba County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map, in press.
- Dreimanis, A., 1962, Quantitative determinations of calcite and dolomite by using Chittick apparatus: Journal of Sedimentary Petrology, v. 32, no. 3, pp. 520-529.
- Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico-guidebook control of Rio Grande base level in late Quaternary time. However, to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.
- , Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, no. 5, pp. 347-360.
- Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey, Water-supply Paper 1753, 107 pp.
- Jackson, M. L., 1973, Soil chemical analysis-advanced course (2nd revised edition): Published by author, Madison, Wisconsin, 895 pp.
- Kelley, V. C., 1979, Geomorphology of Espanola Basin: New Mexico Geological Society, Guidebook 30, pp. 281-288.
- Leopold, L. B., 1951, Pleistocene climate in New Mexico: American Journal of Science, v. 249, pp. 152-168.
- Machette, M. N., 1978, Dating Quaternary faults in the southwestern United States by using calcic paleosols: U.S. Geological Survey, Journal of Research, v. 6, no. 3, pp. 369-381.
- , 1982, Morphology, age, and rate of accumulation of pedogenic CaCO₃ in some calcareous soils and calcretes of the southwestern United States (abstract): Geologic Society of America, Abstracts with Programs, v. 14, pp. 182-183.
- Manley, K., 1976, The late Cenozoic history of the Espanola Basin, New Mexico: Ph.D. thesis, University of Colorado, Boulder, 171 pp.
- , 1979, Stratigraphy and structure of the Espanola Basin, Rio Grande rift, New Mexico; *in* Riecker, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 71-86.
- Martin, P. S., and Mehringer, P. J., Jr., 1965, Pleistocene pollen analysis and biogeography of the Southwest; *in* Wright, H. E., and Frey, D. G. (eds.), The Quaternary of the United States: Princeton University Press, pp. 433-451.
- Moss, J. H., 1977, The formation of pediments: scarp backwearing or surface downcutting? *in* Doebring, D. O. (ed.), Geomorphology in arid regions: Annual Geomorphological Symposium no. 8, State University of New York at Binghamton, Publications in Geography, pp. 51-78.
- Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey, Miscellaneous Geological Investigations Map 1-571.
- Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-supply Paper 1525, 258 pp.
- Van Devender, T. R., and Spaulding, W. G., 1979, Development of vegetation and climate in the southwestern United States: Science, v. 204, pp. 701710.



Narrow-gauge yard at Antonito. This is now the eastern terminus of the Cumbres and Toltec Scenic Railroad. It was formerly the point where the branch lines to Santa Fe and Durango separated.