

GENERAL SOIL-LANDSCAPE RELATIONSHIPS AND SOIL-FORMING PROCESSES IN THE PAJARITO PLATEAU, LOS ALAMOS NATIONAL LABORATORY AREA, NEW MEXICO

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Abstract—Soils in the landscapes of the Pajarito Plateau, located on the east side of the Jemez Mountains of northern New Mexico, have been strongly influenced by the volcanic origin of this ignimbritic plateau. The overall character of many soils in this region ultimately reflects their formation in parent materials with abundant, silica-rich volcanic lithologies in a generally semi-arid climate on geomorphically stable landforms. Increases in the degree of soil development in certain properties such as soil reddening and iron oxide accumulation and values of the soil profile development index are largely time-dependent, but climatic variability and slope position have also affected soil development in this region. Chemical weathering explains the development of some soil properties, but the entrapment and incorporation of dust in this semiarid climate can also strongly influence soil development. In upland positions on the Pajarito Plateau, the most recent period of rapid accumulation of eolian material exceeded the rate at which dust could be incorporated within soils, causing the burial of older landscapes and soils on mesa tops. The formation of a very strongly developed soil on mesa tops of the Pajarito Plateau over possibly several hundred thousand years owes to the widespread deposition of alluvium on the underlying, resistant Bandelier Tuff. Such a soil could not have formed in the dense, fractured tuff itself, but could form in the permeable alluvium given the subsequently long interval of surface stability; moreover, the tuff's presence may strongly affect soil-forming processes in the alluvium by influencing deeper soil-water movement. The presence of the widespread, welded tuff has also favored the evolution of many narrow, deep canyons that cut the plateau, circumstances generally unfavorable for preservation of older Pleistocene fill terraces. Thus, only weakly or very weakly developed soils typically occur on Holocene terraces and associated colluvial deposits in many canyons. Such soil-landscape patterns markedly contrast in many respects with those typical of other landscapes flanking mountains elsewhere in New Mexico and other areas of the Southwest.

INTRODUCTION

Ignimbrite plateaus surrounding the Jemez volcanic field, including the Pajarito Plateau on which Los Alamos National Laboratory (LANL) is located on the eastern flanks of the Jemez Mountains, are mostly the product of two caldera-forming eruptions that occurred within the last 1.6 Ma (Goff et al., 1989). The Pajarito Plateau (Fig. 1) is characterized by a series of gently inclined mesas and canyons, typically sloping to the east or southeast and linked by relatively steep slopes composed principally of Bandelier Tuff bedrock. The geomorphic evolution of the landscapes of this area has increasingly been the subject of several investigations. Prior to the early 1990s, however, the only formal soil study conducted in this area was that of Nyhan et al. (1978), focusing on soil clas-

sification and survey. This investigation did not entail a study of the chemistry, mineralogy and texture of the soils or a detailed study of their soil-geomorphic contexts.

The principal goals of this study were to (1) characterize the morphologic, textural, chemical and mineralogic properties of soils of this region in various landscape positions in order to identify the major processes and rates of soil formation in Quaternary surficial deposits in this region; and (2) provide a soil-geomorphologic perspective utilizing the "state factor" approach of Jenny (1941, 1980) to the interpretation of landscape evolution, as discussed in McFadden and Knuepfer (1990) and Tonkin (1994). The research also provides the basis for comparing the observed pattern of soil-landscape relations in this area with those observed elsewhere in or near the Jemez Mountains as well as other mountain-front landscapes in New Mexico. In addition, both surface and subsurface contamination of many areas of Los Alamos National Laboratory has occurred by virtue of its having been the site of weapons research and other related activities since the early 1940s (Rogers, 1977; Purtymun et al., 1988; Fernbaugh et al., 1990). Soil chemistry plays an important role in influencing contaminant transport (e.g., Longmire et al., 1995; Watt, 1996; Watt, in prep.). Accordingly, given varying, diverse surficial environments and, consequently, varying and diverse soils in the landscape, environmental cleanup activities will require a basic understanding of soil-landscape relationships.

SOILSTATE FACTORS

Relief and parent materials

Many previous studies (e.g., Gile et al., 1966, 1981; McFadden and Tinsley, 1985; McFadden et al., 1986; McDonald, 1994) have demonstrated that in a semi-arid climate such as the Los Alamos area, the development of certain key pedogenic features requires a minimum of several centuries to several tens of thousand years. Therefore, relatively stable geomorphic surfaces are necessary for the formation of at least weakly to moderately developed soil profiles. On the basis of observations from this study and those of others (e.g., Nyhan et al., 1978), landforms sufficiently stable to be conducive for development of soils with pronounced horizonation were identified and were classified into three general slope settings (Fig. 2): gently sloping (usually less than 5°) mesa tops, steeper slopes below canyon walls (5-15° slopes), and alluvial terraces in can-



FIGURE 1. Soil sampling sites in the Los Alamos area. Open circles represent sites mentioned in this paper.

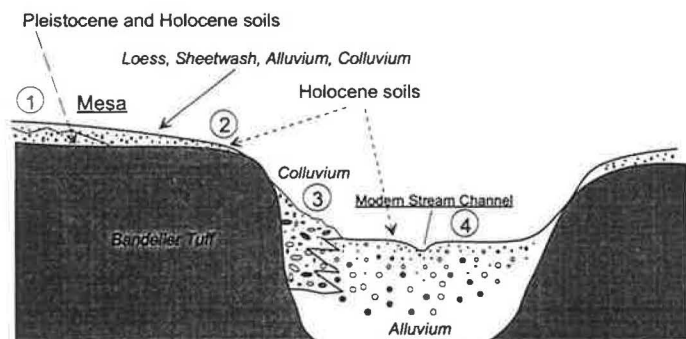


FIGURE 2. Schematic representation of soil age - soil landform relationships on the Pajarito Plateau. Numbers represent (1) slope-summit settings near inland areas, (2) slope-summit settings near mesa edges, (3) slope-alluvial aprons, and (4) alluvial terrace settings of canyon bottoms. Canyon depths vary from tens to several hundred meters. Canyon widths vary from hundreds of meters to several kilometers.

yon bottoms associated with ephemeral streams, such as those that drain Ancho Canyon and Water Canyon (slopes less than 7°). Soils formed in alluvial deposits can also be subdivided on the basis of similarities in parent material, general amount and type of vegetation, and slope angle.

In addition to information in Nyhan et al. (1978), data in more recent reports compiled as part of seismic hazard or other environmental investigations include some data concerning soil stratigraphy and morphology or soil occurrence that provide additional information on soil parent materials (Reneau et al., 1995; Reneau et al., this volume; Reneau et al., in press; Kolbe et al., unpubl. reports for LANL; Longmire et al., in press; Wong et al., unpubl. report for LANL; McFadden, unpubl. report for LANL; Drake et al., this volume; Eberly et al., this volume; McDonald et al., 1994; this volume). Data from these studies indicate that all soils in the area are formed primarily in reworked volcanic parent material, i.e. alluvium, colluvium and sheetwash derived from both volcanic lithologies; and relative soil ages vary significantly from site to site, including sites with similar geomorphic positions, reflecting a complex history of landscape change over thousands to hundreds of thousands of years.

Climate and vegetation

The Los Alamos area has a generally semi-arid, temperate, continental mountain climate. The annual precipitation in the region varies strongly from west to east, such that annual precipitation at lower, more easterly parts of the study area may be approximately half that of higher, more westerly sites near the mountain front (Bowen, 1990). For example, average annual rainfall in this region varies from about 30 cm on the eastern Plateau at elevations as low as 2000 m, to 50 cm to the west at elevations of about 2500 m. The climate is strongly seasonal, with as much as 40% of the rain falling between May and October. Maximum average daily temperatures are typically between 30 and 35°C, and minimum average daily winter temperatures range between 16 and 20°C. At increasingly higher elevations in the Los Alamos area, most of the winter precipitation falls as snow.

Local vegetation varies in the Los Alamos area, depending on elevation and aspect. North-facing slopes, for example, are more moist and more strongly vegetated than south-facing slopes. Vegetation supported at the higher elevations include Ponderosa pine or mixed Ponderosa-piñon/juniper pine woodland; whereas at lower elevation sites, typical vegetation includes cactus, juniper, piñon and grasses.

METHODOLOGY

A total of 32 soil profiles were sampled from various parts of Los Alamos County (Fig. 1). Complete profile descriptions and laboratory data and other details on sample location and geomorphic setting are given in Watt (1996) and Longmire et al. (1995). Several representative profiles are discussed in this report to illustrate typical variations in soils within and between different geomorphic settings. For each horizon in the soil profile, a single, homogenized, bulk sample of approximately 1 kg representing the entire horizon was collected in order to conduct sub-

sequent laboratory analyses. Soil morphological properties (e.g., soil horizon thickness, depth, color, texture, structure, and the presence, quantity and types of clay films, pores and roots) were recorded according to the methods of Birkeland (1984), Birkeland et al. (1991) and Buol et al. (1989).

Soil profiles located at mesa-top positions include the Twomile Mesa site (TA-69) and the Ancho Mesa site (TA-39). The Twomile Mesa site was located in a trench excavated for hydrologic studies, which exposed a soil up to 0.9 m thick. Soil profiles located along footslope to toeslope transition positions include the upper Los Alamos Canyon and Water Tank (TA-16) sampling sites. The upper Los Alamos Canyon site is located at the base of a steep, forested, north-facing slope. The Water Tank (TA-16) site, located at the base of a steep, forested slope, was sampled in a trench excavated at the base of the main scarp of the Pajarito fault zone. Soil profiles observed in alluvial terraces in canyons include Ancho Canyon and Bayo Canyon (TA-10).

Laboratory analyses of soil samples were conducted as outlined by the Soil Conservation Service (1981). These analyses included measurement of bulk density (Singer, 1986), soil pH, cation-exchange capacity (Thomas, 1982), particle-size distribution analysis (Day, 1965), iron oxide and oxyhydroxide content by the dithionite-citrate-bicarbonate technique (Fe_o ; Mehra and Jackson, 1960) and the oxalate technique (Fe_o ; McKeague and Day, 1966; Janitzky, 1986), calcium carbonate content (Machette, 1986) and organic-carbon content (Metson, 1961). The ratio of Fe_o to Fe_t is generally regarded as a proxy or index of soil iron oxide crystallinity (Schwertmann and Taylor, 1977) and has been observed to change systematically in a time-dependent manner in soils of chronosequences (McFadden and Hendricks, 1985; McFadden and Weldon, 1987).

For selected soils of the mesa tops and the alluvial terrace settings, a soil-development index (SDI) was calculated based on the method of Harden (1982) as a means of semiquantitatively evaluating overall degree of soil profile development. The method entails conversion of soil property data (e.g., soil structure, clay films, color) to an index for the entire profile by comparing soil property characteristics to those of the assumed initial parent material, normalizing individual property values by comparison with property values from maximally developed soils, and summing values for all horizons to acquire an index for the entire soil. Many studies show that increases in the SDI of soils in soil chronosequences are strongly time dependent (Harden, 1982; Harden and Taylor, 1983; Birkeland, 1984; McFadden et al., 1986; McFadden and Weldon, 1987; McDonald et al., this volume). Harden (1982) proposed maximal soil values for calculation of the SDI based on older Pleistocene or Pliocene soils of central California; however, maximal soil horizon property values based on characterization of soils of other geographic provinces can also be used to determine SDI values and are perhaps more appropriate (McFadden et al., 1986; McFadden and Weldon, 1987). The maximum degree of development for selected soil properties, therefore, was based on pedogenic properties reported in the literature for old, strongly developed soils in New Mexico presently in a generally semiarid climate and formed in gravelly, largely noncalcareous alluvium (e.g., McGrath and Hawley, 1987; data provided in Watt, 1996). SDI values for soils in chronosequences in climatically similar regions calculated using either method are generally comparable (McFadden and Weldon, 1987). Also, as the SDI value is strongly dependent on profile thickness as well as age (Harden, 1982), we also calculated a "thickness-normalized profile index" as described in Ponti et al. (1985) to assess this effect.

RESULTS

Mesa tops

In the Pajarito Plateau area, the most well-developed soils were uniformly located on the mesa tops, typically at least 100 m away from mesa edges and often near upland areas at the base of the Jemez Mountains (e.g., Twomile Mesa, TA-69). These soils are characterized by a well-developed, clay-enriched and strongly reddened Bt (Argillic) horizon overlying indurated tuff (Fig. 3, Table 1), and can be observed in roadcuts or trenches excavated as part of environmental studies in many areas of the Pajarito Plateau (Nyhan et al., 1978; Kolbe et al., 1994; Watt, 1996; Longmire et al., in press). The tuff exhibits minimal chemical weathering, and our observations show that these soils have not formed by in

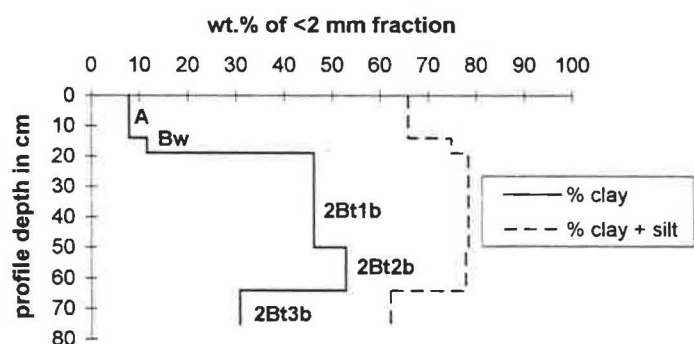


FIGURE 3. Particle-size distribution with depth for a well-developed mesa-top soil profile on Twomile Mesa (TA-69 north).

situ weathering of the Bandelier Tuff. Instead, the strongly developed, buried soil has developed chiefly in alluvium deposited over weathered Bandelier Tuff. The alluvium occurs in paleochannels or paleosoles formed in the tuff bedrock, perhaps representing remnants of an old alluvial fan (Longmire et al., in press).

At all sites, a typically several decimeter thick, nongravelly unit is present above the Bt horizon. At the Twomile Mesa site, the pronounced increase in clay content, reddening, soil structure, and appearance of coarse clasts at a depth of 19 cm is interpreted as the boundary between a younger surficial soil and associated deposits, and a buried soil (Fig. 3, Table 1). Although the upper part of the profile has been interpreted as representing an A-A2 horizon sequence (i.e., an A-E horizon sequence, using the more recent terminology of Soil Conservation Service, 1981)

TABLE 1: Particle-size distribution, Fe_2O_3 (Fe_d) and CaCO_3 contents for representative soil profiles in the study area.

Sample site	Horizon	Clay content (wt.%)	Silt content (wt.%)	Sand content (wt.%)	Gravel content (wt.%)	Fe content (wt.% Fe_2O_3)	CaCO_3 (wt.%)
Representative Slope Summit Settings							
Twomile Mesa (TA-69 north)	A	7.6	58.2	34.2	7.0	1.05	0.16
	Bw	11.6	63.3	25.1	7.6	0.79	0.12
	2Bt1b	46.2	32.2	21.7	33.1	1.30	0.08
	2Bt2b	52.8	25.0	22.2	37.7	0.96	0.20
	2Bt3b	30.8	31.3	37.8	37.4	0.78	0.18
Ancho Canyon (TA-39)	A1	11.6	51.4	36.9	4.7	0.79	0.21
	A2	12.3	54.0	33.7	0.7	0.86	0.17
	Bt	32.8	44.3	22.9	8.9	1.11	0.21
	Bwkb	23.9	52.1	21.4		0.80	1.56
	Btkb	53.6	33.7	12.7	22.9	1.10	1.33
	K	34.0	36.4	29.7	69.4	0.73	24.11
Representative Footslope/Toeslope Transitional Settings							
TA-16	A	16.2	58.0	25.8	46.8	0.72	0.29
	BA	13.8	49.5	36.7	34.1	1.23	0.14
	2Bt1b	25.9	47.5	26.6	29.8	0.78	0.07
	2Bt2b	20.1	48.7	31.2	37.0	1.39	0.22
	2Bt3b	15.9	43.7	40.3		0.77	0.17
	2CB	16.4	6.6	77.1	80.6	0.56	0.22
Upper Los Alamos Canyon	A1	18.3	49.5	32.2	26.3	0.61	0.25
	A2	12.7	50.1	37.2	37.6	0.65	0.56
	BA	7.9	37.5	54.6	52.8	0.52	0.14
	Bw	8.2	47.0	44.8	20.8	0.60	0.21
	Cb	5.7	35.3	59.0	27.1	0.47	0.13
	Ab2	16.9	39.6	43.5	71.0	0.72	0.72
Representative Alluvial Settings							
Lower Los Alamos Canyon (Tsankawi)	A	7.4	19.1	73.5	44.7	0.26	0.11
	C	2.4	14.2	83.4	8.0	0.24	0.14
Ancho Canyon	2Cb	3.0	20.6	76.4	16.3	0.25	0.12
	A1	7.4	17.5	75.1	4.3	0.49	0.18
	A2	3.1	8.5	88.4	6.5	0.50	0.16
	Bw1	9.3	43.2	47.5	9.1	0.62	0.22
	Bw2	8.1	26.0	65.9	13.0	0.45	0.18
	Bw3	3.3	8.4	88.3	4.6	0.53	0.19
	Btb	9.4	27.0	63.6	27.1	0.58	0.15
	Bwb	10.3	25.6	66.1	21.2	0.55	0.18
	Ckq	1.3	5.0	93.7	40.6	0.40	0.19
	C'	0.7	4.0	95.3	11.0		
	C	2.3	4.8	92.9	7.8		

genetically related to the underlying Bt horizons (Nyhan et al., 1978), we interpret the horizons as an A-Bw sequence formed in sediment overlying the buried Bt horizon. The presence of an eluvial "E" horizon is inconsistent with the slightly alkaline pH (Watt, 1996) and high base/alumina and base/ R_2O_3 (where R_2O_3 signifies chemically conservative elements) molar ratios of this part of the soil profile (Fig. 4). Occasionally the El Cajete pumice fall, with an age of 50 to 60 ka (Reneau et al., 1996), possessing a moderately developed soil also overlies the strongly developed, buried soil, (Watt, 1996; Kolbe et al., unpubl. report for LANL; Reneau et al., this volume; McDonald et al., this volume; Longmire et al., in press).

The clay content and silt+clay content increase substantially with depth (Fig. 3). This data, and the presence of illuvial clay films indicate substantial clay translocation. The relatively high CEC values of these soils (Fig. 5), locally as high as 35 meq/100g, are consistent with both large clay content and the large fraction of smectite clay in the clay fraction (Watt, 1996). Soil iron-oxide content, represented by Fe_d , also increases significantly with depth (Fig. 6), paralleling the down-profile increase in reddening. In addition, the Fe_d/Fe_o ratio increases with depth (Fig. 6).

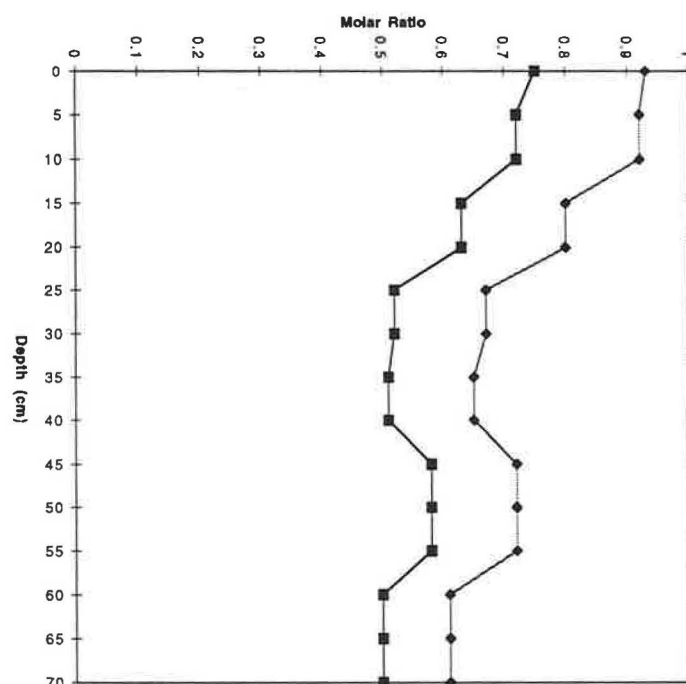


FIGURE 4. Molar ratios (bases/alumina - squares; bases/ R_2O_3 - diamonds) with depth for the soil profile on Twomile Mesa (TA-69 south; located 5 m from TA-69 north). A-Bw horizons at 0-20 cm, 2Bt1b, 2Bt2b, and 2Cb horizons at 20-57 cm, R/Bt at 57 to 70 cm.

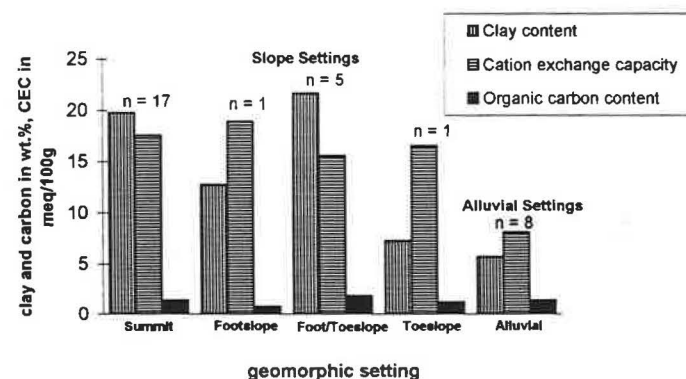


FIGURE 5. Average clay, cation-exchange capacity and organic carbon contents of soils in alluvial and slope geomorphic settings in the study area.

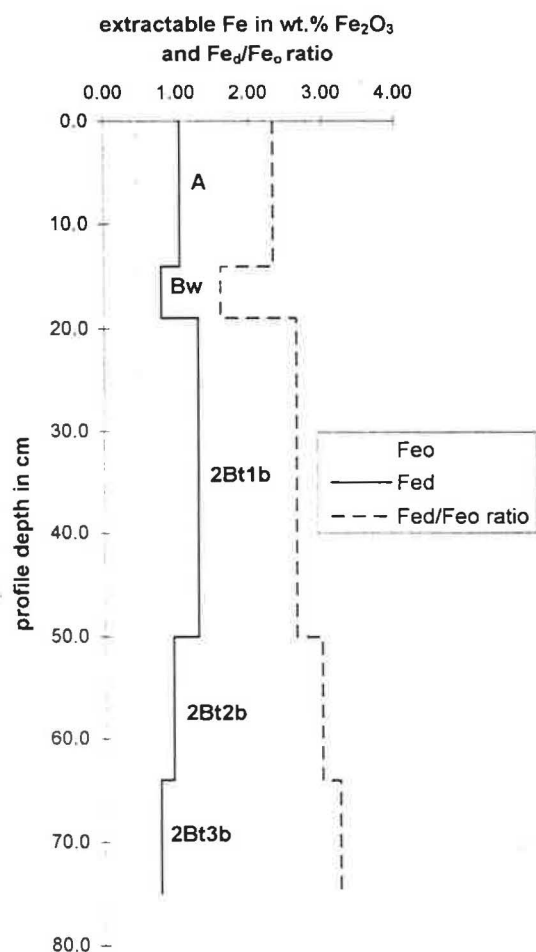


FIGURE 6. Extractable iron oxides with depth for the soil profile on Twomile Mesa (TA-69 north).

suggesting an increase in pedogenic iron oxide crystallinity, probably reflecting the presence of pedogenic hematite (McFadden and Hendricks, 1985). Significant declines in key molar ratios in these horizons with depth (Fig. 4) also indicate at least some chemical weathering, shown by the loss of more soluble bases relative to chemically conservative components in the soil parent materials.

Silt-plus-clay content also increases markedly in the upper horizon. This data, the lack of coarse clasts in these horizons, the presence of carbonate in these horizons, and changes in bulk chemical composition of the soil shown by high base/alumina and high base/R₂O₃ molar ratios indicate that this is eolian, or reworked eolian sediment and not strongly chemically weathered tuff-rich alluvium.

The maximum possible age of soils on the mesa tops must be less than 1.2 Ma, the apparent age of the Tshirege Member of the Bandelier Tuff. The alluvial deposits and much of the associated buried soil must also be older than the El Cajete pumice, 50 to 60 ka. To date, other geochronologic data has not been acquired to further constrain the age of this soil. The SDI value for the buried soil on Twomile Mesa is 35.2. This value suggests soil development over a duration of about 35 ka when compared to the rate of SDI increase determined by McDonald et al. (this volume) for late Quaternary soils in Rendija Canyon, north of the study area. These soils, however, are very thick, and the older soils are 3 m or more thick. McDonald et al. (this volume) attribute this largely to slow accumulation of fines and cumelic soil formation subsequent to formation of gravelly terraces. When thickness-normalized SDI values are computed for the soils of Rendija Canyon that are estimated to be 100 to 200 ka, values of 0.25 and 0.37 are obtained. The thickness-normalized value of the Twomile Mesa soil is 0.63. This not only indicates that this soil formed over a similar duration (i.e., 100 to 200 ka), but also that it may

well be considerably older. Such an age is also consistent with the development of a K horizon with stage IV morphology at the mesa-top site at Ancho Canyon (see Table 1). Many studies of calcic soils in New Mexico indicate that at least 100,000 years of soil development are required to attain this stage of pedogenic carbonate morphology in noncalcareous parent materials (Gile et al., 1981; Dethier and Demsey, 1984; Dethier et al., 1988; Machette, 1985).

Alluvial terrace settings

Soils typically associated with alluvial terraces in canyon bottom settings are weakly developed, characterized by sandy texture, minimal rubification and low contents of pedogenic clay, carbonate and iron oxide contents, and generally low cation-exchange capacity (Table 1; Figs. 5, 7, 8). In many profiles, observable soil properties extend downward only a few tens of centimeters into the sediment. For example, the soil described in a terrace in Bayo Canyon (TA-10) displays a Bw horizon, but the absence of illuvial clay films in the profile signifies that much of the observed increase in silt content is associated with initial parent material attributes (Fig. 7). Notably, the upper 25 cm of this soil is characterized by mixed colluvial and alluvial materials which contains wire and metal fragments, demonstrating the very young age of the sediment.

There is essentially no indication of significant pedogenic iron oxide accumulation, and the Fe_d/Fe_o ratio changes in an apparently nonsystematic manner with depth. This probably reflects iron-oxide content related to initial stratigraphic and sedimentologic variability, rather than variation in the crystallinity of pedogenic iron oxides exhibited by much older soils on the mesa tops.

The presence of pumice of the El Cajete pumice in soil parent materials in the Bayo Canyon and Ancho Canyon sites demonstrates that the soils are younger than 50 to 60 ka. In addition, numerous radiocarbon dates have been obtained from sediments associated with terraces in which soils have formed that exhibit similarly weak pedogenesis in this area

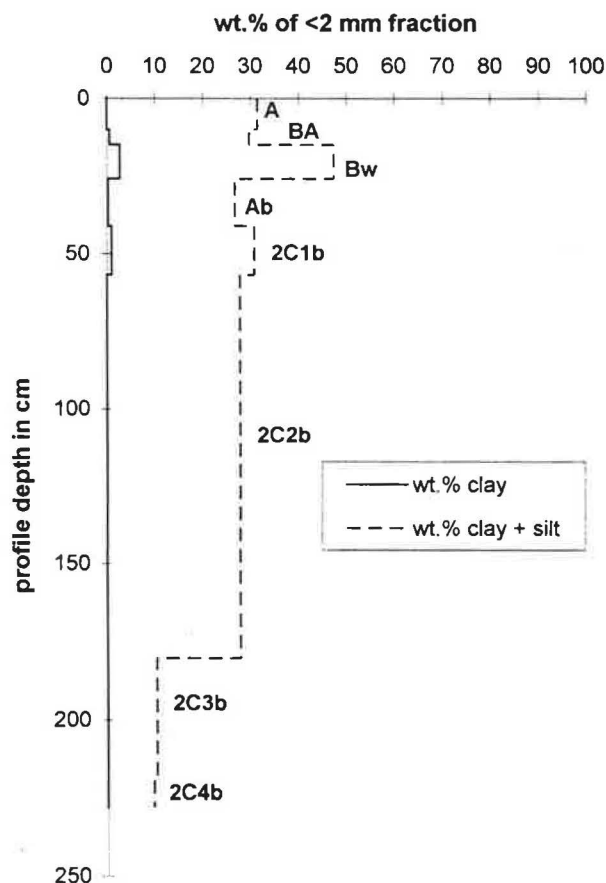


FIGURE 7. Particle-size distribution with depth for a weakly-developed, valley-bottom soil in Bayo Canyon (TA-10, profile 4).

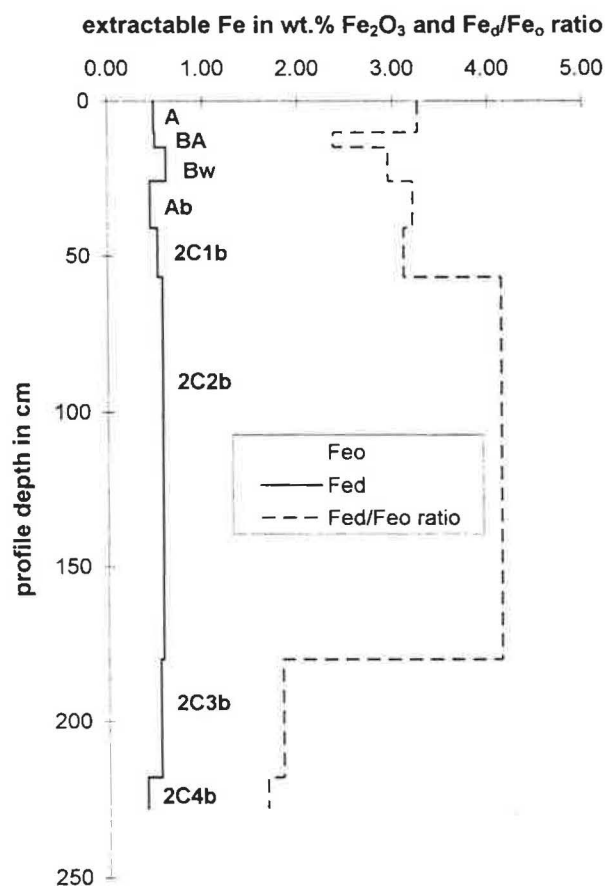


FIGURE 8. Extractable iron oxides with depth for a weakly-developed valley-bottom soil in Bayo Canyon (TA-10, profile 4).

(e.g., Reneau et al., 1993; Reneau, 1995; Reneau et al., this volume; Longmire et al., in press; Gardner et al., 1990; Drakos et al., this volume; McDonald et al., this volume). SDI values for the soils at the Tsankawi site and the Ancho sites are 2.08 and 17.17, respectively. Based on evaluation of the available radiocarbon dates as well as the soil age-SDI relation observed by McDonald et al. (this volume), very weakly to weakly developed soils of terraces in the study area are primarily associated with terraces of late to early Holocene age.

Footslope and toeslope positions

Several soils were sampled in footslopes and toeslopes of landforms associated with colluvial deposits in the deep canyons. One such soil in upper Los Alamos Canyon developed in colluvial material characterized by layers of coarse, locally angular material containing abundant clasts of Bandelier Tuff and sand and silty-sand layers, attributed to deposition of fluvial sediment during floods along the canyon (Watt, 1996; Longmire et al., in press). The soil at the Water Tank site (TA-16) was exposed in a trench excavated between Canon de Valle and Water Canyon as part of the Seismic Hazards Investigation Program (Wong et al., 1995). The trench dissects the base of the main scarp of the Pajarito fault zone and the slope extends 35 m above the sampling location. The trench exposes the soil, which formed in surficial colluvial deposits shed off this slope, as well as up to 1.2 m of the underlying El Cajete pumice. Colluvial deposits and sediments below the El Cajete pumice contain angular clasts of Bandelier Tuff, but no pumice.

Clay content in these soils is relatively high; but the parent material of these soils may contain initially both high silt and clay (Table 1). The soil in upper Los Alamos Canyon contains the highest abundance of organic material of all sites studied in the Los Alamos area. The B horizons are weakly developed, contain no translocated clay, and do not display significant rubification. Little pedogenic carbonate has accumulated and there is no indication of calcic horizon formation below a noncalcareous

B horizon. Two radiocarbon dates from charcoal collected at 0.85 and 1.35 m depth in this soil provided ages of 100 yr. B.P. and 3050 yr. B.P., respectively (Watt, 1996; Longmire et al., in press).

The soil formed at TA-16 is slightly better developed, exhibiting a Bt horizon in the pumice-rich unit. This deposit and associated soil is less than 50 to 60 ka; and radiocarbon dates of 1120 ± 80 yr. B. P. and 5840 ± 90 yr. B. P. have been obtained from charcoal within the overlying materials in which the A-BA horizon sequence has formed (Wong et al., 1995). Soils located on slope positions such as this site and at other sites in the study area are typically higher in clay and iron content compared with soils from alluvial settings (Table 1). Profile attributes such as these, with weak to moderate soil development in thick, relatively young deposits indicate strongly cumelic pedogenesis, as has been observed in numerous studies of soils in settings where nearby slopes provide a constant source of colluvial materials or fine-grained sediments from overland flow (Birkeland et al., 1991; Harrison et al., 1993; McDonald et al., this volume). Accordingly, the somewhat high iron oxide and clay contents of these soils are attributable to partial inheritance from the soil parent material.

DISCUSSION

Some characteristics of the soil-landscape relations in the Pajarito Plateau area are similar to those associated with many landscapes flanking mountainous areas of New Mexico and elsewhere in the southwestern United States—the most weakly developed, youngest soils occur on floodplains or relatively young terraces associated with the main drainages emanating from the mountain front; more well-developed soils are associated with older, topographically higher geomorphically stable surfaces. The well-developed mesa-top soils were present before the eruption of the El Cajete pumice 50 to 60 ka, and probably had been forming in this relatively stable geomorphic setting for a few hundred thousand years. Approaching the edges of the mesa tops, the soil is often much thinner or is completely absent. In areas of exposed bedrock near cliffs throughout this region, however, such fracture-filling materials are observed. The presence of reddened, clay-enriched materials in fractures in the tuff many meters below the surficial soils has been attributed to translocation of materials from the overlying soils (Davenport et al., 1995), indicating that such soils and associated old alluvium had once been present above now-exposed bedrock. This is evidence for the substantially larger, past areal extent of this alluvium.

Usually, far less well-developed soils are associated with Holocene alluvium in canyon bottom settings or in colluvial materials associated with canyon walls flanking low terraces and floodplains of the canyon bottoms. Some relatively weakly developed Holocene soils are also associated with channels in mesa-top settings, such as those exposed at a site east of the Los Alamos townsite ("EG&G site", see Fig. 1) (Watt, 1996; Reneau et al., this volume). In many areas of the Pajarito Plateau, the El Cajete pumice has been completely removed by erosion or reworked into younger alluvial materials; however, in relatively geomorphically stable sites, weak to moderately developed soils have formed in the El Cajete pumice and overlying fine-grained materials (Watt, 1996; Longmire et al., in press; Reneau et al., this volume; McFadden, unpubl. data). Soils in some relatively thick, well-preserved sections of the El Cajete pumice have weak, reddened argillic horizons, expressed partly as illuvial Bt laminae or layers, potentially formed over 50 to 60 ka.

The redder colors, far higher pedogenic clay and iron oxide contents, and much higher SDI values of soils on the mesa tops reflect soil development over time spans exceeding 10^5 years. Some changing soil properties, such as higher Fe_o/Fe_o ratios and Fe_o/Fe_o depth functions in the older soils, result from chemical weathering of initial soil parent materials. As noted above, other characteristics of these and younger soils can be attributed to progressive additions of eolian material, a process that strongly influences soil development throughout arid and semiarid regions (Gile et al., 1981; Birkeland, 1984; McFadden et al., 1986; McDonald, 1994; McDonald and McFadden, 1994; McDonald et al., this volume). When rates of dustfall in the late Quaternary were fast, the rate at which dust could be transferred into the soil was exceeded, causing deposition of loess and the burial of an underlying soil. Lower dustfall rates permit incorporation of dust largely below the soil surface. The

presence of pedogenic calcium carbonate in Holocene soils in the study area, for example, primarily reflects such additions of calcium from dustfall or rainfall, given the noncalcareous nature of the soil parent materials (Gile et al., 1966; 1981; Machette, 1985; McFadden and Tinsley, 1985). Also, constitutive mass balance modelling based on data for the bulk chemical composition of the mesa-top argillic B horizon indicates significant inputs of Ca, Fe, Al and other elements from external sources (Eberly et al., this volume). The development of soils on the Pajarito Plateau is the complex result of chemical weathering of the parent material, dust incorporation, and chemical weathering of components in incorporated dust.

Pedogenesis characterized by net mass addition through incorporation of externally derived materials is associated with dilational, volumetric strain accumulation (Brimhall and Dietrich, 1987; Eberly et al., this volume). As noted above, illuvial clay-rich, reddened soil materials are observed in fractures in the tuff; however at many mesa-top sites these materials are also present in *horizontal to subhorizontal* fractures in tuff bedrock up to several centimeters wide directly below Bt horizons in alluvial parent material. The latter could be partly attributable to translocation of soil materials into the fractures and progressive, dilational pedogenesis.

A systematic progression from stage I to IV in the morphology of pedogenic carbonate is not observed in most parts of the study area. Instead, the observed sequence at areas of lower elevation is largely characterized by soils with stage I or stage IV morphology, whereas at higher elevations younger soils are noncalcareous and old soils of mesa-tops have minimal pedogenic carbonate at lower depths. The stage I through IV progression is observed elsewhere in relatively similar climates and noncalcareous parent materials in northern New Mexico, such as along the Rio Chama (Dethier and Demsey, 1984), along the Pecos River (Karas, 1988), and along the mountain front of the Sangre de Cristo range (Kelson, 1986; Pazzaglia and Wells, 1990). As progressive dust accumulation apparently has impacted soils in the Quaternary in this area, one obvious reason for the lack of soils with stage II and III morphology is the lack of terraces of the appropriate age that would probably have developed this morphology. The presence of a soil with stage IV morphology and one with only minimal carbonate at depth formed in otherwise similar soil-landscape settings, however, indicates that spatial climatic variation may also play an important role in influencing calcic soil formation. Soils at higher elevations occasionally have O horizons and generally have more organic-material rich, thicker A horizons than do soils at lower sites (Watt, 1996), probably owing to the slightly wetter climate, increased plant cover, larger annual biomass production, and cooler soil temperatures at higher elevations as compared to lower elevations. An edaphic environment at such sites associated with increased soil CO₂ respiration, combined with deeper soil-water movement, may favor leaching carbonate to much greater depths.

The soil at the Twomile site contains virtually no carbonate in the Bt horizon despite the very high clay and silt content that should limit leaching depths. Reneau et al. (this volume) and Rogers and Smartt (this volume) propose that this region may have been subject to cooler and effectively wetter climates during glacial intervals. Such a climate during the last glacial period could conceivably account for the lack of carbonate in this soil, an explanation suggested for such aspects of soils in other areas of the western United States (Gile et al., 1981; McFadden and Tinsley, 1985; Machette, 1985; McDonald, 1994). There may be, however, another explanation. Although the K horizon of the soil at the Ancho Canyon site has formed at an altitude less than 140 m lower than the soil at the Twomile Mesa site, it seems unlikely that Quaternary climatic changes could account completely for this profound contrast in calcic horizon development given the observed modern or past climate variations in the study area. The study of Wilcox et al. (this volume) conducted at the Twomesa site indicates that interflow is an important process of downslope, soil-water and solute movement, favored by melting snow-pack, soil insulation, and the presence of the sloping surface of the underlying dense Banderlier Tuff below the argillic horizon. Interflow could also cause loss of enough dissolved calcium in soil water to prevent carbonate accumulation in the soil profile, except in fractures where some

water may percolate. At lower elevation sites the magnitude of this process may be much smaller, enabling precipitation of soil carbonate within the profile, at the tuff-soil interface, as well as in deeper fractures.

Drainages on piedmonts flanking many mountain fronts in New Mexico are associated with nested suites of terraces, typically including Holocene, late Pleistocene, late middle Pleistocene, middle Pleistocene, and occasionally even early Pleistocene terraces or fan surfaces. Some examples include the Sangre de Cristo range (Kelson, 1986; Menges, 1988; Pazzaglia and Wells, 1990), the Sandia Mountains (Connell, 1995), The Los Pinos Mountains (Treadwell, 1994); the Socorro Mountains (McGrath and Hawley, 1987), the Magdalena Mountains, (McGrath and Hawley, 1987), the San Mateo Mountains (McFadden et al., 1994), and the Organ Mountains (Gile et al., 1981). This is not the generally observed soil-landscape pattern in this part of the Pajarito Plateau. Ultimately the origins of this contrast relate to the evolution of the landscapes in the region since eruption of the Tshirege Member of the Banderlier Tuff at 1.2 Ma. This event obliterated virtually all of the preexisting topography, replacing it with an extensive ignimbrite gently dipping away from the Valles caldera. Assuming this landscape as an initial condition, a simple model for subsequent soil-landscape evolution in the region is depicted in Figure 9. Post-Banderlier Tuff incision probably commenced relatively soon after its emplacement (Gonzalez, 1993; Reneau, 1995; Reneau and Dethier, this volume; Fig. 9a). Incision of drainages into the Plateau north of White Rock Canyon may have been delayed as the Rio Grande eroded through resistant basalts in this area, and thus extracaldera streams emanating from Jemez uplands could have deposited alluvium directly atop the plateau (Reneau and Dethier, this volume). Integration of the fluvial system in this area finally resulted in the series of mesas separated by major tributaries of the Rio Grande or tributaries of these streams that originate on the Plateau (Fig. 9b).

The sediment in which the strongly developed soil has formed is possibly that proposed by Reneau and Dethier to have been deposited prior to integration of the fluvial system. The presence of the erosional unconformity on welded tuff shows that at least some time was also required to erode less well-consolidated or welded material of the initial ignimbrite sheet prior to deposition of the alluvium. The age of the soil and the alluvium suggested by the thickness-normalized SDI does not preclude an age of possibly several hundred thousand years; moreover, the soil may once have been much thicker. Erosion of the soil near the margins of canyons has completely removed or decreased the thickness of this soil. Such erosion is partly responsible for accumulation of some of the fine-grained colluvial deposits in canyons. In addition, Reneau et al. (this volume) suggest that the Pleistocene-to-Holocene climatic change might have even accelerated erosion on the Pajarito Plateau, triggering aggradation observed in many narrow canyons of the Pajarito Plateau.

As noted above, recent alluviation in small streams on the Pajarito Plateau locally occurs, but another plateau-wide aggradation event of the magnitude of the older, Pleistocene event seems unlikely, given both the limited size of basins draining onto plateau remnants and the limited width of many plateau remnants (Fig. 9c). On the other hand, despite evidence of rapid erosion on parts of the Pajarito Plateau described previously and documented in plot-scale studies of Wilcox (1994), the long-term stability of parts of the Pajarito Plateau is demonstrated not only by preservation of an older Pleistocene soil in many areas, but is also shown by the locally substantial thickness of the El Cajete pumice. The accumulation of, and soil development in, the overlying nongravely surficial deposit, which is at least early Holocene in age (Reneau et al., this volume) also provides evidence of surface stability. This long-term surface stability can be attributed to several factors. First, the Banderlier Tuff is erosionally resistant—it served as regional base level for streams emanating from drainage basins in the Jemez Mountains prior to incision of canyons into the mountains, enabling deposition of the older alluvial deposits. It continues to serve as base level for some streams of small basins in the Jemez Mountains. The strong development of the soil itself also owes to the contrast in nature of tuff and alluvium as potential soil parent materials. The combination of the dense, massive nature of nearly impermeable tuff and the generally semi-arid climate of the region permits only limited soil development in such material. Chemical analysis

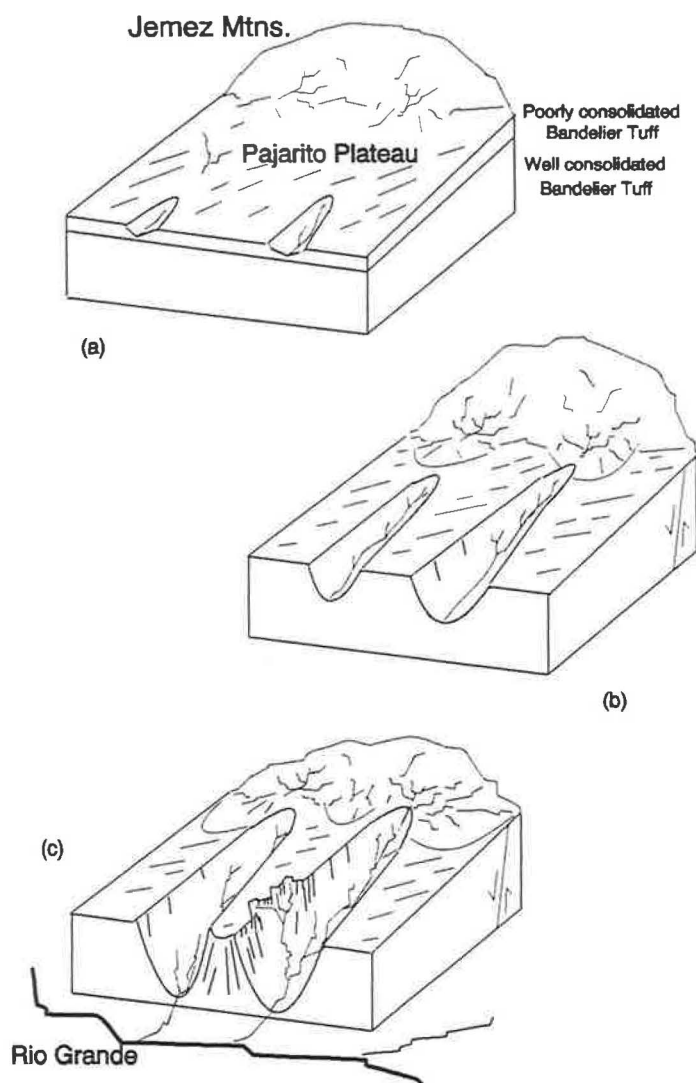


FIGURE 9. Schematic diagrams depicting stages of landscape evolution based on the observed soil-landform and soil-stratigraphic relationships in the study area and results of other geomorphologic studies in the region. (a) Subsequent to emplacement of youngest unit of Bandelier Tuff, drainage basins begin to develop in extra-caldera areas of the Jemez Mountains. Concomitant erosion removes unknown thickness of more poorly-consolidated tuff originally present in upper part of ignimbrite sheet. Sedimentation on parts of plateau during this early post-Bandelier incision of the Rio Grande initiates development of drainages in distal parts of the ignimbrite sheet; (b) Continuing long-term incision of the Rio Grande is conducive to continued headward erosion and deepening of the canyons; some drainage basins in Jemez continue to provide sediment deposited as fans on the remaining continuous region of plateau flanking Jemez Mountains; (c) Extension of deep canyons into Jemez Mountains eliminates many larger drainage basins as sources of sediment deposited on increasingly more isolated remnants of plateau; erosion of some sediment and soils favored near margins of deep canyons. Depicted fault is the Pajarito Fault.

of tuff below the Bt horizon of soils reveals little alteration, and the studies of Davenport et al. (1995) also show minimal chemical weathering of the tuff in deeper fractures. The flow of most percolating meteoric water in tuff is limited to the fractures, and thus it is in fractures where most pedogenesis occurs.

In marked contrast, the permeable character of gravelly alluvium is conducive for soil development in this semi-arid climate. First, the exposed surface area of the tuff parent material is larger, favoring a greater magnitude of chemical weathering. Second, as McDonald (1994) hypothesized, the initially topographically rough surface of fans or terraces helps to entrap dust. This dust can subsequently be pedogenically modi-

fied (McFadden and Hendricks, 1985; McFadden and Weldon, 1987). The permeable nature of alluvium ensures movement of meteoric water in a more uniform manner throughout the material and transfer of pedogenic materials below the A horizon. The accumulation of colloidal material acts to increase the water-holding capacity of the soil and increase soil-water residence time, circumstances that may also favor an increase in the magnitude of chemical weathering (McFadden and Weldon, 1987).

The predominance of Holocene alluvial terraces or colluvium and lack of older Pleistocene terraces in many of the canyons may also be related to the presence of the Bandelier Tuff. Extensive post-Bandelier canyon incision has been driven by downcutting of the Rio Grande (Reneau and Dethier, this volume); but the resistant nature of the thick, welded part of the tuff has favored development of steep, narrow canyons. Canyon widening is primarily by cliff retreat, presumably a geomorphically relatively slow process, thereby favoring preservation of mesa-top remnants and soils. Narrow, deep canyons, however, may be unfavorable for preservation (or even the formation) of older, higher fill terraces that might have existed in earlier times in the Pleistocene in the canyons, assuming the canyons were present. Presumably, occasionally large flood discharges through the narrow canyons are able to entrain and remove previously stored alluvial sediment. Geologically rapid cycling of sediment storage and transport through some canyons in this area occurs on a scale of tens to hundreds of years (Drakos et al., this volume). Many latest Pleistocene or Holocene fill terraces in these narrow canyons are relatively thin and overlie bedrock, as shown for example by studies in Cañon del Valle, Ancho Canyon, and Frijoles Canyon (Reneau et al., 1993; this volume). Older Pleistocene deposits are not buried below younger alluvium in these canyons, and this is probably the case in many other narrow canyons in the area. In much wider canyons, the treads of fill terraces are also initially wide, and they persist for longer time spans, enabling formation of strongly developed soils. In a few places on the Pajarito Plateau and elsewhere in the Jemez Mountains, wide canyons that contain older terraces with older Pleistocene soils do occur (e.g., Rendija Canyon, McDonald et al., this volume; Cochiti Canyon, Aby, this volume; San Diego Canyon, Rogers and Smartt, this volume; Formento-Trigilio and Pazzaglia, this volume). The factors ultimately responsible for the widths of these canyons is not clear, although it is notable that the size of some of their associated drainage basins (e.g., Cochiti and San Diego Canyons) is significantly larger than those associated with most drainages on the Pajarito Plateau. Over most of the Pajarito Plateau, however, the presence of deep, narrow canyons at the mountain front has apparently not been conducive for formation and preservation of such terrace sequences, and thus most older Pleistocene soils are found in the alluvial deposits that buried the Bandelier Tuff.

CONCLUSIONS

The development of soils and the evolution of soil-landscape patterns over much of the Pajarito Plateau has been strongly influenced by the volcanic character of this ignimbritic plateau. The character of the soils ultimately reflects formation in alluvial or colluvial parent materials with abundant, silica-rich volcanic material in a generally semi-arid climate on landforms sufficiently stable to enable development of pedogenic properties. Increases in the degree of soil development, such as increasing rubification, clay content, and soil structure, or soil chemical properties (e.g., the Fe_2/Fe_1 ratio) are largely time-dependent, although spatial climatic variation and climatic changes in the Quaternary and, locally, slope position have also influenced the rates and magnitude of pedogenic processes, expressed most clearly by the observed pattern of pedogenic carbonate accumulation. Although chemical weathering is responsible for the development of some properties, the entrapment and incorporation of dust in this semiarid climate has been conducive to development of increasingly thicker argillic horizons and, locally, calcic horizons. Periods of very rapid accumulation of fines as loess or reworked material are responsible for the burial of older soils and deposits or cumulate soil development. The subsequent development of a darkened, organic matter-enriched A horizon in this material creates the appearance of an A-E-B profile sequence; however, soil property data demonstrate the presence

of an A-Bw sequence developed largely in the Holocene subsequent to burial of older soils with reddened argillic horizons.

The widespread deposition of alluvium on the Pajarito Plateau provided an opportunity for the formation of a strongly developed soil over potentially several hundred thousand years. Such soil development could not have occurred in massive, welded tuff; but the presence of the Bandelier Tuff not only enabled deposition of the older alluvium in which this soil could develop, but its resistance to weathering has also favored (1) plateau development, surface stability and soil development in materials atop it, and (2) the evolution of narrow, deep canyons that presently separate plateau remnants on which these soils are preserved. Geomorphic processes in such narrow canyons generally do not favor preservation (or perhaps the formation) of older Pleistocene fill terraces; thus, flights of nested terraces with older Pleistocene soils typical of other landscapes flanking mountainous areas in New Mexico are uncommon. Instead, younger Holocene terraces, colluvial deposits and associated weakly developed soils are usually present. More well-developed soils do occur in a few wide canyons where originally broad terrace treads had formed or they are associated with the late Pleistocene El Cajete pumice, preserved in geomorphically stable settings. Such features vividly illustrate the impacts of Quaternary volcanic activity that has continued into the late Pleistocene on the nature of soil-landscape patterns in the Jemez Mountains.

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