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Micromorphology of Pedogenically Derived Fracture Fills in Bandelier Tuff, New Mexico

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ABSTRACT

Fractures in the Bandelier Tuff are potential paths for water movement and transport of contaminants from waste disposal sites and other contaminated areas at Los Alamos National Laboratory, Los Alamos, NM. Contaminants transported in this way could ultimately be found in Los Alamos drinking water or in the Rio Grande, which flows through heavily populated areas in both the USA and Mexico. We conducted this study to determine (i) the morphology and origin of soil-like material in the fractures, and (ii) the likelihood of significant water movement through the fractures. We examined thin sections of fracture fills, soils, and tuffs to obtain fabric and mineralogical data, and collected field data on soil horizons, color, texture, structure, clay films, and root abundance. Fracture fills consist of clay, $CaCO_3$, or combinations of the two with minor inclusions of tuff and sand grains. Clay consists of thick, highly oriented argillans aligned parallel to fracture walls, and of discrete books in fracture interiors. Carbonate consists of massive microcrystalline calcite, which completely fills some fractures, and laminae or infillings between clay laminae or books in clay-dominated fractures. The carbonate was precipitated after clay deposition, suggesting a change to a more arid climate. Weaker development of argillans and carbonate features in the soils suggests that the fractures may be derived from older soils that have been stripped by erosion. The presence of live roots throughout the fracture fills indicates the presence of water, but the smectitic clay and massive carbonate make it unlikely that significant water movement is now taking place through the fractures. The potential creation of new macropores by a variety of processes, however, including seismic activity and biologic disturbance, could allow rapid water movement and contaminant transport.

GROWING CONCERNS about environmental contamination increase the importance of identifying and evaluating possible routes of contaminant transport in soils and shallow land burial waste disposal sites. Fractures in the Bandelier Tuff are potential conduits for water and contaminant transport on the Pajarito Plateau of north-central New Mexico. Los Alamos National Laboratory, an area with numerous waste disposal facilities, as well as sites with surface and subsurface soil contamination, occupies much of the plateau. Morphology of the fractures and fracture-fill materials may provide important information about the processes of rock weathering, soil formation, landscape evolution, and water movement in this area. Purtymun and Kennedy (1971) and Rogers (1977) suggested that the fractures in the Bandelier Tuff are effectively sealed at or near the surface by clay and $CaCO_3$, both of which formed directly from in situ weathering of the tuff. A cohesive explanation of the diverse morphology seen in the Bandelier Tuff fracture fills has been lacking, however, and the assertion that the fractures are sealed has not been rigorously tested. Although the regional water table is some 200 m below the surface (Purtymun and Johansen, 1974), the vertical extent and abundance of these fractures makes them possible conduits for rapid movement of water to great depths. The role that the fractures play in movement of water in this semiarid region is not known, but field observations suggest that the movement of water among soil, rock, and fracture fill is complex.

A number of studies have examined various aspects of fractured and welded tuffs, many in association with the proposed high-level radioactive waste disposal site at Yucca Mountain, NV, where mineral-filled fractures have raised concerns about possible high water tables in the past. Isotopic analyses (Quade and Cerling, 1990; Stuckless et al., 1991), x-ray diffraction, and micromorphologic examination (Vaniman et al., 1988, 1992) of mineral deposits in fractures and faults at Yucca Mountain provide clear evidence that those fill materials (particularly carbonates) are the result of pedogenic or near-surface processes. Fuller and Sharp (1992) examined weathered surfaces in fractured Santana Tuff in Texas, and concluded that a thin weathering rind reduces the permeability of the tuff by about an order of magnitude, thereby reducing movement of water between fractures and the tuff matrix. Wang and Narasimhan, in their report on models of fluid flow in tuffs (1990), stated that data on unsaturated flow in fractures, faults, and even the matrix of tuffs, is very limited, but that available laboratory data on fractured tuffs suggests that water flow takes place primarily through the unsaturated tuff matrix rather than fractures.

Our study of the Bandelier fractures has been based on the assumption that the morphology of materials filling the fractures can provide information about the processes that produced that morphology. The origin of the fracture-fill material, for example, is important to our understanding of water movement through fractures. An in situ origin would suggest that water movement has been dominantly through the tuff matrix (as discussed by Wang and Narasimhan, 1990), whereas water deposition (illuviation) of these materials would indicate that the fracture openings have been the main path of water movement.

The objectives of our study were to: (i) document the micromorphological properties of the fracture-fill materials, the tuffs, and the associated surface soils; (ii)

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determine how the fill material relates to the soil and the tuff in terms of micromorphology and mineralogy: and (iii) understand the mechanisms by which the fractures were filled. We propose and provide evidence for the hypothesis that fractures in the Bandelier Tuff have been filled by translocation of soil material, and that this process was controlled or modified by a shift to drier climatic conditions.

MATERIALS AND METHODS

Description of Study Area

The study area is located within the National Environmental Research Park of Los Alamos National Laboratory (LANL), on the Pajarito Plateau of north-central New Mexico (Fig. 1). The Pajarito Plateau covers approximately 800 km^2 between the Jemez Mountains and the Rio Grande. The plateau slopes to the south-southeast from an elevation of 2380 m against the flank of the Jemez Mountains to 1890 m at White Rock Canyon above the Rio Grande. Erosion has dissected the plateau into a number of finger-like mesas separated by steep canyons. Through these canyons flow a number of mostly intermittent streams, which form a parallel drainage network to the Rio Grande (Griggs, 1964). The area has a semiarid, temperate mountain climate. Mean annual precipitation for the study area is estimated to be about 36 cm, based on data from LANL meteorological stations (Bowen, 1990). About 40% of the annual precipitation occurs during July and August. Mean annual snowfall is 132 cm (about 7 cm water equivalent). Both rainfall and snowfall amounts increase with elevation. Native vegetation at the study site is dominated by piñon pine (*Pinus edulis* Engelm.) and one-seed juniper [*Juniperus monosperma* (Engelm.) Sarg.], with blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lagasca ex Griffiths] as the most common grass species. The study site is near the upper elevational boundary of the piñon–juniper zone at about 2100 m, and has conditions (elevation, climate, vegetation, geology, and soils) similar to those at several LANL waste management facilities.

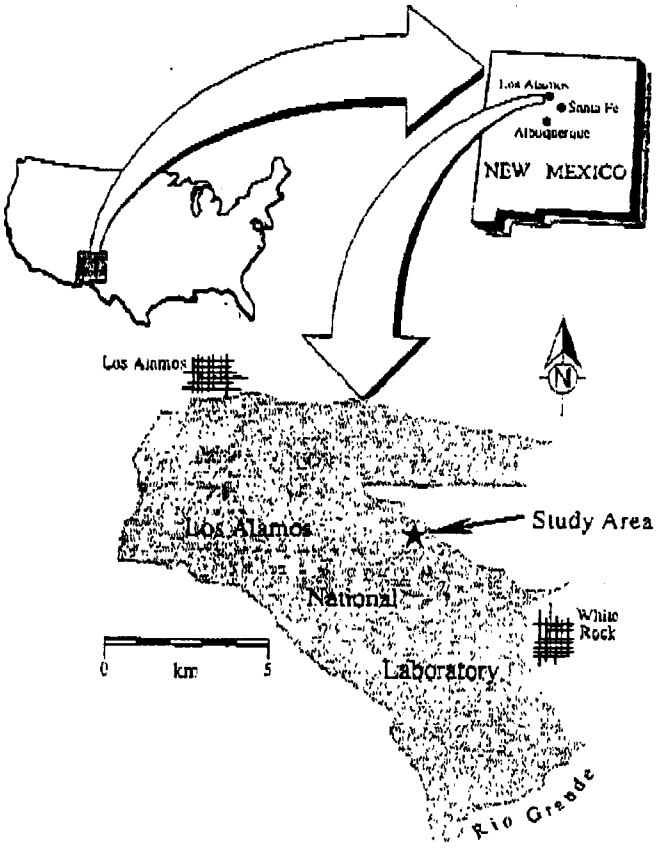

Fig. 1. Location of study area.

The Bandelier Tuff is divided into lower (Otowi) and upper (Tshirege) members. These members have been radiometrically dated at 1.4 and 1.1 million years, respectively (Spell et al., 1990). Our study concerns only the upper portion of the Tshirege member (more specifically, mapping unit 2b of Purtymun and Kennedy [1971]), which forms the plateau surface in the study area: here it is approximately 20 m thick.

The Tshirege member consists of ash-flow tuffs that range from nonwelded to densely welded. A striking feature of the unit is the large number of near-vertical fractures or joints, believed to have formed by shrinkage of the ash-flow deposits as they cooled (Purtymun and Kennedy, 1971). These range in width from <1 mm to >100 mm and extend at least 6 m from the base of the soil zone. It is possible that some of the major fractures extend through the entire vertical thickness of the Tshirege member. In the study area, the fracture density ranges from one fracture in 2 to 3 m up to several fractures per meter. Most of the fractures are filled (entirely or partially) with clay-rich, soil-like material, which also contains carbonate and inclusions of sand grains and tuff fragments. Some fractures are devoid of fill for some portion of their depth and lateral extent (Griggs, 1964; Purtymun and Kennedy, 1971; Crowe et al., 1978).

Field Study

Numerous fractures are exposed in two waste disposal pits within an area of ≈ 1 ha on Mesita del Buey (Technical Area 54, LANL). The soil is also exposed for up to 50 m on each of four long pit walls (each pit measures approximately 20 by 50 m). The four soil pedons that served as the basis for our study were selected because they overlie relatively wide fractures in the Bandelier Tuff (Fig. 2). Fractures were selected to represent the variety of fracture-fill types (clay, carbonate, clay and carbonate) observed in the area (Table 1). Each pedon was described and sampled in the field and was classified using soil taxonomy (Soil Survey Staff, 1975, 1992). Each fracture was also described in detail and sampled. Each profile was overlain by a 0.3- to 1.0-m-thick layer of spoil consisting of unconsolidated tuff material removed from the pits and spread on the surface during excavation (Fig. 2). Care was taken to sample only clearly undisturbed portions of the A horizons.

The soils of the study site have been mapped as the Hackroy series of clayey, mixed, mesic Lithic Haplustalfs (Nyhan et al., 1978). On the basis of our field descriptions (Table 2) and supplemental laboratory analyses of individual pedons, we classified the soils as shown in Table 1 (Soil Survey Staff, 1992). The soils are typically shallow (30–70 cm), but are deeper (up to 130 cm) over large (greater than about 3 cm wide) fractures, filling pockets or depressions that extend below the normal soil–tuff boundary (Fig. 2). The soil material in these pockets usually comprises a thickened argillic horizon that appears to be continuous with the fracture-fill material.

Bulk samples and intact peds (for thin sections) were collected, where possible, from each horizon in the soil pedons. In some cases, the soil material was so friable that intact ped samples were not obtainable. In these cases, grain mounts (rather than thin sections) were used to examine the mineralogy of the horizon. Bulk and intact samples of fracture fill were collected at vertical intervals of about 30 cm throughout the

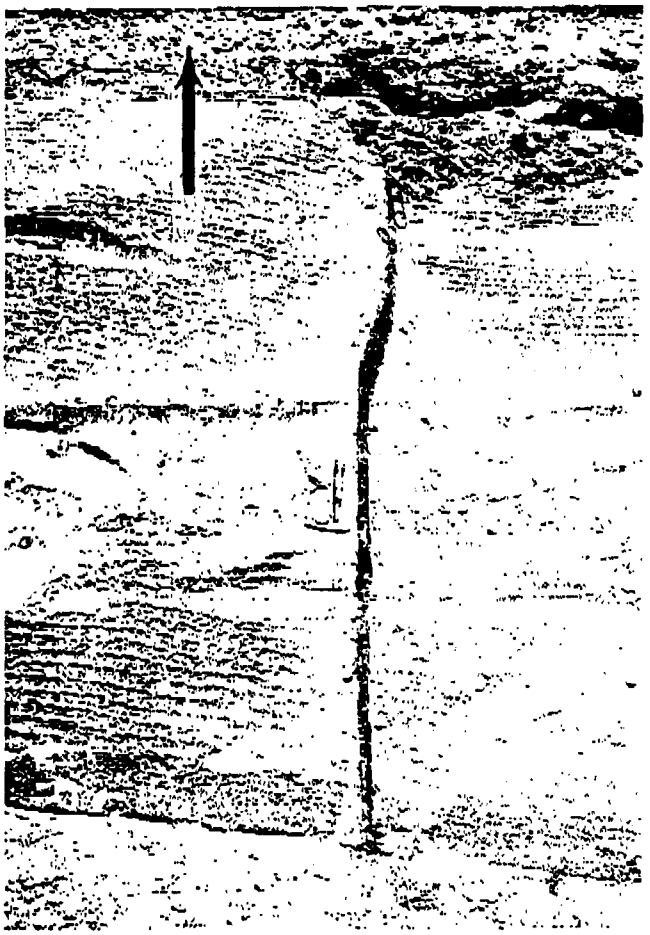

Fig. 2. View of soil profile F5 and soil "pocket" above clay-filled fracture. Fill consists mostly of oriented clay with some carbonate. Rock hammer is 32 cm long. Approximately 40 cm of spoil (arrow) overlies soil profile.

exposed depth of the fractures. The intact samples were obtained by using gypsum plaster to stabilize blocks of tuff spanning the fractures (Davenport, 1993). For comparison, we collected samples of unweathered and slightly weathered tuff from areas of the pit walls farthest from any major fractures (and therefore least likely to have been affected by processes associated with the fractures, such as illuviation of clay and weathering).

Laboratory Study

Standard thin sections were prepared (Ireland, 1971; Cady et al., 1986) from selected samples of soil, fracture fill, and tuff. The samples were impregnated with epoxy resin (Shell R-815, refractive index = 1.51–1.55, Shell Chemical Co., Houston, TX), cemented to glass slides, processed to a final thickness of 0.03 mm, and examined petrographically using plane-polarized and cross-polarized light (Bloss, 1961; Phillips and Griffen, 1981). Each sample was described using the soil micromorphology terminology of Brewer (1976), including fabric; presence and degree of development of clay films; degree of weathering of mineral grains; presence of volcanic features such as spherulites, pumice fragments, and glass shards; and types of voids. In addition, related distribution patterns (Bullock et al., 1985) were noted.

Grain mounts were prepared from sand and silt fractions of selected samples. Grains were mounted on glass slides in immersion oils, normally with a refractive index of 1.54 to facilitate differentiation between quartz and feldspar. We identified and counted at least 300 grains on each mount and calculated the percentage of each of the most commonly observed minerals (quartz, alkali feldspars, tridymite/cristobalite, glass, hornblende, plagioclase feldspars, and opaque grains). Particle-size distribution was determined for soil and fracture-fill samples by hydrometer (Bouyoucos, 1951).

RESULTS

Tuffs

The mineralogy of the Bandelier Tuff has been examined in detail by other researchers (Doell et al., 1968; Warshaw and Smith, 1988), and our findings are generally consistent with these reports. The tuffs we examined consist mainly of a fine matrix of feldspars, cristobalite, tridymite, quartz, and devitrified glass shards, with abundant euhedral phenocrysts of sanidine. Grain counts of very fine sand show the tuff to be composed of 50% tridymite and cristobalite, followed by 40% alkali feldspars and 5% quartz (see Table 3). Glass shards, hornblende, and opaque minerals are present only in minor amounts (<5%). Spherulites (radial clusters of fibrous mineral crystals) and lithophysae (hollow or filled glassy bubbles), both features common in pyroclastic rocks (Ross and Smith, 1961), are present but not common. The lithophysae typically consist of somewhat flattened bubbles filled with wedge-shaped crystals of tridymite; the bubble walls are formed of fine, interlocking crystals of cristobalite (and possibly feldspars). The fabric of the tuff is best described as microporphyritic (Best, 1982) (Table 4). The related distribution pattern is everywhere porphyric, ranging from single spaced to open. Argillans are present only as coatings in channels and in packing voids near the fracture walls. Channel argillans are typically up to 0.5 mm thick and show strong orientation,

Table 1. Selected characteristics of soils, fractures, and fills.

Profile	Soil classification	Fracture depth (exposed)	Average fracture width	Fill type
		m	cm	
F1	loamy, mixed, mesic Lithic Haplustalf	3.5	2.0	carbonate
F2	fine-loamy, mixed, mesic Aridic Haplustalf	2.0	1.4	clay, carbonate
F3	—†	5.0	5–10	none, clay, sand‡
F4	fine, montmorillonitic, mesic Aridic Paleustalf	3.5	2.8	clay, carbonate
F5	clayey, montmorillonitic, mesic Lithic Haplustalf	4.5	4.4	clay, minor carbonate.

† Soil not described due to height of pit face.
‡ Fracture is open in places; fill consists of alternating horizontal layers (5–10 cm thick) of clay and horizontally laminated fine sand.

Table 2. Field description data from soil profiles and fracture fills.

Horizon	Depth	Color (moist)	Texture† (field)	Sand/Silt/Clay (texture) (lab analysis)	Structure‡	Clay films§	Roots¶	Boundary#
	cm			%				
				F1 pedon (loamy, mixed, mesic Lithic Haplustalf)				
A	0–9	7.5YR 3/3	L	58/31/11 (SL)	1 SBk	none	M f, m	Cl, S
BA	9–19	7.5YR 3/3	L	60/26/14 (SL)	1 SBk	none	M f, m	Cl, W
Bt	19–26	7.5YR 3/4	CL	54/29/17 (SL)	2 SBk	thin, disc	M f, m	Cl, W
Cr/Bt	26–34	7.5YR 4/4	CL	48/28/24 (L)	2 SBk	thin, disc	M f, C m	Ab, W
R	34–260+	10YR 6/1	LS	75/21/4 (LS)	M	none	none	–
fill	59–79	10YR 8/1	–	30/3/67 (C)	M	none	C f	–
fill	119–129	10YR 8/1	–	32/5/63 (C)	M	none	C f	–
fill	199–214	10YR 8/1	–	60/11/29 (SCL)	M	none	C f	–
				F2 pedon (fine-loamy, mixed, mesic Aridic Haplustalf)				
A	0–9	7.5YR 3/3	L	49/33/18 (L)	1SBk, 2 Gr	none	M f, m	Cl, S
Bt1	9–36	7.5YR 3/4	CL	36/40/24 (L)	2 SBk	thin, disc	M f, m	Gr, W
Bt2	36–59	7.5YR 3/4	CL	47/33/20 (L)	2 SBk	thin, disc	C f, m	Cl, W
Bk/Cr1	59–104	7.5YR 4/4	SCL	54/31/15 (SL)	1 SBk	thin, disc	C f, m	Gr, W
Bk/Cr2	104–125	7.5YR 4/4	SCL	60/29/11 (SL)	1 SBk	thin, disc	F f, m	Ab, W
R	125–265+	10YR 6/1	LS	75/21/4 (LS)	M	none	none	–
fill	145–155	7.5YR 4/4	–	46/9/45 (SC)	2 SBk	thin, cont	F f, m	–
fill	165–185	7.5YR 4/4	–	48/12/40 (SC)	2 SBk	thick, cont	F f	–
fill	225–245	7.5YR 4/4	–	56/11/33 (SCL)	2 SBk	thick, cont	F f	–
fill	245–265	7.5YR 4/4	–	51/12/37 (SC)	2 SBk	thick, cont	F f	–
				F4 pedon (fine, montmorillonitic, mesic Aridic Paleustalf)				
A1	0–7	7.5YR 3/3	L	53/31/16 (VFSL)	1 SBk	none	M f, m	Cl W
A2	7–12	7.5YR 3/3	L	44/33/23 (L)	1 SBk	none	M f, m	Cl, W
Bt1	12–31	7.5YR 4/4	C	16/25/59 (C)	2 SBk	thin, disc	M f, m	Gr, W
Bt2	31–42	7.5YR 4/4	C	29/26/45 (C)	2 SBk	thick, cont	C f, m	Gr, W
Bt3	42–55	7.5YR 4/4	C	25/28/47 (C)	2 Bk	thick, cont	C f, m	Ab, W
R	55–400+	10YR 6/1	LS	75/21/4 (LS)	M	none	none	–
fill	115–135	7.5YR 4/4	–	70/19/11 (SL)	2 SBk	thick, cont	C f, m	–
fill	145–165	7.5YR 4/4	–	31/35/34 (CL)	2 SBk	thick, cont	C f, m	–
fill	265–285	7.5YR 4/4	–	78/18/4 (LS)	2 SBk	thick, cont	C f	–
fill	315–335	7.5YR 3/3	–	11/3/86 (C)	2 Bk	thick, cont	F f	–
fill	365–395	7.5YR 3/3	–	40/9/51 (C)	2 Bk	thick, cont	F f, m	–
				F5 pedon (clayey, montmorillonitic, mesic Lithic Haplustalf)				
A	0–7	7.5YR 3/3	L	48/38/14 (L)	1 SBk	none	F f, m	Cl, W
Bt1	7–16	5YR 3/4	C	29/24/47 (C)	2 SBk	thin disc	C f, m	Cl, W
Bt2	16–45	5YR 3/4	C	26/19/55 (C)	2 Bk	thick, cont	C m, c	Ab, Irr
R	45–500+	10YR 6/1	LS	75/21/4 (LS)	M	none	none	–
fill	55–75	5YR 4/4	–	4/4/92 (C)	2 Bk	thick, cont	M m	–
fill	85–105	5YR 4/4	–	2/3/95 (C)	2 Bk	thick, cont	F m	–

† L = loam; CL = clay loam; SCL = sandy clay loam; C = clay; fracture-fill textures were determined only in the lab.
‡ 1 = weak; 2 = moderate: SBk = subangular blocky; Bk = blocky; Gr = granular.
§ disc = discontinuous; cont = continuous.
¶ M = many; C = common; f = fine; m = medium; c = coarse.
# Cl = clear; Gr = gradual; Ab = abrupt; S = smooth; W = wavy; Irr = irregular.

whereas packing-void argillans are somewhat thinner and less oriented. Less than 5% of the tuff examined in thin sections contains isolated domains of weakly oriented clay and of microcrystalline calcite filling packing voids in the tuff matrix. Feldspars show low to moderate weathering (Class 0 to 1, Bullock et al., 1985), the more weathered grains usually being found within 1 to 2 mm of the fracture walls, where only a thin (usually 3–5 mm) weathered layer has developed in the tuff.

Soils

The A horizons are characterized by insepic or skel-insepic plasmic fabric (Brewer, 1976) (Fig. 3, Table 4). The related distribution pattern is single-spaced porphyric (Bullock et al., 1985), with a dominant grain size of fine sand to silt. The coarser fabric units include quartz and alkali feldspar grains as large as coarse and very coarse sand, few spherulites, and rare pumice fragments. Isolated domains of clay occur throughout the matrix. The most abundant mineral grains in the very fine sand fraction are alkali feldspars (mainly sanidine, 40–50%) and quartz (25–45%), with much lesser amounts of tridymite and cristobalite, devitrified glass shards, hornblende, plagioclase feldspars, and opaque minerals (Table 3). All of the A horizons contain signifi-

Table 3. Mineral composition (percentage of grains counted†) of very fine sand from selected soil horizons.

Horizon	Quartz	Alkali feldspar	Tridymite–cristobalite	Glass‡	Hornblende	Opaque minerals	Plagioclase feldspars
	%						
F1 A	25	50	10	10	<5	<5	<5
F1 Bt	25	30	25	15	<5	<5	<5
F2 A	45	40	5	5	<5	<5	<5
F2 Bt1	25	40	25	10	<5	<5	<5
F4 A1	35	45	10	5	<5	<5	<5
F4 Bt2	25	35	25	10	<5	<5	<5
Hard tuff	5	40	50	<5	<5	<5	<5

† Reported to nearest 5%: minimum of 300 grains counted per horizon.
‡ Including identifiable devitrified glass shards.

Table 4. Micromorphological properties of selected soil horizons, tuffs, and fracture fills.

Sample	Depth	Fabric	Argillan		Feldspar weathering
			Orientation	Thickness	
	cm				
		F1 pedon			
A	0–9	insepic	low	thin	moderate-high
Cr/Br	26–34	skel-masepic	moderate	thick	low-moderate
tuff	88–98	microporphyritic	–	–	low-moderate
fill	88–98	omnisepic	high	thick	low-moderate
tuff	220–230	microporphyritic	–	–	low
fill	220–230	calclasepic	–	–	low
		F2 pedon			
A	0–9	skel-insepic	moderate	thin	moderate
Bt1	9–36	mosepic	moderate	thin	high
Bt2	36–59	omnisepic	moderate	thin	moderate-high
Bk/Cr1	59–104	omnisepic	moderate	thick	moderate
tuff	142–152	microprophyritic	–	–	moderate
fill	142–152	skel-mosepic	high	thin	moderate
tuff	305–315	microprophyritic	high	thin	low
fill	305–315	omnisepic	very high	very thick	low-moderate
		F4 pedon			
A1	0–7	insepic	low	thin	moderate-high
Bt1	12–31	omnisepic	high	thick	low
Bt2	31–42	skel-masepic	high	thick	moderate-high
tuff	244–264	microprophyritic	low	thin	high
fill	244–264	omnisepic	very high	very thick	moderate
tuff	519–526	microporphyritic	low	thin	moderate
fill	519–526	omnisepic	very high	thick	NA
		F5 pedon			
tuff	371–381	vosepic	low	thin	low-moderate
fill	371–381	omnisepic	very high	very thick	–

cantly more quartz than does the tuff, and two of the A horizons also contain 5 to 10% more alkali feldspars (Table 3). These data suggest the addition of windblown material to the surface of these soils (Birkeland, 1984), concentration due to weathering, or conversion of tridymite and cristobalite to quartz. The A horizon quartz grains are subrounded to subangular, and do not appear to be pseudomorphs after tridymite or cristobalite, so it is unlikely that conversion of tridymite and cristobalite has been a significant source of quartz. The A horizon

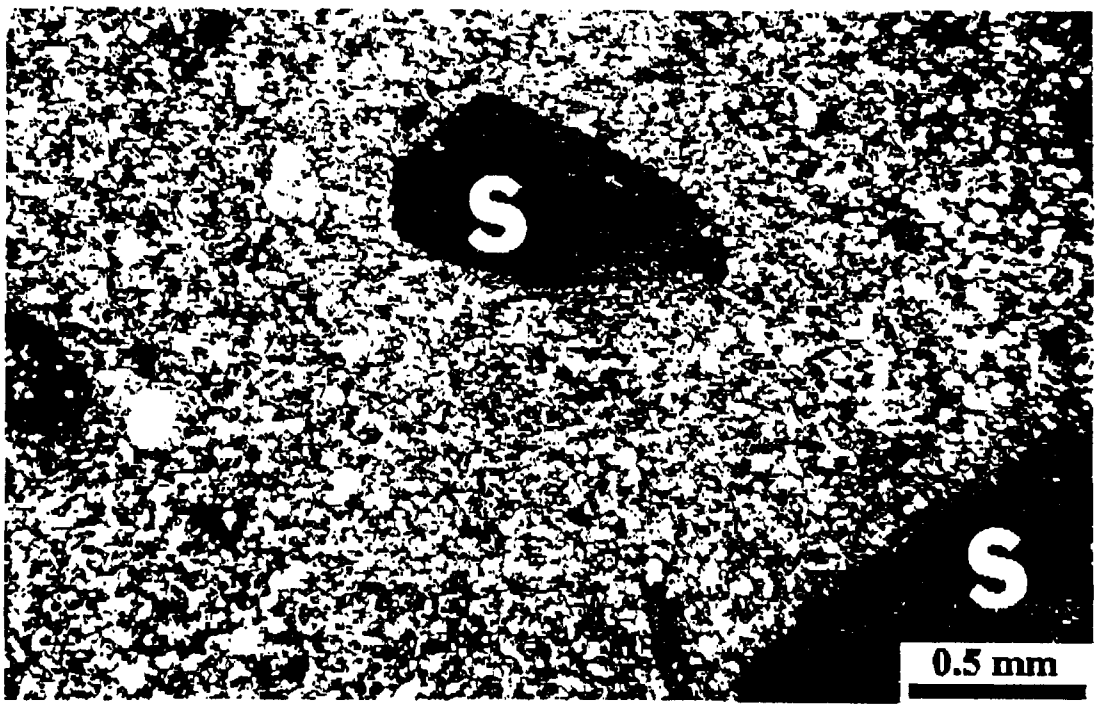

Fig. 3. Photomicrograph of F4 soil A horizon. Insepic plasmic fabric; spherulites (S) indicate volcanic origin of parent material; portion of quartz skeleton grains are probably eolian in origin. Cross-polarized light.

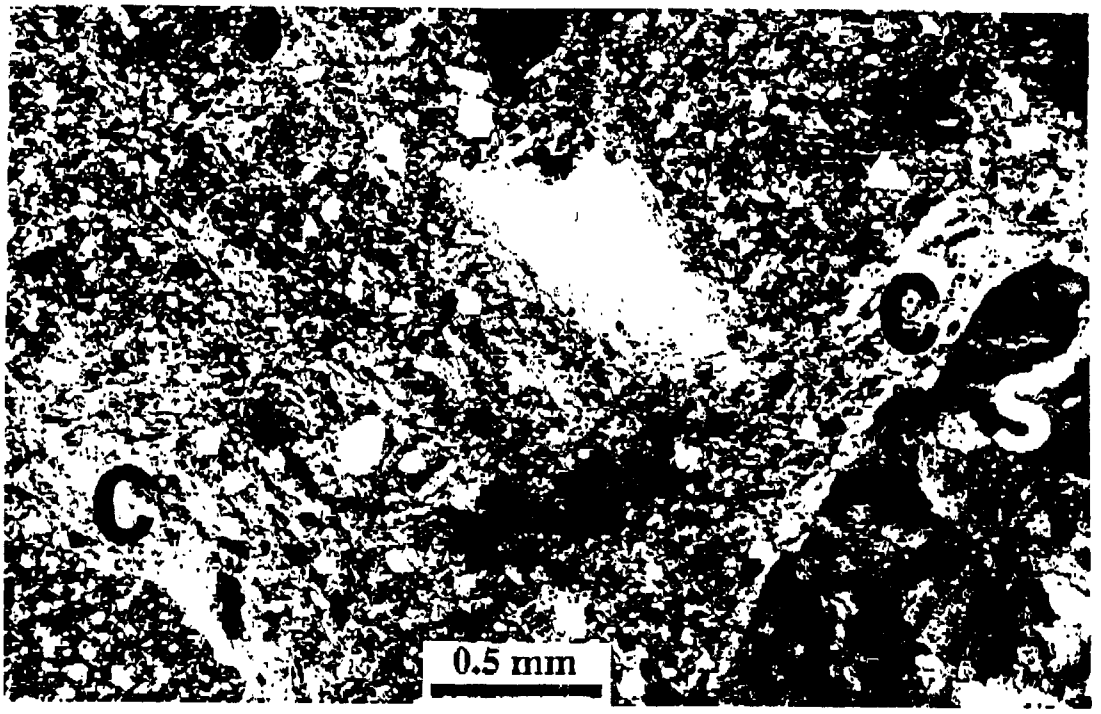

Fig. 4. Photomicrograph of Bt portion of F1 soil Cr/Bt horizon, which consists of domains of weathered tuff and soil material. Feldspar (F) in center of photo, with thin grain argillans; spherulite (S) in lower right. Clay (C) is present as argillans, pressure-oriented coatings, and as striated plasma separations in the soil matrix. Cross-polarized light.

feldspars exhibit moderate to high weathering (Class 1 to 3 of Bullock et al., 1985), but weathering products such as clay and Fe oxides were not observed on weathered cleavage planes or on grain margins, indicating eluviation of these materials. Organic matter is sparse, with the exception of fine to medium roots (Table 2). Thin sections reveal very little organic staining and few fragments of organic matter. Overall, the morphology of these horizons is characteristic of Alfisol A horizons, with depletion of clays and relatively little accumulation of organic matter (Buol et al., 1989).

The Bt horizons have mosepic, skel-masepic, or omnisepic plasmic fabrics (Table 4), indicating moderate to strong illuviation of clay. The related distribution pattern is porphyric. Clay is present as moderately to highly oriented grain argillans of variable thickness and as elongated domains and isolated patches in the matrix. Channels are also lined with strongly oriented clay. The skeleton grains consist of euhedral sanidine, quartz, cristobalite or tridymite, spherulites, and pumice. Weathering of the feldspars is highly variable, ranging from low to high (Class 0 to 3). The weathering products from the feldspars may be present, either subsequently oriented by illuviation or obscured by the abundant illuvial clay. Field descriptions indicated that all four pedons have argillic horizons. This is confirmed by the presence of argillans as seen in thin sections and by particle-size distribution analysis. The argillic horizons of the F1 and F2 pedons are only weakly developed, however, as judged by the laboratory-determined clay content and weakness of clay films (Table 2).

Transitional horizons (Cr/Bt, for example) also have strong illuvial features, though the presence of abundant fragments of tuff precluded their designation as simple Bt horizons. They exhibit omnisepic or skel-masepic plasmic fabrics (Table 4), having characteristics of both argillic horizons and tuff (Fig. 4). The related distribution pattern is porphyric. Argillans are typically thick, and show moderate to high orientation. They are found as coatings on spherulites, pumice, and skeleton grains, and lining channel walls. Elongated domains of clay, not associated with grains or channels, are also present in the matrix (Fig. 4). Although feldspars in these horizons typically exhibit low to moderate weathering (Class 0 to 1), most of the tuff fragments appear relatively unweathered (Class 0).

The tuff underlying the soils has been described as an R layer (Soil Survey Staff, 1992), despite the fact that it contains numerous fractures filled with clay, carbonate, and other material apparently of pedogenic origin. Soil taxonomy does not allow for the designation of rock layers that include pedogenic features (Graham et al., 1994), leading to difficulties in the description of these materials. We have opted to designate the tuff as R for the following reasons: (i) the fractures in question are typically more than 10 cm apart; (ii) the tuff can be dug with a spade only with difficulty, and only in some places; (iii) roots are found in the fractures, but very rarely in the tuff itself. It would be useful to include subordinate distinctions with the R layer in order to more accurately describe the nature of the material. The tuff might then be described as an Rt, where t indicates that the joints or fractures contain clay accumulations.

Fracture-Fill Materials

The most commonly observed morphological feature of filled fractures is strongly oriented argillans on the fracture walls (Fig. 5). These coatings are up to several millimeters thick, as observed in the field. Vertical thin sections show that the clay is strongly aligned parallel to the fracture walls and is draped over irregularities or large mineral grains protruding into the fractures. These argillans typically consist of multiple laminae of clay that vary in color from light yellowish brown (10YR 6/4) to dark reddish brown (5YR 3/4). Much of the interior portion of the fractures is filled with aggregates, or "books," of clay (Fig. 5). Although the clay is strongly oriented within books, the books do not always show orientation among themselves. In some of the larger books, more than one set of laminae, with different orientations, can be distinguished, and the equivalent of an unconformity surface marks the boundary between sets. These features indicate that clay has been deposited in multiple episodes, and that the clay fill has been fractured and disrupted, probably by repeated wetting and drying cycles.

Clays are sufficiently oriented that, in some sections, optic-axis interference figures are observable. These indicate that the minerals are biaxial negative with a $2V_x$ of about 20 to 30°, consistent with most smectite species, kaolinite, and possibly illite, although illite usually has $2V_x < 10°$. The clays also exhibit moderate to high birefringence (second- and third-order colors), characteristic of smectite and illite but not of kaolinite (Deer et al., 1966; Phillips and Griffen, 1981). Analysis of clays by x-ray diffraction indicates that smectite (probably montmorillonite) is the most abundant clay mineral in the fractures (Davenport, 1993; Fig. 6). Fracture fills exhibit mostly omnisepic plasmic fabrics (Table 4), but skel-masepic plasmic is also observed where a significant number of sand-sized grains are present in the finer matrix. The related distribution pattern is usually open porphyric when these larger grains are present, and monic when they are absent. The strong parallel orientation and thick layering of the clays, both in coatings and in books, is clear evidence that the clays are illuvial in nature (Brewer, 1976; Graham et al., 1994).

In many cases the clay books in fracture fills are interlaced with microcrystalline calcite, which constitutes either relatively thick (up to 0.5 mm) vertical laminae that alternate with clay laminae, or thin (20–50 μm) veins of carbonate between clay books (Fig. 7). Calcite has not been observed in a finely dispersed form in the clay fills, but only in the form of distinct infillings of virtually pure calcite between books or layers of virtually pure clay. This morphology is evidence that the clay and the calcite were deposited at different times, and that the precipitation of the calcite followed the deposition of the clay, similar to the situation described and interpreted by Ransom and Bidwell (1990).

In F1, the fracture fill consists of almost pure microcrystalline calcite (Fig. 8), the fabric of which is best described as calciasepic (Brewer and Sleeman, 1988). The matrix consists mostly of micritic (1–4 μm; Folk, 1980) and, less commonly, microsparitic (4–20 μm; Blatt

Fig. 5. Photomicrograph of fracture fill from F3, showing clay coating (C) oriented parallel to fracture wall. Tuff (T) in left portion of photo; left arrow indicates fracture wall. Coatings are broken into books in right portion of photo (right arrow), toward fracture interior. Cross-polarized light.

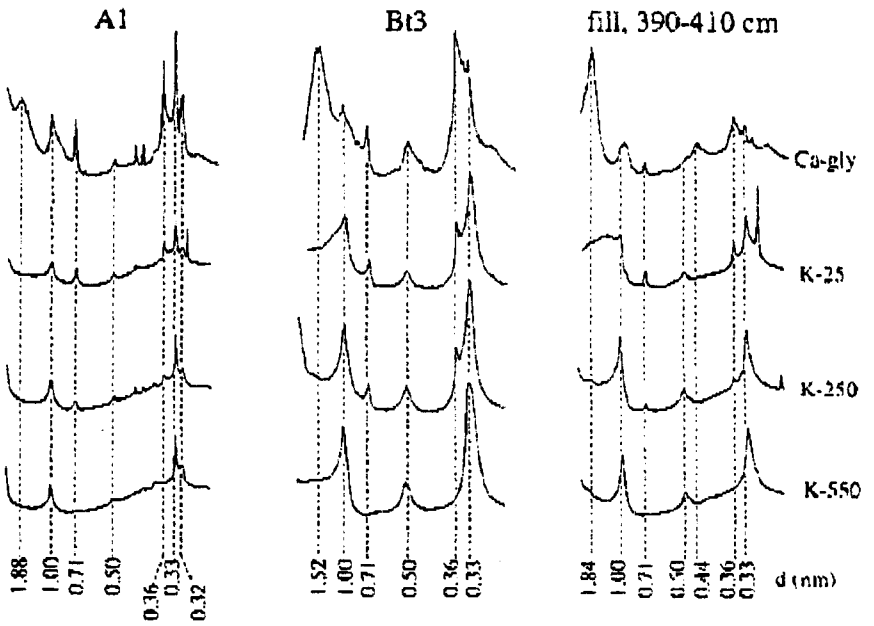

Fig. 6. X-ray diffractograms of clay from A1 and Bt1 horizons, and fracture fill (390–410 cm below surface) of F4 pedon. Treatments, from top to bottom, are: Ca saturated, glycerol solvated; K saturated, 25°C; K saturated, 250°C; K saturated, 550°C.

et al., 1980) calcite crystals. Grains of feldspar and quartz are scattered within the matrix of carbonate fills, giving these fills a porphyric-related distribution pattern. Where present, these grains exhibit low to moderate weathering (Class 0 to 1). Clays were observed in the carbonate fills only in a few samples, as strongly oriented clay stringers (about 0.5 wide by 5.0 mm long) isolated within the calcite matrix. These stringers are always oriented parallel to the fracture walls, but generally are not in close proximity to them. The origin and significance of these stringers is not clear: they may represent remnants of former fracture-wall coatings that somehow were largely stripped away, leaving behind small fragments that later were engulfed by the precipitation of calcite. The progressive precipitation of calcite may have forced the clay stringers away from the wall into the center portion of the fill. In places, the carbonate fill has a laminar appearance similar to that of pedogenic

Fig. 7. Photomicrograph of fracture fill from F4, showing calcite (arrow) filling 20-μm-wide space between clay books. Cross-polarized light.

Fig. 8. Photomicrograph of calcite fracture fill from F1. Root channel (R) in upper right portion of photo, tuff (T) at left; arrow indicates fracture wall. Cross-polarized light.

laminar carbonate horizons (Gile et al., 1966), although the laminar fabric is only weakly developed. The laminae in these areas are typically oriented parallel to fracture walls and are undulose in form. While the fracture fills tend to show well-developed carbonate morphology similar to Stage II to III (Gile et al., 1966; Birkeland, 1984, Table A-4), the carbonate features in the Bk/Cr soil horizons of the study area are not as well developed (i.e., thin coatings, threads, and soft masses of carbonate, similar to Stage I–II). These differences in morphology may be due to precipitation of carbonate in different matrices (soil vs. fracture), but could reflect formation under different climatic or pedogenic regimes.

In some thin sections comprising both tuff and fracture fill, clay is present within the tuff matrix, typically within 1 to 2 mm of the fracture walls and associated with mineral grains and glass shards. Clay fillings are also present in the tuff in voids near the fracture walls. Clays in the tuff, both in the matrix and in voids, are pale yellow (5Y 8/3) to yellow (5Y 8/8) in color, in contrast to the light yellowish brown (10YR 6/4) to dark reddish brown (5YR 3/4) of fracture-fill argillans. In most cases, the tuff matrix clay exhibits a low degree of orientation, but some of the tuff void-filling clays show moderate orientation. The poor orientation of the matrix clays suggest that they have been formed in situ, probably through devitrification of glass shards and weathering of feldspars. The presence of moderately oriented void-filling clays suggests that some clay has also been transported short distances from the fractures into the tuff. This process would be precluded once illuvial clay formed a thin continuous coating on the fracture wall, but presumably could take place in the initial stages of illuviation. Some neoformed clay may have been transported short distances within the tuff and reoriented in voids.

DISCUSSION AND CONCLUSIONS

The mineralogy of the soil horizons (the presence of tridymite, cristobalite, devitrified glass, and spherulites) confirms that the soil parent material is derived mainly from the Bandelier Tuff. The vertical sequence of horizons, from eluviated A horizons to argillic and mixed horizons (with domains of soil and weathered tuff), is consistent with soil formed by in-place weathering of the tuff. It is likely that eolian additions have altered the soil mineralogy near the surface, as evidenced by greater amounts of quartz in the A horizons than the tuff. The A horizons also contain significantly more volcanic glass in the very fine sand size range than does the tuff, but this is probably traceable to an overall reduction in size by fracturing and chemical weathering of these less resistant grains.

Both the fracture-wall coatings and the books of clay in the interior of fractures have the appearance of very thick, strongly oriented argillans. The high degree of orientation of these clays points to an illuvial rather than an in situ origin (Brewer, 1976; Graham et al., 1994). The books of clay were probably formed by desiccation cracking of thick clay laminae in the fractures, and the more random orientation among books may be due to repeated shrinking and swelling of the fill material with

concomitant mixing (similar to that observed in soils with vertic properties). The strong development of argillic and carbonate features in the fractures (compared with the soil horizons) probably indicates that fracture filling took place under an older soil (or multiple soils) that has since been removed or truncated by erosion. The current surface soils, by the criterion of carbonate morphology, appear to be relatively young, especially compared with the age of the parent material (Bandelier Tuff).

The spatial relationships between clay and carbonate in the fracture fills show that the calcite was precipitated after the clay was deposited in the fractures. It appears likely that the fractures filled with illuvial clay until permeability was reduced to the point that little or no further illuviation was likely. At some later time, macropores formed in the clay fill and were progressively filled by the precipitation of calcite. Carbonate was probably precipitated by percolating water during wetting-drying cycles associated with intermittent or seasonal precipitation. The mechanism for creation of macropores in the clay fill is not clear. Drying of the clay by plant extraction of water, seasonal dry periods, a climatic shift to more arid conditions, or combinations of these processes (simultaneously or in series), could produce shrinkage cracks, since the clay is high in smectite (Davenport, 1993). It is also possible that the growth of tree roots wedged blocks of tuff apart, creating macropores by enlargement of the fractures. Another possibility is that macroporosity was created through fracture enlargement caused by tectonic or seismic activity.

The overall morphology of the fill materials, both in the field and in thin sections, is consistent with shrinkage cracking of clays. However, visible signs of expansion-induced mechanical weathering (fractured grains and overall particle-size reduction, for example) have not been observed in the tuff adjacent to fractures. The presence of these features could be expected (Graham et al., 1994), but their absence does not necessarily eliminate shrink–swell as a dominant process in the fractures.

The geometry of some of the fractures (Fig. 2, for example) appears consistent with small-scale (10–20-cm) vertical movements of fracture-bounded tuff blocks. This suggests that tectonic activity has played a role in enlarging some of the fractures. Paleoseismic studies have shown that multiple ruptures have occurred on three faults in the vicinity of Los Alamos within the past 200 000 yr (Gardner and House, 1987; Wong et al., 1993). Two of these, the Rendija Canyon and Guaje Mountain faults, have been active during the last 10 000 yr. These figures are preliminary estimates, but it is clear that the Pajarito Plateau has experienced seismic activity in the geologically recent past. Enlargement of fractures by this activity cannot be ruled out.

Anecdotal evidence also exists for the contribution of erosional unloading to enlargement of fractures—in particular, observations that the fractures tend to be more open (wider) near the periphery of mesas (Rogers, 1977). This apparently occurs as slabs of tuff at the mesa edges move due to gravity (D.T. Vaniman, 1994, personal communication), but it is not known to what extent this may allow enlargement of fractures toward the central portions of mesas.

The micromorphology of the fracture fills alone does not provide conclusive evidence to support one of these mechanisms for the creation of macropores over the other. Although shrink–swell-induced macroporosity can explain the morphology of fracture fills containing mostly clay with secondary amounts of carbonate, it does not clearly explain why some fractures contain almost pure carbonate but very little or no clay. The possibility of tectonic or erosion-induced macroporosity has the advantage of offering a plausible explanation for the carbonate-filled fractures: these fractures might have been very narrow during the early, clay-dominated period of fracture filling, and were enlarged only later, when carbonate precipitation was the dominant process.

It is possible that all of these processes — shrink–swell, root growth, tectonism, and erosional release of stress — have played a role in the creation of macroporosity. These processes might have acted concurrently, or one or more of the processes may have been dominant at different times. It seems likely that desiccation cracking of clays would be a more or less continual process, whereas tectonic or erosional enlargement of fractures would occur more episodically.

It is clear that these possible explanations of macropore formation have very different implications for the potential movement of water, now and in the future. If shrinkage cracking of clay is the sole mechanism responsible for creation of macropores, it is likely that at some point the fractures become so full of clay that further cracking is minimized. Because the fractures are confined by massive tuff, as the clay fill is wetted by infiltrating water, swelling should effectively and rapidly close most macropores and thereby greatly reduce water movement. If, on the other hand, fracture enlargement by root growth, tectonic activity, or the release of stress by erosion is responsible for creating macroporosity, then the continuation (or reactivation) of these processes could create new openings in fracture fills (or minute unfilled fractures) through which water could move quite rapidly.

A clue to the hydrologic status of the fractures comes from vegetation. The presence of live roots in the fractures at virtually all depths indicates that the fractures normally contain sufficient moisture to sustain plant growth. Since plants extract soil moisture through their roots, it follows that the moisture in the fractures must be replenished either episodically or continuously. It is not clear whether this occurs by percolation of soil water directly into the fractures or by capillary movement of water from the tuff into the fractures. The former mechanism would have greater potential for transport of contaminants into and through the fractures.

All of the mechanisms described allow for the possibility that the climate on the Pajarito Plateau has changed, from somewhat higher precipitation in the past to the current semiarid conditions, and our findings may in fact provide evidence for such a change. It is known that during times of increased precipitation, both the quantity of pedogenic clay produced and the quantity that is

translocated within soils increases, regardless of the parent material (Birkeland, 1984; Buol et al., 1989). In contrast, pedogenic carbonate accumulation in soils derived from noncalcareous parent material usually takes place in a relatively low-precipitation environment (Marbut, 1951; Allen and Hajek, 1989), such as the current climate of the Pajarito Plateau. When soils are high in carbonate, flocculation tends to inhibit the translocation of clay (Jenny, 1941; McKeague and St. Arnaud, 1969; Birkeland, 1984). Not only, then, would the translocation of the clay that we find in abundance in the argillic soil horizons and in the fractures have required relatively higher precipitation, but it must have taken place in a relatively carbonate-free environment (which also points to an environment characterized by higher precipitation than at the present time). The presence of carbonates in both the soils and the fracture fills thus probably reduces the likelihood of present-day clay translocation, and active filling of fractures under the current climate is likely to proceed mostly by precipitation of calcite. If calcite continues to be precipitated in the fractures, it is probable that the bulk density of these fills will increase, with a corresponding decrease in porosity and permeability (Machette, 1985). Although water movement through filled portions of fractures is likely to be quite slow, the presence of unfilled fractures (and portions of fractures), as well as the unknown potential for creation of additional macropores in fills and widening of small fractures, leaves open the possibility of significant and rapid water movement, groundwater recharge, and contaminant transport.

Our data provide evidence that the climate of the Pajarito Plateau has changed from one of relatively high precipitation to the current semiarid climate. The timing of this change is unknown, but results of other studies (in progress) of the fracture fills may provide approximate dates. Climatic shifts have been documented at locations throughout the USA by a variety of methods (paleobotanical and isotopic studies, for example), and our data document the effects of these changes on a pedologic system. This information may have significance for the long-term stability of surfaces on the Pajarito Plateau by providing clues to the history of erosion and pedogenesis in the area. The recognition of past climate changes requires us to allow for the possibility of climate change in the future. Long-term increases in precipitation could significantly change the role and importance of fractures in the hydrology of this area. An understanding of erosion processes and landscape stability, as well as hydrology, is important for effective land-use planning and environmental protection. These studies could also have implications for other volcanic landscapes, especially in semiarid regions.

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