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MICROMORPHOLOGY, MINERALOGY, AND GENESIS OF SOILS AND
FRACTURE FILLS ON THE PAJARITO PLATEAU, NEW MEXICO

by

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A DISSERTATION

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CHAPTER I

INTRODUCTION

Soils are natural bodies which function as open systems within a landscape. A wide variety of processes contribute to, and are reflected in, the properties of individual soil profiles (pedons). Material and energy fluxes occur into, within, and through soils as a function of parent material, climate, topography, organisms, time, and a variety of possible other factors (Jenny, 1941). Ideally, the existing properties of an individual soil can provide information about the environment(s) in which it formed, and the processes that have acted upon it.

The town of Los Alamos, and the Los Alamos National Laboratory (LANL), are located on the Pajarito Plateau in north-central New Mexico (Figure 1). Environmental concerns have recently focused attention on the numerous fractures in the Bandelier Tuff, the series of volcanic rock units that make up most of the plateau. These fractures have come into question as possible conduits for transport of contaminants downward through the tuff. This study arose out of a need to evaluate the potential for contaminant transport in the fractures.

Because the fractures are typically filled, or partially filled, with soil-like material, and appear to be physically continuous with the soils on the surface of the Pajarito Plateau, it was decided to approach the question of the fractures from a soil genesis and morphology standpoint. Specifically, it was believed that soil characterization techniques, including soil micromorphological and mineralogical analyses, could provide information about the dominant processes (past and present) acting in the soils and fractures.

The specific objectives of this research were to investigate: (1) the physical, mineralogical and chemical nature of fracture-filling materials in the Bandelier Tuff, as

Figure 1. Geographic features in the vicinity of the Pajarito Plateau.
from Purtymun and Johansen (1974)

well as associated surface soils; (2) the relationships among fracture-fills, tuff bedrock, and surface soils of the Pajarito Plateau; (3) the processes responsible for the development of the fracture-fills; and (4) the likely sequence of events leading to the present morphology of the soils and fracture-fills.

CHAPTER II

LITERATURE REVIEW

Description of the Study Area

General Description of the Pajarito Plateau

The Pajarito Plateau (Figure 2) is a gently-sloping apron of volcanoclastic and sedimentary rocks which extends from the Jemez Mountains (Sierra de los Valles of Figure 1) on the west to the Rio Grande on the east. The plateau is formed by the Santa Fe Group (Miocene-Pliocene) and the Bandelier Tuff (Pleistocene) (Ross et al., 1961). The ash-flow, ash-fall, and pumice deposits that make up the upper portion of the plateau (Bandelier Tuff) were deposited by two major volcanic eruptions which occurred 1.4 and 1.1 million years ago (Spell et al., 1990). Erosion by intermittent streams has dissected the plateau into a series of finger-like mesas (including Mesita del Buey, where the study area is located), separated by steep-sided canyons 50 to 100 feet deep. The elevation at the western margin of the plateau is approximately 6900 feet (2100 meters) above sea level, and at the eastern margin is about 6600 feet (2012 meters) (Purtymun and Kennedy, 1971).

The study area is located on Mesita del Buey, at Area J, TA-54 of LANL. Mesita del Buey is a southeast trending mesa, bounded by Pajarito Canyon on the south and by Cañada del Buey on the north. The mesa is about 3.2 km long, and varies in width from 402 m to 91 m (Rogers, 1977).

Stratigraphy

The rocks of the Pajarito Plateau consist of the Santa Fe Group and the Bandelier Tuff. The Bandelier Tuff is exposed at the surface of the plateau, and rocks of the Santa Fe Group are exposed mainly to the east and at the base of the plateau.

Figure 2. View of the Pajarito Plateau, looking west toward Los Alamos and the Jemez Mountains.

The Santa Fe Group includes the Tesuque and Puye Formations, as well as some basalt flows. The Tesuque formation consists of siltstones and sandstones containing lenses of conglomerates and clay, and some basalt flows interbedded in the sedimentary units (Purtymun and Johansen, 1974). The Puye Formation consists of a poorly consolidated channel-fill conglomerate overlain by a fanglomerate deposit composed of volcanic debris. Although the rocks of the Santa Fe Group are exposed along the eastern margin of the Pajarito Plateau, they are well below the surface at the study site.

The surface rocks at Mesita del Buey and most of the Pajarito Plateau are rhyolitic ash flows and ash falls of the Bandelier Tuff, which unconformably overlie the Puye Formation and Chino Mesa basalt flows (Griggs, 1964; Purtymun and Johansen, 1974).

Description of the Bandelier Tuff

The Bandelier Tuff is subdivided into two major units (Ross et al., 1961), or into three units by some authors (Griggs, 1964; Purtymun and Kennedy, 1971). These units are the Guaje, Otowi, and Tshirege members. (The Guaje member is alternatively considered to be a part of the Otowi member.)

The lowermost deposits of the Bandelier Tuff are an ash-fall pumice and a thin water-deposited pumiceous tuff, together called the Guaje Member. Where present, these deposits vary in thickness from about 3 to 9 m, and generally thicken from east to west (Purtymun and Kennedy, 1971).

The Otowi Member is a light gray, nonwelded, pumiceous rhyolite tuff. It consists mostly of ash flows, and contains quartz crystals, glass shards, and fragments of rhyolite, latite, and pumice, with minor amounts of mafic minerals (Purtymun and Kennedy, 1971). The Otowi Member is not exposed on Mesita del Buey, but its thickness in the subsurface varies from nearly 400 feet at the western edge of the

plateau, to approximately 100 feet at the eastern margin (Purtymun and Kennedy, 1971).

The Tshirege member of the Bandelier Tuff is the uppermost unit, and forms the surface of most of the Pajarito Plateau, including the study areas on Mesita del Buey. The Tshirege Member is a series of rhyolitic ash flows containing glass shards, phenocrysts of sanidine and quartz, and fragments of rhyolite, latite, and pumice (Purtymun and Kennedy, 1971). It consists of three units which vary in degree of welding, lithology, and color.

Unit 1, the lower unit of the Tshirege member, is divided into Units 1a and 1b. Unit 1a is a light orange to light brown pumiceous tuff breccia, containing lumps of pumice up to 15 cm long. This unit ranges from about 9 m thick at the western end of the mesa, to about 3 m thick at the eastern end. Unit 1b contains fewer and smaller pumice fragments, and larger quartz crystals. This unit is about 7.5 m thick.

Unit 2 forms the walls and surface of Mesita del Buey, and is also divided into a lower unit (2a) and an upper unit (2b). Unit 2a is a light-gray pumiceous tuff, containing fragments of pumice, latite, and rhyolite, as well as some quartz phenocrysts. The unit consists of two ashflows, and its thickness varies from 26 m on the west end of the mesa to 9 m on the east. Unit 2b is light-gray to brown, and contains fragments of pumice, latite, and rhyolite, with abundant phenocrysts of quartz and sanidine. The pits of the study area are in Unit 2b of the Tshirege member.

The thickness of the entire Tshirege member ranges from about 60 m at the western margin of the plateau, to about 36 m at the eastern margin. The ash flows dip 2 to 3 degrees to the southeast (Purtymun and Kennedy, 1971).

Structure

The Bandelier ash flows are broken by numerous fractures which are considered to be joints formed by shrinkage as the ash flows cooled (Purtymun and Kennedy, 1971). The fractures range in width from about 1 mm to 10 cm. On average, there is one major fracture in every 2.2 m of horizontal distance (based on an analysis of 1078 joints; Purtymun and Kennedy, 1971), with numerous minor fractures in between. The fracture density tends to be higher in more highly welded units (Purtymun and Kennedy, 1971). The major fractures usually have a mostly vertical orientation, but some horizontal ones have been observed. The fractures cross boundaries between different cooling units, and intersect other fractures in complex patterns. Purtymun and Kennedy (1971) measured the orientation of 1078 of the fractures in Unit 2b on Mesita del Buey, and found three sets of fractures intersecting at angles (based on averages) of 30° and 90°.

A fault with several hundred feet of vertical displacement (Jemez Fault) exists near the western margin of the plateau (Ross et al., 1961; Purtymun and Johansen, 1974), dividing the plateau from the Jemez Mountains (Sierra de los Valles). It has been observed that the density of fractures in the tuff appears to be higher near the fault zone (Wilcox, 1993).

Some of the fractures are open, but most are filled with clay and calcium carbonate. The fill ranges from nearly pure clay to nearly pure carbonate, with various combinations of the two. It is not known to what depth the fractures may be filled, but they have been observed to contain fill material to a depth of 10 m. It has been noted that the fractures tend to become more open near the periphery of the mesa (Rogers, 1977).

Climate

The climate on the Pajarito Plateau is semiarid, with precipitation amounts increasing at higher elevations. The town of White Rock, at 1944 m elevation, receives 34 cm mean annual precipitation, while Los Alamos, at 2259 m elevation, receives 49 cm. The study area is at approximately 2040 m elevation. Roughly two-thirds of the annual precipitation falls from May to October, with the highest rainfall amounts usually occurring in August. The average winter snowfall is 127 cm (Nyhan et al., 1978).

The annual mean maximum temperature at Los Alamos is 22°C, and the annual mean minimum temperature is -4°C (Nyhan et al., 1978).

Vegetation

The dominant vegetation at the study site (Area J) consists of piñon pine and one-seeded juniper, with a variety of grasses present, especially blue grama. At one supplementary study site (TA-69), the vegetation is dominated by ponderosa pine, reflecting a higher elevation and higher precipitation.

Hydrology

The permanent water table is well below the surface of the plateau. At the western margin, it is about 400 m below the surface, and is about 200 m below the surface at the eastern end of the plateau. This aquifer is within the Santa Fe Group. Outflow is to the Rio Grande at the eastern end of the plateau. The rate of movement of water in this aquifer has been estimated at about 30 cm/day (Purtymun and Johansen, 1974).

Previous Work

Purtymun and Kennedy (1971), discussing the geology and hydrology of Mesita del Buey, detailed the subdivisions of the Bandelier Tuff, including the Guaje ashfall pumice, the Otowi ashflow tuff and pumice beds, and the Tshirege ashflows. They further divided the Tshirege member into three units, based on the work of Baltz and others (1963), and two of these into two subunits each. The fractures in the Bandelier tuff are discussed as joint systems, formed by shrinkage during cooling of the ashflows. They estimated that, in pit walls, one major joint occurs in every 2.2 m of horizontal distance. The authors stated that clay fill in the joints prevented precipitation from entering the joints, although water could move into open joints. They judged the clay fill to be derived from weathering of the tuff, and to have been precipitated along the joint openings.

Detailed $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Bandelier Tuff was performed by Spell et al. (1990). This study reported the results of isochron analyses based on numerous individual sanidine crystals. They place the age of the upper Bandelier (Tshirege) at 1.14 ± 0.02 Ma, and the lower Bandelier (Otowi) at 1.51 ± 0.03 Ma.

A number of studies have been concerned with the evolution of the magmas that formed the Bandelier Tuff. Warshaw and Smith (1988) analyzed pyroxenes and fayalites, reporting the presence of phenocrysts of sanidine, anorthoclase (in upper units), hedenbergite, augite, and fayalite. Stix and Gorton (1990), reporting on comprehensive geochemical analyses of several tuff units, reported the following weight percents of major elements as oxides (whole rock basis): 73% SiO_2 ; 12% Al_2O_3 ; 0.4% CaO ; 4% Na_2O ; and 5% K_2O . These papers provide details of the mineralogical and elemental composition of the tuffs, as well as trends from one unit to another. Doell et al. (1968) reported that the phenocryst mineralogy of the Bandelier Tuff consists of major quartz and sanidine, with minor amounts of clinopyroxene,

fayalite, and oxides. Smith and Bailey (1966) reported there are some systematic changes in the mineralogy. The phenocryst content was reported to vary from 5 to 30 percent, with anorthoclase and hypersthene taking the place of sanidine and fayalite in the uppermost units of the tuff.

No detailed studies have been published on the fractures or fills in the Bandelier Tuff, although Vaniman et al. (1988) reported on a somewhat similar situation in tuffs at Yucca Mountain, Nevada, where CaCO_3 is observed filling fractures. Quade and Cerling (1990) and Stuckless et al. (1991) reported isotopic evidence for a pedogenic or surficial origin of carbonates in fractures at Yucca Mountain. Fuller and Sharp (1992) analyzed fracture patterns, as well as weathering and permeability, in the Santana Tuff of the Trans-Pecos region of Texas. They found that weathering drastically reduced the permeability of this tuff, and that permeability is highly dependent on direction in relation to ash-flow directions.

Soils of most of Los Alamos County were surveyed by Nyhan et al. (1978). Sixty-one soil-mapping units are included in this report, along with useful block diagrams showing the relationship of the mapping units to the landscape. Five of the (then) ten recognized soil orders were identified in the county: Alfisols, Aridisols, Entisols, Inceptisols, and Mollisols. The soil series mapped at the primary study site is Hackroy, a clayey, mixed, mesic Lithic Aridic Haplustalf.

CHAPTER III

MATERIALS AND METHODS

Field Study

Field work was conducted in pits and trenches which had been opened to facilitate other studies or operations at Los Alamos National Laboratory (LANL). The primary study area consisted of two large pits at Area J, TA-54. These pits, excavated for the purpose of waste disposal, were made available for study prior to emplacement of the waste. Each pit was approximately 20 by 50 m in area, with maximum depths of about 7 m. Two soil profiles and their associated fractures were selected on walls of each of the pits. These profiles, designated F1, F2, F4, and F5, were described and sampled in detail (Figures 3-6). Another fracture, F3 (Figure 7), was described and sampled in less detail.

Soil profile descriptions included horizon designations and depths, field textures, Munsell colors, structure, consistence, reaction, boundary type, root size and abundance, and characteristics of clay films. Various site characteristics such as slope, aspect, vegetation, relief, and erosion were also noted.

Soil profiles were sampled by horizon. Bulk samples of approximately 1 kg of soil were collected from each horizon described. In addition, undisturbed soil peds were collected from selected horizons for thin sections.

Fracture descriptions consisted of width, type of fill material, size and abundance of roots, reaction, type and abundance of various inclusions, structure, and the appearance of the tuff on both sides of the fracture.

Fracture-fill materials were collected at vertical intervals of approximately 0.3 m throughout the exposed depth of each fracture. The size of these samples was limited by the narrow cross-section of the fractures exposed. Fracture-fill samples typically

Figure 3. View of F1 fracture and soil profile. Located on north wall of south pit, Area J, TA-54.

Figure 4. View of F2 fracture and soil profile. Located on south wall of south pit, Area J, TA-54.

Figure 5. View of F4 fracture and soil profile. Located near west end, north wall of north pit, Area J, TA-54.

Figure 6. View of F5 fracture and soil profile. Located near east end, north wall of north pit, Area J, TA-54.

Figure 7. View of F3 fracture, showing open space. Located near east end, south wall of south pit, Area J, TA-54.

consisted of approximately 100 g of material. Intact samples of fracture-fill material were obtained by stabilizing blocks of tuff that enclosed fracture-fill. These blocks were stabilized by cutting a space around the blocks and encasing them in gypsum plaster (Plaster of Paris). After stabilization, the blocks were cut out of the pit wall with a hammer and chisel.

Samples of unweathered and weathered tuff were collected from the pit walls. Tuffs were identified as weathered or unweathered based on appearance and hardness. Those tuffs which appeared to contain significant amounts of clay (having a more reddish or brownish color and a less porous appearance) and which offered less resistance to a rock hammer, were considered to be weathered. Unweathered tuffs appeared fresher, more porous, and were slightly pinkish gray or purplish gray in color. Tuffs were collected from each of the pit walls where a soil and fracture were described.

In addition to the primary study area, a number of soil profiles were described and sampled from trenches in other locations on LANL property. These locations included TA-51, TA-53, and TA-69.

Physical and Chemical Analysis

Particle Size Distribution

Percentages of sand, silt, and clay were determined by a modified version of the hydrometer method of Bouyoucos (1951). Approximately 50 g of air-dried soil was placed in a dispersion cup with 5 ml of 10% sodium hexametaphosphate and 200 ml of deionized water. This mixture was mechanically stirred for either 5 or 10 minutes (for medium and coarse or fine textures, respectively). After stirring, the mixture was quantitatively transferred to a 1000-ml hydrometer cylinder, and the volume was brought to 1000 ml by adding deionized water. (Henceforth, "water" or "H₂O" will be understood to be deionized H₂O.) Hydrometer and temperature readings were taken

after 40 seconds following complete mixing. Additional readings were taken after 2 and 6 hours. After correction of hydrometer readings for temperature, the percentage of sand was calculated by the equation

$$\% \text{ sand} = 100 - \left(\frac{\text{corrected 40-second reading}}{\text{oven dry sample weight}} \times 100 \right).$$

The clay percentage was calculated from the temperature-corrected 2 and 6 hour readings using the equation

$$\% \text{ clay} = \left(\frac{\text{corrected 2- or 6-hour reading}}{\text{oven dry sample weight}} \times 100 \right).$$

Silt percentages were calculated by difference.

After the hydrometer readings were completed, the clay fraction was removed from the samples by siphoning the suspension at 24-hour intervals to a depth determined by Stokes' law. After siphoning, the samples were redispersed and the process was repeated until essentially no clay remained in suspension. The clay fraction of all samples was collected, flocculated with 0.3 N CaCl_2 solution (to reduce volume), and saved for further fractionation and x-ray diffraction (XRD) analysis. Sand and silt fractions were also saved for further analysis.

Sand subfractions were separated by dry sieving for 10 minutes on a mechanical shaker. Very coarse, coarse, medium, fine, and very fine sand were separated and weighed. The weights were calculated as percentages of the total sand fraction of each sample.

The clay fraction of selected samples was separated into fine ($< 0.2 \mu\text{m}$) and coarse ($0.2 - 2 \mu\text{m}$) clay by centrifugation. The time required for separation was

calculated using an integrated form of Stokes' law (Whittig, 1965). The ratio of fine to coarse clay was calculated.

Soil Reaction

Soil reaction (pH) was determined on saturated pastes for soil horizons according to the method (Procedure 2) described in USDA Handbook 60 (U.S. Salinity Laboratory Staff, 1954). Pastes were prepared using deionized water, and were allowed to equilibrate for 24 hours. Soil pH was measured using an Orion Research Model 601A Digital Ionalyzer. The pH was not determined for fracture-fills because insufficient sample was available to prepare saturated pastes.

Electrical Conductivity

Electrical conductivity (EC) was determined on extracts of the saturated pastes prepared for pH analysis. Pastes were vacuum extracted through qualitative filter paper as described in USDA Handbook 60 Procedures 2, 3a, and 4b (U.S. Salinity Laboratory Staff, 1954). The EC of the extracts was determined using a Beckman Solu-Bridge conductivity meter. The Solu-Bridge was adjusted for temperature and standardized using a saturated gypsum solution.

Calcium Carbonate Equivalence

Calcium carbonate equivalence (CaCO_3) was determined for samples which were shown to contain CaCO_3 by a qualitative test with 10% HCl. The determination was made using acid neutralization as outlined in USDA Handbook 60 (U.S. Salinity Laboratory Staff, 1954). Each set of samples was run with a blank consisting of pure quartz sand and a prepared standard containing 10% by weight CaCO_3 .

Organic Carbon

Percent organic carbon was determined for all samples using the acid digestion method of Walkley-Black as described by Nelson and Sommers (1982). Each sample set included a blank consisting of 0.5 g pure quartz sand.

Cation Exchange Capacity

Cation exchange capacity (CEC) was determined using Procedure 19, USDA Handbook 60 (U.S. Salinity Laboratory Staff, 1954). Samples were saturated with Na⁺ using 1.0 N NaOAc at pH 8.2, washed with 95% ethanol, then saturated with NH₄ using 1.0 N NH₄OAc at pH 7.0. The concentration of Na⁺ replaced by NH₄ was determined with a Bacharach/Coleman Model 51Ca flame photometer using natural gas and oxygen. Each sample set was analyzed three times, and the readings averaged before calculation of the CEC. Standards of 140 and 350 meq/l were prepared using NaCl and diluted with the same 1.0 N NH₄OAc used for NH₄ saturation of samples. The Na concentration in the supernatant liquid allowed the samples to be analyzed without dilution. The CEC of whole soil was determined for all samples, and calculated in cmol/kg soil. For selected samples, CEC of the clay fraction was determined by the same method, and calculated in cmol/kg clay. A sample of a Wyoming bentonite standard (montmorillonite No. 26, Clay Spur, Wyoming; American Petroleum Institute, 1949) was also analyzed for comparison of the clay samples with a known standard.

Micromorphology

Standard petrographic thin sections (0.03 mm thick) were prepared from selected soil horizons, fracture-fills, and tuffs. Samples were impregnated with epoxy resin (Shell R-815, refractive index = 1.51-1.55), and cover slips were cemented on the

slides after polishing. One slide was prepared using resin with blue color added (Kriegosol blue supra).

Thin sections were examined petrographically, with plane-polarized and cross-polarized light. Samples were described using the soil micromorphology terminology of Brewer (1964). Features described include: 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. Related distribution patterns (Bullock et al., 1985) were also noted. Photomicrographs were taken of selected thin sections.

Grain mounts were prepared from sand and silt fractions of selected samples. These were mounted on glass slides in immersion oils, normally with a refractive index of 1.54 to distinguish quartz from feldspars. At least 300 grains were identified and counted on each of these mounts, and percentages of the most commonly observed minerals were calculated (quartz, alkali feldspars, tridymite/cristobalite, glass, hornblende, plagioclase, and opaque grains).

X-ray Diffraction

Clays from selected samples were analyzed by x-ray diffraction (XRD). Total clays as well as fine clay ($< 0.2 \mu\text{m}$) and coarse clay ($0.2 - 2.0 \mu\text{m}$) fractions were analyzed.

Calcium carbonate was removed from clays before XRD analysis by treatment with 10% HOAc at room temperature. Organic matter was then destroyed by successive treatments with 10%, 20%, and 30% H_2O_2 , followed by gentle boiling to remove excess H_2O_2 .

An aliquot of the treated clay was saturated with Ca^{2+} by repeated washings with 0.3 N CaCl_2 solution. The clay and CaCl_2 solution were shaken for 10 minutes on

a horizontal reciprocating shaker, then centrifuged for 10 minutes at 3600 rpm. The supernatant liquid was decanted, and the process repeated three times. Following Ca-saturation, the clays were solvated by washing with a 1 percent (by volume) glycerol solution. The samples were shaken and centrifuged as before. The supernatant liquid was discarded, and the process was repeated until dispersion was detected.

An aliquot containing approximately 25 mg of Ca-saturated, glycerol-solvated clay was dispersed by mechanical shaking, pipetted onto a glass slide and allowed to air dry. The slides were heated at 60°C until they were no longer sticky, usually 8 to 12 hours. Slides were stored in a desiccator over CaCl_2 until x-ray analysis was performed.

Selected samples were also separately saturated with K^+ by repeated washings with 0.3 N KCl. Aliquots containing approximately 25 mg of K-saturated clay were pipetted onto glass slides and air dried. These slides were x-rayed, heated to 250 °C, x-rayed again, heated to 550 °C, and x-rayed a third time.

Oriented clays from soils and fracture-fills were x-rayed from 2° to 32° 2- Θ , at a scanning rate of 2° per minute. A setting of either 1000 or 2000 counts per second was used, depending on the intensity of the strongest peak. Tuff samples were analyzed in the same way, except that powder samples were analyzed in addition to "oriented" clays. The tuffs were ground to pass a 50- μm sieve, and packed in a random-orientation mount. Powders were x-rayed from 2° to 62° 2- Θ , at a scanning rate of 2° per minute. Sand and silt fractions from selected samples were also x-rayed as powders. All sands were ground to <50 μm before analysis.

All samples were analyzed using a Phillips-Norelco diffractometer operated at 40 kV and 20 mA. Monochromatic Ni-filtered Cu $\text{K}\alpha$ radiation was used in all cases. The d-spacings of diffractogram peaks were calculated using Bragg's law with $\lambda = 1.54184 \text{ \AA}$.

Electron microscopy

Selected samples were examined using a JEOL JEM 100CX electron microscope. Both transmission (TEM) and scanning (SEM) electron microscopy were performed. Specific mineral grains were isolated and their characteristic x-ray spectra analyzed using a Kevex Quantum energy-dispersive x-ray analysis unit, in order to determine the ratios of oxides of Si, Al, O, K, Na, Ca, Fe, and Ti in individual minerals.

CHAPTER IV

RESULTS AND DISCUSSION

Field Study

Soil Profiles

Profile descriptions of soils at the study area are in Appendix A. Additional soil profiles were described at other areas, and these descriptions are in Appendix B.

The soils described at the study area (Area J) are relatively shallow, with only a moderate degree of development. All of the profiles may have been subjected to partial truncation of the A horizon(s), and have a layer of spoil approximately 1 m thick overlying the existing A horizons. The spoil layer consists of variously sized tuff fragments which were removed in the construction of the pits. The contacts between the spoil and the A horizons are abrupt and straight. It is unknown how much, if any, of the A horizons might have been stripped prior to or during pit construction. The A horizons from soil profiles at more undisturbed sites range in thickness from about 5 to 20 cm. If this thickness is assumed to be typical of A horizons on the plateau, then the soils at Area J (average A-horizon thickness is 8 cm) probably were not truncated deeply.

The texture of all A horizons was described in the field as loam. Moist colors are dark brown (7.5 YR 3/3). Soil structure in the A horizons is weak granular or weak subangular blocky. All A horizons described at the study area are less than 10 cm thick.

Field textures in the Bt horizons are clay loam or clay. Moist colors are brown to dark brown (7.5 YR 3/4 or 4/4) or dark reddish brown (5 YR 3/4). Structure in the Bt horizons is subangular blocky to blocky. Clay films of variable thickness and continuity are present on ped faces. Each of the profiles examined at the study area includes an argillic horizon, although in F1 and F2 the Bt horizons only marginally

exceed the minimum clay increase required for an argillic horizon (Soil Survey Staff, 1990). In three of the profiles (F1, F4, and F5), the argillic horizons extended downward into pockets in the tuff, and were described as "argillic tongues." These tongues led directly into fractures in the tuff.

The B horizons of all of the profiles were considered at the time of field description to be argillic horizons. The F1 and F2 soils were viewed as having only weakly developed argillic horizons, with only moderate clay increases over the A horizons, and thin discontinuous clay films. The F4 and F5 soils had strong argillic horizons, with large increases in clay, thicker clay films, and blocky structure.

The F1 soil was classified as a fine-loamy, mixed, mesic, Lithic Haplustalf the F2 soil as a fine-loamy, mixed, mesic, Aridic Haplustalf, the F4 soil as a fine, montmorillonitic, mesic, Aridic Paleustalf, and the F5 soil as a fine, montmorillonitic, mesic, Lithic Haplustalf (Soil Survey Staff, 1990). The placement of the F4 soil in the Paleustalf great group would normally suggest an older, more highly developed soil. However, it should be noted that this profile was only slightly deeper than the others, and that if the Cr horizon were 5 cm closer to the surface, the soil would be classified as a Lithic Haplustalf.

Moreover, the high degree of development of the argillic horizons in the F4 and F5 soils seems somewhat inconsistent with the relatively shallow profiles. The pronounced clay increase at the upper boundary of the Bt horizon, as well as the clayey particle size class throughout the argillic horizons, would place these soils firmly in the Paleustalf subgroup. The shallow lithic contact, however, suggests less mature soils. This inconsistency leads to speculation that the current argillic horizons were derived from a greater thickness of soil material which has been removed by surface erosion. The argillic horizons in this case might be considered relicts of a past soil-forming

environment (Graham et al., 1994), or the cumulative eluviated clay from progressive weathering of the tuff followed by erosion.

Differences between the two soils in the south pit and the two in the north pit are notable in light of the close proximity of the profiles. A distance of less than 100 m separates all of the soils. It should be noted that F4 and F5 are somewhat closer to the edge of a shallow canyon on the north side of the site, while F1 and F2 are closer to the axis of the mesa. It is possible that soils on the northern margin of the site have stronger illuvial features due to somewhat more rapid drainage in proximity with the canyon wall. The thickness of these profiles, however, is not significantly greater than that of the more centrally located profiles. This would seem to indicate either that weathering rates (rates of pedogenesis) are similar in both landscape positions, or that higher erosion rates near the canyon wall have removed a greater portion of those profiles.

Fracture-fill

F1. The fill consists almost entirely of CaCO_3 (calcite or caliche). The carbonate fill contains inclusions of sand-sized grains of sanidine, with small percentages of quartz and tuff fragments. The inclusions appear to be "floating" in the CaCO_3 matrix of the fracture-fill. The fracture averages approximately 4 cm in width, with a range of 1.5 to 10 cm. In the upper portion of the fracture, from 78 to 125 cm, the tuff on both sides of the fracture appears weathered. Below 125 cm, the tuff appears unweathered on both sides of the fracture. The CaCO_3 filling the fracture is composed, in places, of four to six vertical laminae. From 83 to 130 cm, a 2 to 3-mm wide band of darker material was observed running vertically near the center of the fracture-fill, and is thought to consist of CaCO_3 with a silicate clay or organic matter component. Fine

and medium roots were observed as far as 4 m down in the fracture, although most were dead below 2 m.

E2. The fracture has a fill consisting mostly of clay. Flecks of CaCO_3 are present, however, and the clay fill material effervesces mildly when 10 % HCl is placed on it. A few coatings and threads were noted in the lower portion of the fracture, from about 275 to 310 cm. The clay in this portion of the fracture does not effervesce. The fracture averages about 1 cm in width, but is up to 4 cm wide in places. The clay in the fracture is characterized by shrinkage cracks from about 140 to 165 cm, and from 230 to 310 cm depth. The intervening portions show no signs of shrinkage cracks. Live roots up to 4 mm in diameter are present throughout the observable part of the fracture. Inclusions of tuff, up to about 2 cm in diameter, are seen in the fracture-fill, usually in the wider portions of the fracture. The larger inclusions appear to be fragments which have become separated from the fracture wall and become engulfed by the clay matrix of the fracture-fill. For the entire observed depth of fracture, the tuff appears more weathered on one side of the fracture than on the other. This weathering alternates from one side of the fracture to the other without any apparent pattern.

E3. Neither the soil nor the fracture at F3 were described in detail, but the fracture is noteworthy in several respects. The upper portion of the fracture is about 3 cm in average width, and filled with clayey material. At a point about 3 m below the base of the soil zone, the fracture bifurcates into two larger fractures which are both open (containing no fill material) for a vertical distance of about 2 m. Each of these two fractures widens to about 10 cm, then narrows again near the bottom of the pit. The width at the bottom of the exposure is again about 3 to 4 cm. The lateral extent of the open portion of these fractures is unknown, but a metal tape was extended 3 m into the fractures without encountering resistance. A coating of CaCO_3 was observed on the

walls of the fractures. This coating consists, in places, of macroscopic calcite crystals up to 2 mm in length.

At the point where the two fractures narrow, they are again filled. The fill in this lower part consists of alternating horizontal layers of clayey and sandy material. These layers are each about 50 mm in thickness. The sandy layers consist of fine horizontal laminations of sand about 1 mm thick. The clay also appears laminated, with alternating dark and light laminae of 1 mm thickness or less.

E4. The top of the fracture is located at the base of a wedge-shaped pocket of soil, which is essentially an extension of the argillic horizon into the tuff. Immediately above the fracture, the argillic tongue consists of fine horizontal laminations of clay. The fracture-fill immediately below the soil pocket, and throughout much of the fracture, consists of distinct alternating layers of clay and CaCO_3 (Figure 8). These layers are 1 to 2 mm thick, and are oriented parallel to the fracture walls. The fracture varies from about 1 to about 4 cm in width. In places, the fill consists of relatively pure clay with only thin discontinuous coatings of CaCO_3 . In other places, there is a complex intercalation of clay and CaCO_3 , with up to 5 layers of CaCO_3 within a clay matrix. Occasionally, there appear to be thin bands of CaCO_3 lining the fracture wall, with clay filling the interior of the fracture. Typically, however, the fracture walls appear to be lined with clay, and CaCO_3 is present as laminae within the clay matrix. In a few places, the fill consists of CaCO_3 with very little clay in evidence. These areas are neither extensive nor numerous. Fine, medium, and coarse roots are abundant in the soil pocket, especially near the top of the fracture. A root mat about 2 mm thick lines one wall of the fracture from 160 cm to about 185 cm, at which point it moves into a smaller fracture intersecting the main one.

E5. The top of the fracture is also located in a pocket of soil, with an argillic tongue leading into the fracture. This fracture is considerably wider than the other

Figure 8. Close-up view of F4 fracture-fill, showing clay and CaCO₃ laminae.

fractures described, with an average width of about 5 cm. From 90 to about 300 cm, CaCO_3 is present as thin continuous coatings on or near the fracture walls. Abundant threads, coatings, and masses of CaCO_3 were present within the matrix of the fracture-fill above 160 cm. The maximum CaCO_3 is at about 160 cm. The majority of the fracture-fill consists of strongly laminated clay. This lamination is oriented vertically near the fracture walls, but is horizontally oriented in the center portion of the fracture. The vertically laminated clay is about 4 to 5 mm thick. The lamination diminishes near the bottom of the exposure, at about 320 cm. Most of the clay is characterized by abundant shrinkage cracks throughout the fracture. This cracking becomes more pronounced near the bottom of the fracture, until the appearance is that of a fine blocky structure.

Live roots are present throughout this fracture, with large (5 mm diameter) roots present as far down as 3 m (2 m below the solum).

The general appearance of the fracture-fills is of illuviated clay and precipitated CaCO_3 . Previous workers (Purtymun and Kennedy, 1971; Rogers, 1977) remarked that the fracture-fills appear to have formed by *in situ* weathering of the tuff and precipitation of weathering products along the fractures. Field observations do not confirm this interpretation, but rather indicate that the fracture-fill material moved into the fractures from above. The appearance of the zone of weathering of tuff adjacent to the fractures also corresponds to an illuvial origin of the majority of the fill material. It is apparent that weathering of the tuff has occurred along the fractures. The fracture walls are clearly defined in all cases, however, with no transitional zone between solid tuff and fracture-fill. It appears more likely from field observations that clay has been translocated into the tuff adjacent to the fracture walls. The tuff is typically somewhat soft and friable, usually only on one side of the fracture. It is likely that the tuff is weathering slowly away from the fracture. There is evidence for this in the fact that

occasional tuff fragments appear to have been separated from the fracture wall. Apparently, illuvial clay moved into minute fractures in the walls, and subsequent shrinking and swelling of the clay widened the gaps between the fragments and the rest of the tuff. These widening gaps continued to receive clay from above, so that the fragments appear to be suspended in the clay fracture-fill matrix. Weathering of the tuff may have contributed small amounts of clay to the fracture-fills, but the apparent orientation of the clay and the complete lack of tuff-like structure in the fills indicates that most of the clay was emplaced in the fractures by illuviation from above.

Physical and Chemical Analysis

Particle Size Distribution

The results of particle size distribution analysis of samples from Area J are shown in Table 1. The topsoils are loamy in texture, ranging from loam to sandy loam. The clay content of A horizons ranges from 11.4 % in profile F1 to 17.5 % in profile F2.

Textures of B horizons are sandy loam, loams, and clays. The clay content is lowest in the Bt horizon of F1 (17.1 %), and highest in the Bt1 horizon of F4 (58.8 %). The F4 and F5 B horizons have much higher clay contents than do the B horizons of F1 and F2, and much greater increases in clay from the A to the B horizons.

Unweathered tuff has a loamy sand texture, with only 4.4 % clay. Weathered tuff has a sandy loam texture, with 8 % clay.

Percentages of sand subfractions, obtained by dry sieving, are shown in Table 2, along with the ratio of fine to very fine sand. The two tuff samples were coarse-textured, with coarse sand most abundant in the unweathered (hard) tuff, and very coarse sand most abundant in the weathered (soft) tuff. Eleven of the 38 samples analyzed had the following pattern in rank from least to most abundant subfraction:

Table 1. Particle size distribution of samples from Area J, TA-54.

Horizon	Depth	Sand	Silt	Clay	Texture†
	cm	%			
<u>F1 profile</u>					
A	0-9	57.9	30.7	11.4	SL
BA	9-19	59.8	26.4	13.8	SL
Bt	19-26	53.9	29.0	17.1	SL
Cr/Bt	26-34	47.7	27.8	24.5	L
tongue	34-44	47.2	25.3	27.5	SCL
fill	59-79	29.8	3.0	67.2	C
fill	119-129	31.7	4.7	63.6	C
fill	199-214	59.9	11.3	28.8	SCL
<u>F2 profile</u>					
A	0-9	49.1	33.4	17.5	L
Bt1	9-36	36.5	39.7	23.8	L
Bt2	36-59	47.6	32.6	19.8	L
Bk/Cr1	59-104	53.9	31.1	15.0	SL
Bk/Cr2	104-125	60.3	29.3	10.4	SL
Cr	125-200	72.9	18.4	8.7	SL
fill	145-155	46.2	8.9	44.9	SC
fill	165-185	47.9	11.8	40.3	SC
fill	225-245	55.9	11.5	32.6	SCL
fill	245-265	50.8	12.4	36.8	SC
<u>F4 profile</u>					
A1	0-7	52.6	30.8	16.6	VFSL
A2	7-12	44.1	32.6	23.3	L
Bt1	12-31	16.2	25.0	58.8	C
Bt2	31-42	28.7	26.4	44.9	C
Bt3	42-55	25.3	28.3	46.4	C
fill	115-135	70.3‡	19.4	10.3	SL

Table 1, cont.

Horizon	Depth	Sand	Silt	Clay	Texture†
	cm	%			
<u>F4 profile cont.</u>					
fill	145-165	30.8	34.8	34.4	CL
fill	265-285	77.7‡	17.7	4.6	LS
fill	315-335	10.9	3.3	85.8	C
fill	365-395	40.4	9.2	50.4	C
<u>F5 profile</u>					
A0-7	47.9	37.8	14.3	L	
Bt1	7-16	28.7	24.1	47.2	C
Bt2	16-45	26.0	19.3	54.7	C
Bt2 tongue	45-55	17.3	12.8	69.9	C
fill	55-75	3.6	3.9	92.5	C
fill	85-105	1.6	2.9	95.5	C
<u>Tuffs</u>					
Hard	344	75.0	20.6	4.4	LS
Soft	158	73.4	18.6	8.0	SL

‡ Sand content erroneously high due to clay aggregation.

† C = clay; CL = clay loam; SL = sandy loam; LS = loamy sand; L = loam;
SCL = sandy clay loam; SC = sandy clay; VFSL = very fine sandy loam

medium - fine - coarse - very coarse - very fine. This pattern is characteristic of the F1 and F2 soil profiles, where all but two of the soil horizons have the same order of abundance. This pattern was observed neither in any of the F4 or F5 samples, however, nor in the F1 fracture-fill samples.

The ratio of fine to very fine sand ranges from 0.14 (F4 fill, 145-165 cm) to 1.59 (F4 fill, 115-135 cm). The average ratio for soil horizons is 0.44 (18 samples). For fracture-fill samples, the average ratio is 0.72 (18 samples). In all cases where the F/VF ratio is greater than 1 ($FS > VFS$), the sample is from a fracture-fill. Within individual profiles, in each case the uppermost (A) horizon has the lowest or second-lowest F/VF ratio, indicating that very fine sand is more abundant in A horizons than elsewhere in the profiles.

The textures of the soil horizons are generally finer than the sandy loam and loamy sand of the tuff samples, as expected from general weathering relationships between soil and parent material. The differences between the tuff and the soil horizons are greatest in the F4 and F5 profiles. This is consistent with the observation that these soils appear to be more highly developed (with stronger argillic horizons) than the F1 and F2 soils. The F1 and F2 profiles consist of loams and sandy loams, as compared with the loams and clays of F4 and F5. These textures, used in soil index calculations, would be evidence for greater soil development in F4 and F5 (Birkeland, 1984).

Particle size analysis of fracture-fills was problematic in some cases. In a few of the samples, a portion of the clay was in the form of sand-sized aggregates which proved resistant to all dispersion procedures attempted. Prolonged ultrasonic treatment (30 minutes or more) broke down most of the aggregates, but this also resulted in partial destruction of the fundamental clay particles, as shown by x-ray diffraction analysis. The clay aggregates resulted in sand percentage readings which were erratic and in some cases much higher than could be confirmed by feel or by visual examination. The

Table 2. Sand subfractions of selected horizons.

Horizon	Depth (cm)	Very coarse	Coarse	Medium	Fine	Very fine	F/VF
		<u>%</u>					
<u>F1 profile</u>							
A	0-9	20.8	17.7	10.2	11.8	39.5	0.30
BA	9-19	29.4	18.4	9.4	10.3	32.4	0.32
Bt	19-26	23.1	21.3	13.8	14.0	27.7	0.51
Cr/Bt	26-34	25.4	21.6	11.9	12.1	29.0	0.42
tongue	34-44	33.2	20.9	10.6	10.5	24.8	0.42
fill	59-79	18.0	23.7	24.1	20.2	14.0	1.44
fill	119-129	18.7	22.2	17.0	22.0	20.1	1.09
fill	199-214	21.9	23.8	13.5	16.9	23.8	0.71
<u>F2 profile</u>							
A	0-9	19.1	13.8	7.6	11.1	48.4	0.23
Bt1	9-36	17.9	15.0	8.6	10.8	47.6	0.23
Bt2	36-59	25.5	17.9	10.1	11.9	34.6	0.34
Bk/Cr1	59-104	18.7	20.4	13.0	16.5	31.4	0.53

Table 2 cont.

Horizon	Depth (cm)	Very coarse	Coarse	Medium	Fine	Very fine	F/VF
<u>%</u>							
<u>F2 profile cont.</u>							
Bk/Cr2	104-125	20.6	18.4	11.3	17.1	32.5	0.53
Cr	125-200	26.9	21.6	12.5	14.7	24.3	0.60
fill	145-155	23.0	21.3	12.3	16.1	27.4	0.59
fill	165-185	30.8	18.4	11.1	14.1	25.7	0.55
fill	225-245	23.6	19.5	11.2	16.9	28.7	0.59
fill	245-265	24.1	16.9	10.7	16.1	32.2	0.50
<u>F4 profile</u>							
A1	0-7	12.7	13.4	9.4	12.4	52.2	0.24
A2	7-12	9.8	15.4	11.2	13.7	49.8	0.28
Bt1	12-31	15.1	19.0	15.0	20.2	30.7	0.66
Bt2	31-42	18.2	23.6	16.1	17.3	24.8	0.70
Bt3	42-55	8.9	18.8	19.2	25.6	27.6	0.93
fill	115-135	4.8	16.9	26.8	31.6	19.9	1.59

Table 2 cont.

Horizon	Depth (cm)	Very coarse	Coarse	Medium	Fine	Very fine	F/VF
		<u>%</u>					
<u>F4 profile cont.</u>							
fill	145-165	9.3	7.5	4.9	9.5	68.8	0.14
fill	205-225	14.7	24.4	20.8	21.5	18.6	1.16
fill	265-285	20.4	25.3	19.9	18.8	15.5	1.21
fill	285-305	14.7	8.8	5.9	9.5	61.2	0.16
fill	315-335	14.8	11.0	13.3	24.1	36.8	0.65
fill	365-395	14.8	18.6	13.5	23.5	29.6	0.79
<u>F5 profile</u>							
A	0-7	17.1	18.4	11.3	12.0	41.2	0.29
Bt1	7-16	16.6	19.1	12.9	13.7	37.6	0.36
Bt2	16-45	18.9	21.8	14.0	12.2	33.1	0.37
Bt2 tongue	45-55	27.0	23.2	12.5	12.1	25.3	0.48
fill	55-75	5.8	23.7	18.6	16.0	35.9	0.45
fill	85-105	5.8	11.6	13.0	18.8	50.7	0.37

Table 2 cont.

Horizon	Depth (cm)	Very coarse	Coarse	Medium	Fine	Very fine	F/VF
		<u>%</u>					
		<u>Tuffs</u>					
Hard	344	25.4	29.6	16.1	14.0	14.9	0.94
Soft tuff	158	24.9	23.9	14.1	14.8	22.4	0.66

percentages reported for F5 fill (92.5 and 95.5% clay) are considered more representative of the true particle size distributions of the fracture-fills. It is believed that these aggregates form upon air-drying of the samples. A similar phenomenon has been reported in clays from Pullman soils in West Texas (Allen, 1993).

Fine and coarse clay percentages are shown in Table 3. The five A horizons have an average fine clay content of 52% of the total clay. For the nine Bt horizons, the average fine clay content is 56% of the total clay. The twenty-two fracture-fill samples have an average fine clay content of 64% of the total clay. The weathered tuff and Cr horizon samples have only 6% of the total clay in the fine clay fraction. While these percentages point to a progressive increase in fine clay with depth, it should be noted that the fine clay percentages are highly variable, and more so in the fracture-fill samples than near the surface. Moreover, the fine clay does not increase steadily in any of the profiles, but varies erratically. This variability is probably due at least in part to aggregation of the clay. In profiles F1 and F2, the fracture-fills do appear to be significantly higher in fine clay than the soil horizons. However, in F4 and F5, the highest fine clay percentages, on average, are in the A and Bt horizons. It is clear that virtually all soil and fracture-fill samples have much higher fine clay contents than the weathered tuff.

Soil Reaction

Soil horizon reaction (pH) ranges from 6.1 to 8.0 (Table 4). The highest pH values are in profile F1. In profile F4, all horizons except A1 are slightly acidic. Within each profile analyzed, the highest pH is in the upper horizon.

These pH values are typical of many soils of semiarid regions, and indicate that the soils have high base saturation percentages (Buol et al., 1989).

Table 3. Fine and coarse clay contents of selected horizons.

Horizon	Depth	Fine clay	Coarse clay
	cm	%	%
<u>F1 profile</u>			
A	0-9	32	68
BA	9-19	48	52
Bt	19-26	6	94
Cr/Bt	26-34	33	67
tongue	34-44	40	60
fill	49-59	99	1
fill	119-129	75	25
fill	199-214	56	44
<u>F2 profile</u>			
A	0-9	35	65
Bt1	9-36	54	46
Bt2	36-59	46	54
Bk/Cr2	104-125	35	65
C ₁	125-200	7	93
fill	165-185	17	83
fill	225-245	98	2
fill	245-265	55	45
fill	286-298	58	42
<u>F4 profile</u>			
A1	0-7	92	8
A2	7-12	56	44
Bt1	12-31	38	62
Bt2	31-42	95	5
Bt3	42-55	40	60
fill	50-60	45	55
fill	145-165	41	59

Table 3, cont.

Horizon	Depth	Fine clay	Coarse clay
	cm	%	%
<u>F4 profile cont.</u>			
fill	175-195	98	2
fill	205-225	71	29
fill	265-285	70	30
fill	285-305	35	65
fill	315-335	99	1
fill	365-395	97	3
<u>F5 profile</u>			
A	0-7	44	56
Bt1	7-16	95	5
Bt2	16-45	95	5
Bt2 tongue	45-55	99	1
fill	55-75	51	49
fill	85-105	53	47
fill	115-155	50	50
fill	175-215	43	57
fill	225-265	60	40
fill	275-315	68	32
<u>Tuff</u>			
soft	154-162	4	96

Electrical Conductivity

All horizons analyzed show low to moderate electrical conductivity (Table 4). The highest conductivity is in the Bt3 horizon of F4 (1.35 dS/m). All samples were well below the 4.0 dS/m defined as the threshold value of saline soil conditions (U.S. Salinity Laboratory Staff, 1954).

Calcium Carbonate Equivalence

The CaCO_3 equivalent percentages are quite low in all soil horizons, ranging from 0 to 2.6% (Table 4). Significant CaCO_3 accumulations were found in three of the four fractures analyzed. The F1 fill has the highest percentages, as expected from field observations. All of the F1 soil horizons contain less than 1% CaCO_3 , but this percentage jumps to 46% in the uppermost fracture-fill sample. The maximum in this fracture is 66.7% at a depth of about 1 m, or about 30 cm below the soil zone. The F2 fracture-fill contains a maximum of 2.7% , although the Cr horizon has 7.8%. Both F4 and F5 fracture-fills contain significant amounts of CaCO_3 , corresponding to the laminae and coatings described in the field. A maximum of 22.8% is in F4, at a depth of about 85 cm (30 cm below the soil zone). In F5, the maximum is 7.6%, is at a depth of about 95 cm (40 cm below the soil zone). The unweathered and weathered tuffs contain only 0.1 and 0.2%, respectively.

The soils described have relatively weakly developed carbonate segregations, corresponding approximately to Stage I or II (non-gravelly) carbonate accumulations of Gile et al. (1966). The fracture-fill of F1, on the other hand, exhibits Stage III carbonate accumulation, where virtually the entire material is carbonate-impregnated. This fill in fact exhibits a weak laminar fabric characteristic of Stage IV, although no induration was observed. The fracture-fills of F2, F4, and F5 exhibit carbonate features similar to Stage II accumulations. Although the fracture-fills are not soil horizons in the usual

Table 4. Chemical properties of whole soil samples from Area J, TA-54.

Horizon	Depth	CEC	Organic Carbon	CaCO ₃	pH	EC
	cm	cmol/kg	%	%		dS/m
<u>F1 profile</u>						
A	0-9	14.0	0.77	0.1	8.04	1.05
BA	9-19	13.4	0.43	0.0	7.94	0.73
Bt1	9-26	20.6	0.53	0.2	7.53	1.20
Cr/Bt	26-34	17.9	0.41	0.9	--	--
tongue	34-44	28.2	0.24	0.8	--	--
fill	44-59	24.3	0.68	46.4	--	--
fill	69-79	15.9	0.53	58.2	--	--
fill	99	10.4	0.36	66.7	--	--
fill	119-129	16.0	0.46	25.3	--	--
fill	134-149	12.1	0.32	42.9	--	--
fill	199-214	9.5	0.29	23.8	--	--
fill	249-304	10.6	0.27	31.3	--	--
<u>F2 profile</u>						
A	0-9	15.3	0.74	0.4	7.95	0.97
Bt1	9-36	21.2	0.43	0.0	6.43	0.46
Bt2	36-59	17.6	0.12	0.5	7.74	0.25
Bk/Cr1	59-104	19.8	0.17	2.6	--	--
Bk/Cr2	104-125	15.5	0.17	1.0	--	--
Cr	125-200	1.8	0.00	7.8	--	--
fill	145-155	34.2	0.62	2.6	--	--
fill	155-165	37.4	0.63	1.9	--	--
fill	165-185	45.9	0.68	2.6	--	--
fill	185-205	45.1	0.70	2.7	--	--
fill	205-225	44.1	0.82	2.4	--	--
fill	235	34.6	0.53	1.3	--	--
fill	245-265	40.9	0.75	1.3	--	--

Table 4, cont.

Horizon	Depth	CEC	Organic Carbon	CaCO ₃	pH	EC
	cm	cmol/kg	%	%		dS/m
<u>F2 profile cont.</u>						
fill	265-285	42.1	0.46	1.3	--	--
fill	286-298	53.3	0.70	2.5	--	--
<u>F4 profile</u>						
A1	0-7	15.2	0.49	0.2	7.02	0.65
A2	7-12	21.9	0.74	0.7	6.31	0.37
Bt1	12-31	53.7	0.90	1.5	6.13	0.73
Bt2	31-42	45.9	0.83	1.4	6.56	--
Bt3	42-55	63.5	0.95	2.1	6.74	1.35
fill	50-60	88.3	1.21	5.6	--	--
fill	75-95	65.1	0.41	22.8	--	--
fill	115-135	59.5	0.41	17.8	--	--
fill	145-165	62.3	0.41	6.9	--	--
fill	175-195	64.9	0.27	8.3	--	--
fill	205-225	50.5	0.24	8.5	--	--
fill	235-255	54.9	0.31	10.6	--	--
fill	265-285	45.3	0.18	12.0	--	--
fill	285-305	106.9	0.25	7.8	--	--
fill	315-335	102.0	0.29	10.1	--	--
fill	365-395	62.8	0.24	4.6	--	--

Table 4, cont.

Horizon	Depth	CEC	Organic Carbon	CaCO ₃	pH	EC
	cm	cmol/kg	%	%		dS/m
<u>F5 profile</u>						
A0-7	16.3	0.51	0.5	7.58	1.39	
Bt1	7-16	36.3	0.69	1.2	6.86	1.50
Bt2	16-45	43.9	0.74	1.5	7.04	1.09
Bt2 tongue	45-55	54.2	1.02	2.0	--	--
fill	55-75	76.7	0.31	6.1	--	--
fill	85-105	111.2	0.36	7.6	--	--
fill	115-155	107.6	0.59	4.4	--	--
fill	175-215	105.8	0.56	4.4	--	--
fill	225-265	102.0	0.59	3.9	--	--
fill	275-315	98.0	0.46	3.8	--	--
<u>Tuffs</u>						
Hard	344	0.7	0.00	0.1	--	--
Soft	158	2.0	0.00	0.2	--	--

sense, and skeletal grains are few, the comparison to the stages of soil carbonate accumulation suggest an inconsistency between the soil horizons and the fracture-fills. The fracture-fills exhibit a higher level of carbonate accumulation than do the soil horizons. One interpretation of this apparent inconsistency is that the fractures have been the site of pedogenic activity for a much longer period of time than have the soils. This interpretation would suggest that the soils observed at the present time do not represent the entire period of possible pedogenesis on the Tshirege member of the Bandelier Tuff (in theory, about 1.1 million years), and that some quantity of soil material has been removed from the plateau by erosion. In addition, it is possible that carbonate has tended not to accumulate in the soil horizons, but that it has been leached into the fractures and precipitated there. Precipitation might have been sufficient to leach carbonate from the soils but not to completely remove it from the system.

Organic Carbon

Organic carbon (O.C.) is below 1% in all but two of the samples from Area J (Table 4). In the F1 and F2 profiles, O.C. is at a maximum in the uppermost soil horizons (0.77% in F1, 0.74% in F2), and decreases downward. The minimum O.C. content occurs at the base of the soil zone and just above the fracture (0.24% in F1, 0.12% in F2). The O.C. in the fracture-fills then increases abruptly to levels near that of the A horizons (0.68% in F1, 0.62% in F2). In F1, the O.C. then decreases gradually with depth in the fracture. In F2, the O.C. in the fracture-fill remains relatively constant at near-surface levels (about 0.7%).

In fractures F4 and F5, O.C. is low at the surface (about 0.5%), and increases through the soil profile to a maximum value near the top of the fracture (1.21% in F4, 1.02% in F5). In F4, the O.C. in the fracture-fill gradually decreases with depth. In F5, the O.C. drops abruptly at the top of the fracture (0.31% at 55-75 cm), then rebounds to about the level of the A horizon (0.5%) and remains relatively constant with depth.

Cation Exchange Capacity

Cation exchange capacity (CEC) data are shown in Table 4. The average CEC for A horizons is 16.5 cmol/kg of soil. The average for Bt horizons is 37.5 cmol/kg of whole soil. For fracture-fill samples, F1 and F2 have much lower CEC values than did F4 and F5. The average CEC for F1 fill is only 14.1 cmol/kg soil. This low value reflects the relatively high CaCO_3 content of these samples. The average CEC for the F2 fill is 42.9 cmol/kg soil. The F4 fill samples have an average CEC of 69.3 cmol/kg soil. In F5 fill samples, the average CEC is 100.2 cmol/kg soil. Tuff samples have very low CEC values; 0.7 and 2.0 cmol/kg for unweathered and weathered tuff, respectively.

Clay fraction CEC data for selected samples are shown in Table 5. The average CEC for A horizon clays is 73.6 cmol/kg clay. The average CEC for Bt horizons is 108.0 cmol/kg clay. Fracture-fill clays have an average CEC of 103.1 cmol/kg clay. The Wyoming bentonite analyzed with the clay samples has a CEC of 106.2 cmol/kg, suggesting that the mineralogy of the clays in the fractures is similar to that of the Wyoming bentonite (montmorillonite).

While average values are consistent with a montmorillonitic composition for the clays, a few samples had significantly higher CEC values (148 cmol/kg maximum). These high values may be due partly to contributions from amorphous materials, which are probably present in most of the clay samples. Alternatively, leaching of Na from clay-sized grains of albite ($\text{NaAlSi}_3\text{O}_8$) during the CEC analysis could result in erroneously high values. No satisfactory explanation for the high CEC values is apparent at the present time.

Table 5. Cation exchange capacity (CEC) of clays from selected horizons.

Horizon	Depth	CEC
	cm	cmol/kg
<u>F1 profile</u>		
A	0-9	75.6
Bt	19-26	80.3
Bt (fine)	19-26	129.5
Bt (coarse)	19-26	105.7
fill	85-95	133.3
<u>F2 profile</u>		
A	0-9	57.9
Bt1	9-36	84.4
<u>F4 profile</u>		
A1	0-7	50.9
Bt3	42-55	86.9
fill	155-165	70.7
fill	280-300	147.6
<u>F5 profile</u>		
A	0-7	109.9
Bt2	16-45	133.7
fill	320-360	60.8
Wyoming bentonite [†]		106.2

[†] Montmorillonite No. 26, Clay Spur, Wyoming; American Petroleum Institute, 1949.

The high CEC values of most of the fracture fill samples have implications for contaminant transport through the fractures. If contaminants were to enter the fractures in percolating water, it is likely that many waste constituents would be adsorbed by the clay particles. This applies primarily to cationic constituents, however, and anionic constituents would be more likely to be repelled and thus transported due to the high negative charge on the clays.

Micromorphology

Micromorphological data are presented in Table 6. This table includes fabric descriptions according to Brewer (1964) and related distribution terms of Bullock et al. (1985). Because thin sections containing tuff and fracture-fill consist of two very different materials, the decision was made to treat the tuff and the fill material as separate fabrics. The alternative was to treat these samples as single entities, with the fracture seen as a void in the overall fabric. In this case, the fracture-fill material would be considered plasma separations associated with voids, and the fabric would almost invariably be vosepic plasmic (Brewer, 1964). This approach would reduce the amount of information conveyed by the fabric classification. Describing the fill as a separate fabric allows for variations in this material to be included as part of the fabric data.

Soil Horizons

Soil A horizons have insepic or skel-mosepic fabrics (Figure 9). The matrix consists of sand- and silt-sized grains of sanidine, cristobalite, and quartz, with minor amounts of glass shards, spherulites, and plagioclase. Clay is present in these horizons

Table 6. Micromorphological properties of soils, tuffs, and fracture fills from Area J, TA-54.

Thin section	Fabric	Argillan		Location(s) [†]	Feldspar Weathering	Related Distribution
		Orientation	Thickness			
F1 (tuff)	crystic	--	--	--	low	porphyric
F1 (fill)	insepic	--	--	--	low-moderate	porphyric
F1 88-98 A (tuff)	mosepic	--	--	--	low-moderate	porphyric
(fill)	omnisepic	high	thick	Ch, M	low-moderate	porphyric
F1 88-98 B (tuff)	vosepic	low	thin	Ch	moderate	porphyric
F1 88-98 C (fill)	silasepic	high	thick	Ch, M	low	open porphyric
F1 133 (fill)	silasepic	--	--	--	high	porphyric
F1 170-180 A (tuff)	crystic	--	--	--	low	porphyric
(fill)	silasepic	--	--	--	low	porphyric
F1 170-180 B (tuff)	crystic	--	--	--	low-moderate	porphyric
(fill)	insepic	--	--	--	low-moderate	open porphyric
F1 220-230 (tuff)	crystic	--	--	--	moderate	porphyric
F1 220-230 B (tuff)	crystic	--	--	--	low	porphyric

Table 6, cont.

Thin section	Fabric	Argillan			Feldspar Weathering	Related Distribution
		Orientation	Thickness	Location(s) [†]		
	(fill)	silasepic	--	--	low	porphyric
F1 260-270 (tuff)	crystic	--	--	--	moderate	porphyric
	(fill)	silasepic	--	--	low	porphyric
F2 A	skel-mosepic	moderate	thin	G,M	moderate	porphyric
F2 Bt1	mosepic	moderate	thin	M	high	porphyric
F2 Bt2	omnisepic	moderate	thin	M	moderate-high	porphyric
F2 Bk/Cr1	omnisepic	moderate	thick	M	moderate	porphyric
F2 116-126 A	insepic	--	--	--	moderate	porphyric
F2 116-126 C	insepic	--	--	--	moderate	porphyric
F2 142-152 (tuff)	insepic	--	--	--	moderate	porphyric
	(fill)	skel-mosepic	high	thin	Ch, G, M	moderate
F2 175-185 (tuff)	crystic	--	--	--	moderate	porphyric
	(fill)	high	very thick	Ch, G, M	moderate	porphyric

Table 6, cont.

Thin section	Fabric	Argillan		Location(s) [†]	Feldspar Weathering	Related Distribution
		Orientation	Thickness			
F2 212-222 (tuff)	crystic	--	--	--	low-moderate	porphyric
(fill)	skel-masepic	very high	very thick	G, M	moderate	porphyric
F2 212-222 B	skel-masepic	very high	thick	Ch, P, G	low-moderate	porphyric
F2 266-276 (tuff)	crystic	--	--	--	low-moderate	porphyric
(fill)	skel-masepic	very high	very thick	Ch, G, M	low-moderate	porphyric/chitonic
F2 305-315 (tuff)	vo-masepic	high	thin	P, M	low	porphyric
(fill)	omnisepic	very high	very thick	Ch, G, M	low-moderate	porphyric
F3 604-615 A (tuff)	crystic	--	--	--	moderate	porphyric
(fill)	omnisepic	very high	very thick	fracture	--	monic
F3 604-605 B (tuff)	crystic	--	--	--	moderate	porphyric
(fill)	omnisepic	very high	very thick	fracture	--	monic
F4 A1	insepic	low	thin	P	moderate-high	porphyric
F4 Bt1	omnisepic	high	thick	G, M	low	porphyric

Table 6, cont.

Thin section	Fabric	Argillan		Location(s) [†]	Feldspar Weathering	Related Distribution
		Orientation	Thickness			
F4 Bt2	skel-masepic	high	thick	G, M	moderate-high	porphyric
F4 194-198 (fill)	omnisepic	very high	very thick	fracture	--	monic
F4 244-264 A (tuff)	vosepic	low	thin	P	high	porphyric
(fill)	omnisepic	very high	very thick	fracture	moderate	monic
F4 244-264 B (tuff)	vosepic	very high	thick	Ch, P	moderate-high	porphyric
F4 288-298 (tuff)	crystic	--	--	--	low-moderate	porphyric
(fill)	omnisepic	very high	very thick	fracture	low-moderate	monic
F4 405-415 (tuff)	crystic	--	--	--	high	porphyric
(fill)	omnisepic	very high	very thick	fracture	--	monic
F4 519-526 A (tuff)	crystic	--	--	--	low-moderate	porphyric
(fill)	omnisepic	very high	very thick	fracture	--	monic
F4 519-526 (tuff)	vosepic	low	thin	P	moderate	porphyric
(fill)	omnisepic	very high	thick	fracture	--	monic

Table 6, cont.

Thin section	Fabric	Argillan		Location(s) [†]	Feldspar Weathering	Related Distribution
		Orientation	Thickness			
F5 371-381 A (tuff) (fill)	vosepic	low	thin	P	low-moderate	porphyric
	omnisepic	very high	very thick	fracture	--	monic
F5 371-381 B (tuff) (fill)	crystic	--	--	--	low-moderate	porphyric
	omnisepic	very high	very thick	fracture	--	monic

[†] P = pores; G = skeletal grains; M = matrix; Ch = channels; Sh = glass shards

Figure 9. Photomicrograph of A horizon (TA-69 profile). Insepic plasmic fabric, showing spherulite and sanidine grains. Width of photo = 3.5 mm.

as isolated domains in the matrix, and as occasional weakly developed argillans on skeletal grains. Feldspar grains show moderate to high degrees of weathering.

Bt horizons have omnisepic, skel-vosepic, mosepic, or skel-masepic fabrics (Figure 10). Argillans have moderate to high orientation, range from thin to thick, and are located in the matrix and as coatings on skeletal grains. In a few locations within horizons with omnisepic fabrics, isolated domains of lattisepic fabric are present.

Cr/Bt horizons have omnisepic or skel-vosepic fabrics (Figure 11). Strongly oriented clay is present as channel fillings and thick coatings on skeletal grains. Pumice fragments and spherulites are common, and also are coated with clay. The related distribution pattern is mostly porphyric, with domains of a chitonic pattern.

Tuffs

The tuff portions of most samples consist of grains of sanidine, glass shards, cristobalite and/or tridymite, quartz, and occasional hornblende and plagioclase (Figure 12). Pumice fragments are also present in many of the tuffs. Very little clay or calcite is present in the tuff of most samples. Several of the thin sections show clay lining pores and coating grains near the fracture walls. This clay shows strong orientation, but both the degree of orientation and the quantity of clay decrease sharply within a few mm of the fracture wall. Some tuffs show isolated patches of what is believed to be clay formed *in situ*. These patches are most commonly associated with glass shards (Figure 13).

Where clay is present in the tuff, the fabric is mainly insepic, but occasionally is weakly mosepic, vosepic, or vo-masepic (Brewer, 1964). Feldspars typically show low to moderate weathering, and overgrowths on these grains are common. The related distribution pattern in the tuffs is porphyric (Bullock et al., 1985) in all cases.

Figure 10. Photomicrograph of Bt2 horizon (F4 profile).
Omnisepic plasmic fabric, root with probable silica
replacement. Width of photo = 3.5 mm.

Figure 11. Photomicrograph of BC horizon (TA-69 profile).
Omnisepic plasmic fabric. Width of photo = 7 mm.

Figure 12. Tuff portion of F4 fracture-fill sample. Crystic fabric; sanidine grains, glass shards. Bubble-wall shard partially filled with tridymite. Width of photo = 1.4 mm.

Figure 13. Tuff from F2 (212-222 cm), with possible *in situ* clay formation. Width of photo = 1.4 mm.

Bubble-wall shards (Ross and Smith, 1961; Khoury and Eberl, 1979) are a common feature in many of the tuffs. These shards are often filled with what appears to be crystals of tridymite (Figure 12), based on the wedge-shaped form of the crystals (MacKenzie and Guilford, 1980; Deer et al., 1966).

Fracture-fills

Two main types of fracture-fills were observed in thin section: those dominated by clay, and those dominated by calcite. Complex combinations of these two materials were observed, but in these cases either clay or calcite is dominant in quantity. Thin sections from F1 contain predominantly calcite fills, while F2, F3, F4, and F5 fills consist of clay with variable, but lesser, amounts of calcite.

Fracture-fill fabrics are most often omnisepic plasmic, but some are insepic, masepic, skel-masepic, or crystic. Insepic, masepic, and crystic fabrics occur in F1 and F2 fracture-fills. In F1, crystic fabrics are associated with essentially pure calcite fill material. Plasma separations are not apparent, and the calcite has a flecked extinction pattern (Brewer, 1964). The calcite fill occasionally contains isolated patches or elongated zones of clay, and in these cases the fabric is insepic or masepic.

Where clay is the predominant fill material, the typical fabric is omnisepic plasmic (Figure 14). This term is used to describe cases where large quantities of clay are arranged in parallel laminae or in sand-sized aggregates with internal laminations. An alternative classification for this fabric is argillasepic. This classification would be more accurate if the clay laminae and aggregates were not viewed as plasma separations, but merely as plasma aggregates. Since these aggregates also essentially make up the matrix of the fracture-fills, it can be argued that they are not plasma separations. From this perspective, argillasepic plasmic is the appropriate fabric class for these materials. However, the presence of clay as coatings on fracture walls, as

Figure 14. Clay fracture-fill from F3 (371-381 cm).
Omnisepic plasmic fabric. Width of photo = 7 mm.

independent aggregates, and as argillans on some matrix grains, suggests that these accumulations are not mere aggregates but plasma separations created by processes similar to those that create a more typical argillic horizon. Therefore omnisepic plasmic is considered to be more accurately descriptive of these fracture-fill fabrics.

Feldspar grains, where present in the fracture-fills, are characterized by low to moderate weathering. The related distribution pattern is porphyric to open porphyric, with one case of porphyric/chitonic (Bullock et al., 1985), when feldspar grains are present. When these larger grains are not present in the fracture-fills, the related distribution pattern is monic.

Argillans, where present, are associated primarily with channels, glass shards, and other skeletal grains, but also occur as pore coatings (other than channels) and as elongated zones within the matrix. The thickest and most highly oriented argillans are associated with channels, including the actual fractures.

Clays in the F4 and F5 fracture-fills exhibit an extremely high degree of orientation. These highly oriented clays occur as coatings on the fracture walls (Figure 15), as aggregates in the interior of fractures (Figure 14), and as apparent flow structures (Figure 16). It is probable that some of the aggregates in fracture interiors are the result of disruption of clay laminae due to shrinkage and disturbance after exposure of the fractures by excavation of the pits.

Figure 16 presents additional evidence for the deposition of the clays by water. This photo shows flow structures in the clay of the F3 fracture-fill, at a depth of 6 m. These flow structures consist of concave-upward sets of alternating light and dark clay laminae. One sequence of clay laminae can be seen to be truncated and overlain by another set of laminae with a different orientation. This is essentially a micro-unconformity, recording multiple episodes of clay deposition.

Figure 15. Highly oriented clay coating fracture wall in F4 (288-298 cm). Width of photo = 1.4 mm.

Figure 16. Flow structures in clay fracture-fill from F3 (604-615 cm), with micro-unconformity. Width of photo = 3.5 mm.

Fracture-fill clays commonly exhibit 2nd- and 3rd-order interference colors, and in many cases optic axis interference figures are observable. These figures indicate that the clays are biaxial negative, with a fairly small $2V_x$ (about 20° to 30°). This is consistent with most smectites and possibly illite, although illite usually has $2V_x < 10^\circ$ (Phillips and Griffen, 1981; Deer et al., 1966).

Where clay and CaCO_3 are present together, the CaCO_3 is commonly seen filling the space between larger clay aggregates (Figure 17). Where multiple laminae of clay and CaCO_3 are present, a clay layer is most often immediately adjacent to the fracture wall (Figure 18). In the case of F1 fracture-fill, clay is present as occasional thin stringers within a carbonate matrix (Figure 19). These stringers also show a very high degree of orientation, parallel to the fracture walls. Clay and carbonate do not occur in a finely intermixed condition. The fills everywhere consist of distinct domains of clay and of carbonate.

The calcite in fracture-fills is microcrystalline, and commonly exhibits laminae similar to those often observed in pedogenic calcic horizons or calcretes (Figure 20). These laminae are typically oriented parallel to the fracture walls.

The strong optic orientation of the clays in the fracture fills is indicative of illuviated clay (Brewer, 1964; Graham et al., 1994). Graham et al. (1994) state that "weathered rocks that contain illuvial clay often underlie soils that have argillic horizons developed under conditions of prolonged geomorphic stability." Where these rocks underlie relatively weakly developed soils, they add, the illuviated clay may be relict from a more stable soil-geomorphic condition.

The relationship between the clay and the carbonate suggests distinct periods of emplacement of the two materials. The purity of the domains of clay and of carbonate indicate that the clay the carbonate probably did not precipitate from the same water that deposited the clay. This situation is similar to the argillans coated by calcareous

Figure 17. Upper: Calcite filling spaces between clay aggregates (F4, 244-264 cm). Width of photo = 1.4 mm.
Lower: Same as upper photo, Width of photo = 0.35 mm.

Figure 18. Clay and carbonate fracture-fill from F4 (244-264 cm).
Clay lines the fracture wall. Width of photo = 3.5 mm.

Figure 19. Highly oriented clay stringers within calcite fracture-fill (F1, 88-98 cm). Width of photo = 3.5 mm.

Figure 20. Laminar carbonate fracture-fill from F1 (220-230 cm).
Width of photo = 3.5 mm.

(CaCO_3 coatings) reported by Ransom and Bidwell (1990). The authors cited this relationship as conclusive evidence that clay illuviation preceeded the carbonate accumulation. It is clear in the fracture fills that carbonate was precipitated in minute spaces between much larger clay aggregates, and as carbonate coatings on thick argillans that line fracture walls. The geologic principles of superposition and cross-cutting relationships (Krumbein and Sloss, 1963), applied on a microscopic scale, make it clear that in most of the fracture-fills, clay illuviation preceeded carbonate precipitation and accumulation.

It would appear, based on field observations and on micromorphology, that illuvial clay filled the fractures, in large part, before carbonate accumulation began. The carbonate apparently then filled shrinkage cracks in the clay fill. Field observations indicate that the clay fill cracks readily when dried in pit exposures, but the presence of carbonate in shrinkage cracks would require episodic drying of the clay fill to depths of several meters. Once the clay had dried sufficiently to crack, percolating water containing dissolved carbonate or Ca ions leached from the soil could move rapidly into the fractures, rewetting the clay. As the clay became wet, it would tend to swell and close the cracks, reducing permeability and slowing or stopping the percolation of water. As conditions returned to a drier state after the rain or snow event, the water in the fractures and the soils would tend to be removed by transpiring vegetation, precipitating CaCO_3 in the cracks of the drying clay.

The model of fracture filling described here does not relate well to the material of the F1 fracture-fill. The scarcity of clay in this fracture suggests that during the time when most of the fractures were receiving illuvial clay, it (and other fractures in the immediate vicinity) was either not receiving, or not accumulating, clay. It seems unlikely that, if clay was being transported into this fracture, it would not retain some

portion of it as fracture-fill. It is more probable that clay did not move into the fracture in any appreciable amount. The reason for a lack of clay translocation is not clear.

Mineralogy

Mineral grain counts were performed on the very fine sand fraction (50 to 100 μm) of selected soil horizons. The results of these counts are shown in Table 7.

Quartz, alkali feldspars, and tridymite/cristobalite are the dominant minerals, with minor amounts of glass, hornblende, plagioclase feldspars, and opaque grains present. In each of the soil horizons analyzed, quartz is more abundant than in unweathered tuff. Quartz is more abundant in A horizons than in Bt horizons. Glass shards are also more abundant in the soils than in unweathered tuff, but are more abundant in Bt horizons than in A horizons. Alkali feldspars are more abundant in A horizons than in Bt horizons, and the percentages of these minerals in the Bt horizons is similar to the percentage in unweathered tuff. Tridymite/cristobalite is much less abundant in soil horizons than in the tuff, and is significantly less abundant in A horizons than in Bt horizons. Hornblende, plagioclase feldspars, and opaque grains do not vary significantly among the soil horizons and the unweathered tuff.

Minerals observed in very low numbers in all horizons include hypersthene, augite, rutile, and tourmaline.

X-ray Diffraction

Powder Samples

X-ray diffractograms from powder samples of both unweathered and weathered Bandelier Tuff (Figure 21) correlate well with published d-spacings (Joint Committee on Powder Diffraction Standards[†], 1974) of sanidine and tridymite, as shown in Table

[†] Hereinafter referred to as JCPDS.

Table 7. Mineral composition of very fine sand from selected horizons.

Horizon	Quartz	Alkali Feldspar	Tridymite/ Cristobalite	Glass	Hornblende	Opaque	Plag.
	%						
F1 A	26	49	9	11	1	1	1
F1 Bt	24	33	24	16	1	1	1
F2 A	44	40	6	7	1	1	1
F2 Bt1	25	37	23	11	1	1	1
F4 A1	34	45	10	7	1	2	1
F4 Bt2	27	36	24	9	1	3	1
Hard tuff	7	38	53	1	1	1	--

Figure 21. X-ray powder diffractograms of unweathered and weathered tuff.

8. It should be noted that the peaks observed correlate well with tridymite d-spacings, but are not inconsistent with those of cristobalite (JCPDS card no. 11-695, 1974; Drees et al., 1989). Moreover, this pattern is similar to that attributed to opal C-T by Vaniman et al. (1988). Since both tridymite and cristobalite have been observed in thin sections, often in close association with each other, references to the mineral(s) represented by the diffractogram peaks listed for tridymite in Table 8 will be to "tridymite/cristobalite."

Little difference was detected between the patterns of unweathered and weathered tuff, except that some peak intensities decrease slightly while some others increase. In the unweathered tuff pattern, the sanidine peak at 0.32 nm is the most intense peak, followed by the tridymite/cristobalite peak at 0.41 nm. In the weathered tuff pattern, this is reversed, with the 0.41-nm peak the most intense. No peaks were observed corresponding to the common phyllosilicates, such as smectites (1.4 nm), micas or illite (1.0 nm), or kaolinite (0.71 nm). It is possible that these minerals are present in these samples in small quantities (clay content is 4.4% and 8.0% for unweathered and weathered tuff, respectively), and that the random packing used for powder analysis resulted in the peaks being too weak to be detected. Quartz is present in relatively small quantities in both samples, as shown by relatively weak peaks at 0.33 nm and 0.43 nm (Drees et al., 1989).

The very fine sand fractions (50-100 μm) of the Bk/Cr2 and Cr horizons of profile F2 were analyzed in powder form, and show essentially the same assemblage of minerals as do the unweathered and weathered tuff samples. Sanidine and tridymite/cristobalite are again the predominant minerals. Only slight differences in peak intensities were detected among these four patterns.

When powder patterns from very fine sands of the F1, F2, and F5 A horizons are compared to both unweathered and weathered tuffs (Figure 22), it is apparent that all of

Table 8. Comparison of observed d-spacings from powder diffractograms of unweathered and weathered tuff with published values for sanidine and tridymite.

Sanidine		Tridymite	
Observed	JCPDS [†] , 1974 card no. 19-1227	Observed	JCPDS, 1974 card no. 18-1170
6.49	6.50	4.31	4.328 [§]
5.83	5.83	4.23	4.236
3.79	3.76	4.09 [‡]	4.107 [‡]
3.46	3.45	3.81	3.818
3.28	3.27, 3.26 [‡]	3.46	3.461
3.22 [‡]	3.22 [§]	2.99 [§]	2.975
2.99	2.976	2.77	2.776
2.58	2.56	2.31	2.308
2.42	2.416	2.08	2.086
2.17	2.167		
1.79	1.791	[‡] = most intense peak	
1.49	1.493	[§] = second most intense peak	

[†] Joint Commission on Powder Diffraction Standards

Figure 22. X-ray diffractograms of A horizon very fine sand fractions.

Figure 23. X-ray diffractograms of Bt horizon very fine sand fractions.

the peaks due to quartz (0.43, 0.33, 0.25, 0.18, and 0.15 nm) increase in relative intensity. In addition, those peaks due to sanidine and tridymite/cristobalite (0.41, 0.38, 0.32, 0.30 and 0.29 nm) decrease in relative intensity. The same is true for Bt horizons of these profiles (Figure 23), with the exception of the 0.41-nm peak in the F1 Bt pattern. The F1 Cr/Bt pattern shows the same increase in quartz and decreases in sanidine and tridymite/cristobalite.

Oriented clay samples

The oriented total clay fraction of unweathered tuff shows essentially the same mineral assemblage as the whole (powder) sample. Tridymite/cristobalite is predominant, with sanidine and a small quantity of quartz also present (Figure 24). The pattern does not indicate the presence of phyllosilicate clays.

The weathered tuff pattern, however, shows the presence of at least three species of phyllosilicate clay minerals (Figure 24). The presence of a broad peak at about 1.8 nm indicates the presence of smectite. Less intense peaks at 1.0 and 0.71 nm indicate that illite and kaolinite are also present in this sample. Also present are tridymite/cristobalite and sanidine, as in the unweathered tuff. The sanidine appears to be somewhat less abundant in the clay from the weathered tuff than from the unweathered tuff, as evidenced by peaks with diminished intensity, especially the peak at 0.64 nm.

F1. X-ray diffractograms of the total clay from F1 horizons are shown in Figure 25a. All of the horizons clearly show the presence of smectite, with a peak at 1.6 nm in Ca-saturated, glycerol-solvated samples. This peak is fairly broad and of moderate intensity in the A horizon. The peak becomes more intense and somewhat less broad in the BA and Bt horizons. In the fracture-fill samples, the smectite peak is

Figure 24. X-ray diffractograms of oriented total clay from unweathered and weathered tuff.

Figure 25. X-ray diffractograms of total clay from F1. a. Soil horizons.

Figure 25, cont. b. Fracture-fills.

very intense and well-defined (Figure 25b). The 1.6-nm peak collapses to 1.0 nm with K-saturation, further confirming the interpretation of this clay as smectite.

All F1 clay samples contain illite, indicated by a peak at 1.0 nm. For Ca-saturated samples, this peak is most prominent in the A horizon (the peak is enhanced in K-saturated and heat-treated samples by the collapse of smectite to 1.0 nm). The illite peak is of moderate intensity in the soil horizons, but becomes broad and less intense in the fracture-fill samples.

Kaolinite is indicated by the presence of a peak at 0.71 nm in all F1 samples. The second-order kaolinite peak at 0.36 nm is, in all samples, significantly more intense than the first-order peak. Both the 0.71 and 0.36 nm peaks disappear upon heating of the samples to 550°C, confirming that these peaks are due to kaolinite. The kaolinite peaks change little with depth.

In addition to smectite, illite, and kaolinite, tridymite/cristobalite and sanidine are present, particularly in the A and BA horizons. The 0.64-nm 011 peak of sanidine occurs throughout the profile, while the 0.41-nm tridymite/cristobalite peak is fairly prominent in the A and BA samples but diminishes in the Bt horizon and below. The strong 0.33-nm peak is probably due only partly to quartz, since the 0.43-nm peak (100 of quartz) is either not observed or is relatively weak. The 0.33 nm peak probably corresponds also to third-order (003) illite plus the 220 and 202 peaks of sanidine (JCPDS card no. 19-1227, 1974).

E2. The F2 total clay samples contain smectite (1.6 to 1.8 nm), illite (1.0 nm), and kaolinite (0.71 nm) throughout the profile (Figure 26a,b). Smectite again appears to be more abundant in the fracture-fill than in the soil horizons. The illite peak is intense in the A horizon, and is very weak in the fracture-fill. Kaolinite also appears to be decreasing in quantity and/or crystallinity with depth, presenting only weak 0.71- and 0.36-nm peaks on the 250-270 cm pattern. Sanidine appears sporadically in all the

Figure 26. X-ray diffractograms of total clay from F2. (a) soil horizons.

Figure 26, cont. (b) fracture fill.

F2 clays. The 0.32-nm peak is moderately intense on all patterns, but the 0.64-nm peak is very weak with the exception of the Bk/Cr2 horizon, where it is unusually intense.

Tridymite/cristobalite is present in all samples, although the peaks are very weak on the 250-270 cm fracture-fill pattern. Tridymite/cristobalite is present in all samples, although the peaks are very weak on the fracture-fill pattern from 250-270 cm.

E4. Smectite is very abundant in the F4 total clay samples (Figure 27a,b). The d-spacing on these diffractograms range from 1.52 to 1.88 nm. This variability may be due to differences in the degree of glycerol solvation achieved with these oriented samples, or to variable interstratification of the smectite with illite. Where the observed d-spacing is lowest (Bt1 and 420-440-cm fill), the smectite peak merges into the 1.0 nm illite peak. This fact suggests that the variability in smectite d-spacing is due to interstratification. The smectite peak is broadest and least intense in the A1 and A2 horizons, and is very intense in all horizons and fracture-fills below the A2.

The illite peak at 1.0 nm again is sharpest and most intense in the uppermost horizon (A1), becoming broad and weak with depth. The kaolinite peak at 0.71 nm also decreases in intensity with depth, although it remains very sharp throughout. Sanidine and tridymite/cristobalite appear only in the A1 and A2 horizons (Figure 27a), and possibly the 420-440 cm fill sample (Figure 27b).

E5. Clays of F5 contain smectite, illite, and kaolinite, as well as sanidine and tridymite/cristobalite (Figure 28). Smectite in the A horizon is segregated almost completely in the fine clay (< 0.2 μm). The approximate d-spacing of this broad peak is 1.90 nm. In the Bt1 horizon, the smectite peak is somewhat better defined, with a d-spacing of about 1.85 nm. Here also the smectite is almost entirely in the fine clay fraction. In the 320-360 cm fracture-fill sample, smectite appears to be virtually equally abundant in the fine and coarse clay (0.2 - 2 μm) fractions. This apparent distribution

Figure 27. X-ray diffractograms of total clay from F4. (a) soil horizons.

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Figure 27, cont. (b) fracture-fills.

Figure 28. X-ray diffractograms of whole, fine, and coarse clay from F5 soil horizons and fracture-fill.

pattern may be due to poor separation into fine and coarse clay subfractions, or to aggregation of the clay. This peak is very intense and well-defined at 1.80 nm.

Illite appears as a sharp, moderately-intense peak at 1.0 nm in the A horizon, although the peak is somewhat broader in the fine clay fraction of this sample. In the Bt1 horizon and 320-360 cm fill samples, the illite peak is fairly broad, and slopes into the kaolinite peak at 0.71 nm.

Sanidine and tridymite/cristobalite are present primarily in the coarse clay fraction of the A and Bt1 horizons. These minerals do not appear in either the fine or coarse clay in the 320-360 cm fracture-fill sample.

The clay mineralogy of soil and fracture-fill samples is in general dominated by smectite. However, smectite tends to be much more abundant deeper in the soil profiles and in the fractures. The smectite peaks at depth are also typically sharper or better defined than those in near-surface horizons. Smectite in near-surface samples is concentrated almost completely in the fine clay fraction. However, in the fracture-fill samples, smectite is typically very abundant in both the fine and coarse clay fractions.

Illite, in contrast to smectite, is most abundant and produces the sharpest peaks in surface horizons, and diminishes steadily with depth. There is some suggestion of illite/smectite interstratification in some samples. Illite tends to be concentrated in the coarse clay of most soils (Fanning et al., 1989), but that tendency is only weakly expressed in these samples.

Kaolinite is the more constant than smectite and illite in terms of abundance and sharpness of peaks. There is a slight tendency for kaolinite to be less abundant at depth in the fractures, but the peaks remain sharp even in these cases. Kaolinite is usually more abundant in the coarse clay than in the fine clay.

Weathering tends to progress rapidly in volcanic rocks, the abundance of amorphous material facilitating hydrolysis (Chamley, 1989). Smectites in particular are

considered to form readily in volcanic rocks under a range of environmental conditions. A high Si content and high basic cation potentials are considered necessary for the formation and/or preservation of smectite (Borchardt, 1989). These requirements are met in a rhyolitic tuff under semiarid conditions. The neogenesis, or precipitation from solution, of smectites in well-drained volcanic ash has been a topic of debate, since the presence of biotite or other smectite precursors must be ruled out to prove neogenesis (Borchardt, 1989). Only very small traces of weathered biotite have been detected in mineral grain counts, and it has not been detected by XRD analysis or electron microscopy. The possibility exists that eolian material added to the soils included biotite which has since completely transformed to smectite, or that smectite itself was present in dust additions. However, the presence of smectite in slightly weathered tuff which was probably completely isolated from eolian and illuvial materials argues strongly that the smectite in this tuff is neogenetic. The presence of smectite in the fracture-fills is not surprising, given that poorly drained bedrock fissures are a typical environment for the formation and preservation of smectite (Borchardt, 1989). The strongly smectitic mineralogy of the fracture-fills suggests that the fractures are poorly drained, with a concomitant retention of Si and basic cations providing favorable conditions for smectite.

Kaolinite is a widespread soil clay mineral (Allen and Hajek, 1989), possibly due to its formation from a wide variety of minerals (Dixon, 1989). The stability field of kaolinite has been shown to intersect those of K-feldspars and amorphous silica (Garrels and Christ, 1965), both of which are present in the Bandelier Tuff. In addition, kaolinite is considered a relatively stable mineral in a variety of environments (Birkeland, 1984; Dixon, 1989). The presence of a small amount of kaolinite in most of the clay samples from the soils and fracture-fills is consistent, therefore, with the parent material and the present environment on the Pajarito Plateau.

The presence of illite in weathered tuff is somewhat problematic, because no muscovite or other likely precursor minerals were detected in thin sections, grain mounts, or in XRD patterns of unweathered tuff. A few clay-sized grains of mica were, however, detected in the unweathered tuff by electron microscopy in conjunction with energy-dispersive x-ray analysis. Because the strongest expression of the illite XRD peak is typically in A horizons, it is possible that illite has been added to the soils by eolian inputs at the surface. There is also some possibility that illite is forming by the fixation of K by smectites near the surface (Fanning et al., 1989). This mechanism for illitization of smectite or other expansible 2:1 minerals in response to elevated K levels caused by plant cycling has been proposed, but never adequately proven.

CHAPTER V

CONCLUSIONS

Properties of the soils and fracture-fills at Area J indicate that translocation of clay has been an important process in their formation. Argillic horizons are evidence of clay illuviation in the soil profiles. Micromorphological features and mineralogy indicate that illuviation is also responsible for most of the fracture-fills.

It is clear that the soils of the study area have developed mostly from the Bandelier Tuff. The presence of volcanic features such as spherulites, glass shards, and pumice fragments indicate that the present surface horizons of the soils have been strongly influenced by the tuff. Tridymite and cristobalite, found in abundance in the tuff, comprise up to 10 % of soil A horizons. It appears certain that the soils are formed in tuffaceous material. It is possible that a portion of the parent material of these soils was not massive tuff weathering in place, but was alluvium or colluvium derived from Bandelier tuff. However, the relatively fresh appearance of glass shards and spherulites in A horizons suggests that little or no transport of these particles has taken place.

While the presence of volcanic particles in the surface horizons establishes the tuffaceous nature of the parent material of these soils, the mineralogical composition of A and B horizons suggests that additional material has been added from another source. The increases in quartz and alkali feldspars in the very fine sand fraction of the soils relative to unweathered tuff is probably due to eolian dust inputs. If this is the case, the corresponding decreases in the amounts of tridymite and cristobalite in the soils may be only relative decreases rather than due to weathering of these minerals. The differential in glass contents between the tuff and the soils could be a result of decreasing particle size of the glass shards during pedogenesis. The unweathered tuff contains shards in a wide range of particle sizes, only a small portion of which may be in the very fine sand

range. The larger percentage of glass in soil horizons may represent formerly larger shards which have weathered into the very fine sand size range. Some of the shards in the soils, however, exhibit a morphology that suggests an extraneous source.

The mineralogy of clays in weathered tuff is similar to the clay mineralogy of most of the fracture-fills, consisting of smectite, illite, and kaolinite. This similarity allows for the possibility that the fracture-fill clays are derived totally from weathering of the tuff, and eolian inputs are not necessary to explain the fracture-fill mineralogy. Nevertheless, the possibility that some of the clay in the fractures was eolian in origin cannot be ruled out.

Whether the clay was derived from the tuff or was deposited at the surface by wind, it is very clear that the clay was deposited in the fractures by translocation (illuviation). The microscopic form of most of the clay fracture-fills is incompatible with an origin by *in situ* formation. The high degree of orientation and alignment parallel to the fracture walls, as well as abundant flow structures, shows that the clays were carried into the fractures by percolating water. Similarities in mineralogy and color between soil clay and fracture-fill clay suggest that the clay was moved out of the surface soil horizons into the fractures. The fracture-fills do contain occasional inclusions of tuff fragments and quartz and sanidine grains, but these were probably deposited into the fractures from above or sloughed off the fracture walls. These inclusions are not sufficient evidence for *in situ* formation of the fracture-fills.

In most cases where clay and CaCO_3 coexist in fracture-fills, the clay is adjacent to the fracture walls. Using the principle of superposition, it is clear in these cases that the clay was deposited in the fracture before the CaCO_3 . This relationship appears to extend to fill material in the center portions of the fractures as well, where CaCO_3 is commonly seen filling minute spaces between laminae of clay. The most likely scenario to explain this relationship is that the fractures were initially filled in

large part by clay. After this initial filling took place, much of the remaining pore space was filled by the precipitation of CaCO_3 . The pores probably were created as shrinkage cracks during partial drying of the clay.

The precipitation of CaCO_3 from soil water is ubiquitous in arid and semiarid climates. If the interpreted sequence of fracture-filling is correct, it would appear that the initial clay filling took place in an environment in which the precipitation of CaCO_3 was not favored, namely a somewhat more humid environment. The CaCO_3 was precipitated at a later time under dryer climatic conditions. This scenario is compatible with known climatic changes in the Pleistocene, although the specific timeframe for these deposits is not known.

The primary exception to this clay- CaCO_3 relationship is the F1 fracture-fill, which contains very little clay in proportion to CaCO_3 . Where clay is present, it is typically as thin stringers engulfed in the CaCO_3 matrix. This is strikingly different from the other fracture-fills, and is even more striking due to the close proximity of these fractures to the more common clay-dominated fractures. There is no obvious explanation for the differences, other than that for some reason the fractures at and near F1 did not receive the initial influx of clay. Perhaps these fractures were originally below a slight topographic high which directed surface water away from them.

The clay mineralogy of the soils and fracture-fills provides some clues to the drainage conditions existing in the system. It is known that smectites are typically favored by slow-draining or restricted environments with relatively high pH, where basic cations are retained. Kaolinite and, to some extent, illite are favored by a more free-draining environment. The tendency in these deposits for smectite to be more abundant and to give better-defined XRD peaks in the deeper samples, especially in the fractures, suggests that drainage through the fracture-fills may be restricted. The fact

that kaolinite and illite are more abundant in the upper portions of the profiles indicates that drainage is not highly restricted in the near-surface soil horizons.

The presence of carbonate in apparent shrinkage cracks in clay fracture-fills indicates that the clay fill has dried to considerable depths, and that Ca-bearing water moved into those cracks. This wetting of the fracture-fills must have been followed by a drying period in order to precipitate carbonate. It is likely that this alternate wetting and drying was repeated many times, perhaps on a seasonal basis. While the presence of illuvial clay and precipitated carbonate show conclusively that water actively moved into the fractures in the past, these materials do not necessarily indicate that water is currently moving into the fractures (Graham et al., 1994). The presence of live plant roots deep in the fractures does, however, indicate that some water percolates into the fractures. Because plants take in water through their roots and release it to the atmosphere through transpiration, a finite and non-renewable quantity of water in the fractures would rapidly be depleted, and the plants would die. Live roots in the fractures show that water in the fractures is constantly being replenished. It is not known whether this water is coming from the surface by infiltration, or from the tuff. It is likely that the combined effects of growing roots and high shrink-swell clays will over time act to widen the existing fractures and/or fragment the tuff.

In summary, there is strong evidence that the soils of the study area were mostly derived from the Bandelier Tuff, either by weathering in place of massive tuff or by weathering of a surface veneer of unconsolidated alluvium or colluvium derived from the tuff. There is some evidence for eolian inputs of fine-grained quartz and feldspars, as well as exotic minerals such as hornblende and zircon. The clay in fracture-fills was deposited by translocation from above, not by *in situ* weathering of the tuff along fracture walls. This clay was probably pedogenically derived by the weathering of volcanic glass and feldspars in the tuff. The fractures were initially open and devoid of

fill, and clay was deposited on relatively fresh tuff on the fracture walls. The initial deposits in the fractures were virtually pure clay, with minor inclusions of mineral grains and fragments derived from the tuff. After the fractures were largely filled with clay, CaCO_3 was precipitated in shrinkage cracks and other remaining pore space by percolating water. The presence of CaCO_3 points to the likelihood that clay fill alone does not completely seal the fractures or preclude water movement through them.

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APPENDIX A
SOIL PROFILE DESCRIPTIONS AT AREA J, TA-54

F1 (Area J, southwest pit, north wall)

Classification: Fine-loamy, mixed, mesic Lithic Haplustalf

0 to 36 cm -- Spoil

A -- 0 to 9 cm, dark brown (7.5 YR 3/3 moist) loam; weak subangular blocky structure; many fine and medium roots; clear smooth boundary.

BA -- 9 to 19 cm, dark brown (7.5 YR 3/3 moist) loam; weak subangular blocky structure; many fine and medium roots; clear wavy boundary.

Bt -- 19 to 26 cm, dark brown (7.5 YR 3/4 moist) clay loam; moderate subangular blocky structure; thin discontinuous clay films on ped surfaces; many fine and medium roots; clear wavy boundary.

Cr/Bt -- 26 to 34 cm, brown to dark brown (7.5 YR 4/4 moist) clay loam; moderate subangular blocky structure; thin discontinuous clay films on ped surfaces and tuff fragments; many fine and common medium roots; abrupt wavy boundary.

Cr -- 34 to 260+ cm, moderately to slightly weathered tuff.

F2 (Area J, southwest pit, south wall)

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf

A -- 0 to 9 cm, dark brown (7.5 YR 3/3 moist) loam; weak subangular blocky and moderate granular structure; many fine and medium roots; clear smooth boundary.

Bt1 -- 9 to 36 cm, dark brown (7.5 YR 3/4 moist) clay loam; moderate subangular blocky structure; thin discontinuous clay films on ped surfaces; many fine and medium roots; gradual wavy boundary.

Bt2 -- 36 to 59 cm, dark brown (7.5 YR 3/4 moist) clay loam; moderate subangular blocky structure; thin discontinuous clay films on ped surfaces; common fine and medium roots; clear wavy boundary.

Bk/Cr1 -- 59 to 104 cm, brown to dark brown (7.5 YR 4/4 moist) sandy clay loam; weak subangular blocky structure; thin discontinuous clay films on ped surfaces; strong effervescence; common fine and medium roots; gradual wavy boundary.

Bk/Cr2 -- 104 to 125 cm, brown to dark brown (7.5 YR 4/4 moist) sandy clay loam; weak subangular blocky structure; nodules and films of CaCO₃; strong effervescence; few fine and medium roots; abrupt wavy boundary.
Cr -- 125 to 200+ cm, strongly weathered tuff; few fine and medium roots.

F4 (Area J, northwest pit, west end of north wall)

Classification: Fine, montmorillonitic, mesic Aridic Paleustalf

0 to 105 cm -- spoil

A1 -- 0 to 7 cm, dark brown (7.5 YR 3/3 moist) loam; granular to weak subangular blocky structure; many fine and medium roots; clear wavy boundary.

A2 -- 7 to 12 cm, dark brown (7.5 YR 3/3 moist) loam; weak subangular blocky structure; many fine and medium roots; clear wavy boundary.

Bt1 -- 12 to 31 cm, brown to dark brown (7.5 YR 4/4 moist) clay loam; moderate subangular blocky structure; thin discontinuous clay films on ped surfaces; many fine and medium roots; gradual wavy boundary.

Bt2 -- 31 to 42 cm, brown to dark brown (7.5 YR 4/4 moist) clay; moderate subangular blocky structure; thick continuous clay films on ped surfaces; common fine and medium roots; gradual wavy boundary.

Bt3 -- 42 to 55 cm, brown to dark brown (7.5 YR 4/4 moist) clay; moderate blocky structure; thick continuous clay films on ped surfaces; common fine and medium roots; abrupt wavy boundary.

Cr -- 55 to 400+ cm, moderately to slightly weathered tuff.

F5 (Area J, northwest pit, east end of north wall)

Classification: Fine, montmorillonitic, mesic Lithic Haplustalf

0 to 45 cm -- Spoil

A -- 0 to 7 cm, dark brown (7.5 YR 3/3 moist) loam; weak medium subangular blocky structure; firm dry consistence; few medium and fine roots; clear wavy boundary.

Bt1 -- 7 to 16 cm, dark reddish brown (5 YR 3/4 moist) clay; moderate medium subangular blocky structure; very firm dry consistence; thin discontinuous clay films on ped surfaces; common medium and fine roots; clear wavy boundary.

Bt2 -- 16 to 45 cm, dark reddish brown (5 YR 3/4 moist) clay; moderate medium blocky structure; very firm dry consistence; thick continuous clay films on ped surfaces; common medium and coarse roots; abrupt irregular boundary.

Cr -- 45 to 500+ cm, weathered tuff.

APPENDIX B
SUPPLEMENTAL SOIL PROFILE DESCRIPTIONS

TA-51. canopy

- OE -- 0 to 2 cm, very dark brown (10 YR 2/2), black (10 YR 2/1) moist; abrupt wavy boundary.
- A -- 2 to 7 cm, yellowish brown (10 YR 5/4) silt loam, dark yellowish brown (10 YR 3/4) moist; weak prismatic parting to weak granular structure; very friable moist, slightly hard dry; many medium and fine roots; abrupt wavy boundary.
- E/B -- 7 to 11 cm, pale brown (10 YR 6/3) loam, dark yellowish brown (10 YR 4/4) moist, and yellowish brown (10 YR 5/4) loam, dark brown (7.5 YR 3/4) moist; weak subangular blocky structure; friable moist, hard dry; many medium and fine roots; clear wavy boundary.
- Bt -- 11 to 23 cm, dark brown (7.5 YR 3/3) clay, dark brown (7.5 YR 3/4) moist; moderate subangular blocky structure; firm moist, very hard dry; common medium and few fine roots; gradual wavy boundary.
- Bt/Cr -- 23 to 32 cm, dark brown (7.5 YR 3/3) clay loam, dark brown (7.5 YR 3/4) moist, and brown (7.5 YR 5/4) weathered tuff, brown to dark brown (7.5 YR 4/4) moist; weak subangular blocky structure; firm moist, very hard dry; few fine roots; few segregations of CaCO₃ in lower part of horizon; slight effervescence; clear wavy boundary.
- Crk -- 32 to 40+ cm, weathered tuff with common irregular masses of CaCO₃; violent effervescence; very few fine roots.

TA-69. Ponderosa watershed site

- A -- 3 to 10 cm, grayish brown (10 YR 5/2) loam, dark brown (10 YR 3/3) moist; weak subangular blocky structure; very friable moist, soft dry; many fine and medium roots; clear wavy boundary.
- E -- 10 to 25 cm, very pale brown (10 YR 7/3) loam, brown to dark brown (10 YR 4/3) moist; weak platy structure; very friable moist, slightly hard dry; many fine and medium roots; clear wavy boundary.
- Note: The soil below the E horizon down to the observed depth (about 40 cm) consisted of a mixture of E and Bt horizons. The E portions were similar to the overlying E horizon, and the Bt portion was considerably more clayey (silty clay loam).

TA-51 trench, west end, under juniper

OA -- 0 to 2 cm, many fine and medium roots, abrupt wavy boundary.

A -- 2 to 8 cm, dark grayish brown (10 YR 4/2) silt loam, very dark grayish brown (10 YR 3/2) moist; weak subangular blocky structure; slightly firm moist; many fine and medium roots; clear wavy boundary.

E/Bt -- 8 to 14 cm, brown (10 YR 5/3) silt loam, dark brown (10 YR 3/3) moist; weak subangular blocky to weak platy structure; friable moist; common medium and few fine roots; clear wavy boundary.

Bt/E -- 14 to 26 cm, dark grayish brown (10 YR 4/2) silty clay loam, very dark grayish brown (10 YR 3/2) moist; weak subangular blocky to weak platy structure; firm moist; many medium and common fine roots; abrupt wavy boundary.

Crk -- 26 to 88 cm, brown to dark brown (7.5 YR 4/3) weathered tuff, dark brown (7.5 YR 3/3) moist; few medium and fine roots; common thin coatings of CaCO₃; violent effervescence; abrupt wavy boundary.

TA-63, Trench 1, 192 m

A -- 5 to 21 cm, dark yellowish brown (10 YR 3/4 moist) loam; weak subangular blocky structure; firm moist; clear wavy boundary.

BA -- 21 to 44 cm, dark brown (7.5 YR 3/3 moist) loam; weak subangular blocky structure; firm moist; gradual wavy boundary.

Bt -- 44 to 62 cm, dark brown (7.5 YR 3/3 moist) clay loam; moderate subangular blocky structure; firm moist; gradual wavy boundary.

Ab -- 62 to 86 cm, brown to dark brown (7.5 YR 4/3 moist) clay loam; moderate subangular blocky structure; firm moist; clear wavy boundary.

Bwb -- 86 to 94 cm; weak subangular blocky structure; firm moist; abrupt wavy boundary.

Bt/E -- 94 to 98 cm; moderate blocky structure; firm moist; clear wavy boundary.

Bt1b -- 98 to 126 cm; moderate blocky structure; firm moist; gradual wavy boundary.

Bt2b -- 126 to 142 cm; moderate blocky structure; firm moist; clear wavy boundary.

BC -- 142 to 168 cm; massive; very firm moist; clear wavy boundary.

C -- 168 to 195 cm; massive; firm moist.

TA-63. Trench 2. 3A. 2' : fracture T2-13

A -- 0 to 15 cm, dark brown (10 YR 3/3 moist) loam; weak subangular blocky structure; friable moist; many fine and medium roots; clear wavy boundary.

BA -- 15 to 22 cm, brown to dark brown (7.5 YR 4/3 moist) clay loam; moderate subangular blocky structure; friable moist; many fine and medium roots; clear wavy boundary.

Bt1 -- 22 to 38 cm, brown to dark brown (7.5 YR 4/3 moist) clay; moderate subangular blocky structure; friable moist; many fine and medium roots; gradual wavy boundary.

Bt2 -- 38 to 51 cm, brown to dark brown (7.5 YR 4/4 moist) clay; moderate blocky to subangular blocky structure; firm moist; many fine and medium roots; abrupt irregular boundary.

Cr/Bt -- 51 to 78 cm

Cr/C -- 78 to 160 cm

TA-63. Trench 3. fracture T3-11a

A1 -- 0 to 10 cm, very dark grayish brown (10 YR 3/2 moist) sandy loam; moderate granular structure; friable moist; irregular boundary.

R/A2 -- 10 to 55 cm, very dark grayish brown (10 YR 3/2 moist) gravelly loam; weak granular structure; friable moist; irregular boundary.

TA-63. T4-3

A -- 0 to 15 cm, dark brown (7.5 YR 3/4 moist) loam; weak subangular blocky structure; friable moist; common medium and fine roots; clear smooth boundary.

Bt1 -- 15 to 32 cm, dark brown (7.5 YR 3/4 moist) clay loam; weak subangular blocky structure; friable moist; common medium and fine roots; thin discontinuous clay films on ped surfaces; gradual smooth boundary.

Bt2 -- 32 to 52 cm, dark brown (7.5 YR 3/4 moist) silty clay loam; moderate subangular blocky structure; friable moist; common medium and fine roots; thin continuous clay films on ped surfaces; clear irregular boundary.

Ck -- 52 to 94 cm, brown to dark brown (7.5 YR 4/4 moist) loam; massive; friable moist; CaCO_3 coatings on parting surfaces of weathered tuff; few thin discontinuous manganese films; common medium and fine roots; abrupt wavy boundary.

seam -- 94 to 97 cm, yellowish red (5 YR 4/6 moist) clay; massive; very firm moist; few fine roots; abrupt wavy boundary.

Cr -- 97 to 110+ cm, tuff.

TA-51 long trench, 440 cm

A -- 0 to 8 cm, pale brown (10 YR 6/3) loam, dark yellowish brown (10 YR 3/4) moist; traces of very pale brown (10 YR 7/3) loam, brown to dark brown (10 YR 4/3) moist; weak platy to weak subangular blocky structure; friable moist, hard dry; many fine and few medium roots; .

Bt -- 8 to 22 cm, brown to dark brown (7.5 YR 4/3) clay, dark brown (7.5 YR 3/3) moist; weak prismatic parting to moderate subangular blocky structure; very firm moist, very hard dry; common medium and few coarse roots.

Bt/Cr -- 22 to 34 cm, brown (7.5 YR 5/4) clay loam, strong brown (7.5 YR 4/6) moist, and pink (7.5 YR 7/3) loam, brown (7.5 YR 5/3) moist; weak blocky structure; very firm moist, very hard dry; few to common irregular masses of CaCO_3 ; weak to strong effervescence; few fine and medium roots.

Cr -- 34 to 74 cm, brown (7.5 YR 5/4) weathered tuff, dark brown moist; common to many fine and medium strong brown (7.5 YR 5/8) mottles; massive; hard moist, very hard dry; common fine to medium masses, films, and threads of CaCO_3 ; weak to strong effervescence; few fine and medium roots.

R -- 74 to 140+ cm, light gray (10 YR 7/1) tuff, light gray to gray (10 YR 6/1) moist; massive; hard moist, hard dry.

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