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Geologic Map of the Los Alamos National Laboratory Reservation

MARGARET ANNE ROGERS

1995

This document is not intended to be a comprehensive formal report on the geology of the reservation. Rather, it is offered to provide a description of the map units in the subdivided Tshirege Member of the Bandelier Tuff and to provide insight into the background, methods, and investigations of the geologic mapping project.

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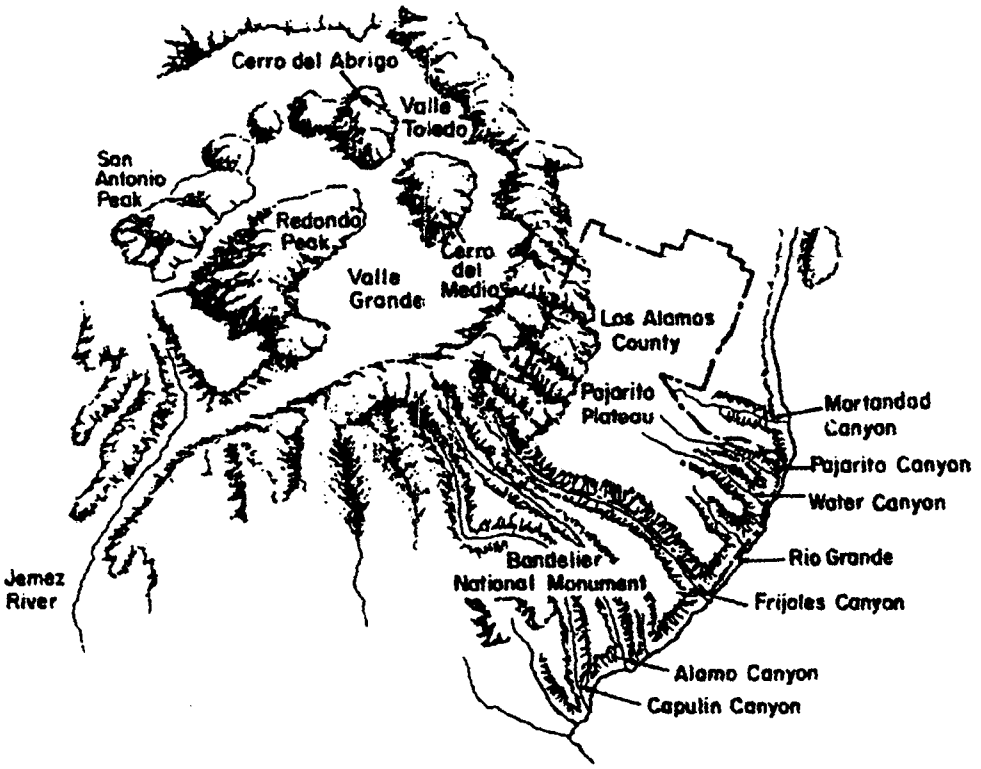

modified LANL drawing

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Geologic Map of the Los Alamos National Laboratory Reservation

BACKGROUND

The geologic mapping project for the LANL Reservation[1] was begun in April 1974. It was part of the Laboratory's[2] waste management Program A415, Waste Disposal Site Studies, a program to satisfy research needs for waste management operations.

Program A415 was initiated in 1973. I was hired as Principal Investigator for the program. The program was one of several newly initiated waste management programs made possible by the U. S. Atomic Energy Commission's (AEC)[3] increased awareness of the importance of environmental/waste-management issues and by its increased willingness to fund such work. Prior to this time, such work at the Laboratory had been severely limited because of budgetary constraints. The stated 1973 management[4] goal was for the Laboratory to become "an example to the nation in how waste management is done".

The first A415 program task was to provide liaison to the U. S. Geological Survey (USGS) which was under contract to the AEC to evaluate facility monitoring practices, both past and present. In September 1973, evaluations were in progress or planned for all major AEC facilities.

Laboratory management accepted the USGS would find deficiencies in the Laboratory monitoring program -- in particular, the absence of site-specific monitoring. At that time, the Laboratory's monitoring program addressed only the issue of whether contamination had left the reservation.

Given the circumstances, management wanted the most favorable evaluation possible. Full cooperation with and assistance to the USGS was emphasized. I was to arrange access to any Laboratory location and/or to any Laboratory employee (past or present) and to find the answers to any USGS question.

Very quickly all kinds of information deficiencies surfaced. Many of these deficiencies had been unknown to or not fully appreciated by Laboratory management.

The USGS focus was on information for Materials Disposal Areas A, B, C, D, E, F, G, and T which had erroneously been identified to them and the AEC as the only waste disposal sites or the only sites of concern. Any information outside the boundaries of these sites was of no interest to the USGS even if the information indicated the Laboratory had not ignored a scientific or technical issue. Detailed disposal-site information, information necessary to establish site-specific monitoring, was not of particular interest to them either. Their task was to evaluate whether adequate monitoring existed -- not to collect information on how adequate monitoring could be established.

By November 1973, a Laboratory source document (Rogers, 1977) was planned to compliment the USGS evaluation (Kelly, 1975). The source document's primary purpose was to provide information to Laboratory personnel. Its secondary purpose was to demonstrate all Laboratory knowledge pertinent to waste-management

1 At this time, the Los Alamos Scientific Laboratory
2 Los Alamos Scientific Laboratory/Los Alamos National Laboratory
3 Succeeded by the Energy Research and Development Administration (ERDA) which was succeeded by the U. S. Department of Energy (DOE)
4 management of environmental/waste-management

operations. By the end of 1974, the need for a continued effort to identify pertinent historical or current information was recognized. ERDA was told that the source document would be updated every 2 years.

The source document officially covered all information discovered or developed before January 1977. In fact, information was continually updated until the report went to press in late 1977. Source document information with early 1977 dates is, therefore, correct. The geology and hydrology sections, however, basically represent 1974 knowledge. Management would not allow these sections to be updated to mid-1977 knowledge because the geologic map and the accompanying comprehensive geologic report would be finished and published in the immediate future. New hydrology studies were planned for a comprehensive new hydrology report which would also include the hydrology of the new geologic map units.

In December 1973, the case for the geologic mapping project was made to environmental/waste-management administrators and funding was secure by April 1974. The practice of spot-mapping, performed through the years by a number of professionals, was not viewed as a solution to development of an adequate monitoring program. Site-specific monitoring, the early-detection system for contaminant migration, and Laboratory-boundary monitoring would need to be integrated. The geologic map was also viewed as pertinent to other environmental and/or waste-management studies as well as to new facility siting.

GEOLOGIC MAPPING PROJECT

Geologic field work continued from May 1975 through December 1980. The geologic mapping project interrupted in early 1981 before any measured sections were completed. Unit descriptions are based on field notes, numerous field samples (collected during mapping), and information from the completed map. References cited are those used during the geologic mapping project. Heiken et al (1986) appears because the earlier references did not describe the Cerro Toledo Rhyolite tuffs. Additional field checking of the color-proof map set was done in May 1994.

Associated Studies

The geologic mapping project included the following studies:

- Joint Study (1973-1980) -- This study covers the Pajarito Plateau in the vicinity of Los Alamos and LANL. Special emphasis was placed on collecting joint data near waste disposal sites. The study distinguishes regional tectonic joints from cooling joints. Tectonic joints may represent a more important potential migration pathway than cooling joints. A total of 1753 joint readings were taken.
- Fracture Fillings Study (1973)[5] -- Fractures in Pits 7 and 24, TA-54 were examined. X-ray diffraction analysis was performed on samples from Fractures 43 and 52, Pit 7, TA-54. Montmorillonite and calcite were the only important secondary crystalline phases present. The caliche appeared to be relatively pure $CaCO_3$. A trace of low cristobalite was associated with the brown clay which was predominantly montmorillonite.
- Secondary Material Study (1977) -- Samples of material deposited in or associated with fractures were analyzed for Na, K, Mg, Ca, Al, Si, and Fe plus any other cations equal to or greater than 0.5% (quantitative spectrometry) and for CO_3, SO_4, and combined H_2O (wet chem or best way). Ten samples of material from 7 specimens were analyzed; 4 of the samples (pink discoloration, yellow discoloration, black discoloration and background) came from the same Pit 18, TA-54 specimen. Li, Be, B, Na, Mg, Al, Si, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Sr, Zr, Sn, Ba, Pb, Bi, CO_3, SO_4, and H_2O were reported in some or all of the samples.
- X-ray Diffraction Secondary Material Study (1977) -- Nine samples were run from the 7 specimens used in the Secondary Material Study. The yellow-discolored material was not run on the Pit 18, TA-54 specimen.

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[5] Jacques R. Renault, New Mexico Bureau of Mines and Mineral Resources.

Both white specimens, north plateau and south plateau, were $CaCO_3$. The Puye Drive specimens, yellow discoloration and red discoloration, were orthoclase and orthoclase/trace hematite respectively. A red fracture filling was orthoclase/trace hematite. A red-orange discoloration was sanidine/cristobolite/hematite. The Pit18, TA-54 samples were all orthoclase/hematite with amount of hematite decreasing from the black to the pink to the tannish-gray normal tuff.

- Polished Thin Section Study of Stratigraphic Section (1978) -- Thin sections were made from 11 Tshirege rock samples selected to represent the stratigraphic column. The following samples were described: 2 -- upper Unit A, 2 -- lower Unit B, 1-- upper Unit B, 1 -- lower Unit C, 2 -- lower Unit D, 1 -- middle Unit D, 1 -- upper Unit E, and 1 -- lower Unit F. One Tshicoma rock sample was also thin sectioned. Quartz and sanidine were identified in all units. Diopsidic pyroxene was identified in all units except Unit D. This preliminary study did not identify any striking differences in texture or mineralogy between Tshirege units.
- Sanidine Axial Angle Study (1978)[6] -- From the above thin sections, 8 were selected. A total of 72 crystals were measured. Units A, C, and E were represented by 1 slide each. Unit B was represented by 2 slides, and Unit D was represented by 3 slides. (Unit F was not intentionally omitted. Work was performed at a time when all stratigraphic relationships had not been defined.) There was a systematic small increase in axial angle from older to younger units.
- Sanidine Microprobe Study (1978) -- A total of 130 measurements, averaging 5 feldspar crystals per slide, were made on the same slides as those in the Sanidine Axial Angle Study. Core, rim, and intermediate area were measured on most crystals. All measurements indicated the feldspar was sanidine. From unit to unit, no definitive changes in the Na-K-Ca ratio pattern were observed.
- Geochemistry Study (1978-1980) -- This was the study which successfully found a means of correlating sub-surface information with outcrop. From 56 locations on the Pajarito Plateau, 142 whole-rock samples (primarily Tshirege, but including Otowi, Cerro Toledo Tuffs, and El Cajete) were analyzed for Na, K, Rb, Cs, Mg, Ca, Sr, Ba, Al, Si, Sn, Pb, Ti, Zr, Hf, As, Sb, Bi, V, Nb, Ta, Se, Mo, W, Cl, Mn, Fe, Co, Cu, Au, Zn, Sc, La, Ce, Sm, Eu, Tb, Dy, Yb, Lu, Th, and U. Total number of analyses was 2025. Discriminant analysis showed that 82.7% of known cases were correctly classified using U, Fe, Th, and Cs values.
- Bandelier "Glass" Study (1979-1980) -- A preliminary study to see if there were characteristic differences in the index of refraction of glasses formed by melting the Bandelier Tuff. Ten samples (one each from the Guaje, Otowi, Cerro Toledo Tuffs, Tsankawi, and Tshirege units A, B, C, D, E, and F) were ground, placed in platinum crucibles, and heated up to temperatures of 1725° C. All samples appeared to form homogenous melts before reaching 1725° C except for units B and D which still contained "white crystals and lots of bubbles". Both of these samples were taken near the top of their respective units in the Baltz et al (1963) type section in Mortandad Canyon. The study was not pursued because of melting difficulties.
- X-ray Fluorescence Study (1979) -- A preliminary study to see if X-ray fluorescence analysis would distinguish units in the Bandelier Tuff. The same samples were used as those in the Bandelier "glass" study. Results were obtained for Ag, Cd, Se, Ni, Br, Cu, Nb, Pb, Sn, W, As, and Zr. Samples from the Guaje and units D and E were submitted to further comparative analysis for K, Mn, Zn, Ga, Rb, Sr, Ba, Fe, Cu, and Pb. Results did not indicate that an expanded study would be useful.
- Feldspar X-ray Fluorescence Study (1979) -- Smith and Bailey (1966) referred to an anorthoclase unit. Roy A. Bailey, USGS, (personal communication) identified the location as the outcrop 1 mile east of the back gate (intersection of State Road 4 and West Jemez Road). This identification appeared to correspond to Unit F; therefore, 8 samples of Unit F were submitted for analysis. All 8 samples showed sanidine plus weak orthoclase with the exception of 1 which showed only sanidine. Samples were also submitted from the Otowi and units A, B, and D; all were sanidine.
- High-magnification Reflected-light Microscopy and Scanning Electron Microscopy (SEM) Study (1979) -- One sample each from Units D, E, and F were analyzed. The reflected-light microscopy revealed textural differences between the 3 units at high magnification (100x). In the sample from Unit F, the SEM identified some mineralogical differences from Units D and E. There appears to be a higher concentration of pyroxenes and other unidentified mineral grains in Unit F. Some of these unidentified minerals contain considerable cerium and titanium. Tentative identifications based on 1 crystal each were ilmenite (Unit F), titanite (Unit F), kaebelite (Unit F), and magnetite (Unit D); and tentative identification based on 3 crystals was magnetite (Unit E). Textural and mineralogical differences were not dramatic enough to warrant a larger study necessary to prove the differences real.

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[6] A. J. Budding, Department of Geoscience, New Mexico Institute of Mining and Technology

Map Construction

In 1973-74, the topographic map of the LANL reservation was an ozalid print of pieced-together USGS topographic sheets. In addition, the engineering groups had topographic information produced by spot-mapping. Existing aerial photography sets were either old and incomplete or extremely high altitude. In consultation with the engineering groups, it was decided that a new aerial photography survey was needed not only for the geologic map but also for a detailed topographic map of the Laboratory. Timing/funding dictated that two surveys be flown. The first was a low-altitude, color-aerial-photography survey flown in September 1974 by Program A415. This aerial photo set, at a scale of 1 inch = 600 feet, was used for geologic mapping. In the next 4 years, the engineering groups flew their own survey (after ground-truth, surveyed, points were established) and developed topographic sheets of the Laboratory at a scale of 1 inch = 400 feet. The new topographic sheets, when they became available in 1978, were used as field maps in combination with the color aerial photos.

Using field notes, field maps, and a stereoscope, contact lines were inked onto the set of color aerial photos. The geologic map was scribed from the aerial photos onto the new topographic base sheets in the Fall of 1980. In May 1994, the 1981 color-proof set of the geologic map was checked by an extensive review of the original color aerial photos.

Discrepancies between the scale-controlled geologic map and the topographic base map exist. Both aerial photographic surveys strove to reduce distortion, but distortion in both exists. In the color set used for the geology, the distortion is recognizable in the lines flown over White Rock Canyon of the Rio Grande. In the set used for the topography, distortion occurs throughout the survey and is particularly evident along the southern boundary of the Laboratory reservation. In addition, the contractor who drew the topographic map set did not have equipment with sufficient depth resolution; therefore, some canyon bottoms are drawn on the tops of the Ponderosa pines. The effect on the geologic map is twofold. Geologic contacts appear to be closer to some canyon bottoms than they actually are; and contacts along the southern edge of the Laboratory reservation were adjusted to more closely match the contours as drawn on the topographic base maps.

Any mapping project has the objective of finding the best explanation of field observations. In detailed mapping, all oddities require explanation. Even with good field work and the best available tools, it is not always possible to arrive at a satisfactory explanation for everything seen in the field or to have a map irrefutably demonstrate field knowledge. There are actual mapping errors as well as perceived mapping errors.

Some of the variables in this mapping project are:

- Field work was begun 20 years ago.
- The project was interrupted for a period of 13 years.
- Access to the entire map area for field checking is no longer possible.
- The topographic map base has errors due to its method of mechanical compilation.
- Errors were introduced into the geologic map compilation in order to make the outcrop pattern more closely parallel the topographic contours as drawn.
- As good as outcrops may be, the place where information may be most wanted is covered by some of the following: vegetation, colluvium, alluvium, fan deposits, El Cajete pumice, constructed fills, buildings, or dumps.
- Aerial photo interpretation was used where direct observation was not possible.
- On aerial photos, the area of most interest may be located on the overlap-edge of 4 stereo pairs with the result that it is never stereoscopically seen without some distortion.

Every attempt was made to address field oddities even if the resulting map depiction would appear to show a mapping error. Most fault lines were not observed in the field. Aerial photo interpretation of lineations was used to come up with the best fit for field observed location and attitude of units. Because this was a detailed mapping project, the bias was to show displacements of as little as 3 feet and to show minor folding. The majority of the structure shown on this map would be ignored by larger-scaled projects.

Location

The Pajarito Plateau flanks the eastern side of the volcanic Jemez Mountains in north-central New Mexico (see Index Map). The plateau is 16 - 24 km wide and more than 48 km long. It is bounded on the west by the Sierra de los Valles, on the east by the Rio Grande, on the northeast by the Puye Escarpment, and on the southwest by Cañada de Cochiti. The LANL reservation occupies the central part of the plateau's northeast-southwest trend. The plateau slopes eastward from an elevation of 2377 m to an elevation of 1890 m. It is cut 61 - 122 m deep by many southeast trending streams. On the western side of the LANL reservation, the named canyons from north to south are: Los Alamos, Sandia, Mortandad, Two-Mile, Pajarito, Cañon de Valle, and Water. On the eastern side of the LANL reservation, the named canyons from north to south are: Barrancas, Bayo, Pueblo, Los Alamos, Sandia, Mortandad, Cañada del Buey, Pajarito, Potrillo, Fence, Water, Indio, Ancho, and Chaquehui. The dissected eastern margin of the plateau rises 91 - 305 m above the Rio Grande and forms the western side of White Rock Canyon.

The two most important canyons in the map area are Los Alamos on the north and Water on the south. Both canyons deeply cut the plateau. Each heads in the Sierra de los Valles, crosses the plateau, and empties into the Rio Grande.

Tshirege Stratigraphy

The Pajarito Plateau is cut in the layered Bandelier Tuff which is predominantly of ash-flow origin. Bailey, Smith, and Ross (1969) revised the Bandelier to include an upper Tshirege Member and a lower Otowi Member. Each member included a basal air-fall pumice bed, the Tsankawi and Guaje respectively. On the LANL Reservation, most of the outcrop is Tshirege. For the detailed geologic mapping project to succeed, the Tshirege had to be subdivisible into map units. According to the Code of Stratigraphic Nomenclature, a map unit is a lithostratigraphic unit. A lithostratigraphic unit is defined by observable physical features and is independent of inferred geologic history.

A cooling unit, defined by Smith (1960a), is a single or multiple ash-flow deposit which has a common cooling history. The cooling history may be essentially uninterrupted, producing a simple cooling unit, or broken by successive emplacements before the underlying flow cooled, producing a compound cooling unit. Smith (1960a, p.813) identified the Tshirege as a multiple-flow compound cooling unit[7]. Smith (1960b, p.157) stated that "the cooling unit, simple or compound, is probably the logical map unit in most unmetamorphosed rocks. It is a closely limited time unit as well as a genetic rock unit." Code of Stratigraphic Nomenclature arguments aside, if the Tshirege is a compound cooling unit and the cooling unit is the map unit, then the layered, 107(?) m thick Tshirege is indivisible.

I agree with Smith (1960a, p. 817) that the Tshirege Member is a compound cooling unit. I do not agree with Smith (1960b, p. 157) that a cooling unit should properly be a map unit. In accordance with the Code of Stratigraphic Nomenclature, I divided the Tshirege Member into 6 lithostratigraphic-mappable units, Units A, B, C, D, E, and F. A detailed description of each unit can be found in the Description of Cenozoic Map Units. It is unknown whether any unit represents a single flow unit. All units have widely-traceable, flow-unit boundaries. Unit boundaries separate rock which is distinct lithologically from that above or below.

The Tshirege Member ash flows show facies changes based on degree of induration. These changes are primarily lateral. In general, the rock with the greatest degree of induration will be found at the proximal end, nearest the source, of a flow. On outcrop, transition from one facies to another can be seen. Some units, however, retain their facies character across the plateau. Induration may be due to welding and/or crystallization. It is volume, temperature, and lithostatic-load related. Hand specimens from the same unit, but different induration facies, have similar physical and chemical properties.

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[7] Roy Bailey (personal communication 1978) stated that he and Bob Smith still considered the Tshirege to be a compound cooling unit.

Field terms for the facies (most highly indurated to unindurated) are: 'horizontal fracture rock', 'rippled rock', 'massive', 'orange blocky', 'hole rock', and 'rotten'. These terms are based on appearance. Degree of induration can be heard in the sound made by a rock hammer striking tuff. Hammer sound divides the tuff into 2 general groups, 'ping' and 'thud'. Color is another indication of induration.

- *'Horizontal fracture rock'*: 'ping' rock, dark to medium gray, densely welded, vapor-phase crystallization present, bench former
- *'Rippled rock'*: 'ping' rock, dark to medium gray, densely welded, vapor-phase crystallization present, tendency to be slope former
- *'Massive'*: 'ping' or 'thud' rock, dark to light gray and orange, densely to moderately welded, vapor-phase crystallization present, bench former
- *'Orange blocky'*: 'thud' rock, orange, moderately to incipiently welded, vapor-phase crystallization present, bench former
- *'Hole rock'*: 'thud' rock, medium to light gray, orange, and white, moderately to incipiently welded and nonwelded, vapor-phase crystallization not present in white rock, tendency to be slope former
- *'Rotten'*: no sound, light gray or white, totally unindurated loose material, blows away in the wind

'Rotten' outcrops are small, few, and easily hidden. Where protected by overlying indurated tuff, 'rotten' facies may be burrowed by insects.

Unit induration, and induration within a facies, increases westward to the mountains. Exceptions are found in Units B and C. The distal part of these units, at the edge of White Rock Canyon, are more highly indurated than their immediate lateral equivalents to the west. Darker color as well as closely-spaced columnar jointing indicate this. Ross and Smith (1961) discuss experimental work which shows that the presence of extremely small amounts of water vapor will significantly reduce the welding temperature.

A through-flowing ancestral Rio Grande existed at the time of the Tshirege eruptions. Immediately west of the White Rock Canyon wall, in the southern part of the map area, Units A and B do fill a north-south channel, perhaps the ancestral Rio Grande. Unit A does not appear to show any increase in induration. Lower Unit B does show increase in induration not only in the vicinity of the channel fill but for almost halfway across the plateau. And Unit C shows an increase of induration in the vicinity of the channel fill. The relative degrees of induration in the units does not make a neat case for addition of water vapor from proximity to an ancestral Rio Grande. In this particular case, Unit C, sitting on top of 110 m of Unit A and B, has the highest degree of induration followed by the lower part of Unit B.

Increase in water vapor may be the reason for the reversal of degree of induration seen in Unit C and in lower Unit B in their distal parts; however, proximity to an ancestral Rio Grande is too simplistic an explanation.

General Unit Characteristics

All unit contacts are flow boundaries with sandy partings. A sandy parting may be a base surge (flow base), lag deposit (flow top), or reworked deposit (flow top). If thick, sandy partings show both laminar and cross bedding.

Phenocrysts are primarily quartz or sanidine. The sanidine may show chatoyancy. Diopsidic pyroxene has been identified and ilmenite, titanite, knebelite, and magnetite tentatively identified.

'Tenting', which may be related to fumarolic activity, is an erosional phenomenon. The upper surface is eroded into irregular tent shapes. There are no caps. 'Tenting' occurs in Units C, D, E, and F, but it is not seen in the distal part of any unit. 'Tenting' does not occur either in nonwelded or incipiently welded rocks. Tent rocks are seen in Unit A where pedestal caps are likely to be Unit C. The tent rocks in Unit A are not related to fumarolic activity.

Fumarole evidence has been seen in all units. Fumarole vents have been identified on upper surfaces of Units A, C, D, and F. Iron-staining, producing a wide variety of colors, has been observed along joints in Units B, D, E, and F. Opalization along joints has been seen in Unit F.

The pink mounds, observed in rock cuts in Units B and C, are probably related to fumarolic activity and vapor-phase crystallization. The mounds have steep sides and gently sloping tops. Only the color of the rock is changed. They cut across original texture creating no textural changes.

Structure

In the map area, tectonic fractures are related to development of the Rio Grande Rift and the Jemez volcanic complex. The Jemez Mountains are located on the western border of the Rio Grande Rift, a linear and topographic depression formed by faulting. The Pajarito Fault Zone separates the Pajarito Plateau from the Sierra de los Valles, the eastern side of the Valles Caldera. In general, the Tshirege Member dips gently to the SE.

In the northeast corner of the map area are three NW-trending faults. With these exceptions, all other N-S faults and fold axes trend NNE. There is E-W faulting which trends NWW.

The Los Alamos Canyon Arch (new term) and the Water Canyon Arch (new term) have similar NE trends to the Pajarito Fault Zone on the west edge of the map area. The Los Alamos Canyon Arch dies out to the south and the Water Canyon Arch dies out to the north. Both arches are named for the first major canyon they cross as they enter the map area. The Los Alamos Canyon Arch is east of the trend of the Water Canyon Arch and synclinal fold into which it dies out.

The Los Alamos Canyon Arch is the eastern limb apex of the synclinal fold that's axis is on-trend with the Water Canyon Arch to the south. The Los Alamos Canyon Arch extends to the south across the map area where it dies out after crossing Cañon de Valle. The arch determines the western limits of exposure for the lower stratigraphic units of the Tshirege.

The Water Canyon Fault depicted by Budding and Purtymun (1976) does not exist. The fault is an arch, the Water Canyon Arch. Facies changes occur immediately east or west of the arch. The Water Canyon Arch dies out to the north after crossing Pajarito Canyon. South of Cañon de Valle, a fault begins which is immediately east of the arch. Northward, south of Two-Mile Canyon, this fault becomes the axis of the synclinal fold which crosses Los Alamos Canyon.

North of the map area is the Los Alamos Fault (Budding and Purtymun, 1976) which dies out to the south. The Los Alamos Fault is a monoclinal fold, on the eastern limb of the syncline, as it crosses Los Alamos Canyon.

Los Alamos Canyon is fault controlled. The Los Alamos Canyon Fault (new term) extends down Los Alamos Canyon from the Pajarito Fault Zone to the Los Alamos Canyon Arch. It is downthrown to the north. This allows the synclinal fold axis to be much deeper on the north side of the canyon. Beginning in the fault zone, is another fault which extends west up the canyon. This fault is downthrown to the south. In the Pajarito Fault Zone, this southward displacement allows eastward displacement and formation of a small graben on the south side of Los Alamos Canyon. On the north side of Los Alamos Canyon, the fault zone is a faulted monoclinal fold which bottoms at the synclinal fold axis. The small displacement faults on the monoclinal fold are downthrown to the west.

A NE trending line, between the Pajarito Fault Zone and the Water Canyon Arch/synclinal fold line from Los Alamos Canyon on the north to Water Canyon on the south, shows NWW trending faults stepping down from the north and south until bottom out between the middle and south E-W branches of Pajarito Canyon on the north edge of TA-9. The NWW faulting is small displacement faulting.

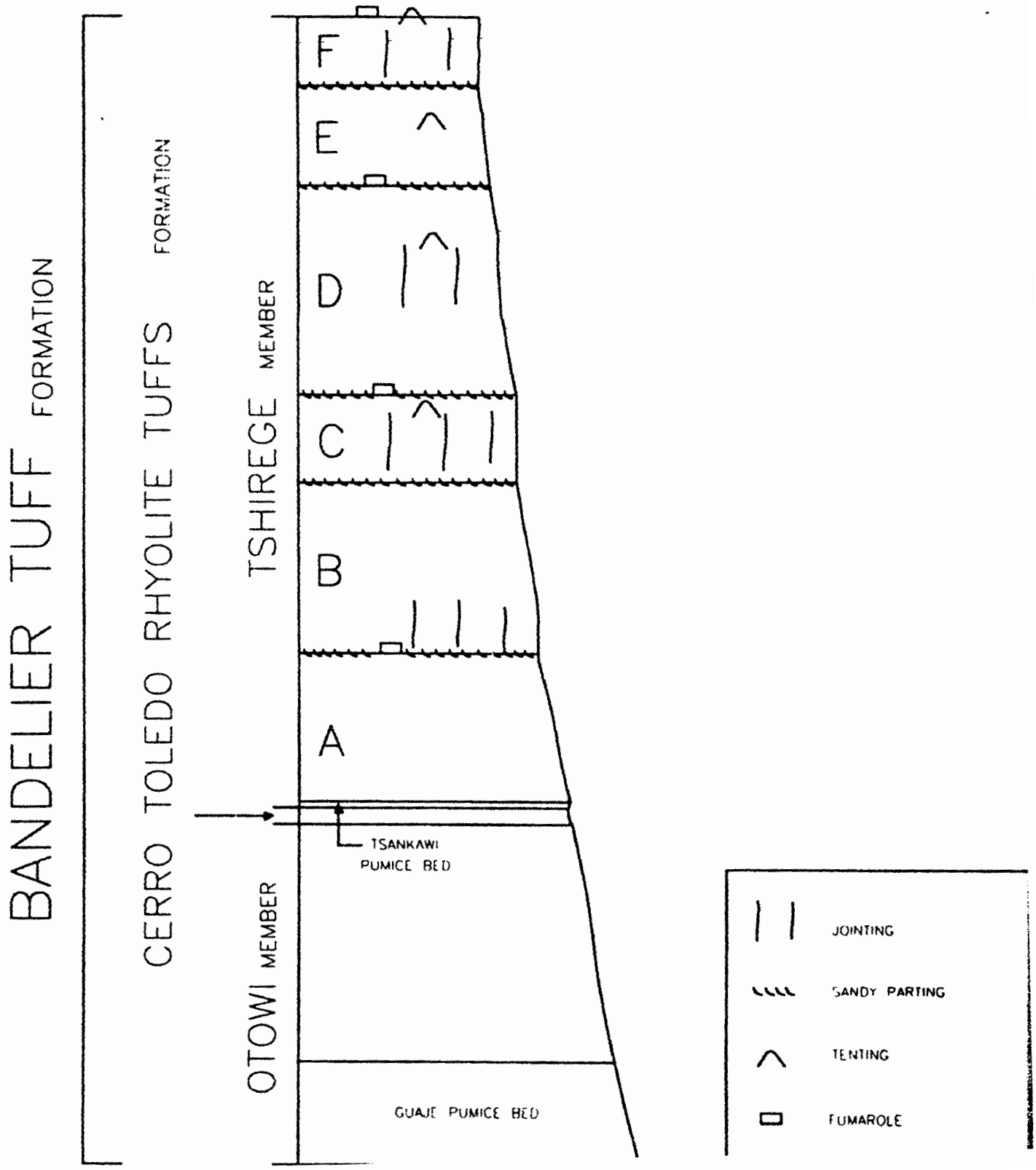
ACKNOWLEDGMENTS

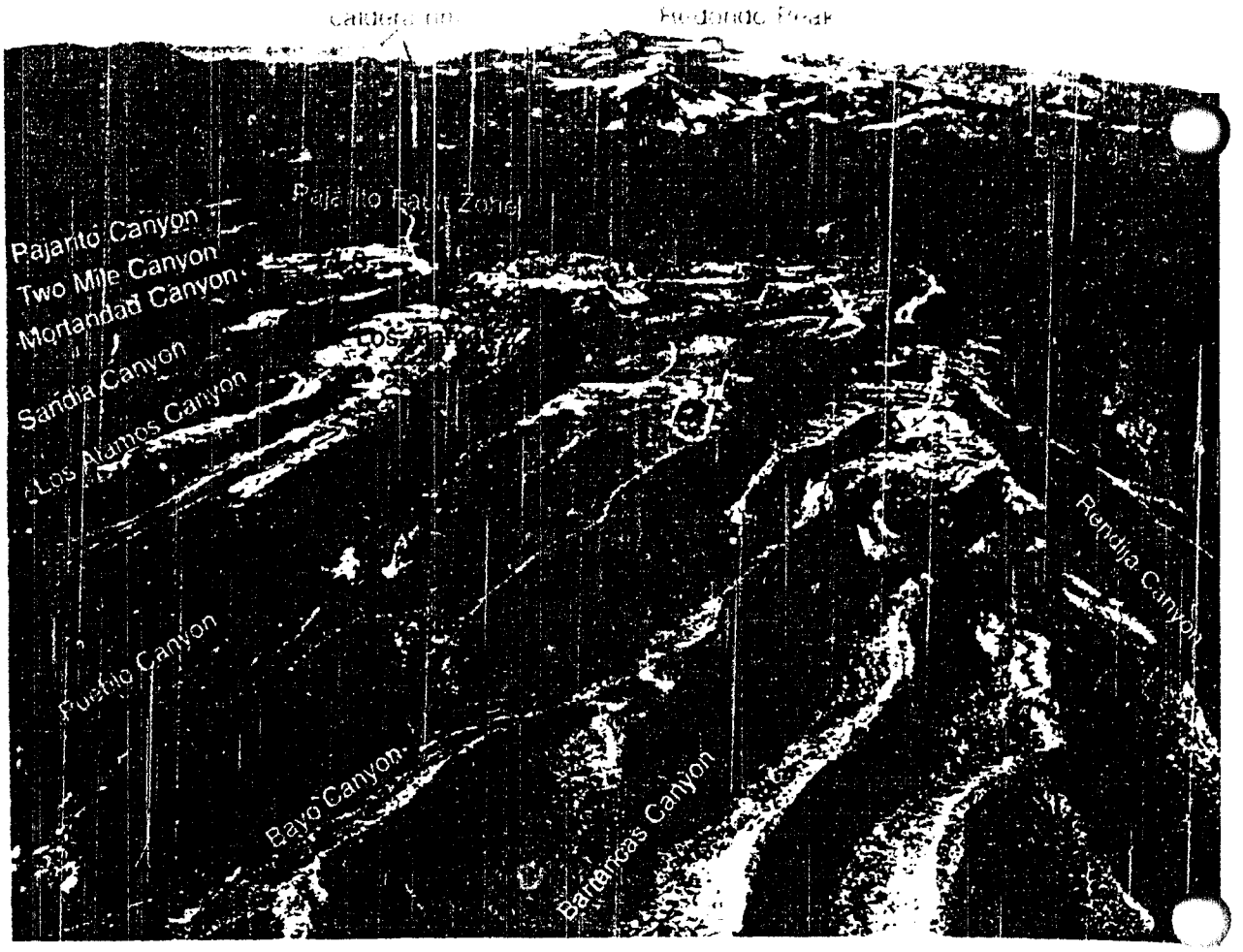
John Purson, Karin E. Budding, Virginia L. Christie, and Barry W. Burton were some of my field assistants. Karin E. Budding, Virginia L. Christie and Barry W. Burton also assisted on some of the associated geologic mapping project studies.

During the years following the end of the LANL geologic mapping project, a number of professionals expressed interest in the map and associated studies. They include Jamie N. Gardner, Fraser E. Goff, and John W. Nyhan of LANL, David Dethier of Williams College, and John W. Hawley of the New Mexico Bureau of Mines & Mineral Resources. John Hawley's continued support ultimately lead to publication. He engaged the interest of William J. Stone, New Mexico Environment Department (NMED) Ground Water Bureau[8] representative at LANL. Bill Stone's support led to a contract to fund the final stages of publication of the map set by the DOE Oversight Program of the Ground Water Bureau.

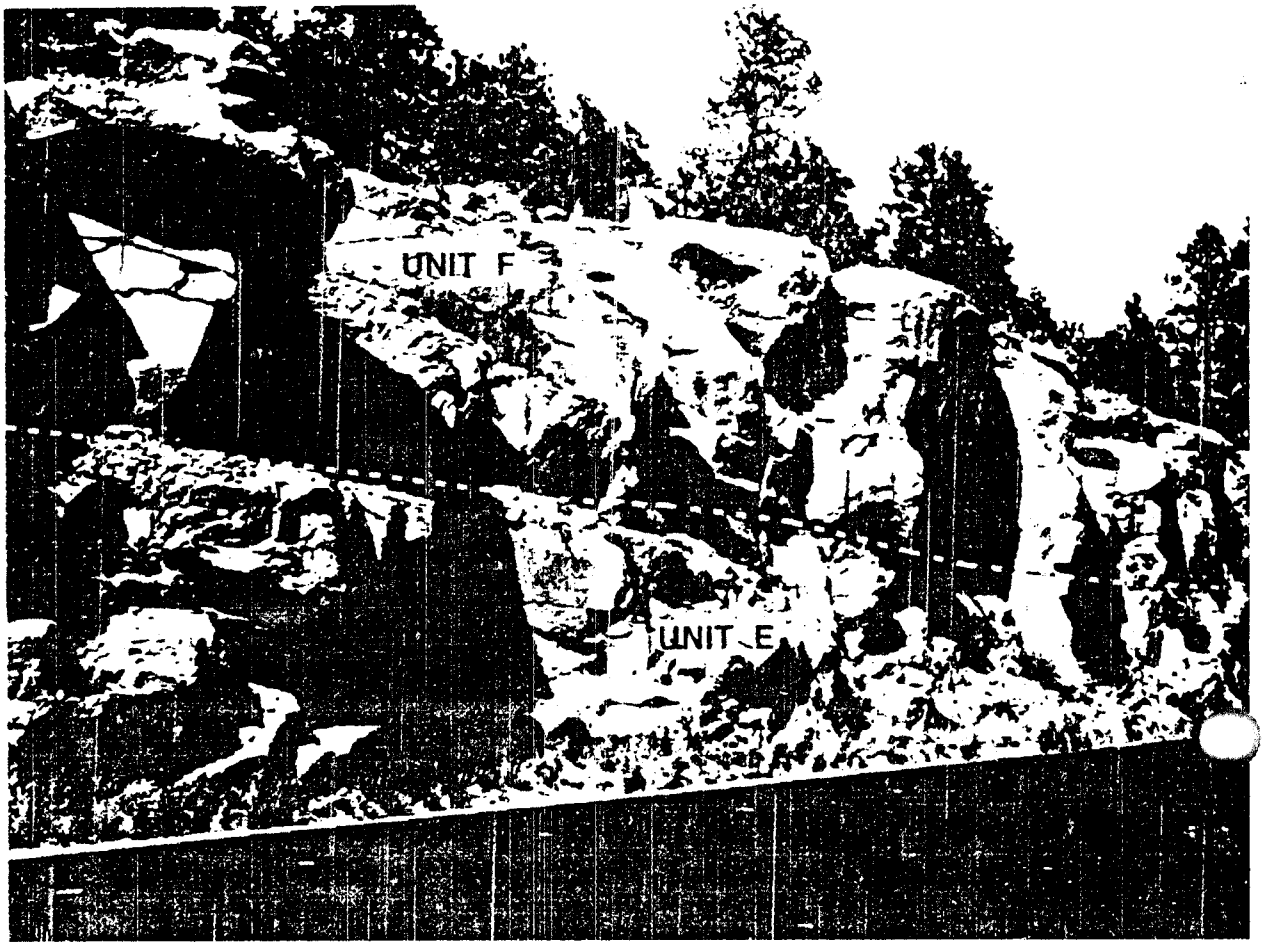
In 1994, many review hours with the original set of aerial photos were made possible by the Records Processing Facility, Environmental Restoration Group EM/ER, LANL. I especially want to thank Barry J. Drennon, Archivist, Records Processing Facility, for seeing that the original set of aerial photos, from which the geologic map was drawn, were saved and later available.

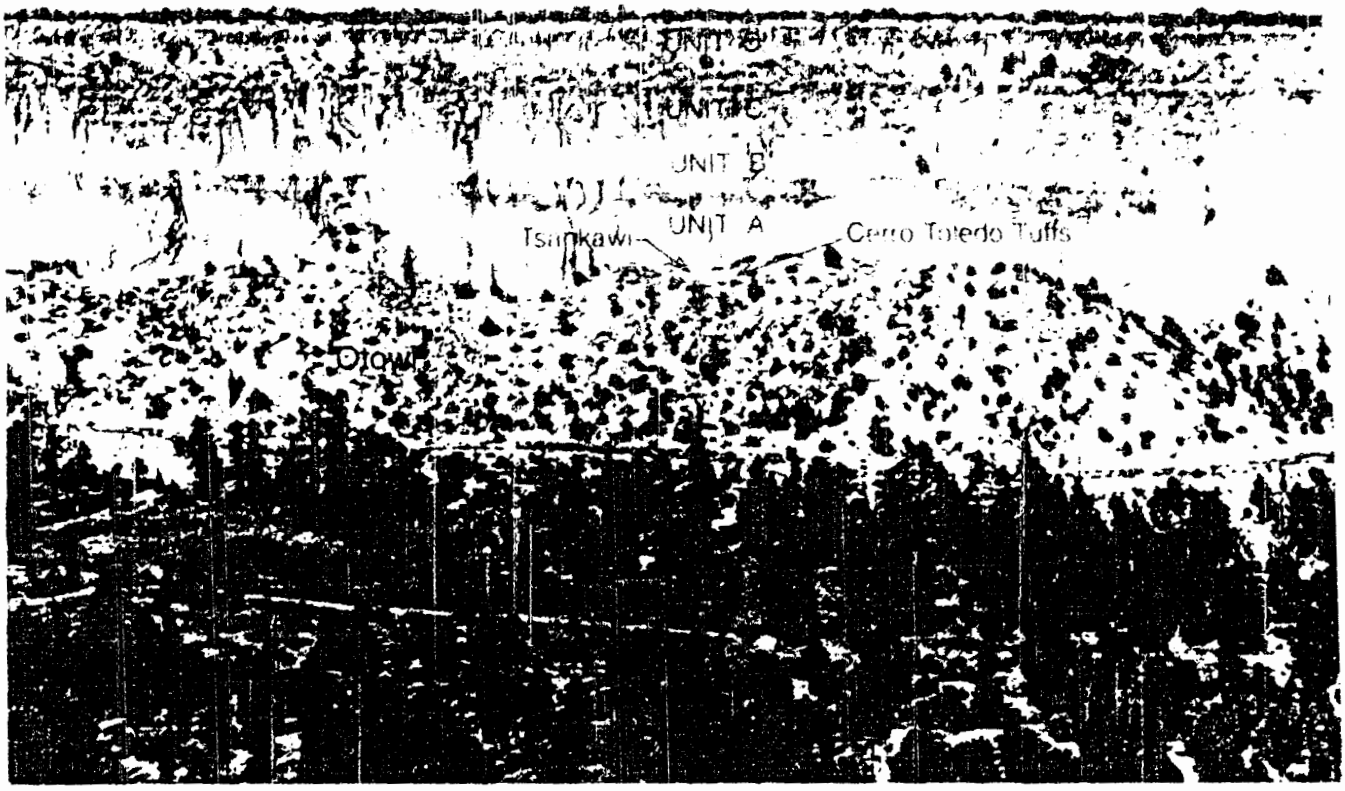
IDEALIZED SECTION
BANDELIER TUFF, PAJARITO PLATEAU



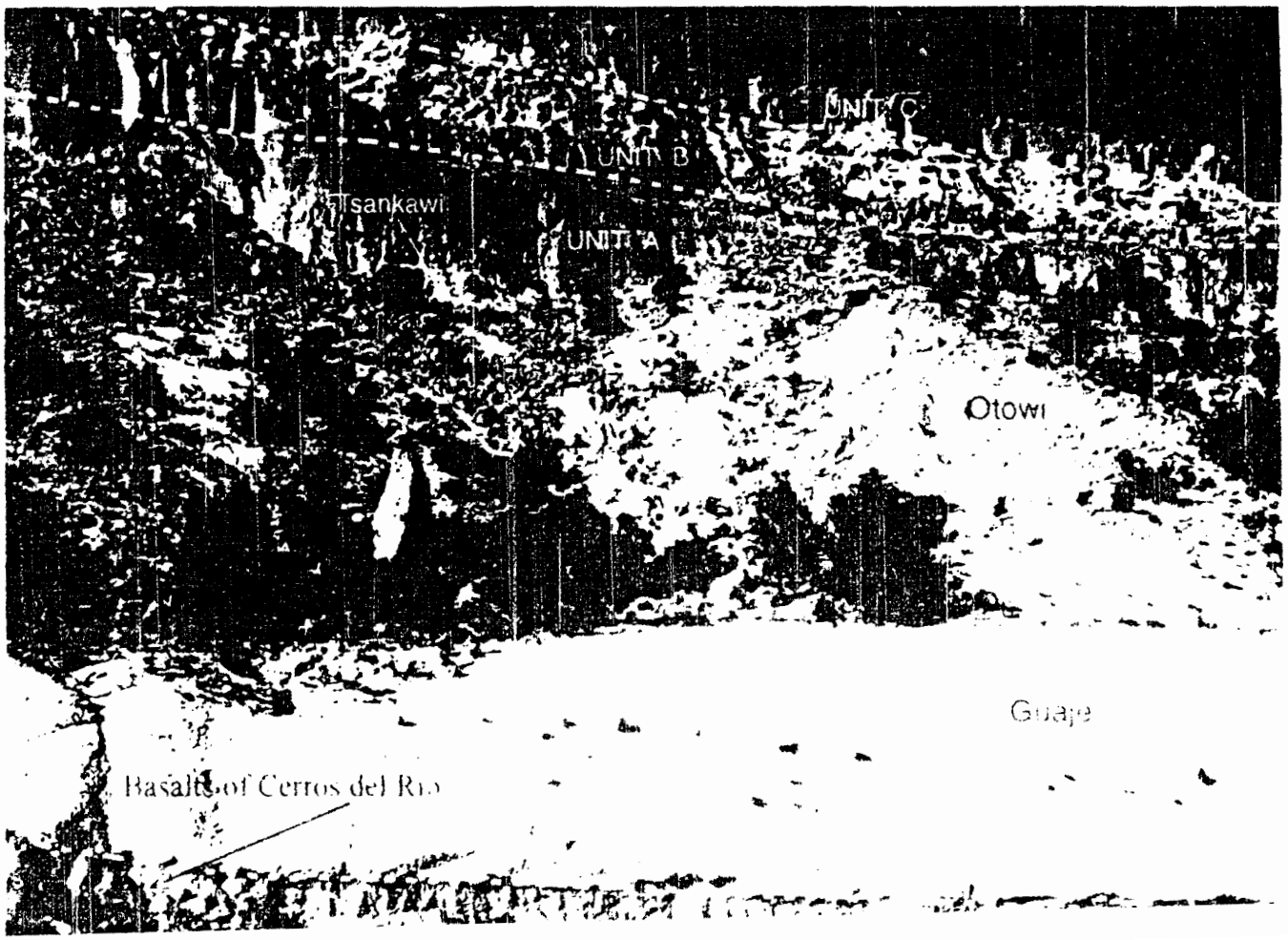


Looking West Across Pajarito Plateau at Valles Caldera



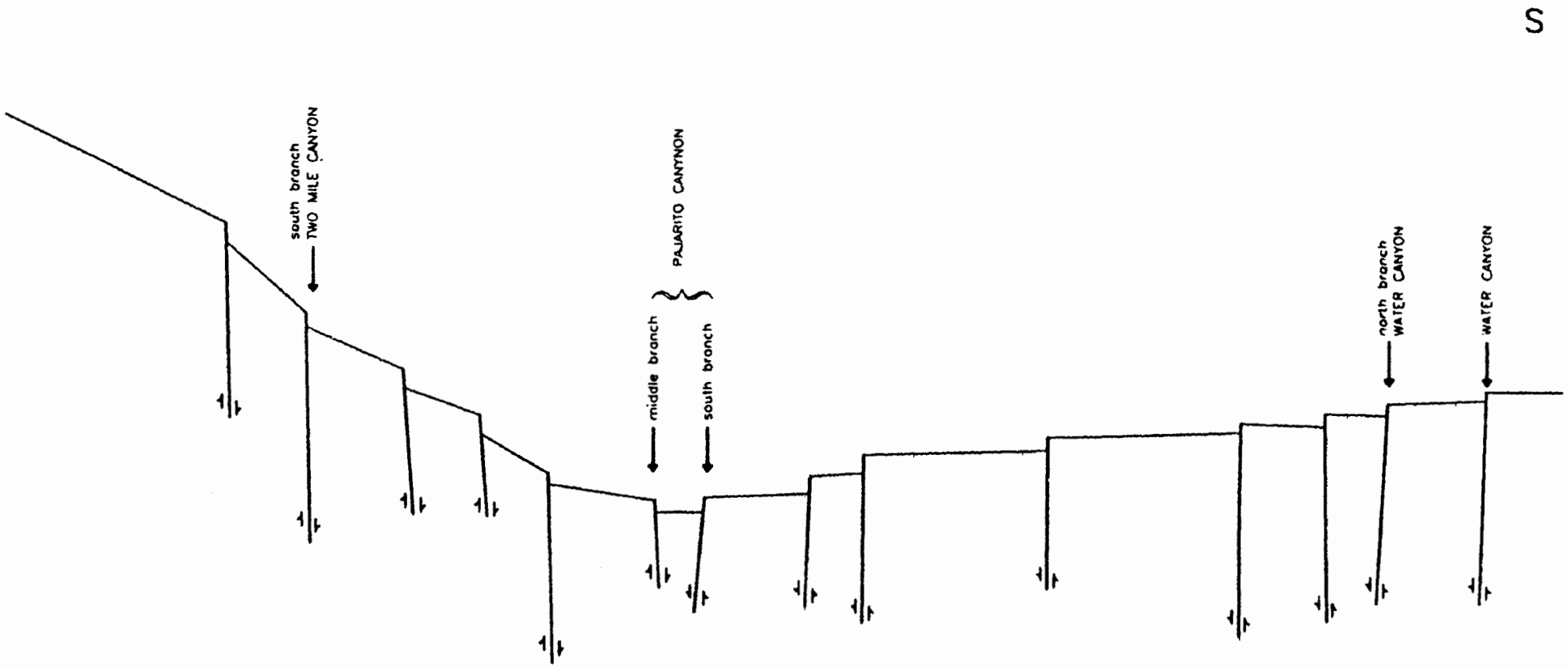


Looking North, Pueblo Canyon, Near Clinton P. Anderson Overlook



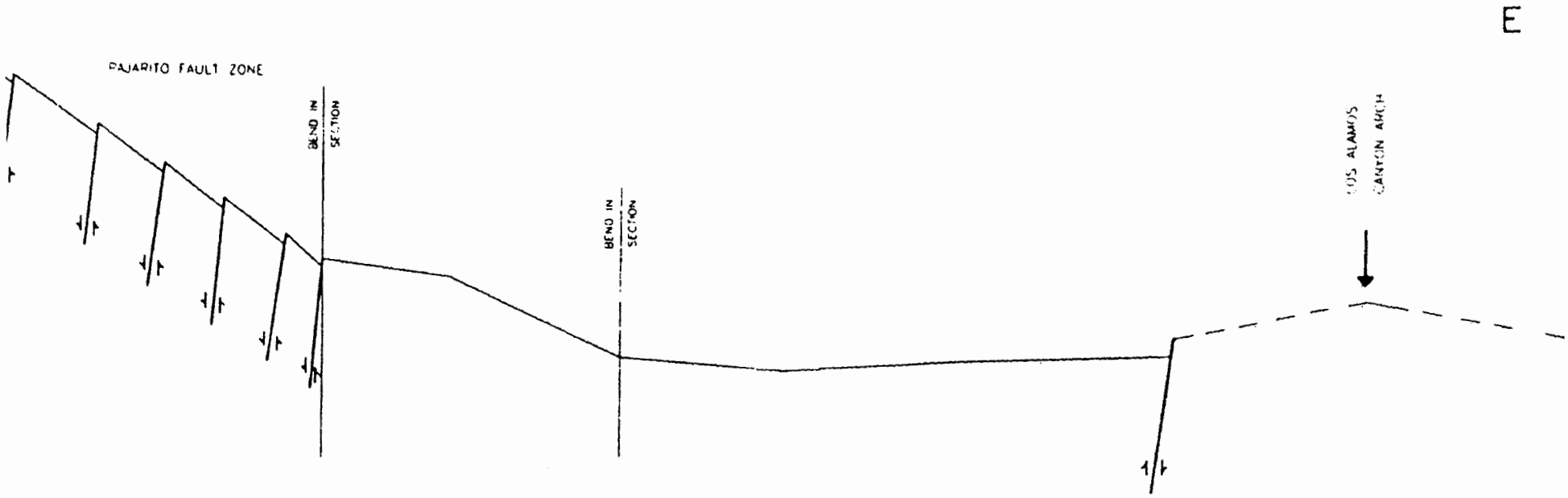
SCHEMATIC STRUCTURE SECTIONS

DRAWN ON CONTACT BETWEEN UNITS E AND F

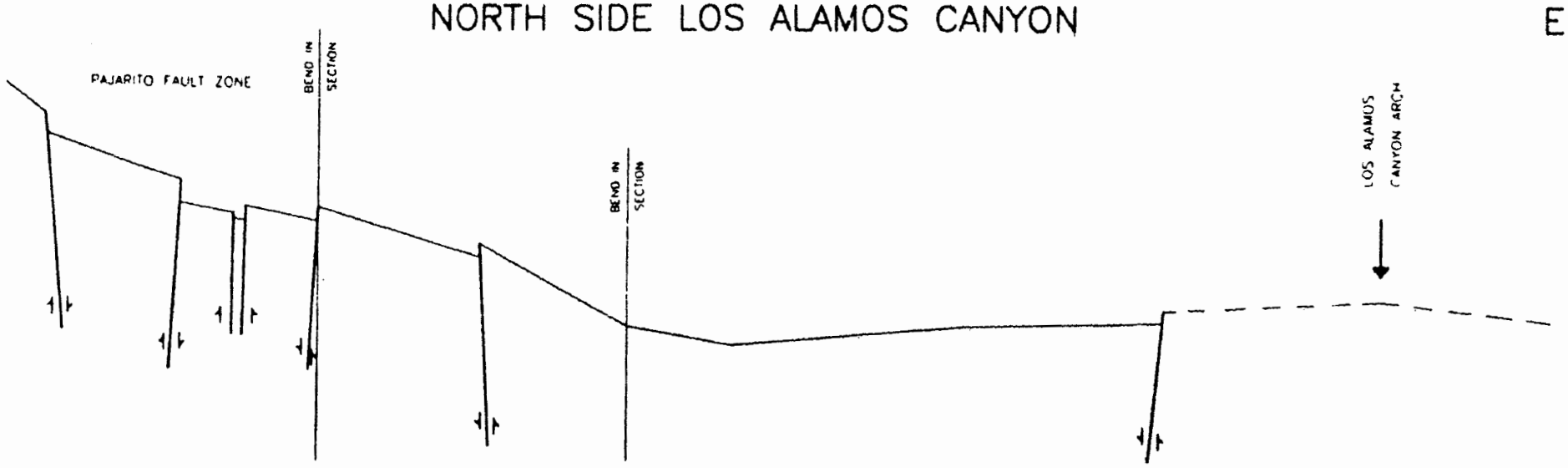


LINE THROUGH MIDDLE OF SHEETS 1, 2 AND 3

DRAWN ON CONTACT BETWEEN UNITS D AND E



NORTH SIDE LOS ALAMOS CANYON



DESCRIPTION OF CENOZOIC MAP UNITS

Qco COLLUVIUM [0-5(?)[1] m] -- loose material on the slopes of the canyon walls composed of soil and rock fragments: deposited by rockfall, rainwash and sheetwash.

Ql LANDSLIDE DEPOSITS [0-30(?) m] -- soil and rock material deposited by slumping: occur on the eastern side of map area where incompetent units in the Puye Formation or in the Santa Fe Group underlie basalts or indurated tuffs.

Qf FAN DEPOSITS [0-8(?) m] -- stream-deposited, loose, pre-Bandelier rock-type material deposited as a result of movement in the Pajarito Fault Zone; occurs mainly along the western edge of map area. Gravels (beneath pumice) can be seen 5.5 km down slope at base of well-developed, mesa-top, soil profiles and approximately 6 km down slope at base of pumice-filled channel cut in mesa top.

Qal ALLUVIUM [0-35(?) m] -- silt, sand, and gravel deposited by recent streams. occurs in all canyon bottoms. Exposed bedrock is rarely seen in canyon bottoms.

Qt_1 TERRACE 1 [0-8(?) m] -- lower terrace gravels of Los Alamos Canyon stream near Los Alamos-Santa Fe county line composed of well-rounded, pre-Bandelier rock types.

Qt_2 TERRACE 2 [0-20(?) m] -- upper terrace gravels of Los Alamos Canyon stream near Los Alamos-Santa Fe county line composed of well-rounded, pre-Bandelier rock types.

VALLES RHYOLITE:

Qvec EL CAJETE MEMBER [0-6(?) m] -- air-fall pumice deposits of rhyolite pumice containing phenocrysts of quartz and sanidine preserved primarily on mesa tops of Pajarito Plateau. Eastern most exposure in the map area occurs in Potrillo Canyon 1.2 km upstream from confluence with White Rock Canyon Thick, well-developed, mesa-top soils appear to correlate with the occurrence of El Cajete pumice.

BANDELIER TUFF:

TSHIREGE MEMBER [0(?)-107(?) m] -- unconsolidated nonwelded to densely welded ash-flow tuffs and a basal, bedded, air-fall pumice, the *Tsankawi Pumice Bed* Unit may not have covered White Rock Basalt High. Ash-flow tuffs are here divided into units, A, B, C, D, E, and F, from bottom to top. Units can be distinguished in subsurface by their respective amounts of uranium (U), iron (Fe), thorium (Th), and cesium (Cs).

As mapped, Unit A includes beds of air-fall pumice, phreatomagmatic ash, and base surge deposits of underlying *Cerro Toledo Rhyolite tuffs* [0-9(?)m] and succeeding basal Tsankawi Pumice Bed [0.15 - 1.15(?)m]. Because of thickness or topographic expression, neither the Cerro Toledo Rhyolite tuffs nor the Tsankawi Pumice Bed are mappable units in map area.

Qbt_1 UNIT F [0-15(?) m] -- gray, pink or orange, moderately welded to densely welded tuff which weathers with thin orange or black rind. Unit contains rare lithics[2] up to 10 cm in length. Pumice fragments, frequently flattened with vapor-phase crystallization, are commonly 1-2 cm in length but may be as long as 4.5 cm. Pumice color may be same as matrix or may be gray, lavender, pink, orange, or red-brown. Vapor-phase crystallization present throughout unit.

1 Thickness is estimated from the geologic map and field notes since there are no measured sections.
2 The term 'lithics', as used in this paper, does not include pumice.

Lithophysae, with concentric shell structure, are occasionally seen near unit base. Contains 1-2 iron-bearing crystals (perhaps, identified diopsidic pyroxene) which weather as pin-head size n spots. Phenocryst content overall is approximately 6%. Phenocryst grain size is fine-sand to mm (pebble).

Highest stratigraphic unit which crops out on the Pajarito Plateau. Unit thins eastward and m represent more than one ash flow. Unit extends farther eastward in southern part of map are Distal edge of unit probably did not extend much beyond Los Alamos grid (LAg) meridi E40+00.

Unit top and unit east of Water Canyon Arch (and east of synclinal fold to north into whic Water Canyon Arch dies out) are less indurated and lighter in color although still 'massive' facie The buff-colored tuff has pink to orange vapor-phase-altered pumice. Weathering produces 'swiss cheese' appearance. Amount and size of pumice increases eastward as does amount c lithics.

At places, unit top surface has fumarole vents and spectacular differential weathering leavin joints in relief. More common is red/pink/orange iron-staining along joints in unit upper part 'Tenting', a weathering feature, is occasionally seen on top surface.

Unit has been intensely altered in vicinity of Water Canyon Arch on both north and south side of Water Canyon. Unit on south side is purplish, densely welded rock with red fiamme. Unit joints appear to have been opalized on north side.

Unit can be identified using U, Fe, Th, and Cs content in 73.3% of cases.

Unit F is separated from Unit E by a sandy parting. Parting may show laminar or cross bedding and may be up to 25 cm thick.

Qbt$_1$ Unit E: [0-90(?) m] -- pink, light orange, light to dark gray, nonwelded to densely welded tuff which weathers with thin light-brown, orange, or black rind. Lithics, 1-10 cm, present in unit upper part in some places. Pumice fragments, generally rare or confined to stringers, show vapor-phase crystallization. Unit top in places is pumice-rich as is some rock in the 'horizontal fracture rock' facies. Even in densely welded rock, pumice may not show much collapse. Pumice fragments, commonly 1-2.5 cm, may be 0.5-23 cm in length. Pumice color may be same as matrix or may be light to dark gray, tan, red-brown, or red. Vapor-phase crystallization present throughout the unit. Lithophysae, with concentric shell structure, are occasionally seen in unit base and top. Contains 1-8% iron-bearing crystals (perhaps, identified diopsidic pyroxene) which weather as pin-head size (and larger) rust spots. Unit top contains the least iron-bearing crystals. Phenocryst content overall is 15-20%. Phenocryst grain size is fine-sand to 4 mm (pebble). Chatoyant feldspar may be seen in unit upper part.

Unit thins eastward and represents four or more ash flows. Each flow is bounded by thin sandy partings. West of Pajarito Fault Zone in Los Alamos Canyon, Unit E appears to be four flows. East of fault zone, complicated Unit E stratigraphy may show more than four.

Unit extends farther eastward in southern part of map area. Distal edge of unit probably did not extend much beyond LAg meridian E180+00. Unit bounded above and below by widely traceable sandy partings. Unit E lithology is different from Unit F above or Unit D below. As a whole, Unit E has a higher degree of welding than any other unit.

Unit flows show facies changes. Lateral facies changes have a northeast trend. Unit induration, for a given LAg meridian, will be less to the south. Field terms for the facies (most densely

welded to nonwelded) are: 'horizontal fracture rock', 'rippled rock', 'massive', 'orange blocky', and 'rotten'. Unit stratigraphy appears to be more complicated from Cañon de Valle south. Along the western edge of map area, Unit F rests on 'rippled' facies in north and on 'massive' in south. In south, a general Unit E section would have 'massive' stacked on 'rippled rock' which is stacked on 'horizontal fracture rock'.

Moving eastward, in north, 'massive' changes color from gray to light-orange and grades into 'orange blocky'. In south, 'horizontal fracture rock' changes to 'rippled rock' to 'massive' to 'orange blocky'. Lateral transition in Unit E from hard gray rock to softer light-orange rock begins immediately west of the Water Canyon Arch (and synclinal fold to north into which Water Canyon Arch dies out). Distal edge of top flow (number 4 (?)) is also immediately west of Water-Canyon-Arch/synclinal-fold line. Distal edge of flow number 2 (?) is immediately to east of Water Canyon Arch in Cañon de Valle.

Bottom flow, number 1, appears to have the greatest lateral extent. Generally, moving eastward from Water-Canyon-Arch/synclinal-fold line, bottom flow 'rippled' facies underlies flow number 3(?) 'orange blocky' facies. Eventually, bottom flow turns into a 'massive' light-orange bench which is separated by a sandy parting from 'orange blocky' facies of flow number 3(?). The distal edge of Unit E is a 1.5 m 'orange blocky' facies which is probably distal edge of bottom flow.

Weathering of all facies generally presents massive appearance. 'Tenting', a weathering feature, is occasionally seen. 'Rippled rock' facies appears to exfoliate.

Unit upper part has red discoloration (in 'rippled rock') along joint faces and also has joint f[illegible] which have been leached white to a depth of 15 cm and then banded by 4 cm of pink tuff w[illegible] grades into normal light-gray ('massive'). Fumaroles are seen in 'horizontal fracture rock' facies i[illegible] Pajarito Fault zone on State Road 4.

Unit has been intensely altered in the vicinity of the Water Canyon Arch on south side of Wate[illegible] Canyon. The entire unit is soft. Beneath contact with Unit F, Unit E is pumice-rich. Unaltere[illegible] pumice (to 20 cm long) weather-out. Beneath pumice zone is a lithic-rich one with lithics up t[illegible] 10 cm long. Unit lower part is white with voids and appears leached. On north side of canyon 'horizontal fracture rock' and 'rippled rock' facies are still present in unit.

Unit can be identified using U, Fe, Th, and Cs content in 41.2% of cases. Number of cases use[illegible] was probably insufficient to characterize given unit complexity.

Unit E boundary partings may show laminar or cross bedding. Upper contact parting may be u[illegible] to 25 cm thick. Lower contact parting may be up to 1.2 m thick. Where lower contact parting [illegible] thick, lithics up to 0.4 m may be found at base of parting.

Qbt_D Unit D [0(?)-34(?) m] -- pink, brownish-gray, light gray to dark gray, nonwelded to dense welded tuff which weathers with thin light-brown, gray, or light-orange rind. Unit contains ra[illegible] lithics up to 25 cm in length. Pumice fragments with vapor-phase crystallization are commo[illegible] 0.2-1.5 cm in length but may be as long as 4.5 cm. Pumice color may be same as matrix or m[illegible] be gray, brown, pink, red, or lavender. Vapor-phase crystallization present throughout the u[illegible] Contains 0-1.5% iron-bearing crystals which may weather as pin-head size rust spots. Unit [illegible] may contain up to 3% iron-bearing crystals. Phenocryst content overall is 15-50%. Phenoc[illegible] grain size is fine-sand to 6 mm (pebble). Chatoyant feldspar may be seen in unit upper or [illegible] part.

Unit thins eastward and may be single flow. Unit extends farther eastward in the southern par[illegible] map area. Distal edge of unit probably extended beyond present day Rio Grande river cou[illegible] Unit D lithology is different from Unit E above or Unit C below. It is predominantly incipie[illegible]

to moderately welded tuff. Densely welded outcrops ('rippled rock' and 'massive' facies) are found in upper Water Canyon west of Water Canyon Arch. Unit is only unit to approximate a single cooling unit.
Unit upper and lower parts are slope formers. They may have easily disaggregated nodules (vapor-phase induration) which weather in relief. Upper part is much thinner than lower part. Middle part, 'massive' facies, forms a bench. 'Tenting', a weathering feature of bench top surface, occurs in vicinity of Los Alamos Canyon Arch or arch lineation west. Weathering of middle part may produce a 'swiss cheese' appearance. Most of unit has some degree of induration although the induration may be largely due to vapor-phase crystallization. 'Rotten' facies is not common.

Fumarole vents are preserved in the middle part. Iron-staining along cooling joints in Unit D is the most colorful and common for all units. Colors seen are yellows, oranges, reds, and purples. All colors may be seen in same outcrop.

Unit can be identified using U, Fe, Th, and Cs content in 94.7% of cases.

Unit D boundary partings may show laminar or cross bedding. Upper contact parting may be up to 1.2 m thick with lithics (up to 0.4 m) at the base. Lower contact parting is thin and rarely seen.

Qbt$_c$ Unit C [0(?)-44.2(?) m] -- pink, light to dark gray, incipiently welded to densely welded tuff which weathers with light-brown or orange-brown rind. Unit contains rare lithics up to 10 cm in length. Pumice fragments show vapor-phase crystallization and are commonly 0.3 to 1.7 cm in length but may be as long as 10 cm. Throughout most of unit, pumice fragments are rare or confined to stringers. In unit base and top, they may represent up to 50% of the rock. Pumice color may be same as matrix or gray. Vapor-phase crystallization present throughout unit. May contain 0.5-1% iron-bearing crystals in unit base up into unit middle. Diopsidic pyroxene identified in unit base. Phenocryst content overall is 5-20% with unit top and base having the smallest percentage. Phenocryst grain size is fine-sand to 3 mm (granule). Contains chatoyant feldspar.

Unit thins eastward and may represent three flows. Westernmost outcrops occur in upper Water Canyon west of Water Canyon Arch in southern part of map area. Distal edge of unit probably extended beyond present day Rio Grande river course.

Unit C lithology is different from Unit D above or Unit B below. Allowing for thickness changes, outcrop appearance over the plateau is remarkably consistent. Unit is 'massive' facies with exception of 'horizontal fracture rock' facies exposed in bottom of Water Canyon just east of Water Canyon Arch. On west side of White Rock Canyon of Rio Grande between Water and Ancho canyons, unit shows closely spaced columnar jointing. At places, unit top surface has fumarole vents.

Evidence for three flows, separated by discontinuous sandy partings, occurs near White Rock Basalt High in Pajarito Canyon and to south. South of Pajarito Canyon, unit reverses eastward thinning. In a north-south band approximately 2.4 km wide, unit may be twice as thick as it is to west or east. Band appears to be influenced by the White Rock Basalt High. Band crosses Potrillo (TA-36), Fence, Water (midreach), Ancho tributary (TA-39), and Ancho canyons.

Unit erases any residual effect of White Rock Basalt High. Unit C crosses channel fills without changing thickness appreciatively.
Unit is bench former. Stripping occurs on upper surface. 'Tenting', a weathering feature, occurs in a northeast-southwest band, approximately 3 km wide, beginning just east of Los Alamos Canyon Arch or arch lineation and extending to the southeast. Weathering affects joint frequency. Joint spacing is greater in Area G, TA-54, pits than on outcrop at edge of Mesita del Buey.

Unit can be identified using U, Fe, Th, and Cs content in 100% of cases.

Unit C boundary partings may show laminar or cross bedding. Upper contact parting is thin and rarely seen. Lower contact parting is also thin. On outcrop, lower parting can thicken from 0.9 cm to 15 cm and thin to 0 cm. Lower parting is more frequently seen from mid-plateau eastward.

Qbt_B Unit B [0-38(?) m] – white, light gray, pinkish gray, purplish gray, light orange, buff, salmon, incipiently to moderately welded tuff which weathers with gray, light-brown, brown, light-orange, or orange rind. Unit contains up to 3% lithics commonly 0.5-1 cm in length but up to 6 cm long. Unit base contains highest percentage of lithics. Pumice fragments show vapor-phase crystallization and represent 5-25% of rock. Generally, unit base and top contain the greatest percentage pumice. Pumice fragments may be up to 6 cm in length. Unit lithology is remarkable for number of pumice fragments in 0.1-1 cm range. Pumice color may be same as matrix or gray, lavender, light-brown, or brown. Vapor-phase crystallization present throughout unit. Lithophysae, with concentric shell structure, are occasionally seen near the unit base. Unit top occasionally contains < 0.5% iron-bearing crystals (perhaps, diopsidic pyroxene identified in top and base). Phenocryst content overall is 1-15%. Phenocryst content appears to decrease from base to top. Phenocryst grain size is medium sand to 3 mm (granule). Chatoyant feldspar may be seen in unit lower and middle part.

Unit thins eastward and may represent more than one ash flow. Distal edge of unit probably extended beyond present day course of Rio Grande. Unit thins to 0 m on White Rock Basalt High on western and northern edge of White Rock. White Rock Basalt High influences thickness north until reach Los Alamos Canyon and south until reach Ancho Canyon.

In both northern and southern parts of map area, unit does not extend west of Los Alamos Canyon Arch or arch lineation. Westernmost outcrops occur in Water Canyon 0.7 km west of confluence with Cañon de Valle in southern part of map area.

Unit B lithology is different from Unit C above or Unit A below. Unit is 'hole rock' facies with one exception. At eastern edge of plateau, lower part is orange welded tuff which may show closely spaced columnar jointing, 'massive' facies. In middle part of plateau, unit lower part, Unit 1b (Baltz et al, 1963), begins to lose its character and becomes indistinguishable from unit upper part, Baltz's Unit 2a. As move westward from Rio Grande, joint number decreases, massive appearance disappears, and finally color fades into gray. All of these changes occur immediately above the notch which marks boundary between Unit A and Unit B.

Unit is slope former in any given section. Unit B is slope between vertical expressions of Unit A below and Unit C above. An oddity since unit induration is Unit A < Unit B < Unit C. Weathering may produce a 'swiss cheese' appearance. Unit weathers to produce large holes. Holes are frequently aligned vertically or at some acute angle.

There are variations in unit profile in the eastern half of plateau. At Rio Grande, unit base is orange bench with a light gray slope above. Moving westward, unit base is orange bench with suggestion of bench forming in middle of light gray slope above. Midway, slope has orange coloration at top and bottom with light gray in middle. Orange coloration at top may be weathering product only. Further west, slope is white or light gray with orange coloration at top.

Unit completes the filling of topographic lows in erosional surface cut in Cerro Toledo Rhyolite tuffs, Otowi tuffs, and basaltic lavas and tuffs of Cerros del Rio. Unit B reaches its maximum thickness, 91(?)m, in a channel fill exposed in lower Water Canyon near the Rio Grande.

Unit can be identified using U, Fe, Th, and Cs content in 91.3% of cases

Unit B boundary partings may show laminar or cross bedding. Upper contact parting is predominantly thin but may be up to 15 cm thick in places. It is more frequently seen from mid-plateau eastward. Lower contact parting is thin and rarely seen.

Qbt$_A$ Unit A [0(?)-43(?) m] -- white, light-gray, gray, light-orange, orange, nonwelded to incipiently welded tuff which weathers with light-orange or orange rind. Unit upper part contains lithics commonly < 2 cm in length. Pumice fragments do not appear to be altered except in unit top where they show vapor-phase crystallization. Pumice fragments, 0.3-15 cm in length, are same color as matrix. Vapor-phase crystallization present in unit upper 1.5-3 m and may be especially intense in unit upper 0.9 m. Lithophysae, with concentric shell structure, are occasionally seen in unit top midway across (west to east) plateau. May contain 0.5% iron-bearing crystals in unit middle part. Diopsidic pyroxene identified in unit top. Phenocryst content overall is 7-10%. Phenocryst grain size is fine-sand to 3 mm (granule). Chatoyant feldspar may be seen in unit upper part.

Unit thins eastward and may represent one ash flow. Distal edge of unit probably extended beyond present day course of Rio Grande. Unit crops out farther westward in northern part of map area. Westernmost outcrops occur in Los Alamos Canyon just east of Los Alamos Canyon Arch. Outcrops in southern part occur 3 km east of outcrop meridian in northern part.

Unit A lithology is different from Unit B above or Otowi Member below. Unit is 'hole rock' facies. Unit primarily white or light gray. Beginning 4.5-6 m from top, unit changes to orange. Color change is associated with beginning of vapor-phase crystallization. Upper 4.5 m show increase in pumice fragments, lithics and crystals. Unit basal 0.6 m shows laminar bedding. Non-orange Unit A has hard pumice fragments which weather in relief. Pumice fragments may remain glassy, with fibrous structure and silky luster, throughout unit.

Unit rests on bedded air-fall tuffs of Tsankawi Pumice Bed, Tshirege Member, which are gray or salmon. In map area, Tsankawi is rarely seen outside of outcrops in Los Alamos and Pueblo Canyons. Tsankawi is frequently covered with colluvium. In places, Tsankawi is absent and Unit A rests on Otowi ash-flow deposits. Otowi upper part contains far more lithics than basal Unit A. Unit A not observed to rest on Cerro Toledo Rhyolite bedded tuffs which have appearance similar to Tsankawi.

Unit is first to fill in topographic lows of erosional surface cut in Cerro Toledo Rhyolite tuffs, Otowi tuffs, and basaltic lavas and tuffs of Cerros del Rio. Tsankawi blankets and preserves the erosional surface. Unit A reaches its maximum thickness, 69(?)m, in a paleotopographic low in lower Chaquehui Canyon near confluence with Rio Grande.

If exposed, unit expression is a vertical profile. Unit is frequently covered with colluvium. Base is rarely seen. Erosion of colluvium cover on lower part may produce tent rocks with Unit A pedestals and Unit C (predominantly) caps. Unit weathers to produce large holes. Holes are frequently aligned vertically or at some acute angle. Jointing does not obviously control hole alignment. Joints are difficult to see and can sometimes be recognized by caliche coatings which may weather in relief. Indian cliff dwellings were built in Unit A. It is thought that Indians enlarged existing holes at base of vertical cliffs.

Unit can be identified using U, Fe, Th, and Cs content in 100% of cases.

Unit upper contact weathers with a distinctive, pronounced notch which is widely traceable across plateau. In smooth-faced vertical cliffs, a darker line marks position where notch will develop. Stripping occurs on indurated top surface. Fumarole vents are preserved on top surface, and

fumaroles can be seen terminating at top surface. Fumaroles in unit do not show iron-discoloration. A thin, rarely seen sandy parting separates Unit A from Unit B.

Qbo OTOWI MEMBER [0(?)-46(?) m] -- nonwelded ash-flow tuffs and a basal, bedded air-fall pumice, the Guaje Pumice Bed. As mapped, does not include Guaje Pumice Bed. Unit may not have covered White Rock Basalt High. Unit deposited on Puye Formation or Basaltic lavas and tuffs of Cerros del Rio.

Ash-flow tuffs represent two or more ash flows. Unit is almost always covered with colluvium. Top is more likely to be seen than base. Upper and lower contacts are rarely seen. Erosion of colluvium cover may produce tent rocks with Otowi pedestals and Unit$_c$ (predominantly) caps.

Qbog Guaje Pumice Bed [0(?)-15(?) m] -- bedded air-fall pumice. Mapped independently from rest of Otowi Member.

QTp **PUYE FORMATION** [12(?)-61(?)] -- conglomerate and coarse sands with interbedded air-fall pumice. Material primarily derived from Jemez Mountains volcanics, Tschicoma Formation. Near Rio Grande, Puye also includes clasts of Precambrian quartzites and crystalline rocks. Landslide deposits in northeast corner of map area are result of Bandelier underlain by lake clays. As mapped, Puye includes these lake clays. Lake clays were not mappable on aerial photos because of their color. Outcrop could not be distinguished from dense growth of particular plant in area.

QTb **BASALTIC LAVAS AND TUFFS OF CERROS DEL RIO** [unknown] -- thick sequence which forms the White Rock Basalt High. In Cerros del Rio on east side of White Rock Canyon of Rio Grande, sequence is more than 396 m thick (Griggs, 1964).

Tsf **SANTA FE GROUP** **As Used By Galusha and Blick (1971)** [unknown] -- strongly deformed, poorly indurated, fossiliferous, basin-fill sediments of the Española Basin. Deposits are not the product of a through-flowing ancestral Rio Grande. Galusha and Blick (1971) give a thickness of greater than 1370 m.

SELECTED REFERENCES

Bailey, R. A., Smith, R. L., and Ross, C. S., 1969, Stratigraphic nomenclature of volcanic Rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey Bulletin 1274-P, 19 p.

Baltz, E. H., Abrahams, J. H., Sr., Purtymun, W. D., 1963, Preliminary report on geology and hydrology of Mortandad Canyon near Los Alamos, New Mexico, with reference to disposal of liquid low-level radioactive wastes: U.S. Geological Survey Open-file Report

Budding, A. J. and Purtymun, W. D., 1976, Seismicity of Los Alamos area based on geologic data: Los Alamos Scientific Laboratoy Report LA-6278-MS

Galusha, T. and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: Bulletin American Museum Natural History, 144 : 1, 127 p.

Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area New Mexico: U.S. Geological Survey Water-Supply Paper 1753, 107 p.

Heiken, G. F., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S., and Hagan, R., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico: Journal Geophysical Research, 91, 1799-1815.

Kelly, T. E., 1975, Evaluation of monitoring of radioactive solid-waste burial sites at Los Alamos, New Mexico. U. S. Geological Survey, Open-file Report no. 75-406, 82 p.

Rogers, M. A., 1977, History and environmental setting of LASL near-surface land disposal facilities for radioactive wastes (Areas A, B, C, D, E, F, G, and T): a source document, Volumes I and II, Los Alamos Scientific Laboratoy, University of California, LA-6848-MS, 425 p.

Ross, C. S., and Smith, R. L., 1961, Ash-flow tuffs: their origin, geologic relations, and identification: U.S. Geological Survey Professional Paper 366, 81 p.

Smith, R. L., 1960, Ash flows: Geological Society America Bulletin, 71, 795-842.

Smith, R. L., 1960, Zones and zonal variations in welded ash flows: U.S. Geological Survey Professional Paper 354-F, 15 p.

Smith, R. L., and Bailey, R. A., 1966, The Bandelier tuff: a study of ash-flow eruption cycles from zoned magma chambers: Bulletin Volcanologique, XXIX, p. 83-104

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Investigations Series Map I-571.