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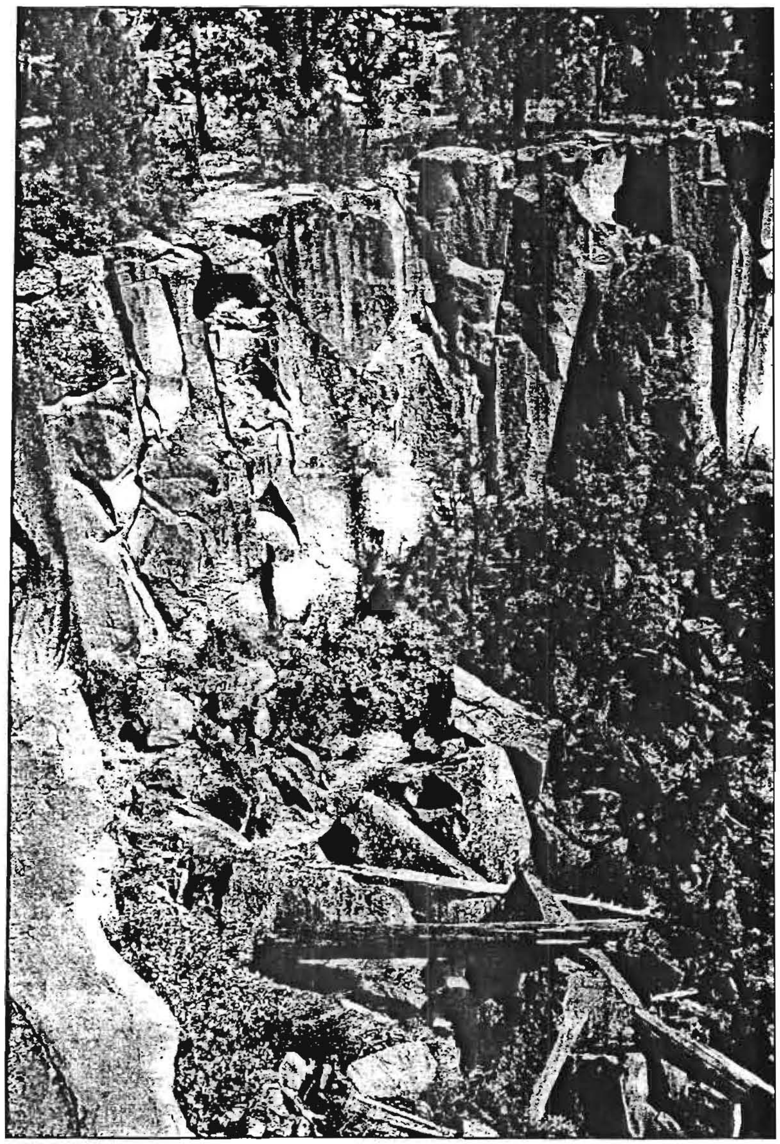
Stratigraphic Nomenclature of the Bandelier Tuff for the Environmental Restoration Proj at Los Alamos National Laboratory



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Cover photo shows view of vertical cliffs in unit 2 of Tshirege Member, located on the north wall of Los Alamos canyon near TA-21. Unit 2 is a prominent cliff-former throughout the Pajarito Plateau because of its welded nature. The bench visible at the top of the photo is developed of soft, nonwelded tuffs of unit 3.

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Stratigraphic Nomenclature of the Bandelier Tuff for the Environmental Restoration Project at Los Alamos National Laboratory

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STRATIGRAPHIC NOMENCLATURE OF THE BANDELIER TUFF FOR THE ENVIRONMENTAL RESTORATION PROJECT AT LOS ALAMOS NATIONAL LABORATORY

by

David E. Broxton and Steven L. Reneau

ABSTRACT

This technical-guidance document sets forth a system of stratigraphic nomenclature for the Bandelier Tuff for use by the Environmental Restoration Project at Los Alamos. It identifies the major lithologic characteristics of the Bandelier Tuff, defines criteria for unit classification, and provides guidance for the consistent use of rock names. This proposed nomenclature system will improve the exchange of information among investigators working at different field units by providing a common stratigraphic framework for discussing the influence of geology on contaminant transport.

The proposed nomenclature, described in ascending stratigraphic order, is as follows. The Otowi Member, except for its basal Guaje Pumice Bed, is treated as a relatively homogeneous sequence of nonwelded ash-flow tuffs, and no change from the formal usage of Bailey *et al.* (1969) is proposed. A sequence of volcaniclastic rocks of mixed provenance lies between the two members of the Bandelier Tuff and is given the informal name of *tephras and volcaniclastic sediments of the Cerro Toledo interval*. This unit contains deposits normally assigned to the Cerro Toledo Rhyolite as well as coarse-grained detritus derived from lava flows of the Tschicoma Formation. The Tshirege Member of the Bandelier Tuff is a compound cooling unit divided into the basal Tsankawi Pumice Bed and four ash-flow tuff cooling units. Because of its complex cooling history, the physical properties of these tuffs vary both vertically and laterally. The lower three cooling units crop out in the central and eastern part of the Laboratory, and the fourth is present

only in the western part. These cooling units, labeled 1 through 4 in ascending order, represent episodes of ash-flow deposition that were separated by partial cooling breaks. Additional subunits are specified within the cooling units to differentiate zones of distinct lithological or rock properties.

The proposed nomenclature is applicable to the Bandelier Tuff in the central and eastern part of the Laboratory. Refinements to the nomenclature will take place after stratigraphic studies in the western part of the Laboratory are complete. These refinements are necessary because the internal stratigraphy of the Bandelier Tuff varies with distance from its caldera sources.

INTRODUCTION

The Bandelier Tuff is a complex volcanic rock unit whose physical properties vary both vertically and laterally. Previous Laboratory investigators divided members of the Bandelier Tuff into subunits for mapping and borehole studies because variations in physical properties can influence the transport pathways of subsurface contaminants. The nomenclature used by earlier workers was not applied consistently, and the Bandelier Tuff has been divided a number of different ways during geologic and hydrologic investigations dating back to the 1940s.

Several of these different nomenclature systems have been incorporated into Environmental Restoration (ER) Project documents such as work plans, phase reports, and the Installation Work Plan. Such inconsistent use of nomenclature impedes communication among ER investigators and confuses regulators and stakeholder groups. This technical guidance document

(1) identifies the major lithologic characteristics of the Bandelier Tuff— particularly of the Tshirege Member,

(2) defines criteria for unit classification, and

(3) provides guidance for consistent use of rock names.

This document is designed to improve the exchange of information among investigators working at different field units by providing a common framework for discussing the influence of geology on contaminant transport.

Figure 1 provides a map of the geographic sites and Laboratory facilities discussed in this report.

HISTORICAL PERSPECTIVE

The Jemez volcanic field has been studied by numerous investigators over the past 50 years. Some studies were regional in nature and covered the entire volcanic field, whereas others were limited to Laboratory property on the Pajarito Plateau. Many of these studies were concurrent or at least overlapped in time. Despite the general interest in defining

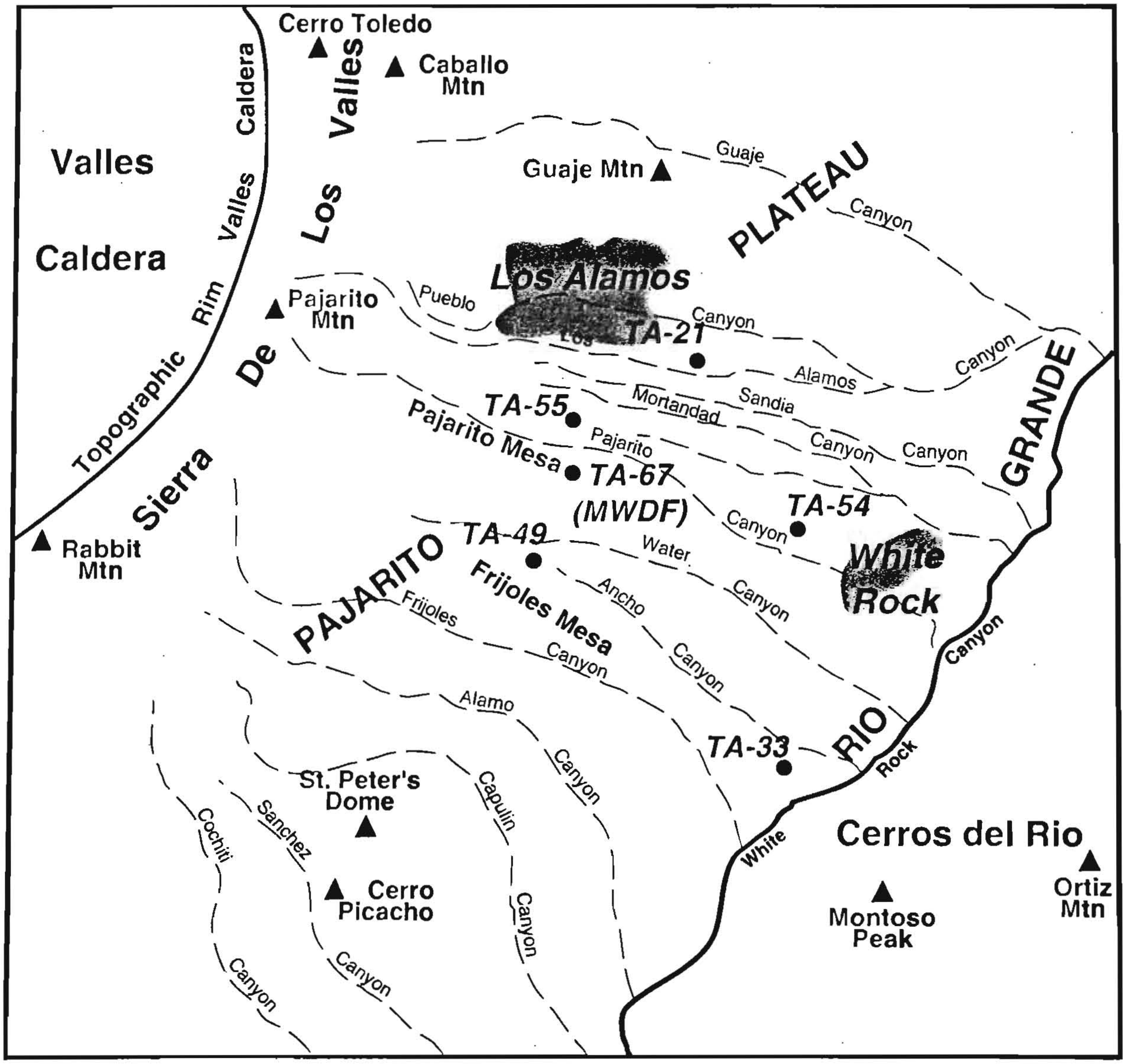

Fig. 1. Location of geographic sites and Laboratory facilities discussed in this report.

subunits of the Bandelier Tuff during these investigations, there was little standardization of nomenclature except within individual research groups. Lack of standardization is partly attributed to evolving stratigraphic concepts, which resulted in different groups of workers using different criteria to identify the units. But equally important, differences in nomenclature arose because many studies were site-specific, whereas the internal stratigraphy of the Bandelier Tuff varies on a regional scale—changing as a function of distance from its caldera sources.

We review the development of stratigraphic concepts for the Bandelier Tuff in the discussion below. This brief review is restricted to those studies that are relevant to the subdivision of the Bandelier Tuff into more narrowly defined units. The discussion is presented in the sequence that field investigations were initiated, not necessarily in the sequence of publication. In fact, overlapping publication dates by different groups of workers contributed to the use of several concurrent systems of nomenclature.

Stratigraphic correlations discussed in this report were achieved by carefully reading the literature to identify the diagnostic characteristics that previous workers used to define and differentiate units of the Bandelier Tuff. Field studies were also conducted at many of the locations cited in the literature to determine how contacts were defined and where they were placed in the tuff sequence.

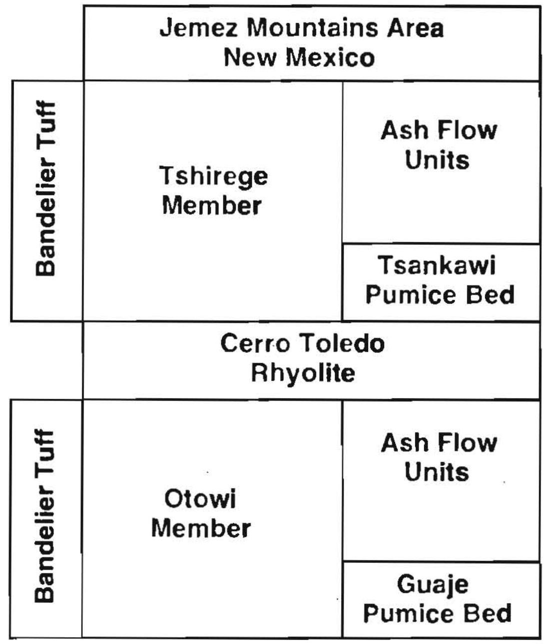

Fig. 2. Nomenclature of lower Pleistocene pyroclastic units of the Jemez Mountain area, New Mexico. After Bailey et al. *(1969) and Smith* et al. *(1970).*

Formal Stratigraphy

The *Bandelier Rhyolite Tuff* was first described by H.T.U. Smith (1938) for outcrops in the Abiquiu quadrangle on the north side of the Jemez volcanic field. Griggs (1964) shortened the name to *Bandelier Tuff* and subdivided the unit into three members, in ascending order:

(1) *Guaje Member*, a bedded pumice-fall deposit,

(2) *Otowi Member*, a massive pumiceous ash-flow tuff, and

(3) *Tshirege Member*, a succession of cliff-forming ash-flow tuffs.

Based on additional knowledge of its overall character and on genetic considerations, Bailey *et al.* (1969) formally subdivided the Bandelier Tuff into two stratigraphic and genetically equivalent members, each consisting of a basal pumice fall overlain by a petrologically related succession of ash-flow tuffs. The Otowi Member of Bailey *et al.* (1969) is equivalent to the Otowi Member of Griggs (1964) but was extended to include the underlying Guaje Pumice Bed (Fig. 2). The upper member of the Bandelier Tuff was designated the Tshirege Member, and it included the basal Tsankawi Pumice Bed and overlying ash-flow tuffs that are equivalent to the Tshirege Member of Griggs.

Eruption of the two members of the Bandelier Tuff was accompanied—in each case—by caldera collapse. The Otowi Member was erupted from the earlier of the two calderas, which was coincident with and largely destroyed by the younger

Valles caldera (Self *et al.*, 1986; Smith *et al.*, 1970). The Valles caldera was the source of the Tshirege Member (Smith and Bailey, 1966; Smith *et al.*, 1970).

The *Cerro Toledo Rhyolite* consists of rhyolitic lava flows, rhyolitic tuffs and tuff breccias, and their associated sediments (Smith *et al.*, 1970). These lava flows and pyroclastic rocks were erupted from the Cerro Toledo and Rabbit Mountain rhyolite domes located in the Sierra de los Valles (Fig. 1). The Cerro Toledo Rhyolite lies between the Tshirege and Otowi Members, but it is not considered part of the Bandelier Tuff (Fig. 2) because of its unique petrologic features and its different eruptive style and source.

The stratigraphic units of Bailey *et al.* (1969) and Smith *et al.* (1970) represent the formal system of nomenclature for the Bandelier Tuff and are widely accepted by the scientific community. The informal designation of subunits is far less straightforward and is the main topic of this technical guidance document.

Informal Stratigraphy

C.S. Ross of the US Geological Survey (USGS) began mapping the Jemez volcanic field in the 1920s. Ross was joined in the mapping effort by USGS colleagues R.L. Smith and R.A. Bailey, and together they completed the map of the volcanic field by 1966 (Smith *et al.*, 1970).

In addition to mapping, the USGS investigations focused on the development and evolution of caldera structures associated with cataclysmic eruptions of the Bandelier Tuff. The Tshirege Member was divided into five informal subunits composed of groups of ash-flow tuffs or petrologically distinct zones that could be correlated throughout the volcanic field (Smith and Bailey, 1966). Correlations of these subunits made for numerous stratigraphic sections were based on welding, crystallization, and mineralogic features of the tuff. This system of nomenclature was published many years after most of the work was completed, and it was not widely available for contemporary investigators to use. In 1966, Smith and Bailey described their subunits in preliminary form, but the descriptions were too general to be of much use to other investigators. More detailed descriptions were never published.

Figure 3 shows the nomenclature developed by Smith and Bailey and includes its probable correlation with nomenclature developed by other investigators. Although the contacts between units developed by Smith and Bailey shown here appear to correlate with the nomenclature proposed in this report, Smith and Bailey's original descriptions are too general for a precise correlation of units.

At the same time that Smith *et al.* were conducting their regional studies, Los Alamos and USGS investigators were conducting geologic and hydrogeologic studies on the Pajarito Plateau in support of Laboratory programs. Like Smith *et al.*, these investigators recognized that the Tshirege Member is not a single homogenous layer of tuff, but consists of a succession of cliff-forming tuffs whose physical properties vary both vertically and laterally. Subunits were defined based on surface-weathering patterns, welding features, and crystallization characteristics. Welding and crystallization characteristics of the tuff were controlled by emplacement temperatures, thick-

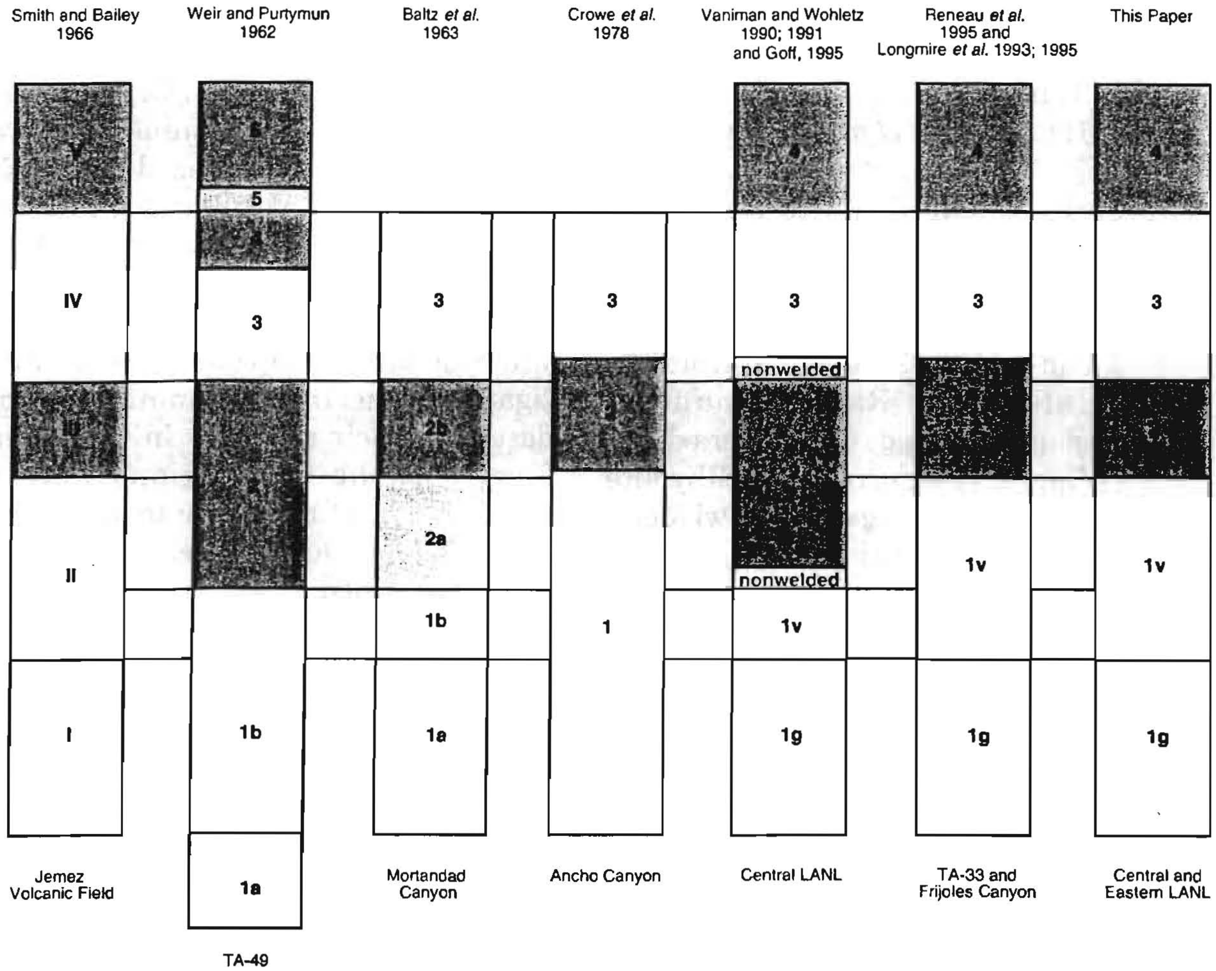

Fig. 3. Chart showing correlation of rock unit names applied to the Tshirege Member of the Bandelier Tuff by various investigators.

nesses, gas contents, and compositions (Smith, 1960a; 1960b). The effect of welding on hydrologic properties was of particular interest because of efforts to understand how groundwaters transport contaminants through the tuffs.

Geologic and hydrologic investigations were conducted at Laboratory Site TA-49 on Frijoles Mesa from 1959 to 1960. The purposes of the TA-49 investigations were to provide geologic information about the rocks at the site and to define the direction and rate of groundwater movement in the zone of aeration as well as in the zone of saturation (Weir and Purtymun, 1962). During their mapping and borehole studies, Weir and Purtymun, aided by E. Baltz, divided the Tshirege Member into six lithologic subunits (Fig. 3). Units in the subsurface were correlated by gamma-ray neutron logs and lithologic logs for four coreholes and five wells.

Baltz *et al.* (1963) divided the Tshirege Member into informal subunits during geologic and hydrologic investigations in Mortandad Canyon from 1960 to 1961. These studies, conducted by the USGS in cooperation with the US Atomic Energy Commission and Los Alamos Scientific Laboratory, were designed to evaluate upper Mortandad Canyon as a disposal site for treated liquid low-level radioactive waste. The Tshirege Member was mapped as several lithologically distinct units to determine the geologic structure and to discover if lithologic differences might affect infiltration of water (Baltz *et al.*, 1963). Baltz *et al.* assigned names to subunits at Mortandad Canyon, as shown in Fig. 3, and made the following correlations of Tshirege subunits between Frijoles Mesa and Mortandad Canyon.

> *"Layers 1a and 1b at Mortandad Canyon correlate with unit 1b ... at Frijoles Mesa. The subsurface unit designated by Weir and Purtymun as unit 1a.... is probably equivalent to the upper part of the rocks assigned to the Otowi Member in the subsurface at Test Well 8 in Mortandad Canyon. Unit 2 at Mortandad Canyon is equivalent to unit 2 of Weir and Purtymun at Frijoles Mesa. The soft lower part of unit 3 at Mortandad Canyon is equivalent to unit 3 at Frijoles Mesa. The ledge-forming upper part of unit 3 at Frijoles Mesa may be equivalent to unit 4 at Frijoles Mesa but was not mapped separately at Mortandad Canyon."*

The units described Baltz *et al.* (1963) were later applied by Purtymun (in Keller, 1968) to TA-53 and by Purtymun and Kennedy (1971) to TA-54. Additional confusion in nomenclature resulted from a drilling program at TA-54 (Kearl *et al.*, 1986), in which workers chose different contacts but used the unit terminology of Purtymun and Kennedy (1971). For example, Purtymun and Kennedy (1971) report an average unit 1b thickness of 25 ft, whereas the logs of Kearl *et al.* (1986) indicate that the same unit is up to 75 ft thick.

In 1977, geologic and geochemical characterization of the Bandelier Tuff was undertaken to evaluate the geology of waste disposal sites at the Laboratory (Crowe *et al.*, 1978). Based on their work and that of Smith (1960a; 1960b) and Ross and Smith (1961), Crowe *et al.* applied the cooling unit concept to divide the Tshirege Member into subunits. A cooling unit, which consists of an ash flow or a sequence of ash flows that weld and cool as a single entity, is the fundamental stratigraphic unit in the study of ash flows (Smith, 1960a, 1960b). Crowe *et al.* delineated three cooling units in the Tshirege Member in the central and eastern part of the Pajarito Plateau (Fig. 3). Partial cooling breaks separate the three cooling units. Each of these cooling breaks represents a brief hiatus in the deposition of the ash flows that strongly influenced the development of alternating welded zones. Because time separating the deposition of individual cooling units was insufficient to allow complete cooling, patterns of welding and crystallization in the Tshirege Member are more complex than might be expected in a simple cooling unit. Smith (1960a) coined the term *compound cooling unit* to describe the ash-flow tuffs with complex cooling histories like that of the Tshirege Member.

In 1990, Vaniman and Wohletz (1990; 1991) mapped the central part of the Laboratory as part of an assessment of seismic hazards in the vicinity of special nuclear facilities. Vaniman and Wohletz adopted the cooling unit framework of Crowe *et al.*, but delineated the boundary between cooling units 1 and 2 differently (Fig. 3). Vaniman and Wohletz also identified separate nonwelded units above and below unit 2. Furthermore, tuffs in unit 1 were divided into a lower glassy part (unit 1g) and an upper crystalline, vapor-phase-altered part (unit 1v). Goff (1995) adopted the nomenclature of Vaniman and Wohletz when he mapped the bedrock geology at TA-21 in 1992. Broxton *et al.* (1995a; 1995b) also followed the nomenclature of Vaniman and Wohletz for stratigraphic studies at TA-21 but placed the boundary between units 1v and 2 higher in the section.

Longmire *et al.* (1993, 1995) and Reneau *et al.* (1995) conducted background geochemistry and geomorphic studies in Frijoles Canyon and at TA-33 from 1990 to 1994. These studies used Vaniman and Wohletz's terminology but also used some of the mapping boundaries of Baltz *et al.* (1963).

The State of New Mexico will publish a bedrock geologic map of the Laboratory by Margaret Anne Rogers & Associates, Inc., in the near future. The geologic map will cover the entire Laboratory at a scale of 1:4800 and will consist of 24 separate map sheets. Units of the Bandelier Tuff will have letter designations (A through F; see Rogers, 1989), but it is uncertain how the map units will correlate to other unit names already in use. The mapping was conducted in the 1970s, but Roger's system of nomenclature can not be treated further in this report because the map is not yet available for review.

RECOMMENDED NOMENCLATURE

This technical-guidance document attempts to resolve the confusion of multiple systems of stratigraphic nomenclature for the Bandelier Tuff. Nomenclature systems developed by previous workers were reexamined and correlated to determine where overlapping unit definitions occur (Fig. 3). Stratigraphic data from recent ER studies were examined to evaluate the criteria for identifying and naming the units (Broxton *et al.*, 1995a; 1995b). The criteria for recognition and recommended nomenclature developed as a part of this process should allow ER investigators to consistently recognize and name these units in the central and eastern part of the Laboratory.

Recommended nomenclature for informal subunits of the Tshirege Member is shown in Figs. 3 and 4. Characteristic features of these subunits (hereafter referred to as *units*) are defined in the following paragraphs. Guidelines for unit definitions are as follows:

(1) Units are divided and named on the basis of cooling units, which are the fundamental mapping units for defining the geometry and distribution of the tuffs.

(2) Lithological characteristics of units are sufficiently distinct that the units can be recognized and correlated in both outcrops and boreholes.

(3) The nomenclature system is flexible enough to accommodate greater or less detail, new information, and other special needs. Lithological characteristics of cooling units vary laterally and, under certain circumstances, distinctions between units may not be recognizable; in such cases, units can be lumped together (for example, unit 1v/2). Additional subunits may also be delineated (for example, unit 3a, 3b, etc.).

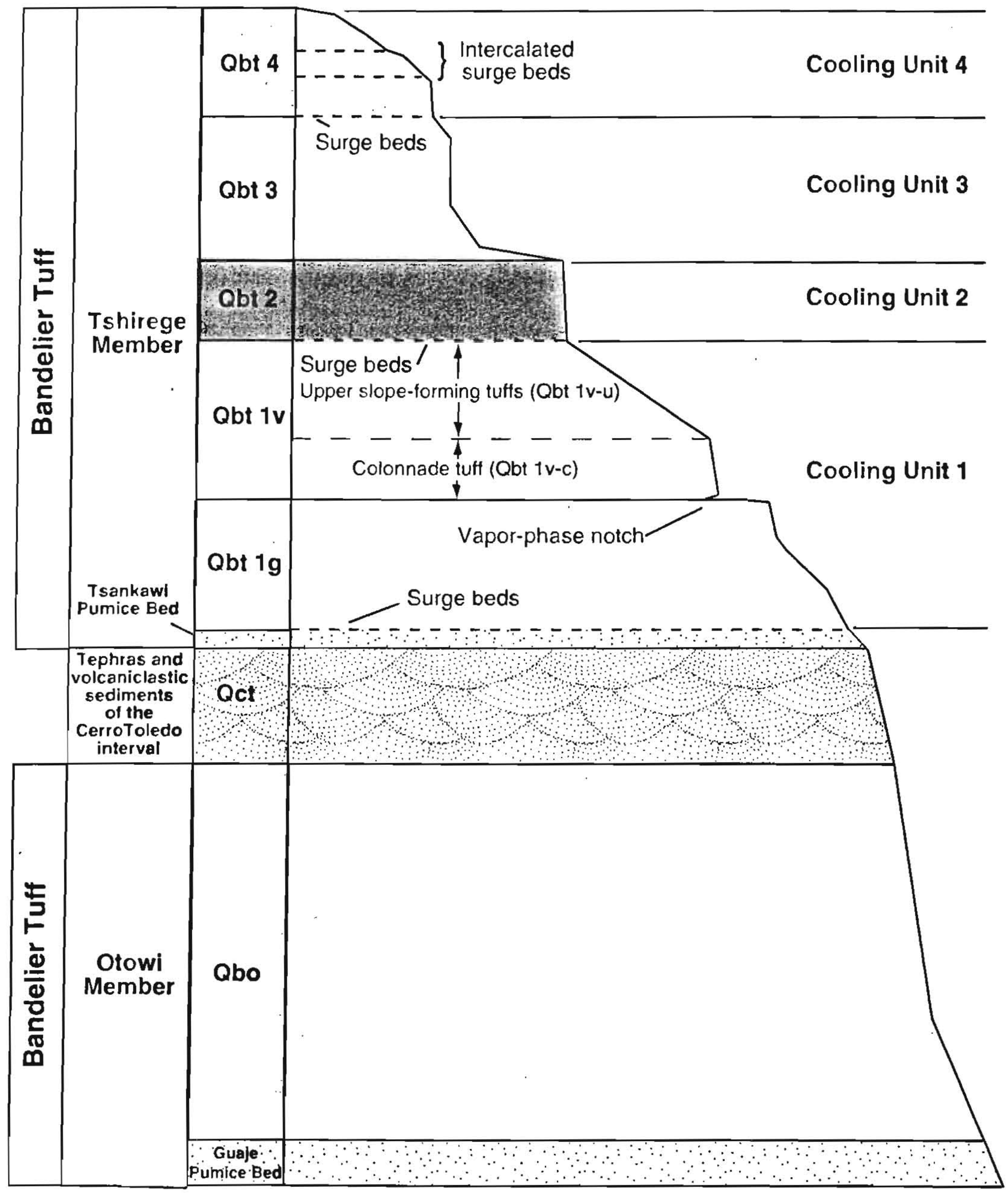

Fig. 4. Nomenclature of the Bandelier Tuff for the Laboratory's ER Project.

(4) To the extent possible, the stratigraphic framework presented here conforms to older systems of nomenclature already in widespread use in the ER Project. For example, many of the contacts and some of the unit designations of Baltz *et al.* (1963) and Vaniman and Wohletz (1990, 1991) are retained in the proposed nomenclature.

The following descriptions summarize the diagnostic features of units within the Bandelier Tuff. These descriptions are applicable to the central and eastern part of the Laboratory. Ongoing studies, directed by the ER Project Earth Science Technical Council, are investigating the characteristics of the Bandelier Tuff in the western part of the Laboratory. In these near-source areas, the ash-flow deposits were thicker and deposition temperatures probably were higher. As a result, it is possible that some cooling units have merged in these areas.

Otowi Member, Bandelier Tuff

The Otowi Member of the Bandelier Tuff (1.61 Ma; Izett and Obradovich, 1994) is a relatively homogenous unit made up of a succession of ash-flow tuffs. The ash-flow tuffs are nonwelded to partially welded in most areas studied, and the entire sequence of tuffs apparently forms a simple cooling unit. The thickness of the Otowi Member is variable across the Laboratory because it was deposited over a deeply dissected paleotopography and was subject to about 400,000 years of erosion before deposition of the Tshirege Member. The Otowi Member's maximum reported thickness is 130 m in Test Well 8 (Baltz *et al.*, 1963), which is located in Mortandad Canyon in the central part of the Laboratory. The Otowi Member also is very thick (126 m) in the southwestern part of the Laboratory at borehole SHB-3 (Gardner *et al.,* 1993). In some areas, including the eastern part of TA-33 (Reneau *et al.*, 1995) and in White Rock, the Otowi Member is absent. The base of the Otowi Member includes the Guaje Pumice Bed, a thick (10- to 20-m), crudely stratified pumice fall deposit. Because of its relative homogeneity, further division of the Otowi Member is unwarranted at this time, and the formal stratigraphy of Bailey *et al.* (1969) should be used.

The Otowi Member is exposed in the central and lower reaches of Los Alamos and Pueblo Canyons, where it crops out in the lower canyon walls. It is a slope-forming unit that consists of light gray to pinkish-orange pumice lapilli supported by a white-to-tan, ashy matrix. The matrix is made up of glass shards, broken pumice fragments, phenocrysts, and fragments of nonvesiculated perlite. The Otowi Member contains 7 to 9% phenocrysts, mostly quartz and sanidine (Broxton *et al.*, 1995a). Shards are glassy and clear, showing no evidence for either post-emplacement high-temperature devitrification or subsequent low-temperature diagenetic alteration. Pumice lapilli typically make up 10 to 30% of the tuff, are equant to subequant (aspect ratios = 1:1 to 2:1), and range from 0.5 to 6 cm in diameter. Pumices are larger (up to 20 cm) and more abundant (~40% of the rock) in the exposed upper part of the member. These pumices have a vitreous luster on fresh surfaces, and the excellent preservation of delicate tubular vesicles gives them a fibrous appearance. Pumice and matrix materials acquire a pinkish-orange coloration near the top of the unit. This coloration may be due to either oxidation of iron by escaping vapors as the ash-flow sheet cooled or incipient weathering of the top of the unit before overlying units were deposited.

In Los Alamos Canyon, the exposed upper part of the Otowi Member contains up to 5% chocolate-brown, black, and red lithics derived from intermediate-composition lava flows. These lithics are smaller and more abundant than those typically found in the overlying Tshirege Member and are diagnostic.

Tephras and Volcaniclastic Sediments of the Cerro Toledo Interval

Tephras and volcaniclastic sediments of the Cerro Toledo interval is an informal name given to a sequence of epiclastic sediments and tephras of mixed provenance that lies between two members of the Bandelier Tuff. The age of this unit is bracketed by those of the Tshirege and Otowi Members (1.22 to 1.61 Ma; Izett and Obradovich, 1994). This unit contains some deposits normally assigned to the Cerro Toledo Rhyolite, including tuffaceous sandstones and siltstones and primary ash-fall and pumice-fall deposits (Smith *et al.*, 1970; Heiken *et al.*, 1986). The Cerro Toledo interval also contains intercalated deposits not normally assigned to the Cerro Toledo Rhyolite; these include poorly sorted coarse-grained detritus derived from lava flows of the Tschicoma Formation. In most cases, both types of volcaniclastic deposits are intercalated, and it is not practical to separate them. Following the usage of Smith *et al.* (1970), deposits of the Cerro Toledo interval are not considered part of the Bandelier Tuff.

The Cerro Toledo interval is 3 to 12 m thick in the vicinity of TA-21 (Broxton *et al.*, 1995a), 11 m thick in borehole 49-2-700-1 at TA-49 (Stimac et al., 1995) 12 m thick in borehole 54-1004 at TA-54 (Caporuscio, 1994), 42 m thick in borehole SHB-1 at TA-55 (Gardner *et al.*, 1993), and 27 m thick in borehole SHB-3 at TA-1 (Gardner *et al.*, 1993). These deposits also crop out in Los Alamos Canyon at TA-41, in DP Canyon east of DP Spring, in Pueblo Canyon, and locally in Ancho Canyon near State Road 4. Cerro Toledo deposits have a widespread distribution throughout the area; however, predicting their presence and thickness is problematic because they were deposited by fluvial systems of unknown extent. In some places, including a prominent exposure in Ancho Canyon along State Road 4, no significant deposits are present in this interval, and the Tshirege Member directly overlies the Otowi Member.

The tuffaceous sediments in the Cerro Toledo interval generally have well-defined stratification imparted by grading and sorting of ash- to block-sized clasts. Bedding characteristics include graded bedding, cross bedding, and planar bedding. Most individual beds pinch out laterally and can not be correlated over wide areas. Orange oxidation and clay-rich horizons suggest that at least two periods of soil development are recorded within the Cerro Toledo deposits (Broxton *et al.*, 1995a).

The tuffaceous portion of the Cerro Toledo interval also contains primary pumice and ash-fall deposits. These pumice and ash falls may be useful time-stratigraphic markers for correlating deposits over wide-spread areas of the Pajarito Plateau, but additional work is needed in order to establish correlations between individual tephras. The pumice falls tend to form porous and permeable horizons within the Cerro Toledo interval, and locally they may provide important pathways for moisture transport in the vadose zone.

Volcaniclastic sediments derived from dacitic lavas of the Tschicoma Formation include sand, gravel, cobble, and boulder deposits interbedded with the tuffaceous sediment. At TA-21, the coarse, dacitic deposits are typically 0.25 to 1.2 m thick and generally occur as overlapping lenticular paleochannels up to 1 m deep (Broxton *et al.*, 1995a).

The proportion of tuffaceous and dacitic detritus that compose deposits of the Cerro Toledo interval vary from location to location across the Pajarito Plateau. Cerro Toledo deposits in Los Alamos Canyon are predominantly tuffaceous in character. However, these deposits are largely made up of dacitic detritus in lower DP Canyon (Goff, 1995) and in the subsurface at TA-55 (Gardner *et al.*, 1993).

Tshirege Member, Bandelier Tuff

The Tshirege Member of the Bandelier Tuff (1.22 Ma; Izett and Obradovich, 1994) is a compound cooling unit divided into four distinct cooling units on the Pajarito Plateau. The lower three units are equivalent to those identified by Crowe *et al.* (1978), and the fourth crops out in the western part of the Laboratory, where it was mapped by Vaniman and Wohletz (1990) and Vaniman and Chipera (1995). These units (labeled 1 through 4 in ascending order, as shown in Figs. 3 and 4) represent episodes of rapid ash-flow eruption and deposition. The episodes were separated by periods of inactivity that were long enough for partial cooling to occur before a subsequent succession of ash flows.

The maximum reliable thickness reported for the Tshirege Member is 171 m—in borehole 48-2-700-1 at TA-49 (Stimac *et al.*, 1995). Somewhat greater thicknesses (~200 m) were reported for boreholes DT-5, DT-5A, DT-P, DT-9, and DT-10 (Weir and Purtyman, 1962), but *tephras and volcaniclastic sediments of the Cerro Toledo interval* were not differentiated from the Tshirege Member. Nonetheless, the deposits of the Tshirege Member are very thick in the southern part of the Laboratory compared to those in the north and central part of the Laboratory (for example, 98 m at TA-21 (Broxton *et al.*, 1995).

The degree of welding in the Tshirege Member varies both vertically and laterally. Welding tends to increase upsection, indicating that tuffs in the upper part of the member generally were emplaced at higher temperatures. Using Fe-Ti and two-pyroxene geothermometry, Warshaw and Smith (1988) showed that the lower part of the Tshirege Member had a pre-eruption temperature of ~700°C, whereas the pre-eruption temperature in the upper part was ~850°C. Welding for all cooling units is typically greatest in the western part of the Laboratory, where these tuffs are thicker nearer to the Valles caldera. In general, this increased welding means that the matrix permeability will likely decrease westward for units of the Tshirege Member. On the other hand, because welded tuffs are more susceptible to brittle failure, fracture permeability may be important for groundwater movement where the tuffs are strongly welded.

Tsankawi Pumice Bed

The Tsankawi Pumice Bed is the basal pumice fall of the Tshirege Member. It is typically 20 to 100 cm thick in the Los Alamos region and consists of angular to subangular clast-supported pumice lapilli up to 6 cm in diameter. Pumices are typically fibrous with a vitreous luster. Pumices in the Tsankawi Pumice Bed are mostly rhyolitic in composition, but there is also a small (<5%) population of medium-gray, dense, finely vesiculated dacitic hornblende-bearing pumice. These hornblende-bearing pumices are a diagnostic feature of the Tsankawi Pumice Bed and of overlying ash-flow units (Bailey *et al.*, 1969). The Tsankawi Pumice Bed is a lithologically distinct unit and it is easily distinguished from the ash-flow tuffs of unit 1g.

Unit 1

Cooling unit 1 is a thick succession of ash-flow tuffs that were deposited over a widespread area of the Pajarito Plateau. These tuffs initially filled canyons and valleys of the pre-Bandelier surface before spreading out laterally as a sheet-like deposit that dips gently east-southeast. Unit 1 is characterized by lack of welding where exposed, despite its great thickness in some areas. The unit is further divided into a lower glassy tuff (1g), which is equivalent to unit 1g of Vaniman and Wohletz (1990; 1991) and unit 1a of Baltz *et al.* (1963), and an upper devitrified and vapor-phase crystallized tuff (1v), which is redefined from Vaniman and Wohletz.

At several locations, distinctive pumice-poor surge deposits form the base of unit 1g (Broxton *et al.*, 1995a). Where present, these deposits are typically 10 to 25 cm thick and contain undulating, laminated, dune-like beds (Broxton *et al.*, 1995a). The deposits consist of coarse ash and abundant broken crystals in beds 0.5 to 9 cm thick. The surge deposits are overlain by a white, pumice-poor ash-flow tuff that grades upwards into the pumiceous tuffs that make up the main body of unit 1g.

The main body of unit 1g is characterized by the presence of abundant volcanic glass, lack of welding, and a distinct Swiss-cheese appearance on weathered cliff faces. These tuffs consist of light-gray, vitreous, pumice lapilli supported by a matrix of coarse ash, shards, pumice fragments, and abundant (12 to 16%) quartz and sanidine phenocrysts (Broxton *et al.*, 1995a). Pumices are commonly 2 to 5 cm in diameter but can reach up to 14 cm locally. The tuff is poorly consolidated and light-gray to white near the base of the unit, but it becomes more consolidated and light orange upsection. In outcrops, the top of unit 1g is a resistant, cliff-forming tuff, the upper part of which forms a bench that is several meters wide locally. The bench marks the base of the vapor-phase notch of Crowe *et al.* (1978)—a thin, horizontal zone of preferential weathering that forms an easily recognizable marker horizon throughout much of the Pajarito Plateau. The vapor-phase notch marks the transition from the glassy tuffs of unit 1g (*g* representing glassy) to the crystallized tuffs of unit 1v (*v* representing vapor-phase crystallization). The contact is gradational over 1 to 2 m and has been arbitrarily selected as the first appearance of volcanic glass going downsection.

Unit 1v forms a combination of cliff-like and sloping outcrops that separate the resistant bench at the top of unit 1g from the near-vertical cliff of unit 2. The basal part of unit 1v is a resistant, orange-brown tuff that overlies the bench on top of unit 1g. This basal part has a "colonnade" appearance because of the abundant vertical fractures that serve as failure planes for rock falls, resulting in smooth dihedral surfaces on cliff faces (Qbt 1v-c in Fig. 4; *c* representing colonnade). This colonnade tuff is equivalent to unit 1b of Baltz *et al.* (1963) and unit 1v of Vaniman and Wohletz (1990; 1991). The colonnade tuff is overlain by mainly slope-forming tuffs that make up the greater part of unit 1v (Qbt 1v-u in Fig. 4; *u* representing upper part). In some areas, slight variations in welding caused the upper part of unit 1v to weather into a series of weakly developed cliffs and benches. The upper part of unit 1v is equivalent to unit 2a of Baltz *et al.* (1963).

Volcanic glass originally present in unit 1v, as well as in overlying units, crystallized to minerals such as alkali feldspar, cristobalite, and minor tridymite during devitrification and vapor-phase crystallization after emplacement.

The colonnade tuff forms a 3- to 10-m-thick cliff and may be slightly welded, although pumices show no discernible compaction at the hand-specimen scale. The tuff consists of soft, chocolate-brown to dark-purple-gray pumice relicts supported by a pinkish-white to light-gray ashy matrix. Pumice relicts typically make up 30 to 50% of the rock and are 0.2 to 6 cm in diameter. The colonnade tuff has a pock-marked appearance because of the selective weathering of soft pumices from the enclosing, more-resistant matrix. This weathering characteristic of pumices is a useful criteria for distinguishing unit 1g from unit 1v in weathered outcrops; in unit 1g, pumices are harder than their enclosing ash matrix, and they stand out in relief on weathered outcrop surfaces.

Fractures are more abundant in the colonnade tuff than in the glassy tuffs of unit 1g. Near-vertical fractures of the colonnade tuff typically die out at the boundary with unit 1g; however, a few fractures persist across this lithologic contact. Fractures are open and fracture walls are commonly free of fracture-lining minerals.

The upper part of unit 1v forms a distinctive grayish-white band of outcrops sandwiched between the darker colored outcrops of the colonnade tuff and unit 2. Although generally slope-forming, the upper part of unit 1v weathers into a series of weakly developed cliffs and benches at some locations (for example, TA-54) due to slight variations in welding. The upper unit 1v tuffs consist of soft, light-gray to medium-gray pumice relicts supported by a white to light-gray ashy matrix. Pumice relicts typically make up 30 to 50% of the tuff and are commonly up to 6 cm in diameter. Pumice accumulation zones and partings, which are indicative of multiple ash-flow tuffs, are common at some locations (such as TA-54) but absent elsewhere (for example, TA-21). Pumice accumulation zones are especially prominent near the top of unit 1v at TA-54, and they provide a means for identifying the unit contact when used in conjunction with the nonwelded nature of the unit.

As defined here, unit 1v includes the colonnade tuff and overlying light-colored, generally nonwelded tuffs because both are thought to be in the upper crystallized part of cooling unit 1. However, the lithologic properties of the two parts of unit 1v are sufficiently distinct at some locations that further subdivision into upper and lower parts of unit 1v should be made where possible. These differences in lithologic properties are important because at some locations (for example, TA-54), the colonnade tuffs have lower saturated and unsaturated hydraulic conductivities than tuffs above and below (Turin *et al.*, 1994).

Unit 2

Cooling unit 2 is a thick succession of ash-flow tuffs that forms one of the most distinctive and widespread units on the Pajarito Plateau. It is the most strongly welded unit of the Tshirege Member in the central and eastern part of the Laboratory and forms medium-brown, vertical cliffs that stand out in marked contrast to light-colored, nonwelded tuffs above and below. Unit 2 is moderately to densely welded (pumice aspect ratios of 3:1 to 10:1) at TA-67 (Broxton *et al.*, 1995b). The degree of welding is less at TA-21 (partially to moderately welded) and TA-54 (partially welded). Nonetheless, unit 2 stands out as a prominent cliff-forming unit in all of its outcrops. Welding increases upsection and is greatest near the top of the unit.

Unit 2 is characterized by medium-gray to gray-brown crystal-rich pumices supported by an ashy matrix of shards, pumice fragments, and abundant phenocrysts. The matrix is light-pink-tan to purple-gray and tends to be more highly colored in the zones of greatest welding. Pumices are generally smaller (<2 cm) and less abundant (2 to 15%) than in underlying tuffs (30-50%), except for local pumice swarms that occur in the lower part of the unit. Devitrification and vapor-phase crystallization have destroyed most of the primary vitroclastic textures in the tuff. In hand specimens, relict pumices have a sugary texture that results from the deposition of coarse (up to 0.3-mm) crystals of tridymite and sanidine. The phenocrysts are more abundant (17 to 32%) than in unit 1, in part because of the lower porosities in these more compacted tuffs.

Numerous, well-developed fractures are characteristic of unit 2. Most fractures are nearly vertical, although some horizontal and low-angle fractures are also present. Many of the fractures extend into the upper part of unit 1v before dying out. In places where unit 2 is overlain by unit 3, fractures are typically open, and their surfaces are free of fracture-lining minerals. Near-surface fractures are filled by clays, tuff detritus, and calcite where unit 2 is the bedrock unit exposed at the surface. For example, at TA-54, where unit 2 forms the mesa caprock, some fractures contain small, glassy El Cajete pumice fragments at depths of 10 m below the present-day land surface. Because the El Cajete deposits post-date the Tshirege Member, these pumice fragments must have washed into fractures from the surface.

The contact between cooling units 1 and 2 is probably the most difficult to assign in outcrop and borehole studies. In general, this contact corresponds to the upward change from the light-colored nonwelded, slope-forming tuffs of unit 1v to the darker, welded, cliff-forming tuffs of unit 2. At TA-54, a partial cooling break marks the contact between unit 1v and unit 2. This cooling break is somewhat unusual in that it separates nonwelded unit 1v from unit 2, which is commonly welded to its base. The abrupt change in welding across this contact indicates that unit 2 was emplaced at significantly higher temperatures than unit 1v was. A cooling break between units is suggested by the lack of gradational welding between the units in the eastern part of the Laboratory.

In outcrop studies, the base of the lowest surge bed or its equivalent horizontal parting should be used to mark the contact between units 1v and 2. Where present, these surge beds and their equivalent partings are excellent stratigraphic markers for outcrop studies. In the eastern part of the Laboratory (for example, at TA-33 and TA-54), thin (0.5- to 6-cm), multiple-surge beds occur within a 1- to 3-m zone at the base of unit 2

The surge beds are discontinuous and grade laterally into horizontal partings that separate thin, pumiceous ash-flow tuffs. At TA-54, the lowest surge bed in the lower part of unit 2 is used to define the base of the unit.

In outcrop studies where surge beds are absent or in borehole studies where these beds are poorly preserved or difficult to recognize, the unit 1v/2 contact should be identified by the change from welded tuffs above to nonwelded tuffs below. Although the criteria for identifying this contact are different for outcrop and borehole studies, the suggested guidelines should make it possible to place the unit 1v/2 contact within approximately 2 m. At TA-21, the contact between units 1v and 2 is gradational, suggesting that the two cooling units merge westward toward their source area. In such cases—where the contact can not be determined with certainty—units 1v and 2 can be combined as unit 1v/2, particularly for borehole studies.

Unit 3

Unit 3, as defined here, is equivalent to unit 3 of Baltz *et al.* (1963). It is a prominent cliff-forming unit that forms the caprock on mesas in the central part of the Laboratory (such as TAs-21 and -67). Unit 3 is absent from large areas in the eastern part of the Laboratory, where it has been removed by erosion; where present, it forms rounded grayish-white outcrops of nonwelded tuff (for example, TA-33).

In outcrop investigations, unit 3 can be further divided into two components:

(1) lower slope-forming tuffs that are equivalent to the nonwelded unit" between units 2 and 3 (Vaniman and Wohletz, 1990; 1991), and

(2) upper cliff-forming tuffs.

However, the contact between these two subunits cannot be recognized in borehole samples because it is gradational. Thus in outcrop studies, unit 3 may be subdivided based on erosional characteristics, but it should be treated as a single unit in boreholes.

The boundary between units 3 and 2 represents an abrupt change in welding characteristics. Although commonly hidden by talus from the cliffs above, the transition from welded tuffs of unit 2 to the nonwelded tuffs at the base of unit 3 occurs within less than 1 m of vertical section. The lower boundary of unit 3 is defined here as the base of these nonwelded tuffs and is easily recognized in boreholes. This boundary represents a partial cooling break and suggests a significant hiatus in the eruption of the Tshirege Member.

In outcrop, the lower part of unit 3 consists of slope-forming tuffs that overlie a broad bench developed on top of unit 2. These nonwelded tuffs form white, soft outcrops that weather into low, rounded mounds. The tuffs consist of white to light-gray ashy material made up of shards, pumice fragments, and abundant pheno-crysts (18 to 33%). Relict pumices are sparse (<5%) and have a sugary texture as a result of extensive vapor-phase crystallization.

The upper part of unit 3 contains 10 to 30% gray to brown pumice relicts in a white to light-gray ashy matrix of shards, pumice fragments, and abundant pheno-crysts. Welding increases upsection within the unit. Although a cliff-former, unit 3 is usually less welded than unit 2, and it tends to form less-steep outcrops at any given location where both units are present. Unit 3 is partially to moderately welded in the western part of the Laboratory and becomes nonwelded to partially welded eastward. The top of unit 3 consists of as much as 10 m of nonwelded tuffs, which weather to low, rounded outcrops.

Fractures are common in the welded cliff-forming part of unit 3. Because unit 3 is the bedrock unit exposed throughout much of the central part of the Laboratory, near-surface fractures commonly are filled by clays and tuff detritus washed in from the surface. Calcite is also present in some of the near-surface fractures, suggesting that some fractures act as pathways for the infiltration of surface waters. Fractures are less abundant in the nonwelded tuffs at the base of unit 3.

Unit 4

Unit 4 crops out in the western part of the Laboratory and is relatively little studied compared to the units described above. The following descriptions are derived from observations made at both Pajarito Mesa, which is being investigated for the Laboratory's potential Mixed Waste Disposal Facility (Vaniman and Chipera, 1995; Broxton *et al.* 1995b), and borehole 49-2-700-1 (Stimac *et al.*, 1995), which penetrates unit 4 at TA-49. Additional studies underway at other sites in the western part of the Laboratory will characterize this unit more fully.

Unit 4 forms a low, resistant ridge along the centerline of western Pajarito Mesa. It thins eastward and is not present east of 1,625,000 ft easting (NAD83 NM State Plane coordinates; Vaniman and Chipera, 1995), where presumably it has been removed by erosion. Unit 4 is a distinctive tuff that consists of a basal, crystal-rich, pyroclastic surge deposit overlain by pumice-poor ash-flow tuffs.

The surge beds at the base of the unit at Pajarito Mesa are up to 15 cm thick, and they are characterized by planar and low-angle cross beds. These surge beds form nearly continuous outcrops and are excellent markers for determining the base of the unit. The surge deposits are zones of crystal enrichment, containing as much as 50% phenocrysts. At TA-49, the basal surge deposits, typically about 60 cm thick, were called unit 5 by Weir and Purtymun (1963). The ash-flow tuffs of unit 4 are nonwelded to partially welded at Pajarito Mesa. These tuffs are characterized by small, sparse relict pumices set in an ashy matrix; overall, the unit has a sandy appearance. The paucity of relict pumice (<5%) is a useful diagnostic feature for distinguishing unit 4 from underlying pumice-rich units. Phenocrysts comprise only about 8% of the tuff, making this unit more crystal-poor than the underlying units of the Tshirege Member (Broxton *et al.*, 1995b). Phenocrysts include sanidine, anorthoclase, quartz, and clinopyroxene. Alkali-feldspar-to-quartz-ratios (9:1) are significantly greater than those in the underlying units (1:1 to 4:1).

In areas near the western boundary of the Laboratory, unit 4 includes multiple ash-flow tuffs that are stratigraphically higher than the unit 4 tuffs at Pajarito Mesa. These additional ash-flow tuffs, which are thicker and more densely welded than those at Pajarito Mesa, contain numerous intercalated surge deposits. The petrographic characteristics of these higher units may differ from those described for unit 4 at Pajarito Mesa; they will be more fully described when current stratigraphic studies of the western part of the Laboratory are complete.

CONCLUSIONS

This technical-guidance document establishes a stratigraphic nomenclature system for the Bandelier Tuff to be used by the ER Project at Los Alamos. Consistent use of rock names project-wide will improve the exchange of information among investigators working at different field units by providing a common stratigraphic framework for discussing the influence of geology on contaminant transport.

The stratigraphic units described in this document are divided and named on the basis of cooling units for the ash-flow tuffs and time-stratigraphic units for sedimentary rocks. For the most part, the geologic characteristics of units are sufficiently distinct that units can be recognized and correlated both in outcrops and in boreholes. However, it probably will be necessary to combine some of the units of the Tshirege Member where they merge nearer to the Valles caldera.

The system of nomenclature proposed in this report is flexible enough to accommodate the need for greater or less detail, additional data, and specific information. To the extent possible, the stratigraphic framework conforms to older systems of nomenclature already in widespread use at the Laboratory.

The Otowi Member of the Bandelier Tuff is a relatively homogenous unit made up of a succession of ash-flow tuffs that overlie the basal Guaje Pumice Bed. The ash-flow tuffs are nonwelded to partially welded in most areas studied, and the entire sequence of tuffs apparently forms a simple cooling unit. Because of the relative homogeneity of the unit, further division of the Otowi Member seems unwarranted at this time, and the formal stratigraphy of Bailey *et al.* (1969) should be used.

Tephras and volcaniclastic sediments of the Cerro Toledo interval is an informal name given to a sequence of epiclastic sediments and tephras of mixed provenance that lie between the two members of the Bandelier Tuff. This unit contains deposits normally assigned to the Cerro Toledo Rhyolite (Smith *et al.*, 1970) as well as to coarse-grained detritus derived from lava flows of the Tschicoma Formation. Following the usage of Smith *et al.* (1970), deposits of the Cerro Toledo interval are not considered part of the Bandelier Tuff.

The Tshirege Member of the Bandelier Tuff is a compound cooling unit divided into four distinct cooling units. Because of its complex cooling history, the physical properties of these tuffs vary both vertically and laterally. The lower three cooling units crop out in the central and eastern part of the Laboratory; the fourth crops out only in the western part. These cooling units, labeled 1 through 4 in ascending order, represent episodes of ash-flow deposition separated by partial cooling breaks. Additional subunits can be specified within the overall framework of these cooling units to identify significant differences in lithology or rock properties.

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