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October 25, 2000

MEMORANDUM

To: Distribution, Branch of Information Services, M.S. 517, Federal Center, Denver, Colorado; attention: Susan Quinn

From: Tim Brady, USGS, WRD, YMPB, Denver, Colorado T.B. 10/25/00

Subject: PUBLICATIONS--USGS Open-File Report 94-469, "Proposed stratigraphic nomenclature and macroscopic identification of lithostratigraphic units of the Paintbrush Group exposed at Yucca Mountain, Nevada," by D.C. Buesch, R.W. Spengler, T.C. Moyer, and J.K. Geslin.

As a consequence of a thorough verification of the source data for the subject open-file report, errors were identified in Appendix 1, on page 32. Two anomalous measurements were noticed in data for borehole UZ-14 during a comparison of the published data with that in DTN GS931208314211.049, and with the original borehole logs. Generally, most lithologic contacts were located within 0 to 0.2 feet with the exception of the following:

Tpbt3 is listed on page 32, column 2 of the subject report, as 53.3 meters (174.9 feet), and on page 24 of Open-File Report 94-342 (original data-source reference) Tpbt3 is given as 102.1 feet; the difference is 72.8 feet.

Tpbt2 is listed on page 32, column 2 of the subject report, as 75.2 meters (246.7 feet), and on page 24 of Open-File Report 94-342 (original data-source reference) the contact is given as 258.6 feet; the difference is 11.9 feet.

The values for the contacts listed on page 24 of Open-File Report 94-342 should be used as the correct picks for the two situations mentioned above.

Please correct the master distribution copy, as appropriate, to inform potential users of this report of the significance of the errors noted herein.

PROPOSED STRATIGRAPHIC NOMENCLATURE AND MACROSCOPIC IDENTIFICATION OF LITHOSTRATIGRAPHIC UNITS OF THE PAINTBRUSH GROUP EXPOSED AT YUCCA MOUNTAIN, NEVADA

by **David C. Buesch, Richard W. Spengler,** U.S. Geological Survey;
Thomas C. Moyer, Jeffrey K. Geslin, Science Applications International Corporation

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U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
millimeter (mm)	0.03937	inch

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Proposed Stratigraphic Nomenclature and Macroscopic Identification of Lithostratigraphic Units of the Paintbrush Group Exposed at Yucca Mountain, Nevada

By David C. Buesch, Richard W. Spengler, Thomas C. Moyer, and Jeffrey K. Geslin

Abstract

This paper describes the formations of the Paintbrush Group exposed at Yucca Mountain, Nevada, presents a detailed stratigraphic nomenclature for the Tiva Canyon and Topopah Spring Tuffs, and discusses the criteria that define lithostratigraphic units. The Tiva Canyon and Topopah Spring Tuffs are divided into zones, subzones, and intervals on the basis of macroscopic features observed in surface exposures and borehole samples. Primary divisions reflect depositional and compositional zoning that is expressed by variations in crystal content, phenocryst assemblage, pumice content and composition, and lithic content. Secondary divisions define welding and crystallization zones, depositional features, or fracture characteristics. Both formations are divided into crystal-rich and crystal-poor members that have an identical sequence of zones, although subzone designations vary slightly between the two units. The identified lithostratigraphic divisions can be used to approximate thermal-mechanical and hydrogeologic boundaries in the field. Linking these three systems of nomenclature provides a framework within which to correlate these properties through regions of sparse data.

INTRODUCTION

Yucca Mountain, Nevada, is being evaluated as a potential site for a high-level radioactive-waste repository. Yucca Mountain is in the southwestern Nevada volcanic field (SNVF), south of the Timber Mountain and Claim Canyon calderas (fig. 1) that were the sources for the volcanic rocks exposed in this area (Byers and others, 1976a and b; Christiansen and others, 1977). The SNVF was active from 15.1 to 7.5 million years (Sawyer and others, 1994), with the Paintbrush Group, comprising most of Yucca Mountain, erupted between 12.8 and 12.7 Ma (Sawyer and others, 1994). The Paintbrush Group is composed of four formations (Sawyer and others, 1994): the regionally extensive ignimbrites of the Tiva Canyon and Topopah Spring Tuffs and the comparatively less extensive ignimbrites of the Yucca Mountain and Pah Canyon Tuffs, in addition to several informally named lava flows and their associated tuffaceous rocks (Byers and others, 1976a and b; Scott and Bonk, 1984; Frizzell and Shulters, 1990; Broxton and others, 1993).

Historically, the lithostratigraphic units at Yucca Mountain were defined by their petrologic features (Byers and others, 1976a and b) and for some units, the weathering characteristics of surface exposures (Scott and Bonk, 1984). Increased underground activity, including logging of core from boreholes and mapping in the Exploratory Studies Facility, necessitates identification of lithologic units and a stratigraphic nomenclature that is not tied to weathering characteristics of surface exposures. Studies of the hydrogeologic and thermal-mechanical properties of these units produced additional systems of stratigraphic nomenclature that are used in the site evaluation process (Office of Civilian Radioactive Waste Management, 1988; Rautman and Flint, 1992; Wittwer and others, 1992).

In this report, the diverse stratigraphic nomenclatures of the Paintbrush Group are linked to a common lithostratigraphic framework that is based on the recently revised large-scale stratigraphy of the SNVF (Minor and others, 1993; Ferguson and others, 1994; Sawyer and others, 1994). Lithostratigraphic formations and members are divided into zones, subzones, and intervals using macroscopic features of the rocks as they appear in core and outcrop. The criteria used includes attributes developed by both primary processes (depositional character, phenocryst content and assemblage) and secondary processes (degree of welding, devitrification and vapor-phase crystallization, fracture habit). Subdivisions closely approximate those defined by laboratory studies of hydrogeologic (Rautman and Flint, 1992; Wittwer and others, 1992) and thermal-mechanical properties (Ortiz and others, 1985). Thus, it may be possible to correlate the

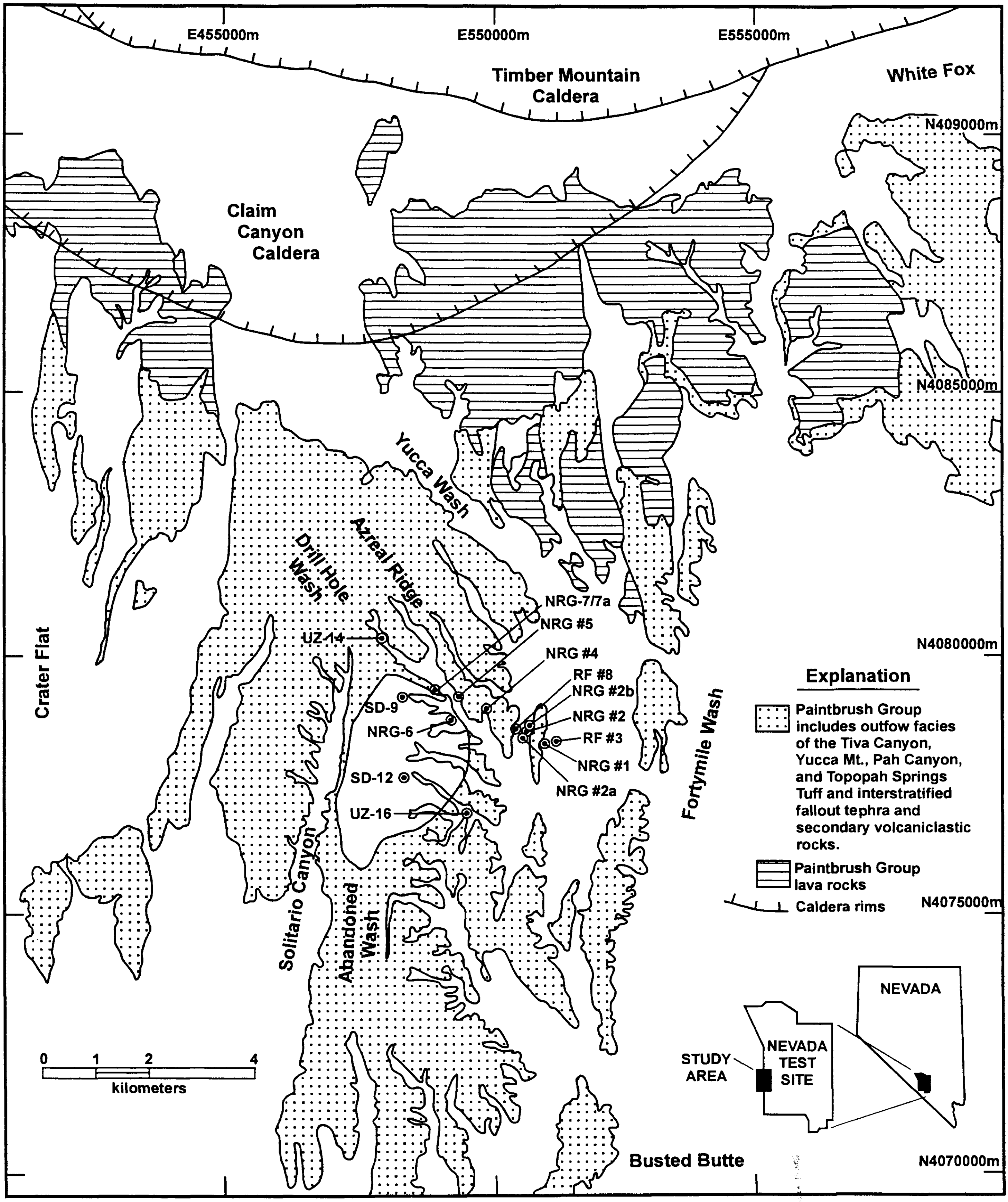

Figure 1. Map showing exposures of the Paintbrush Group at Yucca Mountain is modified from Frizzell and Shulters (1990), and locations of selected boreholes drilled in 1992–93. Conceptual design perimeter of potential repository is outlined. Grid is Nevada State Coordinates in meters.

hydrologic and thermal-mechanical zones throughout Yucca Mountain by developing a three-dimensional model of the distribution of the proposed lithostratigraphic units. These units can be further delimited as information is incorporated from petrographic and geochemical studies, geophysical logs, and borehole televiewer logs.

The system of lithostratigraphic unit identification and nomenclature presented in this report provides a consistent framework for many of the investigations at Yucca Mountain that span a wide range of scales from small scale (greater than 1:6,000) to detailed studies at scales of 1:100 or less. For small scale studies, which include regional mapping and site-scale numerical modeling of the mountain, the rank of zone in the welded ignimbrites will probably be the most detailed unit used. For detailed studies, which include mapping in the Exploratory Studies Facility and selected surface exposures or examining measured sections and core from boreholes, identification of units to the rank of interval is important whereas units such as group to member provide only a general context. Thus, this revised nomenclature with seven hierarchical divisions from age to interval is designed to be used at all scales.

LITHOSTRATIGRAPHIC NOMENCLATURE AT YUCCA MOUNTAIN

The lithostratigraphy of the SNVF was summarized by Byers and others (1976a and b). Scott and Bonk (1984) subsequently described and subdivided the rock units exposed in the Yucca Mountain region. Stratigraphic inconsistencies that were identified following these early works have been resolved by more recent studies (Warren and others, 1989a; Minor and others, 1993; Ferguson and others, 1994; Sawyer and others, 1994; C. Fridrich, USGS, written commun., 1993). The currently proposed stratigraphic nomenclature, in which the Paintbrush Tuff is elevated to group status and some members are elevated to formation status (Warren and others, 1989a; Sawyer and others, 1994), is shown in table 1. In the revised stratigraphic scheme, formations represent either volumetrically significant eruptive units or a series of products interpreted to have formed from a single magma batch.

All lithostratigraphic divisions of formations, including members to intervals (table 1), are informal units following the suggested guidelines of the North American Commission on Stratigraphic Nomenclature (1983). Members are defined by the amount and assemblage of phenocrysts and reflect changes in magma chemistry or eruptive mechanism. Many of the formations in the SNVF, including the Tiva Canyon and Topopah Spring Tuffs, have an upper crystal-rich (greater than 10% phenocrysts) member and a more voluminous lower crystal-poor (less than 5% phenocrysts) member, with a relatively thin transition in phenocryst abundance between members. In the Tiva Canyon and Topopah Spring Tuffs, this transition in phenocryst abundance is typically 5- to 10-m-thick and is included as a crystal-transition zone at the base of the crystal-rich member. Zones, subzones, and intervals are identified on the basis of textures and structures associated with pyroclastic flow and fallout deposits (depositional processes), zones of welding and crystallization (post-depositional processes), and geometry and surface roughness of fractures (mechanical properties of the rock). Zones are defined by (1) vitric versus devitrified pyroclasts, (2) occurrence or absence of lithophysae and related light gray rims and spots and amount of pale red-purple groundmass, and (3) planar versus irregular geometry and smooth versus rough surfaces of fractures. Subzones and intervals are defined by the surface roughness, abundance of pumice clasts, amount of welding, type of alteration or crystallization of pumice clasts, and interstratification of thin units with characteristics of adjacent zones or subzones.

This report focuses on the Paintbrush Group that underlies Yucca Mountain, but recent work by others provides a regional context for this study (Minor and others, 1993; Ferguson and others, 1994; Sawyer and others, 1994; C. Fridrich, written commun., 1993). The Tiva Canyon Tuff exposed at Yucca Mountain correlates with the lower of two cooling units that comprise the formation in the northern Crater Flat region (C. Fridrich, written commun., 1993). Tephra deposits at the north end of Yucca Mountain, which lie between the Yucca Mountain and Pah Canyon Tuffs, are correlated to the eruption of the rhyolite lavas of Delirium Canyon and Black Glass Canyon (Broxton and others, 1993).

The symbol hierarchy proposed by Warren and others (1989a) for the stratigraphic units of the SNVF is adopted and extended for units that occur in the vicinity of Yucca Mountain (table 1). Within their scheme, Tertiary rocks are indicated with T, with stratigraphic groups designated by a second letter (Tp for the Paintbrush Group or Tc for the Crater Flat Group). A third letter denotes formations (Tpc for the Tiva Canyon Tuff or Tpp for the Pah Canyon Tuff). A fourth letter designates informally defined members (Tpdl for lava flow and Tpdb for tuffaceous beds of the rhyolite of Delirium Canyon, or Tptr as crystal-rich and Tptp as crystal-poor portions of the Topopah Spring Tuff). Single or double letters in the fifth and sixth symbol position represent the zones of welding and crystallization (the crystal-poor upper lithophysal zone of the Tiva

Table 1. Hierarchy of stratigraphic and symbol nomenclature at Yucca Mountain

[Revised stratigraphic nomenclature in the southwest Nevada volcanic field (Sawyer and others, 1994). Age-to-member hierarchy proposed by Warren and others (1989a) and Sawyer and others (1994); zone, subzone, and interval proposed in this report.]

Nomenclature	Stratigraphic and symbol hierarchy
PREVIOUS	1 Age
Paintbrush Tuff (formation rank)	2 Group
Tiva Canyon Member	3 Formation
Yucca Mountain Member	4 member (informal)
Pah Canyon Member	5–6 zone
Topopah Spring Member	6–7 subzone
	7–8 interval
REVISED	T Tertiary
Paintbrush Group	p Paintbrush Group
Tiva Canyon Tuff (formation rank)	t Topopah Spring Tuff
Yucca Mountain Tuff	r crystal-rich member
Pah Canyon Tuff	v vitric
Topopah Spring Tuff	1 densely welded subzone
	v vitrophyre interval

Example: Tpcplnc2 - Tiva Canyon Tuff, crystal-poor (member), lower nonlithophysal (zone), columnar (subzone), clay-altered pumice (interval).

Canyon Tuff is Tpcpul, or the crystal-rich nonlithophysal zone of the Topopah Spring Tuff is Tptrn). Subzones are indicated in the sixth or seventh position by letters or numbers, with the lowest number for the stratigraphically lowest subzone (Tptpv1 for the nonwelded subzone of the crystal-poor vitric zone of the Topopah Spring Tuff which is overlain by Tptpv2, the partially to moderately welded subzone). The hackly and columnar zones in the Tiva Canyon Tuff (Scott and Bonk, 1984) are redefined as subzones of the crystal-poor lower nonlithophysal zone (using symbols of Tpcplnh and Tpcplnc, respectively). Intervals are denoted by numerical designators in the seventh or eighth position (Tpcplnc2 for the interval of clay-altered pumice clasts in the columnar subzone).

Tuffaceous beds interstratified with major ignimbrites, but not identified with any established formation, are placed with the superjacent tuff (for example pre-Tiva Canyon Tuff). This designation is arbitrary but consistent with previous usage (Spengler and Rosenbaum, 1980). In adopting and extending the symbol hierarchy proposed by Warren and others (1989a), these tuffaceous beds are designated with the letters "bt" followed by a number indicating the stratigraphic position, with 1 at the bottom of the sequence. This designation is used where the tuffaceous beds are interstratified at the group or formation level. For example, in the Paintbrush Group there are five tuffaceous beds (Tpbt1 to Tpbt5); four of these tuffaceous beds are subjacent to the major ignimbrites (table 2), and the fifth is associated with the Rhyolite of Comb Peak, the youngest erupted material in the Paintbrush Group (R. Warren, LANL, written commun., 1993; table 2).

CRITERIA FOR IDENTIFYING LITHOSTRATIGRAPHIC UNITS

Textural features within the ignimbrites of the Paintbrush Group reflect processes occurring in the magma chamber, during transport and deposition of the fragmented material, and during postdepositional welding and crystallization. Formations, members, zones and subzones within the Paintbrush Group are identified by all these features, and where contacts are gradational, multiple criteria are commonly used. This section summarizes the macroscopic criteria by which the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs, and units within them, are classified in both core and outcrop. The main criteria include the type and abundance of phenocrysts, the

Table 2. Revised nomenclature of the Paintbrush Group at Yucca Mountain

Symbol	Stratigraphic unit
Tp	PAINTBRUSH GROUP - characterized by quartz-free phenocryst assemblage.
Tpk	Rhyolite of Comb Peak - rhyolite lava flows and related tephra; about 2 percent felsic phenocrysts (sanidine > plagioclase), 0.1 percent mafic phenocrysts (hornblende > biotite), and 0.05 percent sphene[1].
Tpki	Pyroclastic flow deposit informally identified as tuff unit "x" (Carr, 1992) and tentatively correlated with the rhyolite of Comb Peak on the basis of petrography and mineral chemistry (R. Warren, written commun., 1994).
Tpv	Rhyolite of Vent Pass - Rhyolite lava flows and related tephra. Similar to crystal-rich Tiva Canyon tuff, with about 15 percent felsic phenocrysts (sanidine > plagioclase), 0.3 percent biotite, and 0.002 percent sphene.
Tpbt5	Post-Tiva Canyon Tuff bedded tuff consists of tuffaceous rocks not correlated with known eruptive units based on detailed tephrostratigraphic studies. This unit commonly consists of numerous depositional sequences separated by possible paleosols. In the NRG#2 borehole complex and RF#3 and 8, Tpbt5 is divided into four depositional sequences, each capped by a possible paleosol (Geslin and others, 1995; Buesch and others, 1994).
Tpc	*Tiva Canyon Tuff*
Tpcy	Tuff of Pinyon Pass - The tuff of Pinyon Pass is interpreted as a second cooling unit of the Tiva Canyon Tuff (C. Fridrich, written commun., 1993). The tuff of Pinyon Pass occurs north and west of Yucca Mountain, but it has not been identified on the mountain.
Tpcyr	Crystal-rich member: 10–15 percent felsic phenocrysts (sanidine » plagioclase, trace quartz), 0.8 percent mafic phenocrysts (biotite > pyroxene » hornblende), and 0.005 percent sphene.
Tpcyp	Crystal-poor member: 5 percent sanidine, 0.1 percent mafic phenocrysts (hornblende > biotite), and 0.05 percent sphene.
Tpcx	Lithic breccia - landslide or eruptive breccia.
Tpcb	Bedded - Nonwelded vitric tuff; use "u" for upper and "l" for lower bedded tuff.
Tpcr	Crystal-rich member: 10–15 percent felsic phenocrysts (sanidine » plagioclase, trace quartz), 0.8 percent mafic phenocrysts (biotite > pyroxene » hornblende), and 0.005 percent sphene. Pumice is mixed colors; light gray (N8-9), medium gray (N6), and very dark yellowish orange (10YR6/8).
Tpcrv	Vitric zone.
Tpcrv3	Nonwelded subzone - includes partially welded and locally devitrified tuff.
Tpcrv3n	Nonwelded interval.
Tpcrv3p	Partially welded interval.
Tpcrv2	Moderately welded subzone - moderately welded with macroscopically identifiable vitroclastic texture and porosity; locally devitrified tuff.
Tpcrv1	Densely welded subzone - densely welded tuff; no macroscopically identifiable porosity.
Tpcrv1c	Clastic texture interval - vitroclastic texture preserved; reddish brown (5YR4/3) to dark gray (N4) glass.
Tpcrv1v	Vitrophyre interval - moderate brown (5YR3/2) to very dark gray (N3) glass. Vitroclastic texture is not macroscopically identifiable.
Tpcrn	Nonlithophysal zone - moderately to densely welded; phenocrysts 10–15 percent; devitrified with minor vapor-phase minerals; no lithophysae, but ≤ 3-mm-diameter cavities in groundmass and pumice fragments.
Tpcrn4	Subvitrophyre transition subzone - pumice-rich, pumice clasts are locally argillic.
Tpcrn4d	Densely welded interval - incipiently crystallized with less than 5 percent macroscopic porosity.
Tpcrn4m	Moderately welded interval - matrix/groundmass and pumice clasts are corroded to form macroscopic porosity of 10 to 25 percent.
Tpcrn3	Pumice-poor subzone - pumice clasts less than 5 percent.
Tpcrn2	Mixed pumice subzone - pumice-rich with mixed colors of pumice clasts.
Tpcrn1	Crystal transition subzone - phenocrysts 5–10 percent, biotite and trace of pyroxene in matrix; few lithophysae. This subzone is locally absent.
Tpcrl	Lithophysal zone - lithophysae are ≥ 5 percent. This zone is locally absent.
Tpcrl1	Crystal transition subzone - phenocrysts 5–10 percent, biotite and trace of pyroxene in matrix; few lithophysae. This subzone is locally absent.
Tpcp	Crystal-poor member: 5 percent sanidine, 0.1 percent mafic phenocrysts (hornblende > biotite), and 0.05 percent sphene. Pumice is mostly light gray (N8-9) with rare, very dark yellowish orange (10YR6/8).
Tpcpul	Upper lithophysal zone - rhyolite and characterized by 10 to 20 percent lithophysae[2].

Table 2. Revised nomenclature of the Paintbrush Group at Yucca Mountain--Continued

Symbol	Stratigraphic unit
Tpcpul1	Spherulite-rich subzone; spherulites are common; centimeter size lithophysal cavities are absent with few large (decimeter size) lithophysal cavities inferred from nonrecovered or rubbled intervals of core. This subzone is locally absent, but where it occurs the remainder of the zone is designated pul2.
Tpcpmn	Middle nonlithophysal zone - high-angle fractures with smooth surface are common. Locally divided into three subzones.
Tpcpmn3	(Upper) nonlithophysal subzone. (Use of upper is optional).
Tpcpmn2	Lithophysae-bearing subzone. Commonly has veinlets and streaks that locally occur in vapor-phase partings parallel or subparallel to foliation. These partings may weather to small benches in surface exposures. This subzone increases thickness to the north and locally comprises the entire middle nonlithophysal zone.
Tpcpmn1	(Lower) nonlithophysal subzone. (Use of lower is optional).
Tpcpll	Lower lithophysal zone - lithophysae 10 to 15 percent in surface exposures[2]; few high-angle fractures with slightly rough surface.
Tpcpllh	Hackly fractured subzone - lithophysae vary from 2 to 15 percent; hackly[3] fracture with polygonal faces on freshly broken surfaces; hackly fracture is typically not as well developed as in the lower nonlithophysal zone.
Tpcpln	Lower nonlithophysal zone - moderately to densely welded tuff; devitrified, locally with vapor-phase minerals. Two subzones are commonly identified.
Tpcplnh	Hackly subzone - hackly fracture with polygonal faces, which are typically < 5 mm across, on freshly broken surfaces. Subhorizontal partings, which are commonly coated with vapor-phase minerals, occur locally, and may weather to small benches in surface exposures.
Tpcplnc	Columnar subzone - moderately to densely welded tuff; groundmass is devitrified to a high temperature mineral assemblage; hackly fracture is not well developed. The base of devitrification is locally in the partially welded tuff below the lowermost densely welded tuff.
Tpcplnc3	Spherulitic pumice interval - pumice fragments are devitrified to high temperature minerals, commonly with spherulitic morphology.
Tpcplnc2	Argillic pumice interval - pumice fragments are altered to reddish-pink (5R6/2) clay or zeolite.
Tpcplnc1	Vitric pumice interval - pumice fragments are preserved as dark-gray (N3) glass.
Tpcpv	Crystal-poor vitric zone.
Tpcpv3	Densely welded subzone - densely welded tuff; no macroscopically identifiable porosity.
Tpcpv3v	Vitrophyre interval - moderate brown (5YR3/2) to very dark gray (N3) glass. Vitroclastic texture is not macroscopically identifiable.
Tpcpv3c	Clastic texture interval - vitroclastic texture preserved; reddish brown (5YR4/3) to dark gray (N4) glass.
Tpcpv2	Moderately welded subzone; moderately welded with macroscopically identifiable vitroclastic texture and porosity.
Tpcpv1	Nonwelded to partially welded subzone; locally devitrified.
Tpcpv1p	Partially welded interval.
Tpcpv1n	Nonwelded interval.
Tpbt4	Pre-Tiva Canyon Tuff bedded tuff consists of tuffaceous rocks not correlated with known eruptive units based on detailed tephrostratigraphic studies.
Tpy	*Yucca Mountain Tuff* - characteristically aphyric with « 1 percent phenocrysts. Nonwelded tuff is composed of light yellow to brown fine-grained bubble-wall glass shards. Where the Yucca Mountain Tuff is thick, it is densely welded, has two well-developed lithophysal zones, and stratigraphic nomenclature similar to the zones in the Tiva Canyon or Topopah Spring Tuffs can be applied.
Tpg	Rhyolite of Black Glass Canyon - rhyolite lava flows and related tephra. Similar to crystal-poor part of Tiva Canyon Tuff, with about 5 percent sanidine phenocrysts, 0.1 percent mafic phenocrysts (hornblende > biotite), and 0.04 percent sphene.
Tpd	Rhyolite of Delirium Canyon - rhyolite lava flows and related tephra. Similar to rhyolite of Comb Peak, with about 5 percent felsic phenocrysts (sanidine > plagioclase), 0.5 percent hornblende and biotite, and 0.02 percent sphene.
Tpe	Rhyolite of Echo Peak - rhyolite lava flows and related tephra. Phenocrysts consist of about 10 percent sanidine and plagioclase, 0.5 percent mafic phenocrysts (biotite » pyroxene), and 0.5 percent sphene.
Tpz	Rhyolite of Zig Zag Hill - rhyolite lava flows and related tephra. Phenocrysts consist of about 10 percent felsic phenocrysts (sanidine > plagioclase), 0.05 percent mafic phenocrysts (biotite » pyroxene), and no sphene.
Tpbt3	Pre-Yucca Mountain Tuff bedded tuff consists of tuffaceous rocks not correlated with known eruptive units based on detailed tephrostratigraphic studies.

Table 2. Revised nomenclature of the Paintbrush Group at Yucca Mountain--Continued

Symbol	Stratigraphic unit
Tpp	*Pah Canyon Tuff* - characterized by large pumice clasts. Phenocrysts consist of about 10 percent felsic phenocrysts (plagioclase ? sanidine), 0.5 percent mafic phenocrysts (biotite » pyroxene), and 0.005 percent sphene.
Tpbt2	Pre-Pah Canyon Tuff bedded tuff consists of tuffaceous rocks not correlated with known eruptive units based on detailed tephrostratigraphic studies. The lower 5- to 15-m-thick part of the bedded tuff sequence is moderately well sorted pumiceous tephra with a thin (2 cm) lithic-rich fallout at the base that overlies a thin (2 cm) very fine-grained ash bed. This basal bedset occurs across Yucca Mountain northeast to exposures near Fortymile Canyon.
Tpt	*Topopah Spring Tuff*
Tptd	Dacitic tephra - thin tephra layer above Topopah Spring Tuff. Phenocrysts consist of about 10 percent plagioclase and 2.0 percent mafic phenocrysts (biotite » pyroxene).
Tptx	Landslide or eruptive breccia.
Tptb	Bedded - nonwelded to partially welded vitric tuff; use "u" for upper and "l" for lower bedded tuff.
Tptr	Crystal-rich member: 10–15 percent felsic phenocrysts (locally 8 to 15) (sanidine > plagioclase, trace of quartz), 0.1 percent mafic phenocrysts (biotite > pyroxene, trace of hornblende), and no sphene.
Tptrv	Vitric zone.
Tptrv3	Nonwelded subzone - includes partially welded rocks; locally devitrified. The nonwelded subzone is moderately well sorted pumiceous deposits capped by a thin (2 cm) very fine-grained ash bed. Locally, this 2-cm-thick very fine-grained ash bed is in the moderately welded subzone.
Tptrv3n	Nonwelded interval.
Tptrv3p	Partially welded interval.
Tptrv2	Moderately welded subzone - moderately welded with macroscopically identifiable vitroclastic texture and porosity; locally devitrified.
Tptrv1	Densely welded subzone - densely welded tuff; no macroscopically identifiable porosity.
Tptrv1c	Clastic texture interval - vitroclastic texture preserved; weak red (5YR4/3) to dark gray (N4) glass.
Tptrv1v	Vitrophyre interval - dusky red (10R3/2) to very dark gray (N3) glass. Vitroclastic texture is not macroscopically identifiable.
Tptrn	Nonlithophysal zone - no lithophysae, but small cavities are in pumice fragments.
Tptrn3	Dense subzone - densely welded; incipiently crystallized; minor amounts of porosity where pumice clasts were corroded by the vapor phase or argillically altered. This subzone, which is subjacent to the vitrophyre interval, is distinguished by a lack of vitreous luster and commonly breaks into thin (1- to 3-cm thick) fragments with smooth fractures.
Tptrn2	Vapor-phase corroded subzone - small cavities in pumice clasts and groundmass appear to have resulted from corrosion by the vapor phase during cooling.
Tptrn1	Crystal transition subzone - phenocrysts 3–10 percent (locally 3 to 8 percent), biotite and trace of pyroxene in matrix; few lithophysae. This subzone is locally absent.
Tptrl	Lithophysal zone - thin zone of 10–20 percent lithophysae near the base of the crystal-rich section, but with 8–10 percent phenocrysts. This zone was probably included in the upper lithophysal zone of some previous workers.
	Tptrl1 crystal transition subzone - phenocrysts 3–10 percent (locally 3 to 8 percent). This subzone is locally absent.
Tptf	Lithic-rich zone - lithic-rich (10 to 50 percent) with crystal-rich matrix[4,5]. This zone straddles the contact of the crystal-rich and crystal-poor member.
Tptrf	Crystal-rich subzone - 3 to 10 percent phenocrysts.
Tptrfl	Lithophysal interval.
Tptrfn	Nonlithophysal interval.
Tptp	Crystal-poor member: Less than 3 percent felsic phenocrysts (sanidine ≈ plagioclase, trace quartz) and 0.05 percent mafic phenocrysts (biotite with trace of hornblende and pyroxene).
Tptf	Lithic-rich zone - lithic-rich rhyolite zone with crystal-poor matrix[4,5]. This zone straddles the contact of the crystal-rich and crystal-poor member.
Tptrf	Crystal-rich subzone - less than 3 percent phenocrysts.
Tptrfl	Lithophysal interval.
Tptrfn	Nonlithophysal interval.

Table 2. Revised nomenclature of the Paintbrush Group at Yucca Mountain--Continued

Symbol	Stratigraphic unit
Tptpul[6]	Upper lithophysal zone - lithophysae, with ≈ 5-mm-wide light-gray rims, volumetrically constitute 5 to 30 percent of core[5] and 5 to 15 percent in surface exposures[2]; small (1–5 cm-diameter) lithophysae are ≥ 5 percent, and subordinate numbers of large (up to 0.5 × 1 m) lithophysae are observed in borehole televiewer log. Intervals of rubbled core and nonrecovered core are common. Locally, where the cavernous lithophysae subzone (pulc) is identified the remainder of the upper lithophysal zone is referred to as the small lithophysal subzone (puls).
Tptpulc	Cavernous lithophysae subzone - small (1–5 cm-diameter) lithophysae are ≤ 2 percent, and numerous large (up to 0.5 × 1 m) lithophysae are observed in borehole televiewer log. Intervals of rubbled core and nonrecovered core are common.
Tptpmn[7]	Middle nonlithophysal zone - locally has a middle lithophysal subzone.
Tptpmn3	(Upper) nonlithophysal subzone. (Use of upper is optional).
Tptpmn2	Lithophysae-bearing subzone - lithophysae are < 5 percent. Commonly has veinlets and streaks that locally occur in vapor-phase partings parallel or subparallel to foliation.
Tptpmn1	(Lower) nonlithophysal subzone. (Use of lower is optional).
Tptpll	Lower lithophysal zone - large, but dispersed, irregularly shaped lithophysae with 10- to 15-mm-wide light gray rims. Characterized by < 10 percent lithophysae in core[5] and 5 to 15 percent in surface exposures[2]. Lithophysae common along fractures. Large, light gray spots in matrix create distinctive mottled coloration.
Tptpllh	Hackly fractured subzone - lithophysae vary from 2 to 15 percent; moderate to well-developed hackly fractures are common in this zone.
Tptpln[7]	Lower nonlithophysal zone - moderately to densely welded tuff; devitrified, locally with vapor-phase minerals. Subzones similar to those in the Tiva Canyon Tuff are locally identified.
Tptplnh	Hackly subzone - hackly fracture with polygonal faces, which are typically < 5 mm across, on freshly broken surfaces.
Tptplnc	Columnar subzone - densely welded tuff; groundmass is devitrified to a high temperature mineral assemblage.
Tptplnc3	Spherulitic pumice interval - pumice fragments are typically devitrified to a high temperature mineral assemblage.
Tptplnc2	Argillic pumice interval - pumice fragments are altered to reddish-pink (5R6/2) clay or zeolite.
Tptplnc1	Vitric pumice interval - pumice fragments are preserved as dark-gray (N3) glass.
Tptpv	Crystal-poor vitric zone.
Tptpv3	Densely welded subzone - densely welded tuff; no macroscopically identifiable porosity.
Tptpv3v	Vitrophyre interval - dark to very dark gray (N4 to N3) glass. Vitroclastic texture is not macroscopically identifiable.
Tptpv3c	Clastic texture interval - vitroclastic texture preserved; weak red (10R4/3) or reddish brown (5YR4/3) to dark gray (N4) glass.
Tptpv2	Moderately welded subzone - moderately welded with macroscopically identifiable vitroclastic texture and porosity. The top of this subzone is typically gradational to densely welded clastic texture interval (pv3c); locally devitrified with vapor-phase minerals.
Tptpv1	Nonwelded subzone - partially welded to nonwelded vitric. Quartz only occurs as resorbed crystals and probably represents xenocrysts.
Tptpv1p	Partially welded interval.
Tptpv1n	Nonwelded interval.
Tpbt1	Pre-Topopah Spring Tuff bedded tuff consists of tuffaceous rocks not correlated with known eruptive units based on detailed tephrostratigraphic studies.

[1]Phenocryst abundances are from Broxton and others (1989) and R. Warren (written commun., 1993). Names and symbols of the rhyolite lava flows and related tephra are from Ferguson and others (1994).

[2]Description from Scott and Bonk (1984).

[3]The term hackly describes the fracturing of a rock into small jagged points (Bates and Jackson, 1987). Many stratigraphic units encountered in the Yucca Mountain area have hackly fracture, and in the case of the Tiva Canyon Tuff, the descriptive term is used in the informal name "hackly subzone". Hackly fracturing results from many processes including cooling and diagenetic alteration.

[4]Description from Lipman and others (1966).

[6]A crystal-poor upper nonlithophysal zone has not been described in the vicinity of Yucca Mountain, but if it occurs then the symbol will be Tptpun.

[7]In exposures near Yucca Mountain where lithophysal zones are not developed, the entire crystal-poor member is in the nonlithophysal zone (Tptpn).

features associated with deposition, the zones of welding and crystallization, and the geometry and surface roughness of fractures. These criteria were initially developed and applied during analysis of core from boreholes drilled in 1992–93 (Appendix 1). A description of criteria to determine lithostratigraphic contacts is discussed in detail in Geslin and others (1995). Subsequent lithologic logging of core from boreholes (Geslin and others, 1995; Geslin and Moyer, 1995; Moyer and others, *in press*) and field mapping has confirmed the use of these criteria and has resulted in only slight modification of the lithostratigraphic nomenclature for a few subzones and intervals.

Phenocryst Assemblage

The phenocryst content and assemblage are the fundamental criteria for subdividing the lithologic units of the Paintbrush Group (table 2). The abundance of phenocrysts, a function of phase equilibrium and mechanical processes during transport and deposition, can be extremely diagnostic, as illustrated by the nearly aphyric Yucca Mountain Tuff and the crystal-poor and crystal-rich members of the Tiva Canyon and Topopah Spring Tuffs. Crystal content of the matrix (not of pumice clasts) is used to identify the transitional subzone between the crystal-rich and crystal-poor members of the Tiva Canyon and Topopah Spring Tuffs. Biotite and a light yellowish-green pseudomorph, probably of pyroxene, occur in the matrix in and above this subzone and rarely in pumice clasts below. Sanidine and plagioclase are abundant phenocrysts in the Paintbrush Group. Therefore, an additional identifying criterion is the sanidine-to-plagioclase ratio, such as the 1:1 ratio of the Topopah Spring Tuff, the 2:1 ratio of the Pah Canyon Tuff, and the greater than 3:1 ratio of the Tiva Canyon Tuff (Broxton and others, 1989).

The occurrence and abundance of accessory minerals also can be used to distinguish formations. For example, the crystal-poor member of the Tiva Canyon Tuff contains accessory hornblende, whereas the crystal-poor member of the Topopah Spring Tuff contains minor biotite. Sphene, which is a characteristic accessory mineral in the Tiva Canyon Tuff, occurs in minor amounts in the Pah Canyon Tuff but is rare in the Topopah Spring Tuff. Paintbrush Group rocks are characterized by the almost complete absence of primary quartz phenocrysts, but quartz is an accessory phase in the crystal-rich part of the Tiva Canyon Tuff and occurs in trace amounts in the lower part of the Topopah Spring Tuff, where it is probably xenocrystic (Byers, 1985).

Depositional Features

The Paintbrush Group at Yucca Mountain consists of primary volcanic deposits from pyroclastic flow and fallout and secondary volcaniclastic deposits from eolian and fluvial processes. Primary deposits can be differentiated from secondary deposits based on features such as grain shape, grain composition, sorting and grading of clasts, imbrication of clasts, crossbedding, and scour at the base of the deposit (Smith, 1960a; Fisher and Schmincke, 1984; Cas and Wright, 1987). The Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs are pyroclastic flow deposits, historically called ash-flow tuffs, that are typically moderately to poorly sorted deposits of crystals, pumice, and lithic clasts in a matrix of glass shards and dust (Lipman and others, 1966). Locally, these tuffs have related, well-sorted, clast-supported fallout deposits. Crossbedding has been observed at the base of primary deposits such as the Tiva Canyon Tuff and probably represent ground layers of the pyroclastic flow, as well as in interstratified, nonwelded tuffs in the Paintbrush Group (Diehl and Chornack, 1990), some of which may be secondary volcaniclastic deposits.

Depositional features that delineate units within tuffs of the Paintbrush Group include the amount of phenocrysts and horizons of increased amounts or sizes of pumice and lithic clasts. For example, abundance of pumice clasts is used to delineate the pumice-rich subzone of the crystal-rich nonlithophysal zone of the Tiva Canyon Tuff (table 2). In the Topopah Spring Tuff, swarms of pumice and lithic clasts have been used to differentiate units and to infer deposition from multiple flow units and significant changes in the eruption history (Lipman and others, 1966; unit Tptpf in table 2). These features also can be used to subdivide the Pah Canyon Tuff.

Welding Zones

Based on the terminology of Smith (1960b), ignimbrites of the Paintbrush Group can be divided by their degree of welding (fig. 2). Criteria that describe the amount of welding include the deformation of shards and pumice, compaction of intershard dust, breakage around or across boundaries of shards and pumice clasts, and the development of foliation. Compaction profiles in ignimbrites show continuous gradation from nonwelded to densely welded textures, but locally the changes in the amount of welding can be very sharp (Riehle, 1973; Sheridan and Ragan, 1977). Lithostatic stress (compaction) and rheomorphic flow

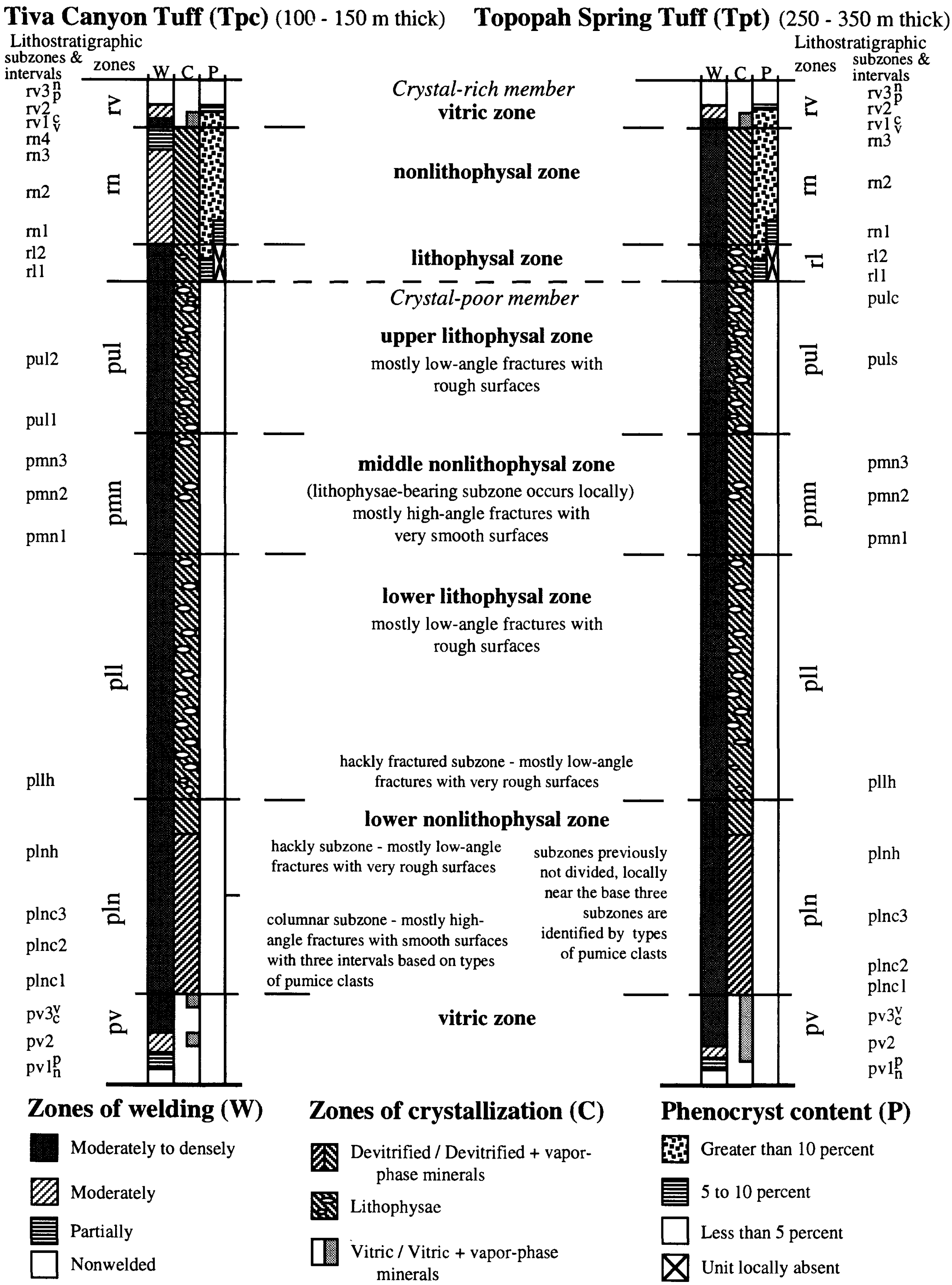

Figure 2. Graphical columns of zones in the Tiva Canyon and Topopah Spring Tuffs, Yucca Mountain, Nevada.

create a well-developed foliation in moderately to densely welded ignimbrites (Smith, 1960b; Schmincke and Swanson, 1967; Chapin and Lowell, 1979). The following welding descriptions are for vitric rocks; however, many of these textures are preserved in devitrified rocks. These criteria are used to identify the degree of welding in rocks of the Paintbrush Group exposed at Yucca Mountain, but these same criteria can be used in other areas as well.

Nonwelded

Shards and pumice clasts are not deformed. Shards typically have bubble-wall and cuspate shapes with sharp terminations. Some shards, which might represent quenching and fragmentation of magma during hydromagmatic interaction, are blocky with sharp interfacial angles. Macroscopic porosity and matrix constituents (intershard ash and dust) are easily visible with a hand lens. Pumice clasts are vesicular. These rocks break along grain boundaries. Elongate pumice and lithic clasts are oriented randomly or are poorly aligned. Colors[1] are typically light gray (N8) to grayish orange (10YR7/4).

Partially Welded

Shards and pumice clasts are slightly deformed. Bubble-wall textures of shards are preserved, but the terminations are slightly rounded. Porosity in the matrix is visible with a hand lens but is reduced. These rocks break along and across grain boundaries. Elongate grains are oriented randomly or have a slight preferred orientation. Colors are typically light grayish orange (10YR7/4) to brownish gray (5YR4/1) or moderate orange red (5YR8/4), with brownish-gray (5YR4/1) shards.

Moderately Welded

Shards and pumice clasts are moderately to significantly deformed. Vitroclastic texture of pumice, shards, and ash are discernible with a hand lens. The rock fractures across all grain boundaries. The amount of macroscopic porosity in pumice and the matrix is small. Elongate grains, especially pumice clasts, define a moderately developed foliation. Colors are typically light pinkish gray (2.5YR6/4), pale grayish red (10R5/2), or moderate brown (5YR3/4).

Densely Welded

Matrix, shards, and pumice are fused, and macroscopic porosity is absent. Based on the amount of preservation of vitroclastic texture discernible with a hand lens, densely welded zones are divided into two intervals; the vitroclastic intervals where vitroclastic textures are easily identifiable, and the vitrophyre intervals where vitroclastic textures are difficult to distinguish. Densely welded rocks break across grain boundaries. Densely welded rocks of the vitroclastic intervals have grayish black (N2) to grayish brown (5YR3/2) pumice clasts in medium dark gray (N4) to pale brown (5YR5/2) matrix. Vitrophyres are typically grayish black (N2) to grayish brown (5YR3/2).

Crystallization Zones

The development of crystallization zones in ignimbrites is controlled by emplacement temperature, glass composition, surface area of the grains, and vapor species and abundance (Smith, 1960b; Ross and Smith, 1961). Figure 2 shows the crystallization zones identified in the Paintbrush Group tuffs: (1) Devitrified zones formed at high temperatures that are characterized by fine-grained aggregates of cristobalite and alkali feldspar in the groundmass (crystallized matrix); (2) vapor-phase zones that are characterized by fine-grained aggregates of tridymite and other minerals (amphibole and pseudobrookite(?)); (3) lithophysal zones where gas cavities up to 1 m in diameter form up to 20 percent of the rock; and (4) zones of fumarolic alteration and crystallization. These zones postdate deposition and, in most cases, probably postdate welding. The following descriptions of crystallization zones pertain to the rocks at Yucca Mountain but also apply to rocks exposed elsewhere in the region.

Vitric Zones

Vitric zones are not included in the original description of crystallization zones (Smith, 1960b), probably because they are defined by the absence of crystallization textures. Vitric zones occur at the top and bottom of the otherwise crystallized Tiva Canyon and Topopah Spring Tuffs. Nonwelded to densely welded rocks can occur within the vitric zone.

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[1]Colors are determined on dry samples using the Rock Color Chart (Geological Society of America, 1991) and the Munsell Soil Color Chart (Kollmorgen Instruments Corp., 1992).

Zone of High-Temperature Devitrification

The zone of high-temperature devitrification contains aggregates of silica polymorphs and alkali feldspar that replace vitroclastic glass to form microscopic to macroscopic groundmass textures. Spherulites and fine-grained granophyric intergrowths are locally well developed and can be identified macroscopically. Devitrified rocks, which comprise the majority of the Tiva Canyon and Topopah Spring Tuffs (fig. 2), are typically pale to moderate purple (5 P-RP 6-4 / 2-4), light to moderate yellowish brown (5-10 YR 6-5 / 4), pale red to pale reddish brown (5-10 R 6-5/ 2-4), or very light to medium light gray (N8-5). They can have either a uniform coloration or appear as a variegated (streaky or blotchy) mass.

Zones of Vapor-Phase Crystallization

Zones of vapor-phase crystallization typically contain abundant euhedral crystals of tridymite, less common sanidine, specular hematite, pseudobrookite(?), manganiferous biotite and amphibole, and rare manganiferous garnet and chlorites (Vaniman and others, 1984; D. Vaniman, LANL, oral commun., 1993; R. Warren, LANL, written commun., 1994). Vapor-phase crystals grow in primary pore spaces in nonwelded to partially welded tuffs, in secondary pore spaces formed by lithophysae or by the corrosion of glass by vapor-phase alteration, or along fractures (Smith, 1960b; Ross and Smith, 1961). The Pah Canyon Tuff contains incipiently lithified rock that is the product of vapor-phase crystallization which overprints a remnant vitroclastic texture (a sillar zone of Fenner, 1948).

Lithophysal Zones

Lithophysal zones occur where vapor concentrates in the densely welded part of ignimbrites to form lithophysal cavities (Ross and Smith, 1961). The vapor can be derived from (1) air and gas interstitial to the pyroclastic material that was trapped during deposition from a pyroclastic flow, (2) exsolution from shards and pumice, or (3) released during devitrification. Lithophysae consist of a cavity, which is commonly coated with vapor-phase minerals on the inner wall of the cavity, a fine-grained rim surrounding the cavity wall, and a thin very fine-grained border (fig. 3). Many lithophysae in the Tiva Canyon and Topopah Spring Tuffs have light-gray (N8) to grayish-orange pink (10R8/2) rims of microscopic to barely macroscopic elongate crystals that radiate from the walls of the lithophysae into the surrounding groundmass. These rims are up to 3-cm wide. Locally, rims have 1- to 3-mm-wide, grayish red-purple (5YR4/2) borders. Associated with the lithophysae are light-gray (N8) to grayish-orange pink (10R8/2) spots 1- to 5-cm in diameter. Some spots may represent the cross sections of rims on lithophysae, whereas others have a crystal or lithic clast in the core that could have acted as a nucleation site. There is no genetic interpretation for the spots; however, they are characteristic for some lithophysal zones. Lithophysal zones in the Tiva Canyon and Topopah Spring Tuffs are identified by a combined occurrence of lithophysae and spots. The shape of the lithophysae and spots and width of the rims on the lithophysae can also be diagnostic of specific zones. Locally, surface exposures contain lithophysae with diameters of up to 1 m; thus, regions of poor core recovery might indicate large lithophysae.

Zones of Fumarolic Alteration and Crystallization

Zones of fumarolic alteration and crystallization occur locally in the upper nonwelded vitric zone of the Tiva Canyon and Topopah Spring Tuffs. Fumarolic alteration produces sillar textures and oxidizes iron in the glass to form variegated red and orange colors. Fumarolic alteration is a localized manifestation of vapor-phase processes, whereas vapor-phase zones are more laterally extensive.

Surface Roughness and Orientation of Fractures

The characteristic fracture patterns in outcrops of several units at Yucca Mountain, such as the columnar, hackly, and clinkstone units of the Tiva Canyon Tuff (as defined by Scott and Bonk, 1984), could partly manifest the response of these rocks to stresses associated with vapor-phase activity, cooling, tectonic activity, or erosion. In recent mapping of the Tiva Canyon Tuff, lithostratigraphic units were identified by the roughness of joints and freshly broken surfaces (Spengler and others, 1994). In these studies, semi-quantitative estimates of surface roughness, termed roughness coefficients, were made by comparing the profile of a fracture surface to profiles assigned numerical values for roughness (see Barton and Choubey, 1977; fig. 4). In outcrops of the Tiva Canyon Tuff, roughness coefficients range from 2 to 18, but individual zones have more restricted and characteristic ranges (Spengler and others, 1994) (table 3). Qualitative descriptions of core samples indicate fracture and surface roughness similar to those observed in outcrop

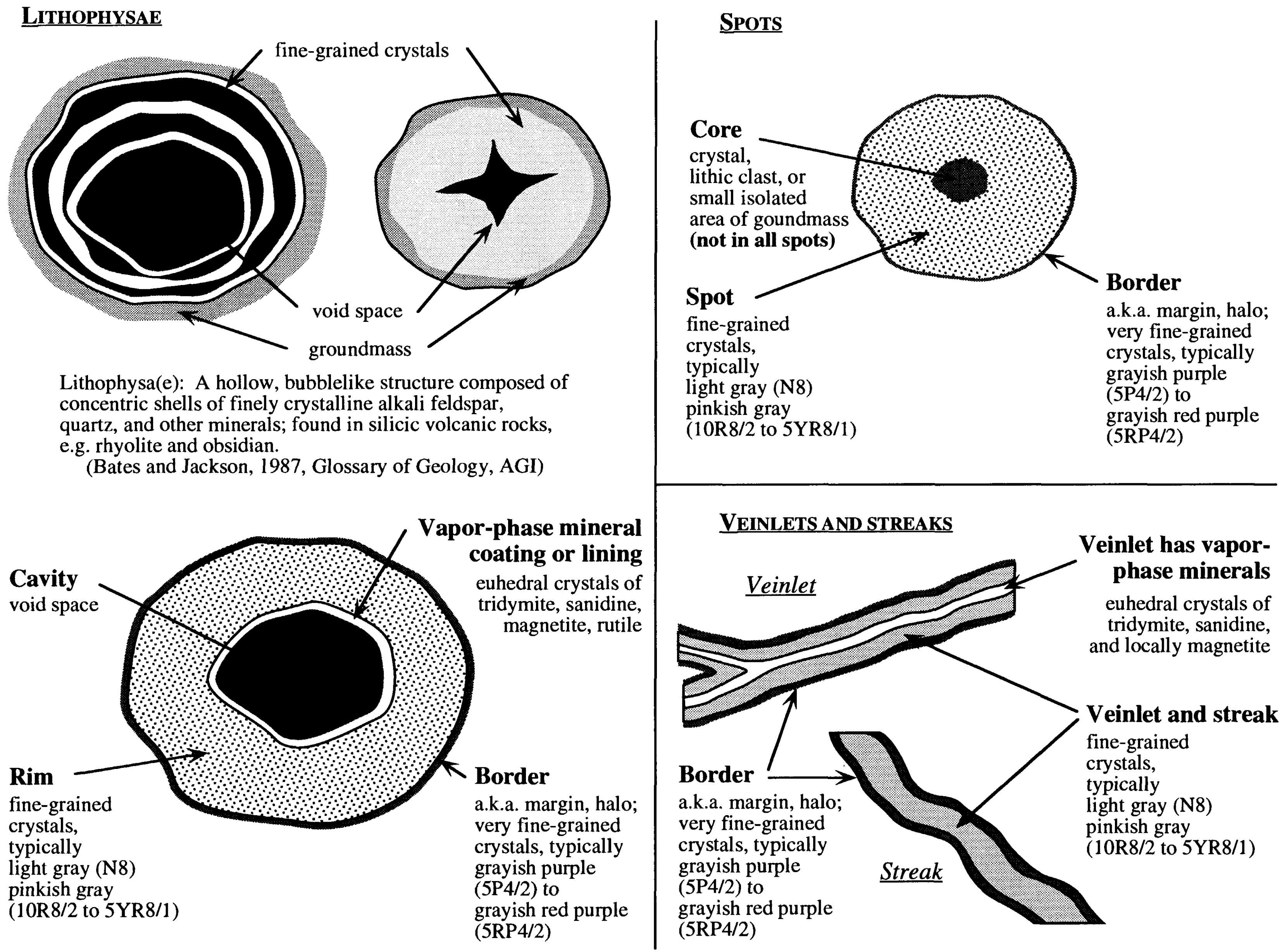

Figure 3. Components of lithophysae, spots, veinlets, and streaks in welded tuffs, Yucca Mountain, Nevada.

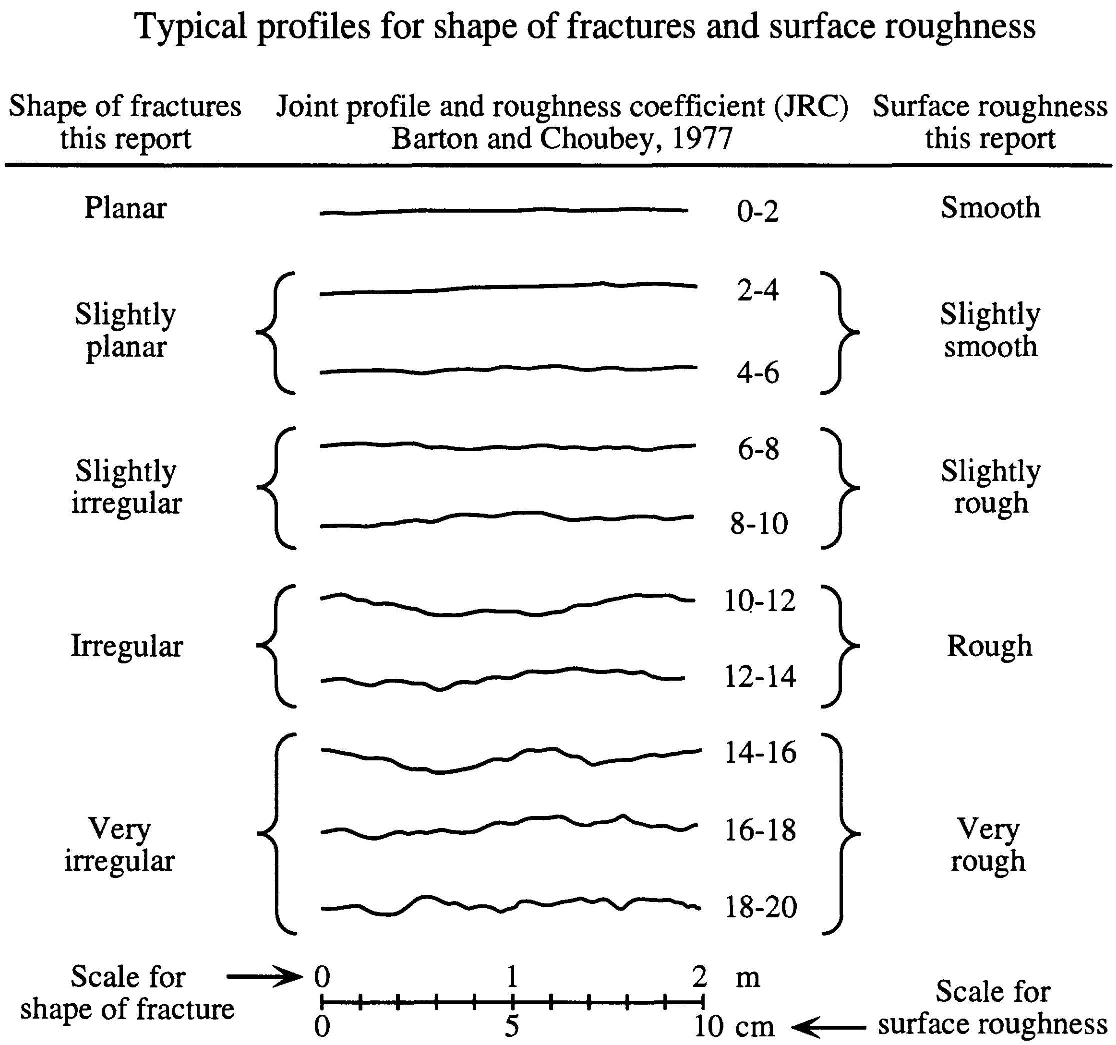

Figure 4. Profiles for shape of fracture and surface roughness in welded tuffs at Yucca Mountain, Nevada.

Table 3. Roughness coefficients of freshly broken surfaces in lithostratigraphic zones of the Tiva Canyon Tuff at Yucca Mountain

[>, greater than; <, less than]

Zone (Spengler and others, 1994)	Roughness coefficient, surface	Zone/subzone (this report)	Roughness coefficient, subsurface
		Crystal-rich member	
Upper cliff.		Nonlithophysal.	
> 10 meters from base.	7–18		Rough to very rough.
< 10 meters from the base.	3–6	Crystal transition.	Slightly smooth.
		Crystal-poor member	
Upper lithophysal.	6–10	Upper lithophysal.	Slightly rough.
Clinkstone.		Middle nonlithophysal.	Smooth to slightly smooth.
Upper contact.	2–4		
Lower contact.	2–8		
Lower lithophysal.	8–12	Lower lithophysal.	Rough.
		Lower nonlithophysal.	
Hackly (lowest exposed unit).	12–18	Hackly.	Very rough.
		Columnar.	Slightly smooth.
		Vitric.	
		Vitrophyre.	Smooth to slightly smooth.
		Moderately welded.	Slightly smooth.
		Nonwelded.	Slightly smooth.

(table 3), except the surface profiles are not as well developed.

Changes in the roughness of fractures and freshly broken surfaces typically coincide with the boundaries of lithophysal and nonlithophysal zones (table 3), but locally, changes in roughness transgress these zone boundaries. These relations indicate the processes that control the fracture geometry are probably coupled with the processes of welding and crystallization, although not completely. Fracture characteristics can be viewed as forming zones similar to those of welding and crystallization. In this report, the zones of fracture are simply referred to by the name of the most characteristic surface roughness. Fracture profiles with very rough surface roughnesses are commonly referred to as having hackly fractures, therefore, the rocks with high roughness coefficients are designated as in the hackly zone. An example of the overlap of zones of fracture, welding, and crystallization is demonstrated in the lower lithophysal and nonlithophysal zones of the Tiva Canyon and Topopah Spring Tuffs. The upper part of the lower nonlithophysal zone commonly has a hackly subzone that coincides with the hackly zone of fracture. The hackly zone locally transgresses the boundary of the lower lithophysal and nonlithophysal zones, and therefore, hackly fractured subzones are formed in the upper part of the nonlithophysal zone and the lower part of the lithophysal zone (fig. 2).

Detailed mapping of surface exposures in the Tiva Canyon Tuff shows that some joints transect two or more lithostratigraphic units, and the morphology and roughness coefficients of these joints change at the contact (Spengler and others, 1994). Joints that occur in outcrops characterized by low roughness coefficients are more planar, whereas joints that occur in outcrops with high roughness coefficients are more irregular.

Lithostratigraphic zones have a characteristic fracture morphology and orientation (high angle versus low angle) in core. The middle nonlithophysal zones of the Tiva Canyon and Topopah Spring Tuffs typically have abundant high-angle fractures (greater than 75° from horizontal) that are planar to curviplanar. Locally, these fractures occur in closely spaced sets of two to five fractures. In contrast, lithophysal zones have abundant, irregular, low-angle fractures (less than 30° from horizontal), many of which could have been induced during drilling, and few, irregular, high-angle fractures. In the upper and lower nonlithophysal zones of both tuffs, high-angle fractures are intermediate in abundance and in profile.

High-angle, anastomosing, discontinuous fractures with irregular profiles occur locally in the hackly-fractured subzone of the lower lithophysal zone and the hackly subzone of the lower nonlithophysal zone in the Tiva Canyon and Topopah Spring Tuffs (fig. 2). These fractures commonly form irregular open cavities that are partially filled with small angular clasts of the surrounding rock. Both the walls and clasts have a thin deposit of vapor-phase minerals. These fractures are restricted to the lower nonlithophysal and lithophysal zones, but are not ubiquitous in these zones and cannot be used as a defining characteristic.

Transition Zones and Unit Contacts

The interplay between depositional, welding, crystallization, and fracturing processes in ignimbrites produces contacts that can be sharp where one of the attributes abruptly change, or gradational where an attribute changes gradually. Depositional contacts such as the base of pyroclastic flow and fallout deposits and redeposited material are examples of sharp contacts. Tops of these deposits are typically sharp, but can be gradational where there is evidence of reworking or pedogenesis. The transition from nonwelded to densely welded tuff is typically gradational, but the welding profile can vary in shape (Riehle, 1973; Sheridan and Ragan, 1977). Shape of the welding profile can be approximated by macroscopic identification of the zones of welding, the thicknesses of these zones, and the width of the gradational contacts between these zones.

The importance of using multiple criteria to define contacts where there are gradational changes in the percent lithophysae, percent light-brown groundmass, fracture shape, and surface roughness is shown in figure 5. In core from boreholes USW UZ-14 and USW NRG-6 (fig. 5), at the upper lithophysal zone/middle nonlithophysal zone contact in the Topopah Spring Tuff, the amount of light-brown groundmass changes abruptly across an interval of less than 1 m and groundmass color is completely changed in 5 m. If only color is used to define this contact, the contact occurs at 218 m in USW UZ-14 and at 222 m in USW NRG-6. By comparison, changes in other attributes occur over 5 to 10 m. If a change in fracture-surface roughness is used to define the contact, then the contact is at 218 m in USW UZ-14 and in the interval from 212 m to 218 m in USW NRG-6. By using criteria in combination, the best fit contact is at about 218 m in USW UZ-14 and 217 m in USW NRG-6. The attributes shown in figure 5 do not stabilize for about 10 m above and below the best-fit contact, forming a 20-m-wide transition interval.

MACROSCOPIC CHARACTERISTICS OF THE PAINTBRUSH GROUP TUFFS

Zones, subzones, and intervals of the Paintbrush Group tuffs as identified in core and outcrop are described below. Some zones and subzones can vary laterally and relations within the Tiva Canyon and Topopah Spring Tuffs illustrate that welding and crystallization zones cross-cut depositional boundaries (the crystal-rich and crystal-poor boundary). A few zones such as the crystal-rich lithophysal zones in the Tiva Canyon and Topopah Spring Tuffs are locally absent. Figure 2 illustrates that the hierarchy of lithostratigraphic zones is identical in the Tiva Canyon and Topopah Spring Tuffs, and the zones are vertically symmetrical above and below the middle nonlithophysal zone. Efforts are continuing to describe the variations within the Pah Canyon and Yucca Mountain Tuffs, therefore, these formations are not divided in this report.

Tiva Canyon Tuff

The Tiva Canyon Tuff is a large-volume, regionally extensive, compositionally zoned ignimbrite that forms most of the rocks exposed at the surface of Yucca Mountain (Christiansen and Lipman, 1965; Byers and others, 1976a and b; Christiansen and others, 1977; Scott and Bonk, 1984). Divisions of the Tiva Canyon Tuff are summarized in figure 2 and table 2 with more detailed descriptions in Appendix 2. Primary divisions reflect depositional and compositional zoning that is expressed by variations in crystal-content, phenocryst assemblage, and pumice composition (Broxton and others, 1989; Warren and others, 1989b; table 2 and fig. 2). Secondary divisions define welding and crystallization zones, depositional features, or fracture characteristics. Welding and crystallization zones are distributed in vertical symmetry around a central zone that is moderately to densely welded and devitrified (compare Smith, 1960b). Petrographic and geochemical studies of surface and subsurface samples in the Tiva Canyon Tuff indicate there is a very good correlation with the zones and subzones identified on the basis of macroscopic features (Singer and others, 1994; Z. Peterman, USGS, written commun., 1994).

The crystal-rich member is composed of a vitric zone underlain by devitrified material that locally contains lithophysae. Subzones of the crystal-rich vitric zone include a nonwelded to partially welded subzone

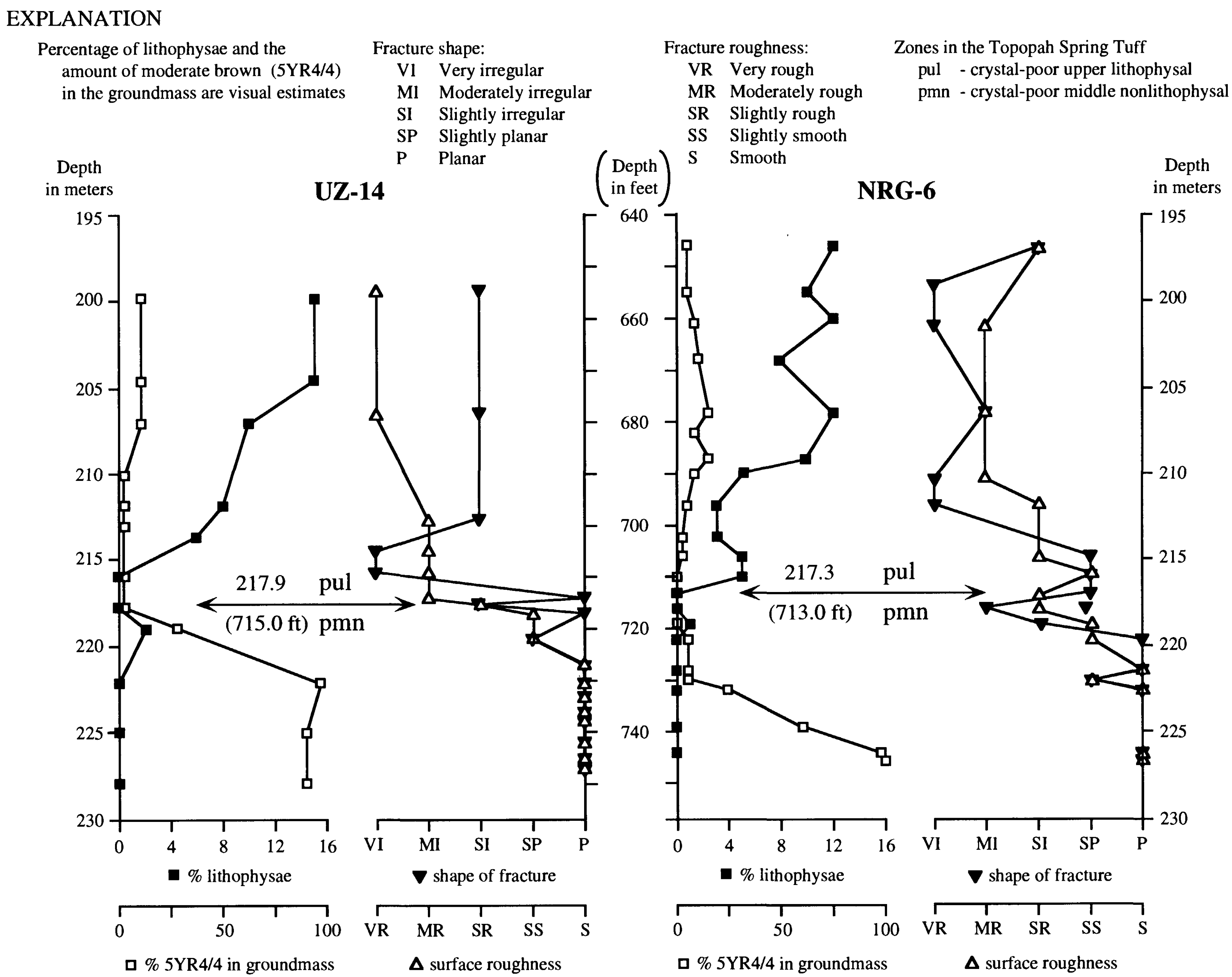

Figure 5. Curves used to identify the contact of the upper lithophysal and middle nonlithophysal zones in the Topopah Spring Tuff in core from boreholes USW UZ-14 and USW NRG-6. Borehole stratigraphic position is plotted versus the: (1) Percentages of lithophysae, (2) percentages of light brown (5YR4/4) groundmass, (3) shape of high-angle fracture, and (4) surface roughness of the fractures. Percentages of lithophysae and groundmass color are visual estimates. Shape and surface roughness are determined qualitatively.

(typically partly altered; Tpcrv3), a moderately welded subzone (locally devitrified or altered; rv2) in which the degree of welding increases sharply with depth, and a densely welded subzone (rv1) that is locally divided into the vitroclastic (rv1c) and vitrophyre intervals (rv1v). The vitric densely welded rocks are locally absent. The underlying crystal-rich nonlithophysal zone (devitrified throughout) is divided into four subzones. The subvitrophyre transition subzone (Tpcrn4) has 5 to 20 percent pumice clasts and decreases downward in the degree of welding. The subzone is locally divided into the densely welded (rn4d) interval and the moderately welded (rn4m) interval in which there is an increase in vapor-phase crystallization downward. The underlying pumice-poor subzone (rn3), characterized by less than 5 percent pumice clasts, overlies the mixed pumice subzone (rn2), typified by abundant (up to 30%) light-gray and dark reddish-gray pumice clasts. A crystal-rich lithophysal zone (rl) locally underlies the mixed pumice subzone. The crystal-rich and crystal-poor members are separated by a thin transitional subzone (rn1 where nonlithophysal, rl1 where lithophysal), in which the crystal content decreases and the ratio of felsic to mafic phenocrysts increases downward.

The crystal-poor member is divided into five zones. The upper lithophysal zone (Tpcpul) locally contains a basal spherulite-rich subzone. In some reports, the spherulite-rich subzone is referred to as pul1, and where pul1 is present, the overlying non-spherulitic rock is designated as pul2. The underlying middle nonlithophysal zone locally is composed of three subzones, upper and lower nonlithophysal subzones (Tpcpmn1 and pmn3) and an intervening lithophysae-bearing subzone (pmn2) that becomes thicker northward. The lower lithophysal zone (Tpcpll) locally has a hackly-fractured subzone (llh). The lower nonlithophysal zone (Tpcpln) is divided on the basis of macroscopic fracture morphology into the hackly (plnh) and columnar (plnc) subzones. The columnar subzone is, in turn, divided into three intervals by the appearance of pumice clasts: an interval with devitrified and locally spherulitic pumice clasts (lnc3) overlies an intermediate interval with argillically altered pumice clasts (lnc2) that overlies an interval with dense, vitric pumice clasts (lnc1). The underlying crystal-poor vitric zone (Tpcpv), defined by the presence of a glassy matrix, is composed of three subzones. A locally preserved, densely welded subzone (pv3) is divided into a vitrophyre interval (pv3v) and a clastic textured interval (pv3c). The moderately welded vitric subzone has characteristic deformed amber shards (pv2). The nonwelded subzone (pv1) has light brown to colorless glass shards in the partially welded (pv1p) and nonwelded intervals (pv1n). Locally, in the lower part of the Tiva Canyon Tuff there are several pyroclastic-flow boundaries identified by concentrations of pumice clasts, changes in size of pumice clasts, and fine-grained, cross-bedded deposits. The nonwelded subzone locally includes a basal, planar to cross-bedded pyroclastic-surge deposit overlying a thin (few centimeter thick) pumice-fall deposit.

Yucca Mountain Tuff

The Yucca Mountain Tuff is a simple cooling unit (Christiansen, 1979) that is nonwelded throughout much of the study area, but partially to moderately welded where it thickens in the northern part of Yucca Mountain. The tuff, which varies in thickness from 0 to 30 m at Yucca Mountain, locally includes a thin (few centimeters), pumice-fall bed at the base of the pyroclastic flow deposit. The ignimbrite is nearly aphyric (phenocrysts approximately 0.1 percent of the rock; Broxton and others, 1989), with sparse, small pumice clasts (commonly less than 1 cm diameter, less than 1 percent of the rock), and rare, small (less than 1 cm), grayish red-purple lithic clasts. The formation is nonlithophysal throughout the study area, but contains lithophysae where densely welded in northern Crater Flat (C. Fridrich, written commun., 1993). Nonwelded portions are grayish orange (10YR8/2) to moderate brown (5YR5/4) with colorless glass shards that have well-preserved bubble-wall textures. Partially welded portions are grayish pink (5YR8/2) to light gray (N8) with fused, black glassy or pinkish gray, devitrified shards.

Pah Canyon Tuff

The Pah Canyon Tuff is a simple cooling unit (Christiansen, 1979) composed of multiple flow units. The formation is absent south of WT-2 Wash, but varies up to 70-m thickness in the northern part of Yucca Mountain. Although flow unit boundaries are difficult to identify in core, a general threefold stratigraphy is apparent. The upper and lower portions are characterized by light-gray (N8) to grayish-orange pink (5YR7/2) pumice clasts in a pink (5YR7/3), pinkish-orange (2.5YR7/6), light-gray (N8), or white matrix. The central part of the formation is typified by abundant (15 to 25 percent of the rock), large (2- to 12-cm diameter), grayish-orange (10YR7/4) pumice clasts in a pink to grayish-orange (10YR7/4) matrix. The large pumice clasts, which commonly have a banded texture, contain distinctive clusters of phenocrysts. Phenocrysts comprise 5 to 10 percent of the rock, with a high ratio of feldspars to mafic (biotite and clinopyroxene) phenocrysts. Lithic clasts (up to 5 percent of the rock) of devitrified rhyolite are common; clasts of porphyritic obsidian occur in some horizons.

The Pah Canyon Tuff varies from nonwelded to moderately welded in the Yucca Mountain region. Throughout much of the study area, vitric pumice clasts are preserved in a nondeformed matrix that is sintered or lithified by vapor-phase mineralization. Shards occur either as poorly preserved clear glass or as devitrified material; locally preserved relict shard shapes may reflect areas where vapor-phase alteration has formed secondary porosity by glass corrosion. Moderately welded zones contain vapor-phase altered pumice clasts in a deformed, devitrified matrix.

Topopah Spring Tuff

The Topopah Spring Tuff has a maximum thickness of about 350 m in the vicinity of Yucca Mountain (Lipman and others, 1966; Byers and others, 1976b) (Appendix 1). The top of the Topopah Spring Tuff has not been explicitly defined (Lipman and others, 1966; Spengler and others, 1981; Maldonado, and Koether, 1983; Scott and Bonk, 1984; Scott and Castellanos, 1984; Spengler and others, 1984). The top of the Topopah Spring ignimbrite is herein defined as a bedset consisting of a thin (2 cm), very fine-grained ash bed that is overlain by a thin (2 cm) lithic-rich fallout tephra. This bedset occurs across Yucca Mountain in core from boreholes and in surface exposures from southwestern flank of Yucca Mountain along Solitario Canyon to north of Yucca Wash near Fortymile Wash. Units that occur between the Topopah Spring ignimbrite and the Pah Canyon Tuff include a 5- to 15-m-thick pumice-rich fallout that is typically altered to clay at the top and a reworked interval (Appendix 2). This sequence is identified independently from the Topopah Spring Tuff and is designated as bedded tuff (Tpbt2). This post-ignimbrite fallout tephra is locally partially to moderately welded and altered by fumarolic(?) gases from the ignimbrite, and therefore, was probably deposited shortly after the ignimbrite. Continued tephrostratigraphic analysis must be completed before conclusively assigning this fallout to the Topopah Spring Tuff or a sequence of subsequent eruptions.

Lithostratigraphic divisions of the Topopah Spring Tuff are summarized in figure 2 and table 2, with more detailed descriptions given in Appendix 2. Figure 6 illustrates that the Topopah Spring zones are easily correlated between several boreholes. Because primary and secondary subdivisions are defined with criteria similar to those used in the Tiva Canyon Tuff, the welding and crystallization zones of the Topopah Spring Tuff are distributed in the same fashion. The Topopah Spring Tuff typically has fewer crystals than many rocks in the SWNVF, therefore, the crystal-rich member has an upper part with 8 to 12 percent phenocrysts and a crystal-transition subzone with 3 to 5 percent phenocrysts. The crystal-poor member typically has 1 to 3 percent phenocrysts. Locally, in areas surrounding Yucca Mountain, lithophysal zones are not well developed and divisions into lower and middle nonlithophysal zones are not possible (Spengler, nonpublished data). In these areas, the entire crystal-poor member is in the nonlithophysal zone (Tptpn).

The crystal-rich member is composed of a vitric zone (Tptrv) underlain by devitrified material that locally contains lithophysae (Tptrn and Tptrl). Subzones of the crystal-rich vitric zone include an upper, nonwelded subzone (typically altered; Tptrv3), an intermediate moderately welded subzone (locally devitrified or altered; rv2) in which the degree of welding increases sharply with depth, and lower, densely welded vitrophyre (rv1). The nonwelded subzone is divided into nonwelded interval (rv1n) that overlies the partially welded interval (rv1p). In the densely welded subzone, the clastic texture interval (rv1c) overlies the vitrophyre interval (rv1v). Locally, the vitric densely welded subzone is absent, and densely welded rocks of the nonlithophysal zone are in contact with devitrified and vapor-phase altered rocks of the moderately welded subzone (rv2). The moderately to densely welded nonlithophysal zone (rn), which is devitrified and variably altered by vapor-phase mineralization, has three subzones; a dense subzone (rn3) overlies the vapor-phase corroded subzone (rn2) that overlies the crystal-transition subzone (rn1). The crystal-rich lithophysal zone (rl) occurs at most locations. Separating the crystal-rich and crystal-poor members is a thin transitional subzone (rl1 where lithophysal, rn1 where nonlithophysal) in which the crystal content decreases and the ratio of felsic to mafic phenocrysts increases downward.

The crystal-poor member is divided into six zones. The lithic-rich zone typically straddles the contact of the crystal-rich and crystal-poor members in the northern part of Yucca Mountain and adjacent areas. Lithic clasts comprise 10 to 50 percent of the rock, some are as much a 50 cm in diameter, and some are fine- to medium-grained plutonic clasts (Lipman and others, 1966; Spengler and Fox, 1989). Based on the amount of phenocrysts and lithophysae, the zone is divided into crystal-rich (Tptrf) and crystal-poor (Tptpf) subzones that are subdivided into lithophysal

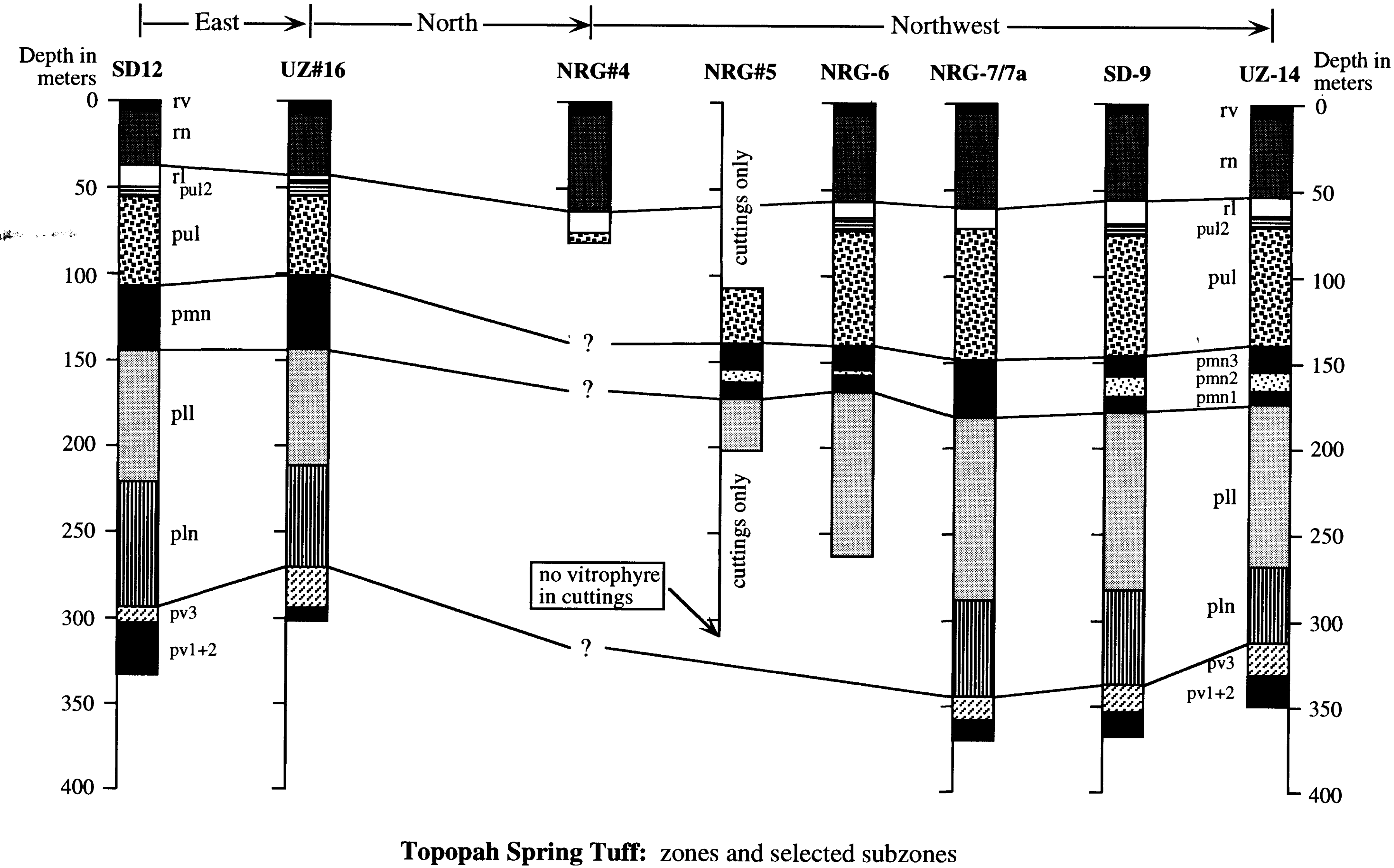

Figure 6. Generalized and partial columnar sections and correlation diagram of Topopah Spring Tuff in boreholes USW SD-12, UE25 UZ#16, UE25 NRG#4, UE25 NRG#5, USW NRG-6, USW NRG-7/7a, USW SD-9, and USW UZ-14 at Yucca Mountain, Nevada. Depths are measured from the top of the ignimbrite. In NRG#5, the crystal-rich vitrophyre subzone was identified in cuttings and the base of this subzone is equated to the same contact in NRG#4 and NRG-6. Data for USW SD-9, USW SD-12, and USW NRG-7/7a is from Geslin and Moyer, 1995, and Moyer and others, *in press.*

(Tptrfl and Tptpfl) and nonlithophysal (Tptrfn and Tptpfn) intervals. The upper lithophysal zone (Tptpul) contains abundant lithophysal cavities enclosed by thin light-color rims. The lithophysal cavities commonly have diameters of a few centimeters, but some are up to 1 m across as identified in the field and in borehole televiewer logs or inferred from intervals of broken or nonrecovered core. Locally, at the top of the zone is the cavernous lithophysae subzone (pulc) that contains few small lithophysal cavities and abundant large (tens of centimeters) lithophysal cavities inferred from intervals of broken or nonrecovered core and observed on borehole televiewer log. Where the cavernous lithophysae subzone occurs, the lower part of the upper lithophysal zone is the small lithophysal subzone (puls). The underlying middle nonlithophysal zone is composed of upper and lower nonlithophysal subzones (Tptpmn3 and pmn1) that are separated by a central thin, lithophysal subzone (pmn2). The lower lithophysal zone (Tptpll) is characterized by a mottled coloration and large, irregularly shaped lithophysal cavities surrounded by thick light gray to pink rims. Locally, where the hackly zone of fracture is well developed, the lower lithophysal zone has a hackly-fractured subzone (pllh). The lower nonlithophysal zone (Tptpln) is locally divided into subzones on the basis of development of hackly fractures (lnh) and the spherulitic (ln3), argillic (ln2), and vitric (ln1) pumice clasts that are similar to the intervals in the Tiva Canyon Tuff. The vitric zone (Tptpv) is distinguished by the presence of matrix glass. Subdivisions of the vitric zone include the densely welded zone (Tptpv3), which overlies the moderately welded subzone (pv2) and the nonwelded zone (pv1) that occurs at the base of the ignimbrite. The densely welded subzone (pv3) is divided into a vitrophyre interval (pv3v) and a clastic textured interval (pv3c). The moderately welded subzone is transitional to the densely welded clastic textured interval, but has macroscopic porosity and is locally devitrified and altered by vapor-phase mineralization. The nonwelded subzone (pv1) is divided into the partially welded (pv1p) and nonwelded intervals (pv1n). In many parts of Yucca Mountain and the adjacent areas to the north, the moderately welded and nonwelded zones are overprinted by zeolite alteration zones (Broxton and others, 1987; Bish and Chipera, 1989).

CORRELATION OF LITHOSTRATIGRAPHIC, THERMAL-MECHANICAL, AND HYDROGEOLOGIC UNITS

Prior to this report, rocks of the Paintbrush Group at Yucca Mountain were described using stratigraphic systems based on the characteristics of surface exposures (Scott and Bonk, 1984), petrographic attributes and chemical composition (Byers and others, 1976b), hydrogeologic properties such as porosity and permeability (Office of Civilian Radioactive Waste Management, 1988; Rautman and Flint, 1992), or thermal-mechanical properties (Ortiz and others, 1985). An advantage to the lithostratigraphic system is that lithologic contacts in outcrops and core can be determined without lengthy laboratory confirmation. In this section, lithostratigraphic zones and subzones are correlated to the units defined in other systems and provide a framework to link the varied stratigraphic nomenclatures used for the Yucca Mountain area.

Scott and Bonk (1984), in their 1:12,000 scale mapping of the Yucca Mountain region, subdivided the Tiva Canyon Tuff into seven zones based mostly on the characteristics of surface exposures and, to a lesser extent, the petrologic, depositional, welding, and crystallization features of the unit. Although many zones are similar to those of Scott and Bonk (1984) (fig. 7), the descriptions used in this report apply to both surface exposures and core, and divide the Paintbrush formations on a smaller scale. Most field units of Scott and Bonk (1984) are generally correlated with lithostratigraphic zones and subzones for the Tiva Canyon Tuff (fig. 7 and Appendix 3). For example, the upper cliff and lower part of the caprock zones (Scott and Bonk, 1984) correlate with the crystal-rich, nonlithophysal, mixed pumice subzone (Appendix 3).

Porosity is one of the criteria used in identification of lithostratigraphic units and is a significant criteria in determining hydrogeologic and thermal-mechanical units, but the relationship of macroscopic estimates to laboratory measurements must be understood. In densely welded rocks such as the crystal-rich and crystal-poor vitrophyres of the Topopah Spring Tuff, there is no macroscopic porosity, but samples from these units have laboratory measurements that vary from 0.025 to 0.1 cm^3/cm^3 (Rautman and Flint, 1992; Rautman and others, 1993; L. Flint, USGS, written commun., 1994). Porosities of nonwelded tuffaceous rocks determined by macroscopic estimates and laboratory measurements are commonly 0.3 to 0.6 cm^3/cm^3. The differences in macroscopic estimates

Nomenclature and symbols Scott and Bonk (1984)		Correlation	Symbols and nomenclature this report	
Tiva Canyon Member	**Tpc**		**Tpc**	**Tiva Canyon Tuff**
caprock zone	ccr		cr	crystal-rich member
			crv	vitric zone
			rv3	nonwelded
nonwelded		⟶	v3n	nonwelded
			v3p	partially welded
			rv2	moderately welded
			rv1	densely welded
			v1c	clastic textured
vitrophyre		⟶	v1v	vitrophyre
			crn	nonlithophysal zone
brown devitrified		→	rn4	subvitrophyre
yellow-brown devitrified		→	rn3	pumice-poor
brown-gray devitrified		→	rn2	mixed-pumice
upper cliff zone	cuc	→	crl	lithophysal zone[1]
			rn1, rl1	crystal-transition[2]
			cp	crystal-poor member
upper lithophysal zone	cul	⟶	cpul	upper lithophysal zone
clinkstone/rounded step zone	cks/crs	⟶	cpmn	middle nonlithophysal zone
middle lithophysal : cml			mn3	(upper) nonlithophysal
other facies: clc, cgks, crks		⟶	mn2	lithophysae-bearing
cuks, clks			mn1	(lower) nonlithophysal
lower lithophysal zone	cll	⟶	cpll	lower lithophysal zone
			llh	hackly fractured
			cpln	lower nonlithophysal zone
hackly zone	ch	⟶	lnh	hackly
columnar zone	cc	⟶	lnc	columnar
			c3	spherulitic pumice
			c2	argillic pumice
			c1	vitric pumice
			cpv	vitric zone
			pv3	densely welded
vitrophyre		⟶	v3v	vitrophyre interval
			v3c	clastic textured
flattened pumice[3]		→	pv2	moderately welded
basal[3]		→	pv1	nonwelded welded
			v1p	partially welded
			v1n	nonwelded welded

Symbols		Stratigraphic rank
⟶	Correlative units based on similar descriptions. Revised descriptions are more detailed and specific than those of Scott and Bonk, 1984.	member
→	Probably correlative units based on similar descriptions	zone
		subzone
		interval

[1] The crystal-rich lithophysal zone is laterally equivalent to the lower part of the crystal-rich nonlithophysal zone

[2] The crystal-transition subzone, defined by the downward decrease from 10 to 5 percent phenocrysts, occurs in the crystal-rich nonlithophysal (rn1) or crystal-rich lithophysal zone (rl1).

[3] The flattened pumice and basal subzones have been referred to as the "shardy base" in Rautman and Flint (1992).

Figure 7. Comparison of stratigraphic nomenclature and symbols for the Tiva Canyon Tuff and Topopah Spring Tuff at Yucca Mountain from Scott and Bonk (1984) and this report.

Nomenclature and symbols Scott and Bonk (1984)			Symbols and nomenclature this report	
Topopah Spring Member	**Tpt**		**Tpt**	**Topopah Spring Tuff**
caprock zone	tc		tr	crystal-rich member
			trv	vitric zone
nonwelded		⟶	rv3	nonwelded
			v3n	nonwelded
			v3p	partially
			rv2	moderately welded
			rv1	densely welded
			v1c	clastic textured
vitrophyre		⟶	v1v	vitrophyre
		⟶	trn	nonlithophysal zone
devitrified		⌉	rn3	dense
rounded zone	tr	⌋	rn2	vapor-phase corroded
thin lithophysal zone: ttl		→	trl	lithophysal zone[1]
			rn1, rl1	crystal-transition[2]
			trf	lithic-rich zone (plutonic clasts)
			tp	crystal-poor member
			tpf	lithic-rich zone (plutonic clasts)
red lithophysal zone	trl	⟶	tpul	upper lithophysal zone
other facies: tul, tll, tl			pulc	cavernous lithophysal
nonlithophysal zone	tnl	⟶	tpmn	middle nonlithophysal zone
orange-brick lithophysal: tobl		⌉	pmn3	(upper) lithophysal
other facies: tgnl, to, tb, tob, tbob		⌊→	pmn2	lithophysae-bearing
			pmn1	(lower) lithophysal
grayish-red lithophysal zone	tgrl	⟶	tpll	lower lithophysal zone
other facies: torl, tml, tpbl, trbb,tbol			pllh	hackly fractured
mottled zone	tm	⟶	tpln	lower nonlithophysal zone
			plnh	hackly fractured
			plnc	columnar
			lnc3	spherulitic pumice
			lnc2	argillic pumice
			lnc1	vitric pumice
			tpv	vitric zone
			pv3	densely welded
vitrophyre zone	tv	⟶	v3v	vitrophyre
			v3c	clastic textured
			pv2	moderately welded
			pv1	nonwelded welded
partially welded zone	tpw	⟶	v1p	partially welded
			v1n	nonwelded

Symbols		Stratigraphic rank
⟶	Correlative units based on similar descriptions. Revised descriptions are more detailed and specific than those of Scott and Bonk, 1984.	member zone
→	Probably correlative units based on similar descriptions	subzone interval

[1] The crystal-rich lithophysal zone is laterally equivalent to the lower part of the crystal-rich nonlithophysal zone

[2] The crystal-transition subzone, defined by the downward decrease from 10 to 5 percent phenocrysts, occurs in the crystal-rich nonlithophysal (rn1) or crystal-rich lithophysal zone (rl1).

Figure 7. Comparison of stratigraphic nomenclature and symbols for the Tiva Canyon Tuff and Topopah Spring Tuff at Yucca Mountain from Scott and Bonk (1984) and this report--Continued.

and laboratory measurements of porosity result from microscopic pores and small aperture fractures, and therefore, are a function of the scale at which method the porosity is examined. Thus, macroscopic estimates of porosity will differ slightly from laboratory-determined values, but macroscopic estimates can provide preliminary approximations of porosity that can be refined with subsequent laboratory tests. Determining a correlation function of macroscopic estimates and laboratory-measured porosity for individual samples and lithostratigraphic units as a whole may provide the means of approximating porosities in areas where laboratory data are not available.

Paintbrush Group rocks are included in parts of five generalized hydrogeologic units where hydrogeologic unit boundaries occur at large changes in hydrogeologic properties (Office of Civilian Radioactive Waste Management, 1988). The preliminary correlations of the boundaries of hydrogeologic units with lithostratigraphic subzone boundaries (table 4) are based on (1) changes in macroscopic features that define lithostratigraphic units, and (2) the preliminary correlation of macroscopic porosity estimated in various lithostratigraphic units with preliminary laboratory measurements as discussed above. For example, porosity is commonly high, 0.5 to 0.4 cm^3/cm^3 and as high as 0.6 cm^3/cm^3, in the nonwelded Paintbrush Tuff hydrogeologic unit (PTn) and low, between 0.25 and 0.025 cm^3/cm^3, in the moderately to densely welded Tiva Canyon and Topopah Spring hydrogeologic units (TCw and TSw, respectively) (Rautman and Flint, 1992; Rautman and others, 1993; L. Flint, USGS, written commun., 1994). Large changes in porosity correlate with stratigraphic intervals where (1) the amount of welding increases abruptly such as in the crystal-rich vitric zone of the Topopah Spring Tuff, or (2) the transition occurs from vitric to high-temperature devitrified rocks such as in the moderately welded crystal-poor vitric and lower nonlithophysal zones of the Tiva Canyon Tuff. Detailed correlation of lithostratigraphic and hydrogeologic units is an ongoing and iterative study with other investigators where the goal is to refine the identification of lithostratigraphic zones, subzones, and intervals such that hydrogeologic units can be statistically well characterized.

Table 4 shows the first step in correlating lithostratigraphic units with the top and bottom of the PTn, as described in the Site Characterization Study Plan (Office of Civilian Radioactive Waste Management, 1988), where the top of the crystal-poor vitric moderately welded subzone in the Tiva Canyon Tuff is equated to the top of the PTn, and the base of the crystal-rich vitric moderately welded subzone in the Topopah Spring Tuff is equated to the base of the PTn. The Tiva Canyon and Topopah Spring Tuffs have crystal-poor and crystal-rich, vitric, densely welded subzones that typically include the vitrophyre interval at the bottom and top of the devitrified zones, respectively (table 4). These vitrophyres have laboratory measured porosities as low as 0.1 to 0.025 cm^3/cm^3 compared with rocks from the devitrified zones that range from 0.25 to 0.08 cm^3/cm^3 (L. Flint, USGS, written commun., 1994). Because the vitrophyres have very low porosities and they separate moderately welded vitric and moderately to densely welded devitrified rocks that have higher porosities, the vitrophyres probably form important boundaries to the main parts of the hydrogeologic units TCw and TSw and are included in the TCw and TSw units (table 4). Where the crystal-poor vitric densely welded subzone of the Tiva Canyon Tuff does not occur, the contact of the devitrified rocks in the columnar subzone and the vitric rocks in the moderately welded subzone corresponds to the top of the PTn (table 4).

Rocks of the Paintbrush Group are included in parts of seven thermal-mechanical units (Ortiz and others, 1985). As with the hydrogeologic units, correlations of the boundaries thermal-mechanical units with lithostratigraphic zone and subzone boundaries (table 4) are based on (1) changes in macroscopic features that define lithostratigraphic units, and (2) the preliminary correlation of lithostratigraphic units with preliminary laboratory measurements (thermal-mechanical data from Martin and others, 1994; R. Price, SNL, written commun., 1994). Most of the thermal-mechanical unit boundaries correspond to lithostratigraphic subzone contacts that mark the transition from vitric partially or moderately welded rocks to densely welded or high-temperature devitrified rocks (table 4). There are additional thermal-mechanical divisions of the Topopah Spring Tuff that are based on the percentage of lithophysae (greater than 10 percent for TSw1; less than 10 percent for TSw2) and the identification of the crystal-poor vitrophyre (TSw3) (Ortiz and others, 1985). The change in percentage of lithophysae does not occur at a consistent stratigraphic position in the crystal-poor upper lithophysal zone and can occur up to 30 m above the Tptpul-Tptpmn lithostratigraphic contact (Spengler and others, 1984; Spengler and Fox, 1989). The TSw1-TSw2 contact is difficult to identify where core is broken or not recovered. To provide consistency and to facilitate identification of the TSw1-TSw2 contact in core, the pul-pmn contact is used to approximate this thermal-mechanical boundary. Subsequent analyses of borehole televiewer log videos and geophysical logs may help to determine the in-situ percentage of lithophysae and establish the TSw1-TSw2 contact as defined by Ortiz and others (1985).

Table 4. Correlation of lithologic, thermal-mechanical, and hydrogeologic units on the basis of the revised lithostratigraphy

Lithologic units (this report)	Thermal-mechanical units (Ortiz and others, 1985)	Hydrogeologic units (Office of Civilian Radioactive Waste Management, 1988)
PAINTBRUSH GROUP		
Rhyolite of Comb Peak (Tpk)		
includes tuff unit "x" (Tpki)		
Rhyolite of Vent Pass (Tpv)	Undifferentiated overburden[1] (UO)	Unconsolidated surficial materials (UO)
Post-Tpc bedded tuff (Tpbt5)		
Tiva Canyon Tuff (Tpc)		
Crystal-rich		
Vitric		
Nonwelded (rv3: v3n, v3p)		
Moderately welded (rv2)		
Densely welded (rv1: v1c, v1v)		
Nonlithophysal (rn: n4, n3, n2, n1)		
Lithophysal (rl: l2, l1)		
Crystal-poor	Tiva Canyon welded unit (TCw)	Tiva Canyon welded hydrogeologic unit (TCw)
Upper lithophysal (pul)		
Middle nonlithophysal (pmn: mn3, mn2, mn1)		
Lower lithophysal (pll)		
Hackly-fractured (pllh)		
Lower nonlithophysal (pln)		
Hackly (plnh)		
Columnar (plnc: c3, c2, c1)		
Vitric (pv)		
Densely welded (pv3: v3v, v3c)[2]		
Moderately welded (pv2),		
Nonwelded (pv1: v1p, v1n)		
Pre-Tpc bedded tuff (Tpbt4)		
Yucca Mountain Tuff (Tpy)	Upper Paintbrush nonwelded unit (PTn)	Paintbrush nonwelded hydrogeologic unit (PTn)
Pre-Tpy bedded tuff (Tpbt3)		
Pah Canyon Tuff (Tpp)		
Pre-Tpp bedded tuff (Tpbt2)		
Topopah Spring Tuff (Tpt)		
Crystal-rich		
Vitric		
Nonwelded welded (rv3: v3n, v3p)		
Moderately welded (rv2)		

Table 4. Correlation of lithologic, thermal-mechanical, and hydrogeologic units on the basis of the revised lithostratigraphy--Continued

Lithologic units (this report)	Thermal-mechanical units (Ortiz and others, 1985)	Hydrogeologic units (Office of Civilian Radioactive Waste Management, 1988)
Densely welded (rv1: v1c, v1v) Nonlithophysal (rn: n3, n2, n1) Lithophysal (rl: l2, l1) Crystal-poor Upper lithophysal (pul: ulc, uls)	Topopah Spring welded unit lithophysae-rich (TSw1)[3]	Topopah Spring welded hydrogeologic unit (TSw)
Middle nonlithophysal (pmn: mn3, mn2, mn1) Lower lithophysal (pll) Hackly-fractured (pllh) Lower nonlithophysal (pln) Hackly fractured (plnh) Columnar (plnc: c3, c2, c1)	Topopah Spring welded unit lithophysae-poor (TSw2)	
Vitric Densely welded (pv3: v3v, v3c)	Topopah Spring welded unit vitrophyre (TSw3)	
Moderately welded (pv2) Nonwelded (pv1: v1p, v1n) Pre-Tpt bedded tuff (Tpbt1) CALICO HILLS FORMATION	Calico Hills and Lower Paintbrush nonwelded unit (CHn1)	Calico Hills nonwelded hydrogeologic unit (CHn)

[1]Thermal-mechanical unit UO of Ortiz and others (1985, p. 11) includes "alluvium; colluvium; nonwelded vitric ashflow tuff of the Tiva Canyon Member of the Paintbrush Tuff; and any other tuff units that stratigraphically overlie the welded, devitrified Tiva Canyon Member."

[2]Where preserved, the base of the densely welded subzone forms the base of the TCw thermal-mechanical and hydrogeologic units.

[3]The TSw1-TSw2 contact is where the amount of lithophysae changes from greater than to less than 10 percent of the total rock volume (Ortiz and others, 1985). This change in the amount of lithophysae occurs up to 30 meters above the upper lithophysal-middle nonlithophysal zone contact as identified by multiple criteria.

CONCLUSIONS

Stratigraphic analysis of the Paintbrush Group rocks at Yucca Mountain, Nevada, permits a revision in nomenclature that is consistent with the regional stratigraphic system and that can be applied to surface exposures and subsurface studies in the Exploratory Studies Facility and from borehole samples. This revised nomenclature with seven hierarchical divisions from age to interval is designed to be used for a wide range of site-scale and detailed studies. The Tiva Canyon and Topopah Spring Tuffs are divided into members, zones, subzones, and intervals based on the macroscopic criteria of crystal content, phenocryst assemblage, depositional texture, degree of welding, high-temperature crystallization to groundmass minerals and textures, features related to the activity of and precipitation from the high-temperature vapor phase, and fracture character. The crystal-rich and crystal-poor members of both tuffs are divided into an identical sequence of zones. These zones, and even most subzones and intervals, form a vertical symmetry above and below the middle nonlithophysal zone. The crystal-rich members contain a vitric zone (rv), a nonlithophysal zone (rn), and locally, a lithophysal zone (rl). The crystal-poor members contain an upper lithophysal zone (pul), middle nonlithophysal zone (pmn), lower lithophysal zone (pll), lower nonlithophysal zone (pln), and vitric zone (pv). These divisions refine the lithostratigraphic units to the point that thermal-mechanical and hydrogeologic units can be closely approximated in the field. Linking these three systems of nomenclature provides a framework within which to correlate these properties through regions of sparse data.

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APPENDIXES

Appendix 1. Depths to base of lithostratigraphic units in core from boreholes examined in 1993, Yucca Mountain, Nevada. All depths are in meters.

	UE25 UZ#16	USW UZ-14[b]	USW NRG-6	UE25, NRG#5	UE25 NRG#4	UE25 NRG#3[c]	UE25 NRG#2a	UE25 NRG#2b	UE25 NRG#2[d]	UE25 NRG#1	UE25 RF#8	UE25 RF#3
Northing[a]	231,870.48	235,155.29	233,758.01	234,112.69	233,865.92	233,612.99	233,445.09	233,465.01	233,483.26	233,341.04	233,424.02	233,407.04
Easting	172,212.66	170,774.79	172,008.28	172,185.94	172,810.97	173,267.10	173,475.95	173,541.02	173,515.94	173,720.45	173,411.55	174,115.85
Elevation	1,219.8	1,349.5	1,247.6	1,251.9	1,249.8	1,165.6	1,152.6	1,159.0	1,156.1	1,144.7	1,154.8	1,115.2
Lithologic units												
QTac[e]	12.1	12.1									9.8 spot	27.7
Tmr								30.5[f]	42.4		core	
Tmbt[g]							24.6[h]	47.9	50.2		15.2	62.3
Tmki[g]							46.0[h]	70.3			29.1	77.4
Tpbt5[g]							50.6	70.8			30.9	80.6
Tpc rv							52.4				34.6	83.3
rn						30.5	79.7		fault	9.3		
pul	depositional					63.0				32.9	**39.0**	**94.5**[i]
pmn	contact					81.7	**81.0**				TD	TD
pll	22.9		16.8				TD	fault		**45.8**		
pln						**100.6**			51.8	TD		
lnh[j]	28.5		24.4	cuttings	cuttings	TD			65.5			
lnc	42.9		41.2	only	only				84.2			
pv												
v2	46.9		45.8						86.2			
v1	49.0	depositional	48.4									
Tpbt4[f] 50.6	contact							**89.6**				
Tpy	53.3	23.8			114.3			79.2	TD			
Tpbt3[f] 57.5	31.1	53.3		116.1			87.0					
Tpp	ND[k]	73.3	67.3		139.6			98.8				
Tpbt2[g] 63.9	78.8	75.2		142.7								
Tpt rv	72.8	87.2	80.2		149.0			**100.4**				
rn	109.0	131.1	130.8		201.3			TD				
rl	113.1	142.6	141.9		216.4							
pul2	120.7	149.2	149.7	210.3								
pul	167.3	217.9	217.3	242.6								
pmn	210.3				**221.3**							
mn3		233.3	233.5	257.6	TD							
mn2		244.4	237.4	264.9								
mn1		252.4	246.9	274.8								
pll	278.9	346.9		303.5								
pln	338.7	389.9	**335.3**									
pv3	355.2	409.6	TD	**411.5**								
pv1+2	366.2	428.0		TD								
Tpbt1	faulted?											
Ta	452.6											
Tcp												
	514.0[i]											
	TD											

a Northing, easting, and elevation are from C.E. Ezra (EG&G, written commun., April 29, 1994).

b Borehole location is the pre-dilling surveyed position. Logging not complete.

c Borehole is inclined 30° from vertical ; azimuth of 100°; corrected to stratigraphic thickness.

d Borehole is inclined 30° from vertical; azimuth of 100°; corrected to stratigraphic thickness.

e Lithologic units not described in this report: QTac - alluvium, Tmr - Rainier Mesa Tuff, Ta - Calico Hills Formation, Tcp - Prow Pass Tuff (Sawyer and others, in press). Tmki - informal unit described as tuff unit "x" by Carr (1992).

f Contact in nonrecovered interval; identification by D. Buesch based on correlation with geophysical logs in adjacent boreholes and exposures in trench NRT-1.

g Bedded tuff. Electron microprobe analysis of samples from stratigraphically similar intervals indicate probable correlations with Tpk for some Tmbt1, Tmki, and Tpbt5; Tpcp for Tpbt4; Tpg and Tpd for Tpbt3; Tpt for Tpbt2 (R. Warren, LANL, written commun., 1994).

h Base of a noncored interval indicated by centered, underlined value.

i Total depth (TD) occurred in unit above the line; base of unit not encountered.

j Subzones; associated depths are indented.

k ND, not deposited.

APPENDIX 2. DETAILED STRATIGRAPHIC DESCRIPTIONS OF THE TIVA CANYON AND TOPOPAH SPRING TUFFS AT YUCCA MOUNTAIN, NEVADA

Descriptions in this appendix are from macroscopic examination of core from boreholes listed in Appendix 1 with supplemental descriptions from Geslin and others (1995), Geslin and Moyer (1995), and Moyer and others (*in press*). Emphasis is on boreholes and field exposures in the central part of Yucca Mountain from Azreal Ridge on the north to Abandoned Wash on the south, the area where most underground workings of the site-characterization studies will be conducted. Unit thicknesses are approximate and will likely vary from the limits stated. All textures and minerals can be observed with a hand lens, but a standard binocular microscope aids identification. Sizes of clasts and lithophysae are the maximum dimension unless otherwise stated. Sizes of clasts and lithophysae determined from core might be less than the actual size. Lithophysae, or lack thereof, are only described in crystallized ignimbrites where lithophysal and nonlithophysal zones can form. Based on surface mapping (Scott and Bonk, 1984) and well-defined beds in the nonwelded bedded sequences, dips in the area are commonly 2° to 10°; therefore only dips greater than 10° are specifically described.

Tiva Canyon Tuff (Tpc)

Crystal-rich member (Tpcr)

The crystal-rich member of the Tiva Canyon Tuff (cr) is characterized by greater than 5 percent phenocrysts in the rock, and the member is divided into the vitric (rv) and nonlithophysal (rn), and locally the lithophysal zones. The vitric zone is distinguished by the preservation of the volcanic glass to form rocks with a vitreous luster. Rocks in both the nonlithophysal and lithophysal zone are devitrified, and the division is based on the presence or absence of lithophysae.

Crystal-rich vitric zone (Tpcrv)

The crystal-rich vitric zone (rv) is divided into the nonwelded (rv3), moderately welded (rv2), and densely welded (rv1) subzones based primarily on the degree of welding.

Nonwelded subzone (Tpcrv3) (0- to 2-m thick)

Rocks in the nonwelded subzone (rv3) have nondeformed pumice clasts in a poorly indurated to sintered matrix, and are composed of 75 to 89 percent groundmass, 5 to 10 percent phenocrysts, 5 to 15 percent pumice clasts, and 1 to 3 percent lithic clasts. Matrix grades downward from pale-orange pink (7.5YR8/2) in nonwelded interval (rv3n) to grayish orange (10YR7/4) to light pinkish brown (2.5YR6/4) as the degree of sintering and welding increases to the partially welded interval (rv3p). Porous matrix varies from glassy to incipiently devitrified. Phenocrysts include abundant feldspar and nonaltered to slightly oxidized biotite, and less common hornblende and pyroxene. Pumice are light gray (N8 to N9) or very dark yellowish orange (10YR6/8) with average diameters less than 1 to 5 cm. Pumice clasts are either glassy or locally replaced by silica, vapor-phase minerals, or altered to clays. Foliation grades from absent to very poorly developed in the nonwelded interval (rv3n) to poorly developed in the partially welded interval (rv3p). Dark grayish-red (5YR4/1) volcanic lithic clasts have average diameters of less than 0.5 cm. Fractures, which are rare and locally filled with calcite, are steeply dipping with moderate roughness.

Moderately welded subzone (Tpcrv2) (0- to 2-m thick)

Rocks in the moderately welded subzone (rv2) have slightly to extensively deformed pumice clasts in a sintered to moderately welded matrix. These rocks are composed of 75 to 82 percent groundmass, 8 to 10 percent phenocrysts, 10 to 15 percent pumice clasts, and 0 to 3 percent lithic clasts. Matrix density increases downward (macroscopic porosity decreases), and color grades from light pinkish brown (2.5YR6/4) to pale grayish red (10R5/2), grayish brown (2.5YR3/2) or moderate brown (5YR3/4). The matrix is vitric, but locally devitrification varies from incipient to complete. Phenocrysts include abundant feldspar and nonaltered to slightly oxidized biotite, and less common hornblende and pyroxene. Pumice clasts are less than 3 cm, and are light gray (N7 to N8) or moderate yellowish brown (7.5YR4/6). Pumice clasts are glassy, but locally replaced by silica, altered to clays (?) or zeolites (?). Pumice clasts become increasingly elongate (flattened) with depth, defining a well developed foliation near the base of the unit; most flattening occurs across an interval of less than 0.6 m. Dark grayish-red (5YR4/1) or brown (5YR6/4) volcanic lithic clasts have average diameters of less than 1.0 cm. Fractures are rare and have moderate surface roughness.

Densely welded subzone (Tpcrv1) (less than 2-m thick)

Rocks in the densely welded subzone (rv1) have densely welded shards and pumice clasts in a vitric matrix with no macroscopic porosity. These rocks are composed of 70 to 80 percent groundmass, 10 to 15 percent phenocrysts, 10 to 15 percent pumice clasts, and 0 to 1 percent lithic clasts. Matrix glass, which grades downward from reddish brown (5YR4/3) to dark gray (N4) in the clastic texture interval (rv1c) to moderate brown (5YR3/2) to very dark gray (N3) in the vitrophyre interval (rv1v). The vitrophyre can be variably hydrated or contain a few percent of small spherulites. Phenocrysts include abundant feldspar and nonaltered to slightly oxidized biotite, and less common hornblende and pyroxene. Pumice clasts define a well developed foliation, and are glassy and dark gray (N4) or incipiently devitrified (?) and light-brown (5YR5/6). Typically, pumice clasts have length- to thickness-aspect ratios of greater than 6:1. Light gray (N8) or dark reddish-gray (5YR4/1) volcanic lithic clasts have average diameters of less than 1 cm. Fractures are commonly irregular and rarely smooth. The upper and lower contacts of this unit are generally very sharp (transition of less than 10 cm).

Crystal-rich nonlithophysal zone (Tpcrn)

The crystal-rich nonlithophysal zone (rn) is divided into four subzones including, from top to bottom, the subvitrophyre transition (rn4), pumice-poor (rn3), mixed pumice (rn2), and the crystal-transition (rn1) subzones. These divisions are primarily based on depositional features including the minor amount of pumice clasts in rn3 and downward decrease in rn1 in the amount of crystals from greater than 10 to less than 5 percent of the rock. Other criteria include the degree of welding and the amount of vapor-phase corrosion and subsequent crystallization in the matrix and pumice clasts.

Subvitrophyre transition subzone (Tpcrn4) (less than 1- to 2-m thick)

Rocks in the subvitrophyre transition subzone (rn4) have nondeformed to extensively deformed pumice clasts are in a sintered to densely welded matrix/groundmass. These rocks are composed of 70 to 85 percent groundmass, 10 to 15 percent phenocrysts, 5 to 15 percent pumice clasts, and less than 1 percent lithic clasts. The subvitrophyre transition subzone is divided into a densely welded interval (rn4d) that overlies a moderately welded interval (rn4m). In the densely welded interval (rn4d), the matrix is incipiently devitrified to a low-porosity dense groundmass that is dark reddish gray (10R4/1). In the moderately welded interval (rn4m), the matrix/groundmass increases in porosity, is replaced or partially coated with vapor-phase crystals, and is light grayish brown (2.5YR5/2). Phenocrysts include abundant feldspar and nonaltered to oxidized biotite, and less common hornblende, and nonaltered to altered pyroxene (alteration and oxidation of mafic silicates increases downward). Pumice clasts, which decrease in abundance downward from 10 to 15 percent to about 5 percent, are argillically altered and yellowish brown (5YR6/6) or pale reddish brown (10R5/3) in rn4d, but are typically corroded or replaced by vapor-phase minerals in rn4m. Foliation, defined by the elongation of pumice clasts, decreases markedly downward. Volcanic lithic clasts are rare, but typically are devitrified and dusky red (5R3/4), but locally, in rn4d, a few clasts are vitric and light gray (N7). Fractures in rn4d are slightly planar to slightly irregular and slightly smooth to slightly rough, whereas in rn4m fractures are irregular and rough. The upper and lower contacts of rn4d typically are very sharp (less than 5 cm), and the base of rn4m is commonly sharp (less than 10 cm).

Pumice-poor subzone (Tpcrn3) (2- to 6-m thick)

Rocks in the pumice-poor subzone (rn3) have scattered nondeformed pumice clasts in a vapor-phase corroded and crystallized matrix/groundmass. These rocks are composed of 80 to 90 percent groundmass, 10 to 15 percent phenocrysts, 1 to 5 percent pumice clasts, and less than 1 percent lithic clasts. The matrix/groundmass, which is macroscopically porous and crystallized by vapor-phase mineralization, has a characteristic color that varies from light pinkish brown (2.5YR6/2, 2.5YR5/3) to grayish red (10R4/2) or pale reddish brown (10R5/3). Silica (vapor-phase minerals?) locally fills pore spaces, imparting a speckled texture to the rock. Phenocrysts include abundant nonaltered to altered feldspar, oxidized (bronze colored) biotite, and less common hornblende and altered yellow (5Y7/8) pseudomorphs of pyroxene(?). Pumice clasts are typically less than 1 cm in diameter. Pumice clasts are porphyritic and dark reddish-gray (2.5YR4/1), or aphyric and light-gray (N8). Locally in field exposures in the northern parts of Yucca Mountain, light-gray pumice clasts as much as 15 cm in diameter form horizons where the amount of clasts can be about 5 percent of the rock. Lithic clasts are vary rare. Foliation in the matrix/groundmass is absent or poorly developed, and foliation defined by the alignment of pumice clasts is poorly to moderately developed. The unit has fractures with irregular surfaces, and some fracture surfaces have black spots of alteration minerals (Mn oxides?). This subzone represents a pumice-poor depositional unit that occurs in the northern parts of Yucca Mountain, but the southern extent is not well constrained. The lower contact of this unit is gradational over an interval of 1.0 to 2.5 m.

Mixed pumice subzone (Tpcrn2) (17- to 20-m thick)

Rocks in the mixed pumice subzone (rn2) have abundant slightly to moderately deformed pumice clasts in a moderately to densely welded matrix/groundmass. These rocks are composed of 55 to 83 percent groundmass, 10 to 15 percent phenocrysts, 7 to 30 percent pumice clasts, and less than 1 percent lithic clasts. Groundmass density increases and porosity decreases downward as color grades from pale red (10R6/2) to pale reddish gray (10R6/1 or 10R7/1). Phenocrysts include abundant nonaltered feldspar and oxidized biotite, and less common nonaltered hornblende and altered yellow (5Y7/8) pseudomorphs of pyroxene(?) (pyroxene abundance decreases downward). Total pumice clast content increases from 7 to 8 percent at the top of the unit to 20 to 30 percent in the middle of the unit, then decreases to 10 to 15 percent near the base of the unit. Pumice clasts are typically less than 1 cm in average diameter, but are locally greater than 6 cm, are light gray (N8 to N9) or dark reddish gray (5YR4/1). Pumice clasts are corroded, replaced by silica, or coated with vapor-phase minerals, and the dark reddish-gray pumice commonly contains acicular hornblende.

Foliation is more strongly developed downward as pumice clasts are increasingly elongated. Lithic clasts are rare. Fractures are irregular and rough, and locally in borehole RF#3 are filled with very fine-grained, pumiceous material. The lower contact of this unit, which is defined where phenocrysts become less than 10 percent of the rock, is gradational over a distance of less than 0.6 m.

Crystal transition subzone (Tpcrn1)
(See description below)

Crystal-rich lithophysal zone (Tpcrl2)
(0- to 10-m thick)

Rocks in the lithophysal subzone (rl2) have moderately to extensively deformed pumice clasts in a moderately to densely welded, devitrified lithophysal matrix/groundmass. These rocks are composed of 65 to 82 percent groundmass, 5 to 15 percent lithophysae, 8 to 12 percent phenocrysts, 5 to 10 percent pumice clasts, and less than 1 percent lithic clasts. Groundmass density increases downward until macroscopic porosity disappears. The groundmass is pale reddish gray (10R7/1) that grades downward into pale reddish gray (5R4/2) with few light-gray (N8) spots. Lithophysae increase in abundance downward, and are 3 to 4 cm in average diameter. Phenocrysts include abundant nonaltered feldspar, rare nonaltered hornblende, rare oxidized biotite, and rare altered, yellow (5Y7/8) pseudomorphs of pyroxene(?). Pumice clast content decreases from 5 to 10 percent near the top of the zone to 5 percent midway, with pumice clasts becoming more elongated over this interval. Pumice clasts are very light gray (N9 to N8) with minor amounts of pale brown (5YR5/2). Lithic clasts are rare. Foliation, as defined by pumice elongation, is moderately to well developed. Fractures are slightly planar to slightly irregular and slightly smooth to slightly rough. The crystal-rich lithophysal zone (Tpcrl2) is a lateral facies of the lower part of the mixed pumice subzone (Tpcrn2). The lower contact of this unit, which is defined where phenocrysts become less than 10 percent of the rock, is gradational over a distance of 1 m to less than 0.6 m.

Crystal transition subzone (Tpcrn1 or Tpcrl1)
(4- to 6-m thick)

Rocks in the crystal transition subzone (rn1 or rl1) have moderately to extensively deformed pumice clasts in a moderately to densely welded, devitrified matrix/groundmass. These rocks are composed of 75 to 90 percent groundmass, 5 to 10 percent phenocrysts, 5 to 15 percent pumice clasts, and much less than 1 percent lithic clasts. Groundmass density in rn1 increases downward in the upper few meters of the subzone to where macroscopic porosity disappears, and the groundmass density in rl1 is high throughout the subzone. Groundmass color is an even, pale reddish gray (10R7/1). Scattered lithophysae (less than 2 percent of rock) occur throughout rn1, and are more common near the base where they are 3 to 4 cm in average diameter. In rl1, lithophysae are greater than 5 percent and typically 3 to 5 cm in average diameter. Phenocrysts decrease downward from 10 percent of rock to less than 5 percent and include abundant nonaltered feldspar, rare nonaltered hornblende, rare oxidized biotite, and rare altered, yellow (5Y7/8) pseudomorphs of pyroxene(?). Pumice clast content decreases from 10 to 15 percent near the top of rn1 to less than 5 percent midway, and is about 5 percent in rl1. Pumice clasts are more elongated in the lower part of the subzone. Pumice clasts are very light gray (N9) with minor amounts of grayish-orange pink (5YR7/2), and in rn1 are typically replaced by silica, and commonly contain a central cavity. Lithic clasts were not observed. Foliation, as defined by pumice elongation, is moderately to well developed. Fractures are slightly smooth to slightly rough. The contact with the underlying crystal-poor upper lithophysal zone is defined where phenocrysts are less than 5 percent and this boundary is gradational across 0.5 to 3 m.

Crystal-poor member (Tpcp)

The crystal-poor member of the Tiva Canyon Tuff (cp) is characterized by less than 5 percent phenocrysts in the rock, and the member is divided into the upper lithophysal (pul), middle nonlithophysal (pmn), lower lithophysal (pll), and the lower nonlithophysal (pln) zones. All rocks in the member are devitrified. Divisions are based primarily on the presence or absence of lithophysae, but other features included in the multiple criteria are color and fracture geometry.

Crystal-poor upper lithophysal zone (Tpcpul)
(21- to 24-m thick)

Rocks in the upper lithophysal zone (pul) have extensively deformed pumice clasts in a densely welded, devitrified, lithophysal matrix/groundmass. These rocks are composed of 60 to 90 percent groundmass, 2 to 40 percent lithophysae, 2 to 5 percent phenocrysts, 0 to 10 percent pumice clasts, and much less than 1 percent lithic clasts. The dense groundmass is pale reddish gray (10R7/1) with a somewhat mottled texture that grades downward into reddish gray (5R4/2) with light-gray (N8) spots. Lithophysae increase downward from a few percent to as much as 40 percent of the rock. The size of lithophysae decreases downward from greater than 3 cm (average) diameter with 1- to 2-mm-thick light gray rims to 1- to 3-cm diameter with 3- to 5-mm-thick rims. Below the spherulite-rich subzone (pul1), lithophysae comprise only a small percentage of the rock and have average diameters that vary from 1 to 3 cm. Lithophysae co-exist with spherulites above and below the spherulite-rich subzone boundary. Phenocrysts are mostly nonaltered feldspar with rare oxidized biotite and altered pyroxene. Pumice texture decreases downward and eventually is obliterated by crystallization. Pale brownish-pink (10R6/2) volcanic lithic clasts have average diameters of less than 1 cm. High-angle fractures are rare and have comparatively rough surfaces. Core runs with greater than 20 to 30 percent nonrecovered intervals probably represent intersections with lithophysal cavities that have diameters greater than that of the core. The contact with the underlying middle nonlithophysal zone is sharp with a transition of less than 0.6 m.

Spherulite-rich subzone (Tpcpull) (2- to 3-m thick)

Rocks in the spherulite-rich subzone (pull) are densely welded, nonlithophysal with spherulitically devitrified groundmass textures. This subunit is similar in most regards to the upper lithophysal zone. It is distinguished by an absence of lithophysae and an abundance of spherulites. Spherulites are typically 1 to 3 mm in diameter and commonly are cored by a felsic phenocryst. The upper boundary of this subunit can grade over an interval of 1 to 2 m and is defined by the disappearance of lithophysae. The lower boundary is comparatively sharp and is commonly 0- to 3-m above the base of pul.

Crystal-poor middle nonlithophysal zone (Tpcpmn) (16- to 20-m thick)

Rocks in the middle nonlithophysal zone (pmn) are densely welded and devitrified the zone is locally divided into three subzones where the upper (pmn3) and lower (pmn1) nonlithophysal subzones are separated by a lithophysae-bearing subzone (pmn2). These rocks are composed of 90 to 97 percent groundmass, 3 to 4 percent phenocrysts, 0 to 5 percent pumice clasts, and less than 1 percent lithic clasts. Groundmass is typically brownish red (5R6/2) in pmn1 and pmn3, but is commonly reddish purple (5RP5/2) in pm2. Approximately 1 m above the basal contact, the matrix/groundmass changes abruptly to a mottled mixture of pale brownish pink (10R6/2) and grayish orange pink (5YR7/2), the latter occurring as subrounded 1- to 3-mm-sized spots or as 1- to 3-mm-thick rims on felsic phenocrysts. Spherulites locally occur in the upper few meters of the unit, but disappear downward. In the southern part of the central block of Yucca Mountain, lithophysae are virtually absent except the lower 4 m of the unit where they comprise less than 2 percent of the rock; therefore, there is no tripartite division of the pmn zone in the south. North of about northing N:4077000m, the thickness of pmn2 increases northward to fully consume the pmn zone. The pmn2 has less than 2 percent lithophysae with diameters that vary from 2 to 6 cm, and less than 0.5-m-thick vapor-phase partings composed of anastomosing veinlets that are subparallel to foliation defined by elongate lithophysae. These vapor-phase partings in pmn2 probably weather near the ground surface to produce the stepped morphology of the rounded step zone of Scott and Bonk (1984). Lithophysae are associated with light-gray (N7) streaks that become more prevalent downward. Phenocrysts include feldspar with rare oxidized hornblende or biotite. Devitrification has typically destroyed most pumiceous texture throughout. Light gray (N7) volcanic lithic clasts typically have diameters less than 1 cm. High-angle fractures with comparatively planar geometry and smooth surfaces are common and distinctive. The lower contact of this unit is sharp and marked by the change from intact, solid core to rubble and poorly recovered core, an increase in lithophysae, and a change in fracture characteristics.

Crystal-poor lower lithophysal zone (Tpcpll) (10- to 17-m thick)

Rocks in the lower lithophysal zone (pll) are densely welded, devitrified, and have 2 to 10 percent lithophysal cavities. These rocks are composed of 85 to 96 percent groundmass, 2 to 10 percent lithophysal cavities, 2 to 3 percent phenocrysts, 0 to 5 percent pumice clasts, and less than 2 percent lithic clasts. The groundmass is a comparatively even-textured and red purple (5RP5/2), pale red (5R6/2), grayish red (10R4/2), or light brownish gray (5YR6/1). Lithophysae, including rims, and light gray (N7) spots increase downward from 0 to 2 percent to as much as 20 percent of the rock, but decrease markedly to less than 2 percent in the lower 1 to 2 m of the unit. Lithophysal cavities, which are commonly less than 2 cm and locally up to 6 cm in average diameter, are 2 to 10 percent of the rock and are enclosed in light gray (N7) rims that locally are surrounded by pinkish-gray discoloration (5YR7/2). In the lower 1 to 2 m of this unit, lithophysae decrease in size to less than 1 cm in average diameter, have approximately 5-mm wide light-gray (N7) rims, and commonly form along fracture surfaces imparting a streaky texture to the rock. Phenocrysts include feldspar with rare oxidized hornblende or biotite. Locally, devitrification has destroyed pumice texture. Devitrified, light gray (N7) volcanic lithic clasts are typically less than 1 cm in diameter. High-angle fractures have rough to very rough surfaces and are less common than in the middle nonlithophysal zone. Locally, a hackly-fractured subzone (pllh) occurs where the rough to very rough fracture surfaces are well developed. The upper 1 to 2 m of the zone is locally rubble and poorly recovered, with significant (greater than 0.6 m) nonrecovered intervals. The lower contact of the zone, which is defined by the rapid decrease in size and abundance of lithophysae to less than 2 percent of the rock is gradational over 1 to 3 m.

Crystal-poor lower nonlithophysal zone (Tpcpln)

The lower nonlithophysal zone (pln) is divided into the hackly (plnh) and columnar (plnc) subzones. This division is based primarily on the fracture characteristics, and the typically better preservation of and greater variety in pumice clast textures in the columnar subzone than in the hackly subzone.

Hackly subzone (Tpcplnh) (5- to 12-m thick)

Rocks in the hackly subzone (plnh) are densely welded, devitrified, have distinctive irregular fractures, and locally have rare lithophysae near the top of the subzone. The rocks are composed of 80 to 98 percent groundmass, 2 to 4 percent phenocrysts, 0 to 15 percent pumice clasts, and less than 1 percent lithic clasts. The groundmass is a mottled mix of moderate brown (5YR3/4) and pale brown (5YR4/1) that gradually lightens to grayish-orange pink (5YR7/1) in the lower 1 to 2 m of the subzone. Lithophysae are rare (less than 1 percent of the rock) in the upper few meters. Locally near the top of the subzone, there is a 1- to 4-m-thick lithophysae-bearing interval that contains 1 to 4 percent lithophysae, but the fracture characteristics are more similar to the hackly subzone than the lithophysal zone. Phenocrysts include feldspar with rare oxidized hornblende or biotite. Crystallization has destroyed pumice texture in the upper part of the subzone, but pumice clasts reappear very gradually beginning in the middle of the subzone. Pumice clasts content is estimated at 10 to 15 percent in the lowermost meter. Dark reddish-gray volcanic lithic clasts are less than 1 cm in diameter. Fractures are so prevalent and irregular throughout this subzone that the rock commonly breaks into polyfaceted gravel-sized pieces (termed hackly fracture). A second type of fracture habit, which has a curviplanar shape to the planar to slightly planar geometry with smooth to slightly smooth surface roughness, develops in the lower 3 m and produces wedged-shaped core terminations where two or more fractures intersect. Locally in the middle to lower part of the subzone, there are one or more intervals where hackly fractures are poorly developed and the fracture characteristics are slightly planar and slightly smooth. The lower contact, which is defined by the disappearance of hackly fracture, is gradational over a 1 to 3-m interval.

Columnar subzone (Tpcplnc) (8- to 19-m thick)

Rocks in the columnar subzone (plnc) are moderately to densely welded and devitrified. These rocks are composed of 80 to 96 percent groundmass, 2 to 4 percent phenocrysts, 2 to 15 percent pumice clasts, and less than 1 percent lithic clasts. This subzone is divided into three intervals: plnc3 contains pumice clasts that devitrified at high-temperature and commonly have spherulitic textures; plnc2 contains pumice clasts that are argillically altered; plnc1, which is locally absent, contains vitric pumice clasts. The groundmass grades downward from pale-orange pink (5YR7/3) to pale reddish brown (2.5YR6/2) to light brown (5YR6/5) mottled with light reddish gray (2.5YR7/1) to moderate yellowish brown (10YR6/4). Phenocrysts are mostly feldspar with rare hornblende and altered pyroxene(?). In the upper half of the subzone, pumice clasts can vary in size and amount, and typically are 1 to 2 cm in diameter and comprise 10 to 15 percent of the rock, but decrease downward in abundance to less than 2 percent. The lower half of the subzone contains 2 to 5 percent pumice clasts with size populations that vary from 1.5 ±0.5 cm to 6 ±2 cm. In interval plnc3, dark-gray (N4) to dark reddish-gray (10R3/1) pumice clasts are spherulitically devitrified with rare argillically altered pumice clasts. Interval plnc2 contains pumice clasts that are partially to wholly altered to grayish-pink (5R8/2) to pale orange-pink (2.5YR7/6) clay minerals. Some of these clasts have spherulitic cores, are axiolically devitrified, or are corroded. Locally, near the base of the interval is a horizon as much as 2-m thick where pumice clasts are corroded, crystallized, and coated with very fine-grained vapor-phase minerals. Pumice clasts in interval plnc1 are dark-gray (N3) glass. Dark reddish-gray lithic clasts with average diameters less than 1 cm. Foliation varies downward from moderately developed to poorly developed to moderately well developed depending on the preservation of pumice texture. Fractures are curviplanar to planar and are comparatively smooth, with mineral coatings that are variously light brown or white (crystalline or amorphous silica). The lower contact of this subunit is defined by either the comparatively abrupt change to a vitric matrix or, where the vitric densely welded subzone is absent, by the appearance of vapor-phase minerals in pumice clasts and preserved vitric shard texture in the incipiently devitrified matrix of the vitric moderately welded subzone.

Crystal-poor vitric zone (Tpcpv)

The crystal-poor vitric zone (pv) is divided into the densely welded (pv3), moderately welded (pv2), and nonwelded (pv1) subzones based primarily on the degree of welding.

Densely welded subzone (Tpcpv3) (0- to 3-m thick)

The densely welded subzone (pv3) occurs only in the southern part of the central block of Yucca Mountain, and is exposed locally on the flank of Yucca Mountain in Solitario Canyon. Rocks in this subzone are composed of 80 to 95 percent groundmass, 3 to 5 percent phenocrysts, 2 to 15 percent pumice clasts (locally 25 percent), and less than 1 percent lithic clasts. Where exposed, the densely welded subzone consists of extensively deformed pumice in a densely welded, vitric matrix. In the vitrophyre interval (pv3v), the vitroclastic texture is not macroscopically identifiable and the rock is moderate brown (5YR3/2) to very dark gray (N3) glass. The vitroclastic texture preserved in the clastic texture interval (pv3c) with moderate brown (5YR3/2) to very dark gray (N3) dense pumice clasts in reddish brown (5YR4/3) to dark gray (N4) matrix. Phenocrysts, mostly feldspar with rare hornblende. Pumiceous horizons with pumice clasts as much as 25 percent of the rock occur locally near the base of pv3 and the upper part of pv2, and might indicate depositional boundaries within or between flow units. Fractures in the subzone are typically slightly planar to slightly irregular and slightly smooth to slightly rough, but locally pv3v is highly fractured with small fractures that result in a very rough surface roughness. Contacts at the base of each interval are typically gradational across 0.2 to 1 m.

Moderately welded subzone (Tpcpv2) (1- to 5-m thick)

Rocks in the moderately welded subzone (pv2) have partially deformed pumice clasts in a moderately welded, locally vapor-phase altered matrix. These rocks are composed of 90 to 96 percent groundmass, 3 to 5 percent phenocrysts, 1 to 3 percent pumice clasts, and less than 2 percent lithic clasts. The moderately welded, pink (7.5YR7/3) matrix contains reddish-yellow (7.5YR6/8) glass shards that increase in abundance downward. Where pv3 is absent, vapor-phase alteration occurs throughout the subzone with the most intense interval near the middle. Phenocrysts, mostly feldspar with rare hornblende. Pumice clasts are incompletely flattened, are less than 1.5 cm in average diameter, and are either vitric, devitrified (light reddish gray: 2.5YR7/1), or replaced by vapor-phase minerals (pale red: 2.5YR6/2). Volcanic lithic fragments are dark reddish-gray (5YR3/1), and less than 1 cm in average diameter. Fracture shape and roughness changes downward from slightly irregular to irregular and slightly rough to rough. Welding gradually decreases from the top to base of the subzone, and the lower contact of this subzone is defined as the point where pumice clasts are not deformed.

Nonwelded welded subzone (Tpcpv1) (2- to 9-m thick)

Rocks in the nonwelded subzone (pv1) have nondeformed pumice clasts in a nonwelded (pv1n) to partially welded (pv1p) matrix. These rocks are composed of 90 to 96 percent groundmass, 3 to 5 percent phenocrysts, 3 to 5 percent pumice clasts, and less than 5 percent lithic clasts. The matrix is vitric to incipiently devitrified or vapor-phase altered, with abundant reddish-yellow (7.5YR6/8) glass shards with bubble-wall textures. Phenocrysts are mostly feldspar with rare hornblende. Pumice clasts, which are 1- to 2-cm diameter, are either glassy and reddish yellow (7.5YR6/8) or wholly or partially replaced by vapor-phase minerals. Some pumice clasts are enclosed in a rind of pink, devitrified matrix material. Pumice clasts in pv1p form a poorly developed foliation, whereas in pv1n the clasts are very poorly aligned or have no systematic orientation. Locally, in the 1 to 3 m above the base of the deposit, there are pumiceous intervals where pumice clasts up to 4-cm diameter comprise 10 percent of the rock and have a poorly developed foliation that probably resulted from processes during deposition. Dark reddish-gray (5YR3/1) volcanic lithic clasts are typically 1 to 2 cm in diameter. In most locations, a characteristic 1- to 5-cm-thick ground layer of planar to cross-bedded, pumiceous, moderately sorted, pyroclastic flow/surge deposits occurs at the base of the Tiva Canyon Tuff. Fractures are typically irregular to very irregular and rough to very rough, and this geometry results from the breaking of the rock along grain boundaries rather than across the grains.

Pre-Pah Canyon Tuff bedded tuff

Pre-Pah Canyon Tuff bedded tuff (Tpbt2) (2- to 7-m thick)

Pre-Pah Canyon Tuff bedded tuff (Tpbt2) is described herein because it has been variously described as post-Topopah Spring Tuff bedded tuff or part of the Topopah Spring Tuff (Lipman and others, 1966; Spengler and others, 1981; Maldonado, and Koether, 1983; Scott and Bonk, 1984; Scott and Castellanos, 1984; Spengler and others, 1984). These tuffaceous beds consists of pumice-rich fallout and pyroclastic flow(?) deposits that are capped by a 1-m thick, moderately sorted, reworked(?) tuffaceous bed. These deposits are identified separately from those of the large-volume climatic eruption of the Topopah Spring Tuff until tephrostratigraphic methods such as mineral and pumice chemistry confirm a petrogenetic correlation. As tephrostratigraphic data become available, beds correlated to the Topopah Spring Tuff can be redefined to the upper bedded tuff unit (Tptbu).

Although the fallout and pyroclastic flow (?) deposits of Tpbt2 are not included in the deposits formed from the climactic Topopah Spring Tuff eruption, four types of field-based relations indicate at least some of these deposits represent small eruptions that occurred shortly after the climactic eruption. There are close similarities in the assemblages of phenocrysts, and pumice and lithic clasts. Near the base of Tpbt2, pumiceous deposits are partially to moderately welded, and the welding profile appears continuous with that of the underlying Topopah Spring Tuff. The partially to moderately welded pumiceous deposits are locally corroded and have vapor-phase minerals coating and replacing the vitroclastic texture. Locally, the nonwelded to partially welded deposits in Tpbt2 have been altered by fumaroles.

Tuffaceous beds in Tpbt2 include a reworked(?) bed at the top and a series of fallout and pyroclastic flow(?) deposits. The reworked(?) bed contains 1- to 5-mm-diameter grains of porphyritic obsidian (2 to 5 percent of the rock) and 4-mm- to 2-cm-diameter white (5YR8/1) and reddish-yellow (5YR7/6) microvesicular pumice (2 to 15 percent of the rock). This reworked(?) bed occurs in most core from boreholes and in surface exposures, therefore, forming a good marker bed. Locally, at the top of the fallout and pyroclastic flow(?) deposit sequence is a 0.5- 1-m-thick light to dark red (10R6/6 to 3/6) clay-altered interval. The fallout and pyroclastic flow(?) deposit sequence consists of 1 to 25 percent phenocrysts, 10 to 75 percent pumice clasts, 10 to 20 percent matrix with 10 to 30 percent lithic clasts. Several beds are indicated by variations in the grain size, sorting, and abundance of pumice and lithic clasts, but correlation of these beds between boreholes and surface exposures has not been attempted. Matrix and pumice clasts are white (N9 to 2.5Y8/1) to pale yellow (2.5Y8/2) and are moderate red (5R4/6), pink (5YR8/4), and yellow (2.5Y8/6) where altered by fumarolic activity. Phenocrysts include nonaltered sanidine and plagioclase, nonaltered to oxidized biotite, and rare hornblende and pyroxene. Pumice clasts are up to 5 cm. Most lithic clasts are 2 to 8 mm and slightly porphyritic. Some lithic clasts are devitrified grayish-red purple (5RP3/2), but most are gray to very dark gray (10YR6/6 to 3/1) to red (2.5YR6/6) obsidian. The base of the sequence is a thin (2 cm), well-sorted, lithic-rich fallout with a maximum grain size of 5 to 10 mm.

Topopah Spring Tuff (Tpt)

Crystal-rich member (Tptr)

The crystal-rich member of the Topopah Spring Tuff (tr) is characterized by greater than 10 percent phenocrysts in the rock with a crystal-transition subzone at the base where the percent phenocrysts increase from 5 to 10 percent. The member is divided into vitric (rv) and nonlithophysal (rn), and locally lithophysal zones. The vitric zone is distinguished by the preservation of the volcanic glass to form rocks with a vitreous luster. Rocks in both the nonlithophysal and lithophysal zones are devitrified, and the division is based on the presence or absence of lithophysae. The top of the member is a 2-cm thick, very fine-grained, light-red (2.5YR7/6) fallout tephra bed.

Crystal-rich vitric zone (Tptrv)

The crystal-rich vitric zone (rv) is divided into the nonwelded (rv3), moderately welded (rv2), and densely welded (rv1) subzones based on the degree of welding.

Nonwelded subzone (Tptrv3) (0- to 7-m thick)

Rocks in the nonwelded subzone (rv3) consists of nonwelded (rv3n) to partially welded (rv3p) intervals of vitric and locally fumarolic altered tephra. These rocks are composed of 10 to 70 percent matrix, 2 to 10 percent phenocrysts, 15 to 85 percent pumice clasts, and 1 to 20 percent lithic clasts. With increasing welding, the nonaltered matrix and pumice changes downward from light gray (10YR7/1), very pale brown (10YR8/2), and light brown (5YR5/6) to moderate brown (5YR4/6), pale red (10YR6/2), dark brown (7.5YR3/4), and dark reddish brown (10R3/4). Fumarolic altered matrix and pumice is moderate red (5R4/6), pink (5YR8/4), and yellow (2.5Y8/6), and commonly forms bands of colors. Phenocrysts include sanidine and plagioclase, nonaltered to oxidized biotite, and rare hornblende and pyroxene. Pumice clasts are vitric or locally altered by fumarolic vapor phase, and typically less than 1 cm in diameter, but a few are as much as 4 cm. Most volcanic lithic clasts are slightly porphyritic, some are devitrified grayish-red purple (5RP3/2) to dark-reddish brown (5YR3/2) and pale red (5R6/2), and others are black (N1), very dark gray (N3), or grayish-red (10R4/8) obsidian.

Moderately welded subzone (Tptrv2) (0.5- to 5-m thick)

Rocks in the moderately welded subzone (pv2) have partially deformed pumice clasts in a moderately welded, vitric to locally devitrified matrix. These rocks are composed of 10 to 70 percent matrix, 2 to 10 percent phenocrysts, 25 to 90 percent pumice clasts, and 1 to 10 percent volcanic lithic clasts. Color of the matrix varies downward from yellowish brown (7.5YR6/6) and pinkish gray (2.5YR7/2) to dark yellowish brown (10YR4/2), pale grayish red (10R6/1), or pale red (5R6/2) as the local argillic alteration gives way to vapor-phase mineralization. Phenocrysts include sanidine and plagioclase, nonaltered to oxidized biotite, and rare hornblende and pyroxene. Pumice clasts have average diameters of 2 to 3 cm, and light gray (N7), yellowish brown (7.5YR4/4), and grayish orange (10YR7/4). Pumice clasts are light gray (N7) to grayish orange pink (5YR7/2) in the argillic interval, but greenish gray (5GY7/1) where affected by vapor-phase mineralization. Pumice clasts immediately above the densely welded zone contact are extremely altered, containing only a vestige of textures that predated vapor-phase alteration. Locally where the vitric densely welded subzone (pv1) does not occur, rocks in the dense interval of the nonlithophysal zone (rn3) are in contact with moderately welded rocks (rv2) and the vapor-phase alteration is greater than where there is an intervening vitric densely welded subzone (pv1). Volcanic lithic clasts are less than 1 cm in diameter and locally are as much as 20 percent of the rock. Most lithic clasts are slightly porphyritic, some are devitrified grayish-red purple (5RP3/2) to dark-reddish brown (5YR3/2), and others are vary from medium light gray (N6) and very dark-gray (N3) to grayish-red (10R4/8) obsidian. Foliation is poorly to well developed. Fractures are irregular to very irregular and rough to very rough. The contact with the subjacent vitric densely welded subzone (rv1) is typically sharp with the transition less than 0.5 m, but where there is no rv1 the transition is more gradational (0.5 to 2 m) to the nonlithophysal dense subzone (rn3).

Densely welded subzone (Tptrv1) (0- to 3-m thick)

Rocks in the densely welded subzone (rv1) have densely welded shards and pumice clasts in a fused vitric matrix with no macroscopic porosity. These rocks are composed of 75 to 85 percent matrix, 10 to 15 percent phenocrysts, 2 to 10 percent pumice clasts, and trace amounts of lithic fragments. The densely welded subzone is divided into a vitroclastic texture interval (rv1c) that overlies the vitrophyre interval (rv1v). The matrix glass is dark reddish brown (2.5YR3/3) to dark red (10R3/8) in rv1c and dusky red (5R3/4), dark reddish gray (10R3/1) to very dark gray (N3) in rv1v. Locally, the glass is slightly hydrated. Phenocrysts include sanidine, plagioclase, nonaltered to oxidized biotite, and rare hornblende and pyroxene. Pumice clasts are black (N1 to N2) glassy lenses that vary in average diameter from 2 to 3 cm, and have long to short axis aspect ratios between 4:1 to greater than 8:1. Lithic clasts are rare to absent. Foliation, defined by pumice flattening, is moderately well developed. Fractures are slightly planar to slightly smooth, and locally are irregular and very irregular in rv1v. The lower contact of this subzone is defined as the point where the matrix becomes incipiently devitrified and lacks a vitreous luster, and the pumice clasts are devitrified, argillically altered, or replaced by vapor-phase mineralization.

Crystal-rich nonlithophysal zone (Tptrn) (36- to 54-m thick)

Rocks of the crystal-rich nonlithophysal zone are densely welded, devitrified, and composed of 60 to 90 percent matrix/groundmass, 10 to 15 percent phenocrysts, 2 to 25 percent pumice clasts, and trace amounts of lithic clasts. This zone is divided into three subzones where the dense subzone (rn3) overlies the vapor-phase corroded subzone (rn2) that locally overlies the crystal-transition subzone (rn1).

Dense subzone (Tptrn3) (2- to 4-m thick)

Rocks of the dense subzone are densely welded, devitrified, and composed of 60 to 90 percent matrix/groundmass, 10 to 15 percent phenocrysts, and 2 to 25 percent pumice clasts. The groundmass is incipiently devitrified and grades downward from grayish-black (N2), dusky brown (5YR2/2), or dark reddish-brown (10R3/4) to moderate reddish-brown (10R4/6) or pale brown (5YR5/2). Phenocrysts include nonaltered to altered sanidine and plagioclase, and minor amounts of biotite, and rare nonaltered pyroxene and hornblende, altered yellow (5Y7/8) pseudomorphs of pyroxene(?), and (accessory) magnetite(?). Pumice clasts are typically less than 2 cm, but locally are greater than 6 cm, and field exposures at the northern end of Yucca Mountain have clasts as large as 15 × 80 cm. Pumice fragments are incipiently devitrified and dark gray (N4 to N6), argillically altered and pinkish gray (5YR8/1) to pale red (10YR6/2), or are locally replaced by vapor-phase minerals and light gray to white (N7 to N9). Fractures are planar to slightly planar and smooth to slightly smooth.

Vapor-phase corroded subzone (Tptrn2) (32- to 54-m thick)

Rocks of the vapor-phase corroded subzone are densely welded, devitrified, and composed of 60 to 90 percent matrix/groundmass, 10 to 15 percent phenocrysts, 2 to 25 percent pumice clasts, and less than 2 percent volcanic and plutonic lithic clasts. The groundmass grades downward from grayish red (10R4/2) or pale red (5R6/2) to light brown (5YR5/6) to pale brown (5YR5/2) or red purple (5RP5/2) with localized light gray (N7) and white (N9) spots and veinlets. The groundmass is a mix of vapor-phase altered and devitrified material, the latter dominating lower in the subzone. Locally, intervals of well developed vapor-phase alteration and crystallization are as much as 10- to 40-ft thick. Phenocrysts include nonaltered to altered sanidine, plagioclase, and biotite, and rare altered yellow (5Y7/8) pseudomorphs of pyroxene(?), nonaltered hornblende, and (accessory) magnetite(?). Pumice fragments, which are replaced by vapor-phase minerals, are predominantly light gray to white (N7 to N9), but locally are pinkish gray (5YR8/1), pale red (5R6/2 to 10YR6/2), reddish gray (2.5YR5/1), and dark to medium gray (N4 to N6), with an increase in the amount of porphyritic pale brown (5YR5/2) to pale red (5R6/2) in the lower part of the subzone. The size of pumice clasts varies with stratigraphic position; the average size of pumice clasts varies from 1 × 3 to 4 × 20 mm, whereas the maximum clast size ranges from 2 × 9 to 38 × 60 mm. Volcanic (10R6/2) and fine-grained plutonic (5YR6/1) lithic fragments are typically less than 5 mm. The fine-grained plutonic clasts are probably part of the "quartz monzonite" xenolithic assemblage that initially occur in the lithic-rich zone (Tptpf). Lithophysae do not occur in this zone, but cavities with average sizes of 1 × 1 mm occur in small amounts (less than 1 percent). Larger cavities have a maximum size of 19 × 40 mm and commonly occur where pumice clasts were partially corroded. Cavities typically have thin (1- to 3-mm thick) deposits of vapor-phase minerals. Locally, a foliation defined by alignment of pumice or matrix texture is poorly to well developed with dips 5° to 30°. Fractures are slightly irregular and slightly rough.

Crystal transition subzone (Tptrn1) (See below)

Crystal-rich lithophysal (Tptrl2) (1- to 7-m thick)

The crystal-rich lithophysal zone (rl2) occurs locally and is a lateral facies of the lower part of the crystal-rich nonlithophysal zone (rn2). Rocks of the crystal-rich lithophysal zone are densely welded, devitrified, and composed of 60 to 85 percent matrix/groundmass, 10 to 12 percent phenocrysts, 2 to 15 percent pumice clasts, 2 to 10 percent lithophysae, and 0 to 2 percent volcanic and plutonic lithic clasts. The groundmass is a mix of vapor-phase altered and devitrified material, and is pale red (10R6/2), pale yellowish-brown (10YR6/2), reddish-brown (5YR5/4) to light brown (5YR6/4). Phenocrysts include nonaltered to altered sanidine, plagioclase, biotite, and rare altered yellow (5Y7/8) pseudomorphs of pyroxene(?), and nonaltered hornblende. Pumice clasts are gray (N6), white (N9), pale brown (5YR5/2), or pale red (10R6/1), and are commonly replaced by vapor-phase minerals. Pumice clast sizes are typically less than 4 cm, but locally exceed 8 cm. Light-brown (5YR6/4) volcanic and white (N9), fine-grained, plutonic lithic clasts are less than 1 cm in diameter. Lithophysae vary greatly in size, typically are less than 1 cm, but locally are up to 3 × 7 cm. The amount of lithophysae increases downward. Foliation is moderately to poorly developed with an average dip of 10° to 15°. Fractures are very irregular and very rough. Core is commonly not recovered or is rubbly.

Crystal transition subzone (Tptrnl or Tptrll)
(4- to 11-m thick)

Rocks of the crystal transition subzone, whether in the non-lithophysal (rnl) or lithophysal (rll) zones, are densely welded, devitrified, and composed of 60 to 95 percent matrix/groundmass, 3 to 10 percent phenocrysts, 2 to 15 percent pumice clasts, 0 to 2 percent lithic fragments, and 3 to 15 percent lithophysae in the lithophysal zone. The groundmass grades from light brownish gray (5YR6/1) or light brown (5YR5/6) to grayish red-purple (5RP5/2), pale red (10R6/2), or medium light gray (N6). Characteristic of the crystal transition zone is the decrease in amount of phenocrysts from greater than 10 percent at the top to less than 5 percent at the base, but commonly, the amount decreases to about 3 percent prior to remaining relatively constant throughout the crystal-poor member. Phenocrysts include nonaltered to altered sanidine, plagioclase, biotite, and rare altered yellow (5Y7/8) pseudomorphs of pyroxene(?), and nonaltered hornblende. Pumice clasts typically vary in size from 1 to 4 cm, but locally exceed the 8-cm diameter of core. Pumice clasts are aphyric and gray (N6) to white (N9), or are porhyritic and vary from pale brown (5YR5/2) to moderate brown (5YR4/3) to pale red (10R6/1). Porphyritic pumice clasts have 10 to 12 percent phenocrysts and contain the same mineral assemblage as the matrix; therefore, probably represent cognate fragments. Volcanic and fine-grained plutonic clasts are typically less than 1 cm. In the lithophysal zone, lithophysae are commonly 1 to 3 cm, and locally as much as 3 × 10 cm. The base of this subzone is where the phenocrysts are less than 3 percent of the rock and the amount is relatively constant throughout the crystal-poor member. Because the decrease in the amount of phenocrysts is gradational, macroscopic identification of the base of the subzone may be difficult to determine with more accuracy than 1 to 4 m.

Crystal-poor member (Tptp)

The crystal-poor member of the Topopah Spring Tuff (tp) is characterized by less than 3 percent phenocrysts in the rock, and the member is divided into the upper lithophysal (pul), middle nonlithophysal (pmn), lower lithophysal (pll), and the lower nonlithophysal (pln) zones. All rocks in the member are devitrified. Divisions are based primarily on the presence or absence of lithophysae, but other features included in the multiple criteria are color and fracture geometry.

Lithic-rich zone (Tptpf or Tptrf) (0- to 40-m thick)

The lithic-rich zone occurs in the northern part of Yucca Mountain and adjacent areas, and is poorly represented in the boreholes near Drill Hole Wash. Descriptions herein are summarized from Lipman and others (1966) and Spengler (USGS, written commun., 1994). Rocks of the lithic-rich zone are moderately to densely welded, devitrified, and composed of 45 to 80 percent matrix/groundmass, 1 to 12 percent phenocrysts, 0 to 15 percent pumice fragments, 0 to 20 percent lithophysae, and 10 to 50 percent of lithic fragments. Based on the amount of phenocrysts in the matrix, the lithic-rich zone is divided into crystal-rich (rf) and crystal-poor (pf) subzones, and based on the presence or absence of lithophysae, these subzones are divided into lithophysal and non-lithophysal intervals (pfl and pfn, or rfl and rfn). Lithic clasts comprise 10 to 30 percent of the rock and commonly have size ranges from 5 to 15 cm, but locally clasts are as much as 50 percent and diameters of 1 to 2 m. Lithic clasts consist of light-purplish-gray crystal-poor welded tuff, flow-banded lava flow rocks, and fine- to medium-grained quartz monzonite. Quartz monzonite clasts are typically the least abundant clast type, but are characteristic of this zone, and occur in minor amounts in the overlying units. Contacts at the top and base of the zone can be very sharp or gradational.

Crystal-poor upper lithophysal zone (Tptpul)
(46- to 77-m thick)

Rocks of the crystal-poor upper lithophysal zone are moderately to densely welded, devitrified, and composed of 70 to 90 percent matrix/groundmass, 1 to 3 percent phenocrysts, 0 to 25 percent pumice clasts, 2 to 40 percent lithophysae, and trace amounts of volcanic lithic fragments. Where the cavernous lithophysae subzone (pulc) is identified, the lower part retains the designation pul and is referred to as the small lithophysae subzone. The 0- to 9-m-thick pulc has few (less than 2 percent) small (less than 3 cm) lithophysae in core, hence the name. In pulc, the core is commonly rubble with numerous surfaces covered with vapor-phase minerals, and the amount of nonrecovered core is typically 20 to 30 percent; thus, large lithophysae are inferred. Borehole televiewer logs confirm the occurrence of cavernous lithophysae (greater than 10 cm in diameter). Groundmass of the upper part of pul, including pulc, is light to medium light gray (N7 to N6) or grayish orange pink (5YR7/2) to pale red purple (5RP6/2). Groundmass of the lower part of pul is variegated with pale-red purple (5RP5/2), pale red (10R6/3), and varying amounts of pale pink (5RP8/2), medium light and very light gray (N6 and N8), light and moderate brown (5YR6/4 and 5YR4/4), and grayish red purple (5RP4/2). Medium light and very light gray (N6 and N8) to pinkish gray (5YR8/1 to 10R8/2) spots are have sizes that range from 1- to 8-mm and locally comprise 10 to 25 percent of the groundmass. Lithophysae average 1 to 2 cm in size, with a maximum size of 7 cm. Borehole televiewer logs indicate the local occurrence of large lithophysae (greater than 10-cm diameter). Rims on lithophysae are commonly 1- to 5-mm wide, and medium light and very light gray (N6 and N8) to pinkish gray (5YR8/1 to 10R8/2). Phenocrysts include sanidine, minor amounts of plagioclase and biotite, and magnetite. Pumice clasts are highly variable in amount, size, and color. Pumice clasts are typically 2 to 10 percent of the rock, but locally are up to 25 percent. Pumice clasts have an average diameter of less than 3 cm and maximum size of 12 cm. Most pumice clasts are light gray (N8), but locally in the upper quarter the porphyritic and pale to moderate brown (5YR5/2 to 5YR4/4) clasts are the largest and most abundant. In the lower half of the zone, pumice clasts are few and difficult to identify. This apparent lack of pumice clasts could result where no pumice clasts were deposited, or the clasts were obscured by crystallization. Flow-banded lava flow and welded tuff lithic clasts occur locally, vary in maximum size from 1 to 30 mm, and are medium gray (N5) to white (N9) with some moderate brown (5YR4/4). Locally, foliation is poorly to well developed, with dips from 10° to 35°. Low-angle fractures are typical in this zone, and high-angle and near-vertical fractures occur but are not common. Fractures are typically irregular to slightly irregular and have very rough to slightly rough surfaces. Based on the downward decrease in the amount and size of lithophysae, and the changes in groundmass color and fracture characteristics, the lower contact is gradational can be gradational across thicknesses of 5 to 15 m, but use of multiple criteria can narrow the gradational interval to less than 2 m.

Crystal-poor middle nonlithophysal zone (Tptpmn) (29- to 38-m thick)

Rocks of the middle nonlithophysal zone are densely welded, devitrified, and composed of 90 to 99 percent matrix/groundmass, 1 to 2 percent phenocrysts, 0 to 5 percent lithophysae, 1 to 5 percent pumice clasts, and 1 to 5 percent lithic fragments. Locally, the zone is divided into three subzones where the upper and lower (pmn3 and pmn1) have the main attributes of the zone, but the lithophysae-bearing subzone (pmn2) has attributes that are similar to lithophysal zones. The lithophysae-bearing subzones does not occur, or is poorly developed, in the southern part of Yucca Mountain, and is more abundant in the northern part of the mountain where it is 4- to 14-m thick. In the nonlithophysal subzones (pmn3 and pmn1), the groundmass is typically grayish-orange pink (5YR7/2) to light brown (5YR6/4) or red purple (5RP5/2) to pale red (5R4/2) with minor amounts of light to very light gray (N7 to N8) to pinkish gray (5YR8/1) spots or veinlets and grayish to pale purple (5P5/2) borders on spots and veinlets. In pmn3, spots comprise 1 to 5 percent of the rock and are pinkish gray (5YR8/1). In pmn1, high-angle fractures are associated with veinlets and streaks. The groundmass in pmn2 is grayish to pale purple (5RP4/2 to 5P5/2) with varying amounts of very light gray (N8) and light to moderate brown (5YR4/4, 5YR6/4). In pmn2, the average size of lithophysae is less than 2 cm, with a maximum size range of 2 to 8 cm. In pmn2, spots comprise 2 to 5 percent of the rock and are pinkish gray (5YR8/1), and the combination of lithophysae and spots are 5 to 7 percent of the rock. Phenocrysts include sanidine, with minor amounts of plagioclase, biotite, and magnetite, and rare altered pyroxene(?). Pumice clasts are typically less than 2 cm, and are locally altered by vapor-phase crystallization. Pumice clasts are light gray (N7), pale brown (5YR5/2), pale red (5R6/2), grayish orange pink (5YR7/2), and locally are spherulitic and light brownish gray or grayish pink (5YR6/1 or 5R8/2). Lava flow and welded tuff lithic clasts vary in maximum size from 2 mm to 7 cm and are gray to white (N7 to N9) to light brownish gray (5YR6/1). In the lower part of the zone, lithic clasts locally form intervals where clasts are as much as 5 percent of the rock and many of the largest clasts are concentrated. Foliation is not developed or very poorly developed, except locally in pmn2 where it dips 15° to 20°. Near vertical, planar, smooth-surfaced fractures are common and locally occur in sets of 2 to 5 joints per set. Fractures in pmn2 have slightly irregular shapes and slightly rough surfaces, attributes that are shared with lithophysal zones.

Crystal-poor lower lithophysal zone (Tptpll) (69- to 104-m thick)

Rocks of the lower lithophysal unit are densely welded, devitrified, and composed of 70 to 96 percent groundmass, 1 to 7 percent lithophysae (locally 20 percent), 1 to 3 percent phenocrysts, 1 to 10 percent pumice clasts, and 1 to 5 percent lithic clasts (locally 10 percent). The groundmass is extremely variegated, but tends to be a mixture of purple, gray, and brown including pale red (5R6/2 to 10R6/2), grayish-red purple (5RP4/2), pale-red purple (5RP5/2), pale pink (5RP8/2), medium light and very light gray (N6 and N8), and light and moderate brown (5YR6/4 and 5YR4/4). Shard texture is locally preserved. Lithophysal cavities are typically less than 3 cm, but locally are up to 6 cm, and are commonly oblate. Rims on lithophysae are 1- to 15-mm wide, and are grayish orange pink (5YR7/2) or pale pink (5RP8/2) to medium-light and very light gray (N6 and N8), and locally narrow borders are grayish red purple (5RP4/2). Spots up to 4 cm in diameter are pale pink (5RP8/2) to grayish orange pink (5YR7/2) to medium-light and very light gray (N6 and N8). Spots and rims on lithophysae are 3 to 30 percent of the rock. Core is commonly rubble; therefore, large lithophysae are inferred. Locally, borehole video indicates cavernous lithophysae have diameters greater than the borehole (greater than 30 cm). Phenocrysts include sanidine, minor amounts of plagioclase, biotite, and magnetite, and rare quartz and altered pyroxene(?). Pumice clasts are less than 2 cm with maximum size of 7 cm. Pumice clasts are light gray (N7) to light brownish gray (5YR6/1) or pinkish gray

(5YR8/1), and rare pale yellowish brown (10YR6/2). Flow-banded lava-flow and welded-tuff lithic clasts are less than 1 cm with the maximum size 5 cm. Flow-banded lava-flow, hypabyssal, and welded-tuff lithic clasts are medium to very light gray (N6 to N8) to pale reddish brown (10R5/4), pale brown (5YR5/2), and rare clasts are porphyritic and pale red (5R6/2). Pumice and lithic clasts and lithophysae have the largest average and maximum sizes in the middle of the zone. Foliation is poorly developed in the upper third of the zone and is poorly to moderately developed in the lower two-thirds of the zone with dips of 3° to 30°. Low-angle fractures are typical, and high-angle and near-vertical fractures occur but are not common. Fractures are typically irregular to slightly irregular and are slightly rough to very rough. Where fractures are rough to very rough a hackly-fractured subzone (pllh) can be divided from the rest of the zone. Locally, in the lower part of this zone, there are high-angle, anastomosing, discontinuous fractures with irregular profiles that form irregular open cavities. These cavities are partially filled with small, angular clasts of the surrounding rock, and the walls and clasts have a thin deposit of vapor-phase minerals. The lower contact of this zone can be gradational across a 2- to 4-m-thick interval.

Crystal-poor lower nonlithophysal zone (Tptpln) (48- to 72-m thick)

Rocks of the lower nonlithophysal zone are densely welded, devitrified, and composed of 75 to 97 percent groundmass, 1 to 2 percent phenocrysts, 1 to 15 percent pumice clasts, and 1 to 10 percent lithic clasts (locally 10 to 20 percent). As with the Tiva Canyon Tuff, this zone can be divided into two subzones based on fracture characteristics; a hackly subzone (plnh) with rough to very rough fractures, and a columnar subzone (plnc) with smooth to slightly rough fractures. Rocks in plnc have a high heft, implying a high density. The columnar subzone is divided into three intervals: a spherulitic pumice interval (plnc3), an argillic pumice interval (plnc2), and a vitric pumice interval (plnc1). The groundmass changes color with depth. In plnh and the upper part of plnc3, the groundmass is approximately equal parts pale-red to grayish-red purple (5RP6/2 to 5RP4/2) and pinkish gray (5YR6/2) with minor amounts of pinkish gray (5YR8/1) and very light gray (N8). In plnc3, the groundmass is dusky-red purple (5RP3/2) and light brown (5YR5/4) with minor amounts of light and very light gray (N7 and N8). In plnc2 and plnc1, the groundmass is grayish brown (5YR3/2) with minor amounts of gray (5YR5/1). Remnant shard texture occurs locally. Phenocrysts include sanidine with minor amounts of plagioclase and biotite, and magnetite, and trace quartz. Pumice clast sizes are less than 2 cm, and locally maximum sizes are 6 cm. In plnc3, pumice clasts are devitrified, light gray (N7), and commonly have spherulitic minerals that have grown from the walls. In plnc2, spherulites occur in some pumice clasts but most clasts are altered to grayish-orange (10YR7/4) to light-brown (5YR5/6) clay. In plnc1, pumice clasts are vitric and very dark gray (N2) or locally argillic (5YR5/6). Lava-flow, hypabyssal, and welded-tuff lithic clasts are 1 cm, and the maximum size is 7 cm. Lithic clasts are medium light gray to very light gray (N6 to N8), grayish brown (5YR4/2), pale red (5R6/2), or porphyritic and pale red (5R7/2) to pale yellowish brown (10YR6/2), or rare light olive gray (5Y5/2). Both the average and maximum size of lithic clasts are greatest in the middle and lower parts of the zone, but concentrations of clasts occur locally throughout the zone. Foliation is poorly to well developed, and dips vary from 5° to 25°. High-angle and subhorizontal fractures occur throughout the zone with high-angle, planar, and relatively smooth fractures more common in plnc. Locally in the hackly subzone, there are high-angle, anastomosing, discontinuous fractures with irregular open cavities that are similar to those in the lower lithophysal zone.

Crystal-poor vitric zone (Tptpv)

The crystal-poor vitric zone (pv) is divided into the densely welded (pv3), moderately welded (pv2), and nonwelded (pv1) subzones based primarily on the degree of welding.

Densely welded subzone (Tptpv3) (10- to 20-m thick)

Rocks in the densely welded subzone (pv3) are densely welded with vitreous luster and no macroscopic porosity, and are composed of 75 to 96 percent matrix, 1 to 2 percent phenocrysts, 0 to 15 percent pumice clasts, and 2 to 10 percent lithic clasts. Based on the amount of preservation of vitroclastic texture discernible with a hand lens, the densely welded zone is divided into two subzones. The vitrophyre subzone (pv3v) is where vitroclastic textures are difficult to distinguish, and the clastic texture subzone (pv3c) is where vitroclastic textures are discernible. Densely welded rocks break across grain boundaries. Vitrophyres are typically grayish black (N2) to grayish brown (5YR3/2), and locally have pale red (5R6/2) spherulites comprise 2 to 3 percent of the rock. Densely welded rocks of the clastic texture subzone have grayish black (N2) to grayish brown (5YR3/2) pumice clasts in medium dark gray (N4) to pale brown (5YR5/2) matrix. Phenocrysts include sanidine, with minor biotite and magnetite, and rare quartz. Quartz grains are interpreted as xenocrysts (compare Byers, 1985). Pumice clast sizes range from 5 mm to 6 cm. Lava-flow and welded-tuff lithic clasts are typically less than 1 cm with maximum size of 5 cm. Lithic clasts are light gray (N7), grayish red (10R4/2), and grayish-red purple (5RP3/2), and rare moderate brown (5YR4/4). Fractures in the densely welded subzone are planar to curviplanar and smooth. Locally, rocks in the vitrophyre subzone have well developed anastomosing fractures that result in rough surfaces. Fractures are commonly coated with very fine-grained pale-blue (5PB7/2) mineral. Along some fractures, alteration of glass resulted in yellowish-gray (5Y7/2) to grayish-orange (10Y7/4), very fine-grained material.

Moderately welded subzone (Tptpv2) (2- to 12-m thick)

Rocks in the moderately welded subzone (pv2) are vitric and have moderately to strongly deformed pumice clasts in a moderately welded matrix. These rocks are composed of 75 to 93 percent matrix, 1 to 2 percent phenocrysts, 3 to 20 percent pumice clasts, and 3 to 7 percent lithic clasts. The matrix has a well-defined vitroclastic texture and grades downward from grayish black (N2) to light gray (N6), moderate brown (5YR4/4) to light brown (5YR6/4) and grayish-orange pink (5YR7/2) and individual glass shards are grayish black (N2) to moderate yellowish brown (10YR5/4). Macroscopic porosity is about 1 to 10 percent of the rock. Locally, the matrix is devitrified and has vapor-phase minerals. Where altered and zeolitized, the rocks are pale red (10R6/2), light brown (5YR6/4), pinkish gray (5YR7/2), or pale yellow (5Y8/3), and the vitroclastic texture is preserved by the clay and zeolite minerals. Phenocrysts include sanidine, minor biotite and plagioclase, and rare quartz. Pumice clasts are less than 2 cm in size, and vitric, but locally are corroded and coated with vapor-phase minerals. Pumice clasts grade downward from grayish to brownish black (N2 to 5YR2/1) to light brown (5YR6/4) to grayish orange (7.5YR7/4) and pale orange-pink (5YR8/3). Lava-flow and welded-tuff lithic clasts generally have sizes less than 4 mm, but locally are 15 mm. Lithic clasts are sparsely porphyritic and light gray (N7) grayish-red purple (5RP3/2), grayish red (10R4/2) or dark reddish brown (5YR3/2). Foliation, defined by the alignment of pumice clasts and glass shards, is well developed at the top of the subzone and decreases downward to moderately developed. Near vertical fractures are slightly irregular to irregular and slightly rough to rough. The lower contact can be gradational across a 0.5- to 2-m thick interval.

Nonwelded subzone (Tptpv1) (5- to 22-m thick)

Rocks in the nonwelded subzone (pv1) are vitric and characterized by partially to nondeformed pumice clasts in a partially welded to nonwelded matrix. These rocks are composed of 93 to 97 percent matrix, 1 percent phenocrysts, 0 to 10 percent pumice, and 0 to 7 percent lithic clasts (locally 10 to 20 percent). This subzone is locally divided into a partially welded interval (pv1p) and a nonwelded interval (pv1n). Matrix is moderate brown (5YR4/4), light brown (5YR6/4) and grayish-orange pink (5YR7/2) to grayish orange (10YR7/4) in pv1p, and grayish-orange pink (5YR7/2), grayish orange (10YR7/4) to light gray (N8) in pv1n. Glass shards are grayish black (N2), yellowish brown (10YR4/2), grayish yellow (5Y2/4) to colorless. Locally, rocks in this subzone are altered and zeolitized, and are light brown (5YR6/4) and pale-yellow orange (10YR8/6) to grayish-orange pink (10R8/2) and moderate yellow (5Y7/6). Phenocrysts include sanidine, minor amounts of biotite and plagioclase, and rare quartz. Pumice clasts are typically less than 2 cm and have a maximum size of 6 cm. Pumice clasts all have similar colors to the matrix, and locally they are argillic(?) and grayish orange (10YR7/4) or zeolitic(?) and grayish pink (10YR8/2). Lava flow and welded tuff lithic clast sizes are typically less than 1 cm and locally are up to 8 cm. Lithic clasts are vitric and dark to light gray (N3 to N8) or devitrified and very light gray (N8) or grayish-red purple (5RP3/2) to dark reddish brown (5YR3/2). About 1 to 2 m above the base in UZ-14 and UZ-16, in an interval of poor core recovery, there are several 5 to 6 cm-diameter fragments of clasts that might represent a concentration of large lithic clasts. Core recovery can be moderate to poor near the base. Locally there is a 1-cm thick, pinkish gray (10YR8/1), fine-ash bed deposited on a paleosol(?).

APPENDIX 3. CORRELATION OF FIELD UNITS AND SURFACE AND SUBSURFACE UNITS OF THE TIVA CANYON TUFF AT YUCCA MOUNTAIN, NEVADA

[Bold type indicates zone and subzone names and characteristic features. Mineral symbols: S - sanidine; P - plagioclase; Q - quartz; B - biotite, CP - clinopyroxene, H - hornblende; Sp - sphene; s - sparse; tr - trace. Arithmetic symbols indicate relative abundance: greater than (>), much greater than (») , less than (<), less than or equal to (≤), approximately equals (?). Lines between columns correlate units. Solid line at top of columnar zone of Scott and Bonk (1984) is based on their definition that part of this unit is glassy. Queried line shows how the columnar zone is commonly mapped: an upper, devitrified, cliff-forming zone underlain by a vitric zone that is locally cliff-forming. The vitric part of the columnar zone of Scott and Bonk (1984) correlates with the crystal-poor vitric zone in this report.]

Field units (Spengler and others, 1994)

caprock zone: (ccr)
not mapped in study area
15 % phenocrysts
(S » **P** » **Q**) (B » **CP** ≈ H) (Sp)
nonwelded to densely welded
vitric, but base is devtrified
red brown color (5YR5/2)
mixed pumice

upper cliff zone: (cuc)
thickness: 10 - 35 m
(S » P) (**B** > **H**) (Sp)
euhedral oxy-biotite in matrix
mixed pumice: ≤ 15 -20 cm diameter
light gray (N8-9)
medium gray (N6)
very dark yellowish orange (10YR6/8)
ISRM Hardness: I
Subzones: (subzones not mapped)
7 - 15 % phenocrysts
Roughness coefficient: 7 - 18
subvitrophyre pumice-rich subzone
pumice-poor subzone
pumice-rich subzone
subzone not specified
Transition subzone:
6-10 m above contact
5 - 7 % phenocrysts
Roughness coefficient: 3 - 6
lithic clasts: light gray (N7) to moderate red (5R5/4) (≤ 1 % of rock)
pumice: smaller and fewer than above
lithophysae: long axis = 3 - 100 cm
aspect ratio 1:1 - 3:1

upper lithophysal zone: (cul)
thickness: 15 - 25 m
2 - 5 % phenocrysts
(S) (B > H) (Sp)
H in matrix, but not B
Roughness coefficient: 6-10
ISRM Hardness: II
pumice: mostly light gray (N8)
6 - 10 m from top, minor amounts of very dark yellowish orange (10YR6/8)
lithophysae: 30-50 %
0.5 - 30 cm, aspect ratio 1:1 - 3:1
subzone:
spherulites, 1 mm diameter, well developed
≈ 2 - 4 m-thick near base

Field units (Scott and Bonk, 1984)

caprock zone: (ccr)
thickness: 25+ m
15 % phenocrysts
(S » **P** » **Q**) (B » **CP** ≈ **H**) (**Sp**)
mixed pumice:
"more" mafic: medium light gray (N6)
(≤ 5 cm diameter)
"more" silicic: light gray to white (N8-9)
(≤ 30 cm diameter)
Subzones:
nonwelded subzone
includes partially welded
vitric, abundant mafic pumice
moderately welded devitrified base
vitrophyre subzone
abundant mafic pumice
brown devitrified subzone (5YR5/2)
abundant mafic pumice
yellow-brown devitrified subzone (10YR6/2)
minor mafic pumice
brown-gray devitrified subzone (5YR6/1)
minor mafic pumice
≤ 15 % lithophysae, ≤ 5 cm

upper cliff zone: (cuc)
thickness: 0 - 11 m
moderately to densely welded
rhyolitic; **12 - 15** % phenocrysts
(S » P) (**B s**) (Sp)
cognate pumice, 0.1 - 2 cm
5 - 10 % **lithophysae**, 10 - 50 cm

upper lithophysal zone: (cul)
thickness: 5 - 35 m
rhyolitic; 10-12 % phenocrysts
(S) (**B s**) (Sp)
cognate pumice, 0.2 - 2.5 cm
10-20 % lithophysae, 10 - 30 cm
convolute with gray (N8) rims

Surface and subsurface units (this report)

crystal-rich unit: (cr...)
10-15 % phenocrysts
(S » **P** » **Q**) (B » **CP** ≈ H) (Sp)
B in matrix
mixed pumice: light gray (N8-9)
medium gray (N6)
very dark yellowish orange (10YR6/8)

vitric zone: (crv...)
nonwelded to densely welded
Subzones:
nonwelded (v3: v3n, v3p)
moderately twelded (v2)
locally devitrified
densely welded (v1: v1c, v1c)

nonlithophysal zone: (crn...)
densely to partially welded
devitrified with vapor-phase minerals
small (≤3 mm) cavities in pumice and matrix, these are not lithophysae
Subzones:
subvitrophyre transition (n4)(2.5YR5/2)
pumice-poor (n3) (10R4/2)
mixed pumice (n2) (10R6/1)
crystal transition (n1) (10R7/1)
8 - 12 % phenocrysts
minor lithophysae
pumice: ≤10 % light gray (N8-9)
very rare, very dark yellowish orange (10YR6/8)

crystal-poor zones: (cp...)
≤ 5 % phenocrysts (S) (H » B) (Sp)
pumice: light gray (N8-9)
rare, very dark yellowish orange (10YR6/8)

upper lithophysal zone: (cpul)
moderately to densely welded
devitrified with vapor-phase minerals
pumice: light gray (N8-9)
very rare, very dark yellowish orange (10YR6/8)
lithophysae: 5 - 40 % of rock
10 - 30 cm diameter
1- to 5-mm-thick, light-gray (N8) rims
high-angle fractures are rare
slightly rough surface roughness
Subzones:
spherulite-rich subzone (ul1)
spherulites are well defined and 1 - 3 mm diameter
slightly smooth surface roughness
rare lithophysae
subzone is 2- to 4-m thick and 1 - 3 m above base of cpul
lower transition interval of few small lithophysae ≈ 1 - 3 m thick

Field units (Spengler and others, 1994)	Field units (Scott and Bonk, 1984)	Surface and subsurface units (this report)
clinkstone zone: (cks) thickness: 20 - 30 m 2 - 5 % phenocrysts: (S) **Roughness coefficient:** **2 - 4** near top, **2 - 8** near base **concoidal fracture** ISRM Hardness: II-III lithic clasts, 0 - 6 m above base light gray (N8) to moderate red (5R5/4), and 2 - 30 mm diameter **rare lithophysae** (≤ 1%) locally, middle lithophysal subzone 1 - 20 cm, aspect ratio ≤ 4:1	**clinkstone zone**: (cks) locally rounded step (crs) thickness: 0 - 55 m rhyolitic; **8-12** % phenocrysts (S) **(B tr)** (Sp) cognate pumice, 0.2 - 2 cm **concoidal fracture** no lithohysae, but **locally** a **middle lithophysal subzone**	**middle nonlithophysal zone**: (pmn) moderately to densely welded devitrified with minor amounts of vapor-phase minerals along fractures **high-angle fractures common** **smooth to slightly smooth roughness** pumice: light gray (N8-9), but very difficult to recognize because of crystallization in groundmass lithophysae: trace amounts locally ≤ 2 % in lower 4 m **Subzones:** lower and upper (mn1 and 3) lithophysae-bearing (mn2) lower transition interval (≈ 3 m thick) of small-scale, poorly developed, hackly fractures and ≤ 2 % lithophysae
lower lithophysal zone: (cll) thickness: 5 - 10 m 2 - 5 % phenocrysts (S) **Roughness coefficient: 8-12** fractures break through groundmass textures and lithophysae ISRM Hardness: I 2 - 10 % **lithophysae** maximum size = 8x15 cm 0.5x4 cm average, aspect ratio ≤ 2-8:1	**lower lithophysal zone**: (cll) thickness: 0 - 25 m rhyolitic; **6 - 8** % phenocrysts (S) (B tr) (Sp) cognate pumice, 0.2 - 1.5 cm **10 - 15 % lithohysae**, 1 -5 cm spherical to oblate pinkish-gray (5YR 8/1) margins around lithophysae **hackly fracture near base**	**lower lithophysal zone**: (pll) moderately to densely welded devitrified with vapor-phase minerals **minor high-angle fractures** **slightly rough fractures** **where rough fractures** (pllh) pumice: light gray (N8-9), difficult to recognize due to crystallization **lithophysae:** ≈2 % in upper 12 m 5 - 10 % in most of unit up to 6 cm, commonly ≤ 2 cm light gray (N7) rims, 1 - 4 mm wide
hackly zone: (ch) thickness: > 20 m 2 - 5 % phenocrysts: (S) (B) (Sp) **Roughness coefficient: 12-18** ISRM Hardness: III lithophysae occur locally, near the top	**hackly zone**: (ch) thickness: 2 - 26 m rhyolitic; **6 - 8** % phenocrysts (S) (B tr) (Sp) cognate pumice, 0.2 - 2 cm irregular **hackly fracture** breaks into pieces 1 - 5 cm diameter	**lower nonlithophysal zone**: (pln...) moderately to densely welded devitrified with minor amounts of vapor-phase minerals along fractures no lithophysae, except locally near top **Subzones:** **hackly subzone:** (plnh) **minor high-angle fractures** **rough "hackly" surface fractures** pumice: light gray (N8-9) lithophysae: ≤ 2 % in upper 6 m **columnar subzone:** (plnc...) **high-angle planar fractures** **smooth surface fractures** subzones, based on pumice: spherulitic, grayish brown (5YR3/1) (c3) argillic, pink (5R6/2) (c2) vitric, black (N3) (c1)
columnar zone: not included in the study	**columnar zone**: (cc) thickness: 11 - 31 m rhyolitic; **5 - 8** % phenocrysts (S) (B, Sp rare) **partially glassy** cognate pumice, 0.2 - 1.5 cm Subzones: vitrophyre subzone (local) flattened pumice subzone devitrified (not stated) nonwelded subzone vitric	**vitric zone:** (cpv...) nonwelded to densely welded **Subzones:** densely welded (v3: v3v, v3c) (local) matrix, shards, and pumice are fused fractures across grain boundaries moderately welded (v2) locally devitrified with v-p minerals matrix, shards, and pumice partially fused, minor amounts of porosity fractures across most boundaries non-welded welded (v1: v1p, v1n) fractures along grain boundaries

? ?

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