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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STRATIGRAPHIC AND STRUCTURAL RELATIONS OF VOLCANIC ROCKS IN DRILL HOLES USW GU-3 and USW G-3, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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ABSTRACT

Stratigraphic and structural studies of drill holes USW GU-3 and USW G-3, are part of a coordinated effort by the U.S. Geological Survey to evaluate the geologic, geophysical, and hydrologic potential of the thick sequence of Miocene age ash-flow tuff and related volcanic rock of Yucca Mountain as an underground high-level nuclear waste repository in southern Nevada. The geologic relations of more than 1,500 m of continuous core from these holes in southern Yucca Mountain have been correlated with similar results of drilling in central and northern Yucca Mountain and with results of surface mapping to produce a conceptual model of the geology of the rock volume being considered as the potential repository.

Major silicic ash-flow tuffs extend through Yucca Mountain with only minor variations in thickness, but the tuffs vary somewhat in degree of welding, physical properties, and extent of alteration. The uppermost member f the Paintbrush Tuff, the Tiva Canyon Member, caps most of Yucca Mountain to a thickness of approximately 100 m or more. Below this cap, the densely welded, 300-m-thick, Topopah Spring Member of the Paintbrush Tuff, targeted as the repository unit within the unsaturated zone, is the most uniform of these ash-flow tuffs. Variation in lithophysal content is the most significant variable in the rock, ranging from over 30 volume percent void, in the northern exposures near the source area, to less than 5 volume percent in the most suitable zones in the southern part of the potential repository. The tuffaceous beds of Calico Hills form a nonwelded interval below the Topopah Spring Member. This nonwelded sequence of ash flows and minor bedded tuffs decreases in thickness from nearly 300 m to 30 m and changes in degree of alteration from highly zeolitized to vitric from north to south within Yucca Mountain. A lower sequence of ash-flow tuffs, including the Prow Pass, Bullfrog, and Tram Members of the Crater Flat Tuff and the Lithic Ridge Tuff, have only minor variations in thickness, degree of welding, and type of alteration throughout Yucca Mountain. Dacitic to rhyodacitic lava flows and breccias found above and below the Lithic Ridge Tuff in the northern part of Yucca Mountain pinch out toward the south.

Two major fault sets cut Yucca Mountain at the surface. One set consists of Basin and Range style normal faults. These faults strike north-northwest to north-northeast, and in oriented core from USW GU-3 and USW G-3, have a dominant north-northwest strike. Although most movement on the faults occurred between 13 and 11.5 m.y. ago, minor activity has persisted into the Pleistocene. The other fault set consists of northwest-striking strike-slip faults that appear to have right-lateral offset with activity restricted to between 13 and 11.5 m.y. ago. In age, attitude, sense of offset, and geographic location these faults seem to be related to the Walker Lane-Las Vegas Valley shear zones. These faults are largely restricted to the northern part of Yucca Mountain and are not observed in core from drill holes USW GU-3 and USW G-3.

Fractures in drill holes USW GU-3 and USW G-3 have a dominant north-northwest strike and a steep southwest dip parallel to fractures observed on the surface. In the upper kilometer of rock, fracture densities in densely welded tuff are between 20 and 40 fractures per unit cubic meter and between less than 1 and about 3 fractures per unit cubic meter in nonwelded tuff. Below depths of 1 kilometer, the density of fractures is roughly an order of magnitude lower, from 3.5 fractures per unit cubic meter in moderately welded tuff to 0.3 fractures per unit cubic meter in nonwelded tuff. Because fractures provide the major conduits for movement of both vadose and ground water in these tuffs, the correlation between density of fractures and degree of welding of these tuffs becomes important for characterization of this potential nuclear waste repository.

INTRODUCTION

During the last 5 years, the U.S. Geological Survey (USGS) has participated in examining the feasibility of emplacing nuclear wastes in southern Nevada, as part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project, administered by the Nevada Operations Office (NV) of the U.S. Department of Energy (DOE) under Interagency Agreement DE-AI08-78ET44802. The principal role of the USGS is the geological characterization of rock masses being considered as underground nuclear waste storage sites. Site-specific investigations have concentrated upon Yucca Mountain, an erosional remnant of a thick sequence of Miocene ash-flow tuffs and related rocks. The mountain consists of gently tilted mesa-like structural blocks in the southwestern Nevada Test Site (NTS) and adjacent areas (fig. 1).

This report concerns the stratigraphic and structural character of two drill holes, USW GU-3 and USW G-3, drilled 30 m apart as a two-stage coordinated drilling and geophysical logging program. These two drilling sites are the southernmost of a series of geologic drill holes within the immediate area of investigation as a potential nuclear repository in the central portion of Yucca Mountain (fig. 2). Continuous core was obtained between January and June 1982 from these two drill holes to a depth of 1,533 m with sufficient overlap to insure correlation between holes. Although emphasis in this report is placed upon the lithologic, stratigraphic, and structural character of the core recovered at drill holes USW GU-3 and USW G-3, stratigraphic correlation between preexisting drill holes and structural correlation with surface mapping on Yucca Mountain are also presented.

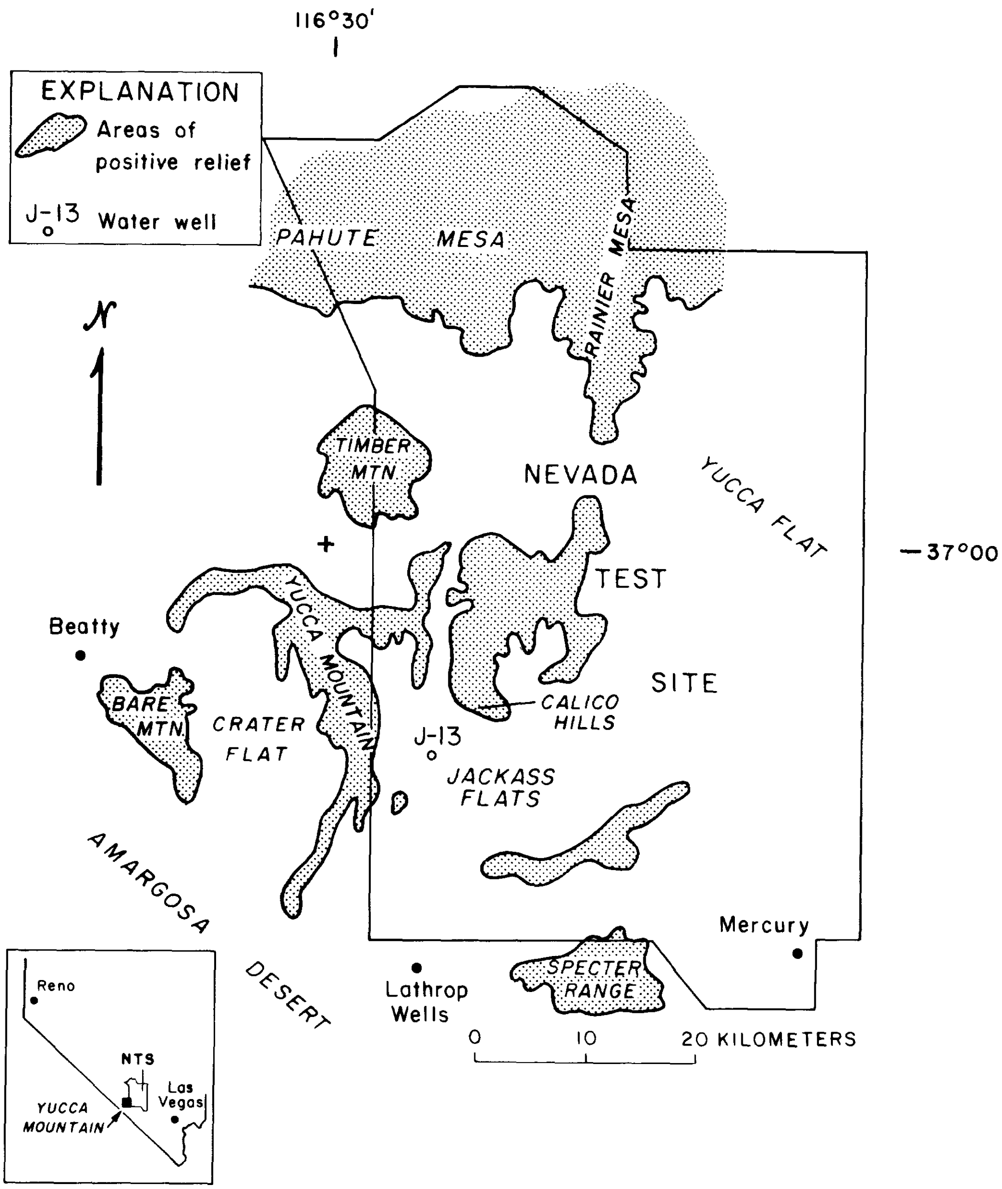

Figure 1.--Location map of Yucca Mountain. Note that the eastern portion of Yucca Mountain lies within the Nevada Test Site (NTS) boundary.

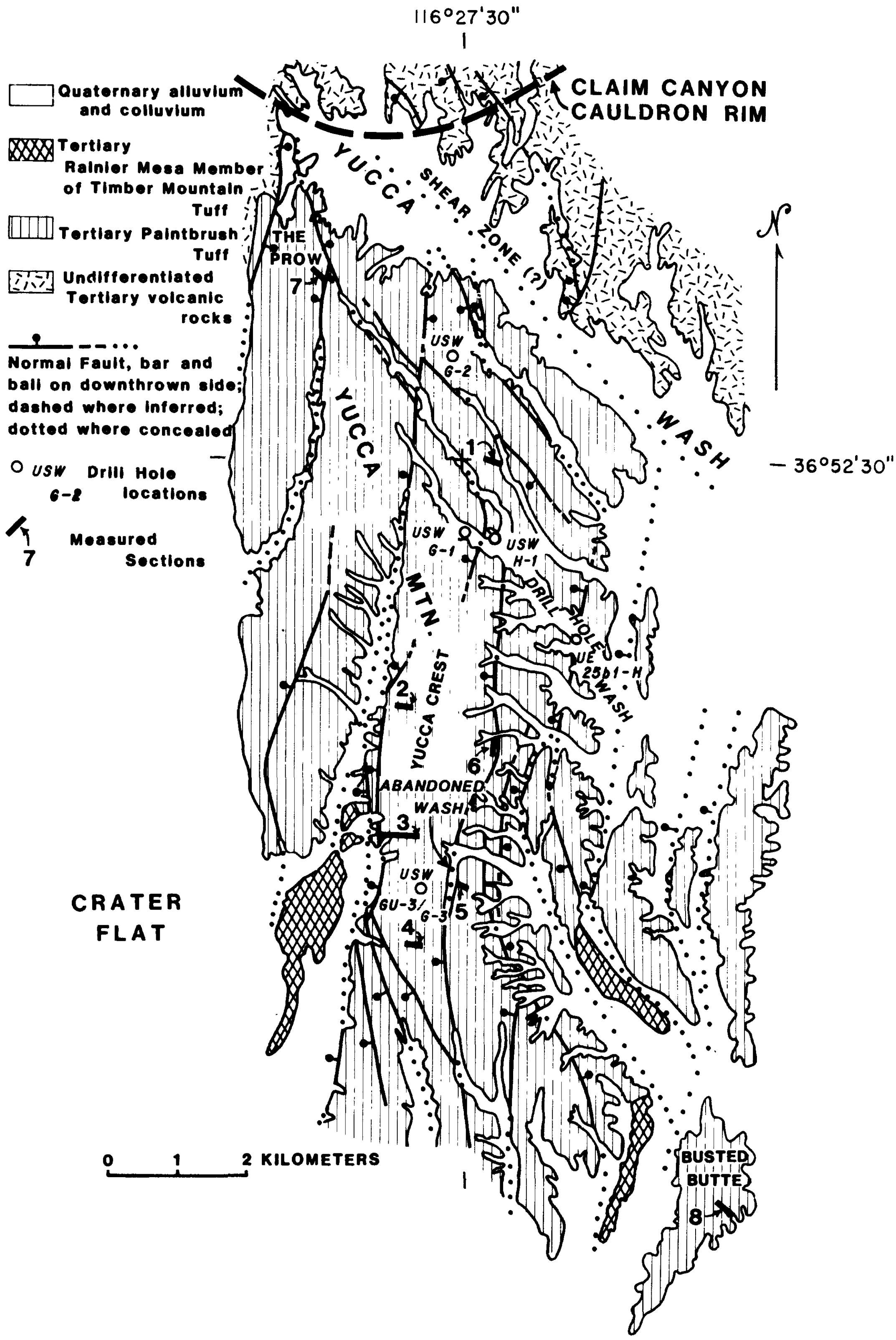

Figure 2.--Location of drill holes USW GU-3, and USW G-3, USW G-2, USW G-1, USW H-1, UE25a-1, and UE25b-1H at Yucca Mountain. Because of the close proximity of drill holes USW GU-3 and USW G-3, they are shown as one site, USW GU-3/G-3.

Metric units are used throughout this report. English unit conversion factors are listed in table 1 for convenience.

Table 1.--Conversion factors for metric to English units

To convert from	To	Multiply by
Kilometers	Miles	0.62137
Meters	Feet	3.2808
Centimeters	Inches	0.39370

Drill-Hole History

The coordinated pair of drill holes, USW GU-3 and USW G-3 were cored in two stages: USW GU-3 was cored in the unsaturated zone and USW G-3 was cored largely in the saturated zone (table 2). This two-stage coring program was designed to obtain maximum hole stability and to optimize conditions for wet-hole geophysical logging above the zone of saturation. Drill hole USW G-3 was spudded January 8, 1982, and completed March 21, 1982; this was followed by drill hole USW GU-3 that was spudded January 26, 1982, and completed June 12, 1982. USW GU-3 was continuously cored from about 10 m to 806 m, and USW G-3 was continuously cored from about 795 m to 1,533 m. The core recovery record is listed in appendix 1.

Table 2.--Abridged drill-hole history of USW GU-3 and USW G-3

Location	USW GU-3	USW G-3
Nevada State Coordinates:	N. 752,690 ft. E. 558,501 ft.	N. 752,780 ft. E. 558,483 ft.
Ground Elevation:	1,480.20 m	1,480.20 m
Drill rigs:	CP Rig (surface casing) Joy #1 (drill hole)	CP Rig (suface casing) Ideco #37 (drill hole)
Drill-hole sizes:	Size/Depth interval 46.99 cm/ 0- 10.7 m 17.15 cm/ 10.7-348.7 m 10.00 cm/348.7-538.9 m 7.57 cm/538.9-805.9 m	Size/Depth interval 44.45 cm/ 0 - 11.68 m 22.23 cm/ 11.6- 792.5 m 12.07 cm/792.5- 794.9 m 10.00 cm/794.9-1,533.4 m
Circulation media:	Polymer and bentonite mud	Air/soap and polymer mud
Drilling record:	Spudded: January 26, 1982 Cored interval: 9.45 to 805.89 m Completed coring: June 12, 1982	Spudded: January 8, 1982 Cored interval: 795.22 to 1,533.39 m Completed coring: March 21, 1982
Well-site geologists, Fenix & Scisson, Inc. (F&S):	M. R. Castellanos M. P. Chornack B. W. Cork G. A. DePaolis L. P. Escobar H. E. Huckins K. A. Johnson L. P. Parrish	M. P. Chornack B. W. Cork G. A. DePaolis L. P. Escobar H. E. Huckins K. A. Johnson L. P. Parrish R. L. Reed

Geophysical logs were run by Birdwell Division of Seismograph Service Corp. and by Dresser Atlas Co. These logs include caliper, electric, induction electric, density (borehole compensated), spectralog (U, Th, K gamma-ray spectral), gamma ray, gamma-ray neutron, compensated densilog, 3-D velocity, geophone survey, neutron borehole compensated, epithermal neutron porosity, and nuclear annulus. Results of investigations of these logs are not presented in this report. In addition to these logs, a compass-oriented TV camera was run to the static water level by Westech Geophysical Co.; strikes of conspicuous fractures and faults are readily measured from tapes of these TV runs. Finally, an Eastman Whipstock directional survey with 15-m stations was conducted to a depth of 1,500 m in drill hole USW G-3. A distinct deviation of the borehole from vertical occurs below 750 m; the hole deviation at a depth of 1,500 m is about 200 m west and 25 m south of the spud position and an inclination from vertical of nearly 25^{0} exists below 1,500 m. Drill-hole deviation will be discussed further in the section "Bedding and Foliation." At select intervals covering approximately 10 percent of the depth cored, oriented core was obtained by American Coldset Co. (appendix 1); the attitudes of bedding, foliations, fractures, and faults that were obtained from these cores will be discussed later.

Site Selection

The site for drill holes USW GU-3 and USW G-3 was chosen in the southernmost portion of the area considered favorable for a nuclear waste repository. The location on Yucca Crest was also picked to avoid shallow encounter with abundant southwest-dipping faults and fractures in the Abandoned Wash area to the east and north of the drill site (fig. 3).

Acknowledgments

We owe our greatest gratitude to the Fenix & Scisson, Inc., well-site geologists who provided 24-hour surveillance of the coring operations and conducted sampling operations; these include M. P. Chornack, B. W. Cork, G. A. DePaolis, L. P. Escobar, H. E. Huckins, K. A. Johnson, L. P. Parrish, and R. L. Reed. Also, the U.S. Geological Survey geologists, M. D. Carr, D. L. Hoover, Florian Maldonado, J. G. Rosenbaum, J. A. Sharps, R. W. Spengler, and W C Swadley monitored coring operations. The conscientious efforts of these two groups insured the quality of data essential to this report. P. D. Blackmon, of the U.S. Geological Survey, provided X-ray diffraction data on the mineralogy of fracture filling materials. Several scientists at the Los Alamos National Laboratory, F. M. Byers, D. L. Bish, and D. Broxton, provided data and advice that have contributed significantly to this report. K. S. Kellogg of the USGS provided a helpful review of the manuscript.

GEOLOGIC SETTING

Yucca Mountain is an eastward-tilted volcanic plateau which consists of a thick sequence of ash-flow tuff and related rocks of Miocene age within the southwestern Nevada volcanic field. Most of the exposures on Yucca Mountain consist of the uppermost member of the Paintbrush Tuff, the Tiva Canyon Member. The caldera source for the Paintbrush Tuff is the Claim Canyon cauldron, a segment of which is preserved immediately north of Yucca Mountain (fig. 4) (Byers and others, 1976; Christiansen and others, 1977).

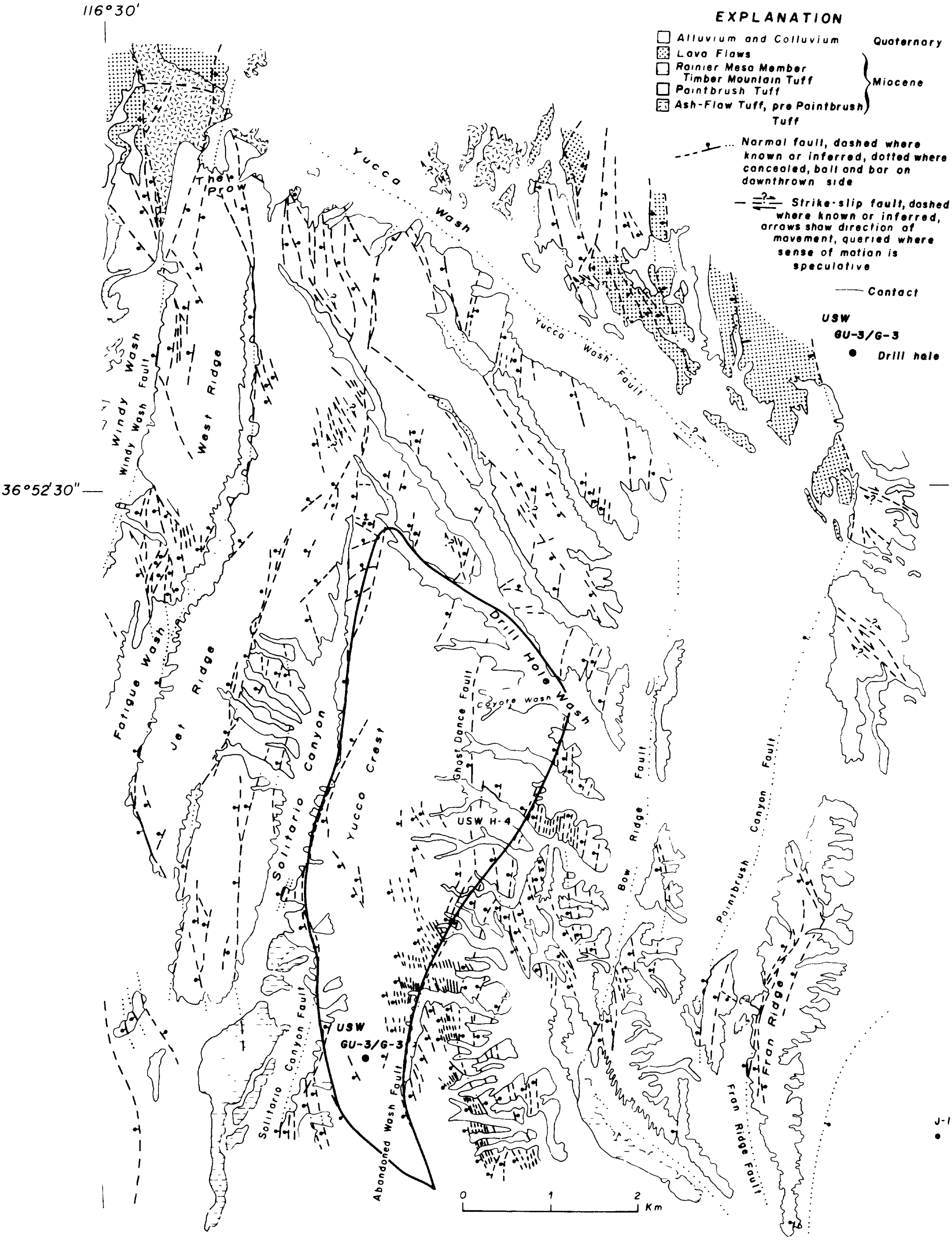

Figure 3.--Generalized geologic map of Yucca Mountain showing the character of detailed faults (R. B. Scott and Jerry Bonk, USGS, written commun., 1983). The heavy line outlines the tentative surface boundaries of the potential nuclear waste repository.

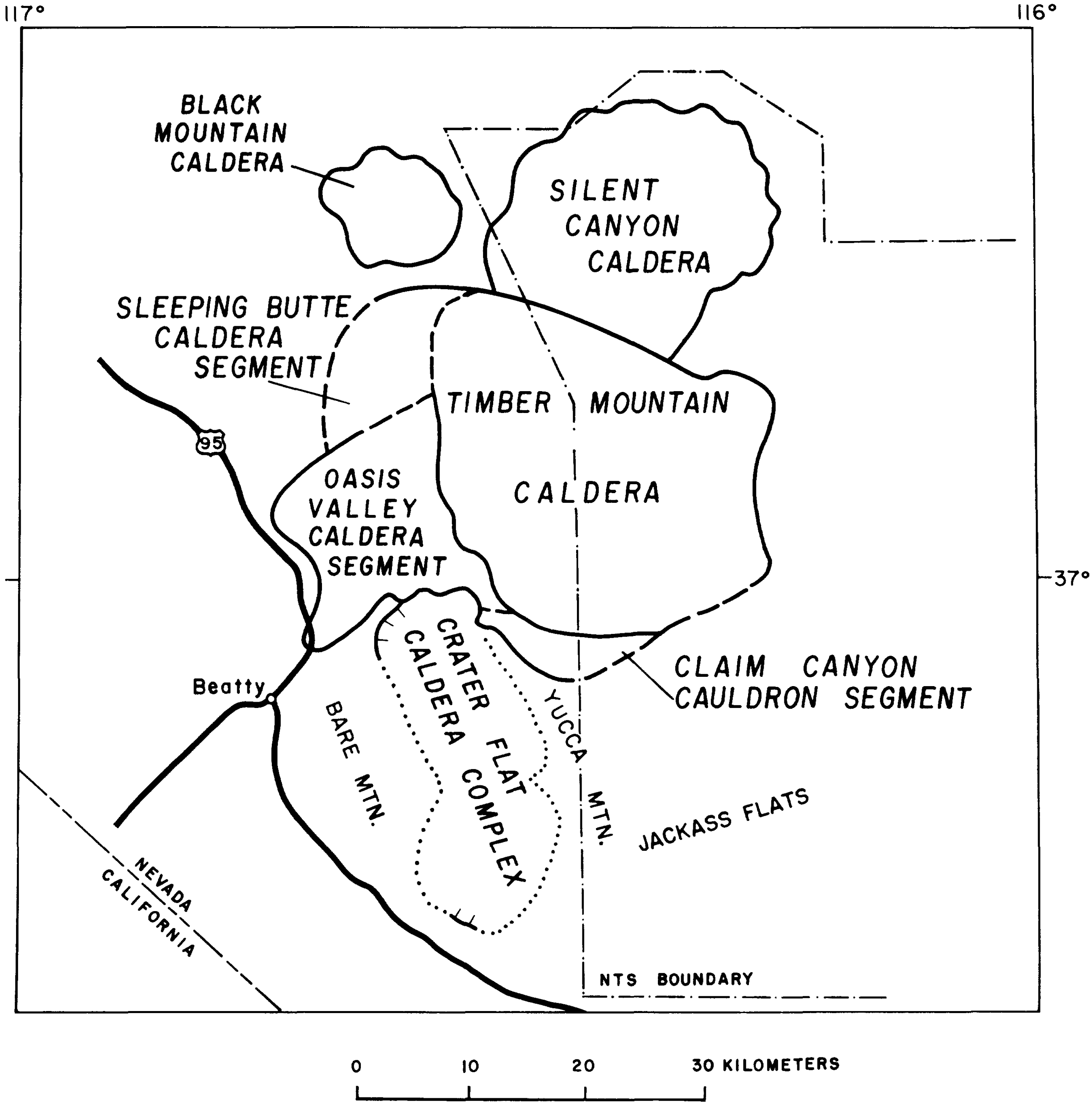

Figure 4.--Map of major calderas in the Timber Mountain-Oasis Valley caldera complex (Byers and others, 1976) and the recently proposed Crater Flat Caldera complex (Byers and others, 1983; Carr and others, in press).

The youngest ash-flow tuff in the Yucca Mountain area, the Rainier Mesa Member of the Timber Mountain Tuff, preserved only in structural valleys (figs. 2 and 3), was erupted from the Timber Mountain caldera. The Crater Flat Tuff, older than the Paintbrush Tuff, is exposed about 1 kilometer northwest of The Prow (fig. 3). These older ash-flow tuffs probably erupted from the Crater Flat caldera complex as proposed by Byers and others (1983), Carr (1982), and Snyder and Carr (1982). Still older ash flows are found only in cores from Yucca Mountain.

Yucca Mountain is cut by two sets of faults (Lipman and McKay, 1965; Christiansen and Lipman, 1965; Scott and Spengler, 1982). One set is a north-northwest- to north-northeast-striking, west-dipping set of normal faults that breaks the gently dipping plateau into several eastward-tilted blocks (fig. 3). Carr (1974) recognizes a component of left-lateral shear along several north-northeast-striking faults in the region, and examples of this sense of displacement are present on Yucca Mountain. The other set consists of a series of northwest-striking strike-slip faults with apparent right-lateral offset that are prevalent in the region between Drill Hole Wash and Yucca Wash. The region near Abandoned Wash contains abundant north-northwest-striking faults with apparent dip-slip displacements and superimposed, minor right-lateral strike-slip motion. The proposed repository block between Abandoned and Drill Hole Washes contains significantly fewer faults of either type (fig. 3).

A generalized geologic section through Yucca Mountain from the rim of the Claim Canyon cauldron rim north of Yucca Wash south to drill hole USW GU-3 and USW G-3 is shown on figure 5. Nearly 2 km of ash-flow tuffs were drilled at drill holes USW G-1, USW H-1, USW G-2, and USW GU-3 and USW G-3; in descending order, these strata consist of the four rhyolitic to dacitic members of the Paintbrush Tuff (Tiva Canyon Member, 13 m.y. old; Yucca Mountain Member; Pah Canyon Member; and Topopah Spring Member, 13.5 m.y. old), the informally named rhyolitic tuffaceous beds of Calico Hills (14 m.y. old), the three rhyolitic members of the Crater Flat Tuff (Prow Pass Member; Bullfrog Member, 14 m.y. old; and Tram Member), unnamed rhyodacitic to dacitic lavas, the rhyolitic Lithic Ridge Tuff, unnamed rhyolitic to dacitic lavas (14.5 m.y. old), and unnamed older ash-flow tuffs and bedded tuffs. The youngest ash-flow tuff in the Yucca Mountain area, the 11.5-m.y. old rhyolitic Rainier Mesa Member of the Timber Mountain Tuff, was not encountered in cores from Yucca Mountain. The Rainier Mesa Member is not exposed along the generalized section on figure 6 because this tuff is restricted to structurally low areas where it covers the hanging wall sides of major north-northeast-striking, west-dipping faults (figs. 2 and 3). Probably the Rainier Mesa Member never covered the plateau-like tops of Yucca Mountain with continuous welded tuffs. Within this report, all K-Ar ages (Marvin and others, 1970; Kistler, 1968) have been converted to new decay and abundance constants (Dalrymple, 1979).

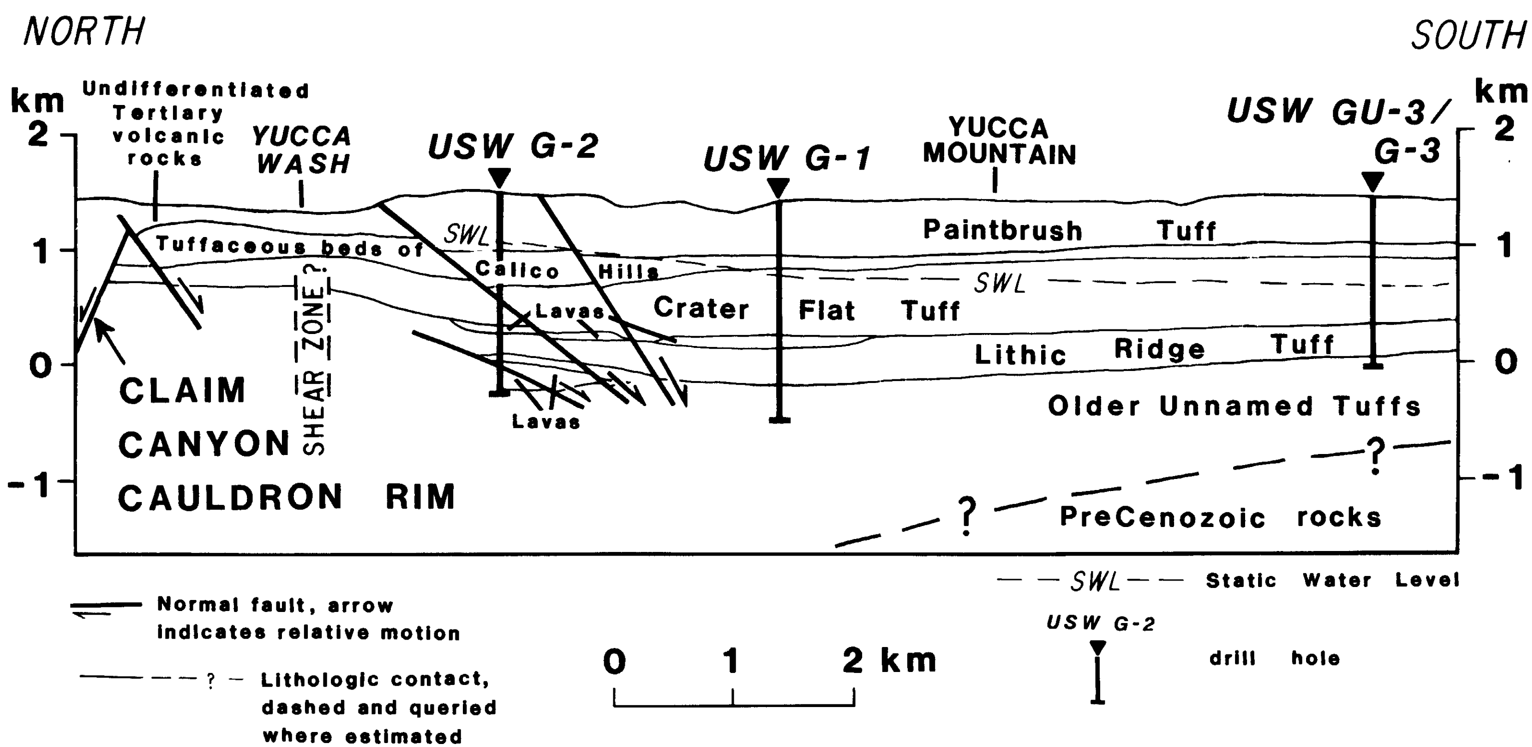

Figure 5.--Generalized north-south geologic section through Yucca Mountain from the Claim Canyon cauldron rim at the northern end to drill holes USW GU-3 and USW G-3 at the southern end. Drill holes USW G-2 and USW G-1 are projected onto the line of section.

STRATIGRAPHY

The vast majority of the rocks cored at USW GU-3 and USW G-3 are ash-flow tuffs. Most of these ash flows are welded, compositionally zoned, and form compound cooling units; examples of nonwelded, compositionally homogenous, and simple cooling units are also present. In the following discussions and appendix summarizing the lithologic character of these units (appendix 2), the quantity of individual phenocryst phases will be expressed in percent of the total phenocrysts; in several figures, the quantity of phenocrysts will be expressed as the percent of the total rock.

In addition to abundant ash-flow tuff, minor intervals of bedded tuffs were recovered; these tuffs include ash-fall tuffs, pumice-fall tuffs, and reworked tuffs. The reworked tuffs have been affected by fluvial action, by aqueous fluidized sheet runoff, and by aeolian reworking. In many cases, distinctions among these different origins cannot be recognized and the general term "bedded tuffs" must be used. These bedded tuffs may be (1) products of subsequent eruptions petrologically related to the underlying welded tuff, (2) products of erosion of nonwelded tops of the underlying welded tuff or subsequent eruptions, (3) products of precursor eruptions, or (4) products of erosion of precursor eruptions. Without extensive and impractical study, distinctions among these possibilities are impossible. Therefore, the bedded tuffs are not assigned to either the overlying or the underlying ash-flow tuffs. By convention, bedded tuffs between ash-flow tuff members or formations are given unnamed formation status. Although lavas were encountered in drill holes USW G-1 (Spengler and others, 1981) and USW G-2 (Maldonado and Koether, 1983), none were cored in USW GU-3 and USW G-3.

The order of discussion will follow the descending stratigraphic order encountered in drilling. Detailed petrographic descriptions of this core in USW GU-3 and USW G-3 are given in appendix 2. Table 3 compares the drilled thicknesses of strata from a series of drill holes on Yucca Mountain. In addition, these stratigraphic units are plotted graphically on plate 1. The drilled thicknesses in appendix 2, table 3, and plate 1 have not been corrected for foliation and bed attitudes or for drill-hole deviation to provide true stratigraphic thicknesses.

The stratigraphic descriptions have two objectives. One objective is to describe the megascopic character of subdivisions observed in the USW GU-3 and USW G-3 core (appendix 2) and to correlate those subdivisions with drill holes USW G-1, USW G-2, and UE25b-1H (Lahoud and others, written commun., 1983). This sequence of megascopic subdivisions is numbered in the order cored, that is, in descending order. A different objective is to define a series of subdivisons that have petrologic significance by using phenocryst modal data, other petrographic thin-section data, and field data. These petrologic subdivisions will provide a framework for more detailed future petrologic investigations. The petrologic subdivisions are designed to identify the sequence of eruptive surges or pulses, and, therefore, are lettered in ascending order to match the eruptive order.

Table 3.--Drilled thicknesses of strata at drill holes USW GU-3 and USW G-3 compared with those at drill holes UE25b-1H, USW G-1, and USW G-2
[Leaders (----) indicate absence of stratigraphic units. Brackets indicate inclusive units.]

Stratigraphic units	USW GU-3 and and USW G-3 (m)	UE25b-1H[1] (m)	USW H-1[2] (m)	USW G-1[3] (m)	USW G-2[4] (m)
Tiva Canyon Member	113.9	27.4	27.4	---	68.6
Bedded tuff			1.5	---	6.0
Yucca Mountain Member	---	---	19.8	12.2	29.2
Bedded tuff		---	9.1	10.7	0.8
Bedded tuff (ash flow)		---	---	---	44.0
Bedded tuff	15.3	---	---	---	3.1
Pah Canyon Member	---	6.1	90.0	30.5	70.9
Bedded tuff		4.6		---	8.8
Topopah Spring Member	299.5	338.3	350.5	356.3	287.0
Bedded tuff	2.0	10.7	4.6	6.6	17.0
Tuffaceous beds of Calico Hills	[5]28.6	142.9	90.5	94.8	288.7
Bedded tuff	16.3		11.1	19.8	---
Prow Pass Member	131.5	152.9	134.7	107.1	176.1
Bedded tuff	4.0	1.7	6.1	6.4	10.2
Bullfrog Member	186.7	149.8	113.4	130.6	67.5
Bedded tuff	6.1	9.1	11.4	11.5	21.6
Tram Member	372.9	310.4	271.5	269.0	103.6
Bedded tuff	8.4	18.0	12.2	11.0	50.3
Lava (dacite) flow and flow breccia	---	---	111.6	110.3	[6]1.6
Bedded tuff	---	---	7.9	7.9	13.8
Lithic Ridge Tuff	303.8	---	265.2	297.2	185.3
Bedded tuff	3.0	---	8.5	5.9	7.3
Older ash flows and bedded tuff of USW G-1	[7]45.1	---	320.0	323.0	[8]8.8
Bedded tuff	---	---	---	---	5.5
Lava (rhyolitic) and flow breccia	---	---	---	---	101.0
Lava (quartz latitic) and flow breccia	---	---	---	---	113.6
Bedded and ash-flow tuff	---	---	---	---	10.1
Lava (dacitic) and flow breccia	---	---	---	---	65.5
Bedded tuff, conglomerate, and ash-flow tuff	---	---	---	---	17.4
Older tuffs of USW G-2	---	---	---	---	19.3

1 Unit thicknesses from Lahoud and others, written commun., 1983.
2 Unit thicknesses from Rush and others, written commun., 1983.
3 Unit thicknesses from R. W. Spengler and others, 1981.
4 Unit thicknesses from Maldonado and Koether, 1983.
5 Correlation with tuffaceous beds of Calico Hills is probable but somewhat indefinite.
6 Lava is rhyodacitic in USW G-2.
7 Unit a (ash-flow) present only.
8 Unit b (ash-flow) present; units a and c missing (Maldonado and Koether, 1983; Spengler and others, 1981).

Paintbrush Tuff

Drill holes USW GU-3 and USW G-3 were spudded into the resistant, moderately welded, quartz-latitic caprock of the uppermost member, the Tiva Canyon Member. An unknown thickness of moderately welded and nonwelded portions of the uppermost Tiva Canyon Member, protected in downdropped blocks bounded by normal faults at a few localities on Yucca Mountain, has been removed by erosion at the drill site. The eroded portion includes the moderately welded upper part of the light-brown caprock and overlying dark-brown caprock and the original uppermost envelope of partially to nonwelded tuff.

Neither the Yucca Mountain nor the Pah Canyon Members were recognized within the bedded tuffs interval between the Tiva Canyon and Topopah Spring Members; as no detailed petrographic examination in this bedded tuff interval was performed, thin nonwelded distal edges of these interjacent ash-flow tuffs may be present.

Tiva Canyon Member

The Tiva Canyon Member is a compositionally zoned, compound cooling, ash-flow tuff that ranges from a high-silica rhyolitic base to a quartz-latitic caprock (Byers and others, 1976). The upper part of the moderately welded portion of the caprock and the nonwelded upper portion are missing at the drill site; the lower portion of the moderately welded caprock and underlying tuffs of the Tiva Canyon Member were drilled in 113.9 m. The Tiva Canyon Member is petrographically distinguished by the mafic-rich (relatively abundant biotite, clinopyroxene, and orthopyroxene phenocrysts) caprock, by the sanidine-rich and hornblende-rich lower portion, and by the presence of sphene (6 to 19 grains per thin section) throughout the unit.

Field Subdivisions.--Field subdivisions of the Tiva Canyon Member have been created to facilitate mapping the zonations within this well-exposed ash-flow tuff at Yucca Mountain; Scott and others, 1983). Field mapping indicates that distinct mappable subdivisions occur in the region of the drill hole. These subdivisions in descending order, are the light-brown caprock, gray caprock, upper cliff, upper lithophysal, lower cliff, gray clinkstone, red clinkstone, lower lithophysal, hackly, columnar, and basal subdivisions (fig. 6). These subdivisions are distinguished on a basis of distinctive mineralogical, degassing, weathering, jointing, and welding features. For example, the hackly subdivision has distinctive uneven fractures that break the weathered surface into centimeter diameter rubble. Petrographic studies indicate that differences in weathering characteristics are related to differences in devitrification textures (Scott and others, 1983; Sharon Diehl, USGS, written commun., 1982). Numerous measured sections (fig. 2) within the Tiva Canyon Member establish the basic stratigraphic framework of the ash-flow tuff on Yucca Mountain (fig. 7).

Megascopic Subdivisions.--Megascopic study of the core recovered at USW GU-3 in the Tiva Canyon Member has identified seven subdivisions; in descending order, these subdivisions are (1) biotite-rich moderately welded, (2) lithophysal moderately welded, (3) non-lithophysal moderately welded, (4) lithophysal moderately to densely welded, (5) non-lithophysal moderately to densely welded, (6) vitrophyre moderately to densely welded, and (7)

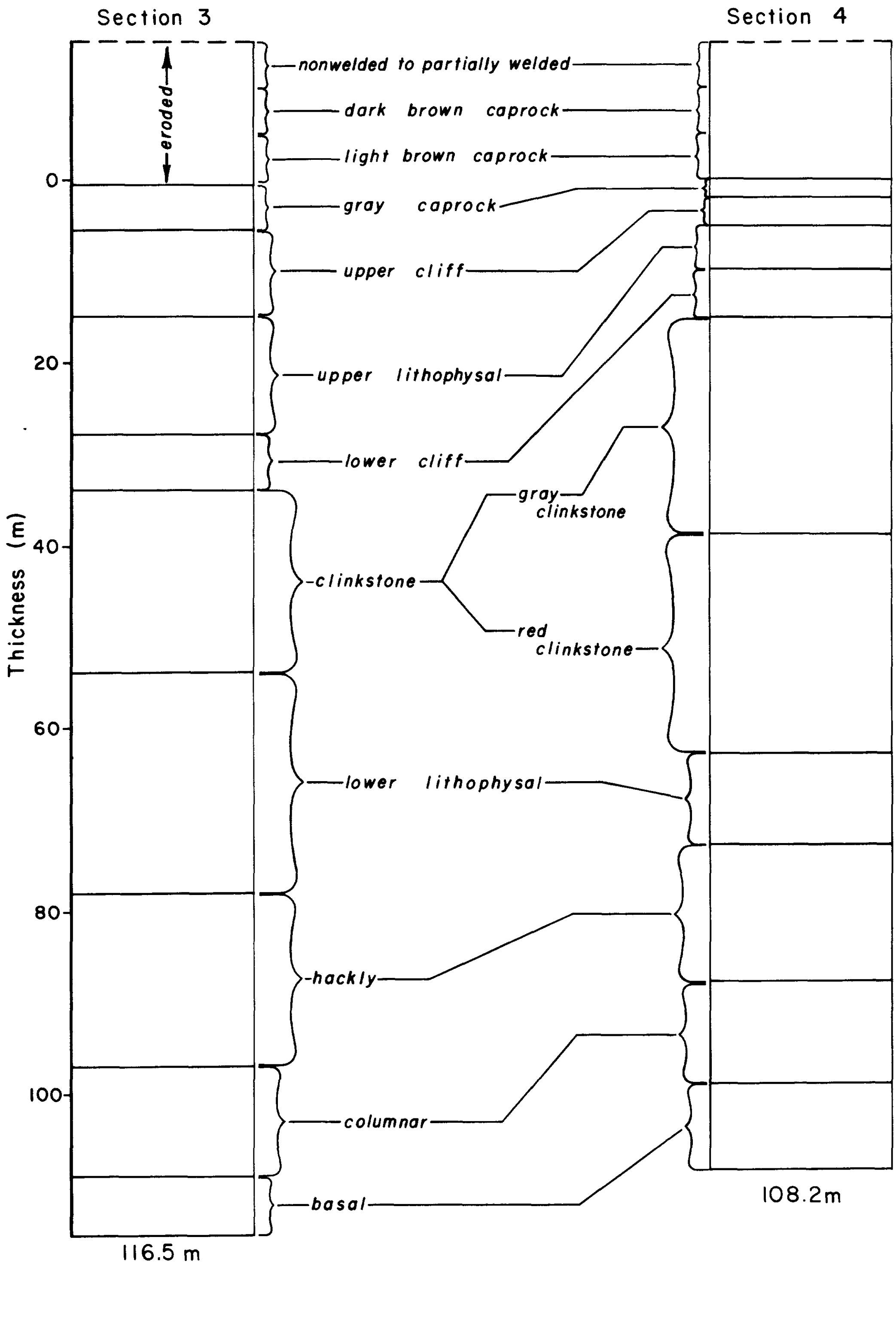

Figure 6.--Field subdivisions of the Tiva Canyon Member based on measured sections northwest (section 3) and southwest (section 4) of the USW GU-3 and USW G-3 drill holes. The thicknesses are indicated at the base of each section. Locations of measured sections are shown on figure 2.

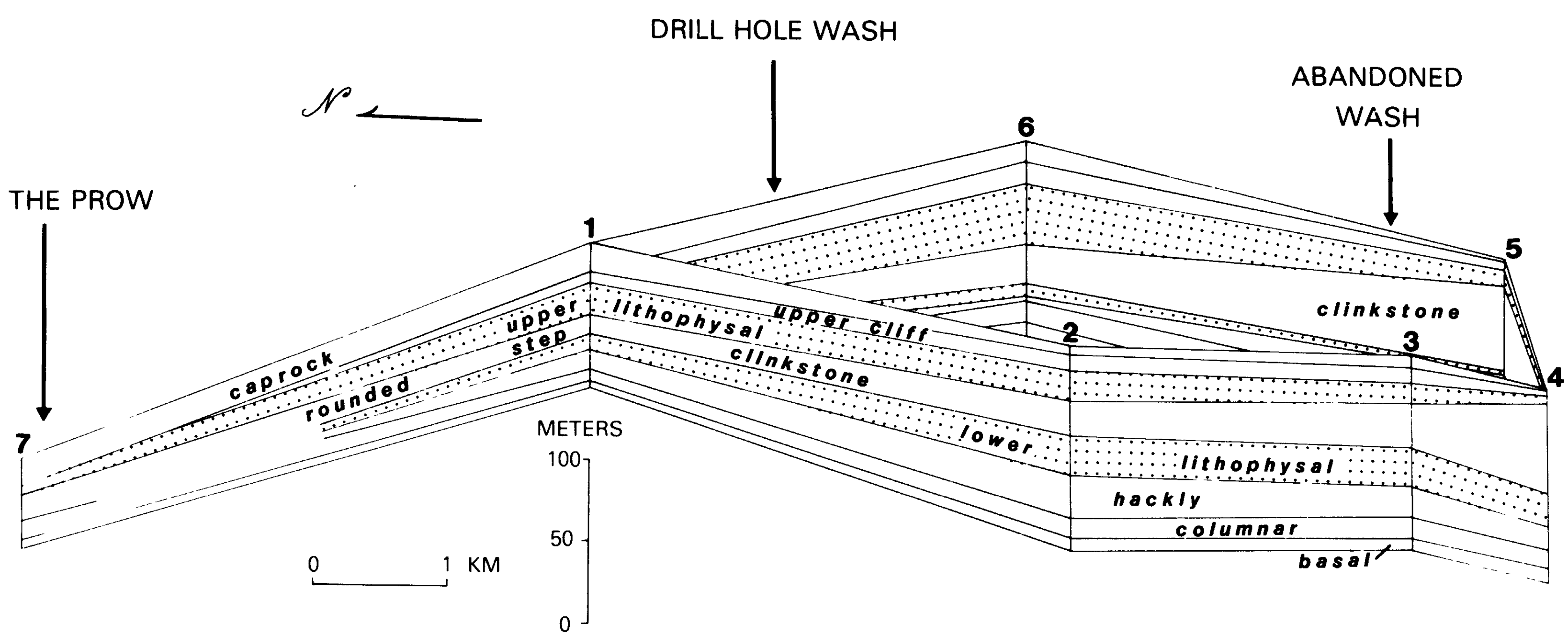

Figure 7.--Fence diagram of subdivisions mapped within the Tiva Canyon Member. Numbers represent measured sections shown on figure 2. Modified from Scott and others (1983).

moderately welded to nonwelded basal subdivisions (fig. 8). These subdivisions are based principally upon visual semiquantitative approximations of the degree of welding, the phenocryst content, and the lithophysal cavity content. Approximations of the degree of welding were made from estimates of the degree of flattening of pumice and the rock density. Detailed descriptions of each of these subdivisions are given in appendix 2. Because other drill holes on Yucca Mountain have penetrated little or none of the Tiva Canyon Member, no drill-hole correlation is presented here. Figure 8 compares the megascopic subdivisions to the percent of phenocrysts in the total phenocrysts, to the percent total phenocrysts in the whole rock, and to the degree of welding.

Petrologic Subdivisions.--Detailed thin section phenocryst modal analyses (table 4 and appendix 2), in conjunction with field and megascopic observations, provide the data to establish subdivisions that form a petrologic framework of the Tiva Canyon Member. The petrologic framework is designed to recognize evidence of separate eruptive surges that are assumed to have tapped different portions of the chemically zoned magma chamber.

In the case of the Tiva Canyon Member, there is fairly close correspondence between field megascopic and petrologic subdivisions, but significant differences do occur (fig. 9). The lithophysal subdivisions are readily correlated from field subdivisions to megascopic subdivisions and to petrologic subdivisions; the assumption is made that these represent especially volatile-rich eruptive surges. The columnar subdivision includes the thin vitrophyre in the core, but the columnar subdivision contains no distinctive petrographic features; only a crystal-rich parting at 104.04 m indicates that two separate eruptive events exist in this part of the Tiva Canyon Member. Although the lower cliff subdivision stands out as a mappable zone, it cannot be observed megascopically or petrographically in core samples. Some confusion exists in the correlation of the uppermost subdivisions; the more biotite-rich and phenocryst-rich gray caprock occurs from 0.5 m below the crest of the mountain to about 5 m below the crest at section 3 (fig. 6), but the same rock was apparently cored at about a 9.5-m depth at drill hole USW GU-3. The uncored portion where the surface casing was set (0-9.5 m) and the cement cored between 9.5 and 13.5 m prevented a resolution of this apparent mismatch.

The Tiva Canyon Member groundmass is unaltered to partially altered, with rare smectite and sparse calcite. The alteration studies of the groundmass, discussed here and elsewhere in this report, are largely the results of investigations by D. Bish (Los Alamos National Laboratory, written commun., 1982) and to a lesser degree by P. D. Blackmon (USGS, written commun., 1982).

Bedded Tuff

Only 15.3 m of nonwelded bedded tuffs occur between the Tiva Canyon Member and the Topopah Spring Member at USW GU-3 and USW G-3. At USW G-2, this interval is 162.8 m thick and consists of Yucca Mountain and Pah Canyon Members in addition to unnamed ash-flow tuffs and intervening bedded tuffs (table 3). The remnants of this thick section at USW GU-3 and USW G-3 probably contain nonwelded equivalents of these ash flows but they have not

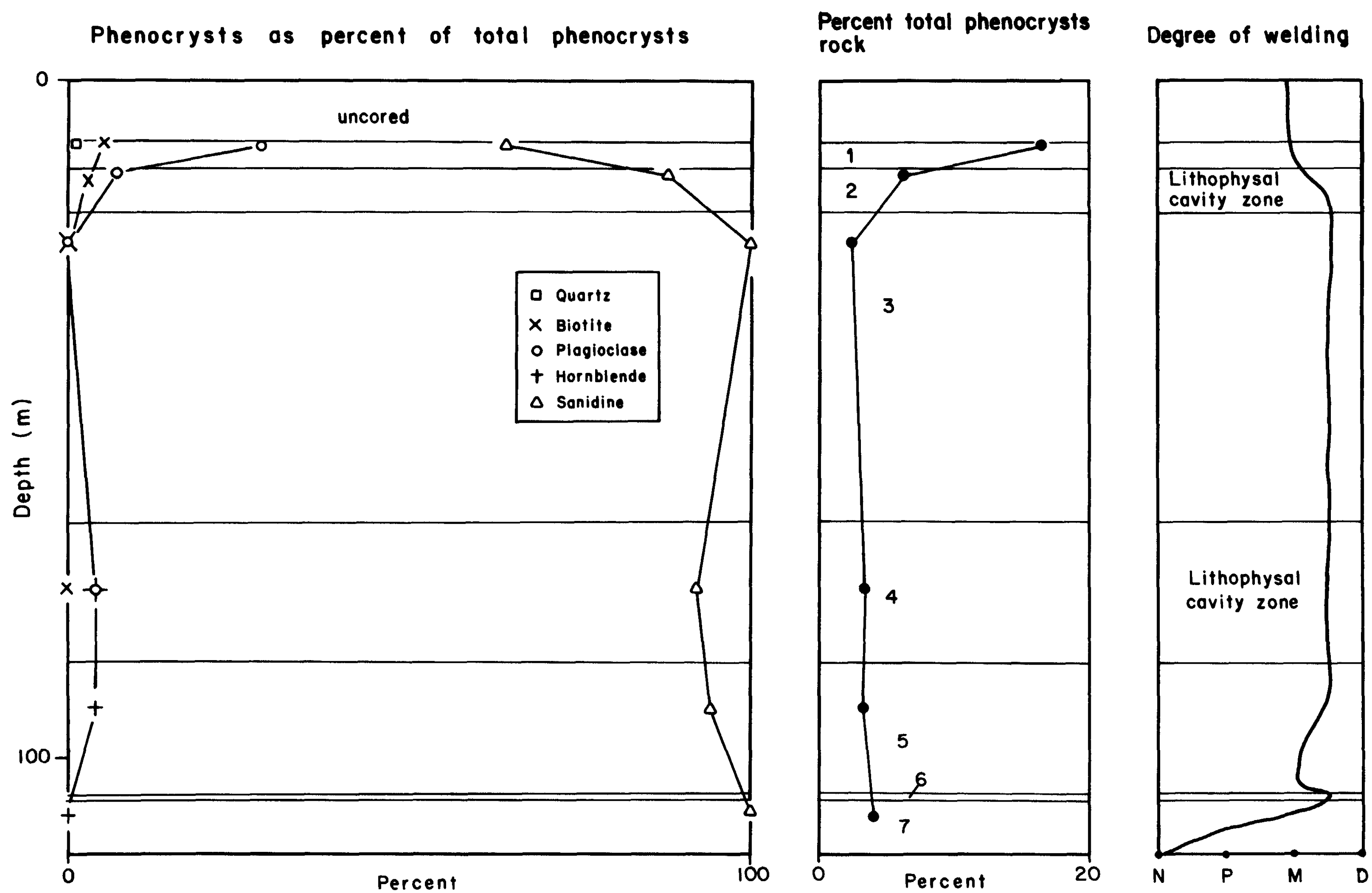

Figure 8.--Phenocrysts as percent of total phenocrysts, the percent total phenocrysts in the rock, and degree of welding of the Tiva Canyon Member cored at USW GU-3. N, P, M, and D refer to nonwelded, partially welded, moderately welded, and densely welded, respectively; as the estimate of degree of welding is subjective, a smooth curve is drawn to represent this subjectivity. The numbers in the central column are the megascopic subdivisions.

Table 4.--Modal analyses of thin sections from USW GU-3 and USW G-3 core

[Values are rounded off to the nearest whole percent except values less than 0.5 percent (tr) and between 0.5 and 1.0 percent (<1); tr=trace; nd=not determined, alt=altered or pseudomorphs. Q=Quartz, S=Sanidine, P=Plagioclase, B=Biotite, H=Hornblende, Cpx=Clinopyroxene, Opx=Orthopyroxene, Opq=Opaque Oxides, Z=Zircon, Ap=Apatite, Sph=Sphene, A or P=Allanite or Perrierite. Analyses by Robert B. Scott, USGS.]

Depth (m)	Unit[1]	Q	S	P	B	H	Cpx	Opx	Opq	Z	AP	Sph	A or P	Percent pheno-crysts in rock	Percent lithic fragments in rock	Total counts
		Percent of phenocrysts								Number of grains observed						
11.66	Tpc	1	64	28	5	0	<1	<1	1	25	15	6	0	16.1	<1	1,480
13.90	Tpc	0	88	7	3	1	tr	tr	1	44	5	10	9	6.2	<1	1,680
23.89	Tpc	0	100	tr	tr	tr	0	0	tr	12	0	9	0	2.5	tr	1,580
74.90	Tpc	0	92	4	tr	4	0	0	tr	22	0	19	5	3.4	<1	1,580
92.56	Tpc	0	94	0	0	4	0	2	tr	21	1	19	7	3.3	1	1,680
108.59	Tpc	0	100	0	0	tr	0	0	tr	13	4	10	6	4.0	<1	1,580
129.33	Tpt	1	56	38	4	tr	tr	0	1	15	5	0	14	5.9	3	1,680
131.27	Tpt	>1	47	43	4	0	2	0	3	32	17	0	19	17.0	<1	1,580
141.58	Tpt	0	65	24	4	0	2	0	5	38	18	0	16	13.7	<1	1,580
160.23	Tpt	0	70	23	3	0	tr	0	4	44	22	0	15	4.9	tr	1,580
193.03	Tpt	0	30	65	5	0	0	0	tr	13	9	0	2	1.2	<1	1,680
234.42	Tpt	tr	20	60	tr	0	0	0	20	7	1	0	1	0.3	<1	1,580
291.04	Tpt	0	5	90	5	0	0	0	tr	13	5	0	2	1.4	<1	1,480
344.52	Tpt	11	28	61	tr	0	0	0	tr	7	1	0	2	1.1	4	1,580
373.94	Tpt	8	38	42	4	0	0	0	8	18	5	0	4	1.5	2	1,630
397.00	Tpt	8	33	42	12	0	0	0	4	2	0	0	0	1.6	8	1,480
419.6	Tpt	25	35	35	tr	tr	0	0	tr	0	0	0	0	[2]22	0	nd
428.4	Tpt	25	25	40	10	0	0	0	tr	0	0	0	0	[2]8	0	nd

Table 4.--Modal analyses of thin sections of USW GU-3 and USW G-3 core--Continued

Depth (m)	Unit[1]	Q	S	P	B	H	Cpx	Opx	Opq	Z	AP	Sph	A or P	Percent pheno-crysts in rock	Percent lithic fragments in rock	Total counts
		Percent of phenocrysts								Number of grains observed						
430.69	Tht?	15	29	48	4	4	0	tr	tr	9	10	0	0	3.2	2	1,480
438.75	Tht?	24	38	35	3	tr	0	0	tr	13	14	0	2	2.1	2	1,580
456.68	Tht?	7	63	30	tr	0	0	0	tr	3	0	0	1	1.8	3/2?	1,480
479.02	Tcp	13	45	39	tr	tr?	0	3	tr	12	4	0	5	7.4	1	1,530
487.33	Tcp	16	30	48	1	tr	0	2	3	12	12	0	8	9.2	1	1,380
488.62	Tcp	6	38	53	1	0	0	1	tr	17	13	0	1	8.3	1	1,680
531.54	Tcp	15	30	52	1.5	0	0	tr	1.5	6	10	0	1	10.7	2	1,280
571.12	Tcp	7	35	54	1	tr	0	1	2	10	23	0	1	9.3	3	1,480
605.40	Tcp	8	46	42	tr	tr	0	1.5	2	10	6	0	1	8.8	2	1,480
615.33	Tcb	19	29	46	3	tr	0	0	3	18	17	0	3	8.8	>1	1,580
631.04	Tcb	16	35	43	4	1	0	0	1	10	6	0	0	11.6	<1	1,530
651.78	Tcb	21	34	39	4	1	0	0	1	20	37	2	3	17.6	<1	1,630
664.85	Tcb	17	32	45	3	1	0	0	2	30	43	0	1	17.5	2	1,380
722.22	Tcb	19	35	41	3	tr	0	0	2	21	25	1	2	19.3	<1	1,580
752.00	Tcb	19	32	43	3	2	0	0	1	36	64	0	4	21.9	<1	1,655
785.61	Tcb	10	33	49	4	1	0	0	2	8	24	1	2	9.0	3	1,480
800.77	Tct	18	15	58	8	0.5	0	0	0.5	20	72	2	3	9.4	1	1,630
809.75	Tct	24	29	41	6	0	0	0	tr	8	29	1	1	11.3	2	1,580
822.60	Tct	28	24	45	2	0	0	0	0.5	20	88	1	0	12.6	4	1,630

Table 4.--Modal analyses of thin sections of USW GU-3 and USW G-3 core--Continued

Depth (m)	Unit[1]	Q	S	P	B	H	Cpx	Opx	Opq	Z	AP	Sph	A or P	Percent pheno-crysts in rock	Percent lithic fragments in rock	Total counts
		Percent of phenocrysts								Number of grains observed						
829.94	Tct	33	30	30	5	0	0	0	2	23	62	0	0	11.8	2	1,630
853.88	Tct	31	32	31	6	tr	0	0	tr	25	59	4	0	12.3	<1	1,580
873.82	Tct	31	31	31	6	tr	0	0	1	14	64	1	2	10.1	2	1,630
888.33	Tct	35	31	27	6	tr	0	0	1	22	44	3	2	15.5	3	1,680
928.22	Tct	28	29	35	6	0	0	0	2	13	98	0	0	13.2	13	1,680
936.38	Tct	30	32	32	4	tr	0	0	2	11	70	2	0	15.2	2	1,680
948.90	Tct	36	26	34	3	0.5	0	0	0.5	25	94	0	0	15.0	14	1,655
964.47	Tct	28	30	37	2	tr	0	0	3	18	43	0	0	13.8	20	1,580
983.28	Tct	32	33	25	6	0.5	0	0	3	13	78	0	0	13.2	18	1,680
1,019.14	Tct	44	23	21	4	0	0	0	3	4	27	0	0	11.2	19	1,680
1,049.00	Tct	36	23	36	2	0	0	0	3	5	38	2	0	11.0	28	1,680
1,059.30	Tct	21	22	44	5	tr	0	0	8	10	59	1	0	8.6	25	1,530
1,122.49	Tct	45	14	32	6	0	0	0	3	10	8	0	0	9.2	34	1,630
1,137.00	Tct	32	22	38	5	0	0	0	2	6	4	0	0	8.0	31	1,580
1,145.74	Tct	24	24	42	5	1	0	0	4	6	0	1	0	9.0	28	1,680
1,183.57	Tlr	2	13	67	13	2	1	0	3	19	58	6	2	22.0	3	1,580
1,221.76	Tlr	2	22	65	7	1	0	0	3	20	80	11	4	11.5	16	1,600
1,231.08	Tlr	7	30	53	4	2	0	0	4	20	77	9	3	8.5	18	1,580
1,264.81	Tlr	11	30	50	4	0	0	0	5	26	84	8	1	8.0	16	1,630

Table 4.--Modal analyses of thin sections of USW GU-3 and USW G-3 Core--Continued

Depth (m)	Unit[1]	Q	S	P	B	H	Cpx	Opx	Opq	Z	AP	Sph	A or P	Percent pheno-crysts in rock	Percent lithic fragments in rock	Total counts
		Percent of phenocrysts								Number of grains observed						
1,292.50	Tlr	10	32	52	3	0	0	0	2	14	38	7	0	8.0	25	1,200
1,307.10	Tlr	5	47	44	1	0	0	0	3	11	30	1	3	10.6	28	1,430
1,337.50	Tlr	6	37	50	4	0	0	0	3	10	42	alt	1	9.8	21	1,580
1,348.13	Tlr	3	45	45	4	0	0	0	2	20	45	alt	2	9.6	17	1,630
1,352.76	Tlr	6	34	50	6	0	0	0	3	13	26	13	3	6.6	30	1,630
1,392.47	Tlr	4	35	58	2	0	0	0	1	8	28	alt	2	11.2	20	1,530
1,429.18	Tlr	10	38	49	2	0	0	0	1	11	40	alt	1	8.8	20	1,600
1,435.22	Tlr	8	35	52	4	0	0	0	1	10	41	alt	0	9.9	22	1,450
1,449.84	Tlr	6	27	59	3	0	0	0	5	5	55	alt	1	11.7	23	1,630
1,474.99	Tlr	10	27	57	3	0	0	0	3	16	52	1	4	10.0	15	1,655
1,495.44	Tt	29	35	34	2	0	0	0	1	20	69	0	2	18.3	2	1,680
1,528.36	Tt	28	33	33	4	0	0	0	2	19	50	0	2	16.2	2	1,650

[1]Symbols for units are the same as given on plate 1.

[2]Washed samples to concentrate rare phenocrysts in nonwelded ash by removing fines <0.5 mm; impregnated with epoxy for counting; very poor counting statistics.

[3]Non-cognate lithics only.

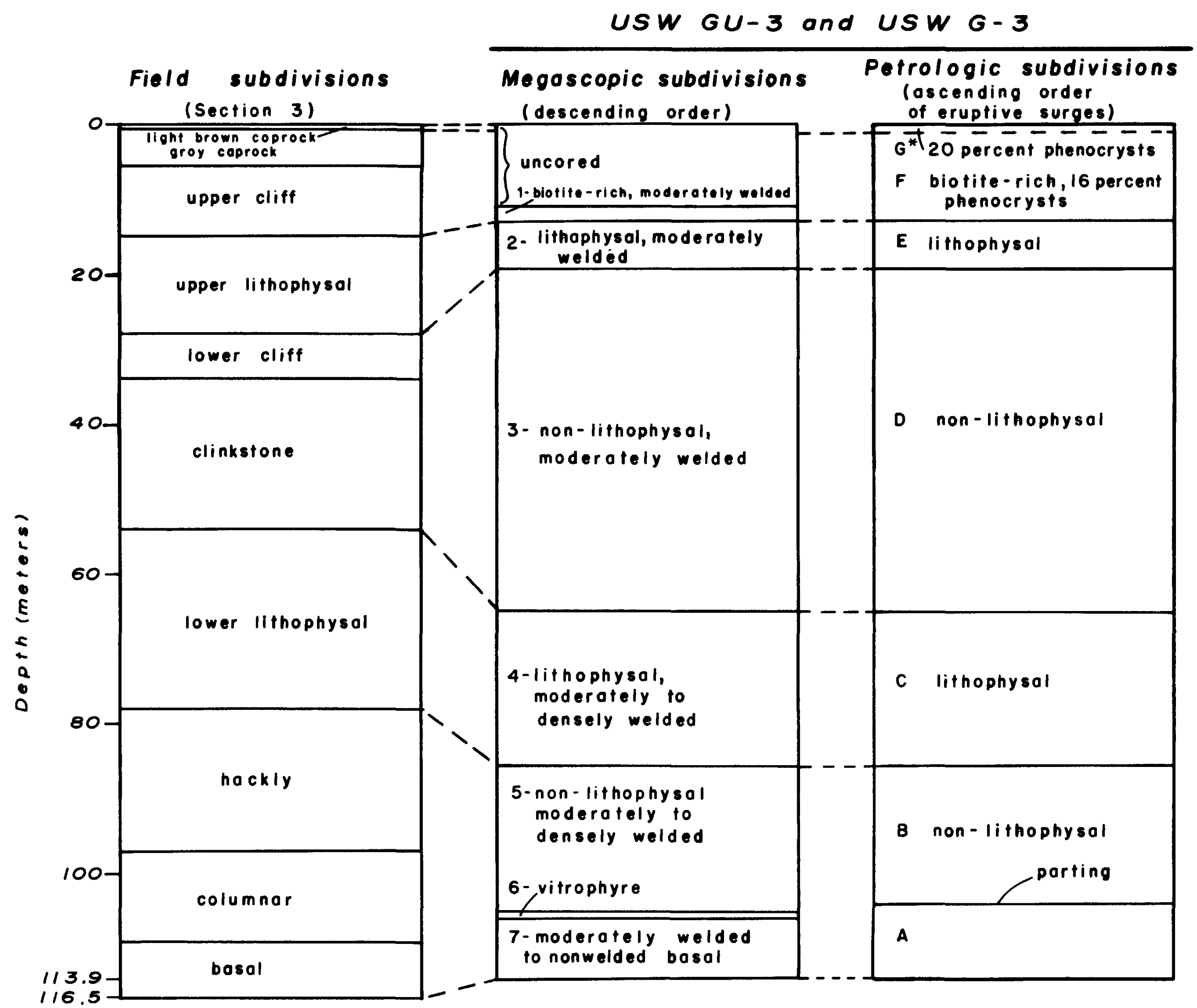

Figure 9.--Comparison of field, megascopic, and petrologic subdivisions of the Tiva Canyon Member at USW GU-3 and USW G-3 and immediate vicinity. G* refers to thin-section data obtained from measured section 3 in the light-brown caprock. At other localities farther north on Yucca Mountain, where higher units were not eroded or were not straigraphically terminated, a layer of distinctive and abundant 10 to 30 cm long white pumice lenses and a dark-brown portion of the caprock constitute surges H and I, respectively, not shown on this figure.

been recognized. Included within these bedded tuffs are abundant layers of pyroclastic-fall tuff, less common layers of nonwelded ash-flow tuff, and rare layers of tuff reworked by fluvial or aeolian processes. For the most part, these tuffs are vitric; however, several distinctive moderate-red, pale-purple, pale-red, and grayish-red layers have been partially altered to sparse to common smectite. These layers are widespread on Yucca Mountain and occur above the Yucca Mountain Member where the member is recognized.

Paintbrush Tuff--continued

Topopah Spring Member

The Topopah Spring Member also is a compositionally zoned, compound cooling unit that varies from a high-silica rhyolitic base to a quartz-latitic caprock (Lipman and others, 1966). Petrographically, the Topopah Spring Member is characterized by a mafic-rich (relatively abundant biotite and clinopyroxene phenocrysts) and perrierite- or allanite-rich (14-19 grains per thin section) caprock, by plagioclase/sanidine ratios greater than one, by a near absence of hornblende in the lower portion, and by an absence of sphene throughout (appendix 2 and table 4).

Megascopic Subdivisions.--Within the 300 m of ash-flow tuff cored at USW GU-3, 12 subdivisions are recognized from megascopic study of core. These subdivisions, in descending order, are (1) biotite-rich nonwelded to moderately welded, (2) biotite- and clinopyroxene-rich moderately welded vitrophyre, (3) biotite- and clinopyroxene-rich moderately welded, (4) less mafic-rich moderately welded, (5) abundant lithophysal moderately welded, (6) rare lithophysal moderately to densely welded, (7) sparse lithophysal moderately to densely welded, (8) rare lithophysal moderately to densely welded, (9) highly mottled moderately to densely welded, (10) densely welded vitrophyre, (11) moderately welded to partially welded, and (12) basal nonwelded subdivisions (fig. 10).

Aside from outstanding changes in degree of welding, state of devitrification, and abundance of mafic phases, these units were recognized by differences in the abundances of lithophysal cavities. Figure 11a shows the results of direct measure of void spaces along one section of the core from the Topopah Spring Member of USW GU-3 compiled by Eric Larsen of Fenix & Scisson (written communication); these data produce the same subdivisions seen in field relationships and cores expressed by visual estimates in figure 11b (Maldonado and Koether, 1983; Spengler and others, 1981; Scott and others, 1983).

Petrologic Subdivisions.--A total of at least nine petrologic subdivisions, or probable individual eruptive surges, of the Topopah Spring Member are proposed at USW GU-3 and USW G-3. The lowermost, A, is based upon a high quartz content (as much as 25 percent). Surge B has intermediate

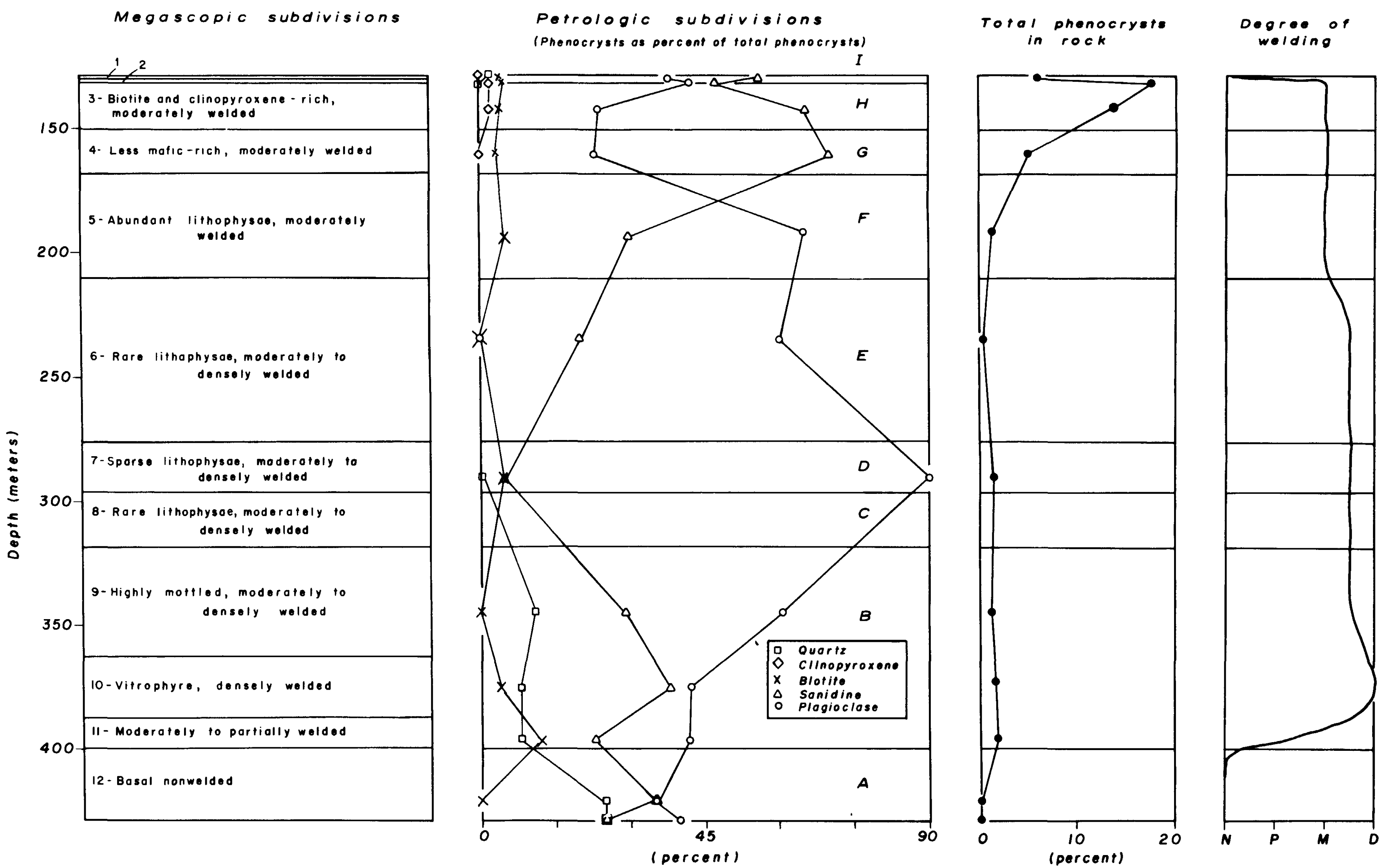

Figure 10.--Comparison of megascopic subdivisions with petrologic subdivisions of the Topopah Spring Member found in core from drill hole USW GU-3. The left column lists the megascopic subdivisions in descending order, based largely upon changes in degree of welding, lithophysal abundance, and mafic phenocryst abundance. Subdivision 1 is biotite-rich, nonwelded to moderately welded; subdivision 2 is biotite- and clinopyroxene-rich vitrophyre, moderately welded. Petrologic subdivisions (A through I) to the right are based upon changes in phenocryst ratios, phenocryst abundance independent of degree of welding, and abundance of lithophysae. N, P, M, and D on the scale at the base of the right column refer to the degree of welding: nonwelded, partially welded, moderately welded, and densely welded, respectively.

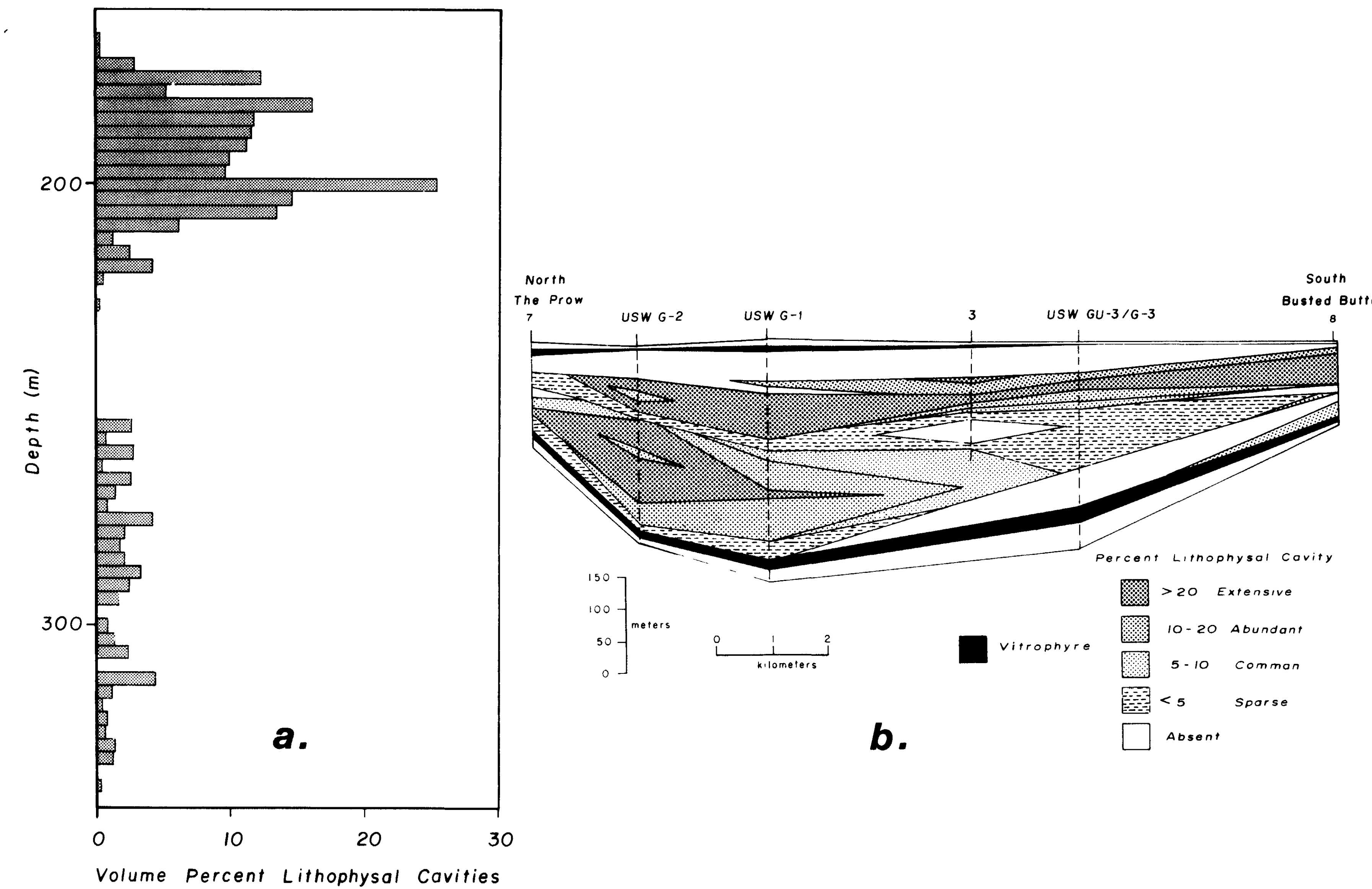

Figure 11.--Lithophysal cavity volume percent zonation in the Topopah Spring Member. (a) Lithophysal cavity volume percent in core from drill hole USW GU-3. (b) Correlation of lithophysal cavity abundances between drill holes USW G-2, USW G-1, USW GU-3, and the measured sections 3, 7, and 8 (fig. 2). The percent lithophysal cavities were made by visual estimation. (Adapted from Scott and others, 1983.)

quartz contents (8 to 11 percent). Surges C, D, E, and F display distinctly different abundances of lithophysal cavities and are assumed to represent more volatile-rich portions of the magma chamber. The upper three surges, G, H, and I, show progressive increases in crystal content from 5 to 17 percent. Although the upper two units have significantly greater clinopyroxene contents, the abundance of biotite relative to total phenocrysts does not seem to change appreciably; thus the increase in total phenocrysts content gives the caprock of the Topopah Spring Member the appearance of being biotite rich. These petrologic subdivisions are very similar to those reported by Lipman and others (1966).

The lower portions (vitrophyre to base) of the Topopah Spring Member are in part unaltered and in part have minor alteration to rare to sparse smectite. In the mottled subdivision (appendix 2), immediately above the vitrophyre, the groundmass is partially altered to a trace of smectite. At the base of the mottled subdivision, however, an interval is locally altered to extensive smectite with 5-15 percent illite mixed layers, heulandite/clinoptilolite, analcime, tridymite, cristobalite, and siderite. This localized alteration seems to be associated with the devitrification reaction formed at the top of the vitrophyre. Alteration of the groundmass above this zone is limited to rare smectite and sparse calcite.

Bedded Tuff

A vitric bedded tuff zone, only 2 m thick, exists between the overlying nonwelded ash-flow tuff of the Topopah Spring Member and the underlying nonwelded ash-flow tuff tentatively assigned to the tuffaceous beds of Calico Hills. This bedded tuff consists largely of poorly indurated vitric pyroclastic fall debris and has no indication of significant alteration to clays or zeolites.

Tuffaceous Beds of Calico Hills

Between the Topopah Spring Member of the Paintbrush Tuff and the Prow Pass Member of the Crater Flat Tuff at Yucca Mountain, a series of rhyolitic nonwelded ash-flow tuffs, lava flows, autobrecciated lava flows, and reworked tuffaceous beds are informally assigned to the tuffaceous beds of Calico Hills. Only the nonwelded ash-flow tuffs and thin bedded tuffs are found south of Yucca Wash. Tuffs within this interval at USW G-2 and USW G-1 are zeolitized, but core at USW GU-3 is vitric.

These tuffs at USW GU-3 are characterized by having an uppermost part that is relatively rich in mafic phenocrysts (8 percent of the phenocrysts consist of biotite, hornblende, orthopyroxene, and opaque phases with plagioclase as the dominant feldspar), a middle part that has an intermediate phenocryst assemblage, and a lowest part that is relatively rich in felsic phenocrysts (only a trace of biotite and orthopyroxene is present, and sanidine is the dominant feldspar) (fig. 12). Also, the lowest part of these tuffs contains larger and more abundant lithic fragments than do the two upper parts. This sequence is probably made up of at least three separate magmatic pulses that tapped different portions of one chemically zoned magma chamber.

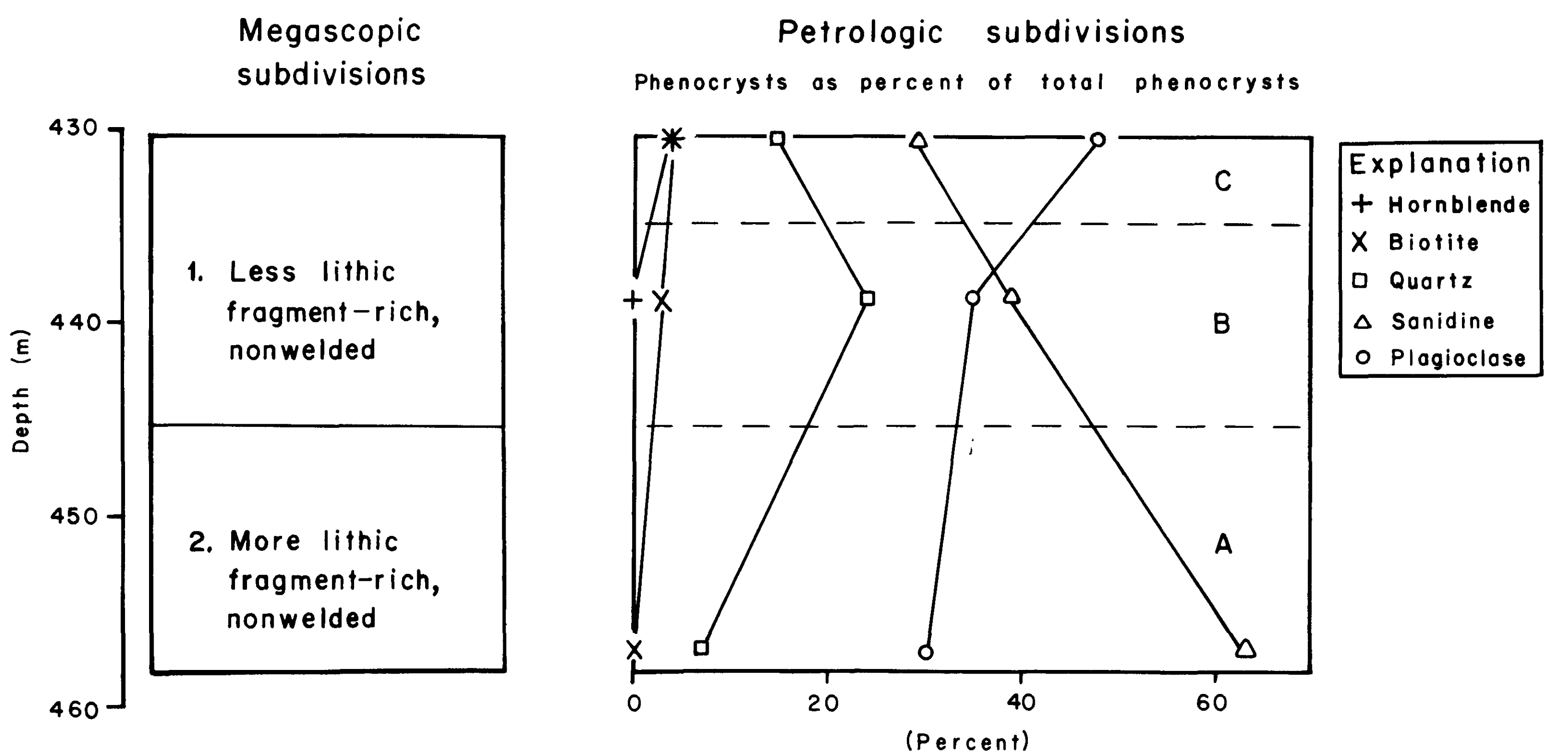

Figure 12.--Comparison of petrologic subdivisions with megascopic subdivisions in nonwelded tuffs tentatively assigned to the tuffaceous beds of Calico Hills from drill hole USW GU-3.

Several lines of evidence suggest that the sequence of tuffs found in core of drill hole USW GU-3 may differ from the tuffaceous beds of Calico Hills at USW G-2 and USW G-1. (1) The hornblende and orthopyroxene found in the upper part of USW GU-3 are not found in other cores. (2) In USW GU-3, the upper part of these tuffs is characterized by a higher phenocryst content, a higher mafic phenocryst content, and a plagioclase/sanidine ratio greater than one, and the lower part of these tuffs are characterized by a lower phenocryst content, a very low mafic phenocryst content, and a plagioclase/sanidine ratio less than one. This sequence of changes in phenocryst ratios is the inverse of that observed at USW G-2 (Maldonado, and Koether, 1983). (3) The tuffaceous beds of Calico Hills thin from 290 m at drill hole USW G-2 to 95 m at USW G-1 over a distance of only 2.5 km. At USW GU-3, almost 4.5 km farther south, these tuffaceous beds are less than 30 m thick, close to the distal ends of these tuffs.

D. L. Broxton of Los Alamos National Laboratory (written commun., 1983) finds evidence to support the conclusion that the tuffs at USW GU-3 are near the distal end of the tuffaceous beds of Calico Hills. The petrographic character of the lowest ash-flow tuff at USW G-2 and USW G-1 is very similar to the ash-fall bedded tuff found beneath the lowest ash-flow tuff of the tuffaceous beds of Calico Hills at USW GU-3. Broxton records 52 percent plagioclase, 30 percent quartz, 12 percent sanidine, 3.2 percent biotite, 1.5 percent hornblende, 1.3 percent opaque oxides, 0.3 percent orthopyroxene, and 0.1 percent clinopyroxene in the ash-fall tuff at USW GU-3 comapred to 51 percent plagioclase, 25 percent quartz, 18 percent sanidine, and 6.6 percent biotite in the lowest ash-flow tuff at USW G-2 (Maldonado and Koether, 1983). Also Broxton emphasizes that the sanidines in these intervals are similar in composition: Those from core of USW G-2 average Or_{73}, those from USW GU-3 average OR_{72}). Biotite Mg/Mg+Fe) ratios are indistinguishable, averaging 0.44 in both locations. Although phenocryst ratios in the core from USW GU-3 are distinctive, Broxton found their compositions to be more similar to phenocryst compositions in the tuffaceous beds of Calico Hills of other cores than to those of the overlying Topopah Spring Member or the underlying Prow Pass Member. We conclude that at distal ends of ash-flow sequences, significant phenocryst ratio variations may occur, either by phenocryst fractionation by flow mechanisms or by the presence of ash-flow not representative of the sequence closer to the source. Correlation within the tuffaceous beds of the Calico Hills remains problematic and more work is necessary to define the tuffaceous beds from this interval, both at drill holes USW GU-3 and USW G-3 and elsewhere.

A fundamental difference in style and degree of alteration exists between the tuffaceous beds at USW GU-3 and the zeolitic tuffs found in cores and exposures farther north in Yucca Mountain. The tuffs in cores from drill hole USW GU-3 are essentially vitric, unaltered to partially altered, with only a trace of smectite and sparse clinoptilolite. This interval in exposures and drill holes in northern Yucca Mountain is highly zeolitic. The difference in degree of alteration is probably related to the depth of the saturated zone, the tuffaceous beds in the southern portion of Yucca Mountain near drill holes USW GU-3 and USW G-3 are about 300 m above the saturated zone.

Bedded Tuff

Between the lowest nonwelded ash-flow tuff assigned to the tuffaceous beds of Calico Hills and the Prow Pass Member of the Crater Flat Tuff are 13 m of pyroclastic-fall tuff cored at USW GU-3. As discussed above, these bedded tuffs have phenocryst compositions and ratios very similar to those of the lowermost ash-flow tuff assigned to the Calico Hills sequence at drill holes USW G-1 and USW G-2. These bedded tuffs represent the distal margin of the lowermost ash-flow tuff of the Calico Hills sequence. No observed sedimentary structures indicate fluvial or aeolian reworking of this series of pyroclastic beds that have grain sizes that range from ash to lapilli pumice. These beds are also largely vitric and are only altered to sparse smectite and rare to sparse clinoptilolite.

Crater Flat Tuff

The three members of the Crater Flat Tuff, the Prow Pass Member, the Bullfrog Member, and the Tram Member (Carr and others, in press) constitute a 700-m-thick sequence, over one-third of the ash-flow tuffs cored at drill hole USW GU-3.

Prow Pass Member

The Prow Pass Member in core from USW GU-3 appears to be a slightly chemically zoned, simple cooling unit. However, the presence of a thin ash-fall tuff in core from USW G-2 in the Prow Pass interval requires that the Prow Pass Member be a compound cooling unit, at least locally, even if these divisions do not occur everywhere (Maldonado and Koether, 1983). Pale-reddish-brown mudstone lithic fragments, phenocrysts of orthopyroxene, and highly embayed quartz distinguish the member petrographically. Quartz is subordinate to the subequal feldspars.

Megascopic Subdivisions.--Only three subdivisions can be distinguished megascopically in the 131.5-m-thick Prow Pass Member at drill hole USW GU-3. These consist of (1) a nonwelded upper unit, (2) a nonwelded to partially welded middle unit, and (3) a relatively lithic-fragment-rich lower unit (fig. 13). Minor trends in the total phenocryst abundance reflect the minor changes in degree of welding.

Petrologic Subdivisions.--The three petrologic subdivisions compare very closely to the three megascopic subdivisions. The lowest eruptive surge (A; fig. 13) is also distinguished by its distinctively higher lithic fragment content (2-3 percent), the middle eruptive surge (B) has a lower lithic fragment content (1 percent) and a low orthopyroxene content (1 percent), and the upper eruptive surge (C) contains significantly higher orthopyroxene content (2-3 percent). These three petrologic subdivisions seem to correlate well with the three subdivisions recognized in core from USW G-2 (Maldonado, and Koether, 1983). Only the thin ash-fall tuff present at USW G-2 is not observed between the lower and middle subdivisions of USW GU-3.

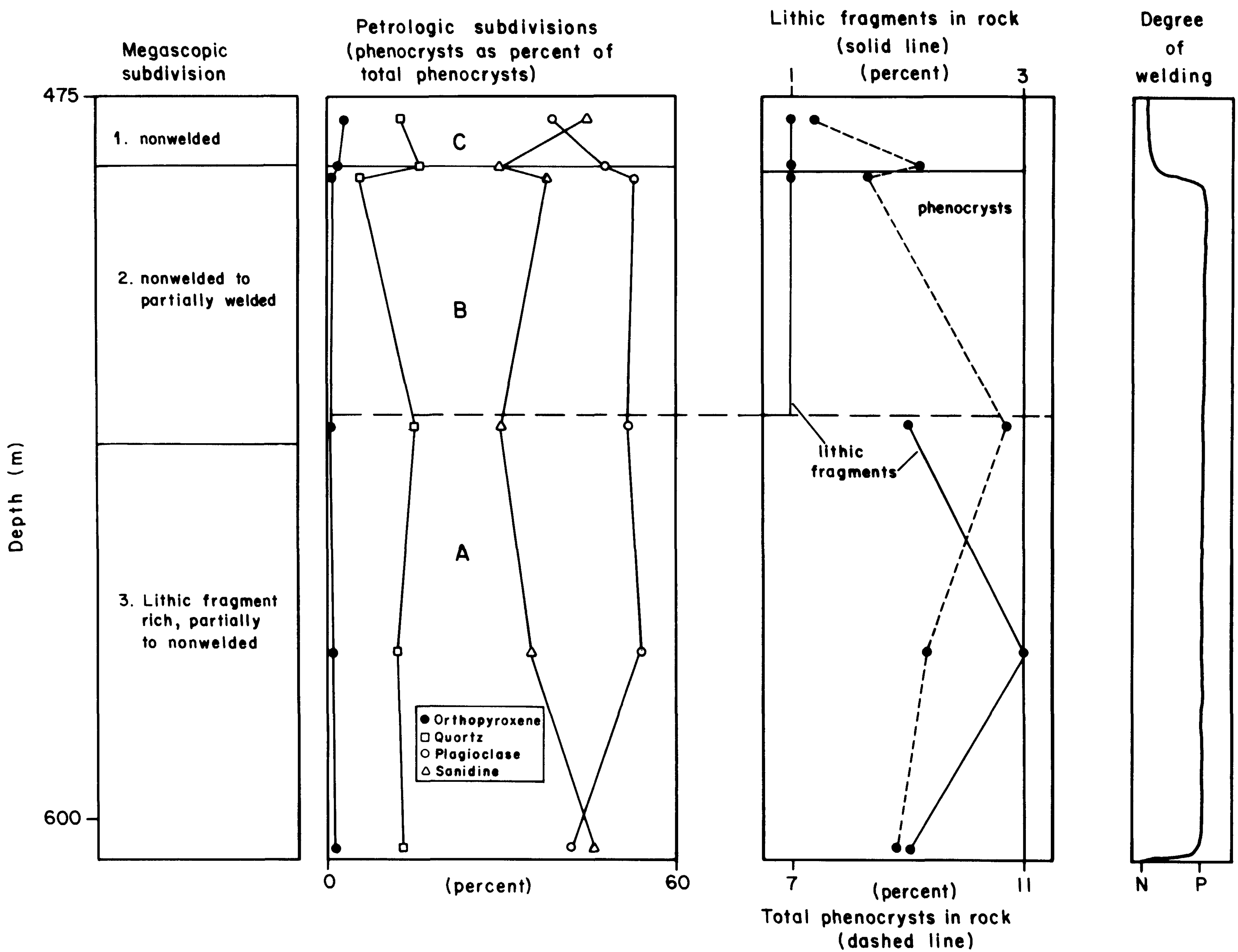

Figure 13.--Megascopic and petrologic subdivisions of the Prow Pass Member of the Crater Flat Tuff found in core from drill hole USW GU-3. N = nonwelded, P = partially welded.

Alteration in the Prow Pass Member is largely limited to rare to sparse smectite and calcite and to common to extensive clinoptilolite, particularly near the nonwelded basal portion. For the most part, the upper portion remains in a relatively unaltered vitric state.

Bedded Tuff

Below the Prow Pass Member of the Crater Flat Tuff in core from USW GU-3 is a 4-m-thick bedded tuff that consists both of layers of distinctly cross-bedded and channel-fill structures indicative of fluvial reworking and of layers of more massive pyroclastic-fall debris. No appreciable rounding of pumice fragments occurs in the fluvial layers; probably transport distances were minimal. These tuffs are partially altered to rare to sparse smectite and abundant to extensive clinoptilolite.

Crater Flat Tuff--continued

Bullfrog Member

At drill hole USW GU-3, the Bullfrog Member consists of two distinct cooling units. An upper 165-m-thick unit is separated from a lower 20-m-thick unit by a meter of bedded tuff, representing a complete cooling break. Laterally, this double cooling unit configuration probably grades into a compound cooling unit as the bedded tuff interval is not recorded elsewhere in Yucca Mountain. Petrographically, the Bullfrog Member is characterized by subequal amounts of feldspar, slightly subordinate quartz, relatively abundant biotite, and minor but persistent, large (commonly 2 mm long) hornblende phenocrysts. No evidence suggests that either of the two individual cooling units at USW GU-3 are compound, and no evidence suggests that the thick upper cooling unit of the Bullfrog Member was produced from a chemically zoned magma chamber.

Megascopic Subdivisions.--The upper cooling unit of the Bullfrog Member is broken into 7 megascopic subdivisions and the lower cooling unit into four megascopic subdivisions (fig. 14). Subdivisions of the upper cooling unit, in descending order, are (1) lithic fragment-poor partially welded, (2) biotite and hornblende-rich, partially welded, (3) biotite and hornblende-rich, moderately welded, (4) moderately welded to moderately to densely welded, (5) mottled moderately to densely welded, (6) moderately welded, and (7) moderately to partially welded. The lower cooling unit is subdivided only on the basis of degree of welding and contains, in descending order, (8) nonwelded, (9) partially welded, (10) moderately welded, and (11) partially welded subdivisions. The bedded tuff that occurs between the subunits F and B is well indurated but nonwelded and contains well sorted ash- and pumice-fall tuff and unsorted ash-flow(?) tuff. Slight flattening of pumice in these layers may be related to alignment of elongate pumice fragments or by deformation during argillization and zeolitization.

Petrologic Subdivisions.--Only one petrologic subdivision can be recognized within either the upper cooling unit or within the lower cooling unit of the Bullfrog Member. The differences in the abundance of phenocrysts seem to reflect merely changes in degrees of welding. Also, volume ratios of sanidine to total feldspars range only between 0.39 and 0.47, and the volume ratios of quartz to total feldspar range only from 0.21 to 0.29, except for

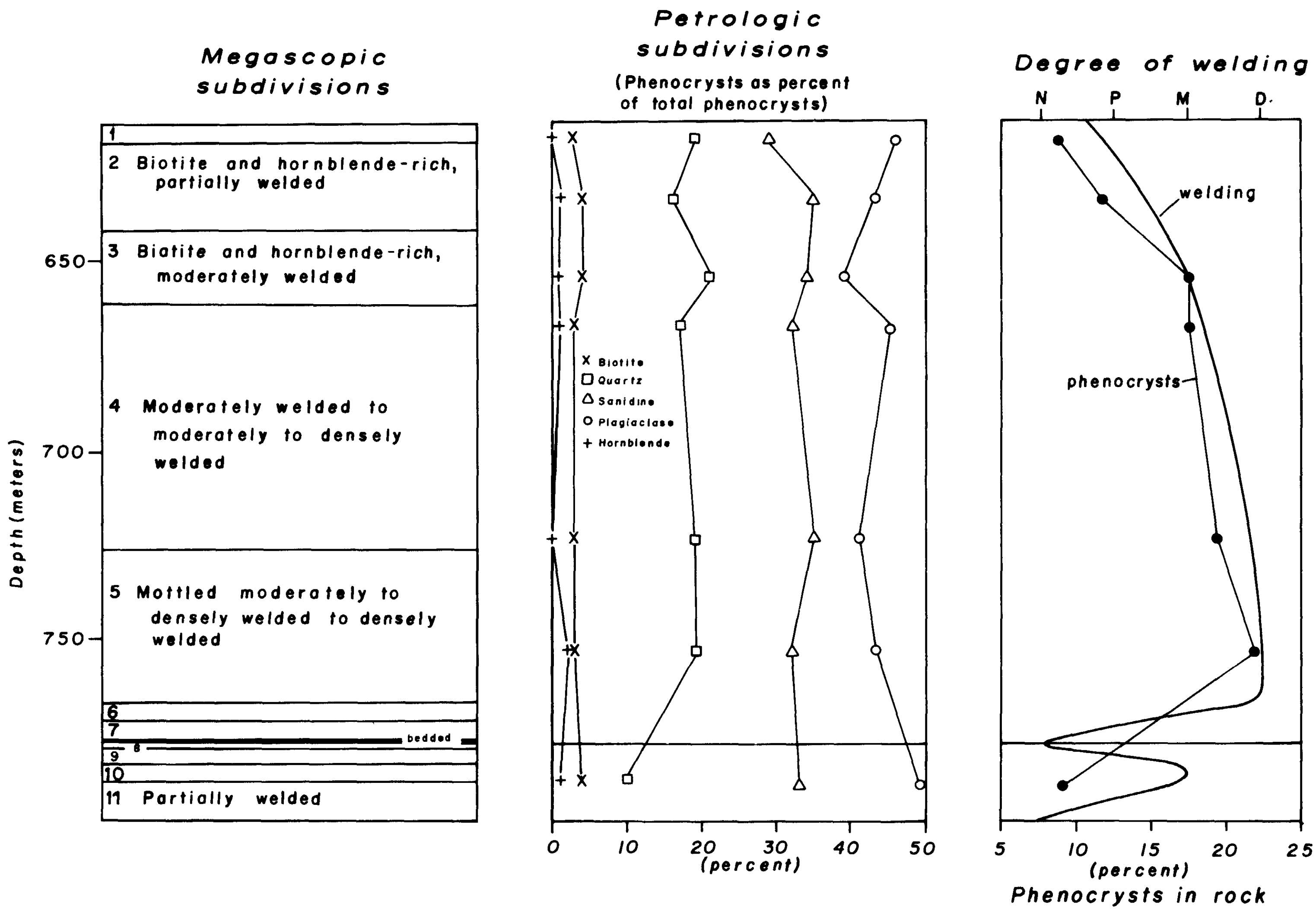

Figure 14.--Megascopic and petrologic subdivisions of the Bullfrog Member of the Crater Flat Tuff found in core from drill hole USW GU-3. Petrologically distinctive ash-flow tuffs are found only in eruptive surges A and B. N, P, M, and D refer to nonwelded, partially welded, moderately welded, and densely welded, respectively. Megascopic subdivisions are described in the text.

the lowermost cooling unit that has a ratio of 0.12. Thus only two magmatic pulses can be recognized from these data, distinguished on a basis of the meter-thick well-indurated pumice-rich and ash-rich pyroclastic-fall layers, and the low quartz to total feldspar ratio.

Within the upper cooling unit, the more highly welded part is relatively unaltered, with alteration limited to rare to sparse smectite. However, the bedded tuff below the upper cooling unit contains common to abundant smectite and common clinoptilolite/mordenite, and the less welded lower cooling unit contains abundant clinoptilolite in addition to rare to sparse smectite. The increase in zeolitization in nonwelded and partially welded tuffs at this depth, approximately 775 m, may be related to the proximity of the static water level, which is approximately 750 m deep, based on extrapolation from the nearby hydrologic drill hole, USW H-3 (William Thordarson, USGS, oral commun., 1983).

Bedded Tuff

Slightly more than 6 m of bedded tuff separate the Bullfrog Member from the Tram Member in drill hole USW GU-3. These beds include both reworked tuffs and pyroclastic-fall tuff. Some of the pumice fragments in reworked intervals appear to be slightly rounded. These tuffs are partially altered to sparse smectite and to common to abundant clinoptilolite/mordenite.

Crater Flat Tuff--continued

Tram Member

The Tram Member (Carr and others, in press) is a thick (370 m), very complex, compound cooling, ash-flow tuff that contains a large number of partial and complete cooling breaks and numerous eruptive surges in core from drill hole USW GU-3. Also, variations in mafic phenocryst abundances suggest it may have been derived from a compositionally zoned magma chamber. Petrographically, the Tram Member contains subequal amounts of sanidine, plagioclase, and quartz, a significantly higher biotite content in the upper portions, and a much higher lithic content in the lower portions.

Megascopic Subdivisions.--The Tram Member contains a very large number of megascopic subdivisions; only the larger ones are separated here in appendix 2 and on figure 15. Particularly near the upper portion of the Tram Member, a large number of very thin (less than 1 cm to less than 1 mm), subhorizontal partings occur within the welded sequence (see appendix 2, from 800.21 to 828.76 m). In thin section, these partings consist of ash-sized particles in layers that drape over lithic fragment and pumice fragment irregularities in the lower subunits. Several of these partings contain layering suggestive of graded bedding; perhaps these resulted from very short periods of ash-fall activity between eruptive surges. Eruptive surges recorded in this interval (816.80-824.54 m) average only 0.6 m thick, and range from 1.0 to 0.07 m thick. Sequences of eruptive surges that may have produced thin deposits similar to these have been observed along the flanks of Mount St. Helens (Christiansen and Peterson, 1981; Rowley and others, 1981).

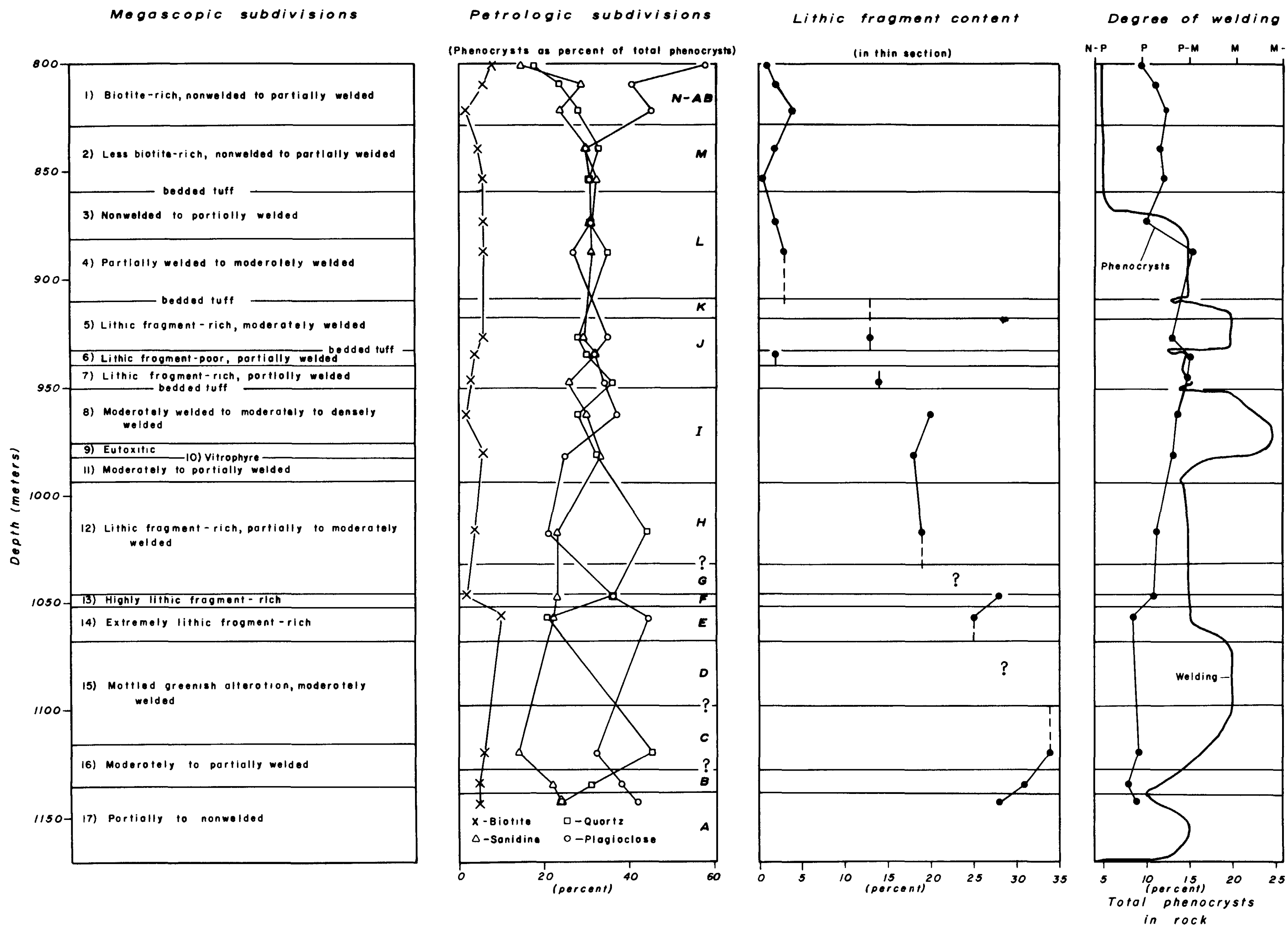

Figure 15.--Megascopic and petrologic subdivisions of the Tram Member of the Crater Flat Tuff found in core from drill holes USW GU-3 and USW G-3. Twenty-eight eruptive surges can be defined by a combination of phenocryst ratios, bedded tuff horizons, subhorizontal partings, changes in lithic fragment abundances and compositions, and changes in the degree of welding. Letters from A to Z and AA and AB are designated for these surges.

Petrologic Subdivisions.--Considerable variation in phenocryst ratios occurs within the Tram Member (fig. 15). Some trends in the ratios of biotite and quartz are evident between about 800 and 825 m and between 925 and 950 m. Also, nearly constant phenocryst ratios occur in the interval between about 830 and 890 m; however, the remainder of the Tram unit has exceptionally random phenocryst ratios. The reason for this variation in phenocryst ratios may lie in the abundance of thin eruptive surges originating from a chemically inhomogeneous magma chamber. Another variable should also be considered: the lithic fragment content also ranges considerably, particularly in the lower part of the unit. These variations can also be used to identify eruptive surges. However a scale problem exists; thin-section-based lithic fragment abundances do not represent an accurate measure of the actual lithic fragment abundance because many lithic fragments are as large or larger than thin sections and are avoided because thin section samples are primarily selected to obtain representative phenocryst ratios. Thus, megascopic estimates and thin section point counts of lithic fragment contents are not highly correlative. Probably a grid count of the core, using slabbed core with 0.5-cm grid spacing, would give a more representative value. Also note that figure 15 shows no close correlation between the degree of welding and the total abundance of phenocrysts, suggesting that variations of phenocryst content are related to primary magmatic features such as variations in composition or degree of crystallization. This relationship also suggests numerous separate eruptive surges. Using a combination of available phenocryst modal data, the occurrence of bedded horizons and horizontal partings, and estimates of lithic fragment abundance and degree of welding a minimum 28 separate eruptive surges are indicated in the 375-m-thick Tram Member in core from USW GU-3 and USW G-3. A closer spaced sequence of thinsections and a more detailed lithic fragment study probably would define a considerably larger number of surges.

The major subdivision of the Tram Member into a lithic fragment-poor upper part and a lithic fragment-rich lower part can be correlated to drill holes USW H-1 (Rush and others, written commun., 1983), USW G-1 (Spengler and others, 1981), and UE25b-1H (R. W. Spengler, written commun., 1982), but the lithic fragment-poor upper part is missing at USW G-2 (Maldonado and Koether, 1983). The lithic fragment-rich lower part contains as much as 30 to 50 percent lithic fragments in all drill holes, but at USW G-2 a 45-m-thick zone containing from 50 to 90 percent lithic fragments at the top of the Tram Member appears to be unique to the northern part of Yucca Mountain.

At drill holes USW GU-3 and USW G-3, in the lithic fragment-poor upper parts of the core, silicic lithic fragments dominate over fragments of more intermediate composition lavas. In the lithic fragment-rich lower part, more intermediate composition lithic fragments dominate down to about 1,068 m, silicic lithic fragments dominate down to about 1,138 m, and intermediate fragments dominate again in the lowermost megascopic subdivision to 1,173 m.

The degree of alteration of the groundmass of the tuff to zeolite and clay is considerably greater than in overlying units. This increase may be the effect of saturation with pore fluids below the static water level, the higher thermal state, and (or) the effect of the lower degree of welding of the Tram Member relative to the Bullfrog Member. The groundmass of the less welded, uppermost megascopic subdivision is partially altered to sparse smectite, abundant clinoptilolite and common mordenite; the more welded subdivisions, 2 to 7, are unaltered to partially altered to rare smectite; the subdivisions above the vitrophyre, 8 and 9, are partially altered to sparse smectite, common clinoptilolite, and a trace of mordenite; the vitrophyre itself, subdivision 10, is partially altered to sparse smectite and clinoptilolite; and subdivisions 15 to 17 have a distinctive greenish alteration with disseminated pyrite in both lithic fragments and groundmass and have pumices that are more extensively altered to sparse to extensive smectite, common clinoptilolite, and sparse mordenite.

Bedded Tuff

The moderately to well indurated bedded tuff under the Crater Flat Tuff is nearly 8.5 m thick in core from drill hole USW G-3 and consists largely of pyroclastic-fall material of both lapilli and ash sizes and may contain minor reworked sedimentary tuff. Pumice fragments are selectively altered to extensive pale-blue-green smectite and the ash is partially altered to a sparse mixed layer clay consisting of smectite and illite, abundant clinoptilolite, a trace of analcime(?), sparse calcite, and disseminated pyrite. Carbonized wood fragments (conifer) occur at 1,173.6 m and suggest that, during the period between eruption of the Lithic Ridge Tuff and the Tram Member, conifer forests were at least locally established.

Lithic Ridge Tuff

The Lithic Ridge Tuff (Carr and others, in press) forms a 304-m-thick, very complex, compound cooling ash-flow tuff that contains multiple eruptive surges at drill hole USW G-3, much like the Tram Member. Also, like the overlying Tram Member, the Lithic Ridge Tuff is compositionally inhomogeneous. The conspicuous presence of sphene in the Lithic Ridge Tuff is the petrographic feature that most readily distinguished these tuffs from those of the Tram Member. Because of extensive alteration, however, the presence of sphene is difficult to ascertain in many intervals. The Lithic Ridge Tuff has a biotite-rich and quartz-poor upper part, and a low quartz, moderate sanidine, and dominant plagioclase content throughout most of the cooling unit.

Megascopic Subdivisions.-- Nine megascopic subdivisions of the Lithic Ridge Tuff have been identified (fig. 16). In descending order, these subdivisions are: (1) biotite-rich nonwelded to moderately welded, (2) biotite-rich moderately welded, (3) partially welded, (4) nonwelded to partially welded, (5) partially welded to moderately welded, (6) partially welded, (7) moderately welded, (8) partially welded to moderately welded, and (9) moderately welded to partially welded. It is of interest that a carbonized conifer wood fragment was recovered in subdivision 9, at 1,485.22 m, just 0.07 m above the bedded tuff underlying the Lithic Ridge Tuff. Thus, in the period between eruption of the older tuffs and the Lithic Ridge Tuff, conifer forests existed between the caldera source of the Lithic Ridge Tuff and the location of drill holes USW GU-3 and USW G-3.

Petrologic subdivisions.--The number of petrologic subdivisions that can be established for the Lithic Ridge Tuff at drill hole USW G-3 is only minimal because a large number of relatively small variations in the degree of welding (subdivisions C, D, and E) and variations in lithic fragment content (subdivision J+) have not been counted. A combination of evidence of separate

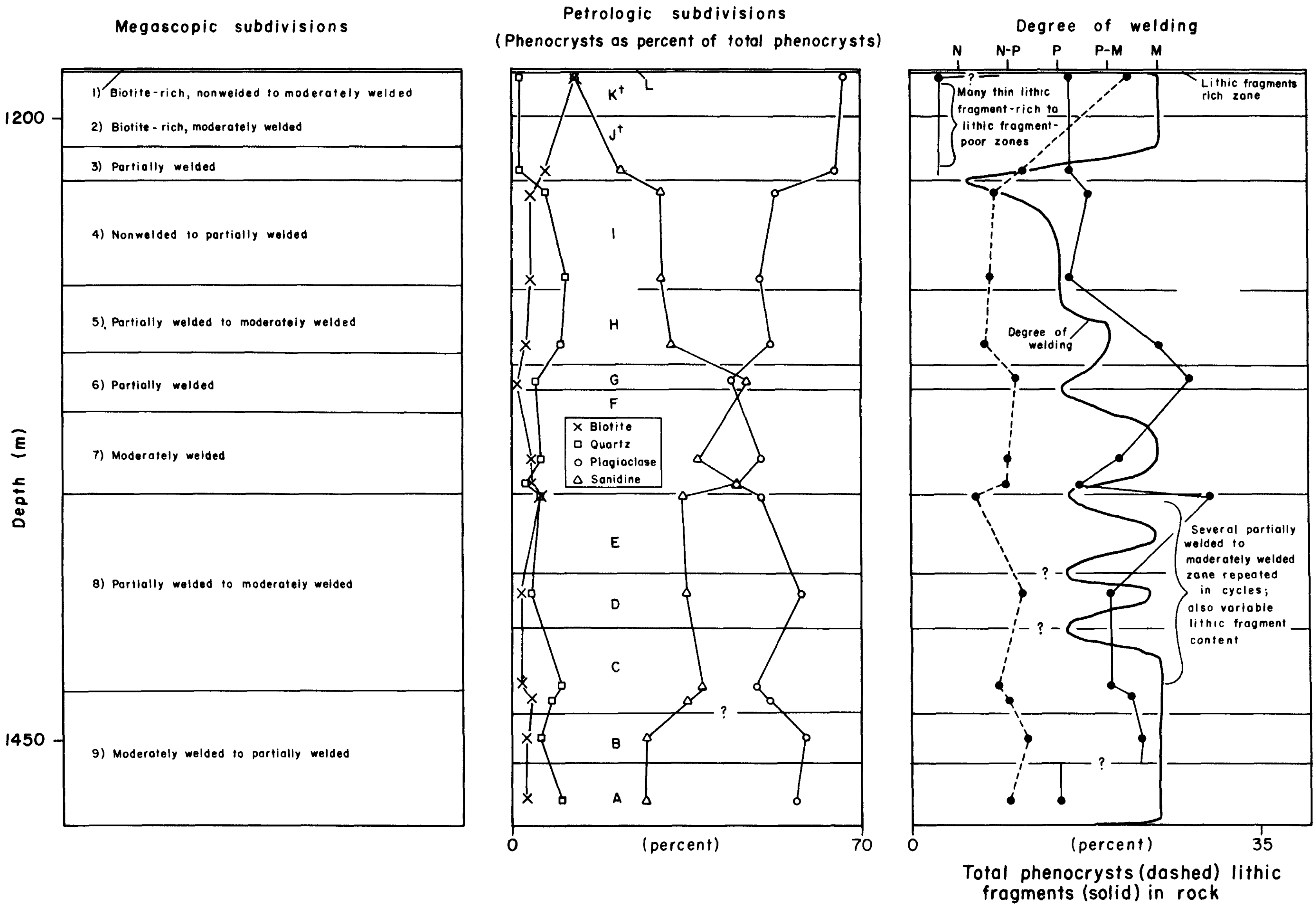

Figure 16.--Megascopic and petrologic subdivisions of the Lithic Ridge Tuff found in core from drill hole USW G-3. The petrologic subdivisions are a minimum number because an uncounted number of eruptive surges must have occurred in subdivision J+ to produce the numerous but uncounted lithic-rich to lithic-poor zones that exist. Also in subdivisions C, D, and E, an uncounted number of repetitive partially welded and moderately welded cycles are observed but uncounted. N, N-P, P, P-M, and M refer to nonwelded, non- to partially welded, partially welded, partially to moderately welded, and moderately welded, respectively.

eruptive surges is based upon total phenocryst content, large changes in degrees of welding, and distinct changes in lithic fragment content. Subdivision A is separated from B on a basis of a distinctly lower lithic fragment content in A. Subdivision B has a significantly lower sanidine and higher plagioclase content than does C. Subdivisions C, D, E, and F are based on cyclic variations in the degree of welding. Subdivisions F and G have subequal feldspars. Subdivision G has a higher lithic content than F, compared to a high plagioclase/sanidine ratio in H. Subdivision H has a significantly higher lithic fragment content than does I. Subdivisions J+ and K+ not only become more crystal-rich but also become progressively more biotite- and plagioclase-rich at the expense of quartz and sanidine; also, these subdivisions contain an uncounted number of alternating lithic-fragment-rich and -poor zones. The uppermost subdivision, L, is more lithic-fragment rich than K+ immediately below.

These petrologic subdivisions cannot be correlated to other drill holes in detail with available data; however, the upper part of the Lithic Ridge Tuff at drill hole USW G-2 has the same petrographic characteristics as subdivisions J+, K+, and L in core from USW G-3. Evidence of chemical inhomogeneity includes (1) difference in phenocryst ratios, (2) coexistence of light and dark colored pumices, and (3) irregular patches of light and dark colored groundmass. The first two are also characteristic of the quartz latitic caprocks of the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff, but the patchy groundmass seems unique. Although detailed petrographic and chemical data have not been collected to prove that patches of groundmass originated from separate parts of a compositionally inhomogenous magma chamber, this seems to be a likely explanation because the patches do not appear to be related to alteration discoloration. These patches or mottled zones are abundant in the megascopic subdivisions 7 and 8.

Alteration of the Lithic Ridge Tuff is more extensive than in higher units, and the transition from clinoptilolite to analcime occurs within this interval. In the upper three megascopic zones, sparse smectite, common clinoptilolite and analcime, and disseminated pyrite occur. Megascopic zones 4 and 5 are similar to those above except smectite is more abundant, zeolites are less abundant, and pyrite is absent. Common smectite and clinoptilolite, sparse analcime, and abundant calcite characterize alteration in subdivisions 6 and 7. Below a transition zone in subdivision 8, where sericitic alteration of plagioclase occurs, subdivision 9 contains abundant analcime, common smectites, and disseminated sulfides.

Bedded Tuff

The bedded tuff below the Lithic Ridge Tuff is only 3 m thick, consists of pyroclastic ash and pumice for the most part, and contains rare evidence of minor fluvial reworking, indicated by the termination of sedimentary bedding planes by sedimentary structures such as channels and crossbedding. These bedded tuffs range from poorly to well indurated and consist of moderately sorted layers that contain variable amounts of ash, pumice, and lithic fragments. Carbonized wood fragments occur at 1,485.47 m, suggesting that these tuffaceous beds are precursors of the Lithic Ridge Tuff which also incorporated fragments of conifers.

Older Ash-Flow Tuffs

The lowest units in drill hole USW G-3 are the unnamed older tuffs. At drill hole USW G-1, a 320-m-thick sequence was cored; at USW G-3, 45 m were recovered, and at USW G-2, only 19 m were cored before drilling was terminated within the older tuffs. The portion of tuff penetrated at USW G-3 forms a rhyolitic, compositionally homogenous, simple cooling unit. Petrographically, very little variation occurs in a subequal sanidine, plagioclase, and quartz phenocryst assemblage that coexists with 2-4 percent biotite; this tuff seems to correlate with unit A in core from drill hole USW G-2 (Maldonado and Koether, 1983).

Two megascopic subdivisions are recognized by changes in degree of welding. No petrologic subdivisions are recognized in this seemingly homogeneous unit (fig. 17).

Alteration within the older tuffs has converted much of the groundmass to sparse smectite and common analcime. Pumice fragments have been totally altered to clays, zeolites, and calcite.

Physical-Property Stratigraphy

For the purpose of nuclear waste disposal, the alteration mineralogy of the matrix and the physical property of the rock are far more significant than are traditional stratigraphic criteria. In the case of ash-flow tuffs, these traditional stratigraphic criteria are based upon petrologic breaks defined by phenocryst ratios that have very little influence upon the capacity of the rock to retain or transmit radionuclides. Original chemistry ranges only from rhyolitic to quartz latitic compositions within these ash-flow tuffs and is regarded as relatively insignificant to radionuclide behavior in vadose or ground water. Secondary mineralogical changes are large; alteration phases are important because of their variable thermal and sorptive properties. Discussion of these changes in greater detail than that presented in the preceding stratigraphic section is beyond the scope of this report; a forthcoming report by D. L. Bish and coworkers of Los Alamos National Laboratory will address the alteration at USW GU-3 and USW G-3; also, detailed reports of the alteration within core from drill hole USW G-1 (Bish and others, 1981) and USW G-2 and UE25b-1H (Caporuscio and others, 1982) are available.

The rockmass physical properties of the tuffs within Yucca Mountain are of considerable interest and concern, primarily because of the high degree of correlation between the degree of welding and related rock mass physical properties such as porosity, dry bulk density, thermal conductivity, and fracture density (Scott and others, 1983). Figure 18 shows the close relationship between degree of welding, porosity, and dry bulk density in the Tiva Canyon Member of the Paintbrush Tuff. Similar relationships exist for lower stratigraphic units except where alteration in the form of zeolitization, argillization, and silicification change both the porosity and density. With increasing depth and increasing degree of alteration, the dependence of physical properties upon the degree of welding decreases; however, the degree of welding is still the primary control of these properties.

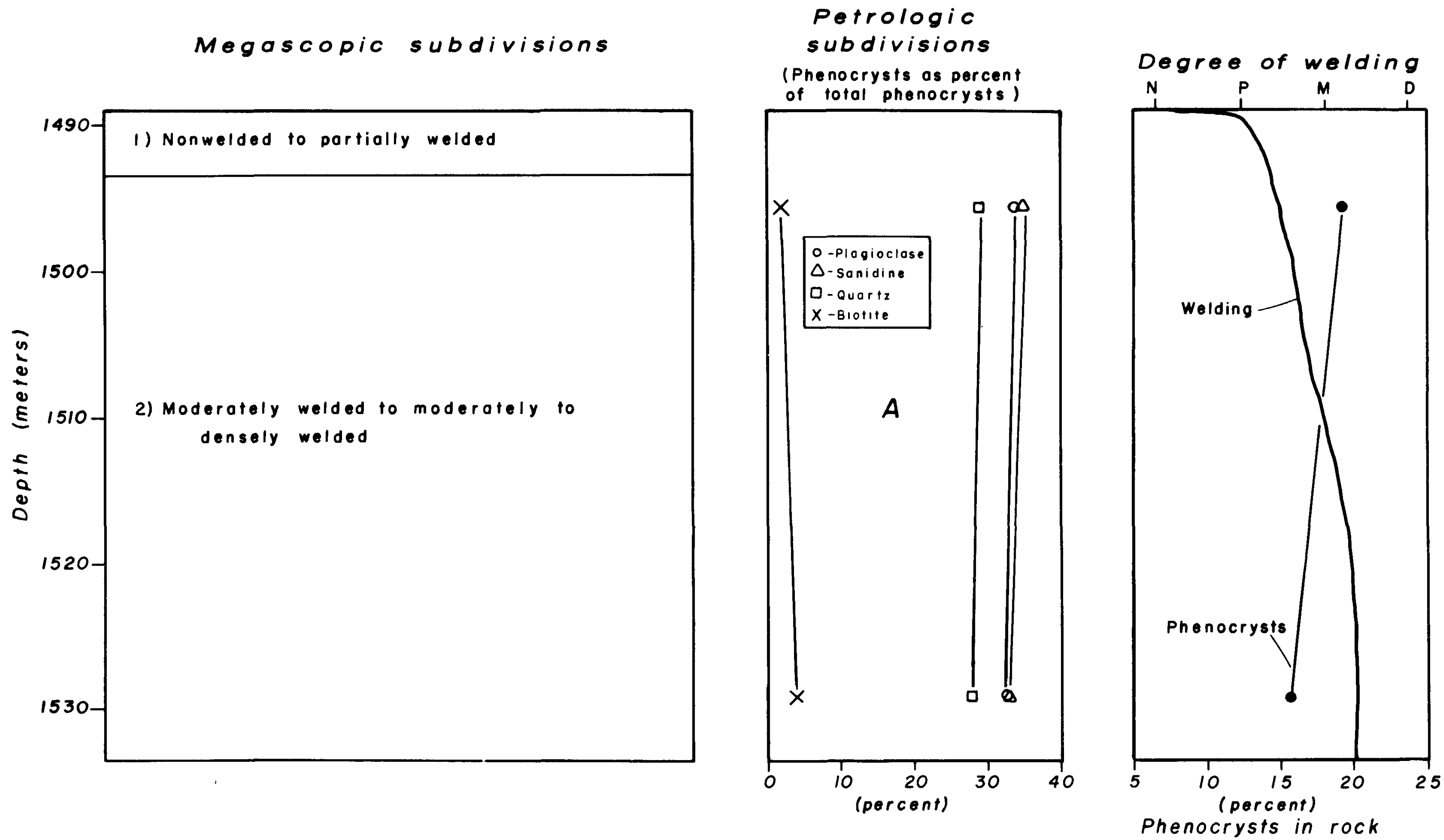

Figure 17.--Megascopic and petrologic subdivisions of the older tuffs from core of drill hole USW G-3. Data do not exist to support more than one eruptive surge; and the two data points that do exist do not form a sound statistical basis for any conclusion.

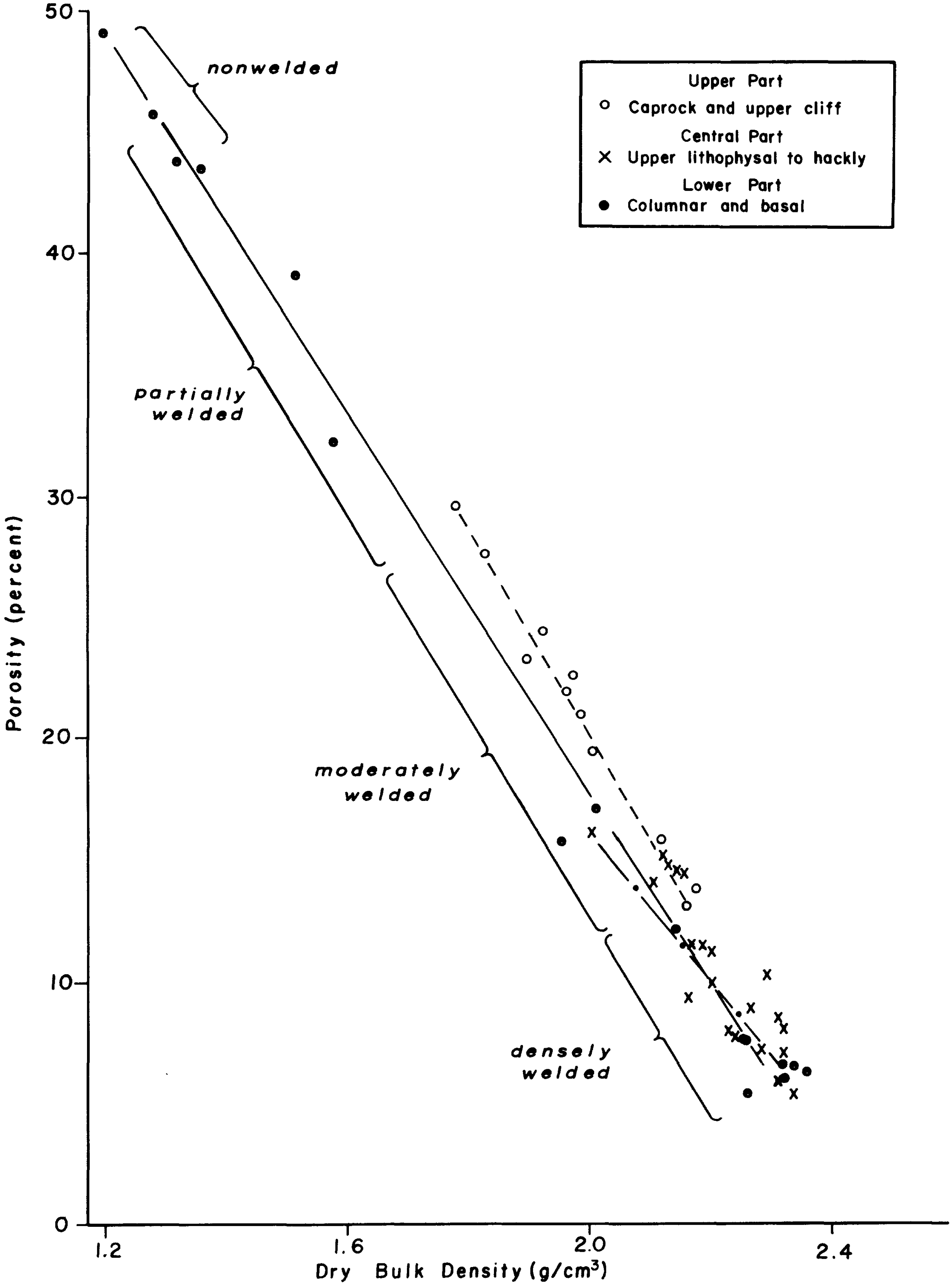

Figure 18.--Relations between dry bulk density, matrix porosity, and degree of welding of the Tiva Canyon Member collected from surface exposures in measured sections at Yucca Mountain. The central portion includes the devitrified zones: the hackly, lower lithophysal, clinkstone, and upper lithophysal field subdivisions. Brackets show the general regions typical of rocks of different degrees of welding. Samples from the lower portion of the cooling unit are shown by solid circles, the central portion by crosses, and the upper portion by open circles. From Scott and others (1983).

Because of this primary control and because of the importance of physical properties to the engineering design of a nuclear waste repository, a valuable way to express stratigraphy is to construct a physical-property stratigraphic sequence from variable degrees of welding (fig. 19). The physical-property subdivisions shown on figure 19 were produced by placing bedded tuffs and nonwelded to partially welded ash-flow tuffs into one category, and moderately to densely welded ash-flow tuffs into a second category. The first category consists of relatively low-density rocks that are more porous and less fractured than those in the second category, which consists of relatively high-density rocks that are less porous and more fractured. The variability in this physical-property stratigraphy over a distance of only 8 km from drill holes USW GU-3 and USW G-3 in the south to drill hole USW G-2 in the north is considerable.

Detailed investigations of the physical properties of the Tiva Canyon Member of the Paintbrush Tuff were possible because of the excellent three-dimensional exposures of this member at Yucca Mountain. The Tiva Canyon Member is very similar in overall character to the less well exposed Topopah Spring Member. This similarity is supported by the observation that the physical properties of surface samples of the welded Tiva Canyon Member are comparable to those of core samples of the welded Topopah Spring Member (Lappin and others, 1982; Olsson and Jones, 1980). In addition to studies of the more welded units, determinations of physical properties have been made for the bedded and nonwelded tuffs (Lappin, 1982). These physical-property studies are augmented by petrological and chemical studies made at the Los Alamos National Laboratory (Caporuscio and others, 1982), which describe the character of clay and zeolite alteration in both welded and nonwelded tuffs.

The funadmental control on the hydraulic conductivity within ash-flow tuffs is the density of fractures; fracture hydraulic conductivities are several orders of magnitude greater than matrix hydraulic conductivities (Scott and others, 1983; Winograd and Thordarson, 1975). Because fractures are at least an order of magnitude more abundant in moderately and densely welded tuffs than in nonwelded or partially welded tuffs, a physical-property stratigraphy defined by degrees of welding is also a very critical parameter for hydrologic considerations.

Chemical Character

The ash-flow tuffs of Yucca Mountain fall into a relatively narrow range of silicic compositions, between high-silica rhyolite and quartz latite. The Tiva Canyon and the Topopah Spring Members of the Paintbrush Tuff contain two compositional end members, high-silica rhyolite in the basal parts and quartz latite in the caprocks, separated by a composition gap (Lipman and others, 1966). The Prow Pass and Tram Members of the Crater Flat Tuff and the Lithic Ridge Tuff show evidence of compositional zonation but to a lesser degree (Byers and others, 1983) with no composition gap. X-ray fluorescence analyses of major and minor elements are summarized in table 5 for ash-fall tuffs sampled in drill holes USW GU-3 and USW G-3, USW G-2, and USW G-1 and from outcrops at Yucca Mountain; normative analyses calculated from major elements are listed in table 6 and plotted on the normative quartz-albite-orthoclase and anorthite-albite-orthoclase phase diagrams (fig. 20). Iron oxidation states are calculated using the dependence of FeO and Fe_2O_3 mole fractions

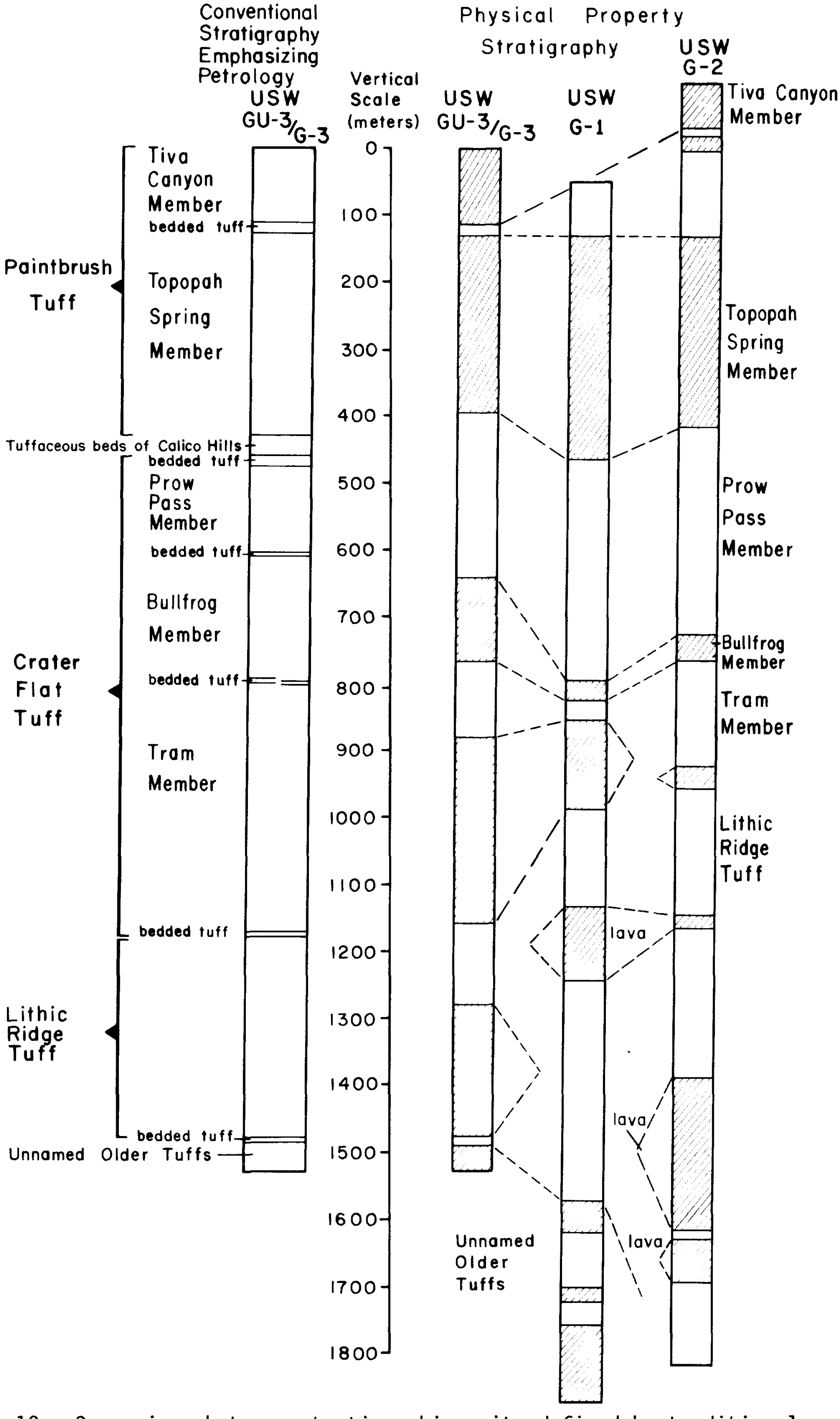

Figure 19.--Comparison between stratigraphic units defined by traditional petrologic criteria and those defined by physical-property criteria. The conventional stratigraphic nomenclature based upon petrologic criteria is given for drill holes USW GU-3 and USW G-3 on the left and the physical-property stratigraphies based on degree of welding for drill holes USW GU-3 and USW G-3, USW G-1, and USW G-2 are drawn in order toward the right. The conventional stratigraphic names of major units are also listed on the far right for general reference but exact boundaries are not shown. The shaded zones represent moderately welded to densely welded rocks; unshaded zones present nonwelded to partially welded rocks. From Scott and others (1983).

Table 5.--Major and minor element analyses of ash-flow tuffs at Yucca Mountain by X-ray fluorescense analysis

Analysis number	Sample[1]	Weight percent of major and minor oxides: SiO_2	TiO_2	Al_2O_3	[2]Fe_2O_3	[2]FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Weight percent loss on ignition	Position in cooling unit and description[3]
1	[4]1BS-13/4/82	67.4	0.49	14.9	0.74	1.12	0.09	0.54	2.62	4.24	5.29	0.13	1.45	Tpc, brown caprock, M-DW, D
2	1BS-15/4/82	56.9	0.31	12.6	0.61	0.92	0.08	0.51	9.55	3.16	5.19	0.07	9.10	Tpc, red caprock, MW, V
3	[4]3BS-13/4/82	75.0	0.13	12.9	0.42	0.63	0.11	0.18	0.20	4.24	4.69	<0.05	0.50	Tpc, columnar, MW, D
4	GU-3-105.47	73.7	0.12	12.1	0.32	0.49	0.1	0.43	0.38	3.65	4.32	<0.05	3.47	Tpc, columnar, MW, V
5	[4]2BS-13/4/82	67.8	0.42	15.8	0.67	1.34	0.09	0.49	1.38	4.33	5.63	0.09	0.52	Tpt, caprock, MW, D
6	GU-3-130.62	70.7	0.26	14.6	0.51	1.01	0.07	0.34	1.27	4.03	5.34	0.06	0.59	Tpt, caprock, MW, PV
7	G-1-397.27	73.7	0.07	12.3	0.28	0.55	0.06	0.11	0.52	3.40	4.65	<0.05	3.16	Tpt, basal vitrophyre, M-DW, V
8	G-2-506.65	73.4	0.08	12.2	0.25	0.50	0.05	0.15	0.60	2.75	5.09	<0.05	4.06	Tpt, basal vitrophyre, M-DW, V
9	[4]8BS-22/10/81	74.1	0.09	12.8	0.42	0.83	0.07	0.53	0.71	3.62	4.79	<0.05	1.16	Tcp, upper portion, P-MW, D
10	G-1-557.44	70.5	0.08	11.7	0.39	0.78	0.05	0.20	0.80	2.47	4.74	<0.05	7.25	Tcp, upper portion, PW, D
11	[4]G-1-583.88	74.3	0.09	13.1	0.41	0.83	0.07	0.19	0.56	3.56	4.99	<0.05	0.93	Tcp, middle portion, P-MW, D
12	G-1-663.48	67.3	0.21	13.3	0.62	1.23	0.08	0.30	1.14	3.63	3.86	<0.05	6.95	Tcb, upper portion, NW, D
13	[4]G-1-768.30	73.6	0.10	13.4	0.38	0.76	0.08	0.19	0.62	3.53	5.17	<0.05	0.90	Tcb, middle portion, M-DW, D
14	G-3-983.10	70.8	0.26	13.1	0.62	1.25	0.04	0.59	1.67	3.41	3.30	0.08	3.79	Tct, middle portion, vitrophyre, MDW, V
15	G-1-1071.85	66.8	0.52	14.2	1.19	2.37	0.04	1.11	1.44	2.06	3.91	0.20	4.83	Tct, basal portion, N-PW, D
16	G-3-1140.12	68.3	0.39	13.6	0.84	1.68	0.24	0.76	1.95	2.35	4.31	0.14	5.41	Tct, basal portion, PW, D
17	G-3-1187.42	67.9	0.31	14.0	0.69	1.04	0.03	0.47	1.53	2.87	5.21	0.07	4.86	Tlr, upper portion, MW, D
18	G-3-1192.36	66.7	0.29	14.1	0.78	1.17	0.05	0.55	1.61	2.92	5.00	0.07	5.31	Tlr, upper portion, MW, D
19	[4]G-3-1475.09	71.2	0.21	13.2	0.60	1.20	0.05	0.49	1.05	3.29	4.31	<0.05	3.39	Tlr, lower portion, MW, D
20	G-1-1500.92	73.4	0.18	12.6	0.44	0.88	0.02	0.47	0.66	2.41	5.60	<0.05	2.62	Tot, unit A, upper portion, PW, D
21	G-1-1512.25	72.3	0.16	13.2	0.43	0.85	0.05	0.71	0.86	2.52	4.35	<0.05	3.44	Tot, unit A, upper portion, PW, D

1 Sample identifications refer to field samples (e.g., 1BS-13/4/82) with sample number, collector's initials and date, and to drill-hole samples (e.g., GU-3-105.47), with drill-hole designation and depth of sample in meters.

2 Fe_2O_3 and FeO values are calculated from oxygen fugacity data (Lipman, 1971) and from compositional effects (Sack and others, 1980). Based on these calculations, units containing sphene are assigned FeO/Fe_2O_3 ratios of 1.5; those without sphene are assigned FeO/Fe_2O_3 ratios of 2.0.

3 First symbol represents unit described, from plate 1. N=nonwelded, N-PW=non- to partially welded, PW=partially welded, P-MW=partially to moderately welded, MW=moderately welded, and M-DW=moderately to densely welded; V=vitric; D=devitrified.

4 Indicates relatively fresh samples containing little evidence of alteration in major and minor element analyses. J. S. Wahlberg, A. Bartel, J. Taggart, and J. Barker of USGS, analysts.

Table 6.--Normative analyses calculated from major elements

[CIPW normative calculation using program developed by Stuckless and Van Trump (1979). Normative minerals Q, C, Or, Ab, An, Wo, En, Fs, Mt, Il, and Ap are quartz, corundum, orthoclase, albite, anorthite, wollastonite, enstatite, ferrosilite, magnetite, ilmenite, and apatite, respectively. Analysis numbers refer to sample numbers from table 5]

Normative minerals	1	2	3	4	5	6	7
Q	17.838	7.050	31.907	35.871	17.387	23.676	35.905
C	0.0	0.0	0.589	0.862	0.295	0.026	0.865
Or	32.042	34.115	28.125	26.689	33.948	32.137	28.839
Ab	36.775	29.743	36.409	32.290	37.387	34.729	30.195
An	6.151	5.415	0.742	1.698	6.386	6.017	2.433
Wo	2.631	19.531	0.0	0.0	0.0	0.0	0.0
En	1.379	1.413	0.455	1.120	1.245	0.862	0.288
Fs	0.824	0.915	0.812	0.652	1.334	1.155	0.813
Mt	1.100	0.984	0.618	0.485	0.991	0.753	0.426
Il	0.954	0.655	0.251	0.238	0.814	0.503	0.140
Ap	0.316	0.184	0.096	0.099	0.218	0.145	0.099

Normative minerals	8	9	10	11	12	13	14
Q	38.085	32.639	38.808	33.212	30.456	31.979	35.170
C	1.232	0.475	1.251	0.938	1.280	0.987	1.129
Or	31.625	28.883	30.529	30.046	24.872	31.216	20.501
Ab	24.466	31.257	22.780	30.695	33.493	30.520	30.335
An	2.855	3.328	4.041	2.565	5.882	2.876	8.160
Wo	0.0	0.0	0.0	0.0	0.0	0.0	0.0
En	0.393	1.347	0.543	0.482	0.815	0.483	1.545
Fs	0.707	1.182	1.167	1.189	1.688	1.088	1.501
Mt	0.381	0.621	0.616	0.606	0.980	0.563	0.945
Il	0.160	0.174	0.166	0.174	0.435	0.194	0.519
Ap	0.100	0.097	0.103	0.097	0.103	0.097	0.199

Normative minerals	15	16	17	18	19	20	21
Q	36.766	34.075	28.776	27.884	33.500	36.709	39.526
C	4.731	1.966	1.089	1.207	1.369	1.520	3.015
Or	24.622	26.934	32.711	31.689	26.630	34.221	26.925
Ab	18.575	21.029	25.802	26.500	29.108	21.089	22.335
An	6.220	9.263	7.579	8.076	5.173	3.116	4.195
Wo	0.0	0.0	0.0	0.0	0.0	0.0	0.0
En	2.946	2.002	1.244	1.469	1.276	1.210	1.852
Fs	2.754	2.320	0.939	1.199	1.520	1.026	1.083
Mt	1.839	1.288	1.063	1.213	0.910	0.660	0.653
Il	1.052	0.783	0.626	0.591	0.417	0.354	0.318
Ap	0.505	0.351	0.176	0.178	0.099	0.098	0.099

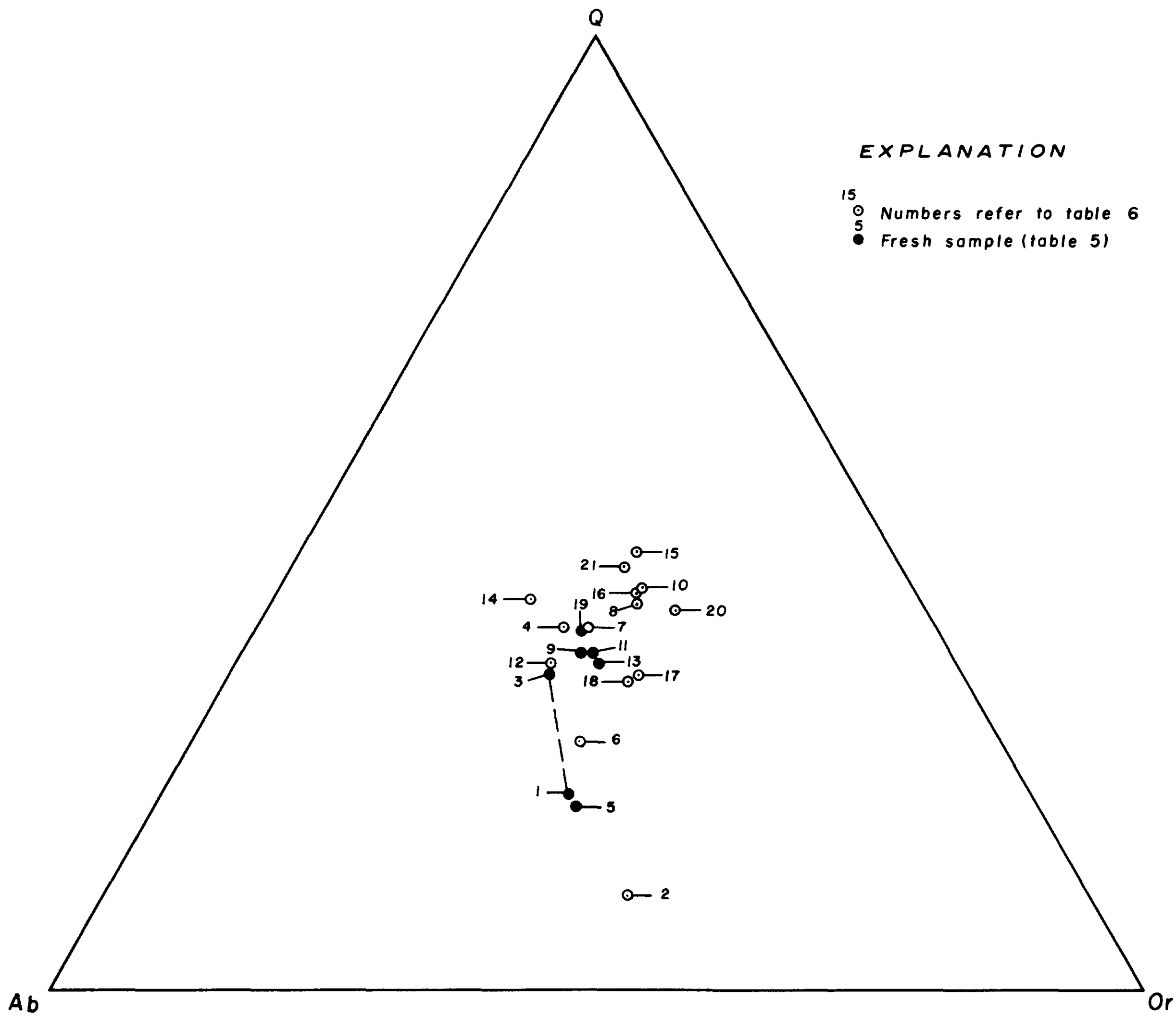

Figure 20.--Normative quartz-albite-orthoclase (Q-Ab-Or) diagram.

upon the fugacity of oxygen, temperature, and major element bulk composition (Sack and others, 1980). Lipman (1971) provided the fugacity of oxygen and temperature data based upon coexisting iron-titanium oxide equilibria. The calculations show the weight percent FeO/Fe_2O_3 ratios to be about 1.93 to 1.94 for the sphene-absent Topopah Spring Member, and about 1.46 to 1.50 for the sphene-bearing Tiva Canyon Member; thus, sphene-bearing ash-flow tuffs are considerably more oxidized. It is of interest to note that the calculated iron-oxide ratios for the rhyolitic bases of each tuff are nearly identical to the more quartz latitic caprocks. This uniform oxidation state suggests that even though a composition gap exists between the quartz latitic caprocks and the rhyolitic basal portions of these two members, oxygen activity communication existed between these portions of their compositionally zoned magma chambers.

Caprock samples 1 and 5 (Tiva Canyon and Topopah Spring Members, respectively) in figure 20 are considerably more normative feldspar-rich than corresponding fresh lower portions of the cooling units (dashed line connects the Tiva Canyon Member pair). This supports Lipman and others (1966) and Hildreth's (1981) conclusions that these caprocks crystallized at relatively greater depths or higher pressures even though these pressures cannot be quantified. Also note the very tight grouping of freshest Prow Pass Member, Bullfrog Member, and Lithic Ridge Tuff samples (9, 11, 13, and 19) suggesting that relatively little petrologic difference exists between these units.

The original chemistry of ash-flow tuffs is almost ubiquitously altered to at least some small degree by reaction with deuteric fluids, ground water, and possible hydrothermal fluids (Scott, 1971a; Scott, 1971b). Lipman (1965) has pointed out that the composition most representative of an original magmatic composition is that of densely welded, relatively nonporous, devitrified tuffs that do not contain high water contents. Those analyses in table 5 that fit this category, and have major element analyses that have no obvious indication of major alteration, are analyses numbered 1, 3, 5, 7, 9, 11, and 13, shown as solid circles on figure 20. Except for the distinct compositionally zoned Tiva Canyon Member (analyses 1 and 3) and Topopah Spring Member (analysis 5), all these analyses fall into a relatively tight cluster. Byers and others (1983) have noted, however, that Crater Flat Tuff analyses indicate an evolution from relatively high pressure crystallization conditions for the oldest member, the Tram, progressively to relatively low pressure during crystallization of the youngest member, the Prow Pass. More explicitly, Byers and others (1983) show a progressive decrease in normative albite in the calculated compositions of melts with decreasing age, suggesting decreases in either total pressure or partially water pressure during crystallization. This trend is correlated with a significant increase in the degree of resorption of quartz phenocrysts with decreasing age, further suggesting that an old Tram Member composition magma and associated phenocrysts progressively migrated to shallower (lower pressure) regions to erupt the Bullfrog Member, and with further evolution and upward migration, to erupt the Prow Pass Member. This change in pressure would not only tend to resorb quartz but would tend to crystallize increasing quantities of feldspars. If these feldspars can be removed by a mechanism similar to plating out on magmatic margins, this evolution would produce an increase in the size of the Eu anomaly (fig. 21; R. B. Scott, written commun., 1983). A

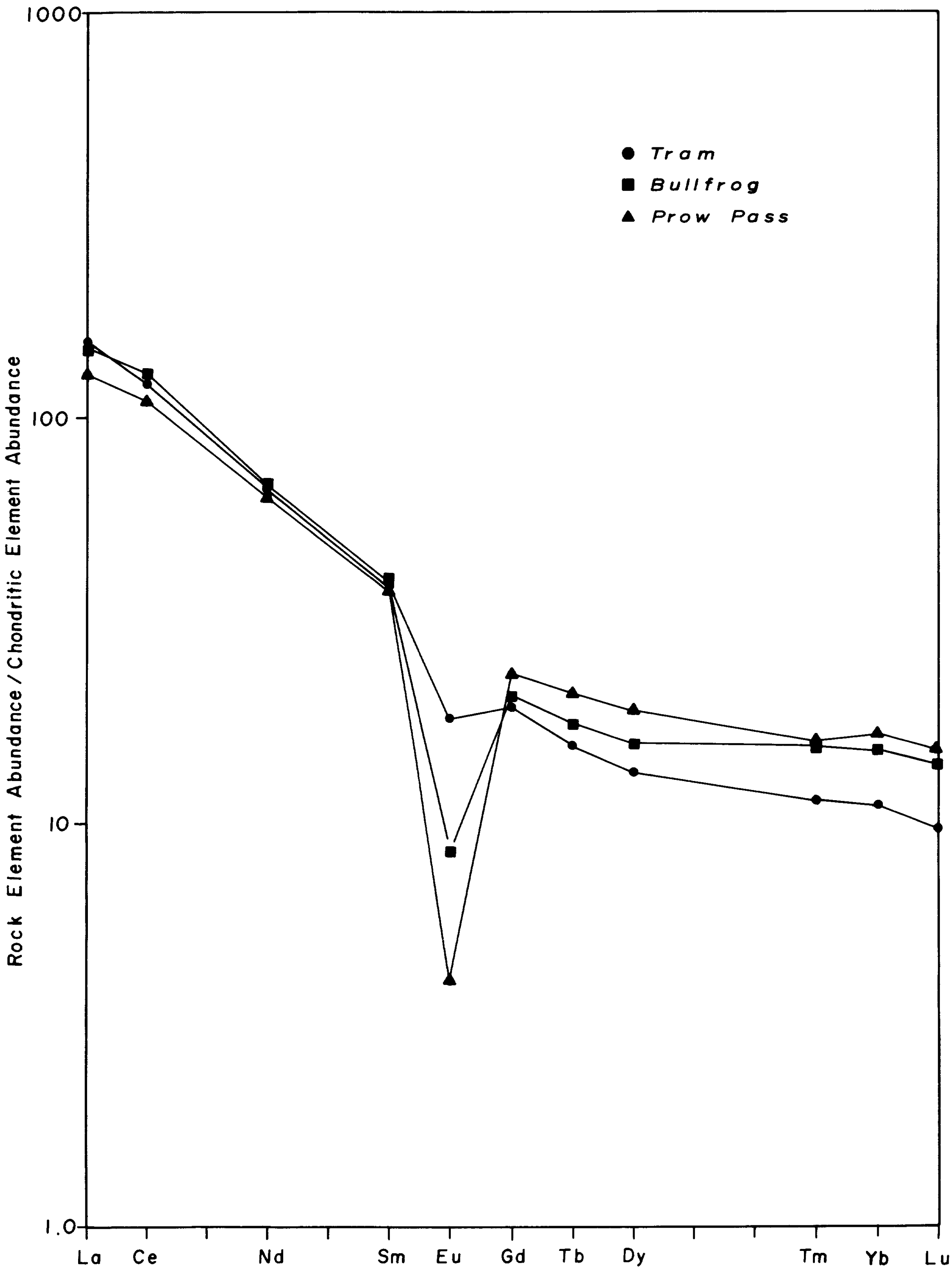

Figure 21.--Chondrite-normalized rare-earth element patterns for the Tram Member (sample G-1-1071.85), the Bullfrog Member (sample Tsv 86e) and the Prow Pass Member (sample 8BS 22/10/8). These analyses are representative of 4 analyses of each tuff. Not only does the size of the negative Eu anomaly increase from the Tram Member to the Prow Pass Member progressively, but the heavy rare-earth element abundance increases significantly and the light rare-earth element abundance tends to decrease. Mechanisms to explain these observations await more extensive studies.

unique interpretation of the mechanism for this evolution of the Eu anomaly is premature; however the progressive growth of this anomaly with decreasing depth is significant independent evidence that the Crater Flat Tuffs are genetically related.

Stable Oxygen and Carbon Isotopic Character

Results of ^{18}O, ^{16}O, ^{12}C, and ^{13}C studies of calcite fracture fillings in Yucca Mountain suggest several relationships. These data are reported in table 7 and shown on figure 22 in terms of $\delta^{18}O$ and $\delta^{13}C$ values.

Data from calcite fracture filling from USW G-2 and UE25a-1 follow a trend of decreasing $\delta^{18}O$ and increasing $\delta^{13}C$ with depth; data from USW GU-3 follow a similar trend but are offset to higher $\delta^{13}C$ values. Studies of meteoric water and calcites from the Nevada Test Site indicate that the source of oxygen is meteoric water (J. N. Rosholt, USGS, written commun., 1982). However, three sources of carbon exist: (1) atmospheric CO_2 which would result in carbonates with $\delta^{13}C$ values near -1 at 20°C, (2) carbon in the tuffs which would result in $\delta^{13}C$ values near -20, or (3) carbon in organic matter which would also result in $\delta^{13}C$ values near -20. Probably the nearly linear relation between $\delta^{18}O$ and $\delta^{13}C$ found in calcites from USW G-2 and UE25a-1 results from an increase in the temperature of the meteoric water as it descends through the tuffs, where atmospheric carbon (CO_2) contribute about 2/3 of the total carbon to the system. In contrast, the trend of USW GU-3 calcites suggests that, although a similar temperature dependent fractionation of oxygen and carbon isotopes affect the system, a significant increase of atmospheric CO_2 enriches the system in ^{13}C.

STRUCTURE

Determination of stratigraphic thicknesses and structural attitudes within a core requires corrections for drill-hole deviation by directional surveys and attitude measurements made from oriented core. The Eastman Whipstock directional survey was made from 15-m stations in drill hole USW G-3 to a depth of 1,500 m and is shown on figure 23. Intervals of oriented core covered about 8.5 percent of the cored rock in USW GU-3 and G-3 combined (appendix 1). Plate 1 reports the drilled thicknesses of units, the uncorrected number of natural fractures per unit distance cored, and the core index. The core index is a measure of the degree of natural and induced breakage during coring (J. R. Ege, USGS, written commun., 1975); this index is a valuable source of data for mining engineering factors for a repository.

Bedding and Foliation

One objective of obtaining oriented core is to determine the attitude of bedding within tuffaceous layers and planes of foliation within ash-flow tuffs. Table 8 lists the depths of oriented cores, the angle of inclination of the drill hole, and the necessary corrections to obtain the true depth. Based on these corrections, the drilled distances to key stratigraphic horizons are contrasted with the true depth to the horizons given at the bottom of table 8. These data are combined with the measure of dips of bedded tuff and foliation planes in welded ash-flow tuffs (table 9) to calculate true thicknesses of major stratigraphic units (table 10). However, these

Table 7.--Stable isotopic analyses of fracture filling calcite from drill holes USW GU-3, USW G-2, and UE25a-1

[Data for USW G-3 from B. J. Szabo and K. Kyser, USGS, written commun., 1983. Data USWG-2 and UE25a-1 from J. N. Rosholt, USGS, written commun., 1982.]

Drill hole	Depth (m)	$\delta^{13}C$ (permil)[1]	$\delta^{18}O$ (permil)[2]
USW GU-3	63	-7.06	+20.23
USW GU-3	131	-5.11	+20.16
USW GU-3	145	-5.44	+20.28
USW GU-3	159	-5.58	+20.04
USW GU-3	318	-5.10	+19.11
USW GU-3	331	-4.54	+18.73
USW G-2	280	-8.35	+19.21
USW G-2	302	-7.90	+19.31
USW G-2	347	-7.43	+18.22
USW G-2	347	-7.37	+18.30
USW G-2	349	-7.47	+18.19
USW G-2	349	-6.93	+18.13
USW G-2	359	-6.82	+17.98
USW G-2	361	-6.56	+17.77
UE25a-1	34	-4.52	+20.00
UE25a-1	283	-6.33	+17.60
UE25a-1	611	-5.41	+15.60

[1] Relative to PDB standard.
[2] Relative to SMOW standard.

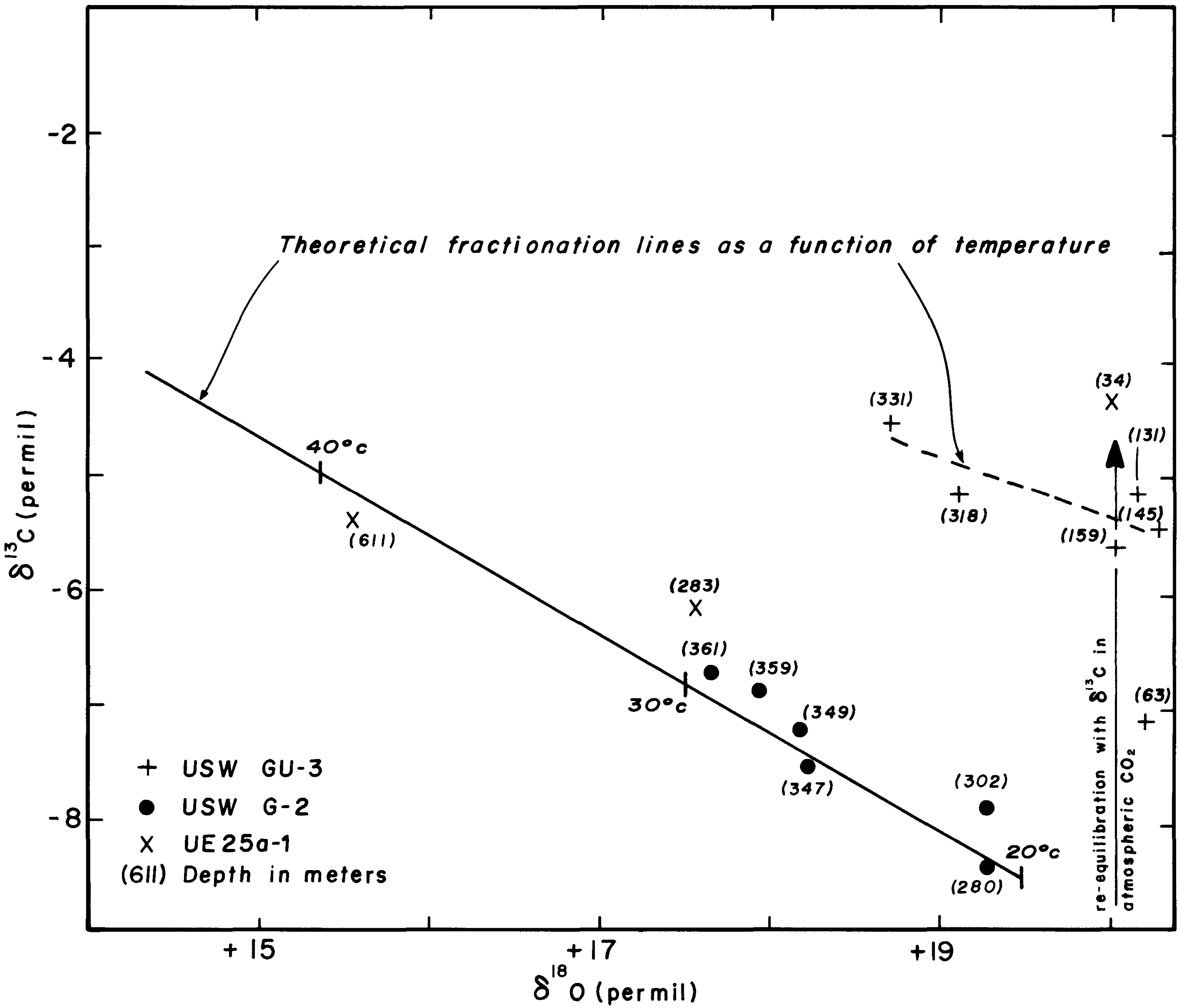

Figure 22.--$\delta^{13}C$ versus $\delta^{18}O$ of calcite fracture fillings from drill holes USW GU-3, USW G-2, and UE25a-1. (Data from J. N. Rosholt, USGS written commun., 1982, and from B. J. Szabo and K. Kyser, USGS, written commun, 1983). The two sloping lines are theoretical fractionation lines controlled by temperature; note that higher temperatures are directly correlated with greater depths. The vertical line on the right is a theoretical mixing line with re-equilibration with atmospheric CO_2.

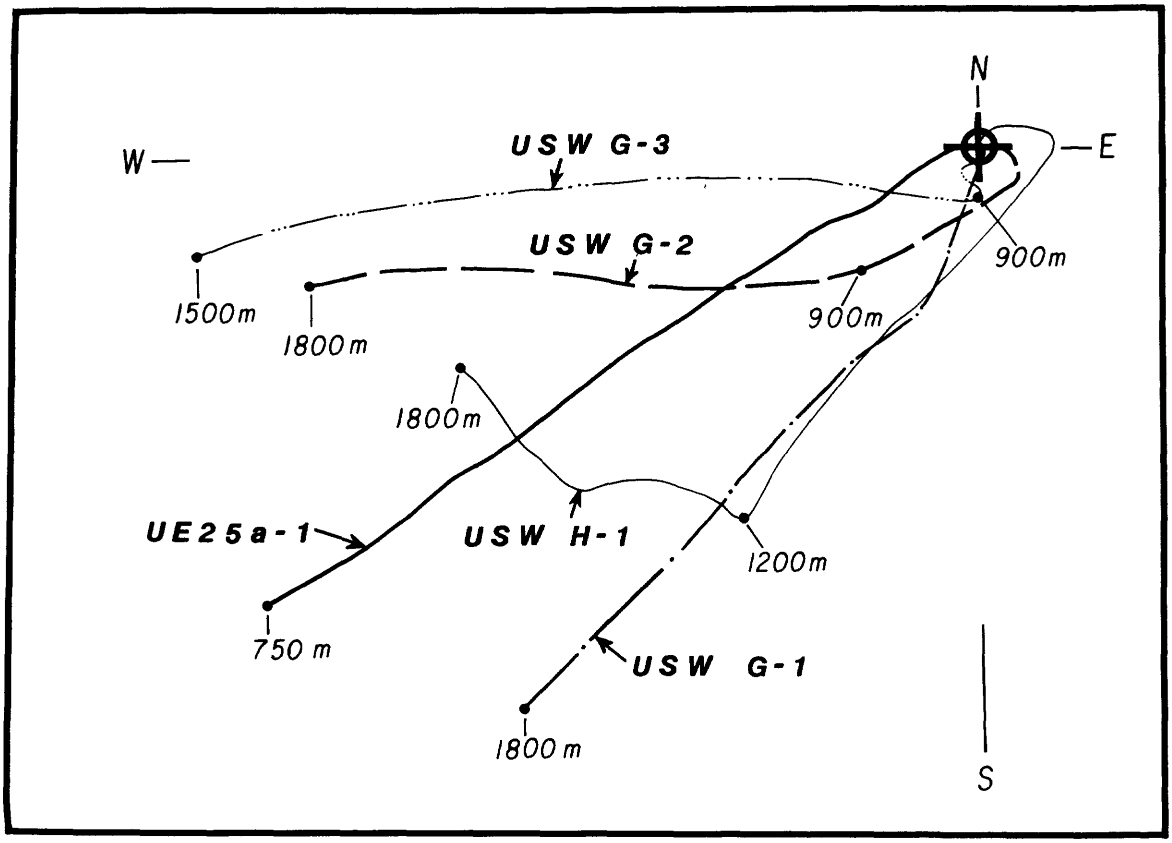

Figure 23.--Drill-hole deviation directions on Yucca Mountain. No horizontal scale is given because the amount of lateral deviation varies greatly between drill holes; for this reason, line lengths represent percent of horizontal deviation. Note that drill holes within Drill Hole Wash deviated in a southwest direction and drill holes outside of the wash deviate slightly south of west. The significance of these deviation directions will be discussed later.

Table 8.--Drill-hole deviation and correction at drill holes USW GU-3 and USW G-3

USW GU-3			USW G-3		
Drilled Distance (m)	Angle[1] (deg)	Correction (m)	Drilled Distance (m)	Angle (deg)	Correction (m)
43.28	1.0	-0.00	819.00	7.0	-3.66
106.68	0.75	-0.01	855.57	7.2	-3.94
162.15	0.9	-0.01	901.90	8.5	-4.37
214.58	1.25	-0.02	945.49	10.2	-4.96
308.76	1.8	-0.05	1,040.89	14.2	-7.20
356.01	2.7	-0.08	1,149.10	14.8	-10.70
431.60	3.4	-0.19	1,212.49	15.2	-12.86
493.16	3.25	-0.29	1,260.35	17.0	-14.74
725.42	5.5	-0.98	1,322.83	18.6	-17.73
762.91	5.1	-1.13	1,387.14	21.5	-21.62
800.71	5.5	-1.30	1,464.56	24.1	-27.67
			1,533.39	24.9	-33.88

Corrected Stratigraphic Horizons

	Drilled Distance (m)	True Depth (m)
Base of Tiva Canyon Member	113.90	113.89
Top of Topopah Spring Member	129.19	129.18
Base of Topopah Spring Member	428.65	428.46
Top of Prow Pass Member	475.56	475.30
Top of Bullfrog Member	611.02	610.38
Top of Tram Member, USW GU-3	803.76	802.45
Top of Tram Member, USW G-3	800.21	796.69
Top of Lithic Ridge Tuff	1,181.52	1,169.72
Top of older tuffs	1,488.27	1,458.46
T. D.	1,533.39	1,499.51

[1]Measured by oriented core inclinations.

Table 9.--Attitudes[1] of folia in ash-flow tuff and in bedded tuff of drill holes USW GU-3 and USW G-3

Depth (m)	Unit	Strike and Dip
(GU-3)		
[2]0 (surface)	Tiva Canyon Member	N.15°E., 6°SE.
33.77	Tiva Canyon Member	E.-W., 10°S.
45.38	Tiva Canyon Member	N.37°E., 10°SE.
107.44	Tiva Canyon Member	N.3°E., 6°SE.
162.46	Topopah Spring Member	N.24°E., 15°SE.
375.20	Topopah Spring Member	N.56°E., 2°SE.
764.01	Bullfrog Member	N.22°W., 8°NE.
801.17	Bedded tuff	N.21°W., 12°NE.
(G3)		
[3]820.03	Tram Member	horizontal
[3]820.64	Tram Member	horizontal
[3]821.34	Tram Member	N.18°E., 20°SE.
[3]821.83	Tram Member	N.6°E., 9°SE.
[3]822.04	Tram Member	N.77°E., 19°SE.
1,389.16	Lithic Ridge Tuff	horizontal
1,490.84	Lithic Ridge Tuff	N.13°E., 13°NW.
1,512.87	Older tuffs	N.20°E., 12°NW.

[1]Measured on oriented core.

[2]Measured by Brunton compass on surface.

[3]"Bedding" surfaces formed by hiatuses in magmatic pulses within a welded sequence.

Table 10.--Thickness of stratigraphic units at drill holes USW GU-3 and USW G-3

Unit	Average [1] attitude of beds or folia (deg)	Drilled thickness (m)	Vertical distance (m)	True thickness (m)
Tiva Canyon Member	8.0	113.90	113.89	112.78
Bedded tuff	n.d.[2]	15.29	15.29	15.14
Topopah Spring Member	8.5	299.46	299.28	295.99
Bedded tuff	n.d.	1.99	1.99	1.97
Tuffaceous beds of Calico Hills	n.d.	26.04	26.00	25.71
Bedded tuff	n.d.	18.88	18.85	18.64
Prow Pass Member	n.d.	131.49	131.11	129.67
Bedded tuff	n.d.	3.97	3.97	3.93
Bullfrog Member	8.0	186.66	186.01	184.20
Bedded tuff	12.0	6.08	6.06	5.93
Tram Member	9.6	372.90	364.68	359.57
Bedded tuff	n.d.	8.41	8.35	8.23
Lithic Ridge Tuff	12.0	303.77	285.94	279.69
Bedded tuff	n.d.	2.98	2.80	2.76
Older tuffs to TD	13.0	45.12	41.05	40.00

[1]Measured from oriented core.

[2]Where not determined (n.d.) that attitude above is used.

thicknesses can not be corrected for thinning related to normal faulting because the offsets are unknown and, therefore, thicknesses listed in table 10 must represent minimal thicknesses. Particular, the Lithic Ridge Tuff may be significantly thicker than calculated in table 8, because two major faults are observed at 1,309.7 and 1,402 m. Abundant fractures and shear zones within core in densely welded to moderately welded intervals of the Tiva Canyon, Topopah Spring, Bullfrog, and Tram Members suggest that significant thinning may also exist in all these units.

Fractures

Numerous planar and nonplanar discontinuities occur in the core of USW GU-3 and USW G-3; because the displacements or absence of displacements of most of these discontinuities have not been established along the surface of these discontinuities, the generalized term fractures is used rather than the more specific terms fault or joint. Several origins can be attributed to structural discontinuities in the rocks: (1) Those fractures that contain mineral coatings, fault gouge, slickensides, breccia, or alteration discoloration on the fracture surface or those that show evidence of displacements along the surface of the discontinuities are assumed to have been created by either tectonic stresses, cooling stresses, or other stresses related to natural joint formation. (2) Those discontinuities that have none of the above features and cut the core at angles not close to attitudes parallel to the core axis are assumed to be mechanical breaks created during coring or core handling. (3) Those fractures devoid of natural fracture formation, that have long segments (1 m or more) that are parallel to the core axis, are assumed to be mechanical breaks created by hydrofracturing the core during the coring operations, particularly where the fractures sharply curve toward the core margin.

Mineralogy of Fracture Coatings

The mineralogies of fracture coatings and veins were determined by X-ray diffraction analysis of 49 selected samples of mineralized fractures, and are listed in table 11. The frequency of occurrence of smectites and 10-A^{o} clays increases downhole. Palygorskite, a chain-lattice clay mineral with a fibrous white appearance, is common on fractures at depths less than 250 m. Zeolites also increase downhole but in the interval where the zeolite II/zeolite III zonation (clinoptilolite reaction to analcime + quartz + water) is found in the groundmass at depths between 1.2 and 1.4 km (D. L. Bish, Los Alamos National Laboratory written commun., 1982), fractures were not sampled in enough detail to establish precisely that reaction boundary. However, the zeolite mineral mordenite is particularly prevalent between 775 and 975 m. Mordenite commonly forms a transitional phase between the clinoptilolite and analcime zones (Sheppard, 1973; Surdam, 1977). Fe and Mn minerals include common occurrences of hematite and less commonly sampled geothite, lepidocrocite, iron oxide, pyrolusite, and cryptomelane. Veins of sulfides are absent even though sulfides are commonly disseminated within the groundmass of the lower portions of the Tram Member and the Lithic Ridge Tuff (appendix 2).

Because sampling of fractures was programmed only for mineral identification, not mineral distribution, the data in table 11 are not representative of either the ranges or frequencies of occurrence. However,

Table 11.--X-ray diffraction analyses of fracture mineralogy (with some groundmass mineralogy) of core from drill holes USW GU-3 and USW G-3

[Paul D. Blackmon, analyst, USGS, Denver. Sample number includes the depth in meters. The nature of the material sampled is also noted. Minerals: Mont=Montmorillonite with parts of Illite mixed layer (I) if any, IM=Illite Mica, Cl=Clinoptilolite, An=Analcime, Q=Quartz, Cr=Cristobalite, Tr=Tridymite, F=Feldspar, H=Hematite, Ca=Calcite, Fl=Fluorite, Am=Amorphous, Other: a=Opaline silica with cristobalite, b=Opaline silica, c=Palygorskite, d=Mica, e=Carbonate by acid reaction, f=Lepidocrocite, g=Mordenite, h=Dolomite(?), i=mostly Pyrolusite (B-MnO2) and less Cryptomelane (KMn_8O_{16}), j=Iron Oxide, k=Geothite, l=Siderite, m=Heulandite/Clinoptilolite, n=Biotite, o=Amphibole; tr=trace <5 percent, <1=5-9 percent, estimates of quantities in parts in ten are semiquantitative. Leaders (--) indicate not detected]

Sample	Minerals (Estimated amount in parts in ten)											
	Mont	IM	Cl	An	Q	Cr	Tr	F	H	Ca	Fl	Am	Other
GU-3-69.72 fracture	--	--	--	--	--	--	--	--	--	--	--	--	10[c]
GU-3-102.22 pumice	8 0.2 I	--	--	--	--	<1[a]	--	1+	--	--	--	--	--
GU-3-111.27 fracture	tr	--	--	--	--	--	--	1+	--	tr[e]	--	8+	tr[b]
GU-3-210.24 fracture	--	tr	--	--	<1	5	2+	1+	tr	--	--	--	--
GU-3-210.77 fracture	tr	tr	--	--	1+	3+	2	2+	tr	--	--	--	--
GU-3-211.84 fracture	tr	tr	--	--	<1	2+	1+	2	--	--	--	--	3[c]
GU-3-212.30 fracture	--	--	--	--	tr	1+	--	--	--	--	--	--	8+[c]
GU-3-225.36 fracture	--	--	--	--	2	1+	6	<1	--	--	--	--	--
GU-3-226.83 fracture	--	--	--	--	1	2	5	2	--	--	--	--	--
GU-3-226.89 fracture	tr	--	--	--	tr	2+	4+	2+	tr	--	--	--	--
GU-3-236.65 fracture	--	--	--	--	1	1+	6	1+	--	--	--	--	--

Table 11.--X-ray diffraction analyses of fracture mineralogy (with some groundmass mineralogy) of core from drill holes USW GU-3 and USW G-3--Continued

Sample	Minerals (Estimated amount in parts in ten)												
	Mont	IM	Cl	An	Q	Cr	Tr	F	H	Ca	Fl	Am	Other
GU-3-237.12 fracture	tr	--	--	--	1	1	6+	1+	--	--	--	--	--
GU-3-243.68 fracture	<1	--	--	--	2	2+	tr	3	--	--	--	1	<1[d],tr[j]
GU-3-246.89 fracture	1+ 0.2-.0.3 I	tr	tr	--	1+	3+	2+	1+	--	tr[e]	--	tr	<1[g]
GU-3-247.55 fracture	tr	--	--	--	2+	3+	--	3	--	--	--	tr	tr(?)[k]
GU-3-249.20 fracture	1	--	--	--	3	--	--	4	--	--	--	<1	1[g]
GU-3-249.23 fracture	1+	--	--	--	3	--	--	4	--	--	1+	--	--
GU-3-250.90 fracture	tr	--	--	--	3	3	--	3	--	--	<1?	--	--
GU-3-250.98 fracture	1+	--	--	--	<1	1+	--	<1	--	--	--	1	4+[c]
GU-3-252.51 fracture	--	--	--	--	--	--	--	tr	--	9+	--	--	tr[b]
GU-3-255.24 fracture	--	--	--	--	4	1+	4	<1	--	--	--	--	--
GU-3-277.86 fracture	--	--	--	--	7+	1	<1	<1	--	--	--	--	--
GU-3-283.32 lithophysal cavity-A	--	--	--	--	2+	--	<1	<1	5+	--	--	--	<1[b]
GU-3-283.32 lithophysal cavity-B	--	--	--	--	5	<1	2	1+	1+	--	--	--	--

Table 11.--X-ray diffraction analyses of fracture mineralogy (with some groundmass mineralogy) of core from drill holes USW GU-3 and USW G-3--Continued

Sample	Minerals (Estimated amount in parts in ten) Mont	IM	Cl	An	Q	Cr	Tr	F	H	Ca	Fl	Am	Other
GU-3-288.01 fracture	--	--	--	--	8	<1	1	tr	--	--	--	--	--
GU-3-288.10 fracture	--	--	--	--	7+	--	2+	--	--	--	--	--	--
GU-3-299.24 fracture	1+	--	--	--	1+	2+	<1	3+	--	--	--	--	--
GU-3-310.32 fracture	--	--	--	--	2+	2+	1+	3+	--	--	--	--	--
GU-3-318.84 fracture	--	--	--	--	8+	tr	--	1	--	--	tr(?)	--	--
GU-3-320.68 fracture	--	--	--	--	4	1	<1	4+	tr	--	--	--	--
GU-3-333.91 fracture	--	--	--	--	8+	tr	1	--	--	--	--	--	--
GU-3-334.16 fracture	--	--	--	--	1+	--	--	--	--	2+	6	--	--
GU-3-334.83 fracture	--	--	--	--	6+	<1	--	2+	--	--	--	--	--
GU-3-326.9 fracture	--	--	--	--	7	tr[a]	--	<1	--	tr	1+	--	--
GU-3-327.05 fracture	--	--	--	--	1	--	--	--	tr	1+	7	--	tr[d]
GU-3-345.10 fracture	tr	--	--	--	tr	--	--	tr	--	7+	2+	--	--
GU-3-348.70 fracture	<1	<1	--	--	2	1+[a]	--	2	--	tr[e]	--	--	2+[f]
GU-3-354.3 fracture	7+ 0.15-0.25 I	--	tr	--	--	2	--	--	--	tr[e]	--	tr	--

Table 11.--X-ray diffraction analyses of fracture mineralogy (with some groundmass mineralogy) of core from drill holes USW GU-3 and USW G-3--Continued

Sample	Minerals (Estimated amount in parts in ten)												
	Mont	IM	Cl	An	Q	Cr	Tr	F	H	Ca	Fl	Am	Other
GU-3-357.5 breccia	4+ 0.15-0.25 I	--	--	--	2+	--	--	1+	--	--	--	<1	<1[g],tr[b]
GU-3-359.65 groundmass	6+ 0.05-0.15 I	--	<1[m]	tr	--	<1	<1	tr	--	--	--	tr	tr[e]
GU-3-359.8 fracture	4 0.2-0.3 I	--	--	--	--	3[a]	tr	2	--	tr[e]	--	--	<1[g]
GU-3-369.3 fracture	3 0.2-0.3 I	--	--	--	--	2[a]	--	1	--	--	4	--	--
GU-3-414.6 groundmass	tr	tr	--	--	tr	--	--	1	--	tr[e]	--	7+	<1[b]
GU-3-428.4 groundmass	tr	tr	--	--	tr	1[a]	--	1	--	--	--	7+	--
GU-3-671.38 fracture	1+	tr	--	--	1	1+	--	3	--	--	--	1+	1[j],tr[k]
GU-3-672.88 fracture	--	--	--	--	10	--	--	--	--	--	--	--	--
GU-3-726.40 fracture	--	--	--	--	6	1+	--	2+	--	--	--	--	tr[n]
GU-3-776.59 pumice	3	tr	tr	--	tr	--	--	3	tr	--	--	--	3[g],tr[o]
GU-3-799.69 pumice	tr	tr	5	--	<1	<1[a]	--	3	--	--	--	--	5[g],tr[e]
G-3-869.38 fracture	<1	tr	--	--	1+	--	--	4	--	--	--	--	3+[g], tr[h]
G-3-893.75 fracture	--	--	--	--	1+	--	--	--	--	8+	--	--	--
G-3-897.95 fracture	--	--	--	--	--	--	--	--	--	10	--	--	tr[d]

Table 11.--X-ray diffraction analyses of fracture mineralogy (with some groundmass mineralogy) of core from drill holes USW GU-3 and USW G-3--Continued

Sample	Minerals (Estimated amount in parts in ten) Mont	IM	Cl	An	Q	Cr	Tr	F	H	Ca	Fl	Am	Other
G-3-938.41 fracture blue					tr					9+			tr[g], tr[b]
G-3-938.41 fracture white	--	--	--	--	--	--	--	--	--	10	--	--	--
G-3-938.41 fracture fibrous	tr	--	--	--	1+	--	--	--	--	8+	--	--	tr[g], tr[d]
G-3-972.50 pumice	7 0.05-0.1 I	tr	--	--	tr	<1[a]	--	1	--	tr[e]	--	tr	tr[g]
G-3-975.99 pumice	7 0.95-0.1 I	tr	--	--	--	<1[a]	--	1+		tr[e]	--	tr	tr[g]
G-3-992.77 fracture	tr	tr	--	--	2+	--	--	1+	--	--	--	--	5[i], <1[b]
G-3-1027.31 fault gouge	2 0.2-0.3 I	tr	1+	--	2+	--	--	2+	tr	--	--	1	tr[b]
G-3-1176.25 pumice	2 0-0.4 I	1+	3+	tr	1	--	--	1+	--	tr[e]	--	tr	--
G-3-1464.05 fracture	tr	--	--	tr	tr	--	--	--	--	tr	9	--	--

semiquantitative data on the frequency of occurrence of fracture minerals were collected systematically by visual identification during fracture character studies. In spite of difficulties in visual distinction between the major mineral groups, clays, zeolites, and fine-grained silica minerals, several trends are obvious on figure 24: (1) The abundance of Mn oxide minerals decreases downward from a high of nearly 50 percent of the occurrences in the Topopah Spring Member to less than 5 percent in the older tuffs. (2) The percent of occurrences of clays increases downhole from about 15 percent for the Tiva Canyon Member to about 50 percent in units below the static water level. (3) The frequency of occurrence of carbonates, largely calcite, decreases from over 30 percent in the Tiva Canyon Member to zero in the tuffaceous beds of Calico Hills, below which the frequency increases to over 40 percent. Probably the carbonate veins near the surface result from windblown carbonates deposited on Yucca Mountain, which eventually dissolved in recharge waters and were precipitated in fractures. Deeper carbonate veins are likely to reflect a more pervasive rockmass pore-water interaction that creates extensive carbonate precipitation in both the rock groundmass and veins. As stated above, the abundance of zeolites probably also increases with depth, as shown in table 11, similar to the clay trend, but difficulties in visual recognition of zeolites tend to obscure such a trend.

Fracture Frequency

Determination of fracture frequency in a volume of rock based on drill-core fracture occurrences requires special geometric considerations, primarily because fractures that cut core at angles nearly parallel to the core axis are far more abundant in the surrounding rock volume than indicated in core. A method of expression of the fracture frequency in a unit volume of rock has been derived (Scott and others, 1983). In the expression

$$F = \frac{d}{z} \sum_{i=1^{\circ}}^{i=90^{\circ}} \frac{f}{\sin i}$$

F is the fracture density per unit volume; z is the thickness of the interval of core studied; d is the diameter of the unit volume chosen; i is the angle, from 1° to 90° (any 0° measurements are counted as 1°), between the attitude of the core axis and that of the fractures; and f is the number of fractures measured within the interval of core studied for each angle i. In this work, an arbitrary unit volume of $1/m^3$ is used and, therefore, the diameter is 1.24 m. Several assumptions are used: (1) The fractures are assumed to extend throughout the rock unit volume. (2) The fractures are assumed to be planar. (3) As the angle i decreases toward 0, the statistical validity also decreases; this problem is accepted because the problem cannot be avoided. The advantages of this expression of fracture density far outweigh these weaknesses, however. Principally, the bias created by the attitude of the core is removed, even if the core attitude changes by significant drill-hole deviation. This philosophy can also be extended to surface fracture surveys along traverses, slant holes, or horizontal holes. The fracture/unit volume value provides a unit of comparison rather than an absolute number of fractures.

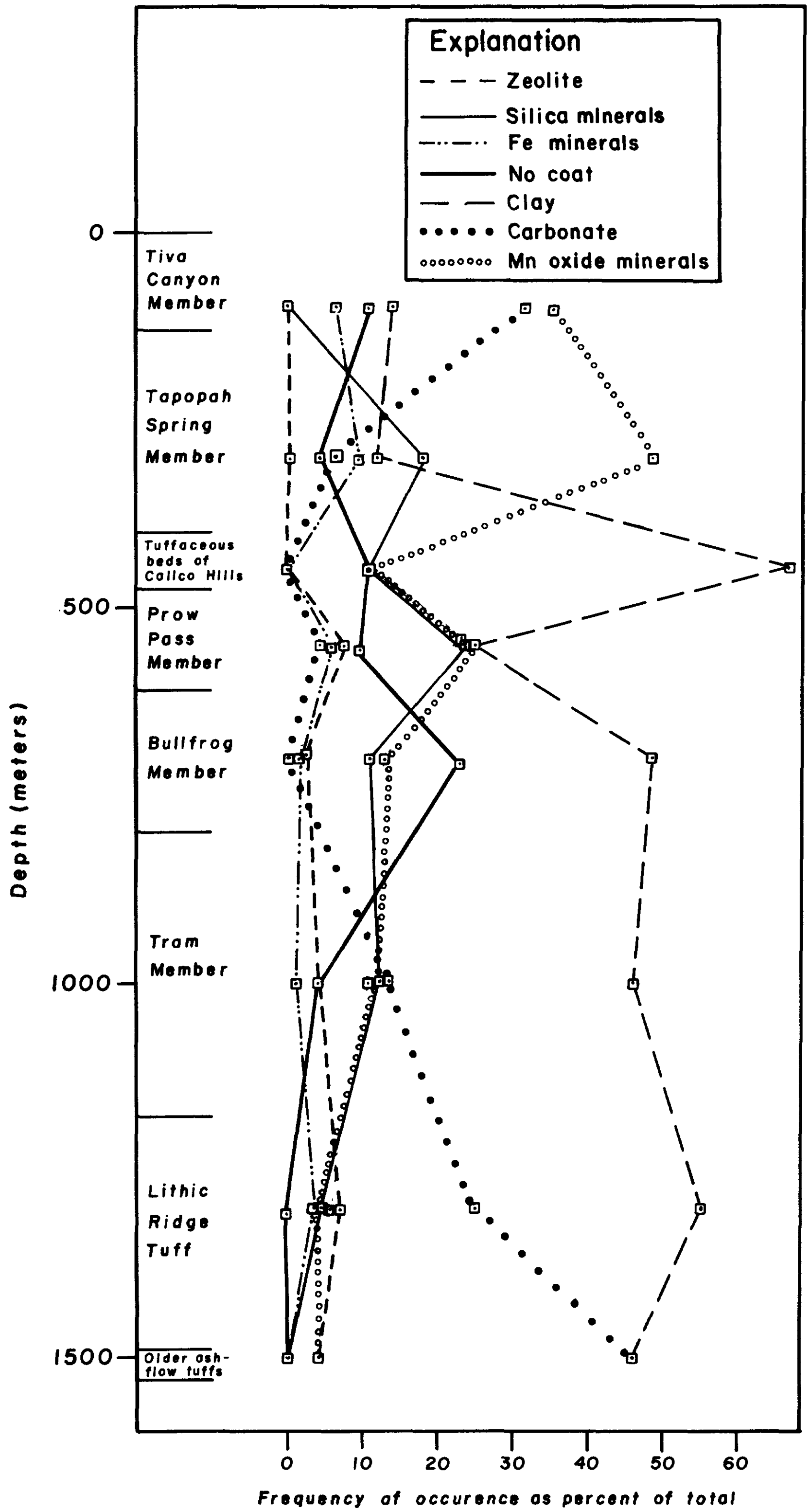

Figure 24.--Frequency of occurrences of secondary minerals found within fractures in core of drill holes USW GU-3 and USW G-3. Identification was made by hand specimen observation and was spot checked by X-ray diffraction at depths indicated in table 11. Because of the difficulties in distinction between clays, zeolites, and fine-grained silica minerals, these data should be treated as semiquantitative only. Certainly zeolites are far more common than indicated on this figure; see table 11 and descriptions in appendix 2 for a better quantitative estimate of the relative zeolite abundance.

Fracture frequency found in USW GU-3 and USW G-3 core is expressed in two ways in this study. The first is to express the number of fractures found in each 3 m (10-ft) interval without corrections for attitude. These data are drawn on plate 1 along with lithologic features. The second is a comparison of the frequency per unit cubic meter with physical-property stratigraphy (fig. 25). Several important conclusions can be reached from this comparison. First, the correlation between high-fracture frequency and degree of welding is profound. Second, the megascopic zonations within densely welded tuffs show very little variation in fracture frequencies; densely welded tuffs have fracture frequencies that range from about 15 to 40 fractures/unit m^3. Lithophysal zones tend to have slightly fewer fractures, 14 to 20 fractures/unit m^3. Lastly, below a depth of about 940 m, there is an abrupt change in the frequency of fractures, independent of degree of welding. About 8 to 23 fractures/unit m^3 are characteristic of moderately welded tuffs in the Tram Member above 940 m, yet below that depth, between 2 and 3 fractures/unit m^3 are present. Explanations for this decrease with depth may be related to (1) variations in the distribution of fracture frequencies independent of depth, such as local concentrations of fractures close to major faults, (2) an increase in confining pressures may produce more ductile behavior, (3) an increase in the degree of clay and zeolite alteration prior to formation of fractures will increase the ductile behavior of a welded tuff (4) some combination of the above.

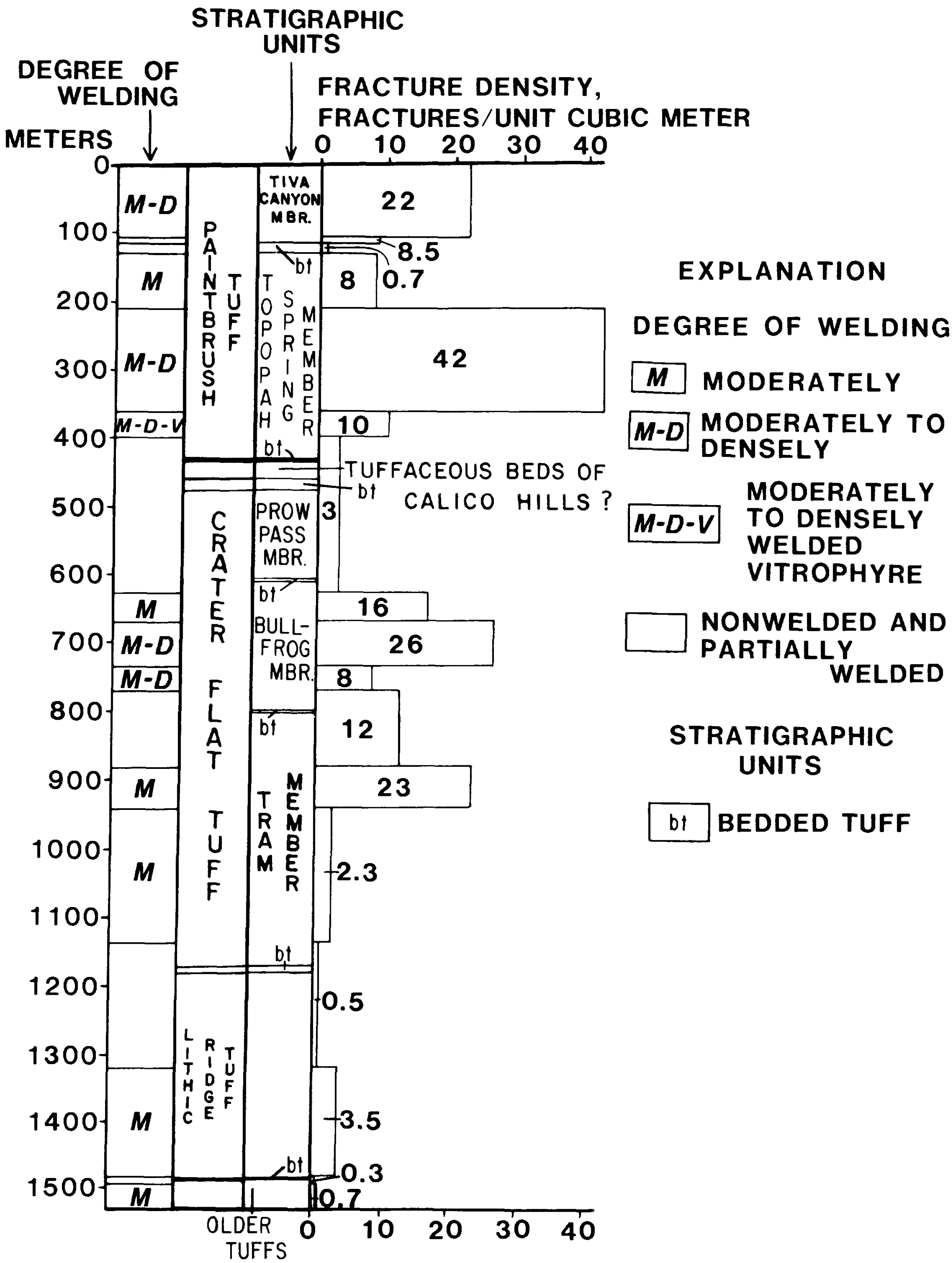

Figure 25.--Frequency of fractures compared to physical-property stratigraphy expressed by differences in degree of welding in drill holes USW GU-3 and USW G-3. These fractures include only mineralized cracks, cracks with altered walls, or cracks that have evidence of shear, such as breccia, gouge, or slickensides. The density of fractures has been calculated per unit cubic meter.

Attitude of Fractures

Fracture attitudes have been determined by oriented cores providing azimuths and inclinations of the fracture planes, by fracture surveys using downhole TV cameras above the water table providing azimuths of fracture planes, and by unoriented cores providing inclinations with no corrections for hole deviation.

Oriented cores at drill holes USW GU-3 and USW G-3 indicate that the observations of fracture attitudes made on the surface are similar to those made at depth (Scott and others, 1983; R. B. Scott and Jerry Bonk, USGS, written commun., 1983). A separate lower hemisphere diagram has been prepared for each major interval of densely welded tuff (fig. 26) and a composite of all these data (174 fractures) indicates that a continuous trend connects two large maxima, N. 2° W., 84° SW. and N. 28°W., 79° SW. A third lesser maximum at N. 52° E., 84° NW. also exists. As previously discussed, drill-hole deviation is probably related to fracture attitudes; the trend and plunge of the dip direction to the calculated fracture plane maxima is from N. 28° E., 79° SW. to N. 2° W., 84° SW., overlapping the trend and plunge of the average drill-hole deviation, N. 8° E., 82° SW.

Strikes of fractures from the surface to a depth of 142 m were collected by visual estimates of the compass direction viewed by TV downhole camera (fig. 27). Dips could not be quantified. Because of the short interval over which these fracture data were collected and the imprecision of the azimuth measurement, these data are not conclusive; but, they do show a broad maximum between N. 35° W. and N. 35° E., in general agreement with the pattern of oriented core data from the entire hole. Only the fractures that are enhanced during drilling will be distinct on TV monitor tapes, producing a bias against fractures not enhanced by drilling.

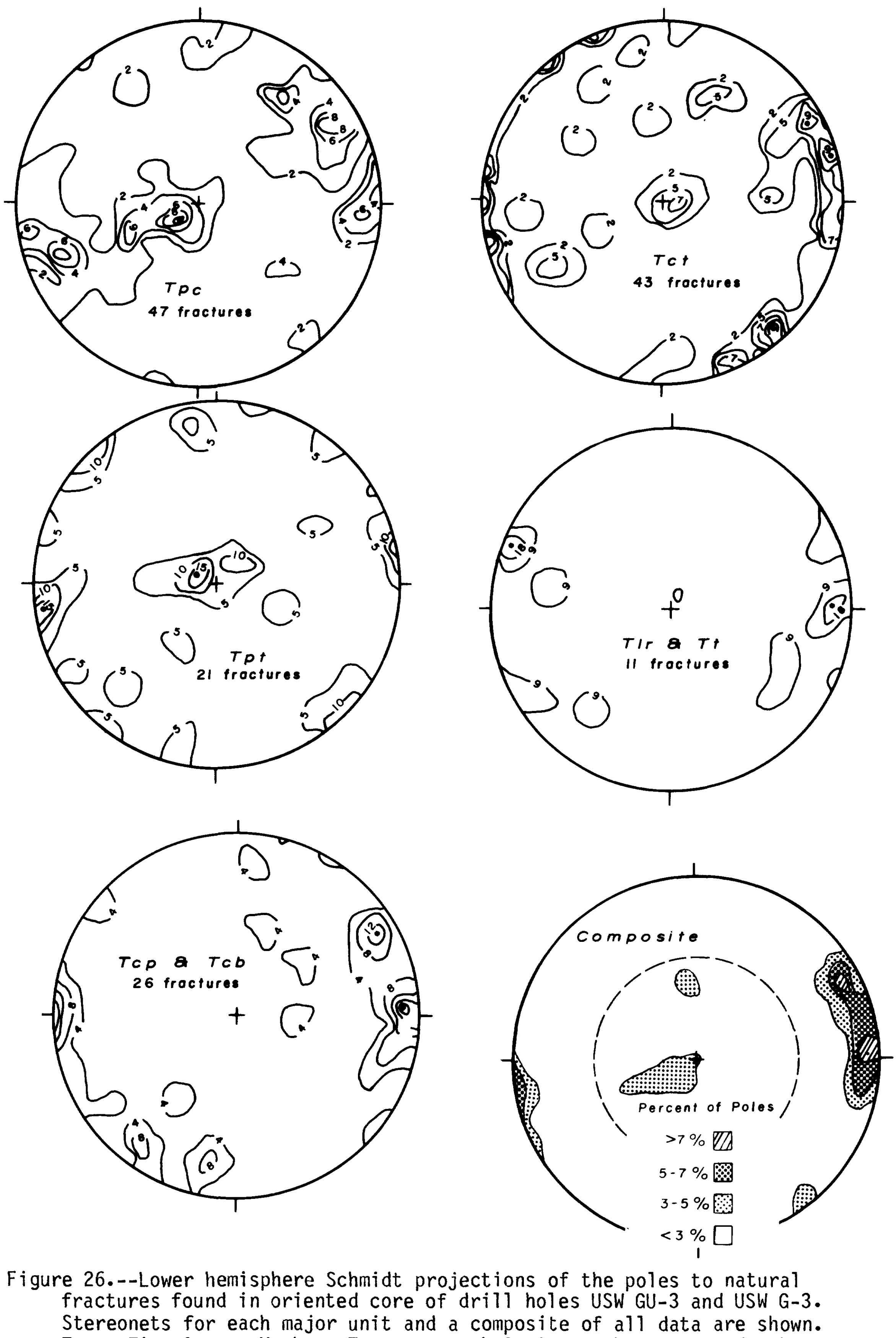

Figure 26.--Lower hemisphere Schmidt projections of the poles to natural fractures found in oriented core of drill holes USW GU-3 and USW G-3. Stereonets for each major unit and a composite of all data are shown. Tpc = Tiva Canyon Member, Tpt = Topopah Spring Member, Tcp and Tcb = Prow Pass and Bullfrog Members, Tct = Tram Member, Tlr and Tt = Lithic Ridge Tuff and older tuffs.

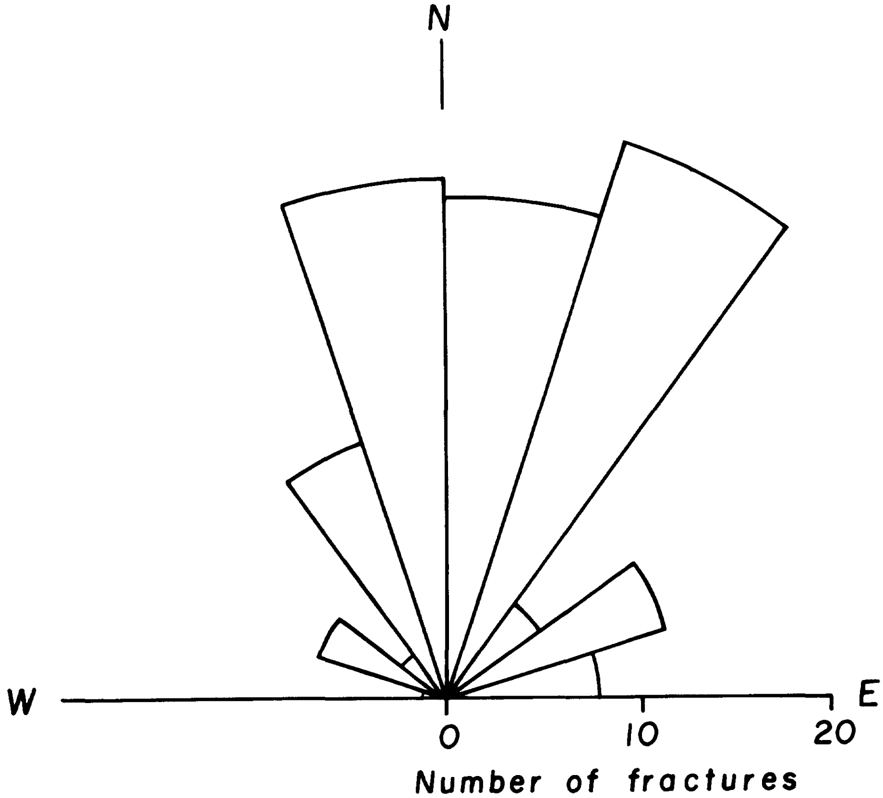

Figure 27.--Rose diagram of the fracture azimuth attitudes determined from visual interpretations of downhole TV camera tapes between 15 and 142 m depth. Magnetic declination corrections have been made, 133 fractures in total. Fractures are summed in 18° sectors.

By study of 1,500 m of core, over 2,700 natural fractures were measured; most have not been oriented in azimuth and, therefore, provide only the inclination (or dip) of the fracture planes. Drill-hole deviation adds a variance to the measure of dip, but the size of this added imprecision is not significant except in the last 400 m of core where the angle of deviation exceeds 14°. As in the case of fracture density calculations, the fracture dip must be corrected for the angle of intersection with the core axis to properly weight steeply dipping fractures. Figure 28 shows the percent of natural fractures in 10° intervals in rose diagrams for each of the major units of the physical-property stratigraphy.

During drilling of the lower portion of the drill hole, nonmineralized fractures appear to have been induced by a process of hydrofracturing the rock ahead of the drill bit. These hydrofractures are preserved in core and are seen in both TV video tapes and in sonic televiewer photographs of the drill hole (J. H. Healy, USGS, written commun., 1983). In core, they consist of nonmineralized, planar but rough fractures that essentially bisect the core for distances as great as several meters. In several cases, attitudes of these long fractures were determined from oriented core (table 12). The mean (N. 16° E.) of their strikes is close to the strikes of hydrofractures produced by hydrofrac experiments measured exterior to the core by J. R. Healy, USGS, written commun., (1983) in drill holes USW G-1 and G-2 (about N. 25° E.). Quaternary faults in Yucca Mountain also have this general attitude. This suggests that a nearly uniform attitude of minimum horizontal stress exists within Yucca Mountain, trending roughly N. 65° W. to N. 75° W.

The absolute age of fracturing is difficult to determine. Dating of fracture filling, both calcite and uraniferous opal, provides minimum ages of fractures, using U-trend and isochron-plot dating techniques. These data (table 13) were provided by J. N. Rosholt, USGS, written commun., 1982, and by B. J. Szabo and K. Kyser, written commun., 1983. The U-series isotopic dates of uraniferous opal in both holes are all older than the technique can detect (>400,000 yr). These opals coexist with younger calcites, 26,000 and 30,000 yr in USW GU-3 and 170,000 to 185,000 yr in USW G-2. Two interpretations exist for these data: (1) Old uraniferous opal veins, formed 13 to 0.4 m.y. ago, were reopened by renewed fault movement or joint formation that occurred no later than 0.17 to 0.185 m.y. ago at USW G-2 and no later than 0.025 and 0.030 m.y. at USW GU-3. (2) The younger calcite dates represent an influx of aeolian carbonate dissolved by meteoric water and reprecipitated by vadose water within fractures only partially filled with uraniferous opal. Discrimination between these interpretations awaits more detailed studies.

Faults

Numerous discontinuities that occur within the USW GU-3 and USW G-3 core have slickensided surfaces, breccia, gouge, or measurable displacement; these are therefore faults. Some 21 faults in the core occur within oriented intervals; the attitudes of these faults are shown on figure 29. The mean fault attitude is about N. 21° W., 73° SW., essentially within the trend of the maximum fracture attitude between N. 2° W., 84° SW. and N. 28° W., 79° SW.

Two types of slickensides occur in oriented core; those with near-horizontal slickensides indicative of almost pure strike-slip motion on nearly

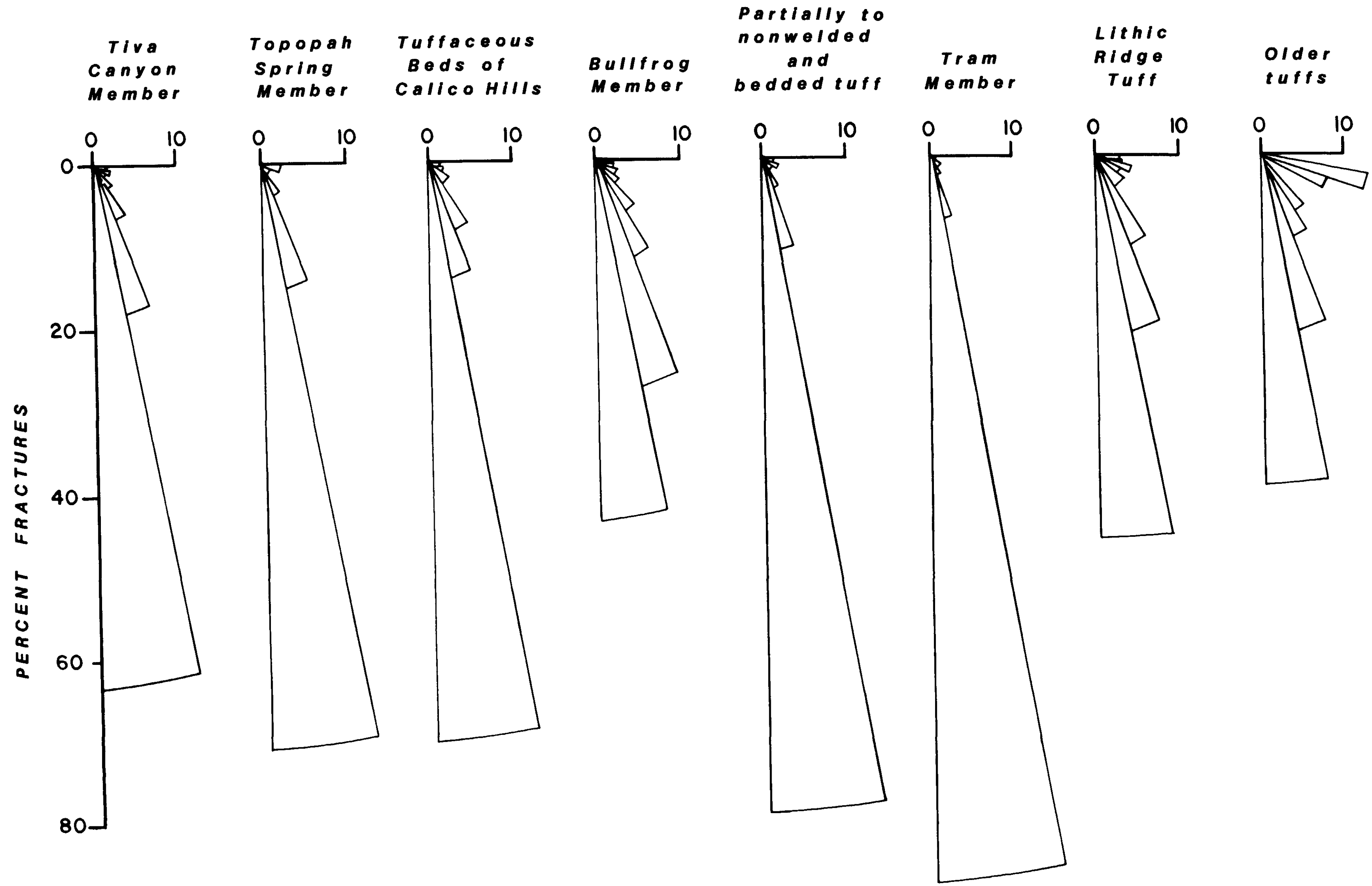

Figure 28.--Rose diagrams of the inclinations of fractures, corrected for drill-hole attitude bias, in 10° intervals for each of the major physical property stratigraphic units in drill holes USW GU-3 and USW G-3.

Table 12.--Attitudes of suspected hydrofractures in oriented cores from USW GU-3 and G-3

Depth (m)	Attitude strike	Dip	Comments
2,380.5	N. 24° W.	76° SW.	
2,382.7	N. 30° E.	82° SE.	
2,390.5	N. 3° E.	70° NW.	
2,747.8	N. 41° E.	87° NW.	3 fractures, nearly parallel, continuous for greater than 5 m
2,754.4	N. 21° E.	84° NW.	
2,756.2	N. 21° E.	87° NW.	
2,814.8	N. 61° E.	78° NW.	
2,853.1	N. 6° W.	80° SW.	1 fracture, slight changes in attitude along length
2,853.2	N. 1° W.	79° SW.	
2,853.4	N. 2° W.	82° SW.	
2,853.5	N. 6° E.	86° SW.	
3,220.6	N. 3° E.	79° NW.	
3,521.3	N. 10° E.	87° NW.	

Table 13.--U-series isotopic data for fracture filling material consisting of calcite and uraniferous opal from drill holes USW GU-3 and USW G-2

[J. N. Rosholt, B. J. Szabo and K. Kyser, analysts, USGS. Leaders (---) indicate data unavailable.]

Depth (m)	Fracture filling material	Uranium (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$ (activity ratios)	$^{230}Th/^{234}Th$	Date (10^3 yrs)
				USW GU-3		
63	calcite	0.558	2.262	35	1.004	227
		±0.011	±0.034	±7	±0.030	±20
[1]131	calcite	3.02	1.431	84	0.216	26
		±0.06	±0.021	±34	±0.009	±2
[1]131	opal	---	---	---	---	>400
		---	---	---	---	
	calcite	0.0836	0.991	2.6	1.101	>400
		±0.0017	±0.015	±0.3	±0.044	
[1]331	calcite	---	---	---	---	30±4
		---	---	---	---	
[1]331	opal	---	---	---	---	>400
		---	---	---	---	
				USW G-2		
280	calcite	0.500	1.032	12.0	1.023	>400
		±0.010	±0.015	±2.4	±0.041	
[2]347	calcite	0.405	1.167	4.29	0.915	189[2]
		±0.008	±0.018	±0.21	±0.037	±30
[2]347	bedrock	6.85	1.135	2.43	0.964	
		±0.14	±0.017	±0.10	±0.039	
349	calcite	10.073	1.02	4.6	0.73	142
		±0.006	±0.03	±0.5	±0.04	±20
[1]359	calcite A	1.21	1.020	261	0.795	170
		±0.06	±0.015	±80	±0.032	±18
359	calcite B	0.644	0.965	36	0.811	185
		±0.013	±0.014	±11	±0.032	±18
[1]359	opal	27	1.068	234	1.04	>400
		±0.5	±0.016	±70	±0.04	

[1] Coexisting portions of fracture filling and bedrock.

2 Isochron-plot date of both calcite and bedrock fractions.

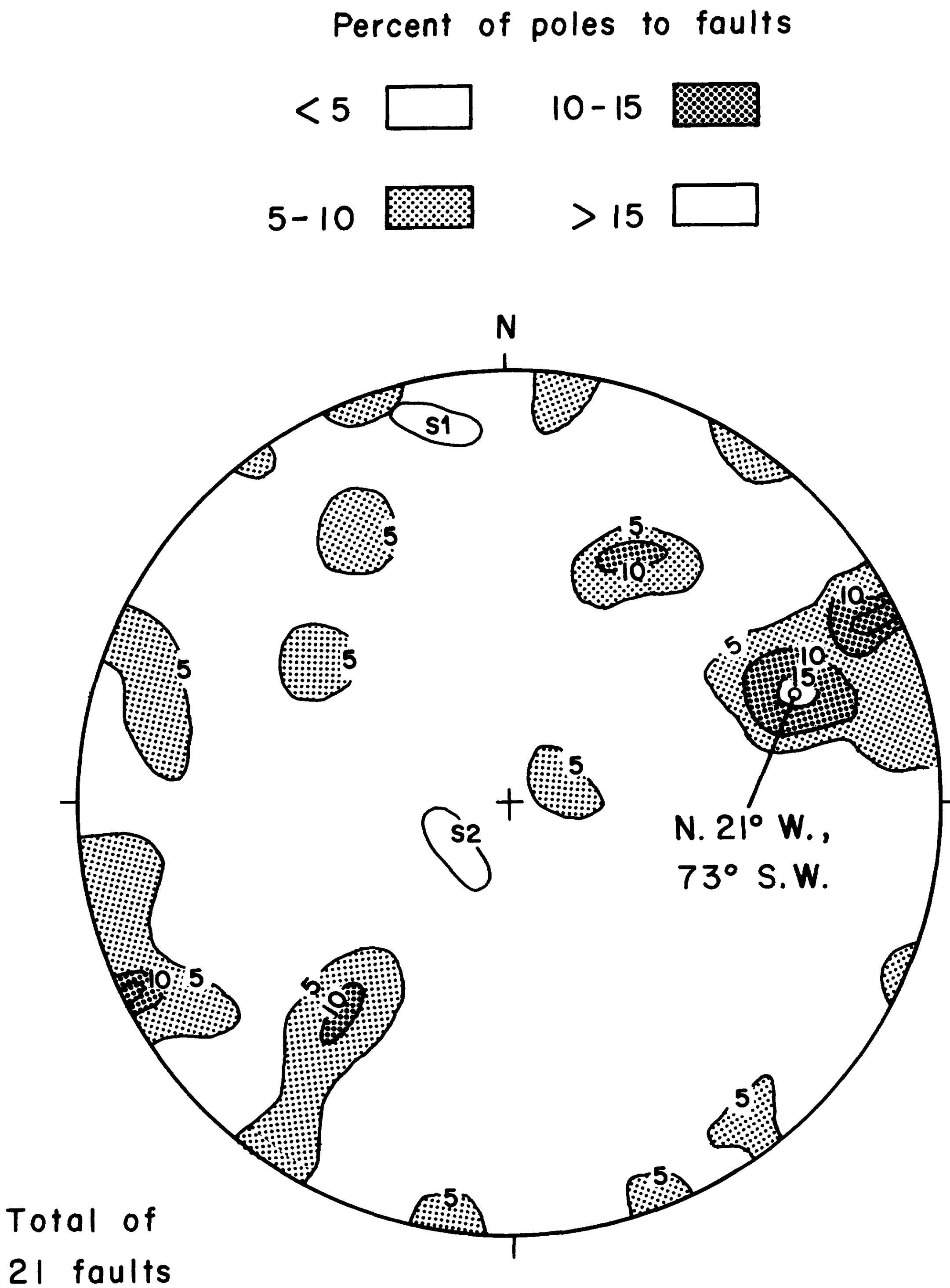

Figure 29.--Poles to oriented faults within core of drill holes USW GU-3 and USW G-3 plotted on the lower hemisphere of a Schmidt net. The maximum is shown in contours of percents of poles per 1° area to be N. 21° W., 73° SW.

vertical fault planes striking northwest, and those with slickensides indicative of almost pure dip-slip motion on fault planes that strike northeast and dip about 60^{0} to the northwest.

Correlation with Surface Structure

Detailed 1:12,000-scale mapping of the surface of Yucca Mountain has identified basically two styles of faults. A generalized structure map of the area is shown on figure 4 (R. B. Scott and Jerry Bonk, USGS written commun., 1983). One style consists of a series of nearly vertical faults that strike northwest and commonly are decorated with subhorizontal slickensides. Geometric relations restrict displacements to less than 100 m. The second style consists of larger displacement normal faults that strike northwest to northeast, dip 60^{0} to 80^{0} mostly to the west, and have dip-slip strike-slip, and oblique-slip slickensides. Thus, these structures found at the surface are generally represented in strucutres found in cores described above.

Major normal faults displace the Tiva Canyon Member, emplaced 13 m.y. ago, by hundreds of meters, but only displace the Rainier Mesa Member, emplaced 1..5 m.y. ago, by ten of meters or less. Thus, major, normal fault movement at Yucca Mountain is about 12 m.y. old (Scott and Spengler, 1982). However, minor normal fault movement and minor oblique- and strike-slip displacements on the normal faults continued to occur (Carr, 1974), at least into the Pleistocene in the NTS region. Geometric constraints on oblique slickensides on normal faults at Yucca Mountain require that right-lateral displacements occurred on normal faults that strike generally northwest, but left-lateral displacements occurred on normal faults that strike generally northeast (R. B. Scott, and Jerry Bonk, USGS, written commun., (1983). Rogers and others (1983) show focal mechanism solutions for earthquakes that infer right-lateral strike-slip motion on preexisting north- to northeast-striking faults in the NTS region. These earthquake data suggest that northwest-striking normal faults at Yucca Mountain with evidence of past right-lateral slip are no longer active. Left-lateral slip on northeast-striking normal faults may still be active on Yucca Mountain although no direct evidence of Holocene faulting is present. Minimum ages of 26,000 and 30,000 yr on calcite fracture filling material from drill hole USW GU-3 are the youngest evidence of possible faulting on Yucca Mountain, as discussed above.

Also the northwest-striking strike-slip faults at Yucca Mountain displace the Tiva Canyon Member tens of meters, but do not appear to displace the Rainier Mesa Member (R. B. Scott and Jerry Bonk, USGS, written commun., 1983). The apparent age, sense of displacement, asizmuth attitude, and location of these strike-slip faults at Yucca Mountain (Scott and others, 1983) conforms with the features of the regional Las Vegas Valley-Walker Lane shear system (Fleck, 1970; Guth, 1981).

The structural geology in the vicinity of drill holes USW GU-3 and USW G-3 and the Abandoned Wash area is shown on figure 30. One major north-northeast-striking normal faults cuts Abandoned Wash and uplifts the block east of the wash relative to the block containing Yucca Crest. Large numbers of small displacement, northwest-striking, west-dipping, normal faults occur west of this major fault where dips on the foliation of welded tuffs range

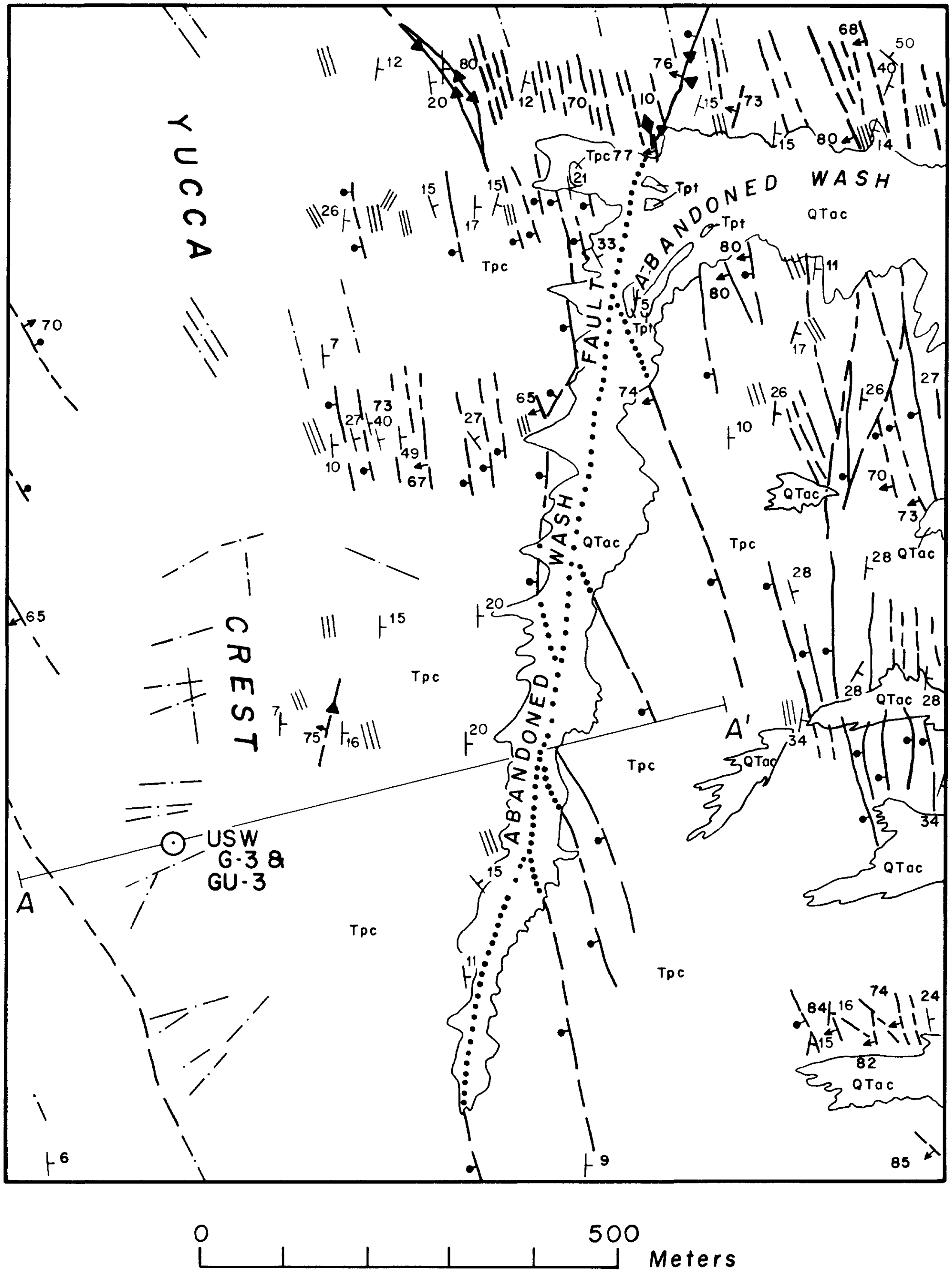

Figure 30.--Structural map in the vicinity of Abandoned Wash.

EXPLANATION

	Normal fault, bar and ball on downthrown side; dashed where inferred; dotted where concealed. Triangles locate breccia
30	*Strike and dip of foliation*
	Strike of fractures
	Strike of fractures observed on aerial photographs
10	*Trend and plunge of slickensides*
	Contact
QTac	*Alluvium and colluvium*
Tpc	*Tiva Canyon Member*
Tpt	*Topopah Spring Member*

Figure 30.--Continued

from 15° eastward to vertical; similar faults are also present on the east side of the Abandoned Wash block where dips range between 15° and 35° to the east. Although these small displacement faults have not been mapped along the section A-A' (fig. 30) drawn through drill holes USW GU-3 and USW G-3, they probably exist under the talus covered slopes between Yucca Crest and Abandoned Wash. Where well-exposed south-facing exposures occur in the northern end of Abandoned Wash, a distinct transition is evident from relatively unfaulted rocks found along Yucca Crest that have 5° to 7° eastward dips to highly faulted rocks farther to the east that have much higher eastward dips.

Projections of drill hole USW G-3 and Abandoned Wash fault are shown along cross section A-A' (fig. 31); a linear projection of the available attitude on the major north-northeast-striking normal fault (dip 77° west) was not found in the core. However, the two thickest gouge zones encountered in core, at 1,309.7-m and 1,402-m depths, may be related to the north-northeast fault provided that the dip of the fault plane decreases with increasing depth. After correction for hole deviation, the gouge zone dips at about 50°W. as shown on figure 31. Rotation of blocks shown on figure 30 and elongate downdropped blocks found elsewhere on Yucca Mountain (R. B. Scott and Jerry Bonk, USGS, written commun., 1983) suggest that concave up shaped faults may be common. Such faults are not uncommon in the Great Basin (Wernicke and Burchfiel, 1982). Also these small displacement faults shown on figure 30 may be similar to the tension fractures reported by Angelier and Colletta (1983).

The dominant north-northwest strikes of both faults and fractures in Abandoned Wash and both faults and fractures in oriented core (figs. 26 and 29) support the conclusions that even though the major fault blocks in Yucca Mountain are bounded by north- to northeast-striking faults, the north-northwest-striking grain characteristic in the Abandoned Wash region is dominant both in core and on the surface. The absence of nearly vertical strike-slip faults in this region also suggests that these north-northwest-striking faults and fractures are not directly related to the strike-slip faults in the more northern part of Yucca Mountain. They may instead be related to minor readjustments along preexisting fractures created by movement on the curved north-northeast-trending Abandoned Wash fault.

The consistent west to southwest deviation direction of drill holes recorded on Yucca Mountain (fig. 23) also requires an explanation. Drill-hole deviation is the cumulative result of drilling torques and physical anisotropies within the rock being drilled. It is commonly observed in drilling sedimentary beds with shallow dips that the drill hole will deviate toward the perpendicular to those beds. In densely welded ash-flow tuffs that have nearly isotropic physical properties with little anisotropy caused by the foliation of flattened shards and pumice, drill-hole deviations seem to have little, if anything, to do with the attitude of the ash-flow foliation. Instead, the deviations seem to be parallel to fracture or fault attitudes. In Drill Hole Wash, where high-angle structures are nearly parallel to the northwest-trending wash and have steep southwest dips, drilling deviations trend southwest, essentially perpendicular to the wash or nearly parallel to the dip of structures. In contrast, drill holes outside of Drill Hole Wash generally trend slightly south of west, essentially parallel to the dominant steeply southwest-dipping fractures observed on the surface (Scott and others,

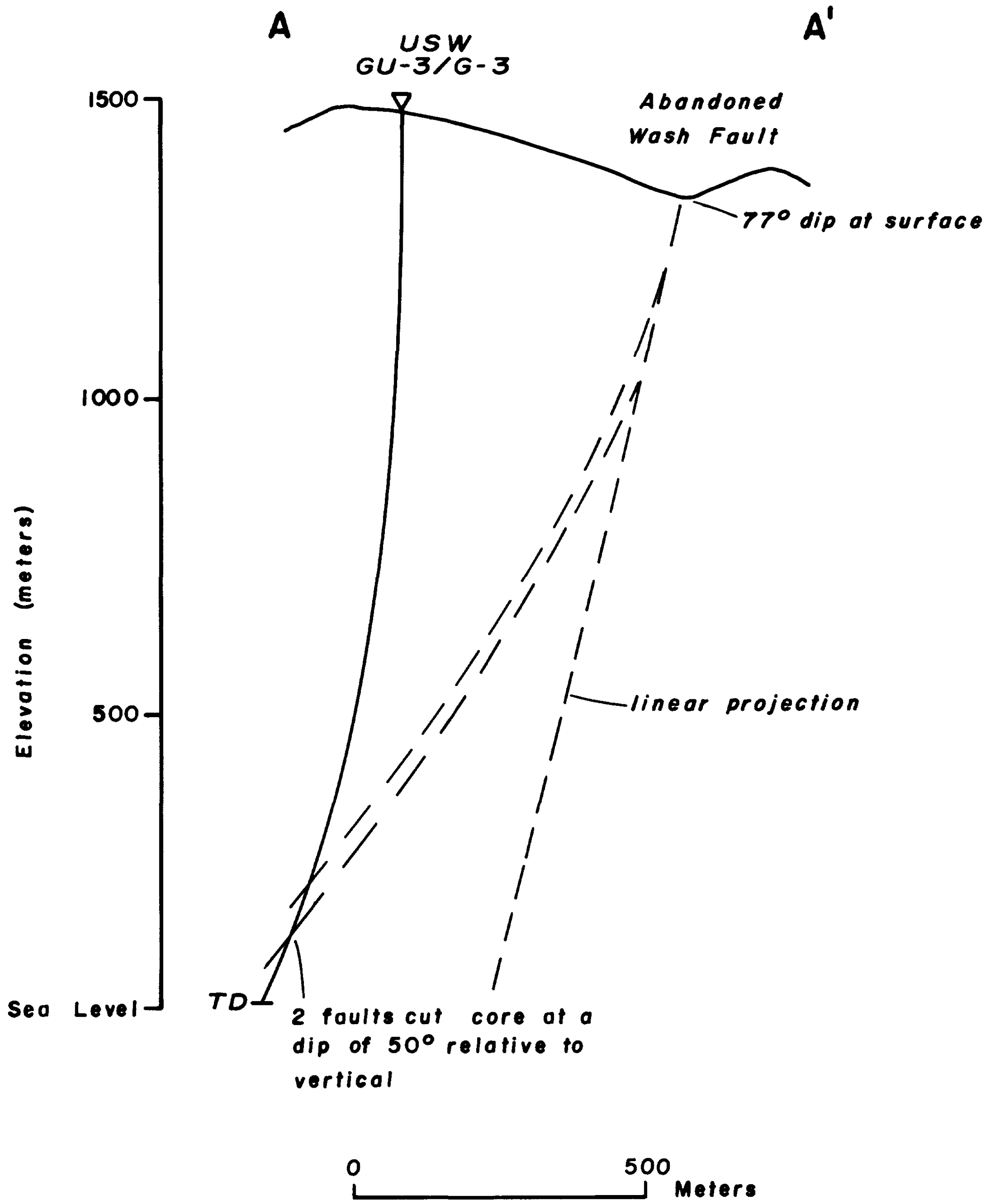

Figure 31.--Cross section along section A-A', shown on figure 30. The principal north-northeast-striking normal fault (Abandoned Wash fault) probably curves concave upward, and connects with the two thick gouge zones at 1,309.7 and 1,402 m encountered in drill hole USW G-3.

1983). It is suspected that where fracture planes dip steeper than the interval angle of friction, in otherwise nearly isotropic rocks, the fractures form the dominant anisotropy, guiding drill bits parallel to these fracture planes. If so, drill-hole deviation in these rocks becomes a sensitive integrator of the anisotropy caused by fracture planes.

SUMMARY

Stratigraphically the ash-flow tuffs cored in drill holes USW GU-3 and USW G-3 are very similar to those found in USW G-1 and USW G-2 with the exceptions that no lava flows are present in the USW GU-3 and USW G-3 core, and the interval represented by zeolitic tuffaceous beds of Calico Hills in the more northern drill holes is vitric and relatively unaltered at USW GU-3 and USW G-3. Thicknesses of major stratigraphic units found in drill holes USW GU-3 and USW G-3, corrected for drill-hole deviation and structural attitude, are: Tiva Canyon Member of the Paintbrush Tuff, 112.8 m; Topopah Spring Member of the Paintbrush Tuff, 296.0 m; tuffaceous beds of Calico Hills, 25.7 m; Prow Pass Member of the Crater Flat Tuff, 129.7 m; Bullfrog Member of the Crater Flat Tuff, 184.2 m; Tram Member of the Crater Flat Tuff, 359.6 m; Lithic Ridge Tuff, 279.7 m; older tuffs greater than 40.0 m. The Topopah Spring Member is slightly thinner at USW GU-3 and USW G-3, reflecting the greater distance from the source area of the Paintbrush Tuff. Also, the much thinner interval of nonwelded ash-flow tuff between the Topopah Spring Member of the Paintbrush Tuff and the Prow Pass Member of the Crater Flat Tuff at drill holes USW GU-3 and USW G-3 relative to other more northerly drill holes conforms with the greater distance USW GU-3 and USW G-3 from the probable source of the tuffaceous beds of Calico Hills. A considerably greater thickness of the Bullfrog and Tram Members at drill holes USW GU-3 and USW G-3 relative to more northerly drill holes suggests a closer proximity of the Crater Flat cauldron(s) to drill holes USW GU-3 and USW G-3 (Carr and others, in press).

Megascopic subdivisions of these stratigraphic units, largely based on changes in degrees of welding, the abundance of lithophysal cavities, and the abundance of lithic fragments, in drill holes USW GU-3 and USW G-3 generally correlate with subdivisions recognized in drill holes USW G-1 and USW G-2. In addition to megascopic subdivisions, petrologic subdivisions reflect changes in the phenocryst assemblages, or breaks in the eruptive processes, and therefore, represent separate eruptive surges. In particular the 360-m-thick Tram Member and the 280-m-thick Lithic Ridge Tuff consist of abundant petrologic subdivisions, 28 and more than 12, respectively.

The most distinct change in physical properties of ash-flow tuff units in Yucca Mountain does not occur at stratigraphic boundaries traditionally defined by changes in phenocryst ratios, but rather at the change from nonwelded and partially welded to moderately welded and densely welded. Because fracture densities are about an order of magnitude higher in more highly welded tuff, it can be proposed that these more welded units have higher fracture hydraulic conductivities, both in the unsaturated and the saturated zones. Thus for purposes of characterizing a sequence of relatively welded and nonwelded ash-flow tuffs as potential host rocks for a nuclear waste repository, physical-property stratigraphy is far more significant than traditional stratigraphy.

Chemically, the ash-flow tuffs from drill holes USW GU-3 and USW G-3 and elsewhere on Yucca Mountain range from high-silica rhyolites to quartz latites. This range is found within each of the chemically zoned compound cooling units of the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff. The Crater Flat Tuff shows little chemical zonation, but both the Paintbrush Tuff and Crater Flat Tuff show light rare earth element enrichment that is greater in the more quartz latitic compositions. Such trends are opposite of those found in basaltic magmas where light rare earth enrichment parallels magmatic evolution. The presence of rare earth phases, such as allanite and perrierite that are concentrated in the quartz latites, suggest unique magmatic fractionation mechanisms; discrimination of the mechanism of magmatic genesis and evolution await further detailed study.

The results of structural investigations of USW GU-3 and USW G-3 core are similar to the results of surface structural mapping. A major fault found east of the drill holes in Abandoned Wash dips westward and is correlated with faults encountered in the core. The dominant fracture and fault attitudes, both in oriented core and on the surface, are north-northwest strikes and westward dips. Dips of bedding and ash-flow tuff foliation increase from about 6^{o} eastward at the top of drill holes USW GU-3 to as much as 20^{o} eastward and southeastward in oriented core of drill hole USW G-3, the same as attitudes of strata predicted from surface projection. A structural mechanism must exist that allows both rotation of blocks and dropping of narrow blocks in the extensional structures of Yucca Mountain.

Drilling induced hydrofractures in oriented core from USW G-3 suggest a N. 74^{o} W. least principal horizontal stress, close to the N. 65^{o} W. trend determined by hydrofracture experiments in drill holes USW G-1 and USW G-2.

Uranium-trend dating of uraniferous opal and calcite fracture filling material in USW G-3 indicates that fractures with older opal fracture filling (>400,000 yr) coexist with younger, 25,000 to 30,000 yr old, calcite filling. This may represent either a period of calcite precipitation following a reactivation of fracturing or a young pulse of calcite precipitation independent of fracturing.

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Appendix 1.--Core recovery from drill holes USW GU-3 and USW G-3. (Cases of core recovery in excess of 100 percent are recorded from intervals where the length of core recovered exceeds that distance cored; although this excess core probably belongs to a higher core interval, ambiguities of precise assignment of excess core require keeping the core arbitrarily assigned to the core run number from which it was recovered. The significant figures for meters reported are at least one place beyond the precision level measurable but are used to avoid rounding off errors. Drillers and drill-site geologists recorded depths to the nearest tenth of a foot.)

USW GU-3

Core no.	Interval (meters)	Meters cored	Meters recovered	Percent recovery	Oriented core
1	9.45 - 11.58	2.13	2.13	100	
2	11.58 - 12.80	1.22	1.22	100	
3	12.80 - 15.54	2.74	2.74	100	
4	15.54 - 18.29	2.74	2.74	100	
5	18.29 - 19.51	1.22	1.16	95	
6	19.51 - 20.73	1.22	1.07	88	
7	20.73 - 21.34	0.61	0.73	120	
8	21.34 - 22.56	1.22	1.13	93	
9	22.56 - 24.08	1.52	1.52	100	
10	24.08 - 26.21	2.13	2.13	100	
11	26.21 - 29.26	3.05	3.05	100	
12	29.26 - 29.87	0.61	0.46	75	
13	29.87 - 32.00	2.13	2.13	100	
14	32.00 - 32.31	0.30	0.30	100	x
15	32.31 - 35.36	3.05	2.93	96	x
16	35.36 - 38.40	3.05	3.05	100	
17	38.40 - 41.45	3.05	3.08	101	
18	41.45 - 43.28	1.83	2.04	112	
19	43.28 - 46.33	3.05	3.05	100	x
20	46.33 - 47.85	1.52	1.83	120	
21	47.85 - 49.68	1.83	1.74	95	
22	49.68 - 52.43	2.74	2.83	103	
23	52.43 - 53.64	1.22	1.37	113	
24	53.64 - 56.69	3.05	2.62	86	
25	56.69 - 57.15	0.46	0.46	100	
26	57.15 - 58.06	0.91	0.91	100	
27	58.06 - 59.59	1.52	1.43	94	
28	59.59 - 61.42	1.83	1.83	100	
29	61.42 - 61.72	0.30	0.30	100	
30	61.72 - 63.70	1.98	1.86	94	
31	63.70 - 65.84	2.13	2.24	105	
32	65.84 - 68.58	2.74	2.74	100	x
33	68.58 - 69.49	0.91	0.91	100	
34	69.49 - 71.63	2.13	2.01	93	
35	71.63 - 74.37	2.74	2.74	100	
36	74.37 - 77.11	2.74	2.50	91	
37	77.11 - 80.16	3.05	3.05	100	
38	80.16 - 83.21	3.05	2.74	90	
39	83.21 - 85.65	2.44	2.13	88	
40	85.65 - 87.48	1.83	1.83	100	
41	87.48 - 87.93	0.46	0.82	180	
42	87.93 - 86.11	1.22	1.22	100	
43	86.11 - 89.61	0.46	0.76	167	
44	89.61 - 90.83	1.22	1.22	100	
45	90.83 - 91.44	0.61	0.70	115	
46	91.44 - 94.49	3.05	2.32	76	
47	94.49 - 95.10	0.61	0.15	25	
48	95.10 - 97.84	2.74	2.77	101	
49	97.84 - 99.97	2.13	2.26	106	
50	99.97 - 101.80	1.83	2.01	110	
51	101.80 - 104.85	3.05	3.05	100	
52	104.85 - 106.68	1.83	1.83	100	x
53	106.68 - 107.29	0.61	0.61	100	x
54	107.29 - 108.36	1.07	1.07	100	x
55	108.36 - 109.88	1.52	1.52	100	
56	109.88 - 111.40	1.52	1.52	100	
57	111.40 - 113.39	1.98	1.98	100	

Appendix 1.--Core recovery from drill holes USW GU-3 and USW G-3--Continued

USW GU-3--Continued

Core no.	Interval (meters)	Meters cored	Meters Recovered	Percent recovery	Oriented core
58	113.39 - 115.21	1.83	1.83	100	
59	115.21 - 118.26	3.05	2.13	70	x
60	118.26 - 121.31	3.05	3.05	100	x
61	121.31 - 124.36	3.05	2.01	66	x
62	124.36 - 127.41	3.05	3.05	100	x
63	127.41 - 130.45	3.05	2.65	87	
64	130.45 - 133.50	3.05	2.96	97	
65	133.50 - 136.55	3.05	2.74	90	
66	136.55 - 139.60	3.05	2.53	83	
67	139.60 - 142.65	3.05	2.96	97	
68	142.65 - 145.69	3.05	3.20	105	
69	145.69 - 148.74	3.05	3.05	100	
70	148.74 - 151.79	3.05	3.05	100	
71	151.79 - 154.84	3.05	2.83	93	
72	154.84 - 156.69	1.83	1.43	78	
73	156.69 - 157.58	0.30	0	0	
74	157.58 - 158.19	0.61	0.70	115	
75	158.19 - 162.15	3.96	3.41	86	
76	162.15 - 164.90	2.74	3.11	113	
77	164.90 - 167.03	2.13	1.68	79	
78	167.03 - 170.08	3.05	2.29	75	
79	170.08 - 171.91	1.83	1.62	88	
80	171.91 - 172.82	0.91	0.64	70	
81	172.82 - 174.65	0.61	1.22	67	
82	174.65 - 175.26	0.61	0.61	100	
83	175.26 - 175.87	0.61	0.91	150	
84	175.87 - 176.33	0.46	0.40	87	
85	176.33 - 176.63	0.30	0.46	150	
86	176.63 - 178.00	1.37	0.85	62	
87	178.00 - 179.53	1.52	1.58	104	
88	179.53 - 182.58	3.05	2.71	89	
89	182.58 - 185.62	3.05	3.05	100	
90	185.62 - 188.06	2.44	2.38	98	
91	188.06 - 190.20	2.13	1.80	84	
92	190.20 - 191.11	0.91	1.04	113	
93	191.11 - 194.16	3.05	3.05	100	
94	194.16 - 197.21	3.05	3.05	100	
95	197.21 - 200.25	3.05	2.93	96	
96	200.25 - 202.39	2.13	1.74	81	
97	202.39 - 205.44	3.05	2.90	95	
98	205.44 - 207.57	2.13	1.92	90	
99	207.57 - 210.01	2.44	2.65	109	
100	210.01 - 211.84	1.83	1.68	92	
101	211.84 - 214.58	2.74	3.05	111	
102	214.58 - 217.02	2.44	2.29	94	x
103	217.02 - 219.46	2.44	2.74	113	
104	219.46 - 222.20	2.74	2.74	100	
105	222.20 - 224.03	1.83	1.83	100	
106	224.03 - 225.86	1.83	1.98	108	
107	225.86 - 226.47	0.61	0.61	100	
108	226.47 - 229.51	3.05	3.05	100	
109	229.51 - 232.56	3.05	3.05	100	
110	232.56 - 235.61	3.05	3.05	100	
111	235.61 - 237.44	1.83	1.68	92	
112	237.44 - 238.96	1.52	1.52	100	
113	238.96 - 239.88	0.91	0.91	100	
114	239.88 - 240.33	0.46	0.46	100	
115	240.33 - 240.94	0.61	0.61	100	
116	240.94 - 241.55	0.61	0.61	100	
117	241.55 - 241.86	0.30	0.30	100	
118	241.86 - 242.62	0.76	0.76	100	
119	242.62 - 243.23	0.61	0.61	100	
120	243.23 - 243.54	0.30	0.30	100	
121	243.54 - 244.45	0.91	0.91	100	
122	244.45 - 245.36	0.91	0.91	100	

USW GU-3--Continued

Core no.	Interval (meters)	Meters cored	Meters recovered	Percent recovery	Oriented core
123	245.36 - 246.28	0.91	0.91	100	
124	246.28 - 247.50	1.22	1.22	100	
125	247.50 - 247.95	0.46	0.09	20	
126	247.95 - 248.26	0.30	0.30	100	
127	248.26 - 248.87	0.61	0.73	120	
128	248.87 - 250.55	1.68	1.92	115	
129	250.55 - 250.85	0.30	1.01	330	
130	250.85 - 251.16	0.30	0.40	130	
131	251.16 - 252.98	1.83	1.83	100	
132	252.98 - 255.12	2.13	2.01	94	
133	255.12 - 256.03	0.91	0.91	100	
134	256.03 - 258.17	2.13	1.95	91	
135	258.17 - 260.60	2.44	2.13	88	
136	260.60 - 261.82	1.22	0.85	70	
137	261.82 - 263.65	1.83	1.37	75	
138	263.65 - 264.57	0.91	0.70	77	
139	264.57 - 265.79	1.22	1.33	93	
140	265.79 - 267.00	1.22	1.22	100	
141	267.00 - 269.14	2.13	1.62	76	
142	269.14 - 270.36	1.22	1.13	93	
143	270.36 - 272.19	1.83	1.22	67	
144	272.19 - 273.25	1.07	1.07	100	x
145	273.25 - 275.23	1.98	1.31	66	x
146	275.23 - 276.15	0.91	0.91	100	
147	276.15 - 278.59	2.44	2.18	90	
148	278.59 - 280.11	1.52	1.25	82	
149	280.11 - 280.42	0.30	0.64	210	
150	280.42 - 283.16	2.74	2.74	100	
151	283.16 - 285.90	2.74	2.56	93	
152	285.90 - 287.43	1.52	1.80	118	
153	287.43 - 290.47	3.05	2.74	90	
154	290.47 - 293.52	3.05	3.05	100	
155	293.52 - 295.66	2.13	1.83	86	
156	295.66 - 297.48	1.83	1.83	100	
157	297.48 - 298.09	0.61	0.61	100	
158	298.09 - 299.62	1.52	1.52	100	
159	299.62 - 301.75	2.13	2.13	100	
160	301.75 - 303.28	1.52	1.52	100	
161	303.28 - 305.41	2.13	1.68	79	
162	305.41 - 305.71	0.30	0.91	30	
163	305.71 - 306.93	1.22	1.68	138	
164	306.93 - 307.24	?	0.40	?	
Depth correction = +1.52 m					
165	308.76 - 309.83	1.07	1.01	94	x
166	309.83 - 310.59	0.76	0.76	100	x
167	310.59 - 311.20	0.61	0.61	100	x
168	311.20 - 311.81	0.61	0.61	100	
169	311.81 - 312.12	0.30	0.37	120	
170	312.12 - 313.64	1.52	1.52	100	
171	313.64 - 314.86	1.22	1.22	100	
172	314.86 - 315.47	0.61	0.61	100	
173	315.47 - 315.77	0.30	0.30	100	
174	315.77 - 316.69	0.91	0.91	100	
175	316.69 - 317.30	0.61	0.61	100	
176	317.30 - 318.21	0.30	0.30	100	
177	318.21 - 319.74	1.52	1.52	100	
178	319.74 - 322.17	2.44	2.44	100	
179	322.17 - 323.09	0.91	0.91	100	
180	323.09 - 324.31	1.22	1.74	143	
181	324.31 - 326.44	2.13	2.04	96	
182	326.44 - 328.57	2.13	1.74	81	
183	328.57 - 331.62	3.05	3.05	100	
184	331.62 - 331.93	0.30	0.34	110	
185	331.93 - 332.54	0.61	0.61	100	x
186	332.54 - 333.76	1.22	1.22	100	x

Appendix 1.--Core recovery from drill holes USW GU-3 and USW G-3--Continued

USW GU-3--Continued

Core no.	Interval (meters)	Meters cored	Meters recovered	Percent recovery	Oriented core
187	333.76 - 336.80	3.05	3.05	100	
188	336.80 - 338.63	1.83	2.16	118	
189	338.63 - 340.46	1.83	1.83	100	
190	340.46 - 342.90	2.44	2.44	100	
191	342.90 - 343.20	0.30	0.46	150	
192	343.20 - 345.64	2.44	2.44	100	
193	345.64 - 346.86	1.22	1.31	108	
194	346.86 - 347.32	0.46	0.37	80	
Drilled 1.37 m					
195	348.69 - 349.91	1.22	1.07	88	
196	349.91 - 350.06	0.15	0.15	100	
197	350.06 - 353.11	3.05	3.20	102	
198	353.11 - 356.01	2.90	2.90	100	
199	356.01 - 358.14	2.13	2.13	100	x
200	358.14 - 360.27	2.13	2.13	100	x
201	360.27 - 360.58	0.30	0.09	30	
202	360.58 - 365.46	4.88	4.88	100	
203	365.46 - 369.42	3.96	3.96	100	
204	369.42 - 372.47	3.05	3.32	109	
205	372.47 - 376.12	3.66	3.26	89	
206	376.12 - 380.70	4.57	4.36	95	
207	380.70 - 383.44	2.74	1.42	52	
208	383.44 - 386.49	3.05	1.80	59	
209	386.49 - 388.92	2.44	1.65	68	
210	388.92 - 392.89	3.96	4.11	104	
211	392.89 - 395.94	3.05	3.05	100	
212	395.94 - 398.98	3.05	2.90	95	
213	398.98 - 400.20	1.22	1.22	100	
214	400.20 - 405.08	4.88	4.88	100	
215	405.08 - 408.13	3.05	3.05	100	
216	408.13 - 409.96	1.83	1.83	100	
217	409.96 - 410.26	0.30	0	0	
218	410.26 - 413.31	3.05	3.05	100	
219	413.31 - 416.36	3.05	3.05	100	
220	416.36 - 419.40	3.05	1.83	60	
221	419.40 - 422.45	3.05	1.52	50	
222	422.45 - 425.50	3.05	3.35	110	
223	425.50 - 428.55	3.05	3.05	100	
224	428.55 - 431.60	3.05	2.38	78	
225	431.60 - 434.64	3.05	3.05	100	x
226	434.64 - 437.69	3.05	3.02	99	x
227	437.69 - 443.79	6.10	6.10	100	
228	443.79 - 449.88	6.10	5.82	96	
229	449.88 - 455.98	6.10	5.94	98	
230	455.98 - 456.90	0.91	0.91	100	
231	456.90 - 459.94	3.05	3.05	100	
232	459.94 - 462.99	3.05	3.05	100	x
233	462.99 - 468.78	5.79	5.58	96	
234	468.78 - 471.83	3.05	2.87	94	
235	471.83 - 474.88	3.05	3.41	112	
236	474.88 - 477.93	3.05	2.99	98	
237	477.93 - 480.97	3.05	3.11	102	
238	480.97 - 484.02	3.05	3.29	108	
239	484.02 - 487.07	3.05	3.05	100	
240	487.07 - 490.12	3.05	2.65	87	
241	490.12 - 493.17	3.05	2.87	94	x
242	493.17 - 496.21	3.05	2.56	84	x
243	496.21 - 499.26	3.05	3.72	122	
244	499.26 - 502.31	3.05	3.05	100	
245	502.31 - 505.36	3.05	3.05	100	
246	505.36 - 508.41	3.05	3.05	100	
247	508.41 - 511.45	3.05	3.05	100	
248	511.45 - 514.50	3.05	3.05	100	
249	514.50 - 517.55	3.05	3.05	100	x
250	517.55 - 522.73	5.18	5.00	96	

USW-GU-3--Continued

Core no.	Interval (meters)		Meters cored	Meters recovered	Percent recovery	Oriented core
251	522.73 -	527.00	4.27	4.27	100	
252	527.00 -	532.79	5.79	5.67	98	
253	532.79 -	538.58	5.79	5.73	99	
254	538.58 -	538.89	0.30	0.12	40	
255	538.89 -	541.32	2.44	1.01	41	
256	541.32 -	544.37	3.05	3.05	100	
257	544.37 -	547.42	3.05	2.83	93	
258	547.42 -	550.47	3.05	3.05	100	
259	550.47 -	553.52	3.05	3.05	100	
260	553.52 -	556.56	3.05	3.05	100	
261	556.56 -	559.61	3.05	2.87	94	
262	559.61 -	562.66	3.05	3.05	100	
263	562.66 -	565.71	3.05	3.05	100	
264	565.71 -	568.76	3.05	2.96	97	
265	568.76 -	571.80	3.05	3.05	100	
266	571.80 -	574.85	3.05	2.99	98	
267	574.85 -	577.90	3.05	3.05	100	
268	577.90 -	580.95	3.05	2.99	98	
269	580.95 -	584.00	3.05	3.05	100	
270	584.00 -	587.04	3.05	3.05	100	
271	587.04 -	590.09	3.05	3.05	100	
272	590.09 -	593.14	3.05	3.05	100	
273	593.14 -	596.19	3.05	3.05	100	
274	596.19 -	599.24	3.05	3.05	100	
275	599.24 -	602.28	3.05	3.05	100	
276	602.28 -	605.33	3.05	3.05	100	
277	605.33 -	608.38	3.05	3.05	100	
278	608.38 -	611.43	3.05	3.05	100	
279	611.43 -	614.48	3.05	3.05	100	
280	614.48 -	617.52	3.05	3.05	100	
281	617.52 -	620.57	3.05	3.05	100	
282	620.57 -	623.62	3.05	1.89	62	
283	623.62 -	626.67	3.05	3.05	100	
284	626.67 -	629.72	3.05	3.05	100	
285	629.72 -	632.75	3.05	3.05	100	
286	632.75 -	635.81	3.05	2.65	87	
287	635.81 -	638.86	3.05	2.77	91	
288	638.86 -	640.08	1.22	1.10	90	
289	640.08 -	641.91	1.83	1.22	67	
290	641.91 -	642.82	0.91	0.91	100	
291	642.82 -	645.87	3.05	3.05	100	
292	645.87 -	648.92	3.05	3.05	100	
293	648.92 -	651.05	2.13	2.13	100	
294	651.05 -	654.10	3.05	3.05	100	
295	654.10 -	655.02	0.91	0.91	100	
296	655.02 -	657.45	2.44	2.29	94	
297	657.45 -	658.67	1.22	1.22	100	
298	658.67 -	660.20	1.52	1.52	100	
299	660.20 -	663.24	3.05	3.05	100	
300	663.24 -	666.29	3.05	2.90	95	
301	666.29 -	669.34	3.05	2.99	98	
302	669.34 -	672.39	3.05	3.05	100	
303	672.39 -	674.52	2.13	2.29	107	
304	674.52 -	677.57	3.05	2.90	95	
305	677.57 -	679.70	2.13	2.59	121	
306	679.70 -	682.75	3.05	2.68	88	
307	682.75 -	685.80	3.05	3.29	108	
308	685.80 -	687.02	1.22	1.22	100	
309	687.02 -	688.85	1.83	1.83	100	
310	688.85 -	691.29	2.44	2.44	100	
311	691.29 -	693.42	2.13	2.13	100	
312	693.42 -	694.94	1.51	1.52	100	
313	694.94 -	697.08	2.13	1.10	51	
314	697.08 -	698.91	1.83	2.01	110	
315	698.91 -	700.74	1.83	1.80	98	

Appendix 1.--Core recovery from drill holes USW GU-3 and USW G-3--Continued

USW GU-3--Continued

Core no.	Interval (meters)		Meters cored	Meters recovered	Percent recovery	Oriented core
316	700.74 -	701.95	1.22	1.22	100	
317	701.95 -	704.70	2.74	3.05	111	
318	704.70 -	707.75	3.05	3.08	101	
319	707.75 -	710.79	3.05	3.05	100	
320	710.79 -	713.54	2.74	2.74	100	
321	713.54 -	716.58	3.05	3.05	100	
322	716.58 -	719.63	3.05	2.90	95	
323	719.63 -	722.68	3.05	3.05	100	
324	722.68 -	724.20	1.52	1.13	74	
325	724.20 -	725.42	1.22	1.71	140	
326	725.42 -	725.73	0.30	0.15	50	
327	725.73 -	728.78	3.05	3.05	100	
328	728.78 -	730.00	1.22	1.22	100	
329	730.00 -	730.30	0.30	0.21	70	
330	730.30 -	730.61	0.30	0.06	20	
331	730.61 -	732.43	1.83	2.74	150	
332	732.43 -	736.40	3.96	3.05	77	
333	736.40 -	740.36	3.96	3.20	81	
334	740.36 -	742.19	1.83	1.22	67	
335	742.19 -	745.24	3.05	0.79	26	
336	745.24 -	746.76	1.51	1.16	76	
337	746.76 -	749.81	3.05	3.05	100	
338	749.81 -	752.86	3.05	3.05	100	
339	752.86 -	755.90	3.05	2.83	93	
340	755.90 -	756.21	0.30	0.30	100	
341	756.21 -	758.95	2.74	1.83	60	
342	758.95 -	760.17	1.22	1.52	125	
343	760.17 -	760.93	0.76	0.76	100	
344	760.93 -	762.30	1.37	1.68	122	
345	762.30 -	762.91	0.61	0.61	100	
346	762.91 -	765.96	3.05	2.99	98	
347	765.96 -	768.10	2.13	2.04	96	
348	768.10 -	770.84	2.74	2.74	100	
349	770.84 -	773.28	2.44	2.44	100	
350	773.28 -	776.33	3.05	3.05	100	
351	776.33 -	779.37	3.05	3.05	100	
352	779.37 -	782.42	3.05	3.05	100	
353	782.42 -	785.47	3.05	2.74	90	
354	785.47 -	788.52	3.05	2.90	95	
355	788.52 -	791.57	3.05	3.05	100	
356	791.57 -	794.61	3.05	3.05	100	x
357	794.61 -	797.66	3.05	0.49	16	x
358	797.66 -	800.71	3.05	2.87	94	x
359	800.71 -	803.76	3.05	1.71	56	
360	803.76 -	805.89	2.13	2.56	120	
GU3 TD	805.89					

G-3

Core no.	Interval (meters)		Meters cored	Meters recovered	Percent recovery	Oriented core
1	795.22 -	796.44	1.22	1.22	100	
2	796.44 -	801.01	4.57	4.42	97	
3	801.01 -	805.59	4.57	4.69	103	
4	805.59 -	809.85	4.27	4.39	103	
5	809.85 -	814.43	4.57	4.57	100	
6	814.43 -	819.00	4.57	4.57	100	
7	819.00 -	822.05	3.05	2.93	96	x
8	822.05 -	823.57	1.52	1.52	100	
9	823.57 -	825.40	1.83	1.62	88	
10	825.40 -	828.45	3.05	0.18	6	x
11	828.45 -	829.36	0.91	3.05	333	
12	829.36 -	832.41	3.05	3.23	106	
13	832.41 -	834.09	1.68	1.77	105	
14	834.09 -	837.29	3.20	3.02	94	
15	837.29 -	840.33	3.05	3.05	100	x
16	840.33 -	843.38	3.05	3.05	100	

G-3--Continued

Core no.	Interval (meters)	Meters cored	Meters recovered	Percent recovery	Oriented core
17	843.38 - 846.43	3.05	3.05	100	
18	846.43 - 849.48	3.05	3.05	100	
19	849.48 - 852.53	3.05	3.05	100	
20	852.53 - 855.57	3.05	3.27	107	
21	855.57 - 858.62	3.05	3.05	100	x
22	858.62 - 861.67	3.05	2.96	97	
23	861.67 - 864.72	3.05	3.05	100	
24	864.72 - 868.07	3.35	3.35	100	
25	868.07 - 871.12	3.05	2.96	97	x
26	871.12 - 875.39	4.27	4.27	100	
27	875.39 - 879.96	4.57	4.57	100	
28	879.96 - 883.01	3.05	3.05	100	
29	883.01 - 887.50	4.57	4.57	100	
30	887.50 - 892.76	5.18	5.18	100	
31	892.76 - 897.33	4.57	4.57	100	
32	897.33 - 901.90	4.57	4.57	100	
33	901.90 - 904.95	3.05	3.05	100	x
34	904.95 - 908.00	3.05	3.05	100	x
35	908.00 - 911.96	3.96	4.39	111	
36	911.96 - 915.01	3.05	3.05	100	x
37	915.01 - 918.06	3.05	2.80	92	
38	918.06 - 922.63	4.57	4.57	100	
39	922.63 - 927.20	4.57	4.57	100	
40	927.20 - 930.25	3.05	2.96	97	
41	930.25 - 932.38	2.13	2.36	111	
42	932.38 - 936.35	3.96	3.90	98	
43	936.35 - 940.92	4.57	4.57	100	
44	940.92 - 945.49	4.57	4.69	103	
45	945.49 - 948.54	3.05	3.05	100	
46	948.54 - 952.44	3.90	3.90	100	
47	952.44 - 957.99	5.65	5.67	102	
48	957.99 - 961.95	3.96	3.96	100	
49	961.95 - 966.83	4.88	5.06	104	
50	966.83 - 971.70	4.88	4.97	102	
51	971.70 - 977.19	5.49	5.46	99	
52	977.19 - 980.24	3.05	3.02	99	x
53	980.24 - 983.13	2.90	2.90	100	x
54	983.13 - 987.25	4.11	3.96	96	
55	987.25 - 991.21	3.96	4.15	105	
56	991.21 - 996.70	5.49	5.61	102	
57	996.70 - 1,002.18	5.49	5.61	102	
58	1,002.18 - 1,007.67	5.49	5.33	97	
59	1,007.67 - 1,013.52	5.85	5.85	100	
60	1,013.52 - 1,019.01	5.49	5.33	97	
61	1,019.01 - 1,024.43	5.43	5.49	101	
62	1,024.43 - 1,026.57	2.13	2.13	100	
63	1,026.57 - 1,032.36	5.79	5.43	94	
64	1,032.36 - 1,037.84	5.49	5.27	96	
65	1,037.84 - 1,040.89	3.05	3.05	100	
66	1,040.89 - 1,043.94	3.05	2.93	96	
67	1,043.94 - 1,047.90	3.96	3.63	92	
68	1,047.90 - 1,053.54	5.64	5.61	99	
69	1,053.54 - 1,059.33	5.79	5.76	99	
70	1,059.33 - 1,064.97	5.64	5.79	103	
71	1,064.97 - 1,070.76	5.79	5.79	100	
72	1,070.76 - 1,073.81	3.05	2.90	95	x
73	1,073.81 - 1,078.99	5.18	5.18	100	
74	1,078.99 - 1,084.48	5.49	5.70	104	
75	1,084.48 - 1,089.96	5.49	5.03	92	
76	1,089.96 - 1,095.15	5.18	5.09	98	
77	1,095.15 - 1,100.94	5.79	5.79	100	
78	1,100.94 - 1,104.90	3.96	4.05	102	
79	1,104.90 - 1,107.95	3.05	3.05	100	
80	1,107.95 - 1,111.00	3.05	3.02	99	
81	1,111.00 - 1,114.04	3.05	3.14	103	

G-3--Continued

Core no.	Interval (meters)	Meters cored	Meters recovered	Percent recovery	Oriented core
82	1,114.04 - 1,118.01	3.96	3.99	101	
83	1,118.01 - 1,123.49	5.49	5.46	99	
84	1,123.49 - 1,129.28	5.79	5.70	98	
85	1,129.28 - 1,132.33	3.05	3.05	100	
86	1,132.33 - 1,133.86	1.52	1.52	100	
87	1,122.86 - 1,136.90	3.05	2.77	91	
88	1,136.90 - 1,139.95	3.05	3.05	100	
89	1,139.95 - 1,143.00	3.05	2.80	92	
90	1,143.00 - 1,146.05	3.05	3.05	100	
91	1,146.05 - 1,149.10	3.05	3.09	105	
92	1,149.10 - 1,150.62	1.52	1.34	88	x
93	1,150.62 - 1,156.11	5.49	5.39	98	
94	1,156.11 - 1,161.29	5.18	5.46	105	
95	1,161.29 - 1,166.77	5.49	5.42	96	
96	1,166.77 - 1,172.26	5.49	5.79	106	
97	1,172.26 - 1,177.44	5.18	4.91	95	
98	1,177.44 - 1,180.49	3.05	3.11	102	
99	1,180.49 - 1,183.84	3.35	3.44	103	
100	1,183.84 - 1,186.89	3.05	3.17	104	x
101	1,186.89 - 1,192.38	5.49	5.24	96	
102	1,192.38 - 1,198.17	5.79	5.79	100	
103	1,198.17 - 1,203.66	5.49	5.70	104	
104	1,203.66 - 1,209.45	5.79	5.76	99	
105	1,209.45 - 1,212.49	3.05	3.11	102	x
106	1,212.49 - 1,215.54	3.05	3.14	103	x
107	1,215.54 - 1,221.33	5.79	5.49	95	
108	1,221.33 - 1,227.12	5.79	5.58	96	
109	1,227.12 - 1,232.61	5.49	5.43	99	
110	1,232.61 - 1,238.10	5.49	5.49	100	
111	1,238.10 - 1,243.58	5.49	5.43	99	
112	1,243.58 - 1,249.07	5.49	5.49	100	
113	1,249.07 - 1,254.56	5.49	5.82	106	
114	1,254.56 - 1,260.35	5.79	5.73	99	
115	1,260.35 - 1,263.40	3.05	3.05	100	
116	1,263.40 - 1,268.58	5.18	4.85	94	
117	1,268.58 - 1,274.37	5.79	5.76	99	
118	1,274.37 - 1,279.55	5.18	4.97	96	
119	1,279.55 - 1,279.70	0.15	0.12	80	
120	1,279.70 - 1,283.82	4.11	4.42	107	
121	1,283.82 - 1,289.61	5.79	5.76	99	
122	1,289.61 - 1,295.10	5.49	5.79	106	
123	1,295.10 - 1,300.89	5.79	5.79	100	
124	1,300.89 - 1,306.68	5.79	5.46	97	
125	1,306.68 - 1,309.73	3.05	2.94	97	x
126	1,309.73 - 1,315.21	5.49	5.79	106	
127	1,315.21 - 1,318.56	3.35	1.94	58	
128	1,318.56 - 1,320.39	1.83	0.72	39	
129	1,320.39 - 1,322.83	2.44	3.32	136	
130	1,322.83 - 1,325.88	3.05	3.32	109	x
131	1,325.88 - 1,328.93	3.05	3.05	100	x
132	1,328.93 - 1,334.72	5.79	5.85	101	
133	1,334.72 - 1,339.90	5.18	5.55	107	
134	1,339.90 - 1,341.12	1.22	1.25	103	
135	1,341.12 - 1,346.91	5.79	5.67	98	
136	1,346.91 - 1,349.96	3.05	3.03	99	
137	1,349.96 - 1,353.01	3.05	3.05	100	x
138	1,353.01 - 1,358.49	5.49	5.35	98	
139	1,358.49 - 1,364.28	5.79	5.79	100	
140	1,364.28 - 1,367.33	3.05	3.05	100	
141	1,367.33 - 1,371.60	4.27	4.54	106	
142	1,371.60 - 1,375.56	3.96	3.87	98	
143	1,375.56 - 1,381.35	5.79	5.73	99	
144	1,381.35 - 1,387.14	5.79	5.70	98	
145	1,387.14 - 1,390.19	3.05	3.14	103	x
146	1,390.19 - 1,395.98	5.79	5.64	97	

Appendix 1.--Core recovery from drill holes USW GU-3 and USW G-3--Continued

G-3--Continued

Core no.	Interval (meters)	Meters cored	Meters recovered	Percentage recovery	Oriented core
147	1,395.98 - 1,401.32	5.33	5.51	103	
148	1,401.32 - 1,407.11	5.79	5.61	97	
149	1,407.11 - 1,410.61	3.51	2.80	80	
150	1,410.61 - 1,415.19	4.57	4.24	93	
151	1,415.19 - 1.420.98	5.79	5.79	100	
152	1,420.98 - 1,422.20	1.22	1.25	103	x
153	1,422.20 - 1,425.24	3.05	2.99	98	
154	1,425.24 - 1,430.12	4.88	5.39	111	
155	1,430.12 - 1,435.91	5.79	5.79	100	
156	1,435.91 - 1,441.70	5.79	5.79	100	
157	1,441.70 - 1,447.19	5.49	5.49	100	
158	1,447.19 - 1,452.98	5.79	5.67	98	
159	1,452.98 - 1,458.77	5.79	5.79	100	
160	1,458.77 - 1,464.56	5.79	5.52	95	
161	1,464.56 - 1,467.61	3.05	3.05	100	
162	1,467.61 - 1,472.79	5.18	5.30	102	
163	1,472.79 - 1,478.58	5.79	5.79	100	
164	1,478.58 - 1,484.38	5.79	5.52	95	
165	1,484.38 - 1,490.17	5.79	5.55	96	
166	1,490.17 - 1,493.22	3.05	3.05	100	x
167	1,493.22 - 1,495.35	2.13	2.04	96	
168	1,495.35 - 1,500.23	4.88	5.18	106	
169	1,500.23 - 1,506.02	5.79	5.67	98	
170	1,506.02 - 1,511.81	5.79	5.82	101	
171	1,511.81 - 1,514.86	3.05	3.05	100	
172	1,514.86 - 1,518.51	3.66	3.90	107	
173	1,518.51 - 1,524.30	5.79	5.76	99	x
174	1,524.30 - 1,527.35	3.05	3.05	100	
175	1,527.35 - 1,530.40	3.05	3.14	103	
176	1,530.40 - 1,533.39	2.99	2.75	92	x
TD	1,533.39				

Appendix 2.--Lithologic description of core at drill hole USW GU-3 and USW G-3

[Phenocryst modal analyses of thin sections of selected core samples by R. B. Scott. Identification of groundmass alteration mineralogy by X-ray diffraction by D. L. Bish (Los Alamos National Laboratory) and fracture mineralolgy by X-ray diffraction by P. D. Blackmon (USGS); degrees of alteration are given in terms to describe relative amounts: Peak intensities of groundmass alteration phases are trace = <1, rare = 1 to 2, sparse = 2 to 10, common = 10 to 30, abundant = 30 to 60, and extensive = 60 to 100. Color designations are from Rock-Color Chart (Goddard and others, 1948). This log contains more explicit information than logs for drill holes USW-G1 and -G2; for example, phenocryst modes and x-ray diffraction data are included. These differences do not detract from the obvious correlations between major units. Attitudes of bedded intervals relative to the core axis are not included in this log because of the large drill-hole deviation (nearly 25^{o} at T.D., total depth); deviation corrected data are presented with corrected thicknesses in tables 6, 7, and 8. Broken dashed lines (-- -- --) represent distinct cooling breaks in the ash-flow tuff sequence]

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Drill hole USW GU-3		
Paintbrush Tuff		
Tiva Canyon Member		
Drilled and cased, surface exposures are similar to cored unit below--	9.45	
Tuff, ash-flow, light-brownish-gray (5YR6/1), devitrified, moderately welded, vapor phase; pumice, two varieties, common, very light gray (N8) and less common, medium-light-gray (N6), as large as 1.5 cm along foliation plane; 16 percent phenocrysts consist of 64 percent sanidine, 28 percent plagioclase, 5 percent biotite, 1 percent opaque oxides, and 1 percent quartz; 1 percent light-gray (N7) silicic volcanic lithic fragments, as large as 1 cm; extensive calcite in groundmass from caliche, groundmass partially altered to sparse smectite------	Thin section at 9.53; 9.55	Biotite-rich moderately welded ash-flow tuff
Cement, casing cement filled cavity (?)--------------------	13.15	
Tuff, ash-flow, light-gray (N7), devitrified, moderately to densely welded, vapor phase; pumice sparse to common, very light gray (N8), as large as 4 cm along foliation plane; 6 percent phenocrysts consist of 88 percent sanidine, 7 percent plagioclase, 3 percent biotite, 1 percent hornblende, and 1 percent opaque oxides; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 0.5 cm; lithophysal cavities form 3 to 15 percent of the rock, as large as core diameter (6 cm); cavities lined with vapor phase crystals of tridymite, cristobalite, hematite platelets, and sanidine, very light gray (N8) reaction rim 1 to 5 mm thick surrounds cavities, some cavities consist of very porous pumice-like lenticules;	Thin section at 13.90	Less mafic, moderately to densely welded ash-flow tuff with sparse to abundant lithophysal cavities

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Tiva Canyon Member--Continued		
calcite coats cavities where fractures intersect cavities; fractures contain calcite------------------------------------	19.51	
Tuff, ash-flow, light-gray (N7) with a slight tint of light-brownish-gray (5YR6/1) grading downhole into light-brownish-gray (5YR6/1), devitrified, moderately to densely welded; pumice, common, white (N9) to very light gray (N8), as large as 4 cm along foliation plane, a few pumice fragments are centers of incipient lithophysal cavities; 3 percent phenocrysts consist of nearly 100 percent sanidine with a trace of biotite and opaque oxides; much less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 0.4 cm; groundmass unaltered to partially altered to rare to sparse calcite; fractures contain calcite, smectite, and breccia--------------------------------	Thin section at 23.89 64.71	Absence or near absence of lithophysal cavities in a moderately to densely welded ash-flow tuff
Tuff, ash-flow, light-brownish-gray (5YR6/1), devitrified, moderately to densely welded, vapor phase; pumice, sparse, pinkish-gray (5YR8/1), as large as 2.5 cm along foliation plane; 3.5 percent phenocrysts consist of 93 percent sanidine, 4 percent plagioclase cores (rimmed with sanidine), and 4 percent hornblende; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 0.4 cm; lithophysal cavities form 2 to 15 percent of the rock, as large as core diameter (6 cm), most have 2 to 8 mm pinkish-gray altered rims, cavities are lined with vapor-phase crystals of tridymite, cristobalite, hematite platelets, and sanidine; groundmass partially altered to rare to sparse smectite; fractures contain calcite, clay, palygorskite, and breccia--	Thin section at 74.90 85.65	Sparse to abundant lithophysal cavities in moderately to densely welded ash-flow tuff
Tuff, ash-flow, light-brownish-gray (5YR 6/1) grading downhole to pale-red (5R6/2) with black flattened eutaxitic pumice, devitrified, moderately to densely welded downhole to 91 m, moderately welded below; pumice, common, light-gray (N7) to medium-light-gray (N6) in the brownish portion grading downhole into black (N1) in the reddish portion, at color change pumice has common spherulitic growths and is altered to pale-red (10R6/2), as large as 4 cm along foliation plane; 3 percent phenocrysts consist of 95 percent sanidine and 4 percent hornblende; 1 percent silicic volcanic lithic fragments, as large as 0.5 cm; subhorizontal parting at 104.04 m contains 18 percent phenocrysts and 5 percent volcanic lithic fragments; groundmass	Thin sections at 92.56 and 104.04	Absence of lithophysal cavities in moderately to densely welded to moderately welded ash-flow tuff with eutaxitic textures near base

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Tiva Canyon Member--Continued		
unaltered to partially altered to a trace of smectite, pumice partially altered to smectite and illite; fractures contain calcite, clay, Mn oxides and hydroxides, and breccia-----	104.70	
Tuff, ash-flow, brownish-gray (5YR4/1) to medium-gray (N5), vitrophyre, moderately to densely welded; pumice common, black (N1), eutaxitic texture, as large as 4 cm along foliation plane; 4 percent phenocrysts consist almost entirely of sanidine with a trace of hornblende; less than 1 percent light-gray (N7) silicic volcanic lithic fragments, as large as 0.2 cm; groundmass partially altered to sparse smectite; fractures contain clays-----------	106.09	Basal vitrophyre of moderately to densely welded ash-flow tuff
Tuff, ash-flow, grayish-orange-pink (5YR7/2) grading downhole to grayish-orange (10YR7/4), vitric, moderately welded downhole to about 108 m, partially welded to about 110 m and nonwelded below, vitric; pumice, common, increasing to abundant in basal 0.5 m, vitrophyric black (N1) except at base where grayish-orange (10YR7/4), as large as 2 cm along foliation plane except near base where as large as 6 cm; 2 to 4 percent phenocrysts consist almost entirely of sanidine with a trace of hornblende; less than 1 percent light-gray (N7) and vitrophyric grayish-black (N2) siliceous volcanic lithic fragments, as large as 2 cm; groundmass partially altered to sparse smectite; fractures contain smectite and calcite-------------	Thin section at 108.59 113.90	Moderately welded to nonwelded basal portion of ash-flow tuff
-- -- -- -- (cooling break) -- -- -- --		
Bedded Tuff		
Tuff, bedded, largely pyroclastic fall, in part nonwelded ash-flow tuff and minor reworked tuff, poorly indurated, grayish-orange-pink (5YR7/2) grading downhole through very pale orange (10YR8/2), through pale-yellowish-brown (10YR6/2) through light-gray (N7) through light-brown (5YR6/4) through pinkish-gray (5YR8/1) to pale-yellowish-brown (10YR6/2) to grayish-orange (10YR7/4) through light-brown (5YR6/4) through moderate-red (5R5/4) through pale pink (5RP8/2) through pale-purple (5P6/2) to pale-red (5R6/2) through grayish-red (10R4/2) and to light-gray (N7); pumice-rich layers alternate with ash-rich layers, beds vary from 0.2 cm to 3 m thick, sorting has concentrated up to 80 percent pumice fragments in layers, pumice as large as 2 cm; vitric material partially altered to sparse to common smectite-----------------------------------	129.19	Bedded tuff
-- -- -- -- (cooling break) -- -- -- --		

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Topopah Spring Member		
Tuff, ash-flow, grayish-red grading downhole over a 0.2-m interval to very light gray (N8) to pinkish-gray (5YR8/1), partially vitric, nonwelded to moderately welded, vapor phase; pumice, common, pinkish-gray (5YR8/1) and light-brownish-gray (5YR6/1), two colors of pumice coexist, as large as 4 cm along foliation plane; 6 percent phenocrysts consist of 56 percent sanidine, 38 percent plagioclase, 4 percent biotite, 1 percent quartz, 1 percent opaque oxides, and a trace of clinopyroxene; 3 percent very light gray (N8) silicic volcanic lithic fragments, as large as 1.5 cm; vapor-phase crystals of tridymite, cristobalite, and sanidine occur; groundmass unaltered to partially altered to sparse calcite--	Thin section at 129.33 130.40	Nonwelded to moderately welded biotite-rich ash-flow tuff
Tuff, ash-flow, light-brownish-gray (5YR6/1) to brownish-gray (5YR4/1) to medium-gray (N5), partially vitric vitrophyre, moderately welded, vapor phase; pumice common, blackish-red (5R2/2), as large as 4 cm along foliation plane; about 17 percent phenocrysts consist of about 47 percent sanidine, 43 percent plagioclase, 4 percent biotite, 3 percent opaque oxides, 2 percent clinopyroxene, and less than 1 percent quartz; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 1.5 cm; vapor-phase crystals of tridymite, cristobalite, and sanidine occur; groundmass unaltered to partially altered to sparse calcite------------------------------	131.00	Biotite- and clinopyroxene-rich vitrophyre, moderately welded ash-flow tuff
Tuff, ash-flow, pale-red (5R6/2) to grayish-pink (5R8/2), devitrified, moderately welded, vapor phase; pumice, common, pinkish-gray (5YR8/1) and light-brownish gray (5YR6/1), two colors of pumice coexist, as large as 6 cm along foliation plane; 14 to 17 percent phenocrysts consist of 47 to 65 percent sanidine, 24 to 43 percent plagioclase, 4 percent biotite, 3 to 5 percent opaque oxides, 2 percent clinopyroxene, and less than 1 percent quartz; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 1.5 cm; vapor-phase crystals of tridymite, cristobalite and sanidine occur; groundmass unaltered to partially altered to sparse calcite; fractures contain clay, calcite, and rare breccia---	Thin sections at 131.27 and 141.58 150.04	Biotite- and clinopyroxene-rich moderately welded ash-flow tuff
Tuff, ash-flow, light-brownish-gray (5YR6/1) to pinkish-gray (5YR8/1) to light-gray (N7) grading downhole to light-gray (N7), devitrified, moderately welded, vapor	Thin section at 160.23	Less mafic-and phenocryst-rich moderately welded

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Topopah Spring Member--Continued		
phase; pumice, common, very light gray (N8), medium-gray (N5), and light-brownish-gray (5YR6/1), as large as 5 cm along foliation plane, different colors coexist, some pumice are very porous and resemble incipient lithophysal cavities lined with vapor-phase tridymite, cristobalite, and sanidine; 5 percent phenocrysts consist of 70 percent sanidine, 23 percent plagioclase, 4 percent opaque oxides, and 3 percent biotite; very rare light-gray (N7) silicic volcanic lithic fragments, as large as 1 cm; fractures contain calcite, clay, and Fe and Mn oxides and hydroxides---	167.90	ash-flow tuff
Tuff, ash-flow, very light gray (N8) to light-gray (N7) grading downhole through light-brownish-gray (5YR6/1) and to pale-red (5R6/2), devitrified, moderately welded, vapor phase; pumice, sparse to common, light-brownish-gray (5YR6/1) to brownish-gray (5YR4/1), as large as 7 cm along foliation plane, lighter colored and more siliceous pumice fragments are centers of lithophysal cavities; 1 percent phenocrysts consist of 65 percent plagioclase, 30 percent sanidine and 5 percent biotite; much less than 1 percent very light gray (N8) silicic volcanic and granitic lithic fragments, as large as 3 cm; convolute and lobate lithophysal cavities form 5 to 20 percent of rock, as large as 7 cm or more, 2 to 5 mm thick pinkish-gray (5YR8/1) alteration zones rim lithophysal cavities, cavities are lined with vapor-phase crystals of tridymite, cristobalite, sanidine, and sparse secondary calcite; groundmass unaltered to partially altered to a trace of smectite and to sparse calcite; fractures contain calcite, Mn oxides and hydroxides, tridymite, hematite, illite mica, and rare breccia----------------------	Thin section at 193.03 210.39	Common to abundant lithophysal cavities in moderately welded ash-flow tuff
Tuff, ash-flow, pale-red (5R6/2) grading downhole through pale-red (10R6/2) through grayish-orange-pink (5YR7/2) and to light-brownish-gray (5YR6/1), devitrified, moderately to densely welded, vapor-phase crystals line lithophysal cavities; pumice, sparse to common, pinkish-gray (5YR8/1) to very light gray (N8), as large as 3 cm along foliation plane; much less than 1 percent phenocrysts consist of 60 percent plagioclase, 20 percent sanidine, and 20 percent opaque oxides; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 3 cm, abundance and size increases downhole; lithophysal cavities form 2 to 5 percent of the rock down to 222 m and	Thin section at 234.42	Gradation from sparse to rare lithophysal cavities downhole in moderately to densely welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Topopah Spring Member--Continued		
form less than 1 percent of the rock below, as large as 6 cm, cavities are lined with vapor-phase crystals of tridymite, cristobalite, and sanidine; groundmass partially altered to a trace of smectite; fractures contain Mn oxides and hydroxides, opaline silica, quartz, tridymite, cristobalite, smectite, illite mica, palygorskite, hematite, clinoptilolite, mordenite, fluorite and calcite--------------	275.52	
Tuff, ash-flow, pale-red (5R6/2), grading downhole through pale-red (10R6/2) to pale-red (10R6/2) mottled with grayish-pink (5R8/2), devitrified, moderately to densely welded, vapor-phase; pumice, sparse, pinkish-gray (5YR8/1) and grayish-pink (5R8/2), as large as 4 cm along foliation plane; 1.5 percent phenocrysts consist of 90 percent plagioclase, 5 percent sanidine, and 5 percent biotite; less than 1 percent very light gray (N8) silicic volcanic lithic fragments, as large as 3 cm, abundance increases gradually downhole; lithophysal cavities form 1 to 3 percent of the rock down to 296.7 m and less than 1 percent below, as large as 6 cm, cavities are lined with tridymite, cristobalite, hematite, and sanidine; groundmass unaltered to partially altered to a trace to sparse smectite; fractures contain Mn oxides and hydroxides, calcite, quartz, tridymite, cristobalite, and smectite------------------------	Thin section at 291.04 318.21	Gradation from sparse to rare lithophysal cavities downhole in moderately to densely welded ash-flow tuff
Tuff, ash-flow, brownish-gray (5YR4/1) mottled with light-brownish-gray (5YR6/1) with subhorizontal stringers and irregular pockets 1 to 3 mm thick grading downhole through grayish-red (5R4/2) to pale-red (5R6/2) mottled with pale-yellowish-brown (10YR6/2) and to brownish-gray (5YR4/1) mottled with grayish-orange (10YR7/4) to pale-yellowish-brown (10YR6/2), devitrified, moderately to densely welded; pumice, common, pinkish-gray (5R8/2) to light-gray (N7) grading downhole through grayish-orange-pink (5YR7/2) and light-gray (N7) and to pale-yellowish-orange (10YR8/6), as large as 4 cm along foliation plane; 1 percent phenocrysts consist of 60 percent plagioclase, 30 percent sanidine, and 10 percent quartz; 4 percent very light gray (N8), yellowish-gray (5Y8/1), and light-brownish-gray (5YR6/1) silicic volcanic lithic fragments, as large as 8 cm; pale-yellowish-brown pumice altered to clay near base, groundmass unaltered to partially altered to a trace of smectite, locally extensively altered to smectite with 5 to 15 percent illite mixed layers, heulandite/clinoptilolite, analcime, tridymite, cristobalite, and siderite; fractures contain	Thin section at 344.52	Highly mottled moderately to densely welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Paintbrush Tuff--Continued		
Topopah Spring Member--Continued		
quartz, cristobalite, tridymite, calcite, clinoptilolite, analcime, mordenite, fluorite, Mn oxides and hydroxides, hematite, lepidocrocite, smectite, and illite mica------------	361.87	
Tuff, ash-flow, medium-light-gray (N6) to medium-gray (N5), vitrophyre, densely welded; pumice, common, black (N1), as large as 6 cm along foliation plane; 1.5 percent phenocrysts consist of 40 percent plagioclase, 40 percent sanidine, 8 percent quartz, 8 percent opaque oxides, and 4 percent biotite; 2 percent very light gray (N8) and pinkish-gray (5YR8/1) silicic to intermediate volcanic lithic fragments, as large as 5.5 cm; groundmass partially altered to rare to sparse smectite; fractures contain clinoptilolite, smectite, illite mixed layer clay, fluorite, and Mn oxides and hydroxides----------------------------------	Thin section at 373.94 386.74	Vitrophyre of densely welded ash-flow tuff
Tuff, ash-flow, grayish-orange (10YR7/4) grading downhole through moderate-orange-pink (5YR8/4) to very pale orange (10YR8/2) to grayish-orange-pink (5YR7/2) speckled with grayish-black (N2), vitric, moderately welded downhole to 396 m, partially welded below; pumice, common, black (N1) in moderately welded portion grading downhole through moderate-brown (5YR3/4) through light-brown (5YR5/6) to grayish-orange (10YR7/4), as large as 6 cm along foliation plane; 1.5 percent phenocrysts consist of about 40 percent plagioclase, 30 percent sanidine, 10 percent quartz, 10 percent biotite, and 5 percent opaque oxides; 8 percent very light gray (N8), medium-gray (N5), and grayish-red (5R4/2) silicic and somewhat intermediate volcanic lithic fragments, as large as 5 cm; groundmass unaltered to altered to rare to sparse smectite and a trace of illite mica; fractures contain calcite-------------------------------------	Thin section at 397.00 399.00	Moderately welded to partially welded base of ash-flow tuff
Tuff, ash-flow, grayish-orange-pink (5YR7/2) through very pale-orange (10YR8/2) to pinkish-gray (5YR8/1), vitric, nonwelded; pumice, sparse to common, as great as 3 cm; about 1 percent phenocrysts consist of about 35 to 40 percent plagioclase, 25 to 35 percent sanidine, 25 percent quartz, and a trace to 10 percent biotite; sparse to common very light gray (N8), grayish-red (5R4/2) and black (N1) silicic volcanic lithic fragments, as large as 2 cm; extremely friable---------------------------------------	Thin section at 419.60 and 428.40 428.65	Nonwelded base of ash-flow tuff

-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- (cooling break) -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Bedded tuff		
Tuff, bedded, pyroclastic fall with very minor possible reworking, moderately to very poorly indurated, grayish-pink (5R8/2) grading downhole through pinkish-gray (5YR8/1) and to very light gray (N8); 1 cm-thick ash-rich layer overlies homogeneous tuffaceous pumice and lithic fragment sandstone with 3 mm maximum grain size; sand-sized lithic fragments consist of silicic volcanic rocks------------------	430.64	Bedded tuff
-- -- -- -- (cooling break) -- -- -- --		
Ash-flow Tuff (tuffaceous beds of Calico Hills?)		
Tuff, ash-flow, very pale orange (10YR8/2) to pinkish-gray (5YR8/1), vitric, nonwelded; pumice common to abundant, white (N9) to very pale orange (10YR8/2), as large as 4 cm; 2 to 3 percent phenocrysts consist of 35 to 48 percent plagioclase, 29 to 38 percent sanidine, 15 to 24 percent quartz, 3 to 4 percent biotite, and a trace to 4 percent hornblende; 2 to 3 percent black (N1) vitrophyric, brownish-gray (5YR4/1), and medium-gray (N5) silicic volcanic lithic fragments, as large as 3 cm; groundmass unaltered to partially altered to a trace of smectite; highly friable------------------------------------	Thin sections at 430.69 and 438.75 445.51	Pumice-rich and lithic fragment-rich nonwelded ash-flow tuff; distinctive obsidian lithic fragments
Tuff, ash-flow, very pale orange (10YR8/2) to pinkish-gray (5YR8/1), vitric, nonwelded; pumice, common, white (N9) to very pale orange (10YR8/2), as large as 2.5 cm; 2 percent phenocrysts consist of 60 percent sanidine, 30 percent plagioclase, and 10 percent quartz; 16 percent black (N1) to grayish-brown (5YR3/2) vitrophyric, light-gray (N7) to medium-gray (N5), and grayish-red (5R4/2) silicic volcanic lithic fragments, as large as 3 cm in upper meter, decreases downhole to 2 cm; groundmass partially altered to a trace of smectite and to sparse clinoptilolite; highly friable to moderately coherent---------	Thin section at 456.68 459.26	Increase in size and abundance of lithic fragments of nonwelded ash-flow tuff
-- -- -- -- (cooling break) -- -- -- --		
Bedded Tuff		
Tuff, bedded, largely pyroclastic fall, moderately to poorly indurated, pinkish-gray (5YR8/1), very pale orange (10YR8/2) and grayish-orange-pink (5YR7/2); lithic and pumice fragment-rich layers form beds as much as 1 m thick that grade vertically into more ash-rich horizons, ash-rich layers vary from 0.5 to 5 cm thick and have several horizons of dessication cracks, in thin zones pumice forms		Bedded tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Bedded Tuff--Continued as much as 70 percent and lithic fragments form as much as 35 percent of the rock, pumice and lithic framgent as large as 1 cm in coarsest layers; no sedimentary structures or textures indicative of fluvial or aeolian reworking present; lithic fragments consist of silicic volcanic rocks; partially altered to sparse smectite and rare to sparse clinoptilolite---------------------------------------	475.56	
-- -- -- -- -- (cooling break) -- -- -- -- --		
Crater Flat Tuff Prow Pass Member Tuff, ash-flow, very pale orange (10YR8/2), vitric, nonwelded; pumice, common, white (N9) to very pale orange (10YR8/2), as large as 1 cm; 7 percent phenocrysts consist of 45 percent sanidine, 39 percent plagioclase, 13 percent embayed quartz, 3 percent orthopyroxene, and less than 1 percent biotite; 1 percent grayish-red (5R4/2) and moderate-brown (5YR3/4) silicic volcanic and moderate-red (5R5/4) mudstone lithic fragments, volcanic fragments as large as up to 2.5 cm and mudstone fragments as large as 0.5 cm; groundmass partially altered to rare to sparse smectite, and sparse calcite; moderately friable tuff---------	Thin section at 479.02 487.07	Mudstone lithic fragments in nonwelded ash-flow tuff
Tuff, ash-flow, pinkish-gray (5YR8/1), grading downhole through light-gray (N7) to white (N9), very light gray (N8) and pinkish-gray (5YR8/1), vitric downhole to 488 m, devitrified below, nonwelded downhole to 487.1 m at a sharp contact to partially welded with distinct vapor-phase zone in the light-gray portion to 488.6 m, partially welded below; pumice, common, very pale orange (10YR8/2) downhole through grayish-orange-pink (5YR7/2) and to very light gray (N8) to white (N9), as large as 3 cm along foliation plane; 8 to 11 percent phenocrysts consist of 48 to 53 percent plagioclase, 30 to 38 percent sanidine, 6 to 16 percent quartz, 1 to 1.5 percent biotite, trace to 3 percent opaque oxides, and trace to 1.5 percent orthopyroxene; 1 to 2 percent grayish-red (5R4/2) to moderate-red (R4/6) to pale-reddish-brown (10R5/4) mudstone and light-gray (N7) and grayish-orange (10YR7/4) silicic volcanic lithic fragments, as large as 4.5 cm; groundmass unaltered to partially altered to rare to sparse smectite and calcite; fractures contain calcite, breccia, and Fe and Mn oxides and hydroxides------------------	Thin sections at 487.33, 488.62, and 531.54 534.86	Nonwelded to partially welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Prow Pass Member--Continued		
Tuff, ash-flow, pinkish-gray (5YR8/1), devitrified, to partially vitric, partially welded downhole to 606 m, nonwelded below; pumice, common, very pale orange (10YR8/2), as large as 3.5 cm along foliation plane; 9 percent phenocrysts consist of 42 to 54 percent plagioclase, 36 to 46 percent sanidine, 7 to 8 percent quartz, 2 percent opaque oxides, less than 1 to 2 percent orthopyroxene, and less than 1 percent biotite; 2 to 3 percent moderate-red (5R4/6) to pale-reddish-brown (10R5/4) mudstone and light-gray (N7) and pale-red (5R6/2) silicic and intermediate volcanic lithic fragments, as large as 4.5 cm; groundmass unaltered to partially altered to sparse smectite and common to extensive clinoptilolite-------	Thin sections at 571.12 and 605.40 607.05	Lithic-rich partially welded to nonwelded ash-flow tuff
-- -- -- -- (cooling break) -- -- -- --		
Bedded Tuff		
Tuff, bedded, moderately indurated, distinct cross-bedding and channel-fill structures indicative of fluvial reworking, other layers are pyroclastic fall, grayish-pink (5R8/2) to moderate-orange-pink (10R7/4); ash-rich beds are as thin as 0.2 cm and massive pyroclastic fall ranges to as much as 1 m thick, thin pumice-rich pyroclastic beds contain as much as 80 percent pumice, and pumice fragments are as large as 2 cm, fluvial horizons have pumice clast sizes that are as large as 1 cm and pumice clasts have no appreciable rounding, silicic volcanic clasts are as large as 0.2 cm in both fluvial and pyroclastic horizons; at 607.8 m reed-like plant fossils occur; partially altered to rare to sparse smectite and abundant to extensive clinoptilolite; fractures contain smectite, clinoptilolite, quartz, and Mn oxides and hydroxides-------------------	611.02	Bedded tuff
-- -- -- -- (cooling break) -- -- -- --		
Crater Flat Tuff--Continued		
Bullfrog Member		
Tuff, ash-flow, grayish-pink (5R8/2) to pinkish-gray (5YR8/1), partially devitrified downhole to 615 m, vitric below, partially welded, vapor phase in lowest 0.3 m; pumice, sparse to common, pinkish-gray (5YR8/1), as large as 1.5 cm; 9 percent phenocrysts consisting of 46 percent plagioclase, 29 percent sanidine, 19 percent quartz, 3 percent biotite and 3 percent opaque oxides; much less than 1 percent brownish-gray (5YR4/1),	Thin section at 615.33	Lithic fragment-poor partially welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
very light gray (N8) and medium-light-gray (N6) silicic volcanic lithic fragments, as large as 4 cm; fractures contain clay and Fe and Mn oxides and hydroxides--------------	616.43	
Tuff, ash-flow, pinkish-gray (5YR8/1) grading downhole through very light gray (N8) to pinkish-gray (5YR8/1) to light-brownish-gray (5YR6/1), devitrified, partially welded; pumice common, very light gray (N8) to grayish-pink (5R8/2), as large as 2 cm along foliation plane; 12 percent phenocrysts consist of 43 percent plagioclase, 35 percent sanidine, 16 percent quartz, 4 percent biotite, less than 2 percent opaque oxides, and less than 1 percent hornblende; much less than 1 percent grayish-red (10R4/2), pale-red (5R6/2), and light-gray (N7) silicic and intermediate volcanic lithic fragments as large as 3.5 cm; groundmass partially altered to rare to sparse smectite; fractures contain breccia, Fe oxides and hydroxides, and clay, slickensides common-----------------	Thin section at 631.04 640.00	Biotite-rich partially welded ash-flow tuff
Tuff, ash-flow, pale-red (10R6/2), devitrified, moderately welded; pumice, common, moderate-orange-pink (10R7/4), as large as 2 cm along foliation plane; 18 percent phenocrysts consist of 39 percent plagioclase, 34 percent sanidine, 21 percent quartz, 3.5 percent biotite, 1.5 percent hornblende, and 1 percent opaque oxides; much less than 1 percent grayish-red (10R4/2), pale-red (5R6/2), and light-gray (N7) silicic and intermediate volcanic lithic fragments, as great as 3.5 cm; groundmass partially altered to rare to sparse smectite; fractures contain breccia, Fe oxides and hydroxides, clay, and common slickensides-----------	Thin section at 651.78 659.43	Biotite- and hornblende-rich moderately welded ash-flow tuff
Tuff, ash-flow, very light gray (N8) to pinkish-gray (5YR8/1) to light-brownish-gray (5YR6/1) grading downhole to grayish-orange-pink (5YR7/2), devitrified, moderately welded increasing in degree downhole, below 666 m moderately to densely welded; pumice, common to sparse, light-brown (5YR6/4) grading downhole through grayish-orange-pink (5YR7/2) and to grayish-red (5R4/2), as large as 3 cm along foliation plane; 18 to 19 percent phenocrysts consist of 41 to 45 percent plagioclase 33 to 35 percent sanidine, 17 to 19 percent quartz, 3 percent biotite, 2 percent opaque oxides, and less than 1 percent hornblende; less than 1 to 2 percent medium-gray (N5) to very light gray (N8) and grayish-red (5R4/2) silicic volcanic fragments, more lithic fragment-rich portion above	Thin sections at 664.85 and 722.22	Moderately welded to moderately to densely welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
675 m, as large as 2 cm; groundmass unaltered to partially altered to rare to sparse smectite; fractures contain Fe and Mn oxides and hydroxides (including goethite?), smectite, illite, mordenite, quartz, and cristobalite; subhorizontal slickensides are common on fault surfaces, slickensides consist of extensive smectite-rich gouge stained with hematite---------------------	724.94	
Tuff, ash-flow, grayish-orange-pink (5YR7/2) mottled with grayish-red (5R4/2) patches grading downhole through grayish-orange-pink (5YR7/2) mottled with pale-yellow-brown (10YR6/2) and pale-brown (5YR5/2) patches and to light-brown (5YR5/6) with abundant grayish-red (10R4/2) patches, devitrified, moderately to densely welded downhole to 739 m, densely welded below; pumice, sparse, grayish-red (5R4/2), as large as 1 cm along foliation plane; 22 percent phenocrysts consist of 43 percent plagioclase, 32 percent sanidine, 19 percent quartz, 3 percent biotite, 2 percent hornblende, and 1 percent opaque oxides; less than 1 percent very light gray (N8), vesicular grayish-red (5R4/2), and moderate-yellowish-brown (10YR5/4) silicic and minor intermediate lithic fragments, as large as 4 cm, one vesicular lithic fragment contains sandstone(?) lithic fragments within itself; fractures contain clay, Fe oxides and hydroxides, quartz, and cristobalite, subhorizontal slickensides are common on fault surfaces, slickensides consist of extensive smectite-rich gouge stained with hematite----------------	Thin section at 752.00 766.15	Mottled moderately to densely welded to densely welded ash-flow tuff
Tuff, ash-flow, grayish-orange-pink (5YR7/2) grading downhole to lighter shades of the same color, devitrified, moderately welded; pumice, sparse to common, very pale orange (10YR8/2), as large as 3.5 cm along foliation plane; about 25 percent phenocrysts consist of about 40 percent plagioclase, 35 percent sanidine, 20 percent quartz, 3 percent biotite, 1 percent hornblende, and 1 percent opaque oxides; less than 1 percent pale-brown (5YR5/2) and dusky-brown (5YR2/2) scoriaceous intermediate and minor silicic volcanic lithic fragments, as large as 7 cm; fractures contain clay, Fe oxides and hydroxides, and quartz---	770.93	Moderately welded ash-flow tuff
Tuff, ash-flow, between very pale orange (10YR8/2) and grayish-orange-pink (5YR7/2) grading downhole to very pale orange (10YR8/2), devitrified, moderately to		Moderately to partially welded to partially welded

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
partially welded grading downhole to partially welded; pumice, common, eutaxitic texture, pale-yellowish-brown (10YR6/2) to pale-brown (5YR5/2), as large as 3 cm along foliation plane; about 20 percent phenocrysts consist of about 40 percent plagioclase, 35 percent sanidine, 20 percent quartz, 3 percent biotite, 1 percent hornblende, and 1 percent opaque oxides; less than 1 percent light-gray (N7) silicic volcanic lithic fragments, as large as 1 cm; groundmass and pumice partially altered to clays; fractures contain clay, Fe oxides and hydroxides, and quartz-----------	776.11	ash-flow tuff
-- -- -- (cooling break) -- -- --		
Bedded Tuff		
Tuff, bedded, well indurated pyroclastic fall and ash-flow(?) tuff, medium-light-gray (N6) to very light gray (N8); 2 cm of well sorted ash-sized pyroclastic fall downhole through 8 cm of ash-flow tuff(?) similar in appearance to the overlying cooling unit base, through 1 cm of well-sorted ash-sized pyroclastic fall, and to a sequence of 4 to 20 cm thick beds of poorly-sorted, pumiceous pyroclastic fall tuff; flattened pumice in both ash-flow and pyroclastic fall tuffs may be related to either slight welding or alteration compaction during argillization; basal 0.3 m contains sparse silicic volcanic and mudstone lithic fragments, as large as 1 cm; partially altered to common to abundant smectite, common clinoptilolite/mordenite, and a trace of hematite--	777.07	Bedded tuff
-- -- -- (cooling break) -- -- --		
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
Tuff, ash-flow, pinkish-gray (5YR8/1), partially devitrified, nonwelded; pumice common, moderate-orange-pink (5YR8/4), as large as 4 cm; about 6 percent phenocrysts consist of about 50 percent plagioclase, 30 percent sanidine, 10 percent quartz, 4 percent biotite, 2 percent opaque oxides, and 1 percent hornblende; about 3 percent grayish-red (5R4/2) to brownish-gray (5YR4/1) silicic volcanic lithic fragments, as large as 0.5 cm; groundmass and pumice partially altered to clay--------------------------	778.07	Nonwelded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
Tuff, ash-flow, between grayish-orange-pink (5YR7/2) and very pale orange (10YR8/2), partially devitrified, partially welded; pumice sparse, very pale orange (10YR8/2), as large as 2.5 cm along foliation plane; about 9 percent phenocrysts consist of about 49 prcent plagioclase, 33 percent sanidine, 10 percent quartz, 4 percent biotite, 2 percent opaque oxides, and 1 percent hornblende; about 3 percent grayish-red (5R4/2) silicic volcanic lithic fragments, as large as 1.5 cm; groundmass partially altered to rare to sparse smectite and abundant clinoptilolite--	782.00	Partially welded ash-flow tuff
Tuff, ash-flow, grayish-orange-pink (5YR7/2) to very pale orange (10YR8/2), partially devitrified, moderately welded; pumice sparse, as large as 2.5 cm along foliation plane; 9 percent phenocrysts consist of 49 percent plagioclase, 33 percent sanidine, 10 percent quartz, 4 percent biotite, 2 percent opaque oxides, and 1 percent hornblende; 3 percent grayish-red (5R4/2) silicic volcanic lithic fragments, as large as 1.5 cm; groundmass partially altered to rare to sparse smectite and abundant clinoptilolite--	Thin section at 785.61 787.00	Moderately welded ash-flow tuff
Tuff, ash-flow, grayish-orange-pink (5YR7/2), to very pale orange (10YR8/2), partially devitrified, partially welded; pumice common, as large as 2.5 cm along foliation plane; about 9 percent phenocrysts consist of about 49 percent plagioclase, 33 percent sanidine, 10 percent quartz, 4 percent biotite, 2 percent opaque oxides, and 1 percent hornblende; about 3 percent grayish-red (5R4/2) silicic volcanic lithic fragments as large as 1.5 cm; groundmass partially altered to rare to sparse smectite and abundant clinoptilolite--	797.68	Partially welded ash-flow tuff
-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- (cooling break) -- -- -- -- -- -- -- -- -- -- -- -- -- --		
Bedded Tuff		
Tuff, bedded, moderately to well indurated, reworked and pyroclastic fall, mottled grayish-pink (5R8/2), moderate-pink (5R7/4) and moderate-reddish-orange (10R6/6) grading downhole through white (N9) and to pinkish-gray (5YR8/1) to moderate-orange-pink (10R7/4); pyroclastic fall tuff occurs in the central 20 cm forming white (N9), pumice-rich beds, reworked tuffs occur above and below pyroclastic interval forming beds greater than 1 m thick;		Bedded Tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Bedded Tuff--Continued		
slightly rounded pumice and lithic fragments are as large as 0.3 cm in reworked intervals and size of pumice and lithic fragments as large as 1.5 cm in pyroclastic fall interval; partially altered to sparse smectite, common to abundant clinoptilolite/mordenite and a trace of siderite; fractures contain Fe oxides and hydroxides and gouge-----	803.76	
-- -- -- -- (cooling break) -- -- -- --		
Crater Flat Tuff--Continued		
Tram Member		
Tuff, ash-flow, moderate-orange-pink (10R7/4), devitrified, nonwelded to partially welded; pumice, abundant, grayish-pink (5R8/2) and very pale orange (10YR8/2), as large as 2 cm; 9 percent phenocrysts consisting of 58 percent plagioclase, 18 percent quartz, 15 percent sanidine, 8 percent biotite, less than 1 percent opaque oxides, and less than 1 percent hornblende (pseudomorphs); 1 percent grayish-red (5R4/2), grayish-brown (5YR3/2), and pale-red (5R6/2) silicic volcanic lithic fragments, as large as 1.5 cm; fractures contain clay and Fe oxides and hydroxides--	Thin section at 804.41 805.89	Biotite-rich, nonwelded to partially welded ash-flow tuff GU-3 Total Depth

[G-3 overlaps with GU-3 at the upper contact of the Tram unit. This contact occurs 3.55 m higher in G-3 than in GU-3. Core in G-3 begins at 795.22.

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Bedded Tuff		
Tuff, bedded, description same as interval 797.68 to 803.76 m in GU-3; upper contact of bedded tuff with the Bullfrog Member not exposed in G-3-----------------------	800.21	
-- -- -- -- (cooling break) -- -- -- --		
Crater Flat Tuff--Continued		
Tram Member--Continued		
Tuff, ash-flow, moderate-orange-pink (10R7/4) grading downhole through grayish-orange-pink (10R8/2) through very pale orange (10YR8/2) through grayish-pink (5R8/2) and to moderate-orange-pink (10R7/4), devitrified, nonwelded to partially welded; pumice, abundant, grayish-pink (5R8/2), very pale orange (10YR8/2), and white (N9), devitrified, as large as 4 cm; 9 to 13 percent phenocrysts consist of 41 to 58 percent plagioclase, 17 to 28 percent quartz, 15 to 29 percent sanidine, 2 to 8 percent biotite (decreases downhole) and less than 1 percent opaque oxides; 1 to 4 percent (increases downhole) grayish-red (5R4/2),	Thin sections at 800.77, 809.75, and 822.60	Biotite-rich, nonwelded to partially welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
grayish-brown (5YR3/2), and pale-red (5R6/2) silicic and rare intermediate volcanic lithic fragments, as large as 2.5 cm; lower portion contains numerous subhorizontal partings that appear to be breaks between individual magmatic pulses at 816.80, 817.80, 819.62, 820.04, 820.42, 820.87, 821.35, 821.66, 821.82, 822.60, 823.32, 823.99, 824.06, and 824.54 m, two pulses have graded bedding of pumice adjacent to contacts (823.99 and 824.06 m); groundmass partially altered to rare to sparse smectite, sparse to abundant clinoptilolite, and sparse to common mordenite; fractures contain clay, gouge, clinoptilolite, mordenite, and Fe oxides and hydroxides----------------------	828.76	
Tuff, ash-flow, grayish-pink (5R8/2) to grayish-orange-pink (10R8/2), devitrified, nonwelded to partially welded, partially vapor phase; pumice, common, grayish-pink (5R8/2) and white (N9), as large as 2 cm; 12 percent phenocrysts consist of 31 to 33 percent plagioclase, 5 to 6 percent biotite, and less than 1 to 1 percent opaque oxides; 1 to 2 percent pale-red (10R6/2), light-brownish-gray (5YR6/1), and grayish-orange-pink (5YR7/2) silicic to intermediate volcanic lithic fragments, as large as 6 cm; groundmass partially altered to rare smectite; fractures contain Fe oxides and hydroxides-------------	Thin sections at 829.94 and 853.88 859.55	Quartz and sanidine-rich nonwelded to partially welded ash-flow tuff
-- -- -- -- (cooling break) -- -- -- --		
Bedded Tuff		
Tuff, bedded, pyroclastic fall, well indurated, grayish-pink (5R8/2); beds range in thickness from 0.4 to greater than 10 cm; pumice content in thin beds as much as 25 percent, size ranges to 0.5 cm; volcanic lithic fragments size range to 0.5 cm; [upper contact of bedded tuff sampled in LANL sample 859.55-859.76, USGS sample 859.76-859.98, or SNL sample 859.98-860.24]------------------	860.46	Bedded tuff
-- -- -- -- (cooling break) -- -- -- --		
Crater Flat Tuff--Continued		
Tram Member--Continued		
Tuff, ash-flow, grayish-pink (5R8/2) to grayish-orange-pink (10R8/2), devitrified, nonwelded to partially welded; pumice, common, grayish-pink (5R8/2) and grayish-orange-pink (10R8/2), as large as 0.5 cm; 10 percent phenocrysts consist of 31 percent quartz, 31 percent plagioclase, 30 per-	Thin section at 873.82	Nonwelded to partially welded ash-flow tuff indistinguishable from unit above bedded tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
cent sanidine, 6 percent biotite, and 1 percent opaque oxides; 1.5 percent light-gray (N7), brownish-gray (5YR4/1), and pale-red (5R6/2) intermediate to silicic volcanic lithic fragments, as large as 4 cm, slight zonation created by size and abundance layering of lithic fragments; fractures contain clay and gouge------------------	882.24	
Tuff, ash-flow, mottled eutaxitic texture, grayish-orange-pink (10R8/2) grading downhole through pale-red (10R6/2) and to pale-red-purple (5RP6/2), darker shades downhole with increasing degree of welding except in lower 2 m where degree of welding decreases slightly, devitrified, partially to moderately welded; pumice, common, grayish-orange-pink (10R8/2), as large as 3 cm along foliation plane; 16 percent phenocrysts consist of 35 percent quartz, 31 percent sanidine, 27 percent plagioclase, 6 percent biotite and 1 percent opaque oxides; 3 percent brownish-gray (5YR4/1), pale-red (10R6/2), and medium-light-gray (N6) silicic to intermediate volcanic lithic fragments, as large as 6 cm; groundmass unaltered to partially altered to rare smectite; fractures contain smectite, illite-mica, Mn oxides and hydroxides, gouge, quartz, calcite and mordenite---------------------------------------	Thin section at 888.33 910.81	Quartz-rich partially to moderately welded ash-flow tuff
Bedded Tuff		
Tuff, bedded, pyroclastic fall with minor reworking, well indurated, absence of total cooling break suggests welding of thin, bedded material, pale-red (5R6/2), grayish-pink (5R8/2) and pale-red-purple (5RP6/2); beds range from 0.1 to 7 cm thick, disrupted by slumping and (or) minor faulting, pumice abundant in pale colored beds, most clasts are in the sand- to silt-size range--------------	911.17	Bedded tuff, only partial cooling break
Crater Flat Tuff--Continued		
Tram Member--Continued		
Tuff, ash-flow, mottled eutaxitic texture with pale-pink (5RP8/2) to pale-red-purple (5RP6/2) grading downhole through mottled pinkish-gray (5YR8/1) and light-brownish-gray (5YR6/1) and to light-gray (N7), darker shades increase downhole with degree of welding in upper 1 m, devitrified, moderately welded, slight decrease in degree of welding in lower 0.4 m; pumice, common, pale-pink (5RP8/2) grading downhole through pinkish-gray (5YR8/1) and to very light gray (N8), as large as 2 cm along foliation plane; 13 percent phenocrysts consist of 35 percent	Thin section at 928.22	Plagioclase-rich and lithic fragment-rich moderately welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
plagioclase, 29 percent sanidine, 28 percent quartz, 6 percent biotite, and 2 percent opaque oxides; 13 percent brownish-gray (5YR4/1), pale-red (10R6/2), grayish-red (10R4/2), and medium-gray (N6) intermediate and silicic volcanic lithic fragments, as large as 5 cm; subhorizontal parting at 919.4 m; groundmass unaltered to partially altered to rare smectite; fractures contain zeolites, clay, calcite, quartz, and gouge-----------------------------	934.15	
Bedded Tuff		
Tuff, bedded, pyroclastic fall with minor to no reworking, well indurated, absence of total cooling break suggested by welding of thin, bedded material, grayish-pink (5R8/2) to light-brownish-gray (5YR6/1); beds range from 0.2 to 1.5 cm thick; pumice abundant in paler beds, clasts mostly in sand-size range--	934.21	Bedded tuff, only partial cooling break
Crater Flat Tuff--Continued		
Tram Member--Continued		
Tuff, ash-flow, slightly mottled eutaxitic texture, grayish-pink (5R8/2) and grayish-orange-pink (10R8/2) to pale-pink (RP8/2), devitrified, moderately to partially welded with slight decrease in degree downhole; pumice, common, white (N9) to grayish-orange-pink (10R8/2), as large as 1.5 cm along foliation plane; 15 percent phenocrysts consist of 32 percent sanidine, 32 percent plagioclase, 30 percent quartz, 4 percent biotite, 2 percent opaque oxides, and less than 1 percent hornblende pseudomorphs; 2 percent brownish-gray (5YR4/1), pale-red (10R6/2), and medium-light-gray (N6) intermediate to silicic volcanic lithic fragments, as large as 4.5 cm; fractures contain calcite and clay--	Thin section at 936.38 940.96	Lithic fragment-poor moderately to partially welded ash-flow tuff
Tuff, ash-flow, slightly mottled eutaxitic texture, grayish-pink (5R8/2) and grayish-orange-pink (10R8/2), devitrified, partially to moderately welded with slight increase in degree downhole with a slight decrease in degree at the base; pumice, common, pale-pink (5RP8/2) to pale-red-purple (5RP6/2), eutaxitic textures, as large as 2 cm along foliation plane; 15 percent phenocrysts consist of 36 percent quartz, 34 percent plagioclase, 26 percent sanidine, 3 percent biotite, less than 1 percent opaque oxide, and less than 1 percent hornblende pseudomorphs; 14 percent medium-gray (N5), medium-light-gray (N6), brownish-gray (5YR4/1), and pale-red (10R6/2) intermediate to si-	Thin section at 948.90	Lithic fragment-rich and quartz-rich partially to moderately welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued Tram Member--Continued licic volcanic lithic fragments, as large as 4 cm; groundmass partially altered to rare smectite; fractures contain calcite and clay--	952.40	
Bedded Tuff Tuff, bedded, pyroclastic fall, poorly indurated, absence of total cooling break suggested by welding of thin, bedded material, grayish-pink (5R8/2); one bed, 4 cm thick; clasts of pumice and volcanic lithic fragments mostly in the sand-size range--------------------------------	952.44	Bedded tuff, only partial cooling break
Tuff, ash-flow, grayish-pink (5R8/2) grading downhole through grayish-orange-pink (10R8/2) and to pale-yellowish-brown (10YR6/2), devitrified, moderately welded downhole to 967 m, moderately to densely welded; pumice, common, white (N9) grading downhole through grayish-pink (5R8/2) and to moderate pink (5R7/4) associated with abundant Mn oxide and hydroxide veins, as large as 3 cm along foliation plane; 14 percent phenocrysts consist of 37 percent plagioclase, 30 percent sanidine, 28 percent quartz, 3 percent opaque oxides, and 2 percent biotite; 20 percent medium-light-gray (N6), brownish-gray (5YR4/1), pale-red (10R6/2), and grayish-red (10R4/2) intermediate to silicic volcanic lithic fragments, as large as 5.5 cm with decreasing size downhole to 3 cm; groundmass partially altered to rare to sparse smectite, to sparse to common clinoptilolite, a trace of mordenite; and a trace of calcite; fracture contains Mn oxides and hydroxides and clay; in the lower 3 m, Mn oxides and hydroxides form dendritic growths within groundmass unaffected by fractures---------------------------	Thin section at 964.47 977.19	Plagioclase-rich and very lithic fragment-rich moderately welded to moderately to densely welded ash-flow tuff
Tuff, ash-flow, distinct eutaxitic texture, pale-yellowish-brown (10YR6/2) grading downhole to pale-brown (5YR5/2), devitrified, moderately to densely welded; pumice, common, grading dowhnole from moderate-pink (5R7/4) and grayish-pink (5R8/2) to white (N9), as large as 3 cm along foliation plane; about 15 percent phenocrysts consist of about 35 percent plagioclase, 30 percent sanidine, 30 percent quartz, 3 percent opaque oxides and 2 percent biotite; about 30 percent medium-light-gray (N6), medium-gray (N5), brownish-gray (5YR4/1), and pale-red (10R6/2) intermediate to silicic volcanic lithic fragments, as large as 5 cm; groundmass partially altered to sparse smectite and common clinoptilolite; fracture contains		Eutaxitic textured moderately to densely welded ash-flow tuff with clay alteration of pumice

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
smectite, clinoptilolite, and Mn oxides and hydroxides; groundmass has been permeated with local dendritic growths of Mn oxide and hydroxides and pumices have been extensively altered to clay--	982.10	
Tuff, ash-flow, distinct eutaxitic texture, brownish-gray (5YR4/1) to dusky-brown (5YR2/2), vitrophyre, moderately to densely welded; pumice, common, light-brown (5YR6/4), as large as 3 cm along foliation plane; 13 percent phenocrysts consist of 33 percent sanidine, 32 percent quartz, 25 percent plagioclase, 5 percent biotite, 3 percent opaque oxides and less than 1 percent hornblende; 18 percent medium-gray (N5), medium-light-gray (N6), brownish-gray (5YR4/1) and pale-red (10R6/2) intermediate to silicic volcanic lithic fragments including conspicuous hornblende-bearing andesites(?), as large as 3 cm; groundmass partially altered to sparse smectite and clinoptilolite--	Thin section at 983.28 983.70	Vitrophyre of moderately to densely welded ash-flow tuff
Tuff, ash-flow, distinct eutaxitic texture, light-brown (5YR6/4), partially vitric downhole to 985.7 m and moderately to partially welded decreasing downhole; pumice, common, grayish-pink (5R8/2) and pale-brown (5YR5/2) grading downhole to white (N9) at 1 m above base, highly eutaxitic near base, as large as 3 cm along foliation plane; about 15 percent phenocrysts consisting of about 30 percent sanidine, 30 percent quartz, 30 percent plagioclase, 5 percent biotite and 3 percent opaque oxides; about 15 percent medium-gray (N5), medium-light-gray (N6), brownish-gray (5YR4/1), and pale-red (10YR6/2) intermediate to silicic volcanic lithic fragments, as large as 7 cm; fractures contain smectite, illite mica, mordenite, calcite, Fe and Mn oxides and hydroxides including cryptomelane, and pyrolusite) and quartz------------------------------------		Moderately to partially welded base of ash-flow tuff 994.73
Tuff, ash-flow, pale-red (5R6/2), devitrified, partially to moderately welded, pumice, common, pale-pink (5RP8/2) and white (N9), as large as 2 cm along foliation plane; 11 percent phenocrysts consist of 44 percent quartz, 23 percent sanidine, 21 percent plagioclase, 4 percent biotite and 3 percent opaque oxides; 19 percent medium-gray (N5), brownish-gray (5YR4/1), and grayish-red (5R4/2) intermediate to silicic volcanic lithic fragments, as large as 5 cm, rare dark-reddish-brown (10R3/4) mudstone lithic fragments occur between 1015 and 1040 m; groundmass partially	Thin section at 1019.14	Quartz-rich and lithic fragment-rich partially to moderately welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
altered to sparse smectite and common clinoptilolite; fractures contain smectite with considerable illite mixed-layer clay, illite mica, clinoptilolite, quartz, Mn and Fe oxides and hydroxides, (hematite) calcite, and gouge--	1048.00	
Tuff, ash-flow, grayish-pink (5R8/2), devitrified, partially to moderately welded; pumice, common, pale-pink (5RP8/2) and white (N9), as large as 2 cm along foliation plane; 11 percent phenocrysts consist of 35 percent quartz, 36 percent plagioclase, 23 percent sanidine, 3 percent opaque oxides, and 2 percent biotite; 28 percent medium-gray (N5), medium-dark-gray (N4), brownish-gray (5YR4/1), pale-red (10R6/2), and grayish-red (5R4/2) intermediate to silicic volcanic and rare hypabyssal granodioritic lithic fragments, as large as 7 cm-------------	Thin section at 1049.00 1054.00	Very lithic fragment-rich partially to moderately welded ash-flow tuff
Tuff, ash-flow, grayish-pink (5R8/2), devitrified partially to moderately welded; pumice, common pale-pink (5RP8/2) and white (N9), as large as 2 cm along foliation plane; 9 percent phenocrysts consist of 44 percent plagioclase, 22 percent sanidine, 21 percent quartz, 8 percent opaque oxides and 5 percent biotite; 25 percent medium-gray (N5), medium-dark-gray (N4), brownish-gray (5YR4/1), pale-red (10R6/2), grayish-red (5R4/2), and white (N9) intermediate to silicic volcanic and rare clastic sedimentary lithic fragments, as large as 7 cm; groundmass partially altered to sparse smectite and common clinoptilolite---------------------------------------	Thin section at 1059.30 1067.93	Very lithic fragment-rich and plagioclase-rich partially to moderately welded ash-flow tuff
Tuff, ash-flow, pale-red (5R6/2) and pale-red-purple (5RP6/2) grading downhole through grayish-orange (10YR7/4) through pale-yellowish-brown (10YR6/2) through pale-red (5R6/2) through yellowish-gray (5Y8/1) through light-olive-gray (5Y6/1) through light-brownish-gray (5YR6/1) and to mottled light-olive-gray (5Y6/1) and light-brownish-gray (5YR6/1), devitrified, moderately welded; pumice, common, white (N9) and very light gray (N8) with extremely pale shades of matrix colors, as large as 5.5 cm along foliation plane; about 9 percent phenocrysts consist of about 45 percent quartz, 30 percent plagioclase, 15 percent sanidine, 5 percent biotite, and 3 percent opaque oxides; about 30 percent yellowish-gray (5Y8/1), light-gray (N7), medium-light-gray (N6), light-greenish-gray (5GY8/1), pale-olive		Very lithic fragment-rich and quartz-rich moderately welded ash-flow tuff with mottled greenish alteration

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
(10Y6/2), brownish-gray (5YR4/1), and brownish-black (5YR2/1) silicic to intermediate volcanic lithics, commonly rimmed with mottled alteration of pale-greenish-yellow (10Y8/2), grayish-green (10GY5/2) and greenish-gray (5GY6/1) colors, as large as 7 cm; greenish colors are related to groundmass partially altered to sparse smectite and abundant clinoptilolite; pumice altered to extensive smectite--	1118.01	
Tuff, ash-flow, light-olive-gray (5Y6/1) and greenish-gray (5GY6/1) grading downhole to mottled grayish-yellow-green (5GY7/2), devitrified, moderately to partially welded decreasing downhole; pumice, abundant, white (N9) and light-greenish-gray (5GY8/1), as large as 4 cm along foliation plane; 8 to 9 percent phenocrysts consist of 32 to 45 percent quartz, 32 to 38 percent plagioclase, 14 to 22 percent sanidine, 5 to 6 percent biotite and 2 to 3 percent opaque oxides; 31 to 34 percent yellowish-gray (5Y8/1), light-gray to medium-gray (N7to N5), brownish-gray (5YR4/1), and white (N9) silicic to intermediate volcanic and rare clastic sedimentary lithic fragments, as large as 6 cm, commonly rimmed by dusky-yellow-green (5GY5/2) to dusky-yellow (5Y6/4) to dusky-red (5R3/4) alteration that in some cases forms concentric Liesegang rings; groundmass partially altered to sparse smectite, common clinoptilolite and sparse mordenite and smectite in the lower portion------------------	Thin sections at 1122.49 and 1137.00 1138.12	Intense greenish alteration of exceptionally lithic fragment-rich moderately to partially welded ash-flow.tuff
Tuff, ash-flow, very light gray (N8) with light-greenish-gray (5GY8/1) tint grading downhole to light-gray (N7), devitrified, partially welded to 1142 m grading downhole through partially to moderately welded to 1164 m through partially welded to 1172 m and to nonwelded below; pumice, common to sparse, light-greenish-gray (5GY8/1), and greenish-gray (5GY6/1), as large as 4 cm along foliation plane; 9 percent phenocrysts consist of 42 percent plagioclase, 24 percent quartz, 24 percent sanidine, 5 percent biotite, and 4 percent opaque oxides and sulfides; 28 percent medium-light-gray to dark-gray (N6 to N3), light-brownish-gray (5YR6/1), and brownish-gray (5YR4/1) intermediate to silicic volcanic lithic fragments, as large as 10 cm, in lower 0.46 m the size and abundance of lithic fragments sharply decreases; pyrite is common in both lithic fragments and groundmass, groundmass partially altered to sparse to common smectite and common clinoptilo-	Thin section at 1145.74	Light-gray matrix and dark lithic fragments of partially welded to partially to moderately welded to partially welded and non-welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Crater Flat Tuff--Continued		
Tram Member--Continued		
lite, pumice altered to extensive smectite; fractures contain gouge and clays--	1173.11	
-- -- -- -- (cooling break) -- -- -- --		
Bedded Tuff		
Tuff, bedded, pyroclastic fall with probable minor reworking in part, light-gray (N7) to very light gray (N8) and greenish-gray (5GY6/1), moderately to well indurated, beds range from 2 to 3.5 cm thick; pumice abundant in less indurated thinner beds and less sorted in thicker beds; volcanic lithic fragment and pumice sizes range from 0.5 to 4 mm; distinctively mottled very light gray to medium-light-gray (N8-N6) ash-rich bed occurs from 1174.90 to 1174.94 m; partially altered to sparse smectite and illite mixed-layer clay, common to abundant clinoptilolite, possibly a trace of analcime, and sparse calcite; pumice altered to extensive smectite, in some layers, pumice altered to pale-blue-green (5BG3/2) colors, pyrite less than 1 mm disseminated within groundmass and lithic fragments; carbonized wood fragments at 1173.6 m---------------------------	1181.52	Bedded tuff
-- -- -- -- (cooling break) -- -- -- --		
Lithic Ridge Tuff		
Tuff, ash-flow, very light gray to light-gray (N8 to N7), devitrified, nonwelded grading downhole through partially welded and to moderately welded; pumice, common, yellowish-gray (5Y8/1) to grayish-green (5GY6/1), as large as 5.5 cm along foliation plane; about 10 to 15 percent phenocrysts consist of about 65 percent plagioclase, 13 percent biotite, 13 percent sanidine, 3 percent opaque oxides and sulfides, 2 percent quartz, 2 percent hornblende, and sphene present; abundant medium-dark-gray (N4), medium-light-gray (N6), light-gray (N7) and light-brownish-gray (5YR6/1) intermediate to silicic volcanic lithic fragments, as large as 5 cm, distinct increase in lithic fragment abundance downhole; pumice altered to extensive clays, groundmass altered to clays to a lesser degree, disseminated pyrite present--------------------------	1182.63	Lithic-rich and biotite-rich nonwelded to moderately welded ash-flow tuff
Tuff, ash-flow, pinkish-gray (5YR8/1) and yellowish-gray (5Y8/1) grading downhole to light-gray (N7), devitrified, moderately welded; pumice, common to sparse, dark-gray (N3) and medium-gray (N5), as large as 6 cm along foli-	Thin section at 1183.57	Lithic fragment-poor to rich zoned, biotite-rich, moderately welded

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Lithic Ridge Tuff--Continued		
ation plane; 22 percent phenocrysts consist of 67 percent plagioclase, 13 percent biotite, 13 percent sanidine, 3 percent opaque oxides and sulfides, 2 percent hornblende, 1.5 percent quartz, and sphene present; 3 percent light-gray (N7), medium-gray (N5), brownish-gray (5YR4/1), and grayish-red 5R4/2) silicic to intermediate volcanic lithic fragments, as large as 6 cm, abundance variable in layers as thin as 2 m; groundmass partially altered to rare to sparse smectite, no trace to common clinoptilolite, and sparse to common analcime, disseminated pyrite present--------	1212.00	ash-flow tuff
Tuff, ash-flow, medium-light-gray (N6) with a light-brownish-gray (5YR6/1) tint, devitrified, partially welded; pumice, common to sparse, white (N9) and light-olive-gray (5Y6/1), two colors coexist, as large as 6 cm along foliation plane; 12 percent phenocrysts consist of 65 percent plagioclase, 22 percent sanidine, 7 percent biotite, 3 percent opaque oxides and sulfides, 2 percent quartz, less than 1 percent hornblende, and sphene present; 16 percent light-gray (N7), medium-gray (N5), brownish-gray (5YR4/1), and grayish-red (5R4/2) silicic to intermediate volcanic lithic fragments, as large as 6 cm, abundance variable in layers as thin as 2 m; groundmass partially altered to rare to sparse smectite, no trace to common clinoptilolite, and sparse to common analcime, pumice altered to common clays, disseminated pyrite present------------------------	Thin section at 1221.76 1225.97	Lithic fragment-poor to rich zoned, partially welded ash-flow tuff
Tuff, ash-flow, very light gray (N8) grading downhole through pinkish-gray (5YR8/1) through light-brownish-gray (5YR6/1), and to grayish-orange-pink (5YR7/2) to light gray (N7) devitrified, nonwelded to partially welded, minor vapor phase downhole to about 1264 m; pumice, common, yellowish-gray (5Y8/1), light-greenish-gray (5GY8/1), greenish-gray (5GY6/1), and very pale orange (10YR8/2), as large as 3 cm along weak foliation plane; 8 percent phenocrysts consist of 50 to 53 percent plagioclase, 30 percent sanidine, 7 to 11 percent quartz, 4 percent biotite, 5 percent opaque oxides, as much as 1.5 percent hornblende, mafic minerals and plagioclase decrease downhole whereas quartz and sanidine increase, and sphene present; 16 to 18 percent light to dark gray (N7 to N3), brownish-gray (5YR4/1), and grayish-red (5R4/2) intermediate to silicic volcanic and rare gra-	Thin sections at 1231.08 and 1264.81	Partial cooling break marked by very light gray colors of non-welded to partially welded ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Lithic Ridge Tuff--Continued		
nitic and granophyric lithic fragments, commonly with dusky-red (5R3/4) alteration rims 1 mm wide, fragments as large as 7 cm, minor differences in size and abundance occur at intervals; groundmass partially altered to sparse smectite, sparse to common analcime, and sparse calcite, pumice altered to common clays and zeolite; fault contains gouge and Fe oxides and hydroxides------------	1268.11	
Tuff, ash-flow, light-gray (N7) grading downhole through yellowish-gray (5Y8/1), through mottled light-gray (N7) and pinkish-gray (5YR8/1) to mottled light-gray (N7), and yellowish-gray (5Y8/1), devitrified, partially welded downhole to 1281 m grading into partially to moderately welded; pumice, common, yellowish-gray (5Y8/1), light-greenish-gray (5GY8/1), greenish-gray (5GY6/1), pinkish-gray (5YR8/1), light-olive-gray (5Y6/1), olive-gray (5Y4/1), and moderate-orange-pink (5YR8/4), as large as 2.5 cm along foliation plane; 8 percent phenocrysts consist of 52 percent plagioclase, 32 percent sanidine, 10 percent quartz, 3 percent biotite, 2 percent opaque oxides, and sphene present; 25 percent light-gray to-grayish-black (N7 to N2) and brownish-gray (5YR4/1) intermediate to silicic volcanic and common granophyric lithic fragments, as large as 12 cm, distinctly more angular downhole; in mottled rock, light-gray areas have a distinctly more porous and vesicular texture than lighter colored areas and light-gray areas become more abundant downhole; groundmass partially altered to common smectite, and sparse calcite, pumice altered to extensive clay; fractures contain calcite--	Thin section at 1292.50 1294.98	Lithic fragment-rich partially welded to partially to moderately welded ash-flow tuff
Tuff, ash-flow, light-gray (N7) grading downhole through mottled very light gray (N8) and light-gray (N7) through light-gray (N7) to very light gray (N8), mottled zone occurs from 1307 to 1310 m, devitrified, partially welded; pumice, sparse to common, white (N9) and medium-gray (N4), as large as 3.5 cm along foliation plane; 11 percent phenocrysts consist of 47 percent sanidine, 44 percent plagioclase, 5 percent quartz, 3 percent opaque oxides, 1 percent biotite, and altered sphene present; 28 percent light-gray to dark-gray (N7 to N3), brownish-gray (5YR4/1), and grayish-red (5R4/2) silicic to intermediate volcanic fragments, as large as 4.5 cm, minor variations in size and abundance occurs at intervals; groundmass partially altered to sparse to common smectite,	Thin section at 1307.10	Subequal feldspar-bearing partially welded lithic fragment-rich ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Lithic Ridge Tuff--Continued no trace to common clinoptilolite, sparse analcime, and rare to abundant calcite, pumice extensively altered to clay and zeolite; fractures and faults contain breccia, gouge, calcite, Fe oxides and hydroxides, smectites, and analcime, one gouge zone 6 cm wide records at least 3 periods of fault movement at 1309.7 m------------------------	1319.00	
Tuff, ash-flow, yellowish-gray (5Y8/1) grading downhole through yellowish-gray (5Y8/1) through light-gray (N7) through mottled very light gray (N8) and light-gray (N7) through light-gray (N8) and to light-brownish-gray (5YR6/1), mottled zone occurs from 1334 to 1335 m, devitrified, moderately welded; pumice, sparse to common, dark-greenish-gray (5GY4/1), light-brownish-gray (5YR6/1), brownish-gray (5YR4/1), and yellowish-gray (5Y8/1), as large as 3.5 cm along foliation plane; 10 percent phenocrysts consist of 42 to 50 percent plagioclase, 37 to 42 percent sanidine, 3 to 6 percent quartz, 4 percent biotite, 2 to 3 percent opaque oxides, and altered sphene present; 17 to 21 percent light-gray to dark-gray (N7 to N3), brownish-gray (5YR4/1), and grayish-red (5R4/2) silicic to intermediate volcanic lithic fragments, as large as 4.5 cm, minor variations in size and abundance occur at intervals; groundmass partially altered to sparse to common smectite, no trace to common clinoptilolite, sparse analcime, and rare to abundant calcite, pumice altered to extensive clay and zeolite; fractures and faults contain breccia, gouge, calcite, Fe oxides and hydroxides smectite, and analcime------------------------	Thin sections at 1337.50 and 1348.13 1351.93	Subequal feldspar-bearing, moderately welded lithic fragment-rich ash-flow tuff
Tuff, ash-flow, yellowish-gray (5Y8/1) grading downhole through mottled very light gray (N8) and yellowish-gray (5Y8/1) through yellowish-gray (5Y7/2) through yellowish-gray (5Y8/1) through very light gray (N8) through light-gray (N7) and to mottled pinkish-gray (5YR8/1) and light-gray (N7), devitrified, partially welded to moderately welded in several repetitive cycles; pumice, common, very light gray (N8) and light-greenish-gray (5GY8/1) in lighter patches and medium-dark-gray to light-gray (N4 to N7) in darker patches, as large as 5 cm along foliation plane; 9 to 11 percent phenocrysts consist of 49 to 58 percent plagioclase, 36 to 38 percent sanidine, 4 to 10 percent quartz, 1.5 to 2 percent biotite, 1 to 1.5 percent opaque oxides, and sphene present; 19 to 20 percent light-gray to dark-gray (N7 to N3), brownish-gray (5YR4/1),	Thin sections at 1392.47 and 1429.18	Partially welded to moderately welded in repeated cycles in ash-flow tuff

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Lithic Ridge Tuff--Continued		
light-brownish-gray (5YR6/1), and reddish-gray (5R4/2), silicic to intermediate volcanic and rare granophyric plutonic lithic fragments, as large as 2.5 cm, numerous distinct variations in abundance and size downhole with no cooling breaks; groundmass partially altered to sparse to common smectite, rare to sparse clinoptilolite, no trace to common analcime, and rare calcite, pumice altered to abundant clay, some plagioclase phenocrysts have sericitic alteration; fractures and faults contain smectite, quartz, Fe oxides and hydroxides, gouge, clinoptilolite, and calcite, one fault zone at 1402 m contains a 10 cm thick zone of probable mylonite-------------------------------	1430.77	
Tuff, ash-flow, mottled pale-red (5R6/2) and very light gray (N8) grading downhole through grayish-pink (5R8/2) through through pale-red (10R6/2) through pinkish-gray (5YR8/1) through light-gray (N7) through very light gray (N8) and to light-greenish-gray (5GY8/1), devitrified, moderately welded to 1484.6 m grading downhole to partially welded; pumice, common, light-greenish-gray (5Y8/1), greenish-gray (5GY6/1) to dark-greenish-gray (5GY4/1) to dusky-green (5G3/2), medium-light-gray (N6), medium-dark-gray (N4), and pinkish-gray (5YR8/1), as large as 3 cm along foliation plane; 10 to 12 percent phenocrysts consist of 52 to 59 percent plagioclase, 27 to 35 percent sanidine, 6 to 10 percent quartz, 2.5 to 4 percent biotite, and 1 to 5 percent opaque oxides, and altered sphene present; 15 to 23 percent light-gray (N7), to dark-gray (N3), light-brownish-gray (5YR6/1), and brownish-gray (5YR4/1) silicic to intermediate volcanic with sparse granitic plutonic lithic fragments, as large as 4 cm, with decrease in abundance and size downhole in the pale-red (10R6/2) matrix, some lithic fragments have pale-brown (5YR5/2) alteration rims, carbonized wood fragments occur at 1485.22 m; groundmass partially altered to rare to common smectite, common to abundant analcime, and rare to sparse calcite, pumice completely altered to clay, zeolite, quartz, and feldspar, disseminated sulfides occur in groundmass and are more abundant in lithic fragments; fractures contain calcite, quartz, smectite, analcime, and fluorite-------------	Thin sections at 1435.22, 1449.84, and 1474.99 1485.29	Pale-red interval at top of moderately welded to partially welded ash-flow tuff
-- -- -- -- -- (cooling break) -- -- -- -- --		
Bedded Tuff		
Tuff, bedded, pyroclastic for the most part, with rare termi-		Bedded tuff

Appendix 2.--Lithologic description of core at drill hole USW GU-3 and USW G-3--Continued

Stratigraphic assignment and lithology	Depth (meters)	Distinguishing features
Bedded Tuff--Continued		
nation of bedding planes as evidence of fluvial reworking, light-gray (N7), medium-light-gray (N6) with a tint of pinkish-gray (5YR8/1) and yellowish-gray (5Y8/1), and light-brownish-gray (5YR6/1), poorly to well indurated; beds range from 2 mm to 0.3 m thick and consist of layers of sorted ash, pumice and lithic fragments; larger clasts are mostly very light gray (N8) pumice altered to clay, abundant in poorly indurated beds, as large as 10 mm; other large clasts are volcanic lithic fragments, moderate-orange-pink (5YR8/4), light-gray (N7), and medium-gray (N5), as large as 10 mm; carbonized wood fragments at 1485.47m------------------------	1488.27	
-- -- -- -- -- -- (cooling break) -- -- -- -- -- --		
Older Tuffs (Unit A?)		
Tuff, ash-flow, pinkish-gray (5YR8/1) grading downhole through very pale orange (10YR8/2) to mottled yellowish-gray (5Y8/1) and medium-light-gray (N6), devitrified, nonwelded to 1488.5 m grading downhole to partially welded; pumice, common, yellowish-gray (5YR8/1) and light-greenish-gray (5GY8/1), as large as 5 cm along foliation plane; about 15 percent phenocrysts consist of about 33 percent sanidine, 33 percent plagioclase, 28 percent quartz, 3 percent biotite, and 2 percent opaque oxides; about 2 percent pale-red (10R6/2) and light-gray (N7) silicic volcanic lithic fragments, as large as 2 cm; groundmass partially altered to rare to sparse smectite and common analcime, pumice altered totally to clay, zeolite and calcite----------	1493.30	Lithic fragment-poor and subequal feldspar-bearing nonwelded to partially welded ash-flow tuff
Tuff, ash-flow, pinkish-gray (5YR8/1) grading downhole through pale-red (5R6/2) through grayish-orange-pink (5YR7/2), and to grayish-pink (5R8/2), devitrified, moderately welded downhole to about 1515 m, moderately to densely welded below; pumice, common, yellowish-gray (5YR8/1), light-greenish-gray (5GY8/1), pale-brown (5YR5/2), greenish-gray (5GY6/1), grayish-green (10GY5/2), and dusky-red (5R3/4), as large as 5 cm along foliation plane; 16 to 18 percent phenocrysts consist of 33 to 34 percent sanidine, 33 percent plagioclase, 28 percent quartz, 2 to 4 percent biotite, and 1 to 2 percent opaque oxides; 2 percent pale-red (10R6/2) and light-gray (N7) silicic volcanic lithic fragments, as large as 2 cm; groundmass partially altered to rare to sparse smectite and common analcime, pumice altered totally to clay, zeolite and calcite, in the pale-red (10R6/2) zone silicification is present; fractures contain calcite---------------	Thin sections at 1495.44 and 1528.36 1533.39	Moderately welded to moderately to densely welded ash-flow tuff USW G-3 Total Depth