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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STRATIGRAPHIC AND STRUCTURAL CHARACTERISTICS OF VOLCANIC ROCKS IN CORE HOLE USW G-4, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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With A Section on Geophysical Logs

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ABSTRACT

Detailed stratigraphic and structural studies, performed in connection with the Nevada Nuclear Waste Storage Investigations program, have been in progress since 1978. The purpose of these studies is to characterize volcanic rocks underlying Yucca Mountain--a volcanic highland situated along the western boundary of the Nevada Test Site in southern Nye county, Nevada. Core hole USW G-4 was cored from 41 ft (13 m) to a depth of 3,001 ft (915 m) at a location approximately 300 ft (91 m) southwest of the proposed site of an exploratory shaft that will be used for in situ studies of the geotechnical, geologic, and hydrologic characteristics of rock in the unsaturated zone to aid in evaluating the suitability of Yucca Mountain for storage of high-level nuclear waste. The primary objectives of this study were to (1) verify that geologic conditions are similiar to those identified in nearby boreholes and (2) determine geologic and geophysical characteristics for use in the design and construction phases of the exploratory shaft.

Stratigraphic section in core hole USW G-4 is composed entirely of thick sequences of ash-flow tuff that are separated by fine- to coarse-grained ash-fall tuff and tuffaceous sediments. All rocks are of Tertiary age and vary in composition from rhyolitic to quartz latitic. Major stratigraphic units include the Paintbrush Tuff, tuffaceous beds of Calico Hills, and Crater Flat Tuff.

All four members of the Paintbrush Tuff were identified in USW G-4. In descending order, the members are the: Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring. The Tiva Canyon and Topopah Spring Members are dominantly densely welded and devitrified, except for the basal part of the Tiva Canyon and upper and lower parts of the Topopah Spring where the rock is non- to partially welded and vitric. In contrast, the Yucca Mountain and Pah Canyon Members are entirely non-to partially welded and vitric. They represent the distal edges of ash-flow tuffs that thicken to the north and northwest.

The thick 1,071 ft (329 m); densely welded zone of the Topopah Spring Member is of special interest as a potential host rock for storage of high-level nuclear waste. This zone contains three distinctive lithophysae-bearing intervals, the lower two of which reach thicknesses of 210 ft (64 m) and 357.9 ft (109.1 m), respectively. The highest content of lithophysal cavities occurs within the middle zone, where a few 10 ft (3 m) intervals contain more than 20 percent voids.

Many of the underlying stratigraphic units are highly zeolitic, containing mordenite and clinoptilolite in amounts that vary from 30 to as much as 70 percent of the rock.

Although a comprehensive structural analysis is still in progress, a preliminary compilation indicates the presence of 2,058 fractures, 10 and 72 percent of which occur in the densely welded zones of the Tiva Canyon and Topopah Spring Members, respectively. This corresponds to apparent fracture frequencies of 26 and 13 fractures per 10-ft (3-m) interval within the Tiva Canyon and Topopah Spring Members. Other less welded units range between 1 and 4 fractures per 10-ft (3-m) interval. Because fractures show a wide range of inclinations, the number of fractures in a cubic meter of rock was estimated. Maximum values of 34, 4, and 7 fractures per cubic meter are representative of densely welded devitrified tuff non-to partially welded tuff and bedded tuff, respectively.

Most fracture faces are partially coated or stained by one or more of the following: manganese and iron oxides and hyroxides, silica, zeolites, smectites, and calcite. However, in the Topopah Spring Member 51 percent of the fracture faces are not coated with secondary minerals but appear altered, presumably a result of weathering.

About 5 percent of the fractures were characterized as shear fractures based on the presence of slickensides, truncation of pumice fragments, and (or) brecciation. None of these indicators provides sufficient data to determine the amount of offset; however, the absence of any abrupt deviations in zonal patterns of ash-flow tuff units suggests all are of small scale. Most shear fractures are distributed throughout the cored interval. However, conspicuous concentrations of shear fractures occur near the top of the densely welded zone of the Topopah Spring Member, within the upper half of the Prow Pass Member, near the top of the Bullfrog Member, and within the upper part of the Tram Member. As in previous subsurface studies, many striated shear surfaces suggest a strong component of lateral movement.

Oriented core and downhole television camera observations provided information on the orientation of foliation, bedding planes, and fractures. Measurements of pumice foliation within the Topopah Spring show a mean dip of about 10° in a N. 75° E. direction. Bedding planes near the base of the tuffaceous beds of Calico Hills dip about 9° in directions that range from N. 59° E. to N. 90° E.

Plots of poles of fractures indicate that conspicuous fracture sets have orientations of (1) N. 22° E., 65° N.W. in the Tiva Canyon Member, (2) N. 12° W., 89-90° N.E. and S.W. in the Topopah Spring Member, and (3) N. 23° E., 45° N.W. and N. 50° E., 55° S.E. in the Crater Flat Tuff. Oriented fracture data obtained from television camera observations show no preferential strike of fractures in the Tiva Canyon Member and a wide range in the strike of fractures in the Topopah Spring Member, most of which strike between N. 30° W. and N. 60° E.

Rock quality characteristics, as defined by the core index, indicate that greater amounts of broken core are associated with densely welded zones in the Tiva Canyon and Topopah Spring Members, and in zones that contain concentrations of shear fractures. Greater amounts of lost core and excessive hole enlargement are associated with vitric, non- to partially welded tuff.

Geophysical logs from USW G-4 correlate well with logs from other drill holes at Yucca Mountain. Anomalous differences between the neutron-porosity and density-porosity logs below the static water level are attributed to undersaturation.

INTRODUCTION

At the request of the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS) has been investigating the geology of Yucca Mountain to aid in evaluating its suitability for storage of high-level nuclear waste. The area is located along the western margin of the Nevada Test Site (NTS) in southern Nevada (figs. 1 and 2). The DOE plans to intensify exploration activities at Yucca Mountain as part of the site characterization stage of the licensing process. These activities will include the construction of a deep, large diameter, exploratory shaft and underground facilities for direct access, observation, and testing of rock units that are currently considered as potential host rocks for storage of nuclear waste.

The purpose of the following report is to describe subsurface lithologic, stratigraphic, and structural features recognized in the nearly continuous core recovered from core hole USW G-4, located approximately 300 ft (91 m) southwest of the proposed site of the exploratory shaft. Primary objectives for subsurface studies at this location were to determine if geologic and hydrologic conditions are similar to those identified in boreholes within the immediate vicinity (UE-25a#1, USW G-1, UE-25a#6, fig. 2), and to study the geologic and geophysical characteristics of the site for use in the design and construction of the exploratory shaft. In so far as possible, references to surface mapping and previously drilled holes are included in this report to assess the continuity and (or) persistence of geologic features existing at Yucca Mountain, and, in particular, near the proposed shaft location. Data on X-ray analyses and mineralogic studies are provided to verify the degree of alteration and megascopic descriptions of core samples.

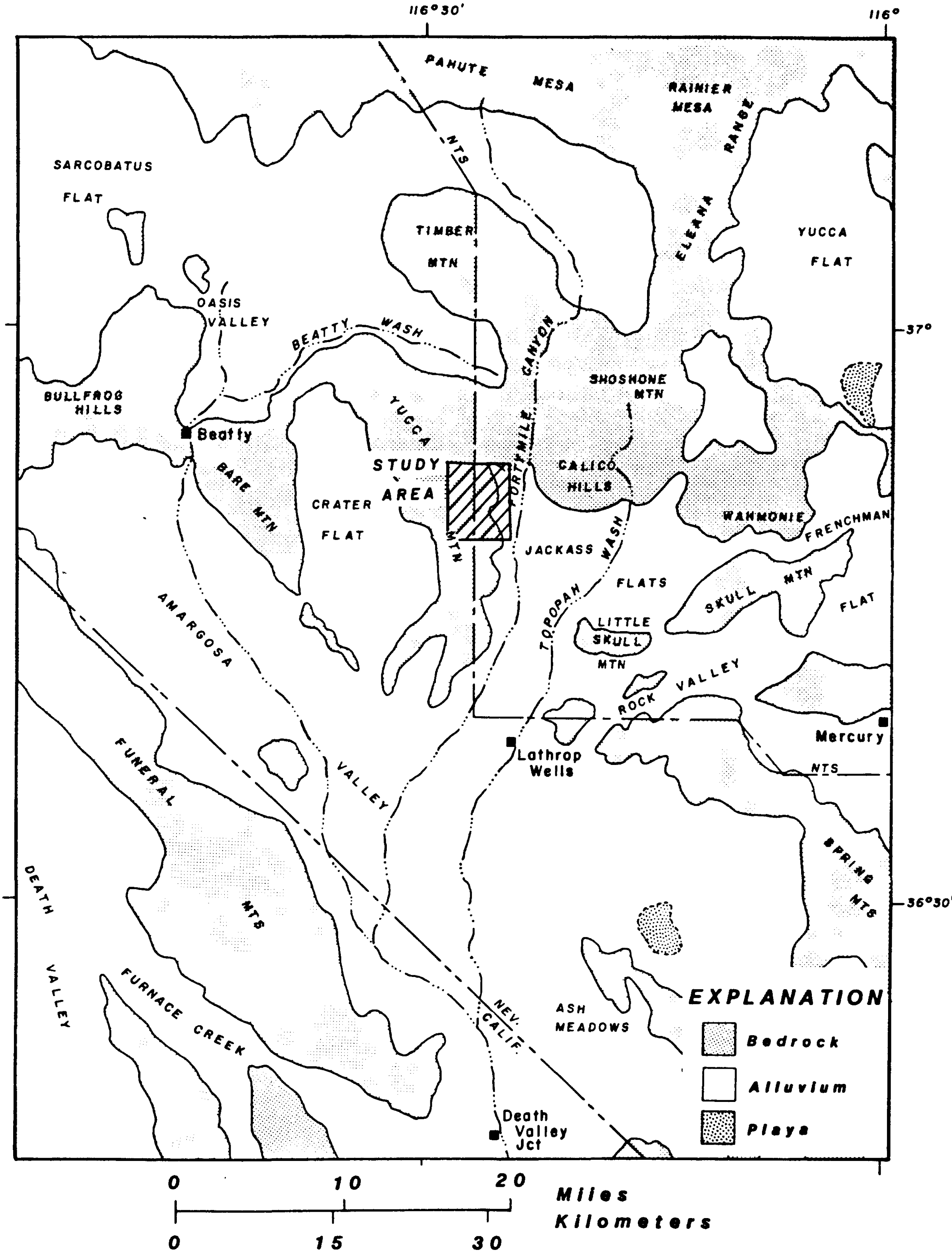

Figure 1.--Map showing Nevada Test Site and vicinity and location of study area.

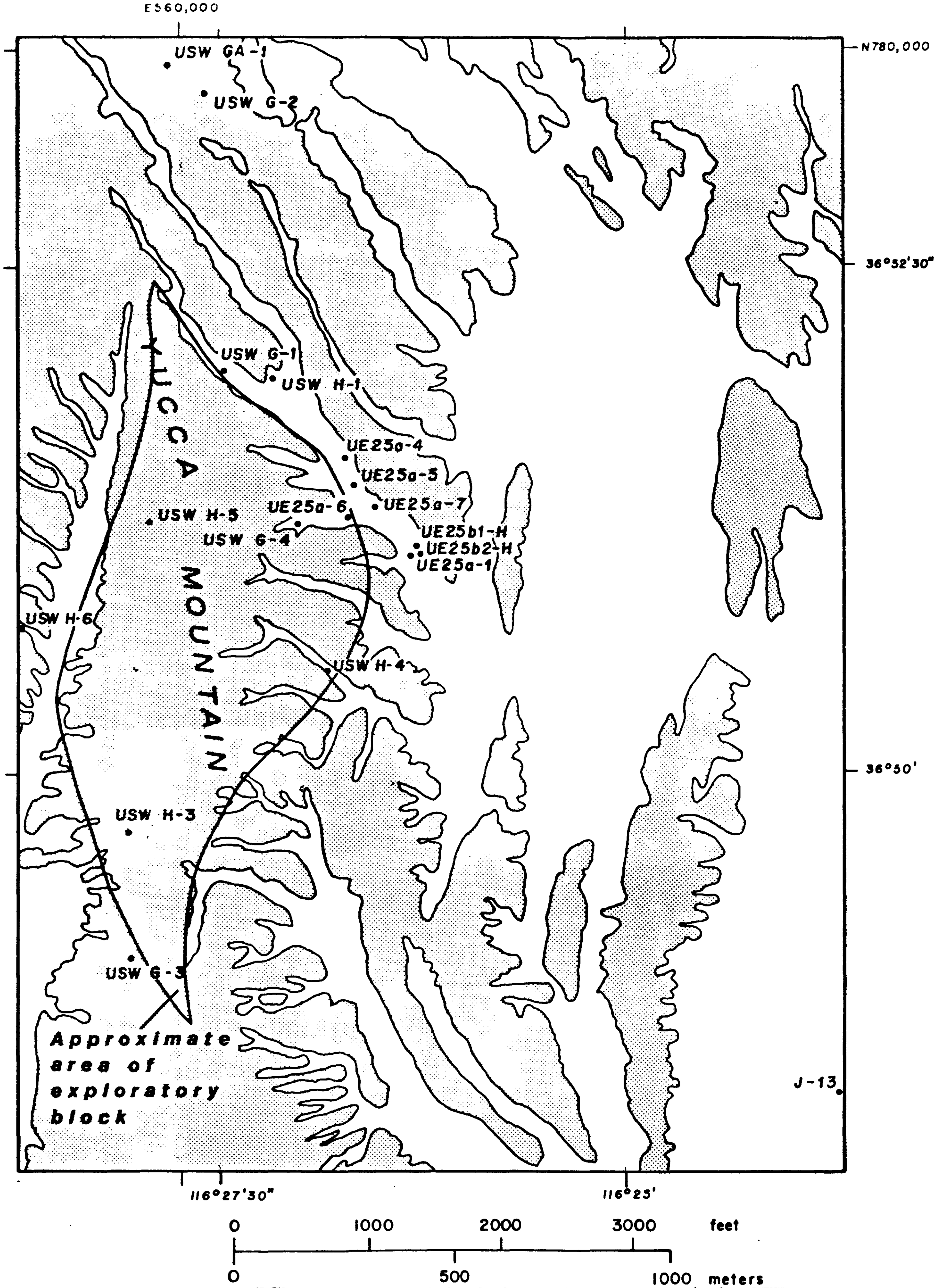

Figure 2.--Location of core holes at Yucca Mountain and approximate area of exploratory block.

Depths and thicknesses of geologic features identified in core are reported in English and metric units. The English system was used for the actual measurements. Where appropriate, thicknesses and depths of geologic features were measured to the nearest 0.1 foot in the core boxes; however, depths reported by drillers may not conform with this precision of measurement.

Acknowledgments

Appreciation is expressed for the valuable assistance given by geologists Mayra Castellanos, B. W. Cork, G. A. DePaolis, H. E. Huckins, K. A. Johnson, and L. D. Parrish of Fenix & Scisson, Inc. (F&S), in monitoring drilling and sampling operations. Sharon Diehl (USGS), assisted by examining selected thin sections taken from core. Several other colleagues in the USGS and Fenix & Scisson also assisted in this study by providing stratigraphic and mineralogic data; these individuals are acknowledged at appropriate places in this report.

SITE SELECTION

A core hole at the site of the proposed exploratory shaft would provide the best opportunity to confidently predict stratigraphic and structural conditions prior to construction of the shaft. However, factors which could potentially alter the natural state of rock adjacent to the proposed exploratory shaft site played a major role in the selection of a drill site 300 ft (90 m) from the shaft location. Principal factors included: (1) possible intersection of the core hole and rock below the shaft site and (2) potential contamination by drilling fluid. To a lesser degree, the anticipated layout of surface facilities for the exploratory shaft that is principally constrained by topography was also considered in site selection.

Experience gained from previous coring at Yucca Mountain has shown that most holes deviate significantly from vertical in a southwesterly direction; in some cases, the direction of borehole drift is coincident with the dip direction of the dominant fracture set (Scott and others, 1983). In order to minimize the likelihood of the core hole intersecting rock units directly beneath the shaft site and perhaps jeopardize future borehole sealing capabilities, sites to the southwest of the shaft were given a higher priority.

As in other core holes at Yucca Mountain, excessive losses of drilling fluid, probably along interconnected fractures, were anticipated in USW G-4 (Spengler and others, 1981; Ellis and Swolfs, 1983). If rock units beneath the shaft site were contaminated with these fluids, serious limitations would be placed on the amount of useful hydrologic data that could be obtained during construction of the shaft. Although the extent of contamination surrounding any of the previously drilled holes has yet to be determined, precautions were taken to minimize the risk of contamination. These precautions included: (1) selection of a site sufficiently removed from the shaft site, but close enough to allow confident projection of geologic data, and (2) the use of an air-foam drilling medium.

DRILLING HISTORY

Beginning on August 22, 1982, a (17.5-in) 43.8-cm hole was drilled to 40 ft (12 m), a depth at which surface casing was installed. Using air foam as a circulating medium, coring operations began at 41 ft (21 m) and continued downhole to a depth of 444 ft (135 m), where the first of three significant drilling problems developed. The core barrel became lodged in the hole, reportedly due to unstable hole conditions between depths of about 233 ft (71 m) and 444 ft (135 m); an interval that roughly corresponds to the upper 211 ft (64 m) of moderately to densely welded Topopah Spring Member. After removing rubble from the hole, coring resumed to 451 ft (138 m) where circulation was lost and efforts to pull the drill string from the hole resulted in the detachment of 50 ft (15 m) of drill string and a 10-ft (3-m) core barrel. Coring was delayed 2 weeks and the hole was enlarged to (6.75 in) 16.9 cm, (9.88 in) 24.7 cm, and, finally, to (12.25 in) 30.6 cm. Geophysical logging was accomplished during each stage of enlargement and most of the drilling tools were recovered except for the core barrel and bit. Downhole television camera observations showed that the core barrel and bit remained in a sidetrack of the hole between 341 ft (104 m) and 351 ft and (107 m). Thus, no core was collected between the interval of 451 ft (138 m) and 470 ft (143 m).

Coring resumed on September 26 and continued to a depth of 997 ft (304 m), where the bit crown was lost in the hole. This required enlargement of the hole a diameter of (6.75 in) 16.9 cm from 467 ft (142 m) to 997 ft (304 m), and installation of (5.5-in) 13.8-cm casing.

Coring continued through the bedded tuff near the base of the tuffaceous beds of Calico Hills, to a depth of 1,742 ft (526 m), where booster pump failure interrupted circulation and resulted in the loss of part of the drill string. The hole was enlarged to (6.75 in) 16.9 cm to 1,724 ft (526 m) in order to recover the drilling equipment.

The coring operation was completed at a depth of 3,001 ft (915 m) on November 7, 1982; geophysical logging was completed by the end of November, and the hydrologic testing program was completed on January 12, 1983. A summary of the drilling history is provided in table 1.

At the completion of the geophysical logging program, a multishot gyroscopic survey was obtained at (25-ft) 8-m stations to a depth of 2,975 ft (907 m) to determine the extent and direction of borehole deviation. This subsurface directional survey indicated that the bottom of the hole was 140.4 ft (42.8 m) south and 217.6 ft (66.3 m) west of its original surface location (fig. 3).

STRATIGRAPHY

Rock units cored in USW G-4 consist entirely of rhyolitic to quartz latitic ash-flow tuff, separated in places by fine- to coarse-grained tuffaceous sediments and ash-fall tuff 2.6 ft (0.8 m) to as much as 55.9 ft (17 m) thick.

Table 1.--Abridged hole history of USW G-4, Yucca Mountain

Location (Nevada State coordinates):	N. 65,807.07 feet (233,418.00 m) E. 563,081.62 feet (171,627.28 m)
Ground elevation:	4,166.6 feet (1,269.98 m)
Hole size (after completion):	see below
Circulating medium:	Air-foam
Drilling record:	Spudded (8-24-82) Completed coring (1-7-82) Completed logging (11-30-82) Completed hydrologic testing (1-12-83)
Static water level (1-83):	1,776.0 feet (541.3 m) (12-3-82)
Reported bridges--feet (m):	125 (38); 160 (49); 180 (55); 233-333 (71-102); 345 (105); 730 (222); 731 (223); 768 (234); 857 (261); 894 (272); 1,180-1,185 (360-361); 1,201 (366); 1,310 (399); 1,949 (594); 1,980 (604)
Circulation losses-feet (m):	444-451 (135-138); 657 (200); 1,352-1,490 (412-454); 1,724 (526); 2,785-2,810 (849-856)
Remarks:	10-foot (3-m) core barrel left in hole from 341 feet (104 m) to 351 feet (107 m)

Hole size (after completion):

Depth Feet (m)	Diameter Inches (cm)
0-40 (0-12)	17.50 (43.75)
40-2,020 (12-616)	12.25 (30.62)
2,020-3,001 (616-915)	8.75 (21.88)

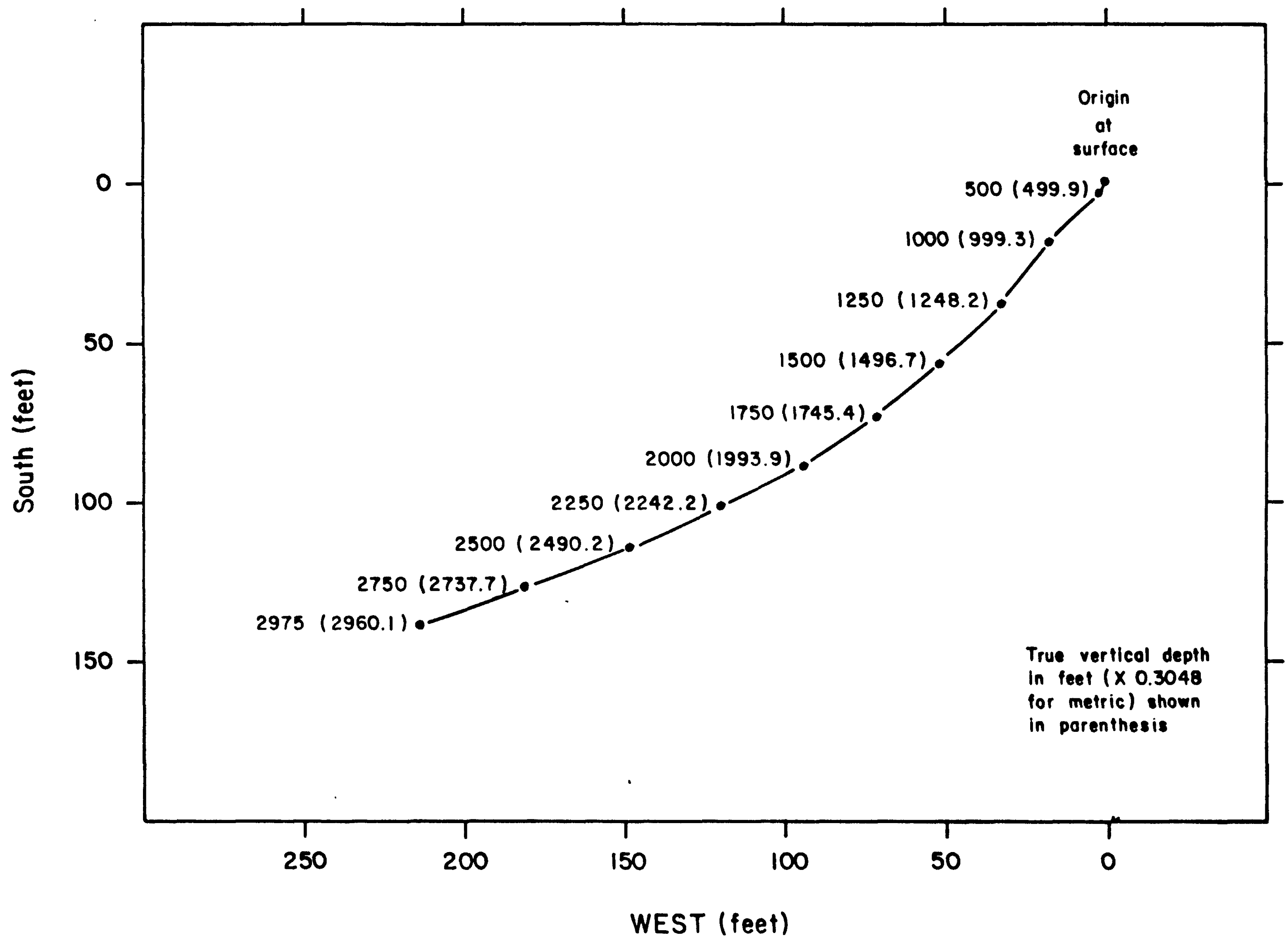

Figure 3.--Horizontal projection of hole deviation in core hole USW G-4.

For the most part, stratigraphic nomenclature conforms with that applied by Byers and others (1976), and Carr and others (in press), Christiansen and Lipman (1965), Lipman and McKay (1965), Orkild (1965). Stratigraphic data obtained from other core holes are presented in detail by Maldonado and Koether (1983), and Scott and Castellanos (1984), Spengler and others (1979, 1981), Spengler and Rosenbaum (1980). Although perhaps unconventional, lithologic descriptions presented in this report separate intervals of bedded tuff from underlying and overlying ash-flow tuff members. Bedded-tuff intervals recognized in the subsurface are commonly very thin in comparison to the ash-flow tuffs and vary considerably in thickness between boreholes; and therefore, their physical and chemical properties may differ markedly from those of non- to partially welded ash-flow tuff.

Major stratigraphic units, along with their respective thicknesses, are outlined in descending order in table 2. Detailed lithologic variations occurring within each major stratigraphic interval are described in the Appendix and supersede descriptions previously published in Bentley (1984). Separate lithologic units primarily describe changes in welding, primary crystallization, alteration, phenocryst content, and lithic content, all of which may influence physical characteristics of the unit. The dominant types of welding, crystallization, and alteration are graphically displayed in columns 1 and 2 of plate 1. Except where otherwise stated, all thicknesses and depths are measured along the axis of the core without regard to hole deviation.

Alluvium and Colluvium

Alluvial and colluvial deposits of Quaternary age, occurring at the surface are typically composed of a poorly sorted mixture of unconsolidated to poorly consolidated, silt to boulder-size fragments of nonwelded to densely welded tuff.

The contact between alluvium and bedrock was not determined accurately because of inadequate sample collection prior to the installation of surface casing at 40 ft (12 m). The contact has been estimated at a depth of about 30 ft (9 m) below land surface; however, it is possible that the contact may be as much as 10 ft (3 m) higher.

Paintbrush Tuff

On the basis of similar petrographic features, ash-flow tuffs that occur between the bottom of the alluvium and a depth of 1,406.8 ft (428.8 m), are included in the Paintbrush Tuff (Byers and others, 1976). In descending order, this formation includes the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members. All four members are present in the USW G-4 core hole, and each is underlain by 10-40 ft (3-12 m) of bedded and ash-fall tuff deposits.

Within the exploratory block (fig. 2), the upper and lowermost members are dominantly composed of welded tuff, and the two middle members (Yucca Mountain and Pah Canyon) are dominantly nonwelded.

Table 2.--Geologic units identified in core hole USW G-4

Rock units	Measured thickness ft	Measured thickness (m)	Measured depth to base of interval ft	Measured depth to base of interval (m)	True vertical depth to base of interval ft	True vertical depth to base of interval (m)	True vertical elevation to base of interval ft	True vertical elevation to base of interval (m)
Alluvium and Colluvium	30.0	9.1	30.0	9.1	30.0	9.1	4,136.6	1,260.8
Paintbrush Tuff								
Tiva Canyon Member	108.0	32.9	138.0	42.1	138.0	42.16	4,028.6	1,227.9
Bedded Tuff	10.0	3.0	148.0	45.1	148.0	45.1	4,018.6	1,224.9
Yucca Mountain Member	0.8	0.2	148.8	45.4	148.8	45.4	4,017.8	1,224.6
Bedded Tuff	19.4	5.9	168.2	51.3	168.2	51.3	3,998.4	1,218.7
Pah Canyon Member	19.8	6.0	188.0	57.3	188.0	57.3	3,978.6	1,212.7
Bedded Tuff	40.0	12.2	228.0	69.5	228.0	69.5	3,938.6	1,200.5
Topopah Spring Member	1,178.8	359.3	1,406.8	428.8	1,404.1	427.8	2,762.5	842.0
Bedded Tuff	2.6	0.8	1,409.4	429.6	1,406.6	428.7	2,760.0	841.2
Tuffaceous beds of Calico Hills	296.1	90.2	1,761.4	536.9	1,756.7	535.4	2,409.9	734.5
Crater Flat Tuff								
Prow Pass Member	476.2	145.1	2,237.5	682.0	2,229.8	679.6	1,936.8	590.3
Bedded Tuff	6.7	2.0	2,244.2	684.0	2,236.5	681.7	1,930.1	588.3
Bullfrog Member	489.1	149.1	2,733.3	833.1	2,721.2	829.4	1,445.5	440.6
Bedded Tuff	22.3	6.8	2,755.6	839.9	2,743.2	836.1	1,423.4	433.8
Tram Member	[1]245.4	74.8	[1]3,001.0	914.7	[1]2,986.0	910.1	[1]1,180.6	359.8

[1]Base of member not penetrated

Tiva Canyon Member

The lowermost part of the Tiva Canyon Member, 108 ft (33 m) of ash-flow tuff of which the upper 88 ft (27 m) are densely and moderately welded were penetrated beneath the alluvial deposits. The lowermost 21.3 ft (6.5 m) of the moderately welded subunit are distinctive, based on the occurrence of smectite-rich pumice fragments. Below a depth of 118 ft (36 m), welding decreases progressively to the base of the member. The lowermost 20 ft (6 m) of the Tiva Canyon are vitric, containing abundant black and yellowish-orange glass shards.

Two thin sections from the moderately and nonwelded basal section of the Tiva Canyon Member at depths of 107 ft (33 m) and 121.5 ft (37.0 m), show phenocryst contents of 5 and 2 percent, respectively. Alkali feldspar is the dominant phenocryst, occurring in proportions of about 93 and 81 percent, respectively. Accessory minerals include sphene, zircon, apatite, and perrierite/allanite. Quartz is absent.

Bedded Tuff

Approximately 10 ft (3 m) of ash-fall tuff separate the Tiva Canyon Member from the underlying Yucca Mountain Member. Almost all of the tuff is composed of vitric pumice clasts and glass shards.

Yucca Mountain Member, Bedded Tuff, and Pah Canyon Member

The stratigraphic interval between 148 ft (45 m) and 188 ft (57 m) includes the Yucca Mountain Member, bedded tuff, and the Pah Canyon Member. Lithologies of these units include ash-flow tuff, reworked tuff, and ash-fall tuff; however, the latter is dominant. As in nearby boreholes, these deposits are commonly friable, vitric, and, in part, slightly argillic. Much of the core can be easily crushed between the fingers.

The friability greatly limits the amount of core recovery, promotes excessive hole erosion (pl. 1), and inhibits characterization of the rock. The average amount of core loss throughout this interval was about 60 percent, an amount far in excess of an average core loss of 9.2 percent for the entire cored section of the hole. As a result, thicknesses of the Yucca Mountain and Pah Canyon Members and bedded tuff cannot be determined with a high degree of accuracy.

Strictly on the basis of available core, thicknesses of the Yucca Mountain Member, bedded tuff, and Pah Canyon Member are 0.8 ft (0.2 m), 19.4 ft (5.9 m) and 19.8 ft (6.04 m), respectively.

Examination of one thin section, cut from a sample taken at a depth of 178.4 ft (54.4 m), showed a phenocryst content of 6.9 percent. Of the total phenocrysts, 52 percent were identified as alkali feldspar, 33 percent as plagioclase, and 9 percent as biotite. Accessory minerals include sphene, apatite, zircon, clinopyroxene, perrierite/allanite, and quartz.

Bedded Tuff

The base of the Pah Canyon Member is separated from the underlying Topopah Spring Member by 40 ft (12 m) of reworked tuff and ash-fall tuff deposits. The major constituent of these tuffs is vitric pumice clasts.

Topopah Spring Member

Since 1982 emphasis has been on identifying ash-flow tuffs occurring above the static water level and assessing their suitability as potential host rock for storage of high-level radioactive waste at Yucca Mountain. On the basis of radionuclide isolation time, allowable repository gross thermal loading, excavation stability, and relative economics, the densely welded, devitrified part of the Topopah Spring Member has been selected as the primary "target" unit (Johnstone and others, 1983).

The Topopah Spring Member is a multiple-flow compound-cooling unit (Lipman and others, 1966). However, zonal patterns deviate only slightly from those of a simple cooling unit, wherein nonwelded basal and uppermost parts grade inward through zones of partial welding into a densely welded center part. The upper and lower parts of the densely welded zone are vitrophyres, in contrast to the internal part of the densely welded zone which is devitrified and contains varying proportions of lithophysae.

In the vicinity of USW G-4, the Topopah Spring Member reaches a total thickness of 1,179 ft (359 m). From the top downward, the member consists of 10 ft (3 m) of nonwelded to partially welded tuff, possessing physical characteristics that are similar to those of the overlying Yucca Mountain and Pah Canyon Members. The rock is vitric, highly friable, composed of both ash-flow tuff and ash-fall tuff, and forms a sharp contact with the underlying vitrophyre. This upper vitrophyre is 3.8 ft (1.2 m) thick. Below the vitrophyre, the member consists of 1,074 ft (327 m) of moderately to densely welded, devitrified tuff, the details of which will be described in the latter part of this section (pl. 1). This thick, welded zone is underlain by a glassy, vitrophyric layer 28.9 ft (8.8 m) thick. In turn, the vitrophyric layer grades downward into nonwelded to partially welded tuff that forms the basal part of the member. Welding progressively decreases toward the base of the member. Core from this zone exhibits a higher degree of cohesion when compared to the upper nonwelded part of the member. This is probably due to an increase in alteration (sample 1, table 3).

The thick welded and devitrified part of the Topopah Spring Member in core hole USW G-4, occurs between the depths 242.8 ft (74 m) and 1,316.5 ft (401.3 m), and displays a fair degree of consistency with respect to welding characteristics; however, subtle variations in crystallization textures and the occurrence of three lithophysae-bearing zones influence the homogeneity of the rock mass.

Directly beneath the upper vitrophyre, a densely welded, devitrified zone, measuring 22.3 ft (6.8 m) in thickness, is referred to as the quartz latitic caprock (Lipman and others, 1966). The caprock grades downward into a zone of moderately to densely welded tuff that contains an abundance of pumice fragments showing evidence of vapor-phase crystallization based on the

Table 3.--X-ray analyses of selected samples from core hole USW G-4

[Analyst: P. D. Blackmon, U.S. Geological Survey. Estimated amounts of minerals present are reported as parts of 10; Tr, trace (<5 percent); <, less than; >, more than; leaders indicate minerals not identified; NWT, nonwelded ash-flow tuff; PWT, partially welded tuff; MWT, moderately welded tuff; BT, bedded tuff; Tpt, Topopah Spring Member; Tht, tuffaceous beds of Calico Hills; Tcp, Prow Pass Member; Tcb, Bullfrog Member; Tct, Tram Member]

Sample No.	Depth ft	Depth m	Strati-graphic unit	Rock type	Mineral content: Mont-moril-lon-ite	Illite-mica	Quartz	Feldspar (potas-sium)	Crist-obal-ite opaline silica	Amor-phous (ash)	Carbon-ate (acid reac-tion)	Clinop-tilo-lite	Clinop-tilo-lite/mor-denite	Mor-den-ite	Hema-tite
1	1,402.8-1,403.0	427.6-427.6	Tpt	NWT	Tr	---	<1	<1	<1	>1	Tr	6	---	---	---
2	1,510.6-1,510.7	460.4-460.5	Tht	NWT	Tr	---	Tr	<1	1	1	Tr	7	---	---	---
3	1,643.6	501.0	Tht	NWT	Tr	---	Tr	<1	1	1	Tr	---	>6	---	---
4	1,762.5-1,762.6	537.2-537.2	Tcp	NWT	1/>1	---	Tr	<1	>1	1	Tr	5	---	---	---
5	1,771.3-1,771.4	539.9-539.9	Tcp	NWT	Tr	---	---	<1	>1	1	Tr	6	---	---	---
6	1,953.3-1,953.4	595.4-595.4	Tcp	PWT	<1	---	---	6	2	1	---	---	---	---	---
7	1,968.9-1,969.0	600.1-600.2	Tcp	NWT	Tr	Tr	Tr	>2	1	1	Tr	---	>4	---	---
8	1,989.4-1,989.5	606.4-606.4	Tcp	NWT	Tr	---	Tr	>1	1	1	Tr	6	---	---	---
9	2,039.0-2,039.1	621.5-621.5	Tcp	NWT	---	---	Tr	3	<1	<1	Tr	---	5	---	---
10	2,069.0-2,069.1	630.6-630.7	Tcp	PWT	---	---	---	3	<1	<1	Tr	---	>5	---	---
11	2,089.9-2,090.1	637.0-637.1	Tcp	PWT	Tr	Tr	---	>1	Tr	1	Tr	---	>6	---	---
12	2,131.5-2,131.7	649.7-649.7	Tcp	PWT	Tr	Tr	Tr	1	---	1	Tr	---	>7	---	---
13	2,202.3-2,202.4	671.3-671.3	Tcp	NWT	Tr	Tr	Tr	<1	Tr	1	Tr	---	>7	---	---
14	2,226.7-2,226.9	678.7-678.8	Tcp	NWT	Tr	---	Tr	>1	Tr	<1	Tr	---	7	---	---
15	2,263.8-2,264.0	690.0-690.1	Tcb	PWT	---	<1	>2	>6	---	Tr	Tr	---	---	---	Tr
16	2,285.3-2,285.5	696.6-696.6	Tcb	PWT	Tr	Tr	>2	>6	---	Tr	Tr	---	---	---	Tr
17	2,551.6-2,551.7	777.7-777.8	Tcb	NWT	Tr	Tr	>2	>6	---	Tr	Tr	---	---	---	Tr
18	2,598.8-2,599.0	792.1-792.2	Tcb	MWT	Tr	Tr	>2	>6	---	Tr	Tr	---	---	---	Tr
19	2,680.7-2,680.9	817.1-817.1	Tcb	PWT	2/ 1	Tr	1	7	---	<1	---	---	---	---	---
20	2,716.8-2,716.9	828.1-828.1	Tcb	PWT	Tr	Tr	Tr	>4	---	Tr	Tr	---	---	>4	---
21	2,738.4-2,738.5	834.7-834.7	Tcb	BT	2/Tr	Tr	>1	4	---	Tr	Tr	---	>3	---	---
22	2,762.6-2,762.7	842.0-842.1	Tct	PWT	Tr	<1	>1	>3	---	Tr	Tr	---	>4	---	---
23	2,788.3-2,788.4	849.9-849.9	Tct	PWT	---	<1	1	4	---	Tr	Tr	---	4	---	Tr
24	2,825.0-2,825.1	861.1-861.1	Tct	PWT	Tr	<1	>1	>3	---	Tr	Tr	---	4	---	---

1/25-35 percent illite mixed layers.

2/20-30 percent illite mixed layers.

presence of tridymite and drusy feldspar. Except for an abrupt decrease in the degree of welding, between the depths of 280 ft (85 m) and 284.5 ft (86.7 m), where the rock is nonwelded to partially welded, this moderately to densely welded zone extends downward to the first zone containing lithophysal cavities.

From a depth of 400.4 ft (122.0 m) to the top of the basal vitrophyre, 1316.5 ft (401.3 m), alternating lithophysal and non-lithophysal zones divide the Topopah Spring Member into discrete subunits of varying physical characteristics. The presence of lithophysae increases porosity and may have an effect on mineability, ground support, and heat capacity of the rock mass (F. B. Nimick; Sandia National Laboratories written comm., 1984), and therefore, efforts were made to identify subtle variations in the volume of lithophysae in the Topopah Spring Member. Fundamentally, a lithophysa can be divided into three basic components. From the center outward, it consists of (1) a central void or cavity, (2) a thin veneer of vapor-phase minerals that line the cavity, and (3) an alteration rind, which commonly appears to be of higher porosity than the surrounding rock matrix. Owing to the gradational nature of contacts separating the lithophysal and non-lithophysal zones within the exploratory block point-count method of estimating the abundance of lithophysae was utilized, whereby a scale, graduated into 0.1-ft (3.0-cm) increments was placed parallel to the core axis alongside joined segments of core. To minimize bias, the linear traverse along the core was selected by rotating the core 90^{0} in a counter-clockwise direction from the existing orientation arrow, which was marked on the core soon after recovery. A count was made of the number of lithophysae (vapor-phase minerals, alteration rinds, and lithophysal cavities) occurring directly beneath any 0.1 ft (3.0-cm) mark. The sum of the counts within a measured interval, commonly 10.0 ft (3.0 m), divided by the total number of 0.1-ft (3.0-cm) marks, provides a reliable estimate of the volume of lithohysae for each interval. Counts of only lithophysal cavities were also compiled separately to illustrate the percentage of voids for each interval. Results of this study, provided in parts A and B of figure 4, show the vertical distribution of lithophysae as well as lithophysal cavities. To determine if spacing between points is sufficiently small, another method of estimating void content of the rock was used (fig. 4, C). By this method, the voids attributed only to lithophysal cavities that were identified along the surface of the core were measured directly along the same linear traverse parallel to the core axis as in the point-count study (fig. 4). The total amount of voids divided by the total measured length, provides results very similar to those displayed in part B of figure 4. A preliminary test to estimate the accuracy of using only one traverse was applied to selected cores from USW G-2. Points were counted along four equally-spaced traverses at four separate 10-ft (3-m) intervals estimated to contain from 2 to 15 percent lithophysal cavities. The average percent of lithophysal cavities based on four traverses did not vary by more than 3 percent from the original single traverse, suggesting that more than one traverse may not be required to obtain reasonable estimates. However, intervals very rich in lithophysal cavities are likely to be slightly underestimated in these studies. When coring through these zones, core commonly breaks easily and commonly jams in the core barrel; increasing the amount of broken core. Highly broken segments of core, smaller than about 0.13 ft (4 cm), were not included in these studies.

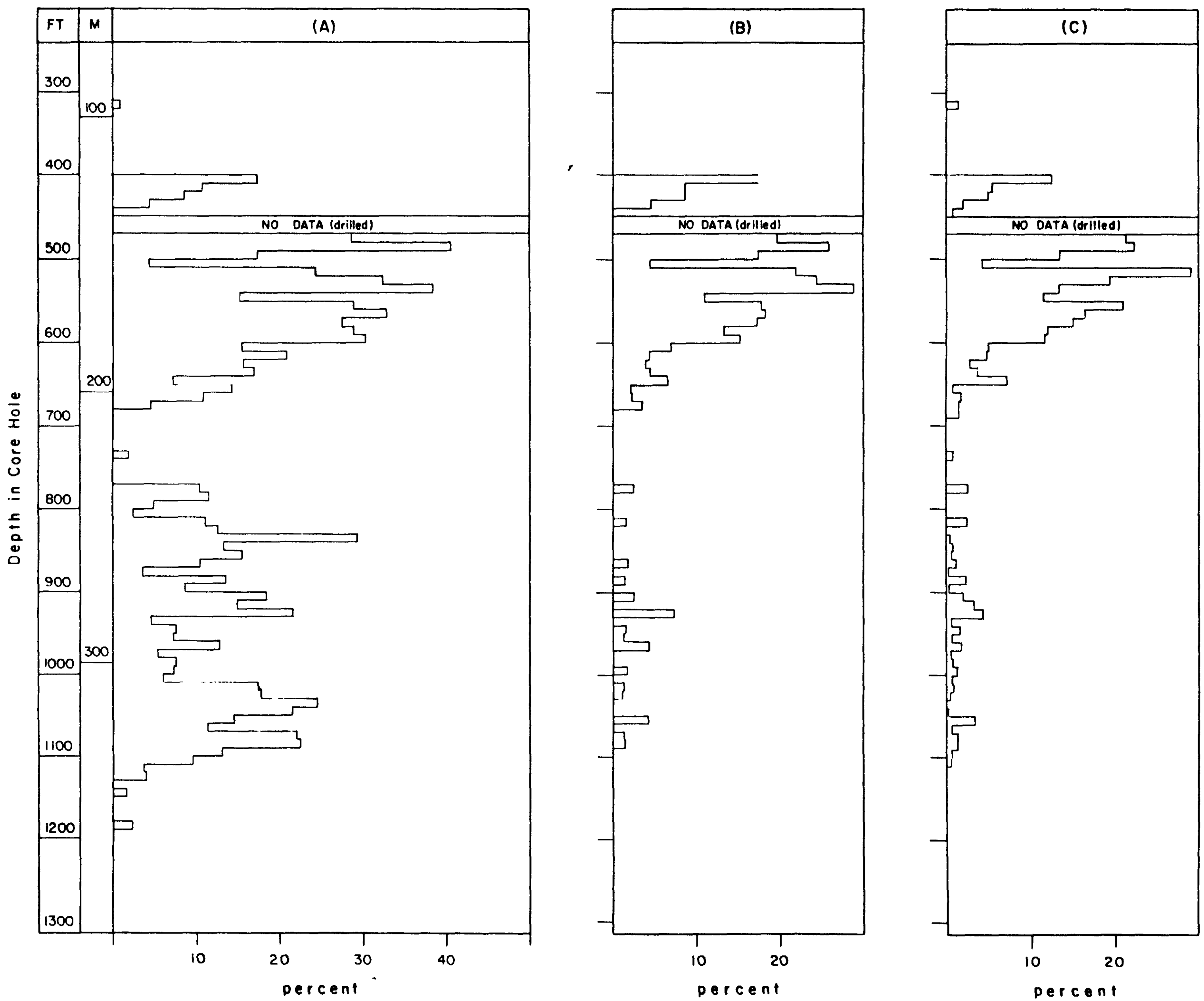

Figure 4.--Vertical distribution of (A) lithophysae, (B) lithophysal cavities, and (C) percent voids within the densely welded zone of the Topopah Spring Member in core from USW G-4. Parts A and B were determined using a point-counting technique; part C was directly measured, as described in text. Data collected by B. W. Cork (F&S).

The uppermost and thinnest of the three lithophysal zones is approximately 40 ft (12 m) thick and occurs between depths of 400-440 ft (122 and 134 m). Lithophysae constitute about 17 percent of the rock near the top of the zone and progressively decrease downward to less than 10 percent at the base. Lithophysae in this interval are principally made up of cavities lined with secondary minerals, dominantly quartz and feldspar and very thin alteration rinds. Many of the cavities are slightly flattened. Lithophysae commonly range in size between 1 and 3 cm.

The most pronounced lithophysae-bearing zone occurs between the depths of 470 ft (143 m) and 680 ft (207 m). More than half of the interval contains from 20 to as much as 40 percent lithophysae. The average length (perpendicular to core axis) and width (parallel to core axis) of these lithophysae, measured along the surface of the core, is 2.7 cm and 2.1 cm, respectively. Most are dominantly composed of cavities and show little or no flattening. Void content commonly varies between 11.0 and 29.0 percent of the rock. About 90 ft (27 m) of moderately to densely welded, non-lithophysal, devitrified tuff separates this zone from the lowermost and thickest lithophysal zone.

The lowermost lithophysal zone, occupying the stratigraphic interval between 770 ft (235 m) and 1,127.9 ft (343.8 m), possesses several characteristics in marked contrast to the upper two zones. Lithophysae rarely exceed 20 percent and most cavities are extremely flattened and, in many cases, completely collapsed. The average length and width of lithophysae are about 3.1 and 2.5 cm, respectively. As indicated in parts B and C of figure 4, the percent of lithophysal cavities is commonly less than 5.

The volume of lithophysae within the rock mass that is considered detrimental to the stability and performance of a repository has yet to be determined. The rock from 1,127.9 ft (343.8 m) to the top of the basal vitrophyre contains very few or no lithophysae and it is this subunit of the Topopah Spring Member that is currently being studied by the DOE for at-depth evaluation in the exploratory shaft as a potential host rock for emplacement of nuclear waste. The stability of the lithophysal zones will further be investigated during construction of the exploratory shaft. Results of these experiments may provide information that will allow flexibility in selecting the appropriate subunit or subunits of the Topopah Spring Member for the proposed underground facility.

Of special interest to characterizing the uniformity of physical properties within the Topopah Spring Member is the lateral continuity of these lithophysal zones. A comparison of thicknesses of lithophysal zones in core holes indicates a relative decrease in these zones from north to south (fig. 5). The uppermost zone pinches out between holes USW G-4 and USW GU-3. The two thicker lithophysal zones appear continuous throughout Yucca Mountain from core holes USW G-1 to USW GU-3; however, thickness of the lowermost non-lithophysal zone appears to decrease significantly north of USW G-4.

In addition to megascopic examination of stratigraphic features in core from the Topopah Spring Member, modal analysis of 29 thin sections were performed (fig. 6). Total number of counts per thin section ranged from 1238 to 1550. The size of phenocrysts rarely exceeds 2.5 mm and commonly is less

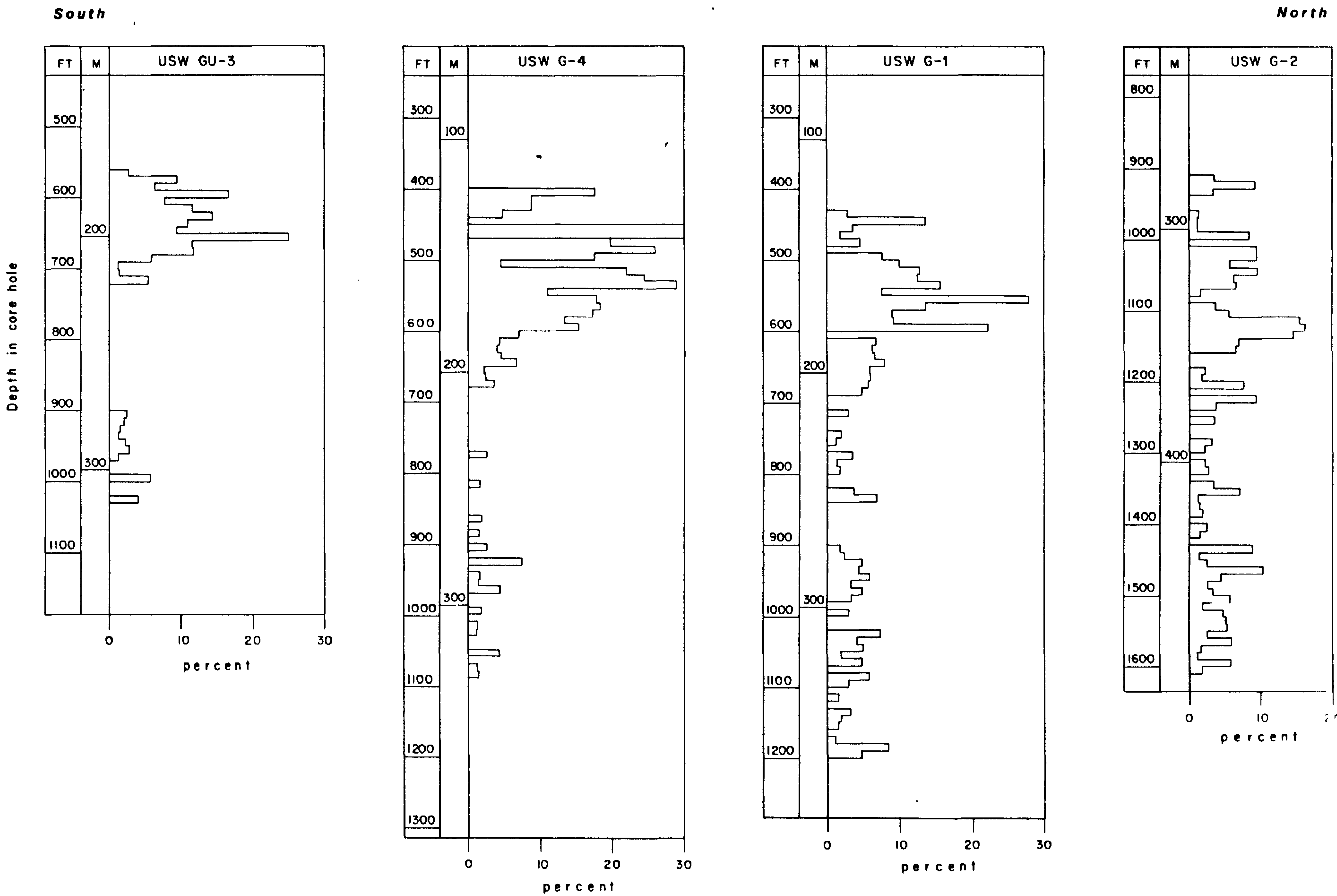

Figure 5.--Variations in lithophysal-cavity content within the densely welded zone of the Topopah Spring Member in holes USW GU-3, USW G-4, USW G-1, and USW G-2 (based on point-count data provided by Eric Larsen and B. W. Cork, F&S).

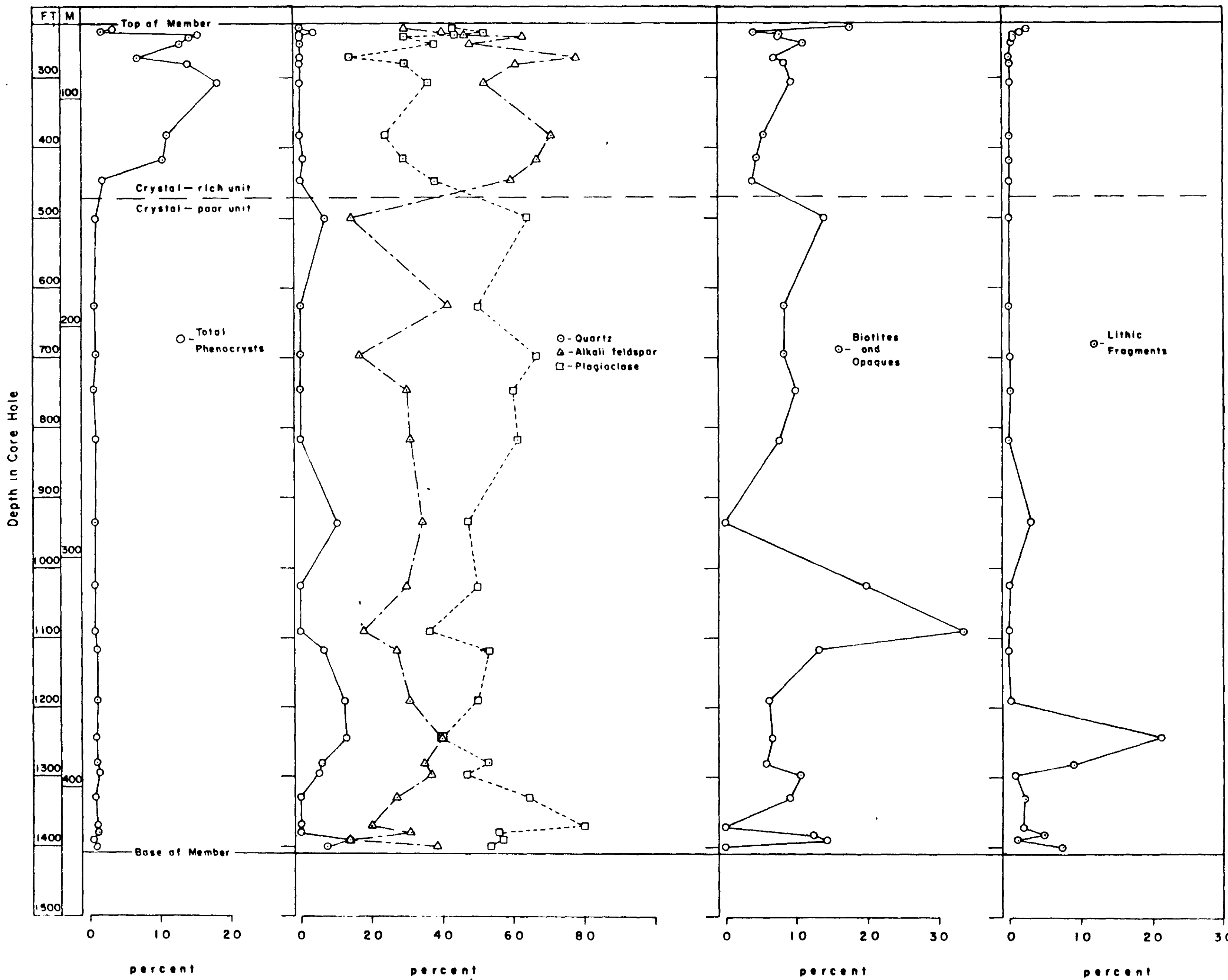

Figure 6.--Modal estimates of the amount of phenocrysts and lithic fragments in the Topopah Spring Member in hole USW G-4 (based on modal analysis of 29 thin sections; counts per thin section ranged from 1238 to 1550).

than 2.0 mm. On the basis of relative proportions of phenocrysts, two contrasting rock types make up the Topopah Spring Member. The upper 242 ft (74 m) of the member to a depth of approximately 470 ft (143 m) contain a relatively high proportion of phenocrysts that commonly ranges from 7.0 to 18.4 percent but decreases to about 2 percent near the upper and lowermost margins (fig. 6) Quartz is virtually absent and the content of alkali feldspar exceeds that of plagioclase. Biotite rarely constitutes more than 10 percent of the phenocrysts, and accessory minerals include clinopyroxene, apatite, zircon, and perrierite/allanite. Although quite gradational, the base of this petrographic unit roughly corresponds to the top of the middle lithophysal zone.

Below 470 ft (143 m), the rock is crystal-poor, containing less than 2 percent phenocrysts. Quartz is rare throughout most of the lower section; however, quartz increases to about 13 percent within an interval that roughly corresponds to the lowermost non-lithophysal zone and as much as 14.3 percent of the phenocrysts were identified as quartz near the base of the member. In all but one thin section, plagioclase is dominant over alkali feldspar. It should be noted that variations in relative proportions of phenocrysts in this section may not be significant because of the scarcity of total phenocrysts.

Bedded Tuff

The basal nonwelded tuff of the Topopah Spring Member rests on 2.6 ft (0.8 m) of ash-fall and reworked tuff chiefly composed of zeolitic pumice fragments. Thicknesses of individual beds average about 1.4 ft (0.4 m).

Tuffaceous Beds of Calico Hills

The name, tuffaceous beds of Calico Hills, has been informally applied to a sequence of tuff beds that occupy the stratigraphic position between the Paintbrush Tuff and Crater Flat Tuff within the central part of Yucca Mountain. Elsewhere, this sequence includes rhyolite lavas, (Christiansen and Lipman, 1965). Most of the rock, 352 ft (107 m), consists of massive layers of nonwelded ash-flow tuff. Approximately 20 percent 71.0 ft or (21.6 m) is made up of reworked tuff and ash-fall tuff, occurring at depths of 1,424.5, 1,447.0, 1,560.6, 1,663.0, and 1,705.4 ft (434.2, 441.0, 475.7, 506.9, and 519.8 m). These layers range in thickness from 0.4 to as much as 9.5 ft (0.1-2.9 m), except near the base of the sequence where 55.9 ft (17.0 m) of bedded tuff occurs.

The entire sequence of the tuffaceous beds of Calico Hills occurs above the static water level 1,776 ft or (541 m); Bentley, 1984). However, all but the uppermost 15 ft (5 m) of the rock in this section has undergone pervasive zeolitization. Alteration products in two samples collected at depths of 1,510.6 ft (460.4 m) and 1,643.6 ft (501.0 m) were determined by X-ray analysis. Both samples showed clinoptilolite, clinoptilolite/mordenite, and montmorillonite; estimated amounts of these minerals were 70, 60, and less than 5 percent, respectively (samples 2, 3; table 3).

The tuffaceous beds of Calico Hills contain few phenocrysts similar to the lower part of the Topopah Spring. Crystal content ranges between 0.9 and 2.8 percent on the basis of modal analyses of seven thin sections (fig. 7). Quartz constitutes from 39 to 62 percent of the phenocrysts except in the upper 23 ft (7 m), where less than 6 percent quartz occurs. The upper 23 ft (7 m) also contains a higher percentage of alkali feldspar (>60 percent) than the rest of the unit where alkali feldspar slightly exceeds that of plagioclase. Biotite content ranges from 0 to about 11 percent.

Thin section analyses indicate a lithic fragment content between 1.7 and 27.2 percent. Estimates of the content of lithic fragments, provided in this report, are based on visual examination of core (appendix) as well as thin section analyses. Estimates based on thin sections may be biased, as most samples were selected to avoid concentrations of the larger lithic fragments.

The low quartz-alkali feldspar ratio found in the upper two thin ash-flow tuff units appears inconsistent with respect to all other ash-flow tuff units that make up the tuffaceous beds of Calico Hills. The abrupt change in proportions of essential minerals occurs at a depth of about 1,437 ft (438 m) near the middle part of the second thin ash-flow tuff unit. However, the overall scarcity of phenocrysts, paucity of point counts (774) obtained from the thin section taken at 1,437 ft (438 m), and absence of a well-defined cooling break suggest a high degree of uncertainty in identifying the contact between quartz-poor and quartz-rich units. Considering sample spacing, the contact may occur at the cooling break between the upper two ash-flow tuffs and the rest of the sequence of tuffs. Regardless of the exact position of the petrographic transition, proportions of essential minerals suggest that the upper few meters of rock within the tuffaceous beds of Calico Hills show a closer resemblance to the overlying Topopah Spring Member of the Paintbrush Tuff than to the underlying ash-flow tuff units included in the tuffaceous beds of Calico Hills. Additional petrographic analyses are underway to determine if these thin ash-flow tuffs represent a transitional phase between the Topopah Spring and the tuffaceous beds of Calico Hills.

Crater Flat Tuff

Tuffs below the tuffaceous beds of Calico Hills can be divided into three recognizable members that constitute the Crater Flat Tuff. In descending order they are: the Prow Pass, Bullfrog, and Tram Members. Rocks within these three members have similar petrographic features and chemical compositions (Spengler and others, 1981).

Prow Pass Member

In core hole USW G-4, the Prow Pass Member has a thickness of 476.2 ft (145.1 m). The member can be informally subdivided into upper, middle, and lower subunits that are traceable to holes USW G-1 and UE-25a#1 on the basis of recognizable differences in the relative abundance of lithic fragments, type of primary crystallization, and degree of alteration. Very thin ash-fall tuff layers or partings separate a few of these subunits in nearby holes, however, in USW G-4, all contacts between subunits are gradational over an interval of a few centimeters.

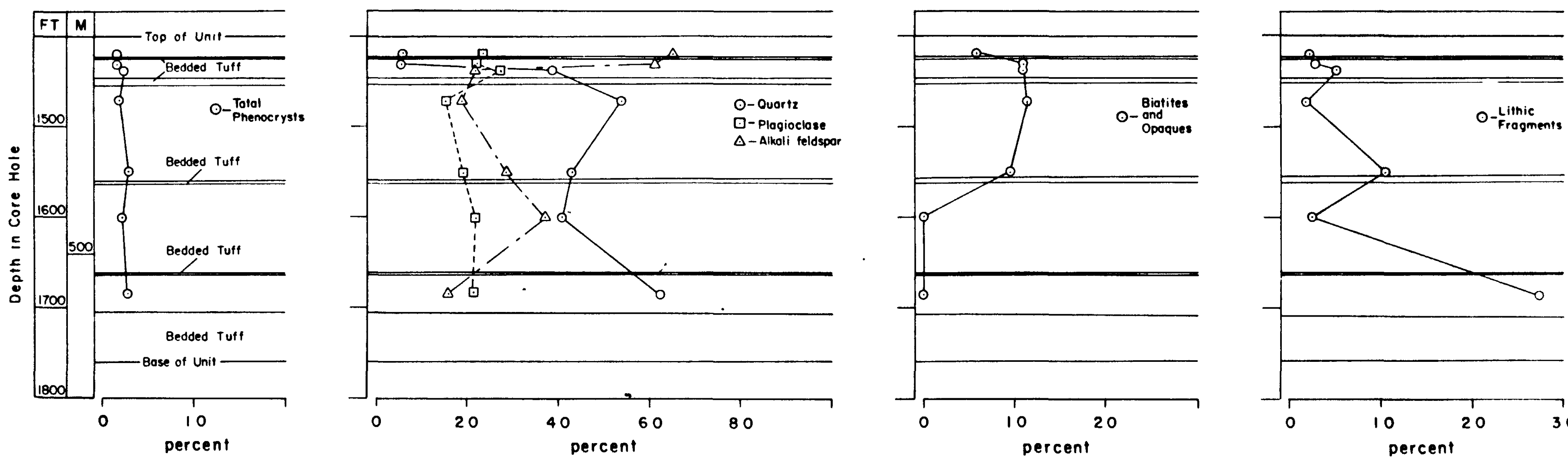

Figure 7.--Modal estimates of the amount of phenocrysts and lithic fragments in tuffaceous beds of Calico Hills in core hole USW G-4 (point counts of 7 samples range from 774 to 1494; size of phenocrysts are commonly less than 1.4 mm).

The upper subunit, beginning at a depth of 1,761.4 ft (536.9 m) and extending to 1,954.6 ft (595.8 m) is nonwelded to partially welded and commonly shows evidence of vapor-phase crystallization based on the presence of tridymite and feldspar intergrowths in pumice fragments, except in the uppermost 16.3 ft (5 m), where the rock is highly zeolitic, and in the lower 26.2 ft (8 m), where the rock is devitrified and slightly argillic. Two samples collected from the upper altered rock at depths of 1,762.5 and 1,771.3 ft (537.2 and 539.9 m) were X-rayed to determine the type and amount of alteration products. Results indicate the presence of clinoptilolite and montmorillonite in estimated amounts ranging from 50 to 60 percent and from 5 percent to about 10 percent, respectively (samples 4, 5; table 3). A sample from the lowermost part of the subunit at a depth of 1,953.3 ft (595.4 m) contains less than 10 percent montmorillonite (sample 6, table 3).

The middle subunit from a depth of 1,954.6 ft (595.8 m) to 2,050.3 ft (624.9 m), displays a noticeable increase in lithic fragments relative to subunits above and below. The lithic fragments are dominantly mudstone, siltstone, and subordinately volcanic and constitute 2 and 4 percent of the rock. Based on megascopic examination of core samples, lithic fragments commonly range in size from 0.2 to 2.0 cm. However, a few fragments as large as 3.3 cm were also noted. Three samples, collected from depths of 1,968.9, 1,989.4, and 2,039.0 ft (600.1, 606.4, and 621.5 m) showed X-ray patterns characteristic of mordenite, clinoptilolite, and montmorillonite. The total zeolite content was estimated to range from 40 to 60 percent. Montmorillonite is present in trace (<5 percent) amounts (samples 7, 8, 9; table 3).

The lowermost subunit of the Prow Pass Member occurs from 2,050.3 ft (624.9 m) to 2,237.5 ft (682.0 m) and is readily identifiable based on the occurrence of large, conspicuous, grayish-yellow, yellowish-brown, and greenish-yellow pumice fragments as large as 6.5 cm. Of the three subunits, the lowermost exhibits the highest degree of secondary alteration, as indicated by five samples collected at depths of 2,069.0, 2,089.9, 2,131.5, and 2,226.7 ft (630.6, 637.0, 649.7, 671.3, and 678.7 m). All samples showed X-ray patterns characteristic of clinoptilolite and mordenite in estimated amounts consistently ranging from about 50 to about 70 percent (samples 10, 11, 12, 13, 14; table 3). Montmorillonite and illite are also present in trace (<5 percent) amounts.

The phenocryst content of the Prow Pass Member as well as other members of the Crater Flat Tuff is significantly higher than in most of the overlying Paintbrush Tuff and all of the tuffaceous beds of Calico Hills. The average phenocryst content is about 9 percent, ranging between 7 and 13 percent (fig. 8). Quartz ranges between 6 and 16 percent; alkali feldspar and plagioclase occur in subequal proportions, and biotite and opaques commonly account for less than 3 percent of the phenocrysts. Accessory pseudomorphs of orthopyroxene(?), and apatite, and zircon also occur as phenocrysts in the groundmass. Based on thin section analysis, lithic fragments constitute from 0.3 to 7.3 percent of the rock and, as described earlier, commonly consist of mudstone and siltstone.

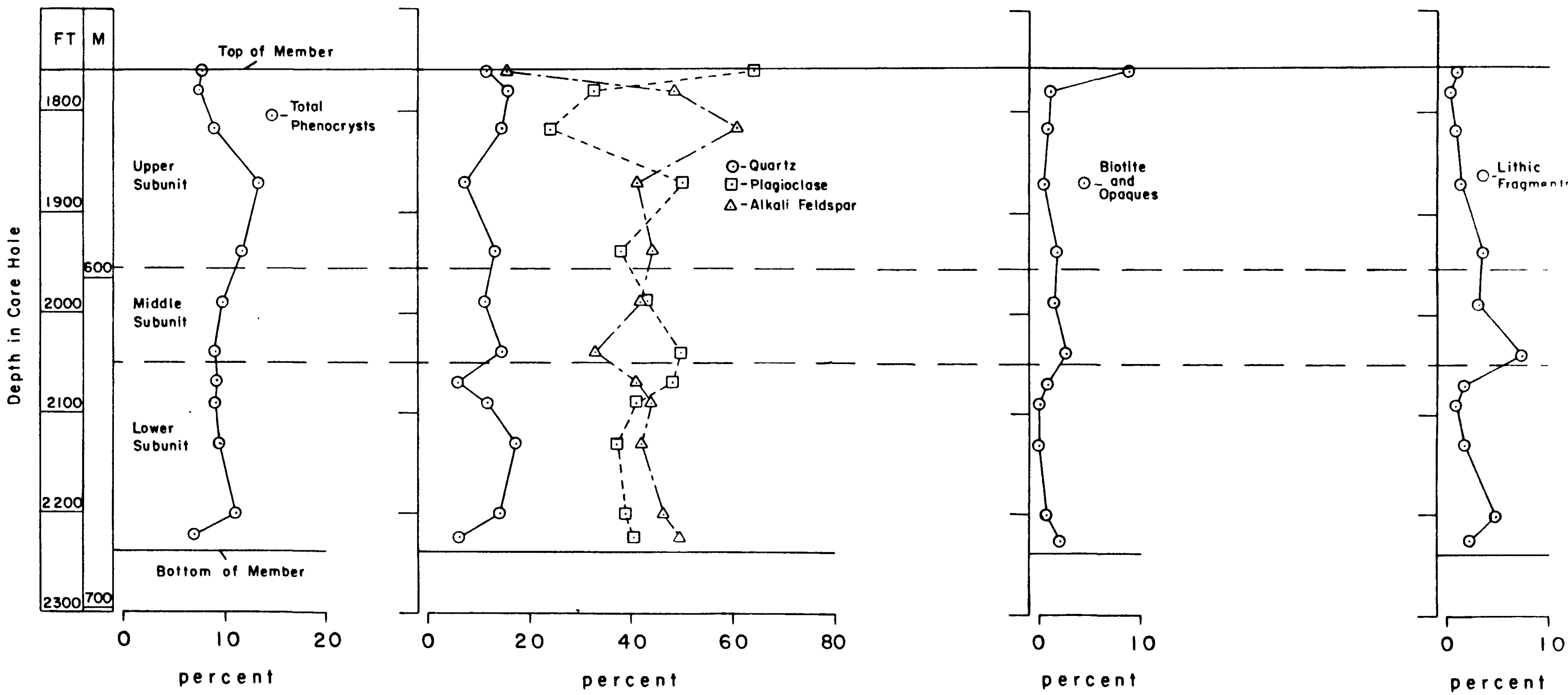

Figure 8.--Modal estimates of the amount of phenocrysts and lithic fragments in the Prow Pass Member in core from USW G-4 (point counts of 12 samples range from 1300 to 1472; size of phenocrysts is commonly less than 2.2 mm).

Bedded Tuff

Bedded tuff, 6.7 ft (2.0 m) thick, that contains layers of ash-fall tuff and reworked tuff, separate the Prow Pass from the underlying Bullfrog Member. A fault marks the base of this unit at a depth of 2,244.2 ft (684.0 m). The amount of displacement could not be determined but it is believed to be minor because the thickness of the upper partially welded and devitrified zone of the underlying Bullfrog Member in USW G-4 does not differ significantly from the thickness of the same zone in nearby holes UE-25b#1 and USW G-1 (Lobmeyer and others, 1983; Spengler and others, 1981).

Bullfrog Member

Rocks of the Bullfrog Member display a large variation in welding characteristics as well as crystallization textures, as shown in columns 1 and 2 of plate 1. The member has a thickness of 489.1 ft (149.1 m) and consists of two parts, separated by 5.6 ft (1.7 m) of welded(?) ash-fall tuff at a depth of 2,528.4 ft (770.7 m).

Above 2,528.5 ft (770.7 m), the Bullfrog Member appears partially welded, except in the interval between 2,370.0 and 2,397.8 ft (722.4 and 730.8 m), where welding increases to moderate. Pervasive vapor-phase crystallization characterizes most of the upper part, although the upper 22.3 ft (6.8 m) are devitrified and slightly altered to clay minerals (plate 1). A sample from 2,263.8 ft (690.0 m) was submitted for X-ray analysis, and indicates that illite occurs in amounts of less than 10 percent (sample 15, table 3).

The base of the welded(?) ash-fall tuff was identified at a depth of 2,534.1 ft (772.4 m). Below this contact, the rock grades from a zone of partial welding into a moderately to densely welded zone beginning at a depth of 2,581.8 ft (786.9 m). This moderately to densely welded zone persists to a depth of 2,680.3 ft (817.0 m), where welding abruptly decreases. The rock below the moderately to densely welded zone is nonwelded to partially-welded, more altered than rocks directly above it, and poorly indurated near the top. X-ray analysis of a sample from a depth of 2,680.7 ft (817.1 m) shows that montmorillonite and illite occur in amounts of 10 percent and less than 5 percent, respectively (sample 19, table 3). Below 2,695.6 ft (821.6 m), the rock increases in the degree of induration and also increases significantly in zeolite content; an observation verified by X-ray analysis that showed the presence of more than 40 percent mordenite (sample 20, table 3).

Modal analyses of 12 thin sections indicates noticeable differences in phenocryst content between ash-flow tuff units above and below the thin welded(?) ash-fall tuff layer. The upper part contains from 12 to 17 percent phenocrysts, in contrast to rock beneath the ash-fall tuff where the phenocryst content decreases abruptly within a narrow range between 9 and 11 percent (fig. 9). The quartz content above the ash-fall tuff averages about 22 percent, whereas, the average quartz content decreases to about 9 percent in the lower part of the Bullfrog (fig. 9).

The alkali feldspar content ranging between 31.5 and 44 percent, does not appear to vary significantly between the upper and lower parts of the Bullfrog Member. However, the amount of plagioclase increases from 38 percent to 51 percent from directly above to directly below the welded(?) ash-fall tuff that separates the upper and lower parts of the Bullfrog (fig. 9).

Within the member, biotite and opaque minerals constitute from 4 to 10 percent of the phenocrysts. Based on thin section analysis, the rock contains less than 3.0 percent lithic fragments. A slight increase in the abundance of lithic fragments and biotite and opaques occurs in rock below the welded(?) ash-fall tuff unit.

Bedded Tuff

About 23 ft (7 m) of bedded tuff separates the Bullfrog Member from the Tram Member between the depths of 2,733.3 ft (833.1 m) and 2,755.6 ft (839.9 m). Rock in the interval is ash-fall tuff and reworked tuff, dominantly composed of zeolitic pumice clasts. Clinoptilolite and mordenite constitute more than 30 percent of the rock (sample 21, table 3).

Tram Member

Only the upper part of the Tram Member was cored in USW G-4 from 2,755.6 ft (839.9 m) to a depth of 3,001.0 ft (914.7 m). Nearly all of this part of the Tram is nonwelded to partially welded tuff, with the exception of the lowermost 2.2 ft (0.7 m) where welding appears to increase somewhat. The rock contains about 40 percent clinoptilolite and mordenite to a depth of about 2,841 ft (866.0 m) (samples 22, 23, 24; table 3). Vapor-phase crystallization occurs within pumice fragments below 2,841 ft (866.0 m).

Modal analyses of seven thin sections indicate that rock in the upper interval of the cored part of the Tram Member contains from 8 to 14 percent phenocrysts. Quartz, alkali feldspar, and plagioclase range from 16 to 38 percent, 23 to 38 percent, and 27 to 50 percent, respectively. With the exception of one sample 2,788.3 ft (849.9 m) the amount of quartz phenocrysts progressively increases to a maximum of 38 percent at a depth of 2,875.6 ft (876.5 m), then decreases to 23 and 27 percent in the lower two samples (fig. 10). The content of plagioclase exceeds that of alkali feldspar through most of the cored part of the Tram, except in the lowermost thin section 3,000.9 ft (914.7 m). Biotite and opaque minerals are relatively common (15 percent) near the top of the unit, but decrease progressively in abundance to 2.8 percent at a depth of 2,875.6 ft (876.5 m). Below this depth, two samples indicate a slight increase to 5.4 and 6.4 percent (fig. 9). Lithic fragments constitute from 0.8 to 19 percent of the rock and commonly consist of silicic to intermediate lava.

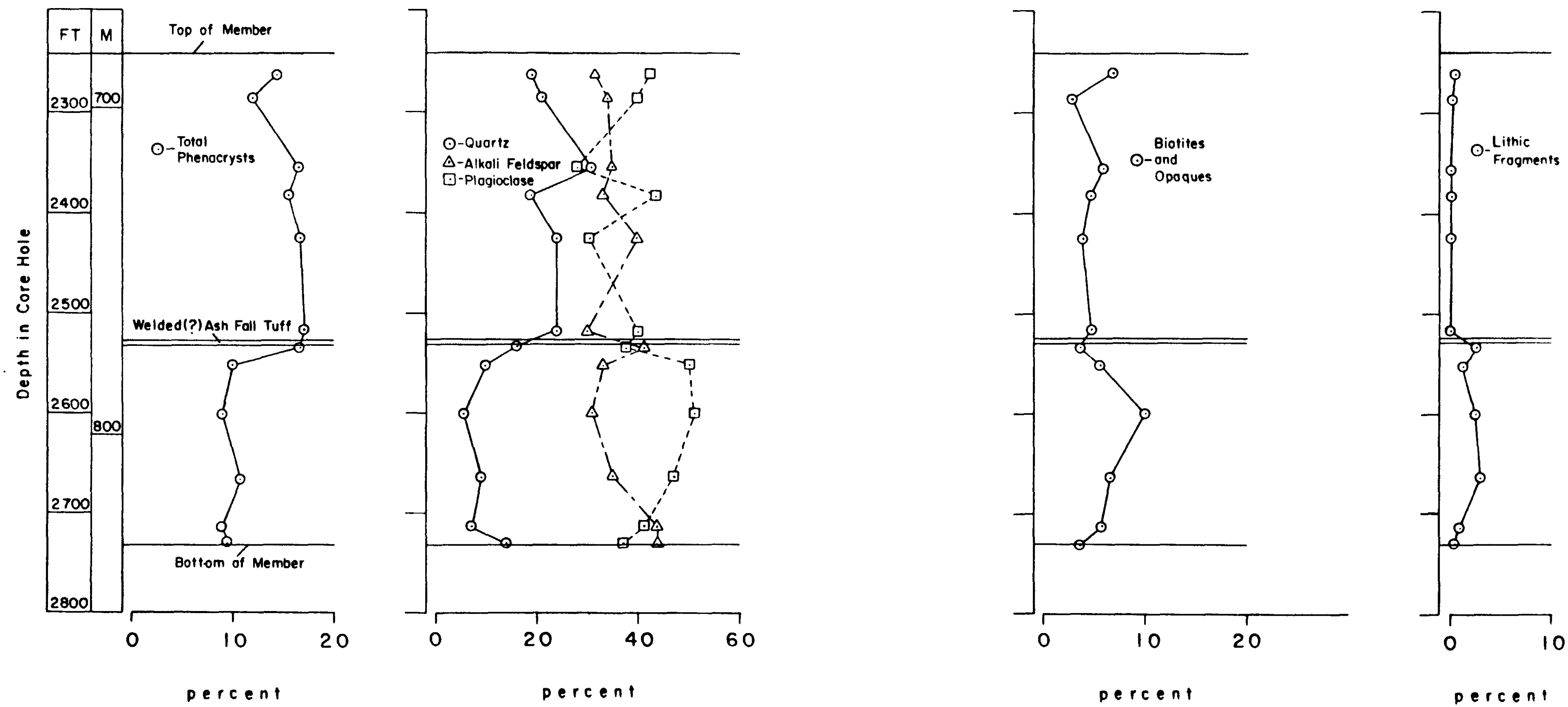

Figure 9.--Modal estimates of the amount of phenocrysts and lithic fragments in the Bullfrog Member in core from USW G-4 (based on 12 thin sections, number of points counts per thin section range between 1350 and 1450; size of phenocrysts is less than 2.6 mm.)

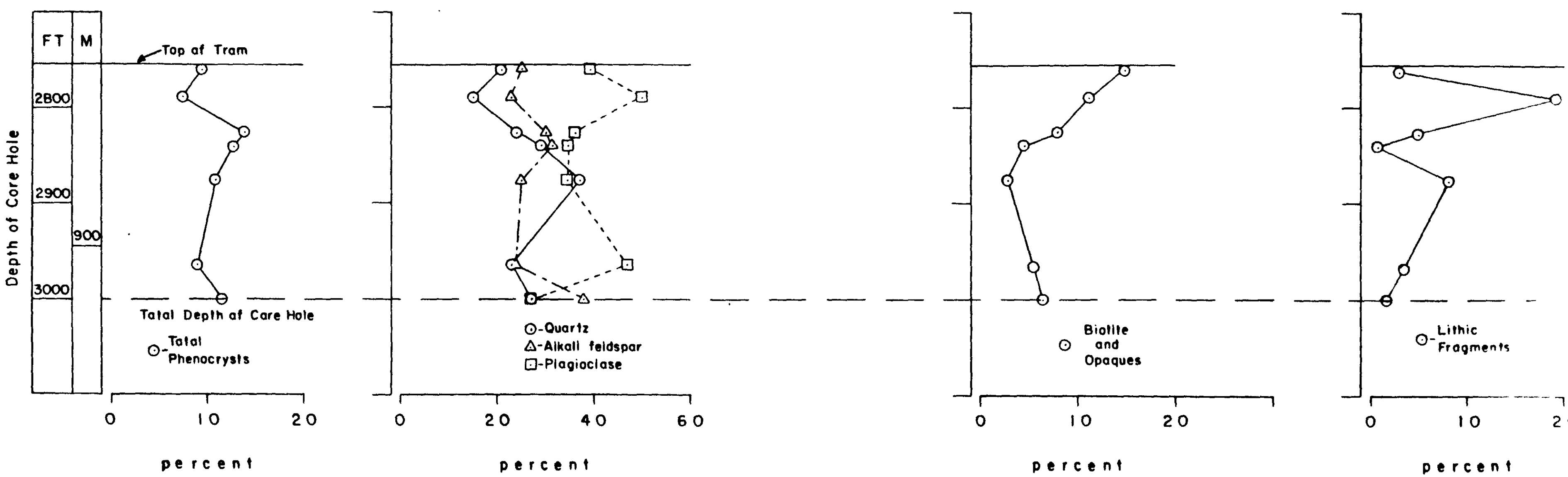

Figure 10.--Modal estimates of the amount of phenocrysts and lithic fragments in the Tram Member in core from USW G-4 (based on seven thin sections; number of points counted per thin section varied between 1350 and 1450; size of phenocysts was less than 2.4 mm.

STRATIGRAPHIC PREDICTIONS

At the request of the DOE, a prediction of the expected stratigraphy was developed by the U.S. Geological Survey prior to the drilling of core hole USW G-4. The prediction was intended to serve as a means of assessing the uniformity and lateral continuity of subsurface units prior to development of a 3-dimensional geologic model of the area. The predicted log was based on subsurface data from holes USW G-1 and UE-25a#1, and presented depths and thicknesses of major stratigraphic units as well as internal stratigraphic zonations of welding and alteration to the base of Prow Pass Member of the Crater Flat Tuff.

A comparison of predicted and actual thicknesses and depths illustrates difficulties in predicting precise thicknesses of, 1) Yucca Mountain and Pah Canyon Members, 2) bedded tuffs, 3) upper and lower nonwelded zones of the Topopah Spring Member, and 4) several subunits in the densely welded zone of the Topopah Spring (table 4).

Except for the depth to bedrock, the predicted depths of contacts above the lower lithophysal zone of the Topopah Spring Member varied between 81.1 and 125.0 percent of the actual depths; predicted depths varied between 93.6 and 100.2 percent of the actual depths below the lower lithophysal zone in the Topopah Spring Member.

STRUCTURE

Preliminary information in regard to the structural setting in the vicinity of the proposed exploratory shaft site has been obtained from surface and subsurface geologic studies. Salient features of these studies are reviewed in the following sections. However, because of the importance of a comprehensive structural analysis prior to shaft construction, much of the structural data provided herein is currently being augmented by highly detailed fracture studies at the surface and on core from USW G-4. For example, current surface studies include 1) detailed analysis of fractures observed along ridges north and south of the proposed shaft site (C. C. Barton, USGS, oral commun., 1984), and 2) fracture analysis of selected pavement areas along ridge tops. These areas have been hydraulically stripped of their talus cover to allow optimal exposure of fracture sets. Both fracture studies will include compilation of: 1) trace lengths, 2) orientations, 3) surface characteristics, 4) relative chronology, 5) roughness, and 6) spacing.

Additional studies of core from USW G-4, currently in progress by USGS personnel, will result in a more comprehensive analysis of subsurface fractures than provided in this report. This analysis will attempt to include: 1) additional fracture orientations based on reassembling small fragments of broken core and extrapolating orientation data to continuously cored unoriented segments, by orienting segments of core and fractures using paleomagnetic methods, and by correlating fracture data identified in television camera logs with fractures observed in core, 2) micro-fracture spacings, 3) fracture apertures, 4) fractography markings along fracture faces such as plumose structures twist-hackles, arrest lines, and hooking to aid in determining modes of formation (Kulander and others, 1979), 5) relative chronology of fracture development, and 6) fracture surface roughness.

Table 4.--Comparison of predicted and actual stratigraphic and lithologic intervals in USW G-4

Stratigraphic and lithologic description	A Predicted thickness of interval feet	(m)	B Predicted depth to base of interval feet	(m)	C Actual thickness of interval[1] feet	(m)	D Actual depth to base of interval[1] feet	(m)	E $\frac{A}{C}$ x 100	F $\frac{B}{D}$ x 100
Alluvium	20	6	20	6	30	9.14	30	9.14	66.7	66.7
Paintbrush Tuff										
Tiva Canyon Member										
Tuff, ash-flow, densely welded, devitrified	60	18	80	24	66.7	20.3	96.7	29.5	90.0	82.7
Tuff, ash-flow, nonwelded to partially welded, vitric	35	11	115	35	41.3	12.6	138.0	42.1	84.8	83.3
Tuff, bedded, vitric	5	2	120	37	10	3.0	148.0	45.1	50.0	81.1
Yucca Mountain Member										
Tuff, ash-flow, nonwelded, vitric	35	11	155	47	0.8	0.2	148.8	45.4	4375.0	104.2
Tuff, bedded, vitric	15	5	170	52	19.4	5.9	168.2	51.3	77.3	101.1
Pah Canyon Member										
Tuff, ash-flow, nonwelded, vitric	65	20	235	72	19.8	6.0	188.0	57.3	328.3	125.0
Tuff, bedded, vitric	5	2	240	73	40.0	12.2	228.0	69.5	12.5	105.3
Topopah Spring Member										
Tuff, ash-flow, nonwelded, vitric	40	12	280	85	11.0	3.4	239.0	72.9	363.6	117.2
Tuff, ash-flow, densely welded, vitrophyre	2	0.6	282	86	3.8	1.2	242.8	74.0	52.6	116.1
Tuff, ash-flow, densely welded (caprock)	20	6	302	92	22.7	6.9	265.5	80.9	88.1	113.8
Tuff, ash-flow, moderately to densely welded, vapor phase[2]	140	43	442	135	134.9	41.1	400.4	122.0	103.8	110.4
Tuff, ash-flow, densely welded, lithophysal zone	35	11	477	145	19.6	6.0	420	128	178.6	113.6
Tuff, ash-flow, densely welded, devitrified	20	6	497	152	50	15.2	470	143	40.0	105.7
Tuff, ash-flow, densely welded, lithophysal zone	623	190	1,120	341	656.6	200.1	1,126.6	343.4	94.9	99.4
Tuff ash-flow, densely welded, devitrified[3]	110	34	1,230	375	187.7	57.2	1,314.3	400.6	58.6	93.6
Tuff, ash-flow, densely welded, vitrophyre	50	15	1,280	390	28.7	8.8	1,343.0	409.4	174.2	95.3
Tuff, ash-flow, nonwelded to partially welded, vitric	80	24	1,360	415	61.1	18.6	1,404.1	428.0	130.9	96.9
Tuff, bedded, zeolitized	10	3	1,370	418	2.5	0.8	1,406.6	428.7	400.0	97.4
Tuffaceous beds of Calico Hills (informal usage)										
Tuff, ash-flow, nonwelded to partially welded, zeolitic; intercalated with thin bedded intervals	315	96	1,685	514	294.4	89.73	1,701.0	518.5	107.0	99.1
Tuff, bedded, zeolitic	55	17	1,740	530	55.7	17.0	1,756.7	535.4	98.7	99.1
Crater Flat Tuff										
Prow Pass Member										
Tuff, ash-flow, partially to moderately welded, devitrified (slightly zeolitic at places)	470	143	2,210	674	473.1	144.20	2,229.8	679.6	99.3	99.1
Tuff, bedded, zeolitic	30	9	2,240	683	6.7	2.0	2,236.5	681.7	447.8	100.2

1/Corrected for hole deviation (true vertical thickness and depth).

2/Includes a thin non-to partially welded unit between the caprock and moderately to densely welded zone which was. not predicted.

3/Proposed host rock.

Surface Structural Studies

The U.S. Geological Survey was requested by the DOE to conduct a preliminary fracture study prior to their final selection of the exploratory shaft site and approval to begin coring USW G-4. The study was specifically designed to compare fracture frequencies in the vicinity of the five potential shaft sites. Two of the sites along the crest of Yucca Mountain proved inadequate for this structural study beyond that of identifying photo lineations displayed on a 1:12,000-scale geologic map, mainly because of poor exposures and disturbance of the surface by earthmoving equipment. However, studies conducted at three candidate sites, located along east-west-trending washes on the east side of Yucca Mountain indicated fracture densities between (1.6 and 2.3 fractures per foot) 5 and 7 fractures per meter (R. B. Scott and Jerry Bonk, USGS written commun. to G. L. Dixon., 1982). Careful examination of contacts between subunits of the exposed Tiva Canyon Member showed several small-scale faults near the proposed exploratory shaft site (fig. 11). These structures trend north 30^{o}-35^{o} west; although the exact amount of displacement could not be determined, it probably is less than a few meters based on the absence of any recognizable offset of gradational contacts between subunits.

Like previous fracture analyses at Yucca Mountain, fracture studies at the potential exploratory shaft site reveal the presence of two conspicuous fracture sets, striking N. 0-36^{o} W. and N. 18-36^{o} E. Strikes of fractures identified along linear traverses, approximately 300 ft (91 m) in length, are given on figure 12. The northwesterly set is dominant. Fracture traverses were made in a direction approximately perpendicular to the dominant northwest-trending fracure set. A fracture-frequency correction was applied using methods outlined by Scott and others (1983) in order to obtain a true fracture density. Analysis of pavement areas located close to the site of the exploratory shaft will provide information in regard to fracture spacings, modes of development, and possible limitations of using the traverse method to collect fracture-spacing and orientation data.

Subsurface Studies

Preliminary study of structures at the USW G-4 location includes (1) identification and compilation of fractures from the nearly continuous core, (2) estimation of the number of fractures per cubic meter, (3) recognition of faults and shear fractures, (4) measurement of attitudes of bedding planes, partings, and fractures from oriented core, and (5) measurement of fracture attitudes utilizing a downhole television camera and compass.

Fractures

A total of 2,058 fractures were identified in core samples from USW G-4. The number of fractures identified in each 10 ft (3-m) interval is shown in columns 4 and 5 of plate 1. The fractures can be divided into two major categories: joints and shear fractures. In this compilation, joints are defined as fractures where fracture faces show no apparent evidence of differential movement. In contrast, shear fractures show evidence of differential movement in the form of minor offsets of pumice fragments, slickensides, and associated brecciation.

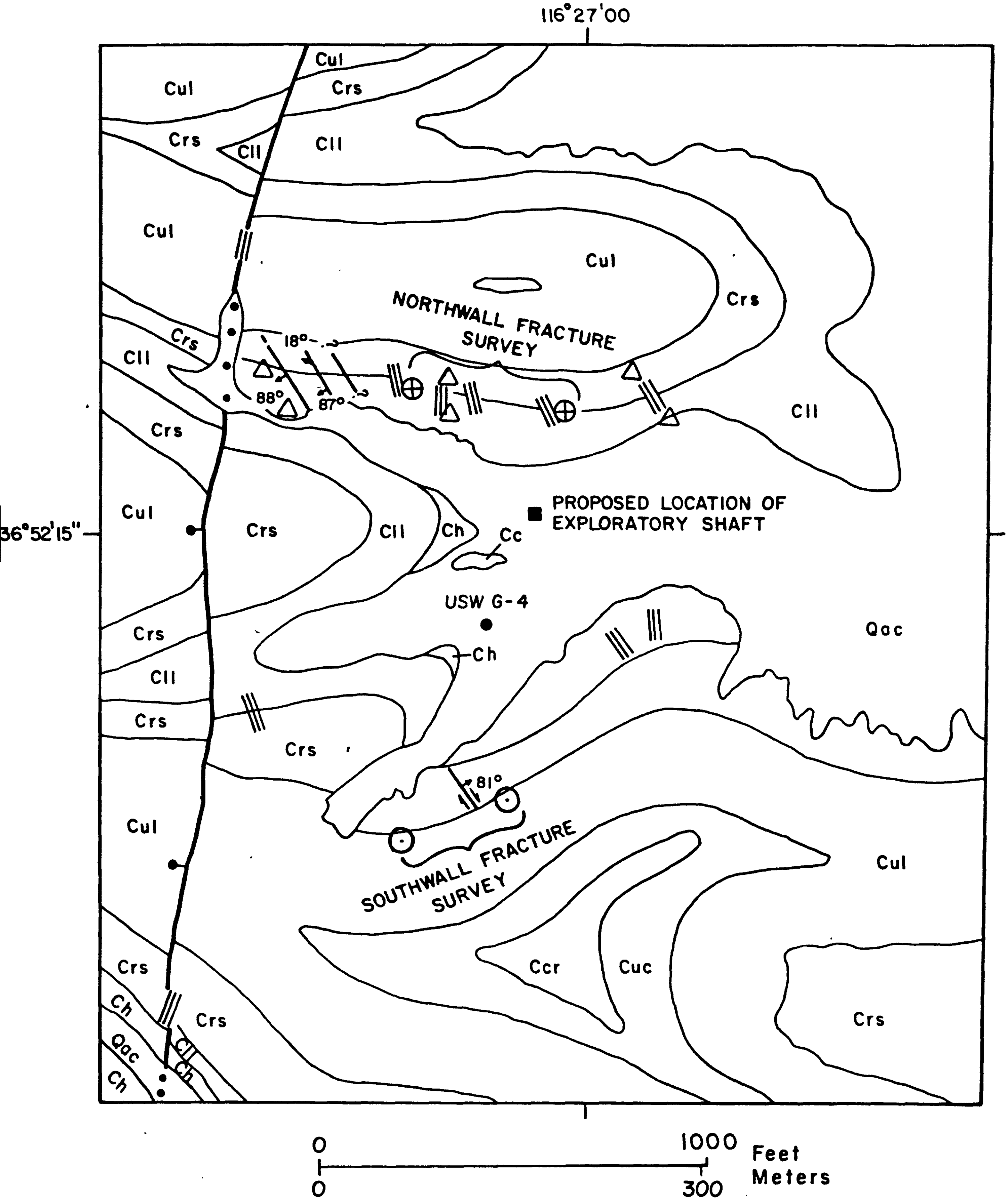

Figure 11.--Detailed geologic map in the vicinity of the site of the proposed exploratory shaft showing subunits and small-scale structural features in the Tiva Canyon Member (modified from Scott and Spengler, written commun., 1980, and Scott and Bonk, written commun. G. L. Dixon, 1982).

EXPLANATION

Qac	Alluvium and colluvium	Quaternary
	Paintbrush Tuff Tiva Canyon Member Subunits	
Ccr	Caprock	Tertiary
Cuc	Upper cliff	
Cul	Upper lithophysal	
Crs	Rounded step	
Cll	Lower lithophysal	
Ch	Hackly	
Cc	Columnar	

Contact (approximate)

Major fault; ball and bar on downthrown side; dotted where concealed

Minor fault, no visible displacement; x^{o} = dip, y^{o} = rake of slickensides

81° Strike-slip fault showing approximate dip of fault plane

?——? Possible fault

Strike of conspicuous fracture sets

△△ Breccia zones

⊕ Approximate limits to northwall fracture survey

⊙ Approximate limits to southwall fracture survey

Figure 11.--Continued

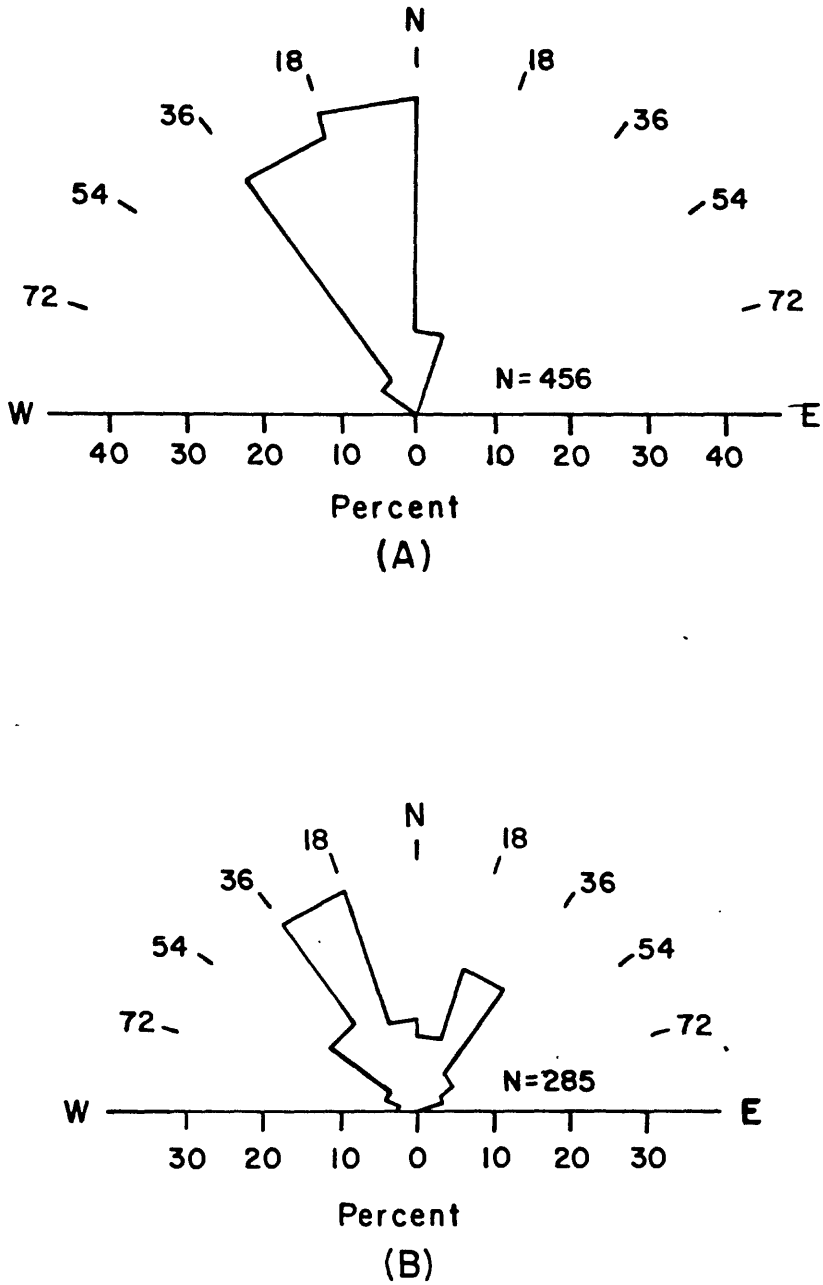

Figure 12.--Strikes of fractures identified in tape traverses along outcrops of the Tiva Canyon Member (A) north of proposed exploratory shaft (northwall) and (B) south of proposed exploratory shaft (southwall) (modified from R.B. Scott and Jerry Bonk, USGS written commun. to G. L. Dixon, 1982).

Previous subsurface studies have shown that the frequency of fractures is strongly influenced by the degree of welding (Spengler and others, 1979; 1981). Therefore, conspicuous differences in apparent fracture densities can best be determined by dividing the rocks into densely welded and less welded sections. In stratigraphic order proceeding downhole, these stratigraphic and lithologic subdivisions include (1) the densely welded tuff of the Tiva Canyon Member, (2) the nonwelded to moderately-welded tuffs of the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members (3) the densely welded part of the Topopah Spring Member, (4) tuffaceous beds of Calico Hills, and 5) nonwelded to moderately-welded tuff of the Crater Flat Tuff. On the basis of these subdivisions, average apparent fracture frequencies are: 25.6, 4.4, 13.3, 0.9, and 2.9 fractures per 10 ft (3 m), respectively (fig. 13).

The highest apparent fracture density is associated with the densely welded Tiva Canyon Member. In nonwelded to moderately welded intervals, average apparent frequencies of fractures are 0.9 and 4.4 per 3 m (10 ft). Approximately 72 percent of the fractures that were identified occur in the densely welded part of the Topopah Spring Member, where about 13 fractures occur per 10 ft (3 m). Intervals that contain abundant lithophysae in the densely welded part of the Topopah Spring Member commonly are associated with a slight decrease in fracturing. Within these intervals, an apparent fracture frequency of about 8 per 10 ft (3 m) is not uncommon. Apparent fracture frequency in the lowermost nonlithophysal zone of the Topopah Spring Member, between depths of 1,127.6 and 1,316.5 ft (343.7 and 401.3 m), is 13.8 fractures per 10 ft (3 m).

Additional information concerning fractures identified in core from USW G-4 is provided on figure 13. Data include: 1) fracture inclinations, 2) number of fractures, 3) types of fracture coatings, and 4) number of healed fractures within selected stratigraphic and lithologic intervals.

Inclinations of fractures are expressed in degrees of dip as measured from the horizontal, assuming a vertical borehole. Because these inclinations have not been corrected for borehole drift, some that were measured between depths of 0-1,000 ft (0 to 305 m), 1,000-2,000 ft (305 to 610 m), 2,000-3,000 ft and (610 to 914 m) may be in error by as much as 5, 6, and 9, respectively.

High-and low-angle fracture sets are present in the Paintbrush Tuff. Within the Tiva Canyon Member (densely welded zone) the low-angle set is inclined between 0 and 40^{o} and accounts for 55 percent of the observed fractures in this interval. High-angle fractures (61^{o} to 90^{o}) constitute 34 percent of the fractures.

Forty-seven percent of the fractures identified within the interval between the densely welded zones of the Tiva Canyon and Topopah Spring Members are inclined between 0 and 30^{o}; 33 percent are inclined between 61^{o} and 90^{o}.

Measurement of fracture inclinations in the densely welded zone of the Topopah Spring Member indicates that about 36 percent are inclined between 0 and 30^{o}. High-angle fractures, inclined between 61^{o} and 90^{o}, account for about 46 percent of the fractures. The number of low-angle fractures in this interval appears to be higher in USW G-4 than in nearby holes (UE-25a#1 and USW G-1; Spengler and others, 1979, 1981). From the top of the densely welded zone 239.0 ft or (72.8 m) to a depth of about 280 ft (85 m), 215 fractures were observed (pl. 1), and most are inclined at very low angles ($0-20^{o}$). Like

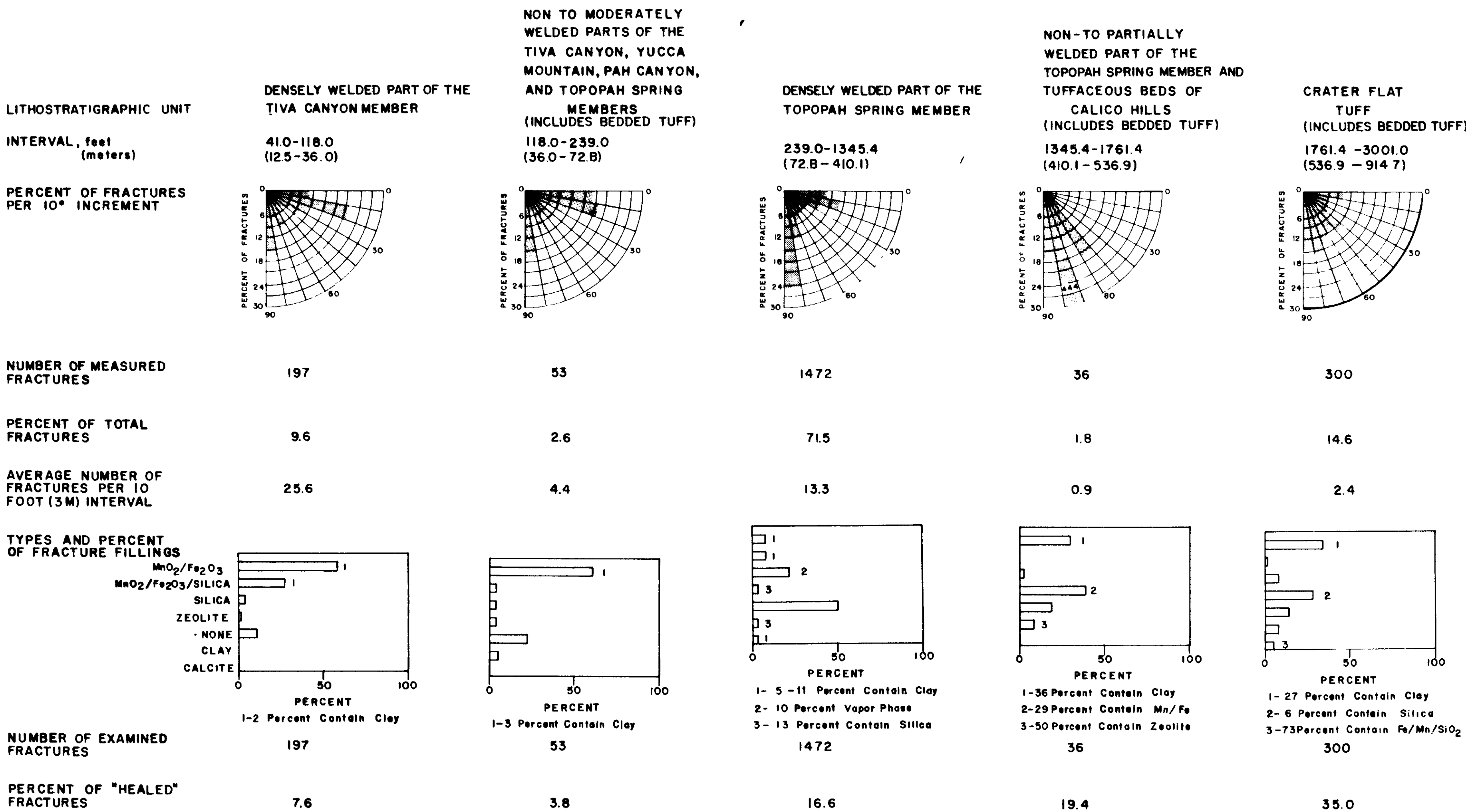

Figure 13.--Inclination of fractures and types of fracture fillings in stratigraphic units.

the flattened pumice fragments found in core from this interval, surfaces of these fractures are commonly dark reddish brown, contain a higher content of bronze biotite, and depict a fair degree of parallel alinement. Fracturing may have formed along these planes of weakness (foliated pumice) in response to unloading, vibrations, and torques inherent in the coring process (Kulander and others, 1979). Further detailed analysis as to the mode of formation of fractures in this interval is in progress.

A pronounced set of low-angle fractures is not apparent in the underlying non-to partially welded zones of the Topopah Spring Member and tuffaceous beds of Calico Hills, or in the Crater Flat Tuff. Almost all of the fractures found in the tuffaceous beds of Calico Hills are inclined between 51^{o} to 90^{o} and 44 percent are inclined between 71^{o} and 80^{o}. As mentioned above, the apparent decrease in dips may be due, in part, to errors related to increases in borehole deviation. However, oriented fractures from the Crater Flat Tuff which have been corrected for borehole deviation (illustrated in section on oriented core) indicate a general decrease in the dip of fracture planes when compared to fracture planes in the Topopah Spring Member.

Fracture Fillings and Coatings

Fracture faces were examined megascopically to determine types of fillings and coatings. Thus, data presented in this section are, at best, semi-quantitative. However, X-ray analyses were made on 42 samples to verify visual identifications of fracture coatings, particularly coatings suspected of containing zeolites or clay minerals (table 5). In order of abundance, basic types of coatings compiled on figure 13 include: 1) manganese oxides (pyrolusite), manganates (cryptomelane and hollandite), iron oxides (hematite, maghemite) and iron hydroxides (goethite), 2) silica (quartz, cristobalite, opaline silica, and tridymite), 3) zeolites (mordenite and clinoptilolite), 4) smectites (montmorillonite and illite), and 5) carbonates (calcite and siderite).

Manganese oxides and iron oxides are the dominant type of fracture coating in the densely welded zone of the Tiva Canyon Member and underlying non-to moderately welded tuff (basal part of Tiva Canyon, Yucca Mountain, Pah Canyon, and upper part of the Topopah Spring Members, fig. 13). Within these two intervals, 83 and 64 percent of the fractures are stained with manganese oxides and iron oxides (a subordinate number of fractures also include silica); 11 and 23 percent contain no coatings. These data agree with the compilation of fracture coatings reported in Spengler and others (1979) for hole UE-25a#1.

In contrast to fracture surfaces observed in overlying stratigraphic intervals, 51 percent of the fractures examined within the densely welded zone of the Topopah Spring Member are free of any type of mineral coating. These fractures are believed to be natural and not the result of drilling or handling based on the presence of a subtle discoloration extending into the rock matrix which is probably a product of weathering. Further detailed analysis of these fracture surfaces is in progress to confirm this classification. The dominant type of coating within the Topopah Spring Member is silica, found along 22 percent of the fractures. Tridymite was identified on 10 percent of these fracture faces. The presence of this high-temperature form of quartz on fracture faces may suggest that some fracture development

Table 5--X-ray analyses of selected fracture fillings from USW G-4

[Analyst: P. D. Blackmon, U.S. Geological Survey. Estimated amounts of minerals present are reported as parts in 10; trace (<0.5); <, less than; >, more than; leaders (---) indicate mineral not identified; (?) possible manganese mineral present; NWT, nonwelded ash-flow tuff; PWT, partially-welded ash-flow tuff; NPW, ash-flow tuff; MWT, mode, moderately welded ash-flow tuff; MDW, moderately to densely-welded ash-flow tuff; DWT, densely welded ash-flow tuff; RWT, reworked tuff; AFT, air-fall tuff; BT, bedded tuff; stratigraphic symbols defined on pl. 1]

Sample	Depth		Strat. Unit	Rock Type	Mineral Content											
	ft	m			Montmorillonite	Illite-mica	Amorphous (ash)	Quartz	Cristobalite/opaline-silica	Feldspar	Tridymite	Hematite	Mordenite/Clinoptilolite	Manganese Minerals	Calcite	Siderite
1	120.0	36.6	Tpc	NPW	2	tr	>1	---	3	3	---	---	---	---	---	---
2	241.8	73.7	Tpt	DWT	>2	2	tr	7	---	---	---	---	---	---	---	---
3	447.0	136.3		DWT	tr	---	---	<1	tr	>1	7	---	---	---	---	---
4	720.7	219.7		DWT	---	---	---	5	>2	<1	1	---	---	---	---	---
5	745.8	227.3		DWT	---	tr	---	<1	---	<1	>3	---	---	---	5	---
6	770.7	234.9		DWT	tr	---	---	<1	<1	2	>6	---	---	---	---	---
7	827.7	252.3		DWT	---	---	---	---	---	---	---	10	---	---	---	---
8	948.8	289.2		DWT	tr	---	---	>6	<1	>2	---	---	---	---	---	---
9	964.3	293.9		DWT	<1	---	---	>4	1	4	---	---	---	---	---	---
10	1125.3	343.0		DWT	tr	tr	---	3	<1	>4	1	---	---	---	---	---
11	1788.5	545.1	Tcp	NWT	---	tr	---	---	>1	2	---	---	>6	---	---	---
12	1990.1	606.0		NPW	---	---	---	---	---	---	---	[1]5	---	[2]2	---	---
13	2062.7	628.7		PWT	---	tr	tr	<1	---	2	---	---	7	---	---	---
14	2066.5	629.9		PWT	---	tr	tr	<1	tr	>2	---	---	>6	---	---	---
15	2070.3	631.0		PWT	---	tr	1+	1	1	>1	---	---	5	---	---	---
16	2081.4	634.4		PWT	tr	tr	tr	<1	<1	3	---	---	5	---	---	tr
17	2083.1	634.9		PWT	tr	tr	tr	<1	tr	2	---	---	[3]>6	---	---	---
18	2086.3	635.9		PWT	---	tr	1+	1	1	>1	---	---	5	---	---	---
19	2099.1	639.8		PWT	---	---	---	tr	---	---	---	---	7	[2]3		
20	2100.5	640.2		PWT	tr	tr	tr	tr	---	3	---	---	>5	?	---	---
21	2131.7	649.7		PWT	tr	tr	tr	tr	---	3	---	---	>5	---	---	---
22	2134.9	650.7		PWT	---	---	---	tr	8	<1	---	---	1	---	---	---
23	2139.4	652.1		PWT	---	---	---	tr	>5	>1	---	---	>2	---	---	---
24	2144.6	653.7		PWT	tr	tr	tr	tr	---	3	---	---	6	---	---	tr
25	2243.9	683.9	BT	AFT	tr	tr	<1	<1	---	4	---	tr	4	---	---	---
26	2273.9	693.1	Tcb	PWT	tr	tr	---	3	---	>6	---	[4]tr	---	---	---	---
27	2387.9	727.8		MWT	---	tr	<1	>4	---	>4	---	---	---	---	---	---
28	2489.1	758.7		PWT	tr	tr	---	>3	---	6	---	[4]tr	---	---	---	---
29	2507.0	764.1		PWT	tr	tr	---	>3	---	>5	---	[4]tr	---	---	---	---
30	2578.3	785.9		PWT	tr	tr	---	4	---	>2	---	tr	---	tr	>2	---
31	2652.0	808.3		MDW	tr	>1	tr	<1	---	>8	---	---	---	---	---	---
32	2798.2	852.9	Tct	NPW	tr	tr	<1	<1	---	>1	---	---	>7	---	---	---
33	2813.6	857.6		NPW	[5]1	<1	<1	2	---	3	---	tr	>2	---	---	---
34	2822.4	860.3		NPW	[5]<1	tr	tr	>1	---	3	---	[4]tr	[3]4	---	---	---
35	2829.5	862.4		NPW	[5]4	<1	---	>1	---	>3	---	tr	tr	---	---	---
36	2837.3	864.8		NPW	---	tr	---	>3	---	6	---	---	---	---	---	---
37	2851.0	869.0		MWT	---	tr	---	>3	---	5	---	[4]tr	---	tr	---	---
38	2892.8	881.7		MWT	---	tr	---	>4	---	5	---	---	---	---	---	---
39	2901.0	884.2		MWT	[6]>1	<1	1	>2	---	>3	---	---	1	---	---	---
40	2922.0	890.6		MWT	tr	<1	---	4	---	5	---	---	---	tr	---	---
41	2947.2	898.3		MWT	---	---	---	>1	---	<1	---	---	---	[7]8		---
42	2987.5	910.6		MWT	---	tr	---	7	---	2	---	tr	---	[8]<1	---	---

[1]Also Contains >20 percent maghemite.
[2]Pyrolucite.
[3]Contains <5 percent clinoptilotite.
[4]Contains some goethite.
[5]10-20 percent mixed layers.
[6]25-35 percent mixed layers.
[7]Cryptomelane.
[8]Hollandite(?).

occurred during or soon after initial cooling of the ash-flow tuff. This stratigraphic interval also marks the first appearance of calcite-coated fractures beginning at a depth of 243 ft (74 m).

Below the densely welded zone of the Topopah Spring Member, dominant fracture coatings include manganese and iron oxides and zeolites (mordenite and clinoptilotite). Within the basal nonwelded to partially welded zone of the Topopah Spring Member and the tuffaceous beds of Calico Hills, 31 and 39 percent of the fracture faces are coated with manganese and iron oxides, and zeolites, respectively.

Manganese oxides, manganates, iron oxides, and iron hydroxides coat 35 percent of the fractures in the Crater Flat Tuff. Zeolites coat 28 percent of the fractures. Several samples of fracture coatings from the Crater Flat Tuff that were suspected of containing iron and (or) manganese were submitted for X-ray analysis (table 5). Results show that in the Prow Pass Member iron-rich minerals include hematite and maghemite. The only manganese-bearing mineral identified was pyrolucite. In the Bullfrog and Tram Members iron-bearing minerals that were identified include hematite and goethite. Manganese-bearing minerals include cryptomelane and hollandite(?). Mention should be made that concentrations of feldspar and polymorphs of silica may be due, in part, to contamination from the enclosing rock matrix.

About 15 percent of the fractures in the Crater Flat Tuff have no coatings. Study of the fractographic morphological features of these fractures is currently underway to determine what proportion may have been induced by either coring or handling.

Fractures referred to as "healed" on figure 13, represent those which have withstood breakage along the fracture plane during coring and handling operations. Even though this reference is highly dependent on coring and handling procedures, it may prove of value in assessing overall fracture permeabilities of various units. About 19 and 35 percent of the fractures in the tuffaceous beds of Calico Hills and the Crater Flat Tuff, respectively, are classified as healed and may not act as pathways for the migratiion of fluids. However, because such a small sample of any fracture surface is visible in core, the likelihood that many fractures (particularly shear fractures) may not be healed along their entire length must be considered. A shear fracture exhibiting unhealed and healed segments along its length was noted in core from the Bullfrog Member between depths of 2,342.0-2,345.7 ft (713.8 and 715.0 m) (see appendix). Aperture widths as large as 0.5 cm were measured.

Fractures Per Unit Volume

If assumptions are made that: 1) fractures identified in core extend throughout the surrounding rock mass, and 2) all fractures are planar, then, the number of fractures contained within a unit volume of rock can be estimated using methods outlined by Scott and others (1983). The equation used to compute fractures per unit volume is expressed as:

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

where 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 all fracture inclinations from 1^{0} to 90^{0} (all horizontal fractures are assigned to 1^{0} between the attitude of the core axis and fracture plane; and f is the number of fractures measured in the interval for every inclination, i. As proposed by Scott and others (1983), a unit volume of $1/m^{3}$ is used, corresponding to a sphere having a diameter of 1.24 m. In this compilation (fig. 14), the thickness of each interval is defined in accordance with changes in welding characteristics as outlined on plate 1.

The densely welded Tiva Canyon Member contains about 34 fractures per cubic meter and the underlying, thin, moderately welded and non-to partially welded zones contain about 41 and 34 fractures per cubic meter, respectively (fig. 14). Below 137.8 ft (42 m), fractures per unit volume decrease significantly, ranging between 0 and 1.3 fractures.

Fracture densities commonly range between 23 and 36 fractures per cubic meter in the densely welded zone of the Topopah Spring Member. Lower densities occur in 1) the upper zone of vapor-phase crystallization (16.3), 2) uppermost lithophysal zone and most of the middle lithophysal zone (3.5), and 3) in an 26 ft(8-m) interval directly above the basal vitrophyre (10.5). Fracture density in the densely welded vitrophyre of Topopah Spring Member is about 36 fractures per cubic meter.

Rock units below the basal vitrophyre of the Topopah Spring Member commonly contain less than about 5 fractures per cubic meter.

Except for the anomalously high fracture densities near the base of the Tiva Canyon Member, the maximum density for densely welded devitrified tuff is 34, non-to partially welded tuff is 4, and bedded tuff is 7 fractures per cubic meter.

Shear Fractures

Indications of differential movement in the form of slickensides, truncation of pumice fragments, fault gouge, and (or) brecciation were recognized along 103 fracture faces. These fractures occur throughout the length of the drill core; however, obvious concentrations can be seen in column 5 of plate 1 at depths of 120-130 ft (37-40 m), 240-280 ft (73-85 m), 370-390 ft (113-119 m), 1,310-1,330 ft (399-405 m), 1,890-1,960 ft (576-597 m), 2,240-2,280 ft (683-695 m), 2,880-2,930 ft (878-893 m). The most pronounced concentration of shear fractures occurs near the base of the devitrified zone of the Prow Pass Member.

Seventy-six shear fractures are conspicuously marked by parallel striations allowing determination of the inclination of the last episode of relative movement along the fracture face. Many shear fractures suggest oblique slip with a strong component of lateral movement similar to shear fractures examined in core from surrounding holes (UE-25a#1 and USW G-1). Forty-one percent of the slickenside fracture surfaces show striations incline between 0^{0} and 20^{0} (fig. 15). Slickensides on the remaining shear surfaces are distributed from 20^{0} to 90^{0}, and 16 percent of the shear fractures that are marked by slickensides are inclined between 81^{0} to 90^{0} suggesting almost total dip-slip movement. Two shear fractures, occurring within the basal vitrophyre of the Topopah Spring Member at depths of 1,327.1 ft (404.5 m), and

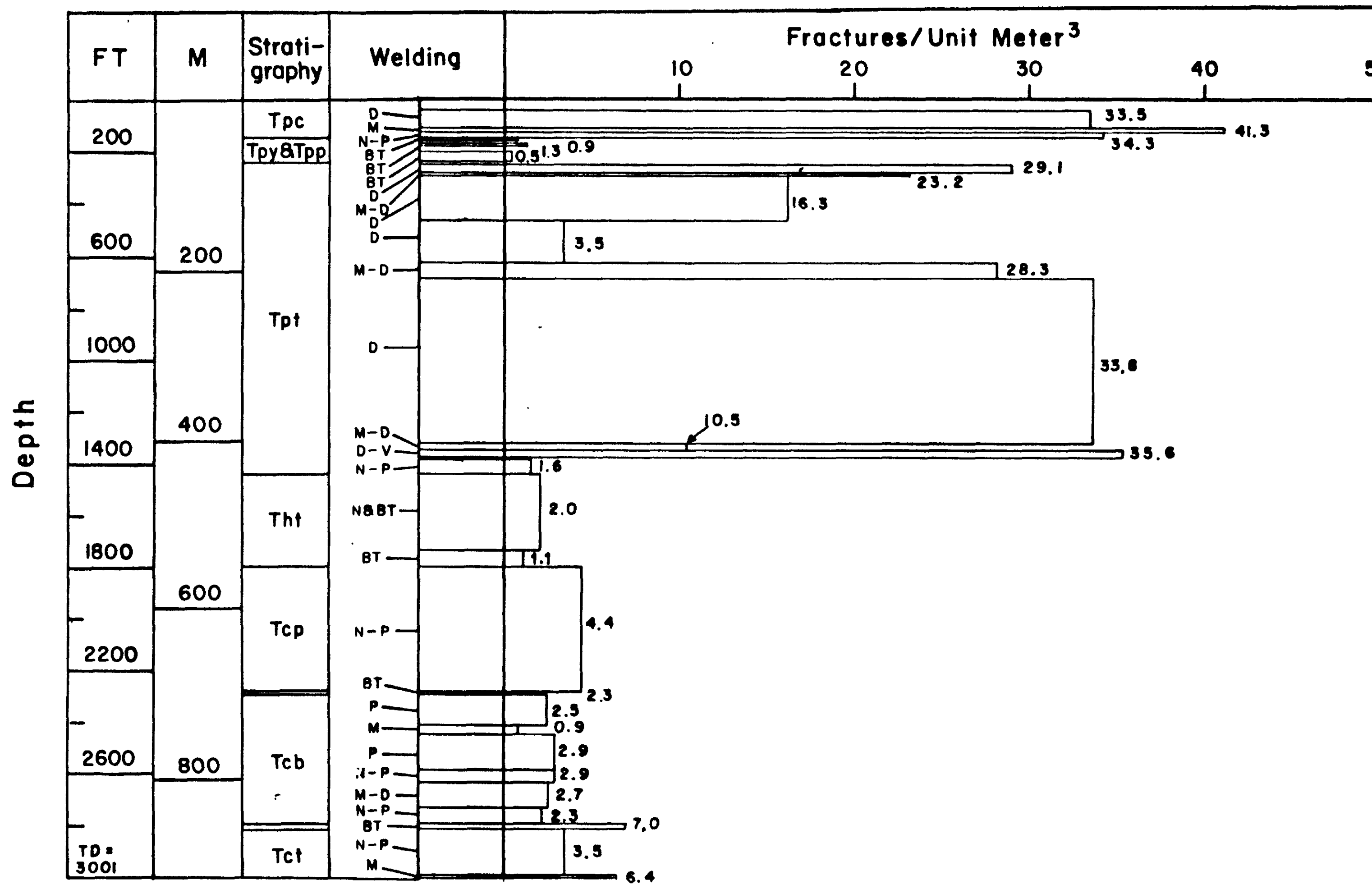

Figure 14.--Number of fractures per cubic meter with respect to the degree of welding described on plate 1. D-V, densely welded vitrophyre; D, densely welded; M-D, moderately to densely welded; M, moderately welded; N-P, non- to partially welded; P, Partially welded; BT, Bedded Tuff; Tpc, Tiva Canyon Member; Tpy and Tpp, Yucca Mounain and Pah Canyon Members; Tpt, Topopah Spring Member, Tht, tuffaceous beds of Calico Hills; Tcp, Prow Pass Member; Tcb, Bullfrog Member; Tct, Tram Member.

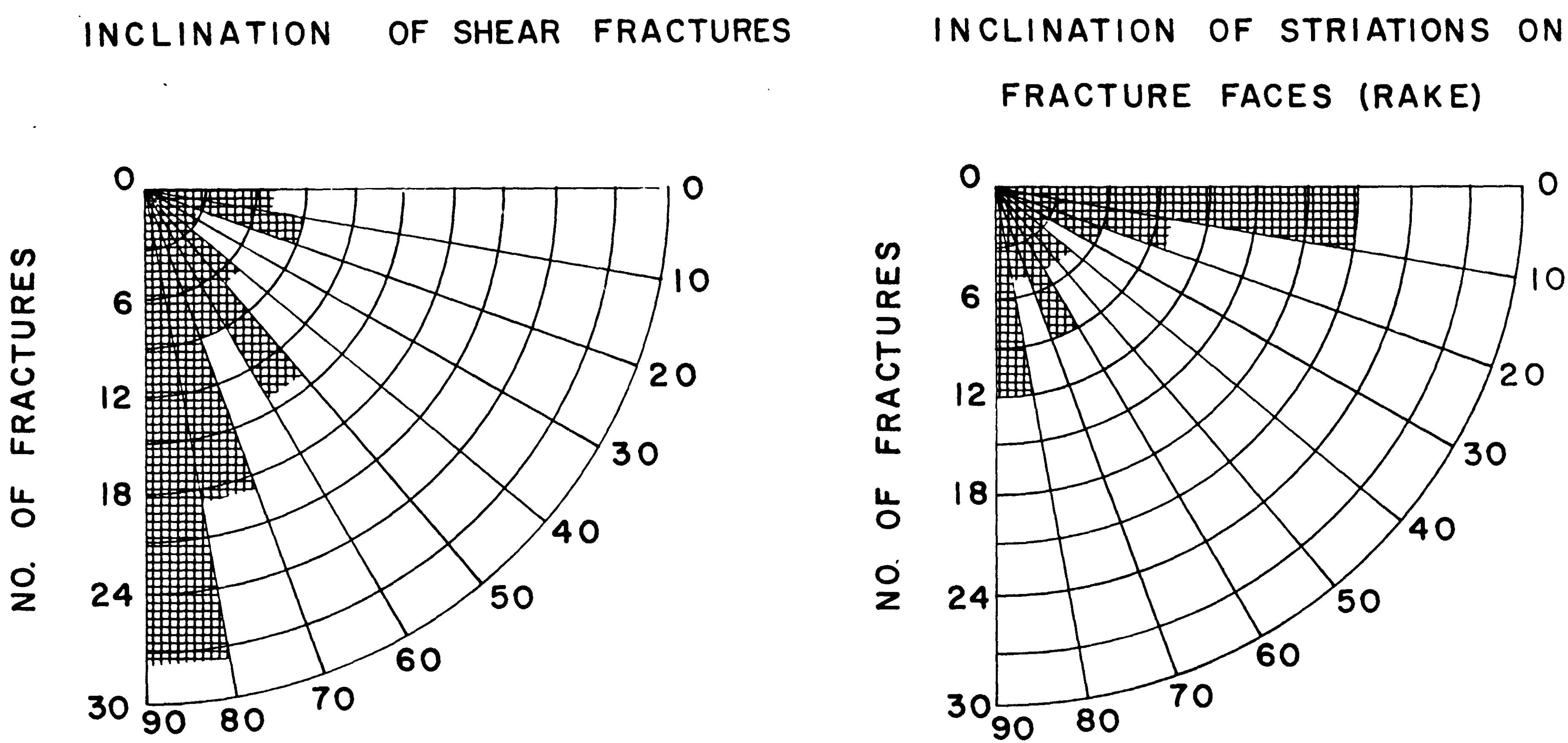

Figure 15.--Inclinations of shear fractures and corresponding rake of striations on fractures in core from USW G-4.

1,327.2 ft (404.6 m) are inclined between 10° and 16°, striated, marked by small-scale mullion structures, and occur in oriented sections of the core, allowing measurement of the lateral slip direction. The two fractures show nearly horizontal movement in a direction between N. 22° W. and N. 10° W.

The amount of offset can rarely be determined along recognized shear fractures. However, the lack of any significant thinning of major stratigraphic units and the absence of any abrupt terminations in welding characteristics of rock on either side of the fractures suggest that displacements are of small scale. The only shear fracture where a reasonable estimate of the amount of vertical offset could be made occurs at a depth of 1,318.7 ft (401.9 m). At this depth, a displacement of 2.0 ft (0.6 m) was determined by matching segments of large distinctive zeolitic pumice fragments that are cut by the fault plane.

Oriented Core

About 13 percent of the core was collected using oriented coring techniques to provide data on the spatial relationships of planar features. The method employs the use of an orienting core barrel, similar to conventional core barrels, except that three triangular scribes are mounted in the "shoe" at the base of the inner barrel. Asymmetric arrangement of the three scribes allows the reference scribe mark to be easily identified. A surveying instrument (compass, timer, and multishot camera) is enclosed within a nonmagnetic drill collar and mounted on top of the inner core barrel and alined with the orienting scribe. During coring operations, drilling is stopped at preselected intervals (commonly every 2 or 3 ft or 0.6-0.9 m to allow the camera to take an orientation photograph showing compass direction of the reference scribe and alinement of the drill hole unaffected by vibration. This procedure is continued until a full core run is completed. With the drift direction and angle from vertical of the hole and reference groove orientations recorded, the recovered core can be placed in a goniometer in its spatial position prior to coring, and orientations of planar features can be measured. Planar features measured in the core hole include eutaxitic structure (flattened-pumice foliation), partings between ash-flow tuffs, bedding planes, and fractures.

Foliation and Layering.--The parallel alinement of flattened pumice fragments is commonly well developed in the upper moderately welded zone containing vapor-phase crystallization and the lowermost densely welded, non-lithophysal zone of the Topopah Spring Member. Twenty-three measurements of foliation trends on core from these two intervals (6 measurements from the upper vapor-phase zone and 17 measurements from the lowermost non-lithophysal zone) in the Topopah Spring indicate dips of 4° to 24° in directions ranging from N. 53° E. to S. 80° E. Five of the 6 measurements of foliation in the upper vapor-phase zone of the Topopah Spring Member dip in directions slightly south of east. Whereas, all 17 measurements of foliation in the lowermost non-lithophysal zone dip in a northeasterly direction (fig. 16a). The average dip of all foliation is about 10° in a mean direction of about N. 75° E. (fig. 16a). The mean angular deviation is 18°.

The mean dip direction of foliation, indicated above, is consistent with mean dip directions of N. 81° E., N. 73° E., and N. 84° E. measured on core collected from the upper moderately welded zone of the Topopah Spring Member

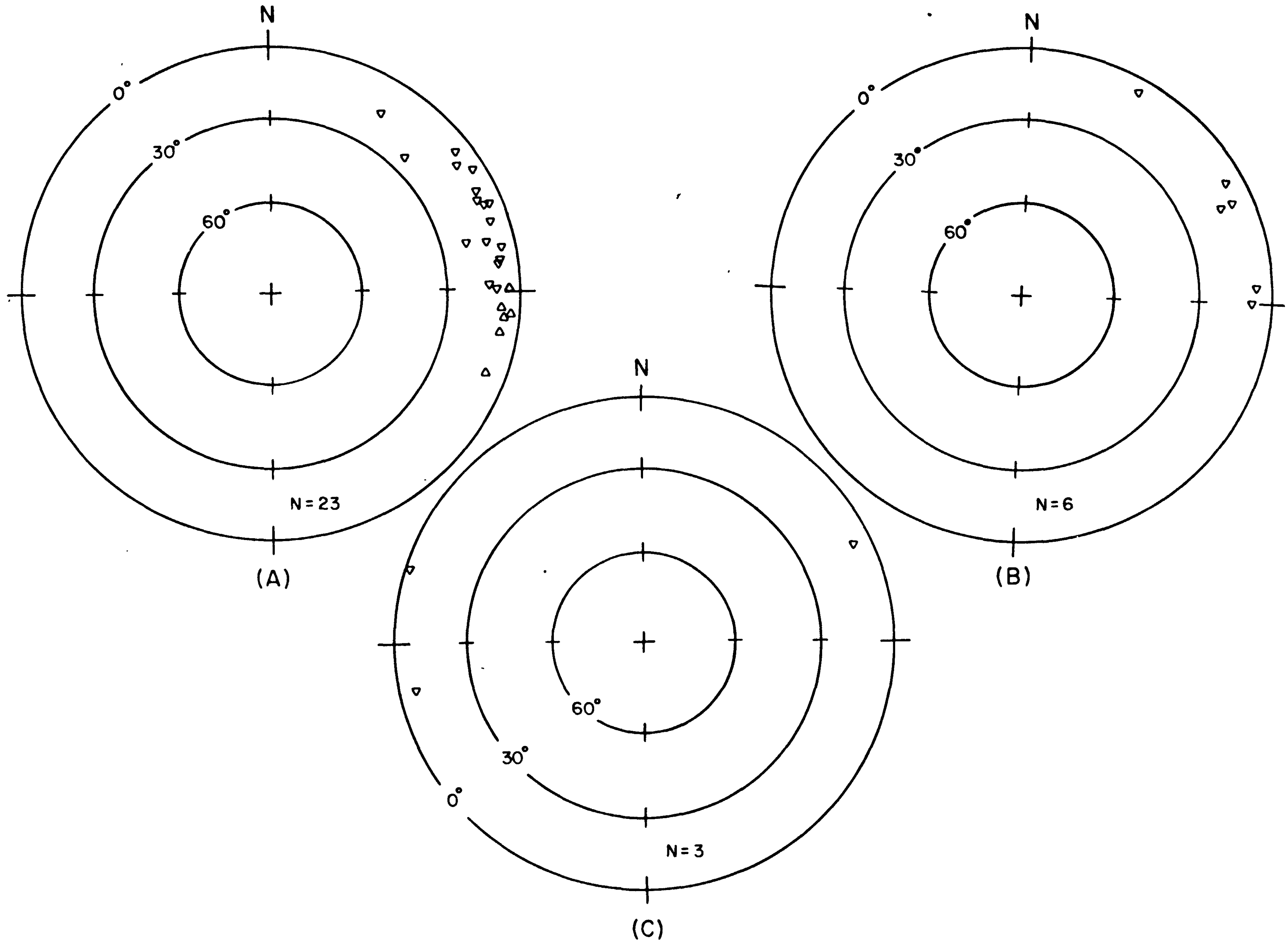

Figure 16.--Orientation of (A) foliation in moderately to densely welded zones of the Topopah Spring Member (Δ, indicates measurements from upper vapor-phase zone; ∇, indicates measurements from the lower non-lithophysal zone); (B) bedding planes near the base of the tuffaceous beds of Calico Hills; and (C) ash-fall and clay partings directly below the base of the Bullfrog Member. Dip-line plot of amount and direction of dip on lower hemisphere of equal-area projection.

in holes UE-25a#4, #5, and #7 respectively, located in Drill Hole Wash east of USW G-4 (fig. 1) and suggests a northeasterly dip direction of foliation in ash-flow tuffs of the Topopah Spring in the vicinity of USW G-4. However, the mean dip direction of foliation observed in USW G-4 is inconsistent with a mean dip direction of S. 67° E. measured on core from the Topopah Spring in hole UE-25a#6, located east of USW G-4 and outside of Drill Hole Wash (Spengler and Rosenbaum, 1980; fig. 1). This inconsistency may be a result of block rotation close to northeasterly trending normal faults located near the site of hole UE-25a#6. This inference does not agree with preliminary conclusions reached by Spengler and Rosenbaum (1980) that foliation directions observed in core from the Topopah Spring in holes UE-25a#4, #5, and #7 are inconsistent with foliation trends typical of the area and that rotation of blocks in Drill Hole Wash are caused by left-lateral movement along northwest-trending faults bounding the wash.

Six attitudes of bedding planes were measured in the thick bedded tuff interval near the base of the tuffaceous beds of Calico Hills 1,739.6-1,754.6 ft (530.2-534.8 m). Five of the 6 dip directions are clustered between N. 59° E. and N. 90° E. Inclinations average about 9° (fig. 16b). The obvious similarity of attitudes of foliation in the moderately to densely welded zones of the Topopah Spring Member and attitudes of bedding planes near the base of the tuffaceous beds of Calico Hills suggests a parallel unconformable relationship between the two units.

Ash-fall tuff and clay partings that were identified directly below the base of the Bullfrog Member at depths of 2,746.1, 2,747.8, and 2,754.6 ft (837.0, 837.5, and 839.6 m) dip in directions of N. 65° E., N. 72° W., and S. 78° W. The amount of dip ranges from 2° to 8° (fig. 16c).

Fractures.--Attitudes of 82 well defined fractures were obtained from three stratigraphic intervals: densely welded zone of the Tiva Canyon Member, densely welded zone of the Topopah Spring Member, and the Crater Flat Tuff. In the Crater Flat tuff, data were obtained primarily from the lowermost part of the Prow Pass Member, the bedded tuff interval below the base of the Bullfrog Member, and the uppermost part of the Tram Member. Maxima of poles to fractures indicate dominant fracture sets of: (A) N. 22° E., 65° N.W., in the Tiva Canyon Member, (B) N. 12° W., 89-90° N.E. and S.W. in the Topopah Spring Member, and (C) N. 23° E., 45° N.W. and N. 50° E., 55° S.E. in the Crater Flat Tuff (fig. 17). These data include only about 4 percent of the total number of fractures recognized in this core, therefore, the results shown on figure 17 may not be statistically valid for the evaluation of trends of fracture attitudes throughout the stratigraphic column. Another technique used to acquire additional fracture orientation is described below.

Downhole Television Camera

The use of an air-foam drilling medium results in borehole walls free of mudcake and allows acquisition of additional data on fracture orientations by using a downhole television camera with a mounted compass. Strike directions of 204 prominent fractures were measured in USW G-4 between depths of 12 and 40.0-1,549 ft (472 m). In addition to strike directions, dip directions were obtained for 151 of the 204 fractures. Figure 18 shows: a) attitudes of fractures from a depth of 40.0 ft (12 m) to the top of the densely welded zone

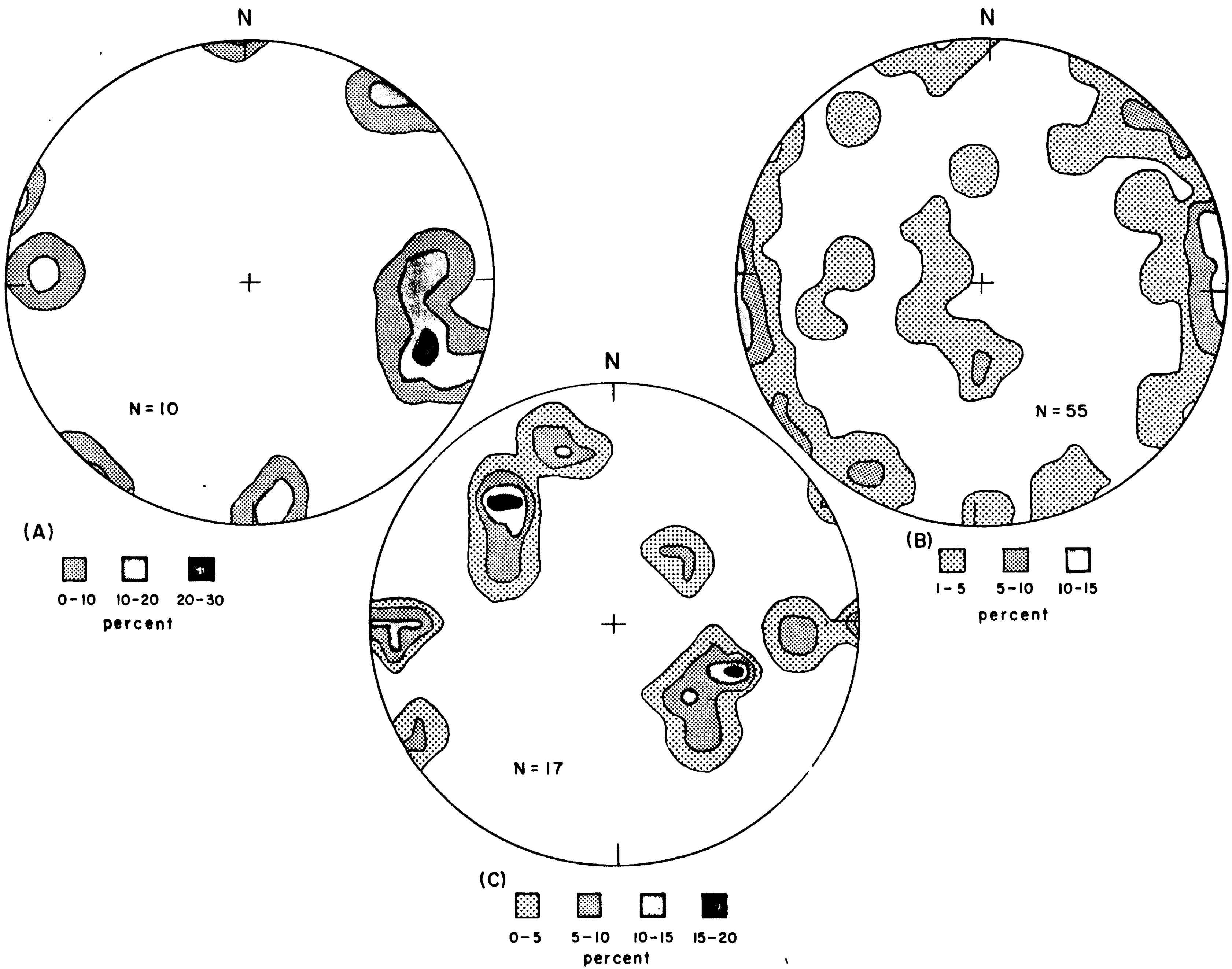

Figure 17.--Contour diagrams of percentages of fracture poles in (A) densely welded zone of Tiva Canyon Member; (B) densely welded zone of Topopah Spring Member; and (C) Crater Flat Tuff (contours represent percent of fractures per 1 percent of total area as plotted on lower hemisphere of equal area projection).

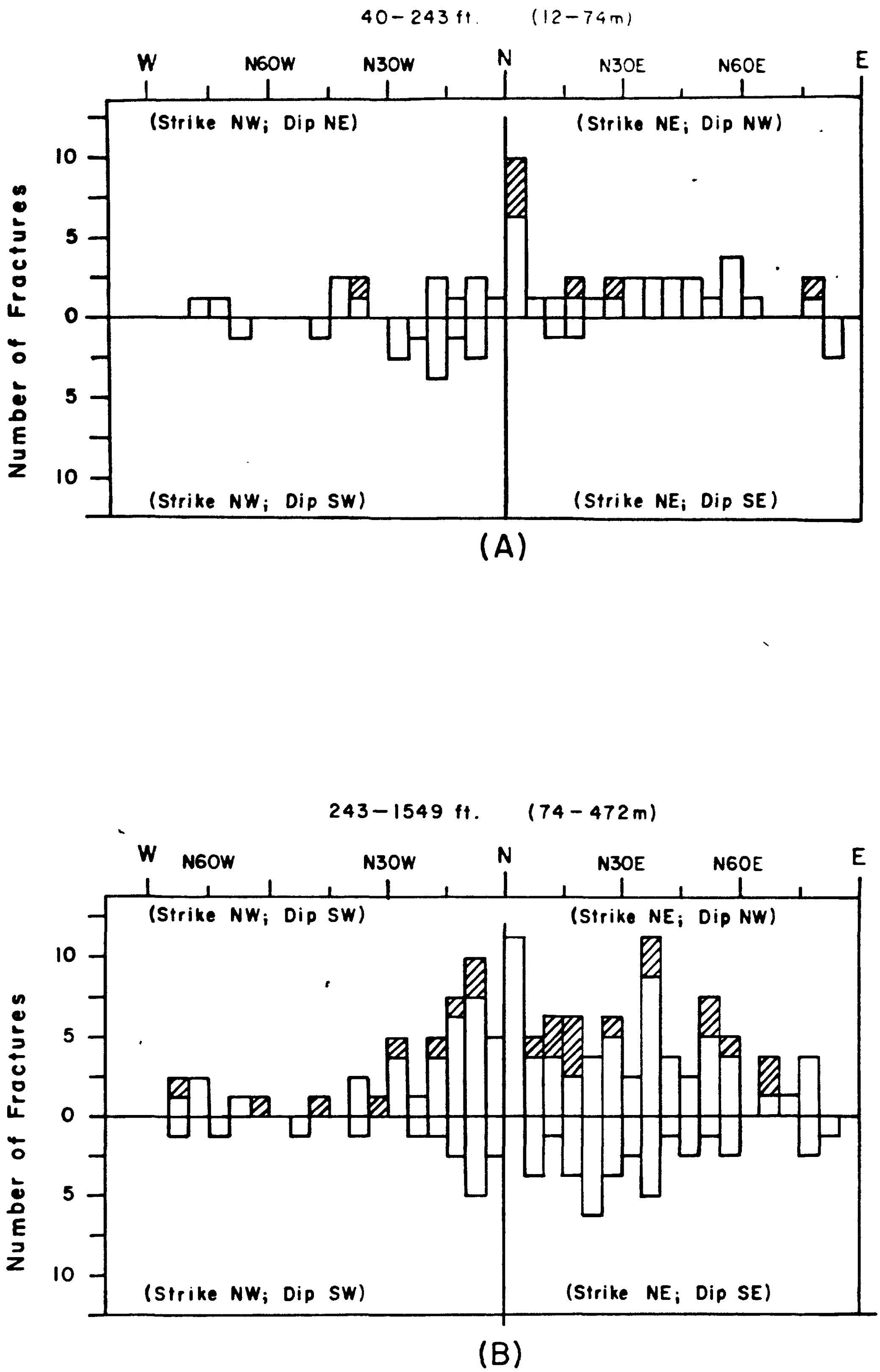

Figure 18.--Attitudes of fractures, based on observations made with downhole television camera and compass, in (A) densely welded zone of the Tiva Canyon Member and (B) densely welded zone of Topopah Spring Member and upper part of the tuffaceous beds of Calico Hills (orientations are adjusted to True North, however, depths on T.V. log have not been corrected to correspond with core depths; for example, top of the upper vitrophyre in the densely welded zone of the Topopah Spring is 239 ft (73 m) in core and 243 ft (74 m) in the T.V. log, top of the basal vitrophyre in the Topopah Spring is 1,316.5 ft (401 m) in core and 1,307 ft (398 m) on the T.V. log; ▨, represents strike and dip directions; □, represents strike direction only).

of the Topopah Spring Member at 243 ft (74 m), and b) attitudes of fractures from the top of the densely welded Topopah Spring Member to a depth of 1,549 ft (472 m).

No preferential orientation of fractures is apparent in the Tiva Canyon Member (fig. 18a). Forty percent and 60 percent of the fractures strike toward the northwest and northeast, respectively.

Strike directions of 141 fractures were measured between depths of 243 ft (74 m) and 1,549 ft (472 m) (fig. 18b). Sixty-five percent strike to the northeast and 35 percent to the northwest. Most of the fractures range in strike between N. 20^{o} W. and N. 60^{o} E. Dip directions, measured on 118 fractures, indicate that most fractures dip to the northwest (43 percent). Twenty-four and 21 percent of the fractures dip toward the southeast and northeast, respectively.

Of the 1,730 natural fractures noted in core between the depths of 41 and 1,549 ft (12.5 and 472 m) only 204 fractures (12 percent) were identifiable and measurable on downhole television camera logs. Poor visibility of borehole walls due to excessive hole enlargement (pl. 1) and poor illumination may limit detection of well defined fracture planes. Another factor that contributes to the low number of identifiable fractures are zones where highly broken and fractured rock was observed on the television tapes, but discrete fracture planes could not be measured confidently. In the television camera logs, three obvious zones were noted between 428 ft (131 m) and 434 ft (132 m), between 860 ft (262 m) and 877 ft (267 m), and between 1,241 ft (378 m) and 1,253 ft (382 m). In core samples, these three zones contain a total of about 50 fractures. Scott and Castellanos (1984) suggested that fractures identified in the downhole television camera log from hole USW G-3 represent only those fractures that were enhanced during drilling, and therefore, result in a bias against other fractures. However, it is possible that a significant number of fractures identified by using the downhole television camera may represent prominent, through-going fractures possessing large enough surface areas to promote enhancement during the drilling process and, therefore, this technique may provide a means of estimating the persistence and directional trends of dominant fractures in the subsurface.

Core Index

The CI (core index) number, compiled by contractor geologists of F&S soon after core recovery, represents an estimate of the joint frequency, core loss, and broken core (core less than 10 cm or 4 in. in length) into one significant number (J. R. Ege, written commun., 1975). The equation used to compute the CI is expressed as:

$$CI = \frac{(\text{m broken}) + (\text{m core loss}) + (0.1\ \text{joints})}{(\text{drilled interval, m})} \times 100$$

An increase in the CI corresponds to an increase in joint frequency, core loss, and broken core, and, therefore, relates to structural in competency. As shown on plate 1, a high CI number is commonly associated with an increase in the degree of welding.

SUMMARY

As stated at the beginning of this report, one of the primary purposes of initiating a subsurface study near the site of the proposed exploratory shaft was to verify expected geologic characteristics based on information previously obtained from nearby holes, particularly UE-25a#1 and USW G-1. The results of this study and comparison with results of studies of other holes, outlined at various places in this report, strongly suggest that only slight lateral variations in stratigraphic and structural characteristics of rock units exist. The salient geologic features principally identified in core recovered from USW G-4 are:

1. Major stratigraphic units identified in USW G-4 include, in descending order: The Paintbrush Tuff (Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members), tuffaceous beds of Calico Hills, and Crater Flat Tuff (Prow Pass and Bullfrog Members and upper part of the Tram Member).

2. Welding characteristics of ash-flow tuff units vary from nonwelded to densely welded. Moderately to densely welded zones are dominantly confined to the Paintbrush Tuff in the upper half of the cored section, where thicknesses of 57.5 ft (17.5 m) and 1,114.6 ft (339.7 m) occur in the Tiva Canyon and Topopah Spring Members, respectively. Below the basal vitrophyre of the Topopah Spring Member 1,353.6 ft (412.6 m) to a depth of 3,001 ft (914.7 m), ash-flow tuff units are almost entirely non-to partially welded, except within the Bullfrog Member from 2,370.0 ft (722.4 m) to 2,397.8 ft (730.9 m) and from 2,581.8 ft (786.9 m) to 2,680.3 ft (817.0 m), where welding increases to moderate and moderate to dense respectively.

3. Bedded tuffs between ash-flow tuff members and within the tuffaceous beds of Calico Hills vary in thickness from 2.6 ft (0.8 m) to 55.9 ft (17.0 m). Almost all of these bedded tuffs are moderately to highly zeolitic, except for bedded tuffs that occur between the Tiva Canyon and Topopah Spring Members, where the rock is dominantly vitric.

4. Zeolitic alteration of rock units occurs below a depth of 1,424.5 ft (434.2 m). Above this depth, densely welded units are dominantly devitrified, and non-to moderately welded tuff units are dominantly vitric. Most of the rock assigned to the tuffaceous beds of Calico Hills and the Prow Pass Member contain 30 to as much as 70 percent clinoptilolite and (or) mordenite.

5. Three obvious lithophysae-bearing intervals occur in the densely welded zone of the Topopah Spring Member. The most conspicuous zone occurs between depths of 470 ft (143 m) and 680 ft (207 m), and commonly contains from 11 to 29 percent voids. The lowermost zone, between 770 ft (235 m) and 1,127.9 ft (343.8 m), contains from 3 to 30 percent lithophysae. Void content attributed to lithophysae in this zone does not exceed 5 percent and commonly is less than 2 percent.

6. A total of 2,058 fractures were identified in core; 81 percent of these occur in the densely welded zones of the Tiva Canyon and Topopah Spring Members. The average amount of fracturing in each of these two intervals corresponds to apparent fracture frequencies of about 26 and 13 fractures per 10 ft (3 m), respectively. Fracturing decreases significantly below the densely welded zone of the Topopah Spring, where less than 17 percent of the total number of fractures occur. The apparent fracture frequency in the tuffaceous beds of Calico Hills (includes lower non-to partially welded Topopah Spring Member) is about 1 fracture per 10 ft (3 m) and is 2.4 fractures per 10 ft (3 m) in the Crater Flat Tuff.

7. Fracture faces in the Tiva Canyon, Yucca Mountain, and Pah Canyon Members are commonly coated with manganese and iron oxides. In the densely welded Topopah Spring, most fractures are either free of any coating but appear to have weathered surfaces or are coated by silica. Below the densely welded zone of the Topopah Spring, dominant coatings include manganese oxides, manganates, iron oxides and hydroxides, and zeolites.

8. Estimates of the number of fractures in a unit volume of rock indicate that densely welded devitrified tuff, non-to partially welded tuff, and bedded tuff commonly contain as many as 34, 4, and 7 fractures per cubic meter, respectively.

9. About 5 percent of the the total number of fractures were described as shear fractures, many of which show a strong component of lateral movement. Although shear fractures are scattered throughout the core, obvious concentrations are present at the base of the Tiva Canyon Member, at the top of the densely welded zone of the Topopah Spring Member, in the upper part of the basal vitrophyre of the Topopah Spring, in the upper third of the Prow Pass Member, and at the top of the Bullfrog Member.

10. Pumice foliation in the densely welded zone of the Topopah Spring Member dips approximately 10^{o} in a mean direction of N. 75^{o} E. Most bedding planes measured at the base of the tuffaceous beds of Calico Hills dip by about 9^{o} in directions between N. 59^{o} E. and N. 90o E.

11. Strike directions of fractures identified from downhole television camera observations in the Tiva Canyon Member 40-243 ft (12-74 m); suggest an absence of any preferred orientation. In the interval that includes the densely welded zone of the Topopah Spring Member and the upper part of the tuffaceous beds of Calico Hills 243-1,549 ft (74-472 m); most fractures strike between N. 30^{o} W. and N. 60o E.

GEOPHYSICAL LOGS FROM USW G-4

by
D. C. Muller and J. E. Kibler

This section briefly addresses each individual log plotted on plate 1 as to the logging method and general tool response characteristics. For more detailed discussion of logging tools and response characteristics the reader is referred to Asquith and Gibson (1982), Freedman and Vogiatzis (1979), Pirson (1963), Poley and others (1978), Rau and Wharton (1980), and Schlumberger (1972 and 1974). Additional experimental log data Yucca Mountain can be found in Daniels and Scott (1981), and Hagstrum and others (1980 a, b).

Specific details of drilling and logging operations that affect the data are discussed later in this report. Logging operations are monitored and actual procedures documented to attain high-quality geophysical log data. Accuracy and precision of tools and data are defined and contracted for by F&S, the primary DOE contractor for logging. Specific information regarding the contracts and contracted standards are available from F&S. On site contract monitoring during logging operations is performed by an F&S logging engineer. A representative of the USGS inspects all logs prior to installation of casing or any other operation that renders the drill hole inaccessable, and recommends additional logging which may be needed to confirm anomalies and to recover any inconsistent or unusable log data.

Caliper

Caliper tools are used to measure the diameter of drill holes. Equally spaced arms on the tool measure equiangular diameters between opposing arms. Three caliper tools are used at Yucca Mountain, a three-arm tool which measures average diameter, a four-arm tool which measures two diameters at right angles and average diameter, and a six-arm tool which measures three equiangular diameters and average diameter. The six-arm tool is used in holes greater than 10 cm in diameter, the three and four arm tools in holes 10 cm and less in diameter.

Neutron

Neutron tools have a source of high energy neutrons located at the bottom of the tool and one or two neutron detectors located up the probe above the source. The neutron detectors count low energy neutrons which are scattered back from the formation. Two types of neutron logs are commonly used, one counts thermal neutrons which are in thermal equilibrium with the rock and the other counts epithermal neutrons which have a higher kinetic energy than the thermal neutrons. Thermal neutrons are easily captured by many elements and therefore, the formation effects are greater than on epithermal neutrons which are harder to capture due to higher kinetic energy. Newer borehole compensated tools count thermal neutrons with two detectors, one near the neutron source at the bottom of the probe and the other located up the probe further from the source. The ratio of the count rates from the two detectors is the formation response compensated for borehole effects. Borehole compensated neutron tools and some single detector neutron tools are sidewall tools which are designed so the source and detector section of the tool maintain contact with the side of the drill hole to minimize borehole effects and enhance formation response.

The primary mechanism for neutron scatter and loss of energy is collision with hydrogen nuclei. For most rocks, essentially all of the hydrogen is bound in water molecules which makes the neutron log a good indicator of the formation water content. In general, high neutron count rates correspond to low water content and low count rates to high water content. Below the static water level, where the assumption of total saturation is valid, borehole compensated neutron logs are calibrated to directly obtain reliable porosity for many rock types. Porosity from calibrated single detector neutron logs is generally not as reliable as compensated neutron porosity unless core data exist which either confirm the single detector neutron porosity, or can be used to develop corrected calibration curves for the specific rocks penetrated by the drill hole.

Above the static water level, in the unsaturated zone, the neutron log count rate can be used as an indicator of relative increases and decreases in formation water content, or for many rock type, calibrations exist to convert the count rate to volume fraction of water in the rock. If the value of either porosity or saturation can be determined by some means, the other value can then be determined from the volume fraction of water from the neutron log. In air-filled boreholes, the neutron log is very sensitive to the borehole diameter and rugosity, the roughness of the borehole wall. Boreholes with diameters larger than the separation between the neutron source and the detector that are air filled do not provide a valid relationship between count rate and water content, and in extreme cases, the relationship can be reversed. This situation rarely occurs because most neutron logs are made with sidewall tools which are not affected by this problem.

Anomalous neutron log responses can be attributed to changes in mineralogy, water of hydration, crystallization in altered zones, and the presence of neutron moderators such as boron. Anomalies are detected and interpreted by comparing the neutron log to other logs that respond to formation water or porosity, such as the density, velocity, and resistivity logs.

Density

Density logs are obtained with borehole compensated gamma-gamma tools that beam gamma rays into the formation and detect the gamma rays that are scattered back from collisions with electrons. The compensated density tool has two gamma-ray detectors, one near the gamma-ray source and another farther away from the source. The near detector response is dominated by gamma rays that are scattered from the borehole and those from the formation near the borehole that may have been altered by the drilling. The far detector response, which is dominated by gamma rays scattered from rock in the range of 15 cm from the borehole wall, is corrected for secondary borehole effects using the near detector response to obtain the compensated formation response. Although the compensated density tool response is to the density of electrons in the formation, it is calibrated to determine the bulk density of most earth materials including the tuffs of Yucca Mountain.

The density tool is a sidewall tool designed to maintain contact with the borehole wall to minimize borehole effects and enhance formation response. The tool often cannot compensate for borehole effects in very rough walled boreholes or through badly caved or washed out intervals. This is particularly true in air-or gas-filled holes where the greatest borehole effects usually occur. Comparison with the caliper log can identify anomalies which are due to borehole effects beyond the limits of compensation.

Changes in density are due primarily to changes in porosity and water content. Alteration that changes the grain density also has a significant secondary effect on formation density. Anomalies are detected and interpreted by comparisons with neutron, velocity, and resistivity logs.

Porosity

The porosity log plot has two traces. One is porosity computed from the density log assuming the grain density of sandstone (2.65 g/cc) and total saturation, which is a valid assumption below the static water level. The other is porosity from a borehole compensated sidewall neutron log, which is also based on the assumption of total saturation and calibrated for a sandstone rock matrix. The borehole compensated neutron tool is calibrated to determine porosity in fluid-filled holes, and normally is not run above the fluid level in the air-filled section of the hole. Logs made with borehole compensated neutron tools in air-filled holes are recorded and reported as two single detector neutron logs.

Values reported for porosities in fluid-filled holes above the static water level are lower than true porosity unless borehole fluid has invaded the rock and has artificially created the condition of total saturation at least to the depth of investigation of the logging tool. Borehole compensated density and neutron tools have different depths of investigation, on the order of 15 cm and 25 cm or more respectively. Porosities from compensated density and neutron tools are expected to agree for saturated silicic rocks, and disagreement between them indicates such conditions as less than total saturation, greater saturation by invasion at the depth of investigation for the density log than for the neutron log, non-silicic mineralogy, alteration, and the presence of neutron moderators such as boron or chlorine in the rock, the formation water, or the borehole fluid.

Velocity

The velocity of sound waves through the formation is determined by measuring the time interval for waves to travel a known distance along the borehole wall parallel to the borehole axis. The distance is divided by the elapsed time to obtain the velocity of the formation. The plot (pl. 1) has three traces showing seismic compressional velocity, sonic compressional velocity (Vp), and sonic shear velocity (Vs).

Sonic compressional velocities are continuously measured with a sonic logging tool which has a relatively high frequency transmitter (typically 20 khz) at the bottom of the tool, and two detectors, one located further from the source than the other typically 3.9 and 5.9 ft or(1.2 m and 1.8 m). Newer borehole compensated sonic velocity tools use a second transmitter above the two receivers so that travel times of signals generated by both transmitters can be averaged to obtain improved measurement accuracy.

The compressional wave is the fastest wave traveling through the formation, and is detected automatically by the sonic tool as the first signal to arrive at each receiver. The shear wave arrives later, and is interpreted by examining displays of the full wave train. Sonic velocities are small-volume measurements which are affected by singular small irregularities such as fractures, joints, and lithophysal cavities. Anomalies are detected and interpreted by comparison with density, neutron, and resistivity logs.

Seismic velocity is determined by using a wall-locking geophone in the borehole to detect the arrival time of a seismic signal at known discrete depths. The seismic signal is generated near the borehole on the ground surface with a mechanical vibrator or other source of seismic energy. Seismic frequencies are relatively low, typically lower than 100 Hz. The resulting plot of velocity versus depth has a square step-like appearance and indicates the average velocity of the formation through the interval between discrete geophone depths. Seismic velocity determined by this method is a large-volume measurement that includes average effects of fracturing, jointing, lithophysae, inhomogeneities, and in some cases refraction effects due to stratigraphy and structure.

Resistivity

Resistivity is a measure of the resistance of the rock around the borehole to the transmission of an electric current through the rock. Borehole resistivity measurements are made with two types of probes. One type uses contacting electrodes to pass a known current through the rock, and to detect the resulting potential using a specified electrode arrangement to determine apparent resistivity. The other type uses a probe containing a transmitting coil to induce current in the rock, and one or more receiving coils to detect the resulting electromagnetic field from which apparent resistivity is determined. Standard induction tools measure resistivity at frequencies in the 20 kHz range. In dielectric tools the induction resistivity is measured in the 47 MHz range and is sometimes reported as an incidental measurement made simultaneously with dielectric permittivity.

Standard induction resistivities are reliable below 200 ohm-m, but are unreliable for higher resistivities. Dielectric tools respond well to higher resistivities, but are unreliable for resistivities lower than about 10 ohm-m. Because resistivity is dispersive and varies with measurement frequency, comparisons amoung direct current or low frequency resistivities, induction resistivities, and dielectric resistivities may show consisderable disagreement.

Most rocks are essentially insulators, so electric current is transmitted by ions in the fluid in the pore spaces, causing measured resistivity to respond to changes in formation porosity and water content. However, borehole geometry, borehole fluid resistivity, changes in formation water salinity, presence of alteration products such as zeolites and clays which have cation exchange capacity and double layer electrochemical properties, presence of metallic minerals, and changes in rock type all have significant secondary effects on the measured resistivity. Anomalies are identified and interpreted by comparison with density, neutron, and velocity logs.

Spontaneous potential

Spontaneous potential (SP) is the electric potential resulting from electrochemical and electrokinetic effects between the borehole and the formation referenced to a buried surface potential electrode. Due to combinations of such conditions as fresh water or drilling mud in the borehole, fresh formation water, high porosities, very low formation rock permeabilities, and variations in rock alteration products, spontaneous potential does not behave predictably at Yucca Mountain and does not correlate well with geology or from drill hole to drill hole. It is presented in this report as an incidental measurement that is made simultaneously with resistivity, but is not usually useful.

Gamma Ray

The gamma-ray log is obtained from two tools, one containing a standard gamma-ray detector, and the other containing a spectral detector. Standard gamma-ray logs measure the total count rate of gamma rays of all energies emitted by the formation in API units, an industry standard. The total count rate is recorded as one of four traces of the spectral gamma log. The potassium, uranium, and thorium channels of the spectral log are made by detecting gamma rays of distinctive energy levels which are emitted by radioactive potassium and by radioactive daughter elements of uranium and thorium. Daughter elements result from radioactive decay of a mother element, and the number of gamma rays emitted by a radioactive daughter can be related to the volume percent of mother element present in the rock.

The volcanic tuffs at Yucca Mountain characteristically exhibit high total gamma radiation levels compared with most sedimentary rocks. Relatively high uranium radiation levels mask the radiation from uranium that may be concentrated in coatings and fillings of fractures so that individual fracture identification with the uranium trace has not been feasible. Spectral gamma-ray logs, particularly the potassium channel exhibit similar characteristics from drill hole to drill hole in some lithostratigraphic units making it useful for lithologic identification and stratigraphic correlation. The gamma ray log is often run simultaneously with other logs, and is used to accurately correlate depths between logs in the same drill hole.

Calculated

Calculated logs are logs which have been calculated from two or more measured logs. Acoustic impedance is calculated from the product of density and sonic velocity. Elastic moduli are calculated from density, compressional velocity, and shear velocity. Poisson's ratio is calculated from the ratio of compressional and shear velocity. Acoustic impedance logs are used to identify horizons where a large change in impedance occurs, indicating a good seismic reflecting horizon. The elastic moduli and Poisson's ratio are measures of the elastic properties of rock. The formulas for computing these values can be found in any geophysics text which contains discussions on seismology, such as Dobrin (1960), and for specific application to sonic logs see Geyer and Myung (1970).

ANALYSIS OF LOG DATA FROM USW G-4

Geophysical logs were obtained in hole USW G-4 during five episodes of logging. Table 6 is a tabulation of the logging dates and hole information useful for evaluating the log data. The porosity log is missing from 469 ft (143 m) to 1,555 ft (474 m) because the hole was air filled at the time of logging and the neutron porosity tool is not calibrated for an air-filled hole. The shallow focus resistivity is also missing in this interval due to lack of fluid in the hole. Induction resistivity is missing through this interval because the resistivity of the rock is too high for the induction tool to measure.

The porosity plotted above 453 ft (138 m) was measured in a fluid-filled hole, but may not be accurate because the rock is unsaturated. The actual porosity is higher unless borehole fluid has invaded and saturated the formation around the borehole, artificially creating the condition of total saturation to the radius of investigation of the compensated neutron porosity tool. The intervals from 1,790 ft (546 m) to 1,890 ft (576 m) and 2,255 ft (687 m) to 2,535 ft (773 m), where neutron porosity and density porosity are significantly different, are anomalous and have the appearance of rock that is undersaturated. Laboratory studies of core are being made to determine the cause of the anomaly.

The spectral gamma-ray log was made through casing above 2,017 ft (615 m). The effect of casing on the spectral gamma-ray total count rate trace is a decreased count rate level due to attenuation. Through the Topopah Spring Member, where the gamma-ray count rate is high, the additional attenuation of a greater thickness of steel at casing collars is seen as low count rate spikes every 40 ft (12 m) on plate 1. There is cement behind the casing from 1,995 ft (608 m) to 2,017 ft (615 m) and the surface casing was cemented from the surface to 39 ft (12 m). The cement causes additional attenuation of gamma rays from the formation in those intervals. Comparing the total count trace with the potassium, uranium, and thorium traces leads to the conclusion that the total count rate of gamma rays through the Tertiary section is a result of potassium and thorium with little contribution from uranium.

The caliper log indicates that the upper section of the drill hole is very rough and enlarged, particularly through the Topopah Spring Member, which contains lithophysae and is highly fractured. The neutron and density logs are very noisy or "spiky" through the Topopah Spring. The spikiness is from the inability of the tools to correctly compensate for the combined effect of the enlarged rough drill hole, fracturing, and lithophysae. Fracture analysis of core described in previous sections and in other reports (Spengler and others, 1979, 1981) confirms that most of the fractures in the Topopah Spring are unhealed. The matrix permeability of tuffs is generally low, so the lack of return circulation and loss of large amounts of drilling fluid during drilling of some holes at Yucca Mountain indicates high fracture permeability (Ellis and Swolfs, 1983). Hydrologic testing in drill hole J-13, east of Yucca Mountain on the east side of Forty Mile Wash, confirms that the fracture permeability in the Topopah Spring is very high (Thordarson 1983).

Table 6.--Summary of geophysical logs from USW G-4

Date	Drilled depth feet (m)	Casing depth feet (m)	Bit size inches (cm)	Fluid level[1] feet (m)	Top of log feet (m)	Bottom of log feet (m)	Log[2]	Comments[3]
09/18/82	455 (139)	39 (12)	6.75 (2.66)	446 (136)	5 (2)	446 (136)	CAL	MAX T = 72°F
09/18/82	455 (139)	39 (12)	6.75 (2.66)	446 (136)	100 (30)	445 (136)	VSP	
09/19/82	455 (139)	39 (12)	6.75 (2.66)	446 (136)	10 (3)	454 (138)	GAM	
09/19/82	455 (139)	39 (12)	6.75 (2.66)	446 (136)	39 (12)	453 (138)	DBC	8.4 lb/gal mud
09/19/82	455 (139)	39 (12)	6.75 (2.66)	<39 (<12)	39 (12)	453 (138)	NBC	
09/19/82	455 (139)	39 (12)	6.75 (2.66)	<39 (<12)	39 (12)	453 (138)	VDS	NG
09/19/82	455 (139)	39 (12)	6.75 (2.66)	<39 (<12)	39 (12)	453 (138)	DIF	Rm = 3.7 at BHT
10/23/82	1,825 (556)	469 (143)	6.75 (2.66)	U	420 (128)	1,798 (548)	CAL	MAX T = 103°F
10/23/82	1,825 (556)	469 (143)	6.75 (2.66)	U	469 (143)	1,790 (546)	VSP	
10/24/82	1,825 (556)	469 (143)	6.75 (2.66)	U	424 (129)	1,776 (541)	CAL	
10/24/82	1,825 (556)	469 (143)	6.75 (2.66)	U	469 (143)	1,775 (541)	DIF	Focus NG <1,560 ft
10/24/82	1,825 (556)	469 (143)	6.75 (2.66)	U	466 (142)	1,776 (541)	DBC	
10/24/82	1,825 (556)	469 (143)	6.75 (2.66)	1,554 (474)	469 (143)	1,776 (541)	NBC	
11/08/82	3,001 (915)	1,825 (556)	4.25 (1.67)	U	1,825 (556)	2,998 (914)	CAL	
11/09/82	3,001 (915)	1,968 (600)	4.25 (1.67)	U	1,750 (533)	2,993 (912)	DBC	Drill Rods at 1,968 ft
11/09/82	3,001 (915)	1,968 (600)	4.25 (1.67)	1,774 (541)	1,968 (600)	2,992 (912)	NBC	
11/09/82	3,001 (915)	1,968 (600)	4.25 (1.67)	1,774 (541)	1,968 (600)	2,988 (911)	IES	
11/09/82	3,001 (915)	1,968 (600)	4.25 (1.67)	1,774 (541)	1,968 (600)	2,992 (912)	VDS	
11/09/82	3,001 (915)	1,788 (545)	4.25 (1.67)	1,774 (541)	1,850 (564)	2,975 (907)	VSP	
11/21/82	3,001 (915)	39 (12)	12.25 (4.82)	1,674 (510)	0 (0)	1,978 (603)	CAL	MAX T = 90°F
11/21/82	3,001 (915)	39 (12)	12.25 (4.82)	1,674 (510)	1,500 (457)	1,984 (605)	DBC	
11/21/82	3,001 (915)	39 (12)	12.25 (4.82)	1,670 (509)	1,500 (457)	1,982 (604)	NBC	
11/21/82	3,001 (915)	39 (12)	12.25 (4.82)	1,670 (509)	1,500 (457)	1,979 (603)	IES	Rm = 3.1 at BHT
11/30/82	3,001 (915)	2,017 (615)	8.75 (3.44)	1,700 (518)	1,960 (597)	2,989 (911)	CAL	MAX T = 97°F
11/30/82	3,001 (915)	2,017 (615)	8.75 (3.44)	1,700 (518)	0 (0)	2,998 (914)	TEM	
11/30/82	3,001 (915)	2,017 (615)	8.75 (3.44)	1,700 (518)	--- ---	--- ---	ABC	NG
11/30/82	3,001 (915)	2,017 (615)	8.75 (3.44)	1,700 (518)	0 (0)	2,996 (913)	SPEC	

[1]U = Unknown.
[2]TEM = Temperature.
CAL = Caliper.
VSP = Vertical seismic profile.
GAM = Gamma ray.
DBC = Borehole compensated density.
ABC = Borehole compensated acoustic.
NBC = Borehole compensated Neutron.
VDS = Variable density sonic.
DIF = Dual induction focus.
IES = Induction electric survey.
SPEC = Spectral gamma ray.
[3]MAX T = Maximum temperature.
NG = No good.
Rm = Mud resistivity.
BHT = Bottom hole temperature.

The geophysical logs in the Tertiary tuffs penetrated by hole USW G-4 correlate well with logs from other holes in the Yucca Mountain area reported by Daniels and Scott (1981), Hagstrum and others (1980 a, b), Muller and Kibler (1983), and Spengler and others (1979). Physical properties measured in laboratories on core from other drill holes and reported by Anderson (1981), and Thordarson (1983), are consistent with the in-situ properties from geophysical logs in this drill hole.

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APPENDIX

Lithologic Log of USW G-4

Lithologic Log of Core Hole USW G-4

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Alluvium		
Boulder- to silt-size fragments of nonwelded to welded tuff	30(?) (9.1)	30(?) (9.1)
Paintbrush Tuff		
Tiva Canyon Member		
Tuff, ash-flow, grayish-red, densely welded, devitrified; pumice, grayish-red, medium-gray, devitrified; 2 percent phenocrysts (sanidine); rare, very light gray, rhyolitic, lithic fragments; few lithophysal cavities (open and flattened; lower contact gradational); began continuous coring at 41.0 ft (12.5 m)	30.5 (9.3)	60.5 (18.4)
Tuff, ash-flow, grayish-red, densely welded, devitrified; pumice, grayish-red, medium-gray, devitrified; 2 percent phenocrysts (sanidine); rare, very light gray, rhyolitic, lithic fragments	18.8 (5.8)	79.3 (24.2)
Tuff, ash-flow, pale-brown, densely welded, devitrified; pumice, brownish-gray, predominantly devitrified but interval contains sparse, moderate-reddish-orange pumice altered to swelling clay; 2 to 4 percent phenocrysts (sanidine and plagioclase); rare, medium-light-gray, rhyolitic, lithic fragments, commonly less than 5 mm in size	17.4 (5.3)	96.7 (29.5)
Tuff, ash-flow, pale-brown, pale-red, moderately welded, devitrified; pumice, pale-red, brownish-gray (devitrified) and abundant moderate-reddish-orange pumice altered to smectite (swelling) clay; less than 2 percent phenocrysts (sanidine and plagioclase); rare, very light gray, rhyolitic, lithic fragments, commonly less than 5 mm in size	21.3 (6.5)	118.0 (36.0)
Tuff, ash-flow, dark-yellowish-orange, partially to nonwelded, vitric; pumice, grayish-orange-pink, vitric and argillic(?); 1 to 2 percent phenocrysts (sanidine and plagioclase); abundant black and dark-yellowish-orange, glass shards	20.0 (6.1)	138.0 (42.1)
Bedded Tuff		
Tuff, ash-fall, light-brown, moderately indurated, vitric, abundant moderate-orange-pink pumice (vitric, argillic) and black glass shards (8.0 ft or 2.44 m of core lost--part of which may be part of subsequent unit)	10.0 (3.0)	148.0 (45.1)
Paintbrush Tuff--continued		
Yucca Mountain Member		
Tuff, ash-flow, pale-yellowish-brown nonwelded, vitric; pumice, grayish-orange-pink, commonly less than 2 mm in size; abundant colorless glass shards	0.8 (0.3)	148.8 (45.4)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Bedded Tuff		
Tuff, ash-fall, bedded, reworked, pale-yellowish-brown, light-olive-gray, light-brown, slightly indurated, vitric, beds predominantly composed of light-olive-gray, vitric pumice and black glass shards; rare, light-brownish-gray, rhyolitic, lithic fragments; bedding planes indistinct (gradational); thickness of beds commonly 0.1 to 2 ft (0.03-0.61 m)	19.4 (5.9)	168.2 (51.3)
Paintbrush Tuff--continued		
Pah Canyon Member		
Tuff, ash-flow, light-brown, nonwelded, vitric; pumice, yellowish-gray, light-olive-gray, dusky-yellow, vitric, commonly 1-3 cm in size; 7 percent phenocrysts (sanidine and biotite); rare, light-red, volcanic lithic fragments	19.8 (6.0)	188.0 (57.3)
Bedded Tuff		
Tuff, reworked, light-brown, poorly consolidated, vitric, well-sorted, predominantly composed of grayish-orange, vitric pumice, less than 1 mm in size; sanidine and biotite present, and light-red, volcanic lithic fragments, less than 1 mm in size; fault plane at 198.6 ft (60.5 m), crushed zone on one side of plane, amount of offset unknown, inclination of plane is 55°	11.6 (3.5)	199.6 (60.8)
Tuff, ash-fall(?), yellowish-gray to light-olive-gray, vitric, poorly consolidated, poorly sorted, predominantly composed of white-yellowish-gray to light-olive-gray pumice fragments, commonly 1-2 cm in size; black, vitrophyric, lithic fragments commonly 5-15 mm, as large as 5 cm; minor constituents are sanidine and biotite; reddish-orange clay in upper 3 ft (0.91 m); fault plane at 202.1 ft (61.6 m), truncation of pumice fragments, amount of offset unknown, plane dips 76°	28.4 (8.7)	228.0 (69.5)
Paintbrush Tuff--continued		
Topopah Spring Member		
Tuff, ash-flow, moderate-reddish-brown, nonwelded (poorly consolidated), vitric; pumice, moderate-reddish-brown, yellowish-gray, light-olive-gray, vitric; 3-4 percent phenocrysts (sanidine and biotite); rare, grayish-red, volcanic, lithic fragments (lower contact gradational)	5.4 (1.6)	233.4 (71.1)
Tuff, ash-fall, light-gray to medium-light-gray, pale-reddish-brown, moderately indurated, almost entirely composed of light-gray, medium light-gray and light-brownish-gray pumice, vitric, commonly less than 1 cm in size; less than 2 percent phenocrysts (quartz, sanidine, and plagioclase); rare grayish-red volcanic lithic fragments	5.6 (1.7)	239.0 (72.8)
Tuff, ash-flow, dark-reddish-brown, black, grayish-red, densely welded, (vitrophyre) perlitic; 15 percent phenocrysts (sanidine, plagioclase, biotite, and pyroxene); rare, very light-gray, rhyolitic, lithic fragments commonly less than 1 cm in size	3.8 (1.2)	242.8 (74.0)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Paintbrush Tuff--continued		
Topopah Spring Member--continued		
Tuff, ash-flow, brownish-gray, densely welded, devitrified (caprock); pumice, very dusky red, brownish-gray, dark-reddish-brown, devitrified (some vapor phase); slight increase in size, 5 mm to 3 cm, and abundance of vapor-phase pumice from 262.0-263.0 ft (79.9-80.2 m) and 264.6-265.5 ft (80.6-80.9 m); 12-14 percent phenocrysts (sanidine, plagioclase, and bronze biotite; lower contact gradational)	22.7 (7.0)	265.5 (81.0)
Tuff, ash-flow, light-brownish-gray, pale-red, moderately to densely welded, vapor-phase crystallization; pumice, blackish-red, yellowish-gray, predominantly vapor-phase crystallization, commonly varies in size from 5 mm to 4 cm; 7 percent phenocrysts (sanidine, plagioclase,and bronze biotite); rare, very light gray, rhyolitic, lithic fragments (lower contact gradational)	12.3 (3.7)	277.8 (84.7)
Tuff, ash-flow, grayish-red, moderately to densely welded, devitrified (caprock); pumice, grayish-red, moderate-reddish-brown, devitrified (some vapor phase), 5 mm to 2 cm; 10-15 percent phenocrysts (sanidine, plagioclase, significantly more bronze biotite than in subunit above; lower contact gradational)	2.2 (0.6)	280.0 (85.3)
Tuff, ash-flow, pale-brown, nonwelded to partially welded, vapor-phase crystallization; pumice, grayish-red, blackish-red, yellowish-gray, vapor phase, commonly 5 to 20 mm; 10-15 percent (sanidine, plagioclase, and biotite)	4.5 (1.4)	284.5 (86.2)
Tuff, ash-flow, grayish-red, moderate to densely welded, devitrified and vapor phase; pumice, pale-red, light-brown, grayish-red, light-gray, medium-light-gray, yellowish-gray; extremely large, grayish pumice, vapor-phase crystallization, distinctive foliation of pumice, commonly 1-6 cm; 11-19 percent phenocrysts (sanidine, plagioclase, and biotite); rare, very light gray rhyolitic lithic fragments, commonly 1-2 cm in size	115.9 (35.3)	400.4 (122.0)
Tuff, ash-flow, pale-red to light-brownish-gray, densely welded, devitrified; pumice, very light gray, pale-brown, devitrified, commonly 5-30 mm; 10-11 percent phenocrysts (sanidine and plagioclase); rare, very light gray, rhyolitic lithic fragments, commonly 1-2 cm; abundant (more than 10 percent) lithophysal cavities, spherical and flattened parallel to axis of core, commonly open, commonly 2-4 cm in size as large as 6 cm, (lower contact gradational)	19.6 (6.0)	420(?) (128(?))
Tuff, ash-flow, pale-red, light-brownish-gray, densely welded, devitrified; pumice, mixture of very light gray, light-gray and brownish-gray, devitrified, commonly 0.5-5 cm in size, brownish-gray pumice commonly the larger size, devitrified and some vapor-phase crystallization; 2 percent phenocrysts (sanidine and plagioclase); sparse 0-10 percent lithophysal cavities, commonly less than 3 cm in length, flattened, open; due to hole problems no core was collected from 452-470 ft (138-143 m)	50 (15)	470(?) (143)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Paintbrush Tuff--continued		
Topopah Spring Member--continued		
Tuff, ash-flow, pale-red to grayish-red, moderate-brown (mottled), densely welded, devitrified; pumice, pale-red, grayish-red, devitrified; less than 2 percent phenocrysts (sanidine and plagioclase); rare, light-gray, rhyolitic, lithic fragments; abundant (commonly greater than 20 percent, as much as 41 percent) lithophysal cavities, commonly open, cavities subrounded and flattened, in upper 50 ft (15 m) cavities are commonly less than 2 cm in size, commonly lined with feldspar, quartz; below 50 ft (15 m) cavities commonly 1-6 cm in size and have pale-red alteration rims; 4.4 ft (1.3 m) of core was recovered from 470-475 ft (143-145 m) using a globe basket (lower contact gradational)	150.0 (46)	620 (189)
Tuff, ash-flow, pale-brown, light-brown, and pale-red (mottled), moderately to densely welded, devitrified; pumice, pale-red, light-gray, devitrified, commonly less than 2 cm in size; 1 percent phenocrysts (sanidine and plagioclase); rare light-gray, rhyolitic, lithic fragments; lithophysae content ranges from 19 percent near the top to 5 percent near the base, many cavities flattened, with large alteration rims; many lithophysae are centered around pumice fragments (lower contact gradational); considerable amount of rubble in subunit probably due to drilling	60 (18)	680 (207)
Tuff, ash-flow, brownish-gray, grayish-red, and light-brown (in places, mottled), densely welded, devitrified; pumice, light-brown, commonly 0.5-3 cm, as large as 6 cm in length, devitrified, spherulitic; 1 percent phenocrysts (feldspar, plagioclase, and biotite); rare, very light gray, rhyolitic, lithic fragments, commonly less than 1 cm in size; lithophysae content ranges from 0 to 2 percent; some high-angle fractures present; in places, core is riddled with quartz-filled veinlets (high and low angle); very little broken core in unit	90 (28)	770 (235)
Tuff, ash-flow, pale-red to light-brown (mottled), densely welded, devitrified; pumice, pale-red, devitrified (some vapor phase), commonly less than 2 cm in length; 1 percent phenocrysts (sanidine and plagioclase); notable increase in amount of very light gray rhyolitic lithic fragments, commonly range in size from 0.5 to 4.0 cm, slight increase in content downward; lithophysae content is highly variable, ranging from 2 to as much as 29 percent, averaging about 13 percent, lithophysae extremely flattened with large alteration rims, commonly range from 2 to 7 cm; broken core intervals common; splintery and conchoidal fracturing common throughout interval (lower contact gradational)	357.9 (109)	1,127.9 (344)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Paintbrush Tuff--continued		
Topopah Spring Member--continued		
Tuff, ash-flow, light-brown, dark-yellowish-brown, and dark-yellowish-orange, densely welded, devitrified; pumice, commonly pale-yellowish-brown to dark-yellowish-brown, occasionally, pumice fragments have pale-yellowish-orange to dark-yellowish-orange alteration rims, commonly 8 mm to 5 cm, devitrified, spherulitic, commonly moderately to highly flattened, and foliated; 1 percent phenocrysts (sanidine, quartz, and plagioclase); sparse (less than 2 percent) very light gray, rhyolitic, lithic fragments, commonly range from 6 mm to 42 mm, as large as 6 cm; no lithophysae present except from 1,140-1,150 ft (347-350 m) and 1,180-1,190 ft 360-363 m) where the content was estimated at less than 2 percent	165.1 (50.3)	1,293.0 (394.1)
Tuff, ash-flow, dark-yellowish-brown to dark-yellowish-orange, moderately to densely welded, partially devitrified, partially argillic and zeolitic(?); pumice, light-brown, dusky-yellowish-brown, pale-yellowish-orange, dark-yellowish-orange, devitrified, zeolitic, and argillic(?), a significant proportion of pumice fragments commonly range from 1 to 5 cm; approximately 2 percent phenocrysts (sanidine, quartz, and plagioclase); sparse, very light gray, rhyolitic, lithic fragments, commonly range in size from 5 mm to as large as 84 mm; fault zone with moderate to intense alteration (smectite?) along near vertical fault plane present at 1,313.9-1,315.2 ft (400.5-400.9 m)		
Tuff, ash-flow, dark-gray to black, densely welded, vitrophyre; pumice, black, glassy; 1 percent phenocrysts (sanidine, quartz, and plagioclase); sparse, very light gray, rhyolitic, lithic fragments, commonly 4 mm to 18 mm, occasionally as large as 3 cm; unit is moderate-olive-brown and contains light-brown pumice fragments that are moderately altered from 1,318.7 to 1,319.7 ft (401.9-402.2 m); unit contains several near-vertical, silica coated, fractures (conchoidal microfractures common; lower contact gradational); fault zone with moderate to intense alteration (smectite?) along near vertical fault plane present at 1,318.4 to 1,320.0 ft (401.8-402.3 m); 2.0 ft (0.61 m) or more of displacement along fault zone as indicated by core sample at 1,318.7 ft (401.9 m)	28.9 (8.8)	1,345.4 (410.1)
Tuff, ash-flow, dark-gray, moderately welded, vitric; pumice, light-brown to brownish-black, vitric, commonly 5-15 mm; 1 percent phenocrysts (sanidine, quartz, and plagioclase); abundant black glass shards; rare, very light gray, rhyolitic, lithic fragments, commonly less than 1.5 mm in size; near vertical fractures cut entire interval (lower contact gradational)	8.2 (2.5)	1,353.6 (412.6)
Tuff, ash-flow, black and light-brown, vitric, partially welded (welding decreases downward); pumice, light-brown and brownish-black, vitric; 1 percent phenocrysts (sanidine, quartz, and plagioclase); rare, very light gray and pale-red, rhyolitic, lithic fragments, commonly less than 12 mm in size, as large as 6 cm (lower contact gradational)	14.7 (4.5)	1,368.3 (417.1)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Paintbrush Tuff--continued		
Topopah Spring Member--continued		
Tuff, ash-flow, moderate-brown, nonwelded, vitric; pumice, black and light-brown, vitric, commonly varies in size from 5 to 26 mm; 1 percent phenocrysts (sanidine, quartz, and plagioclase); abundant black glass shards; sparse light-brownish-gray, medium-light-gray, and brownish-gray, rhyolitic, lithic fragments, vary in size from 0.5 to 3.8 cm	9.5 (2.9)	1,377.8 (20.0)
Tuff, ash-flow, light-brown and grayish-orange-pink, partially welded, zeolitized(?); pumice, light-brownish and pale-yellowish-orange, zeolitic, commonly less than 1 cm in size; 1 percent phenocrysts (sanidine and plagioclase); abundant (3-30 percent of rock) brownish-gray, grayish-red, greenish-gray, rhyolitic and vitrophyric, lithic fragments, vary in size from 0.5 cm to as large as 8 cm, many fragments greater than 2 cm in length (lower contact gradational)	10.1 (3)	1,387.9 (423.0)
Tuff, ash-flow, grayish-orange-pink, nonwelded, partly vitric and partly zeolitic, interval from 1,388.7 to 1,390.5 ft (423.3-423.8 m) dominantly vitric, whereas remainder of interval is dominantly zeolitic (principally clinoptilolite); pumice, very pink orange, grayish-orange-pink, and moderate-yellow, mainly zeolitic, some vitric, commonly range in size from 3 to 20 mm, as large as 42 mm; 1 percent phenocrysts (sanidine, quartz, plagioclase, and biotite); sparse (2-3 percent) volcanic lithic fragments, grayish-brown, brownish-gray, medium-light-gray, rhyolitic and vitrophyric, commonly less than 1 cm in size, a few as large as 4 cm; fault plane cutting core from 1,405.8 to 1,406.8 ft (428.5-428.6 m), fault zone about 2-cm thick, contains silicified breccia, inclined about 72°	18.9 (5.8)	1,406.8 (428.8)
Bedded Tuff		
Tuff, reworked, ash-fall, light-brown, pale-red and light-gray, moderately indurated, zeolitic; dominantly composed of pumice fragments, white to light-gray, and light-brownish-gray, zeolitic, subrounded, commonly less than 5 mm in size, thicknesses of beds are 1.4 and 1.2 ft (0.4 and 0.4 m)	2.6 (0.8)	1,409.4 (429.6)
Rhyolite Lavas and Tuffs of Calico Hills		
Tuffaceous beds of Calico Hills		
Tuff, ash-flow, moderate-orange-pink, moderate-reddish-orange, and light-brown, nonwelded, vitric (slightly zeolitic); pumice, grayish-orange, very pale orange, yellowish-gray, and medium-light-gray, dominantly vitric, commonly range from 0.5 to 5 cm, as large as 11 cm, larger pumice fragments occur in upper 4 ft (1.2 m) of unit; less than 2 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); sparse grayish-red rhyolitic and grayish-black to medium gray, slightly altered, vitrophyric lithic fragments, commonly range in size from 3 to 35 mm; higher concentration of lithics in lower 6.5 ft (2.0 m) of unit	15.1 (4.6)	1,424.5 (434.2)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Rhyolite Lavas and Tuffs of Calico Hills--continued		
Tuffaceous beds of Calico Hills--continued		
Tuff, bedded, reworked, moderate-orange-pink, pale-red, and grayish-orange-pink, moderately to highly indurated, zeolitic; dominantly composed of pumice, grayish-orange-pink and grayish-orange, zeolitic, subrounded, commonly less than 5 mm; abundant grayish-red rhyolitic lithic fragments, commonly less than 2 mm in size; individual beds range from 0.1 to 0.8 ft (0.03-0.2 m)	1.8 (0.5)	1,426.3 (434.7)
Tuff, ash-flow, grayish-orange, grayish-orange-pink, and moderate-reddish-orange, nonwelded, zeolitic, pumice, very pale orange, grayish-orange-pink, moderate-orange-pink, and yellowish-gray, zeolitic, commonly range from 3 to 35 mm, but as large as 5 cm; less than 2 percent phenocrysts (quartz, sanidine, and plagioclase); rare medium-dark-gray and brownish-gray rhyolitic lithic fragments, commonly less than 5 mm, occasionally as large as 5 cm, larger fragments are commonly slightly altered vitrophyric fragments	20.7 (6.3)	1,447.0 (441.0)
Tuff, reworked, ash-fall, bedded, light-brown, pale-red, grayish-orange-pink, and moderate-orange-pink, moderately indurated, zeolitic and, in places, silicified; dominantly composed of pumice fragments having similar colors to those listed above, pumice commonly less than 1 cm in size, zeolitic; subordinate amounts of brownish-gray and medium-gray rhyolitic lithic fragments, less than 1 cm in size; individual beds range in thickness from a few cm to 2.2 ft (0.67 m); where well defined, bedding planes are inclined 5-6°	9.5 (2.9)	1,456.5 (443.9)
Tuff, ash-flow, moderate-orange-pink, grayish-orange-pink, light-brown, grayish-orange, and dusky-yellow, nonwelded zeolitic (dominantly clinoptilolite); pumice, very pale orange, pale-red, moderate-pink, grayish-orange-pink, yellowish-gray, grayish-yellow, grayish-orange, zeolitic, commonly range from 0.2 to 4.5 cm; 1-3 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); rare to sparse moderate-brown and grayish-red rhyolitic lithic fragments, commonly less than 2 cm in size, slight increase in amount of lithics in lower 11 ft (3.4 m) of unit; fault plane with slickensides present from 1,556.4 to 1,557.2 ft (474.4-474.6 m), inclined 77°	104.1 (31.8)	1,560.6 (475.7)
Tuff, ash-fall and reworked, moderate-orange-pink and grayish-orange, moderately indurated, zeolitic; dominantly composed of pumice, grayish-yellow, grayish-orange-pink, dusky-yellow, and very pale orange, zeolitic, commonly less than 2 cm in size, subangular to subrounded, poorly sorted; subordinate amounts (10-20 percent) of volcanic lithic fragments, grayish-red, dark-gray, and medium-light-gray, subangular to subrounded, poorly sorted, range in size from 1 to 23 mm; lower 1.5 ft (0.5 m) of unit contains minor amounts of lithics; individual beds range in thickness from 0.2 to 1.0 ft (0.1-0.30 m)	3.3 (1.0)	1,563.9 (476.7)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Rhyolite Lavas and Tuffs of Calico Hills--continued		
Tuffaceous beds of Calico Hills--continued		
Tuff, ash-flow, grayish-orange, light-brown, and moderate-reddish-orange, and, in places, dark-yellowish-brown, nonwelded, zeolitic (principally clinoptilolite and mordenite); pumice, very pale orange, grayish-yellow, dusky-yellow, moderate-greenish-yellow, zeolitic, commonly range in size from 3 to 31 mm, as large as 57 mm; 1-2 percent phenocrysts (quartz, sanidine, and plagioclase); sparse (1-2 percent) rhyolitic lithic fragments, brownish-gray and brownish-black, commonly less than 1 cm in size; ash-fall parting, 1-cm thick, present at 1,606.8 ft (489.8 m), inclined 7°; fault plane present from 1,631.1 to 1,631.5 ft (497.2-497.3 m), slight offset in pumice fragments inclined 77°; shear fracture with slickensides present from 1,634.0 to 1,634.2 ft (498.0-498.1 m); ash-fall parting, 6.3 cm in thickness present from 1,662.2 to 1,662.4 ft (506.6-506.7 m)	99.1 (30.2)	1,663.0 (506.9)
Tuff, ash-fall, moderate-orange-pink and moderate-reddish-brown, moderately to highly indurated, lower 3 cm of unit slightly silicified(?) zeolitic; dominantly composed of grayish-pink to moderate-orange-pink, zeolitic, pumice fragments, subangular to subrounded, commonly less than 5 mm in size; rare grayish-red volcanic lithic fragments, commonly 1-3 mm in size; dominantly gradational bedding	0.4 (0.1)	1,663.4 (507.0)
Tuff, ash-flow, moderate-orange-pink, light-brown, nonwelded, zeolitic; pumice, very pale orange, pale-yellowish-orange, and grayish-yellow, zeolitic, commonly range in size from 2 to 38 mm; 1-3 percent phenocrysts (sanidine, plagioclase, quartz, and biotite); sparse brownish-gray and brownish-black volcanic lithic fragments, commonly less than 5 mm in size; shear fracture with slickensides present at 1,670.8-1,671.4 ft (509.36-509.4 m)	42.0 (12.8)	1,705.4 (519.8)
Tuff, ash-fall, reworked, tuffaceous sandstone, grayish-yellow, yellowish-gray, light-brown, greenish-gray, moderate-reddish-brown, dusky-yellow, pale-yellowish-brown, grayish-yellow, zeolitic (in places, silicified), moderately to highly indurated; pumice, moderate-orange-pink, grayish-pink, very pale orange, pale-greenish-yellow, and grayish-yellow, zeolitic, commonly less than 5 mm in size; sparse to abundant brownish-black, brownish-gray, and medium-gray rhyolitic lithic fragments, commonly less than 5 mm in size; individual beds range in thickness from a few cm to 5 ft (1.52 m); numerous silicified beds are present from 1,705.4 to 1,708.1 ft (519.8-520.6 m); basal part of unit, from 1,759.1 to 1,761.4 ft (536.2-536.9 m) consists of well sorted, pale-yellowish-brown to dark-yellowish-brown tuffaceous sandstone, abundant biotite, individual beds range from 0.5 to 8.5 cm thick	55.9 (17.0)	1,761.4 (536.9)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff		
Prow Pass Member		
Tuff, ash-flow, pale-brown, nonwelded, zeolitic; pumice, pale-yellowish-orange, moderate-pink, and grayish-orange-pink, zeolitic, argillic, commonly 0.2-2 cm; 5-8 percent phenocrysts (quartz, sanidine, plagioclase, and biotite; rare grayish-red volcanic lithic fragments	1.1 (0.3)	1,762.5 (537.2)
Tuff, ash-flow, pale-reddish-brown, intensely altered to zeolites, original pyroclastic texture almost completely destroyed	1.8 (0.6)	1,764.3 (537.8)
Tuff, ash-flow, yellowish-gray to light-olive-gray, nonwelded, moderately to highly zeolitic, contains montmorillonite, alteration decreases downward; pumice, grayish-yellow, pale-greenish-gray, grayish-orange-pink, zeolitic and argillic; 7-10 percent phenocrysts (sanidine, quartz, plagioclase, biotite, and pyroxene(?) pseudomorphs); rare brownish-black volcanic and moderate-reddish-brown mudstone lithic fragments, commonly less than 3 mm in size (argillic parting at lower contact)	13.3 (4.0)	1,777.6 (541.8)
Tuff, ash-flow, light-brown, nonwelded, devitrified (slightly zeolitic(?) and argillic); pumice, grayish-orange, pale-yellowish-brown, slightly argillic(?), devitrified, commonly less than 8 mm in size; 7-9 percent phenocrysts (quartz, sanidine, plagioclase, biotite, and pyroxene (?) pseudomorphs); rare grayish-red rhyolitic and moderate-reddish-brown mudstone lithic fragments, commonly less than 5 mm in size	9.3 (2.8)	1,786.9 (544.6)
Tuff, ash-flow, light-brown, and black (mottled), nonwelded, slightly to moderately argillic (increase in alteration relative to unit above); pumice, very pale orange, grayish-orange, light-brown, devitrified, argillic, 0.2-3 cm, size of pumice fragments increases to as large as 4 cm in lower 1.9 ft (0.6 m) of unit; 7-9 percent phenocrysts (quartz, sanidine, plagioclase, biotite, and pyroxene(?)); rare grayish-red rhyolitic and moderate-reddish-brown mudstone lithic fragments, commonly less than 5 mm in size, as large as 1 cm	5.5 (1.7)	1,792.4 (546.3)
Tuff, ash-flow, pale-brown, and light- to medium-gray below a parting at 1,793.6 ft (546.8 m), nonwelded, vapor-phase crystallization; pumice, pale-yellowish-brown and light- to medium-gray, vapor-phase crystallization (upper 1.2 ft, 0.4 m), slightly argillic, commonly range in size from 0.2 to 2.5 cm; size noticeably decreases in lower 0.5 ft (0.2 m) of unit; 7-9 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); are moderate-reddish-orange mudstone lithic fragments, commonly less than 2 mm in size; possible shear fracture (abrupt termination of pumice fragments at 1,793.1 ft (546.5 m)	3.7 (1.1)	1,796.1 (547.4)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued		
Prow Pass Member--continued		
Tuff, ash-flow, grayish-orange-pink in upper 10 ft (3 m) of unit, grading downward into light-gray, and medium-light-gray, and light-brownish-gray, partially welded, vapor-phase crystallization; pumice, light-brown, moderate-brown, pale-yellowish-brown, light-gray and medium-light-gray, vapor-phase crystallization dominant (devitrified), commonly less than 1 cm in size; 9 percent phenocrysts (quartz, sanidine, plagioclase, bronze biotite, and pyroxene(?)); rare to sparse moderate-reddish-brown mudstone lithic fragments and brownish-black rhyolitic lithic fragments, commonly less than 5 mm in size (shear fracture with slickensides at 1,796.9 ft or 547.7 m), high-angle fractures with pale-reddish-brown iron oxide(?) staining cut core from 1,852.1 to 1,856.6 ft (564.5-565.9 m); below 1,856.3 ft (565.8 m) opaques (iron oxides(?)) are concentrated in a significant proportion of pumice fragments (lower contact gradational)	74.2 (22.7)	1,870.3 (570.1)
Tuff, ash-flow, light-brownish-gray grading downward into pale-yellowish-brown, partially welded (slight increase in welding relative to unit above), devitrified; pumice, very pale orange to grayish-orange-pink, devitrified (and vapor-phase crystallization), vapor-phase crystallization common in upper 24 feet (7.3 m) and decreases downward; black opaques (iron and (or) manganese oxides concentrated in a significant portion of pumice fragments in upper 15 ft (4.57 m) of unit; pumice fragments noticeably larger than in previous unit, commonly range in size from 0.5 to 2.5 cm, as large as 6.5 cm; 10-13 percent phenocrysts (quartz, sanidine, plagioclase, biotite, hornblende or pyroxene pseudomorphs; pseudomorphs have a noticeable pale-reddish-brown oxidation halo surrounding them); sparse (1-2 percent) moderate-reddish-brown mudstone lithic fragments, commonly less than 0.4 cm in size, as large as 2.0 cm; shear fractures present at 1,894.4-1,898.0 ft (577.4-578.5 m) and 1,910.5-1,911.7 ft (582.3-582.7 m); fault plane indicated by abrupt termination of pumice fragments, cuts core from 1,921.0 to 1,925.4 ft (585.5-586.9 m), slickensides observed along portions of fault	58.1 (17.7)	1,928.4 (587.8)
Tuff, ash-flow, light-brownish-gray and light-olive-gray, stained light-red near fractures (1,946.8-1,949.4 ft (593.4-594.2 m); and 1,951.0-1,954.0 ft (594.7-595.6 m), partially welded, devitrified (slightly argillic(?)), increase in amount of alteration relative to unit above, alteration progressively increases downward to base of unit; pumice, very light gray, light-olive-gray, devitrified (some vapor-phase crystallization), 10-12 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); sparse (1-2 percent) moderate-reddish-brown mudstone lithic fragments, commonly less than 0.4 cm, as large as 1.5 cm; shear fractures present at 1,934.1 ft (589.51 m) and 1,940.1-1,954 ft (591.3-596 m); abrupt contact with lower unit but no apparent ash-fall parting	26.2 (8.0)	1,954.6 (595.8)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued		
Prow Pass Member--continued		
Tuff, ash-flow, grayish-orange-pink, moderate-orange-pink, light-olive-gray, nonwelded to partially welded, moderately to highly zeolitic (clinoptilolite/mordenite); pumice, very pale orange, grayish-pink, moderate-pink, moderate-orange-pink, pale-yellowish-orange, zeolitic, commonly range in size from 0.2 to 2.0 cm, as large as 3.0 cm; 9 percent phenocrysts (quartz, sanidine, plagioclase, biotite,and pyroxene pseudomorphs(?)); 2-4 percent lithic fragments, dominantly moderate-reddish-brown mudstone, minor grayish-red volcanic lithics, commonly 0.2-2.0 cm, as large as 3.3 cm; very thin clay parting at 1,978.4 ft (603.02 m); shear fracture present at 1,956.0-1,956.9 ft (596.2-596.5 m), fault with breccia along plane at 1,990.2-1,992.1 ft (606.6-607.2 m); abruptly gradational contact occurring within an interval of about 5 cm, but no ash-fall parting present	95.7 (29.1)	2,050.3 (624.9)
Tuff, ash-flow, yellowish-gray, pale-olive, moderate-greenish-yellow, pale-yellowish-brown, grayish-orange, partially welded, devitrified, intensely zeolitic (clinoptilolite/mordenite), slightly to moderately silicified; pumice, dominantly light-brown and grayish-orange, pale-yellowish-orange, moderate-yellowish-brown, and grayish-yellow, zeolitic, commonly range in size from 0.5 to 3.5 cm, as large as 6.5 cm; 9-10 percent phenocrysts (quartz, sanidine, plagioclase,and pyroxene pseudomorphs(?)); rare (1-2 percent) lithic fragments, dominantly dark-reddish-brown and light-brown mudstone, subordinate grayish-red and light-brown rhyolitic, commonly range in size from 0.2 to 2.0 cm; moderately to highly indurated from 2,068.6 to 2,101.3 ft (630.5-640.5 m), 2,102.5-2,116.0 ft (640.8-643.7 m), 2,121.3-2,129.9 ft (646.6-649.2 m)	142.3 (43.4)	2,192.6 (668.3)
Tuff, ash-flow, moderate-greenish-yellow, stained moderate-orange-pink in places, nonwelded, intensely zeolitic (clinoptilolite/mordenite); pumice, moderate-greenish-yellow, grayish-yellow, pale-greenish-yellow, zeolitic, commonly range in size from 0.5 to 3.5 cm, as large as 6.5 cm, noticeable increase in abundance of larger pumice fragments relative to unit above; 11 percent phenocrysts (quartz, sanidine, plagioclase, biotite, hematite and/or magnetite); sparse (2-3 percent) grayish-red mudstone and grayish-red and medium-light-gray rhyolitic lithic fragments	24.0 (7.3)	2,216.6 (675.6)
Tuff, ash-flow, moderate-orange-pink, moderate-greenish-yellow (mottled), nonwelded, highly zeolitic (clinoptilolite/mordenite), and slightly argillic, intensity of alteration increases downward to base of unit; pumice, pale-greenish-yellow to moderate-greenish-yellow, grayish-yellow, rarely grayish-pink, highly zeolitic and argillic, commonly range from 0.3 to 2.0 cm; lower 7.7 ft (2.4 m) contain numerous, highly altered, pumice fragments, commonly range from 3 to 5 cm; 7 percent phenocrysts (quartz, sanidine, and plagioclase); sparse (2-3 percent) mudstone lithic fragments moderate-reddish-brown, grayish-red, moderate-olive-brown with subordinate rhyolitic lithic fragments, blackish-red, grayish-red, and medium gray	20.9 (6.4)	2,237.5 (682.0)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Bedded Tuff		
Tuff, bedded, ash-fall, reworked, upper 1.6 ft (0.5 m) consists of tuffaceous siltstone and very fine grained tuffaceous sandstone, lower 4.6 ft (1.4 m) consists of ash-fall and reworked tuff, grayish-orange, moderate-reddish-orange, grayish-yellow, moderate-greenish-yellow, and moderate-reddish-brown; slightly to moderately zeolitic; thickness of bedding ranges from a few centimeters to 3.2 ft (1.0 m); base of unit marked by a fault	6.7 (2.0)	2,244.2 (684.0)
Crater Flat Tuff-continued		
Bullfrog Member		
Tuff, ash-flow, pale-red, light-gray, grades downward into grayish-orange-pink to pale-yellowish-brown, partially welded, devitrified; pumice, moderate-pink and pale-red in upper 6.0 ft (1.8 m) of unit, grades downward into very pale orange, light-brown, pale-yellowish-brown, and grayish-orange, devitrified, commonly 0.2-1.5 cm in size; 14 percent phenocrysts (sanidine, quartz, plagioclase, hornblende, and biotite); very rare (less than 1 percent) grayish-red and blackish-red rhyolitic lithic fragments, occasional moderate-reddish-brown mudstone lithic fragments, commonly range in size from 0.4 to 1.1 cm, as large as 6.0 cm; fault zone from 2,244.2 to 2,248.1 ft (684.0-685.2 m), truncation of pumice fragments along fracture, interval moderately altered, appears to contain fragments of reworked tuff; fault plane dips 73° relative to axis of core; shear fractures present at 2,250.1 and 2,251.5 ft (685.8 and 686.3 m); lower contact gradational	22.3 (6.8)	2,266.5 690.8)
Tuff, ash-flow, pale-yellowish-brown grades downward to light-brownish-gray and light-olive-gray, partially welded, devitrified; pumice, light-brownish-gray, light-olive-gray, and yellowish-gray, devitrified (occasional vapor-phase crystallization), commonly less than 1.6 cm in size; 12 percent phenocrysts (quartz, sanidine, plagioclase, hornblende pseudomorphs, and biotite), noticeable decrease in biotite relative to unit above; very rare (less than 1 percent) lithic fragments of grayish-red mudstone and pale-brown, grayish-red rhyolite, commonly 0.4-0.9 cm, as large as 2.2 cm; shear fractures occur at 2,278.3 and 2,279.2 ft (694.4 and 694.7 m); lower contact gradational	26.5 (8.1)	2,293.0 (698.9)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued Bullfrog Member--continued Tuff, ash-flow, grayish-orange-pink, pale-yellowish-brown, partially welded, devitrified (vapor-phase crystallization); pumice, light-brownish-gray, pale-yellowish-brown, pale-red, and medium-gray, vapor-phase crystallization dominant, commonly less than 1.5 cm, as large as 7 cm; 16-17 percent phenocrysts (quartz, sanidine, plagioclase, hornblende, pseudomorphs(?), and bronze biotite), first occurrence where bronze biotite is dominant type of biotite; very rare (less than 1 percent) lithic fragments, commonly grayish-red, black, and brownish-gray rhyolite, subordinate moderate reddish-brown mudstone, commonly range from 0.5 to 0.7 cm in size, conspicuous near-vertical shear fracture extending along core from 2,342.0 to 2,345.7 ft (713.8-715.0 m), in places aperture along fracture is as wide as 0.5 cm; lower contact gradational	77.0 (23.5)	2,370.0 (722.4)
Tuff, ash-flow, pale-yellowish-brown to pale-brown, moderately welded, devitrified (some vapor-phase crystallization); pumice, pale-brown, pale-red, and medium-gray, devitrified (subordinate vapor-phase crystallization), commonly range in size from 0.5 to 2.5 cm, as large as 7.5 cm; 15-16 percent phenocrysts (quartz, sanidine, plagioclase, biotite, and hornblende pseudomorphs(?)); very rare (less than 1 percent) blackish-red and light-brown lithic fragments of silicic to intermediate lava, many are cognate, commonly range in size from 0.4 to 2.2 cm; lower contact abruptly gradational	27.8 (8.4)	2,397.8 (730.8)
Tuff, ash-flow, grayish-orange-pink, light-olive-gray, grades downward into very light gray, partially welded, devitrified vapor-phase crystallization; pumice, light-gray, medium-light-gray, medium-gray, grades downward into light-brownish-gray and brownish-gray, vapor-phase crystallization dominant, commonly range in size from 0.4 to 2.4 cm, as large as 6.5 cm; 16-17 percent phenocrysts (sanidine, quartz, plagioclase, and biotite); very rare (less than 1 percent) lithic fragments, pale-yellowish-brown, brownish-gray, and pale-brown, silicic to intermediate lava, and mudstone, commonly range in size from 0.7 to 1.8 cm; near-vertical shear fractures occur from 2,438.5 to 2,442.6 ft (743.2-744.5 m), and from 2,445.1 to 2,446.5 ft (745.3-745.7 m)	130.65 (39.9)	2,528.4 (770.7)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued		
Bullfrog Member--continued		
Tuff, ash-fall interbedded with ash-flow(?), very light gray, well indurated, devitrified; much of interval contains abundant medium-light-gray and light-brownish-gray pumice fragments, poorly sorted, devitrified, commonly range in size from 0.4 to 2.5 cm, as large as 6 cm; noticeably foliated; foliation either due to welding or compaction; phenocryst content varies from 10 to as much as 30 percent; rare (1-3 percent) lithic fragments, olive-gray, pale-brown, grayish-red, and moderate-reddish-brown, dominantly mudstone, but intermediate lava and tuffaceous fragments also present, commonly range in size from 0.4 to 2.3 cm, as large as 6.5 cm; slight increase in amount of lithics in lower 1.0 ft (0.3 m) of interval, well sorted, very thin (1-1.5 cm) ash-fall beds at 2,528.45 ft (770.67 m) and 2,528.8 ft (770.78 m)	5.6 (1.7)	2,534.1 (772.4)
Tuff, ash-flow, light-brownish-gray, and grayish-orange-pink, nonwelded, devitrified; pumice, medium-light-gray, yellowish-gray, light-brownish-gray to brownish-gray, devitrified, commonly range in size from 0.7 to 1.7 cm; 10 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); rare (1 percent) lithic fragments, grayish-orange, brownish-gray, dominantly silicic to intermediate lavas, and minor mudstone, commonly range in size from 0.5 to 1.8 cm; lower contact gradational	24.9 (7.6)	2,559.0 (780.0)
Tuff, ash-flow, pale-yellowish-brown to pale-brown, and light-brown, partially welded, devitrified; pumice, pale-yellowish-brown and pale-brown, devitrified, commonly range in size from 0.3 to 3.0 cm; 9-12 percent phenocrysts (quartz, sanidine, plagioclase, black biotite, and hornblende pseudomorphs); sparse (2-3 percent) lithic fragments, dark-reddish-brown, brownish-gray, dark-yellowish-brown, moderate-brown, dominantly silicic, subordinate intermediate lava and mudstone lithic fragments, commonly range in size from 0.2 to 1.6 cm; prominent near-vertical shear fracture from 2,563.1 to 2,571.4 ft (781.2-783.8 m); lower contact gradational	22.8 (6.9)	2,581.8 (786.9)
Tuff, ash-flow, moderate-yellowish-brown, pale-yellowish-brown, moderate-brown, moderately to densely welded, devitrified; pumice, light-brown, pale-yellowish-brown, pale-yellowish-orange, and grayish-orange, devitrified and zeolitic, commonly range in size from 0.2 to 2.6 cm, as large as 4.9 cm, eutaxitic structure, moderately well developed; 9 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); rare (1-2 percent) lithic fragments, dark-gray, grayish-brown, moderate-brown, dark-reddish-brown, dominantly rhyolitic lavas, subordinate mudstone, commonly range in size from 0.2 to 1.8 cm, as large as 4.0 cm; shear fracture from 2,654.1 to 2,656.0 ft (809.0-809.6 m); two low-angle, manganese-oxide-coated fractures with a spacing of 0.3 to 1.1 cm marks base of interval	98.5 (30.1)	2,680.3 (817.0)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued		
Bullfrog Member--continued		
Tuff, ash-flow, dark-yellowish-orange, light-brown, partially welded, poorly indurated, moderately argillic (montmorillonite and illite); pumice, dark-yellowish-brown, light-brown, altered to swelling clay, commonly 0.2-5.5 cm; 9-10 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); sparse (1-2 percent) lithic fragments, light-brownish-gray, dark-gray, light-brown, dominantly silicic lavas, some mudstone, commonly range in size from 0.2 to 1.0 cm, as large as 1.7 cm; lower contact gradational	15.3 (4.6)	2,695.6 (821.6)
Tuff, ash-flow, moderate-reddish-orange, light-brown, and pale-reddish-brown, partially welded, devitrified, moderately zeolitic (mordenite) highly indurated; pumice, pale-reddish-brown, moderate-reddish-orange, light-brown, moderate-brown, moderate-yellowish-green, grayish-orange, devitrified, zeolitic, commonly range in size from 0.4 to 3.5 cm, as large as 6.0 cm; 9 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); rare (1 percent) lithic fragments, moderate-brown, grayish-red, dominantly rhyolitic, sparse mudstone, commonly range in size from 0.3 to 1.4 cm; lower contact gradational	31.2 (9.5)	2,726.8 (831.1)
Tuff, ash-flow, light-brown, grayish-orange-pink, nonwelded, devitrified (slightly zeolitic); pumice, very pale orange, grayish-orange, grayish-yellow, light-brown, devitrified (slightly zeolitic(?)), commonly range in size from 0.2 to 4.0 cm; 9-10 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); rare (1 percent) lithic fragments, grayish-red, blackish-red, pale-brown, dominantly rhyolitic lavas, commonly range in size from 0.3 to 0.8 cm	6.5 (2.0)	2,733.3 (833.1)
Bedded Tuff		
Tuff, ash-fall, reworked, moderate-pink, moderate-reddish-brown, dusky-yellow, pale-yellowish-brown, light-brown, moderate-brown, moderately indurated, in places slightly argillic and slightly zeolitic (mordenite/clinoptilolite), moderately sorted, most beds dominantly composed of pumice fragments, subangular to subrounded, commonly less than 0.6 cm in size; individual beds range in thickness from a few centimeters to 2.0 ft (0.61 m), most contacts gradational; thin clay parting at 2,754.9 ft (839.7 m) and at base of interval	22.3 (6.8)	2,755.6 (839.9)
Crater Flat Tuff--continued		
Tram Member		
Tuff, ash-flow, pale-reddish-brown, grades downward into pale-brown, lower 0.4 ft (0.12 m), pale-reddish-brown, nonwelded, devitrified; pumice, very pale orange, grayish-orange, pale-yellowish-orange, devitrified (slightly zeolitic(?) and argillic), noticeably narrow size range from 0.2 to 0.8 cm, as large as 4.5 cm; 9-10 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); rare (1-2 percent) lithic fragments, grayish-red, light-gray, moderate-brown, and dusky-brown, dominantly rhyolitic lavas, commonly 0.2-1.7 cm in size, as large as 4.5 cm	5.1 (1.6)	2,760.7 (841.5)

Stratigraphic and lithologic description	Thickness of interval feet (meters)	Depth to bottom of interval feet (meters)
Crater Flat Tuff--continued		
Tram Member--continued		
Tuff, ash-flow, light-brown, partially welded, devitrified; pumice, very pale orange, light-brown, moderate-orange-pink, devitrified, commonly less than 1 cm in size; 9-10 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); very rare grayish-red rhyolitic lava lithic fragments, 0.3-1.0 cm in size; base of interval marked by 3 cm of ash-fall tuff(?)	1.6 (0.5)	2,762.3 (842.0)
Tuff, ash-flow, light-brown, nonwelded to partially welded, devitrified, moderately zeolitic (mordenite/clinoptilolite); pumice, very pale orange, grayish-orange and light-brown, devitrified, zeolitic, commonly range in size from 0.1 to 0.8 cm, rarely as large as 1.3 cm; 8-9 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); very rare (less than 1 percent) lithic fragments, grayish-red, moderate-brown, grayish-brown, and medium-light-gray, dominantly silicic lava, commonly range in size from 0.2 to 1.8 cm, rarely as large as 5.5 cm	47.7 (14.5)	2,810.0 (856.5)
Tuff, ash-flow, grayish-orange-pink, light-brownish-gray (lower 1.5 ft or 0.46 m, pale-red), nonwelded to partially welded, devitrified, moderately zeolitic (mordenite/clinoptilolite); pumice, very pale orange, moderate-yellowish-brown, grayish-orange, light-gray, very light gray, devitrified, commonly 0.2-2.5 cm, as large as 6 cm; 12-14 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); sparse (1-3 percent) lithic fragments, light-brown, dark-gray, moderate-brown, silicic to intermediate lava, commonly 0.2-2.0 cm in size	31.1 (9.5)	2,841.1 (866.0)
Tuff, ash-flow, light-brownish-gray, light-olive-gray, and grayish-orange-pink, upper 4.8 ft (1.46 m) mottled, pale-red, moderate-red, and light-brownish-gray, devitrified; pumice, grayish-orange, very pale orange, light-brownish-gray, very light gray, light-gray, yellowish-gray, dominantly vapor-phase crystallization, commonly range in size from 0.2 to 1.7 cm, as large as 3.5 cm; 9-11 percent phenocrysts (quartz, sanidine, plagioclase, and black biotite); sparse (1-3 percent) lithic fragments, light-brownish-gray, brownish-gray, brownish-black, medium-dark-gray, moderate-red, light-brown, silicic to intermediate lava, commonly range in size from 0.2 to 2.5 cm; prominent shear fractures at 2,904.5 ft (885.3 m), 2,913.2 ft (887.9 m), 2,919.6-2,924.2 ft (889.9-891.3 m), 2,929.7-2,931.7 ft (893.0-893.6 m); 2,933.0-2,934.4 ft (894.0-894.4 m), and 2,985.2-2,989.4 ft (909.9-911.2 m)	157.7 (48.0)	2,998.8 (914.0)
Tuff, ash-flow, light-brownish-gray, moderately welded, devitrified; pumice, very light gray, light-gray, and light-brownish-gray, devitrified, 0.3-1.5 cm, as large as 4.0 cm; 12 percent phenocrysts (quartz, sanidine, plagioclase, and biotite); rare (1-2 percent) lithic fragments, brownish-gray, light-brown, grayish-red, silicic to intermediate lava, commonly range in size from 0.2 to 1.0 cm; prominent shear fracture occurs at 3,000.1 ft (914.4 m)	2.2 (0.7)	3,001.0 914.7
	TOTAL DEPTH 914.7	3,001.0