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Geology in the Vicinity of the TYBO and BENHAM Underground Nuclear Tests, Pahute Mesa, Nevada Test Site

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December 2001

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ABSTRACT

Recent radiochemical evidence from groundwater characterization and monitoring wells in the vicinity of the TYBO and BENHAM underground nuclear tests in Area 20 of the Nevada Test Site, suggests that migration of radionuclides within groundwater beneath this portion of Area 20 may be more rapid than previously thought. In order to gain a better understanding of the hydrogeologic conditions in the TYBO-BENHAM area for more accurate flow and transport modeling, a reevaluation of the subsurface geologic environment in the vicinity of the two underground tests was conducted. Eight existing drill holes provided subsurface control for the area. These holes included groundwater characterization and monitoring wells, exploratory holes, and large-diameter emplacement holes used for underground nuclear weapons tests. Detailed and consistent geologic descriptions of these holes were produced by updating existing geologic descriptions with data from petrographic, chemical, and mineralogic analyses, and current stratigraphic concepts of the region. The updated descriptions, along with surface geologic data, were used to develop a detailed geologic model of the TYBO-BENHAM area. This model is represented by diagrams that correlate stratigraphic, lithologic, and alteration intervals between holes, and by isopach and structure maps and geologic cross sections. Regional data outside the TYBO-BENHAM area were included in the isopach and structure maps to better evaluate the geology of the TYBO-BENHAM area in a regional context. The geologic model was then evaluated with regard to groundwater flow and radionuclide migration to assess the model's implications for flow and transport modeling. Implications include: 1) confirmation of the general hydrogeology of the area described in previous studies; 2) the presence of two previously unrecognized buried faults that could act as zones of enhanced permeability within aquifers; and 3) secondary alteration within tuff confining units that is much more complex than previously described.

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List of Acronyms and Abbreviations

$^{40}Ar/^{39}Ar$	argon-40/argon-39 (age-dating technique)
cm	centimeter
DOE	U.S. Department of Energy
DOE/NV	U.S. Department of Energy, Nevada Operations Office
E	easting
ft	feet (foot)
id	inside diameter
in.	inch(es)
km	kilometer(s)
m	meter(s)
Ma	million years ago
mi	mile(s)
N	northing
NTS	Nevada Test Site
SWL	static water level
TD	total depth
UGTA	Underground Test Area
USGS	U. S. Geological Survey
XRD	X-ray diffraction

1.0 Introduction

Recent radiochemical evidence suggests that migration of radionuclides within groundwater in the vicinity of the TYBO and BENHAM underground nuclear tests is more rapid than previously thought (Thompson, 1998). This has led to a reevaluation of the hydrogeologic conditions in the area, including a reevaluation of the subsurface geologic environment in the vicinity of the two underground tests. This report presents results of a detailed subsurface geologic analysis of the TYBO-BENHAM area, and provides new information with important implications for modeling groundwater flow and radionuclide migration on and near the Nevada Test Site (NTS). Work presented in this report confirms the existence of several shallow aquifers that likely underlie the entire area. The recognition of subunits within the Calico Hills Formation using precise petrographic and mineralogic analyses allowed for detailed correlation of tuff confining units and lava-flow aquifers within this lithologically complex and hydrogeologically important formation. Also, two previously unrecognized buried faults were identified that could act as zones of enhanced permeability within the aquifers. In addition, alteration within tuff confining units was found to be much more complex than previously described, consisting not only of zones of zeolitic alteration but also of zones having substantial quartzo-feldspathic secondary alteration.

The TYBO-BENHAM study area lies on the southern edge of Pahute Mesa in southwestern Area 20 of the NTS (Figure 1-1). The study area encompasses 13.7 square kilometers (5.3 square miles), and was the site of five underground nuclear weapon tests conducted in the years 1968 to 1986 (Table 1-1). The area is of particular interest with regards to environmental restoration because underground nuclear tests in the area were conducted near or below the water table (use of the term, "water table" in this report refers to the upper level of saturation in a local area, and does not necessarily imply detailed knowledge of the nature and extent of any perched or semi-perched aquifers). These tests might be located up-gradient from groundwater discharge and extraction sites located approximately 24 kilometers (km) (15 miles [mi]) to the southwest.

This study was conducted for the U.S. Department of Energy, Nevada Operations Office (DOE/NV) Underground Test Area (UGTA) remedial investigation, and is part of the studies associated with the development of models for groundwater flow and radionuclide migration within the Western Pahute Mesa Corrective Action Unit at the NTS.

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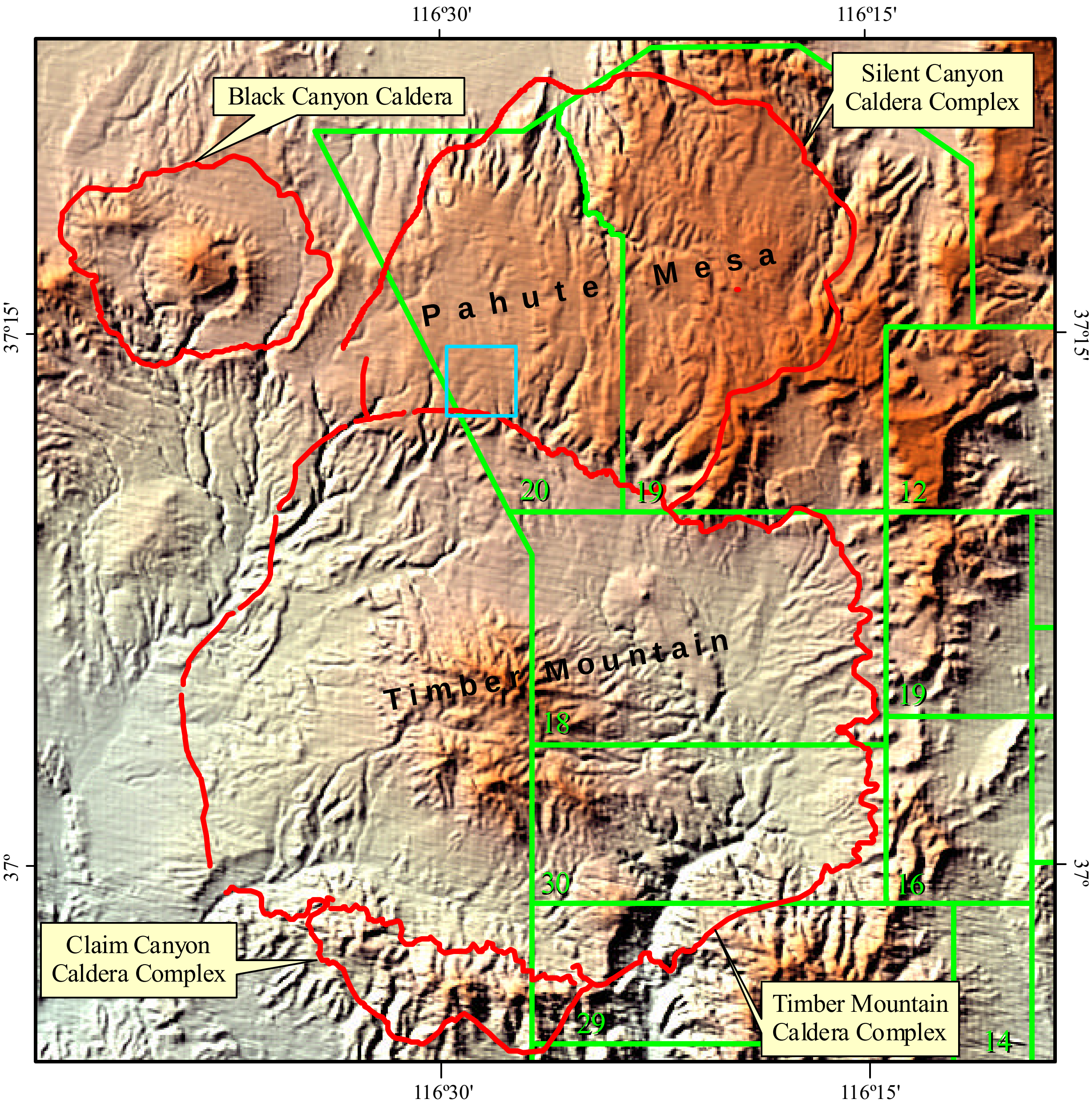

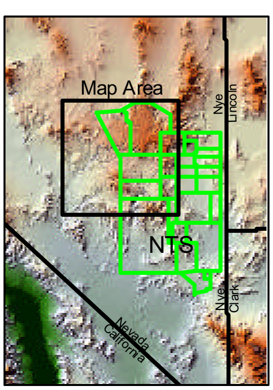

Location Map

Figure 1-1
Shaded Relief Map Showing
Location of the TYBO/BENHAM Study Area

Scale 1:350,000

5 0 5 Miles

TYBO/BENHAM Study Area

Topographic Wall of Caldera: Dashed where buried. (from Wahl et al., 1997)

Nevada Test Site (NTS) Boundary

Operational Areas

N W E S

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Table 1-1
Nuclear Tests Conducted in the TYBO-BENHAM Study Area

Hole Name	Test Name	Date of Test	Announced Yield (in kilotons)	Depth of Burial meters (feet)	Water Level Depth meters (feet)	Working Point Medium
U20ag	MOLBO	1982	20 to 150	638 (2,093)	614.8 (2,017)	Lava
U20ao	GOLDSTONE	1985	20 to 150	549 (1,801)	596.5 (1,957)	Lava
U20as	BELMONT	1986	20 to 150	605 (1,985)	613.6 (2,013)	Bedded Tuff
U20c	BENHAM	1968	1150	1,402 (4,600)	639.2 (2,097)	Bedded Tuff
U20y	TYBO	1975	200 to 1,000	765 (2,510)	630.0 (2,067)	Welded Ash-Flow Tuff

Sources: DOE, 2000; IT, 1995; O'Hagan and Laczniak, 1996.

1.1 Background

Areas 19 and 20 of the northwestern portion of the NTS have been the site of 85 underground nuclear tests conducted from 1966 to 1992 (DOE, 2000; Allen et al., 1997). Due to the remote location of the area, tests were generally larger than those at other testing sites within the NTS. These larger tests required deeper burial to assure that no radioactive by-products of the explosion were released to the atmosphere. Thus, many tests were conducted below the water table, resulting in the introduction of radionuclides into the groundwater system.

In 1995, DOE/NV began drilling a series of groundwater characterization wells near sites of selected underground nuclear tests in Area 20 to obtain data on the nature and extent of radionuclide migration in groundwater. One of these near-field drilling projects was performed near emplacement hole U20y, the site of the TYBO underground nuclear test in 1975. The drilling project, designated Well Cluster ER-20-5, consisted of three holes drilled approximately 278.1 meters (m) (912.5 feet [ft]) west-southwest and presumably down-gradient from U20y (DOE, 1997). Radiochemical analysis of groundwater samples from one of the wells in the cluster indicated the presence of radionuclides from the BENHAM underground nuclear test detonated in 1968 in emplacement hole U20c, located approximately 1,372 m (4,500 ft) north-northeast of Well Cluster ER-20-5

(Thompson, 1998). The presence of radionuclides from U20c in groundwater samples from Well Cluster ER-20-5 suggests that the migration of radionuclides away from U20c has been more rapid than previously thought. This has resulted in a reevaluation of the hydrogeologic conditions in the area to better understand and model groundwater flow and radionuclide migration.

1.2 Objectives

The objectives of the study are listed below:

- Provide consistent and detailed geologic descriptions of area drill holes by updating existing geologic descriptions using existing data, additional laboratory analyses, and current stratigraphic concepts;

- Develop a detailed subsurface geologic model of the area based on the updated descriptions; and

- Evaluate the hydrogeologic implications of the geologic model.

1.3 Methodology

Eight drill holes provide subsurface control for the study area (Table 1-2). These holes include emplacement holes U20y and U20c, the sites for the TYBO and BENHAM underground nuclear tests, respectively; nearby emplacement holes U20ag, U20ao, and U20as; exploratory hole UE20c; and nearby groundwater characterization wells ER-20-1 and Well Cluster ER-20-5. Holes were chosen on the basis of their proximity to emplacement holes U20y and U20c, as well as the amount, quality, and availability of data from each hole. Several post-shot and instrument holes are within the study area, but these were deemed inappropriate for use due to the limited amount and poor quality of the available data from these holes. Well Cluster ER-20-5 consists of three very closely spaced drill holes, for which lithologic data were combined to produce one composite log (see Section 2.2.1).

A variety of drilling and geologic data is available for the TYBO-BENHAM area. These include drilling records, stratigraphic and lithologic logs of the drill holes selected, and results of laboratory analyses for samples from these drill holes. These data were compiled from both published and unpublished sources. Table 1-3 lists sources of previous geologic descriptions of drill holes in the TYBO-BENHAM area. Drilling records and containment evaluation documents from the Weapons Testing Program provided information on drilling, sampling, logging, and geology of the drill holes. U.S. Geological Survey (USGS) Technical Letters provided additional background and geologic information on older drill holes,

Table 1-2
Drill Holes in the TYBO-BENHAM Area Utilized for this Study

Hole Name		Type of Hole	Surface Elevation		Total Depth		Year Drilled
			meters	feet	meters	feet	
ER-20-1		Groundwater characterization and monitoring	1,883.9	6,181	629.4	2,065	1992
Well Cluster ER-20-5	ER-20-5#1	Groundwater characterization	1,902.6	6,242	860.5	2,823	1995
	ER-20-5#2	Groundwater characterization	1,902.6	6,242	819.6	2,689	1995
	ER-20-5#3	Groundwater characterization	1,902.6	6,242	1,308.8	4,294	1996
U20ag		Emplacement	1,900.1	6,234	670.6	2,200	1980
U20ao		Emplacement	1,913.8	6,279	655.3	2,150	1985
U20as		Emplacement	1,897.9	6,227	640.5	2,100	1986
U20c		Emplacement	1,914.4	6,281	1,463.0	4,800	1965
UE20c		Exploratory	1,915.1	6,283	1,630.1	5,348	1964
U20y		Emplacement	1,907.1	6,257	793.1	2,602	1974

Sources: DOE, 1997; RSN, 1990; unpublished data, BN Geology/Hydrology files.

Table 1-3
Sources of Geologic Descriptions of Drill Holes in the TYBO-BENHAM Area

Drill Hole	Sources for Geologic Descriptions		
ER-20-1	McCall, 1992	BN Geology/Hydrology files	Warren et al., 1999
Well Cluster ER-20-5	DOE, 1997	Warren et al., 1999	--
U20ag	Howard, 1981	Ferguson et al., 1994	Warren et al., 1999
U20ao	Howard and Wagoner, 1985	Warren et al., 1999	--
U20as	Wagoner and Clark, 1986	Ferguson et al., 1994	Warren et al., 1999
U20c	Orkild, 1965	Orkild and Jenkins, 1978	Warren et al., 1999
UE20c	Santos, 1964	Orkild and Jenkins, 1978	Warren et al., 1999
U20y	Orkild and Jenkins, 1978	Warren et al., 1999	–

including U20c, UE20c, and U20y. Information for Well ER-20-1 and Well Cluster ER-20-5 was compiled from various UGTA reports. All previous stratigraphic and lithologic data (some modified by later work) and all known laboratory analyses are available in electronic form in Warren et al. (1999), an extensive database of subsurface geologic information for the southwestern Nevada volcanic field. Surface geology of the area is from USGS geologic maps (Byers and Cummings, 1967; Christiansen and Noble, 1968; Ekren et al., 1966; O'Connor et al., 1966; Wahl et al., 1997).

After existing drilling and geologic data from the area were compiled and reviewed, preliminary lithologic logs were produced for each hole. These logs provided a means to evaluate the quality and consistency of existing data and previous interpretations, identify critical gaps in the data, and determine where significant uncertainties still remained. Based on this preliminary analysis, 29 samples were collected for additional laboratory analyses. In addition, highly precise analyses were generated for 35 existing thin sections to replace questionable or less precise analyses. Highly precise laboratory analyses are reported by experienced analysts, and provide data free of serious errors that can compromise accurate geologic interpretations.

Laboratory analyses for samples collected specifically for the TYBO-BENHAM study include petrographic, chemical, and mineralogic analyses. Data from the analyses and descriptions of analytical methods are available in the petrographic/geochemical database of Warren et al. (1999). Table 1-4 summarizes analytical methods used for these analyses.

The additional laboratory analyses prompted revisions of the preliminary lithologic logs to produce final detailed lithologic logs for all eight holes. The final logs, along with surface geologic data, were used to develop a detailed geologic model of the TYBO-BENHAM area. This model is represented by diagrams that correlate stratigraphic, lithologic, and alteration intervals between holes, and by isopach and structure maps and geologic cross sections. Regional data outside the immediate area of the eight drill holes were included in the isopach and structure maps to better evaluate the geology of the TYBO-BENHAM area in a regional context. This geologic model was evaluated with regard to groundwater flow and radionuclide migration to assess its implications for flow and transport modeling.

Table 1-4
Description of Analytical Methods Used for the TYBO-BENHAM Study

Analysis Type	Method	Number of Samples	Description	References for Description of Analytical Method
Petrographic	Detailed	15	Modal analysis of polished thin section for felsic, mafic, and accessory minerals, and preparation for microprobe analysis.	Warren et al., 1999 Warren et al., 1989 Warren et al., 1984
Petrographic	Standard	35	Modal analysis of glass-covered thin section for felsic and mafic minerals.	Byers and Moore, 1987
Chemical	X-ray fluorescence	17	Analysis for 20 major and trace elements and Loss on Ignition using fused disk and matrix-correction computations.	Broxton et al., 1995
Mineralogic	X-ray diffraction	24	20% corundum internal standard using powder from agate mill ground to <5 microns. X-ray source is CuKα. Data reduction from library of in-house reference intensity ratios.	Bish and Chipera, 1988 Bish and Chipera, 1989

1.4 Geologic and Hydrogeologic Setting

The study area is located within the buried Silent Canyon caldera complex of Orkild et al. (1969) (Figure 1-1). The caldera complex consists of at least two partially nested calderas, the Grouse Canyon and younger Area 20 calderas (Ferguson et al., 1994; Sawyer and Sargent, 1989). These calderas were formed and then subsequently filled by voluminous eruptions of almost entirely rhyolitic tuff and lava between approximately 13 and 14 million years ago. Most of the caldera complex is buried by thick and extensive out-flow sheets from the nearby Timber Mountain and Black Mountain calderas located south and west of the study area, respectively. Welded ash-flow tuff assigned to the Trail Ridge Tuff forms most of the surface within the study area (Figure 1-2).

The water table within the study area is approximately 610 m (2,000 ft) below ground surface, and approximately 1,280 m (4,200 ft) in elevation. Groundwater flows south or southwest within aquifers formed by fractured lava and welded ash-flow tuff units (Blankennagel and Wier, 1973). Zeolitic units, particularly bedded tuffs, act as confining units. Table 1-5 summarizes geologic and hydrogeologic relationships within the study area.

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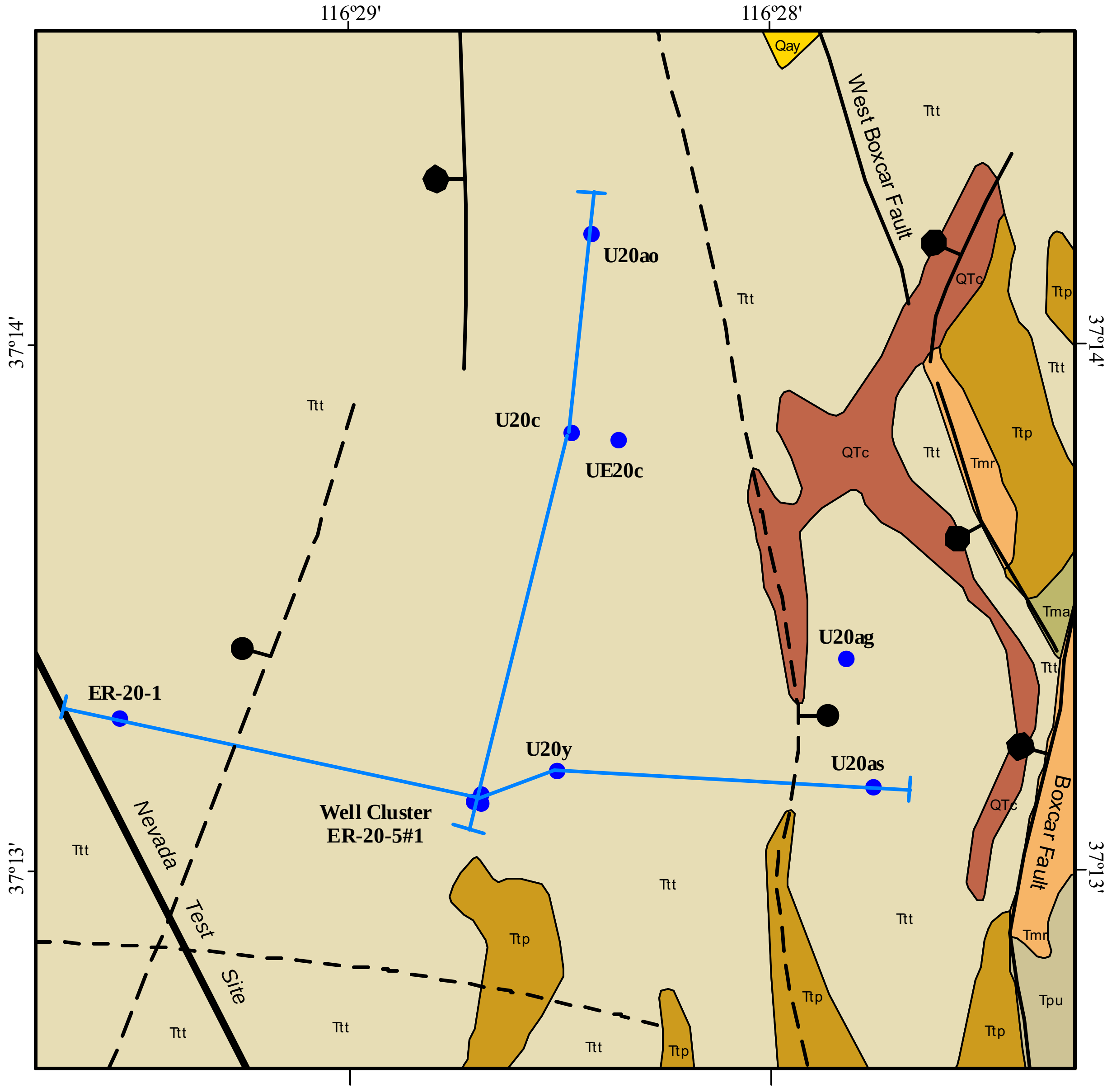

Figure 1-2
Geologic Map of the TYBO-BENHAM Study Area

Scale 1:24,000

500 0 500 Meters

N W E S

Qay	Young alluvium
QTc	Colluvium
Ttt	Trail Ridge Tuff
Ttp	Pahute Mesa Tuff
Tma	Ammonia Tanks Tuff
Tmr	Rainier Mesa Tuff
Tpu	Post-Tiva Canyon rhyolites
●	Drillhole
	Fault, dashed where buried. Bar and ball on down-thrown side.
	Inferred topographic wall of Timber Mountain caldera (Wahl et al., 1997)
	Line of section (See Section 3.0)

Surface geology from Wahl et al., 1997. Buried faults from this study.

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Table 1-5
Summary of Geologic and Hydrogeologic Relationships in the TYBO-BENHAM Area
(Page 1 of 3)

Source Caldera [a]	**Stratigraphic Relationship to Silent Canyon Caldera Complex** [b]	**Stratigraphic Group** [b] (Map Symbol)	**Stratigraphic Unit** [b,c] (Map Symbol) [Age in Millions of Years] [a]	**Dominant Lithology**	**Dominant Hydrogeologic Unit** [d]	**Hydro-stratigraphic Unit** [e]
Black Mountain caldera	Silent Canyon caldera-burying units	Thirsty Canyon Group (Tt)	Trail Ridge Tuff (Ttt) [9.6]	Welded ash-flow tuff	WTA	Timber Mountain aquifer
			Pahute Mesa Tuff (Ttp) [9.6]			
			crystal-rich (Ttpr)			
			crystal-poor (Ttpp)			
			Rocket Wash Tuff (Ttr) [9.6]			
Within Timber Mountain caldera complex	Silent Canyon caldera-burying units	Volcanics of Fortymile Canyon (Tf)	Beatty Wash Formation (Tfb)	Vitric bedded tuff	VTA	
			rhyolite of Chukar Canyon (Tfbr)			
			rhyolite of Beatty Wash (Tfbw) [11.2]			
Timber Mountain caldera complex	Silent Canyon caldera-burying units	Timber Mountain Group (Tm)	Ammonia Tanks Tuff (Tma) [11.4]	Welded ash-flow tuff	WTA	
			mafic-rich (Tmar)			
			mafic-poor (Tmap)			
			bedded (Tmab)			
			Rainier Mesa Tuff (Tmr) [11.6]			
			mafic-rich (Tmrr)			
			mafic-poor (Tmrp)			
			rhyolite of Fluorspar Canyon (Tmrf) [11.6]	Vitric bedded and nonwelded tuff	VTA	Paintbrush vitric-tuff aquifer
			tuff of Holmes Road (Tmrh)			
			rhyolite of Windy Wash (Tm) [12.3]			

Table 1-5
Summary of Geologic and Hydrogeologic Relationships in the TYBO-BENHAM Area
(Page 2 of 3)

Source Caldera [a]	Stratigraphic Relationship to Silent Canyon Caldera Complex [b]	Stratigraphic Group [b] (Map Symbol)	Stratigraphic Unit [b,c] (Map Symbol) [Age in Millions of Years] [a]	Dominant Lithology	Dominant Hydrogeologic Unit [d]	Hydro-stratigraphic Unit [e]
Uncertain	Silent Canyon caldera-burying units	Paintbrush Group (Tp)	rhyolite of Benham (Tpb) [12.7]	Rhyolite lava	LFA	Benham aquifer
Claim Canyon caldera			crystal-poor tuff of Pinyon Pass (Tpcyp)	Zeolitic bedded tuff	TCU	Upper Paintbrush confining unit
			Pahute Mesa lobe of the Tiva Canyon Tuff (Tpcm) [12.7]	Welded ash-flow tuff	WTA	Tiva Canyon aquifer
Uncertain			rhyolite of Black Glass Canyon (Tpg)	Zeolitic bedded tuff	TCU	Lower Paintbrush confining unit
			rhyolite of Delirium Canyon (Tpd) [12.7]			
			Pahute Mesa lobe of the Topopah Spring Tuff (Tptm) [12.7]	Welded ash-flow tuff	WTA	Topopah Spring aquifer
Area 20 caldera	Area 20 caldera-filling units	Calico Hills Formation (Th) mafic-poor (Thp) mafic -rich (Thr) [12.9]		Rhyolite lava and zeolitic bedded tuff	LFA TCU	Calico Hills zeolitized composite unit
		Crater Flat Group (Tc)	rhyolite of Inlet (Tci)	Rhyolite lava	LFA	Inlet aquifer
			tuff of Jorum (Tcj)	Welded tuff, rhyolite lava, and zeolitic bedded tuff	WTA LFA TCU	Crater Flat composite unit
			rhyolite of Sled (Tcps)	Rhyolite lava and zeolitic bedded tuff		
	Area 20 caldera-forming unit		Bullfrog Tuff (Tcb) [13.25]	Zeolitic nonwelded ash-flow tuff	TCU	Bullfrog confining unit

Table 1-5
Summary of Geologic and Hydrogeologic Relationships in the TYBO-BENHAM Area
(Page 3 of 3)

Source Caldera [a]	**Stratigraphic Relationship to Silent Canyon Caldera Complex** [b]	**Stratigraphic Group** [b] (Map Symbol)	**Stratigraphic Unit** [b,c] (Map Symbol) [Age in Millions of Years] [a]	**Dominant Lithology**	**Dominant Hydrogeologic Unit** [d]	**Hydro-stratigraphic Unit** [e]
Grouse Canyon Caldera	Grouse Canyon caldera-filling unit	Belted Range Group (Tb)	Dead Horse Flat Formation (Tbd) [13.5]	Rhyolite lava and welded tuff	LFA WTA	Belted Range aquifer
	Grouse Canyon caldera-forming unit		Grouse Canyon Tuff (Tbg) [13.7]	Welded tuff		
Uncertain	pre-Grouse Canyon caldera units	Older Volcanics, undivided		Welded ash-flow tuff, lava, and zeolitic bedded tuff	WTA LFA TCU	Pre-Belted Range composite unit

a from Sawyer et al., 1994
b after Ferguson et al., 1994
c after Warren et al., 1999
d WTA = welded-tuff aquifer; VTA = vitric-tuff aquifer; LFA = lava-flow aquifer; TCU = tuff confining unit;
e Prothro et al., 1998

1.5 Acknowledgments

The authors would like to thank the people who provided support and assistance during this study. Gayle Pawloski and Jeff Wagoner of Lawrence Livermore National Laboratory (LLNL), and Jim Cole of the USGS provided data and useful insights on the geology of the area and region. Gayle Pawloski of LLNL and Ted McKee of the USGS contributed thoughtful commentary, and Margaret Townsend of Bechtel Nevada provided essential support in document preparation and review. The Bechtel Nevada NTS GIS Group produced Figures 1-1 and 1-2.

Access to lithologic samples (drill cuttings and core) and wireline geophysical logs was provided expeditiously by the personnel of USGS Core Library and Geologic Data Center in Mercury Nevada. Chemical and mineralogical analyses for samples selected specifically for the TYBO-BENHAM study were performed at Los Alamos National Laboratory. Emily C. Kluk provided chemical analyses by X-ray fluorescence, and Steven J. Chipera provided mineralogical analyses by X-ray diffraction. Frank M. Byers, Jr. provided standard modal petrographic analyses from offices of the USGS in Denver.

2.0 Drill Holes

This section summarizes construction and geologic data for the eight drill holes examined for this study. Construction data are from the RSN Drilling and Mining Summary (RSN, 1990 and later updates by BN). Geologic data for these holes came from a variety of sources, mainly the DOE weapons testing program as supported by the Lawrence Livermore and Los Alamos National Laboratories. Some data were also produced in support of the UGTA program. Sources of lithologic data were given in Table 1-3. Warren et al. (1999) compiled lithologic, stratigraphic, and mineralogical data from these and other sources, and serves as a central repository of such data. Drill cuttings for all drill holes are stored at the USGS Core Library in Mercury, NV; geophysical logs for the boreholes are held by BN in Mercury, NV.

2.1 Well ER-20-1

Well ER-20-1 is a groundwater characterization and monitoring well for the UGTA program. It was drilled in 1992 to a depth of 629.4 m (2,065 ft). Table 2-1 provides hole construction information for ER-20-1. No completion strings have been installed in the borehole to date.

2.1.1 Geologic Data for Well ER-20-1

During the drilling of ER-20-1, samples of drill cuttings were collected at 3.0-m (10-ft) intervals from 36.6 to 627.2 m (120 - 2,060 ft) (Table 2-2). These are the only samples available for the hole. Table 2-3 lists the wireline geophysical logs used during this study to help evaluate the geology of ER-20-1. Laboratory analyses were performed for samples of drill cuttings from two depths in ER-20-1 (Table 2-4). These analyses include thin-section petrography, x-ray diffraction, and x-ray fluorescence. No laboratory analyses had previously been performed on lithologic samples from the hole. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.1.2 Geology of Well ER-20-1

Well ER-20-1 was drilled completely within Area 20 caldera-burying rocks, and reached total depth (TD) in moderately welded ash-flow tuff of the Pahute Mesa lobe of the Tiva Canyon Tuff at 629.4 m (2,065 ft). Stratigraphic units encountered are typical for this portion of Pahute Mesa, consisting, in descending order, of units assigned to the Thirsty Canyon, Timber Mountain, and Paintbrush Groups. Figure 2-1 shows that the hole encountered

Table 2-1
Hole Construction Data for Well ER-20-1

LOCATION DATA		
Coordinates:	Central Nevada State Planar:	Northing (N) 900,001 ft Easting (E) 551,000 ft
	Universal Transverse Mercator:	N 4,119,467.6 m E 545,112.9 m
Ground Elevation:	1,883.9 m (6,180.9 ft)	
DRILLING DATA		
Spud Date:	08/06/1992 (Surface Hole) 08/25/1992 (Main Hole)	
Total Depth (TD):	629.4 m (2,065 ft)	
Date TD Reached:	09/08/1992	
Hole Diameter:	121.9 cm (48 in.) from surface to 33.8 m (111 ft); 76.2 cm (30 in.) to 591.3 m (1,940 ft); 52.1 cm (20.5 in.) to 629.4 m (2,065 ft)	
Drilling Techniques:	Dry-auger drilling to 33.8 m (111 ft). Air-hammer drilling with direct circulation using air-foam and a 30-in. bit to 591.3 m (1,940 ft). Dual-string reverse circulation drilling using air and water and a 20½-in. button bit from 591.3 to 629.4 m (1,940 to 2,065 ft).	
Fluid Depth:	605.9 m (1,988 ft) on 06/10/1996	
CASING DATA	36-in. conductor casing from the surface to 33.2 m (109 ft). 24-in. surface casing set at 590.4 m (1,937 ft).	

Source: BN Geology/Hydrology files.

Table 2-2
Lithologic Samples Available for Well ER-20-1

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 36.6 to 627.2 m (120 - 2,060 ft) at 3.0 m (10 ft) intervals. Missing sample at 134.1 m (440 ft) depth.

a Sample depth represents base of sample interval.

ash-flow tuff and bedded tuff above 321.3 m (1,054 ft), rhyolitic lava and flow breccia from 321.3 to 513.6 m (1,054 - 1,685 ft), and nonwelded tuff and welded ash-flow tuff below 513.6 m (1,685 ft). Rocks encountered are mainly vitric or devitrified above 513.6 m (1,054 ft), becoming zeolitic or devitrified below. A detailed lithologic log for ER-20-1 is provided in Appendix A. Fluid level in the open borehole was measured at 605.9 m (1,988 ft) within devitrified moderately welded ash-flow tuff of the Tiva Canyon Tuff.

Table 2-3
Geophysical Logs Used to Evaluate the Geology of Well ER-20-1

Type of Log	Run Number	Date	Interval Logged
6-Arm Caliper/ Gamma Ray	1	09/09/1992	15.2 - 621.2 m (50 - 2,038 ft)
	2	09/10/1992	14.3 - 596.8 m (47 - 1,958 ft)
Dual Induction/ Gamma Ray	1	09/11/1992	21.9 - 599.5 m (72 - 1,967 ft)
	2	09/11/1992	20.7 - 601.4 m (68 - 1,973 ft)
Compensated Densilog/ Gamma Ray	1	09/14/1992	18.6 - 591.0 m (61 - 1,939 ft)
Epithermal Neutron Porosity/ Gamma Ray	1	09/15/1992	14.6 - 592.2 m (48 - 1,943 ft)
Spectral Gamma Ray	1	09/11/1992	24.1 - 604.4 m (79 - 1,983 ft)
Total Magnetic Intensity	1	09/14/1992	35.1 - 605.6 m (115 - 1,987 ft)
Downhole Video	1	09/10/1992	0 - 602.0 m (0 - 1,975 ft)

Table 2-4
Laboratory Analyses for Samples from Well ER-20-1

Depth [a] meters (feet)	Sample Type [b]	Analyses Performed [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
570.0 (1,870)	DA	--	✓	--	✓	✓	--	--
624.8 (2,050)	DA	--	✓	--	✓	✓	--	--

a Depth represents base of sample interval.
b DA = Drill cuttings that represent lithologic character of interval
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.

Note: Stratigraphic, lithologic, and alteration assignments for each sample are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

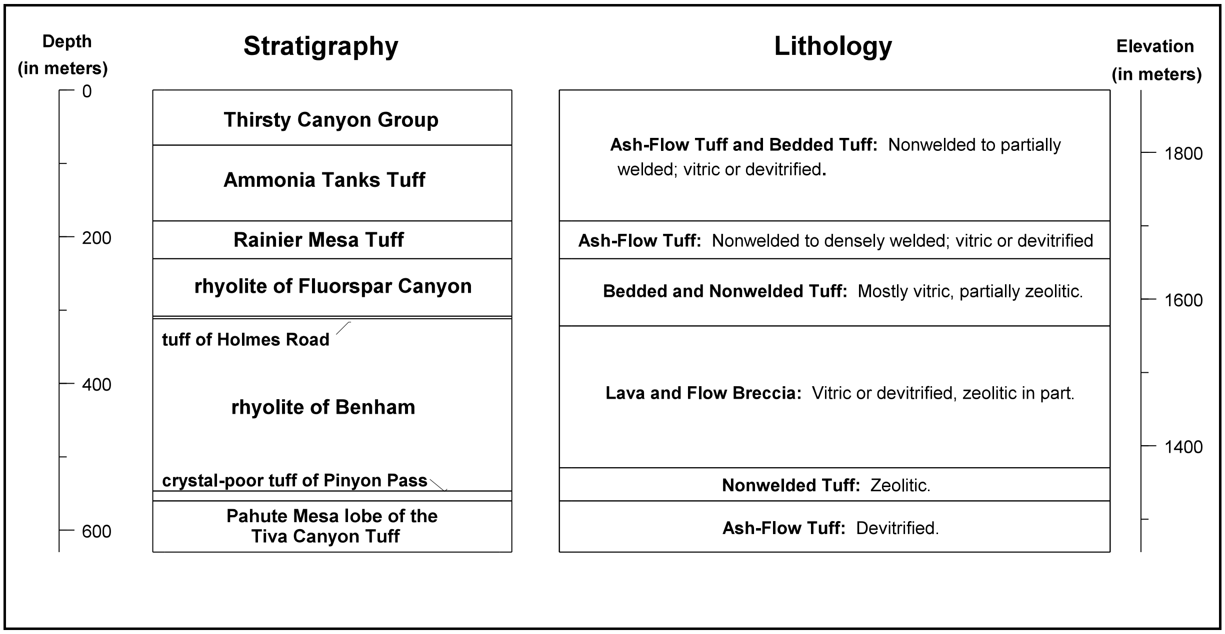

Figure 2-1
Stratigraphic and Lithologic Columns for Well ER-20-1

2.2 Well Cluster ER-20-5

Well Cluster ER-20-5 was drilled in 1995 and 1996 as part of an UGTA near-field drilling project. The purpose of the well cluster was to evaluate hydrogeologic conditions and radionuclide migration in the immediate vicinity of the TYBO underground nuclear test conducted in emplacement hole U20y. The well cluster consists of three holes: ER-20-5#1, ER-20-5#2, and ER-20-5#3. The three holes are located within 45.7 m (150 ft) of each other, and were drilled to various depths ranging from 819.6 m (2,689 ft) for ER-20-5#2 to 1,309 m (4,294 ft) for ER-20-5#3. The well closest to U20y, ER-20-5#1, is approximately 278 m (912 ft) west-southwest and presumably hydrologically down-gradient of the TYBO test. Tables 2-5, 2-6, and 2-7 provide additional hole construction information for the three holes comprising the well cluster.

Table 2-5
Hole Construction Information for Well ER-20-5#1

LOCATION DATA			
Coordinates:	Central Nevada State Planar:	N 899,134 ft E 555,174 ft	
	Universal Transverse Mercator:	N 4,119,208.3 m E 546,385.9 m	
Ground Elevation:	1,902.5 m (6,241.8 ft)		
DRILLING DATA			
Spud Date:	10/15/1995		
Total Depth (TD):	860.5 m (2,823 ft)		
Date TD Reached:	11/02/1995		
Hole Diameter:	91.4 centimeters (cm) (36 inches [in.]) from surface to 3.4 m (11 ft); 66.0 cm (26 in.) to 63.1 m (207 ft); 44.5 cm (17½ in.) to 64.9 m (213 ft); 31.1 cm (12¼ in.) to 860.5 m (2,823 ft).		
Drilling Techniques:	Dry auger-drilling to 3.4 m (11 ft). Rotary drilling with dry air using a 12¼-in. hammer bit and conventional circulation to 11.3 m (37 ft). Rotary drilling with mud (and lost circulation material as needed) to 63.1 m (207 ft). Reaming with 24-in. bit to 63.1 m (207 ft). Reaming with 26-in. bit to 63.1 m (207 ft). Rotary drilling with 17½-in. mill-tooth bit through cement in casing at 55.5 m (182 ft) to 64.9 m (213 ft) with conventional circulation and mud. Rotary drilling with 12¼-in. button bit to TD at 860.5 m (2,823 ft) using air-foam with conventional circulation.		
Fluid Depth:	626.4 m (2,055 ft) on 11/03/1995		
CASING DATA			
	76.2-cm (30-in.) conductor casing from surface to 3.4 m (11 ft). 50.8-cm (20-in.) surface casing set at 62.2 m (204.1 ft). No intermediate casing.		

Source: DOE, 1997.

Table 2-6
Hole Construction Information for Well ER-20-5#2

LOCATION DATA		
Coordinates:	Central Nevada State Planar:	N 899,038 ft E 555,096 ft
	Universal Transverse Mercator:	N 4,119,178.9 m E 546,362.2 m
Ground Elevation:	1,902.6 m (6,242.2 ft)	
DRILLING DATA		
Spud Date:	11/17/1995	
Total Depth (TD):	819.6 m (2,689 ft)	
Date TD Reached:	11/30/1995	
Hole Diameter:	91.4 cm (36 in.) from surface to 3.4 m (11 ft); 61.0 cm (24 in.) to 106.1 m (348 ft); 31.1 cm (12¼ in.) to 819.6 m (2,689 ft).	
Drilling Techniques:	Dry auger drilling to 3.4 m (11 ft). Rotary drilling with mud (and lost circulation material as needed) using 24-in. bit and conventional circulation to 106.1 m (348 ft). Rotary drilling with 12¼-in. button bit through cement in casing at 91.4 m (300 ft) to 104.2 m (342 ft) with conventional circulation and mud. Rotary drilling with 12¼-in. button bit to TD at 819.6 m (2,689 ft) with air-foam and conventional circulation, reaming tight spots as necessary. Bit stuck at 808.6 m (2,653 ft) due to severe hole sloughing after brief shutdown to tighten clamp on rotating head. Fishing operations to recover drill pipe unsuccessful. Leave bottom hole assembly, drill pipe, and one joint of wash-over pipe in hole. Top of fish at 552.6 m (1,813 ft). Bottom of hole and fish cemented in to 500.8 m (1,643 ft). Hole filled with uncontaminated cuttings to 19.8 m (65 ft). Top of hole cemented to ground level.	
Fluid Depth:	Not measured	
CASING DATA		
	76.2-cm (30-in.) conductor casing from surface to 3.4 m (11 ft). 40.6-cm (16-in.) surface casing set at 105.4 m (345.8 ft). No intermediate casing.	

Source: DOE,1997.

Table 2-7
Hole Construction Information for Well ER-20-5#3

LOCATION DATA			
Coordinates:	Central Nevada State Planar:	N 899,031 ft E 555,170 ft	
	Universal Transverse Mercator:	N 4,119,177.0 m E 546,384.7 m	
Ground Elevation:	1,902.5 m (6,241.9 ft)		
DRILLING DATA			
Spud Date:	12/13/1995		
Total Depth (TD):	1,308.8 m (4,294 ft)		
Date TD Reached:	02/05/1996		
Hole Diameter:	91.4 cm (36 in.) from surface to 3.4 m (11 ft); 66.0 cm (26 in.) to 252.1 m (827 ft); 44.5 cm (17½ in.) to 955.5 m (3,135 ft); 31.1 cm (12¼ in.) to 1,308.8 m (4,294 ft).		
Drilling Techniques:	Dry auger drilling to 3.4 m (11 ft). Rotary drilling with mud (and lost-circulation material as needed) using a 26-in. bit and conventional circulation to 252.1 m (827 ft). Rotary drilling with a 17½-in. button bit and mud to 269.1 m (883 ft). Rotary drilling with a 17½-in. bit and air-foam (and polymer as needed) in conventional circulation to 955.5 m (3,135 ft). Rotary drilling with a 12¼-in. button bit and air-foam in conventional circulation to TD.		
Fluid Depth:	627.9 m (2,060 ft) on 02/07/1996		
CASING DATA			
	30-in. conductor casing from surface to 3.4 m (11 ft); 20-in. surface casing to 250.9 m (823.2 ft); 13⅜-in. intermediate casing to 950.0 m (3,116.8 ft).		

Source: DOE,1997.

2.2.1 Geologic Data for Well Cluster ER-20-5

Samples of drill cuttings were collected during the drilling of all three of the well cluster holes (Tables 2-8, 2-9, and 2-10). Drill cuttings were collected from surface to TD of the holes and at intervals ranging from 3.0 to 6.1 m (10 - 20 ft). Twenty-one sidewall core samples were collected from the 963.2- to 1,304.5-m (3,160 - 4,280-ft) depth interval in

Table 2-8
Lithologic Samples Available for Well ER-20-5#1

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 0 to 860.5 m (0 - 2,823 ft) at 3.0 m (10 ft) intervals. Missing samples at: 6.1 m (20 ft), 9.1 m (30 ft), 12.2 m (40 ft), 39.6 m (130 ft), 42.7 m (140 ft), 45.7 m (150 ft), 48.8 m (160 ft), 51.8 m (170 ft), 54.9 m (180 ft), 57.9 m (190 ft), 143.3 m (470 ft), 146.3 m (480 ft), 414.5 m (1,360 ft), 438.9 m (1,440 ft), 448.1 m (1,470 ft), 496.8 m (1,630 ft), 499.9 m (1,640 ft), 743.7 m (2,440 ft), 746.8 m (2,450 ft), 755.9 m (2,480 ft) Hole sloughing degraded the quality of the cuttings below 807.7 m (2,650 ft).

Source: DOE, 1997.

a Individual sample depths represent base of sample interval.

Table 2-9
Lithologic Samples Available for Well ER-20-5#2

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 0 to 106.7 m (0 - 350 ft) at 3.0 m (10 ft) intervals; from 106.7 to 609.6 m (350 - 2,000 ft) at 6.1 m (20 ft) intervals; and from 609.6 to 819.6 m (2,000 - 2,689 ft) at 3.0 m (10 ft) intervals. Missing samples at: 6.1 m (20 ft), 12.2 m (40 ft), 432.8 m (1,420 ft), 493.8 m (1,620 ft), 499.9 m (1,640 ft), 597.4 m (1,960 ft), 603.5 m (1,980 ft), 728.5 m (2,390 ft) Hole sloughing degraded the quality of the cuttings below 807.7 m (2,650 ft).

Source: DOE, 1997.

a Individual sample depths represent base of sample interval.

Table 2-10
Lithologic Samples Available for Well ER-20-5#3

Sample Type	Sample Intervals and Recovery [a]	
Drill Cuttings	From 0 to 610.0 m (0 - 2,000 ft) at 6.1 m (20 ft) intervals and from 610.0 to 1,308.8 m (2,000 - 4,294 ft) at 3.0 m (10 ft) intervals. Missing samples at: 30.5 m (100 ft), 36.6 m (120 ft), 115.8 m (380 ft), 121.9 m (400 ft), 128.0 m (420 ft), 643.1 m (2,110 ft), 646.2 m (2,120 ft), 806.2 m (2,645 ft), 809.2 m (2,655 ft), 827.5 m (2,715 ft), 833.6 m (2,735 ft), 839.7 m (2,755 ft), 855.0 m (2,805 ft), 864.1 m (2,835 ft), 870.2 m (2,855 ft), 963.2 m (3,160 ft), 1,051.6 m (3,450 ft), 1,063.8 m (3,490 ft), 1,069.8 m (3,510 ft), 1,106.4 m (3,630 ft), 1,127.8 m (3,700 ft), 1,204.0 m (3,950 ft), 1,210.1 m (3,970 ft), 1,216.2 m (3,990 ft)	
Sidewall Core	**Core Depth**	**Recovery**
	963.2 m (3,160 ft)	2.5 cm (1.0 in.)
	973.8 m (3,195 ft)	1.9 cm (0.75 in.)
	973.8 m (3,195 ft)	1.9 cm (0.75 in.)
	990.6 m (3,250 ft)	2.5 cm (1.0 in.)
	1,005.8 m (3,300 ft)	3.8 cm (1.5 in.)
	1,033.3 m (3,390 ft)	5.1 cm (2.0 in.)
	1,040.6 m (3,414 ft)	3.2 cm (1.25 in.)
	1,048.7 m (3,440.5 ft)	5.1cm (2.0 in.)
	1,053.4 m (3,456 ft)	1.3 cm (0.5 in.)
	1,066.8 m (3,500 ft)	3.2 cm (1.25 in.)
	1,085.1m (3,560 ft)	5.1 cm (2.0 in.)
	1,112.5 m (3,650 ft)	2.9 cm (1.13 in.)
	1,143.0 m (3,750 ft)	3.8 cm (1.5 in.)
	1,185.7 m (3,890 ft)	5.1 cm (2.0 in.)
	1,204.0 m (3,950 ft)	3.2 cm (1.25 in.)
	1,219.2 m (4,000 ft)	4.4 cm (1.75 in.)
	1,243.6 m (4,080 ft)	4.4 cm (1.75 in.)
	1,275.6 m (4,185 ft)	4.4 cm (1.75 in.)
	1,283.2 m (4,210 ft)	2.9 cm (1.13 in.)
	1,304.5 m (4,280 ft)	4.4 cm (1.75 in.)
	1,304.5 m (4,280 ft)	3.8 cm (1.5 in.)

Source: DOE, 1997.

a Individual sample depths represent base of sample interval.

Well ER-20-5#3. Tables 2-11, 2-12, and 2-13 list the wireline geophysical logs used during this study to help evaluate the geology of the well cluster holes. Due to drilling problems caused by severe sloughing of the ER-20-5#2 borehole, only a caliper log covering the 91.4- to 504.4-m (300- 1,655-ft) depth interval is available for the hole. Laboratory analyses were performed on samples of drill cuttings from nine depths in Well ER-20-5#3 (Table 2-14). Analyses performed included thin-section petrography, x-ray diffraction, and x-ray fluorescence. No laboratory analyses had previously been performed on lithologic samples from any of the holes. Stratigraphic, lithologic, and alteration assignments for each sample are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Because of insufficient data for portions of all three holes, it was impossible to produce a detailed high-quality lithologic log for each hole in the well cluster. Instead, data from each hole that were judged to be of sufficient quality were used to compile a single detailed lithologic log for the well cluster. This approach was deemed appropriate due to the close proximity of the three holes. Geophysical logs from ER-20-5#1 were used to help evaluate the geology of the well cluster from the surface to approximately 823.0 m (2,700 ft). Drill cuttings from ER-20-5#2 were used to describe lithologic intervals of the well cluster from 3.0 to 658.4 m (10 - 2,160 ft). Drill cuttings, sidewall core samples, and geophysical logs from ER-20-5#3 were used to describe the geology of the well cluster from 658.4 to 1,308.8 m (2,160 - 4,294 ft).

Comparison of the detailed lithologic log for the well cluster with data from all three holes showed no major differences between the composite log and the geology encountered within each hole. However, minor differences in the depth of lithologic and stratigraphic contacts can be expected among the three holes. Because the ER-20-5#3 borehole departs significantly from the vertical below 789.7 m (2,591 ft), it was necessary to calculate true vertical depths for lithologic and stratigraphic contacts below 789.7 m (2,591 ft). For the rest of this report, all depths listed for Well Cluster ER-20-5 are true vertical depths. Also, unless otherwise specified, the well cluster will be refered to as simply ER-20-5. In Warren et al. (1999), contacts for the composite log are assigned to ER-20-5#1 to its TD, and contacts below this depth are assigned to ER-20-5#3.

Table 2-11
Geophysical Logs Used to Evaluate the Geology of Well ER-20-5#1

Type of Log	Run Number	Date	Interval Logged
4-Arm Caliper/Gamma Ray	1	11/02/1995	0.6 - 835.2 m (2 - 2,740 ft)
Dual Induction/ 3-Arm Caliper/Gamma Ray	1	11/02/1995	626.4 - 833.3 m (2,055 - 2,734 ft)
Compensated Densilog/ Compensated Neutron/ Gamma Ray	1	11/03/1995	62.2 - 826.0 m (204 - 2,710 ft)
Digital Acoustic Compensated/3-Arm Caliper/Gamma Ray	1	11/03/1995	626.4 - 824.2 m (2,055 - 2,704 ft)
Spectral Gamma Ray	1	11/03/1995	0.6 - 814.4 m (2 - 2,672 ft)
Total Magnetic Intensity	1	11/04/1995	64.0 - 824.2 m (210 - 2,704 ft)
Borehole Televiewer/ Gamma Ray	1	11/03/1995	626.4 - 826.0 m (2,055 - 2,710 ft)
Downhole Video	1	11/03/1995	0 - 701.0 m (0 - 2,300 ft)
Directional Gyroscope	1	11/09/1995	0 - 789.4 m (0 - 2,590 ft)

Table 2-12
Geophysical Logs Used to Evaluate the Geology of Well ER-20-5#2

Type of Log	Run Number	Date	Interval Logged
6-Arm Caliper	1	12/05/1995	91.4 - 504.4 m (300 - 1,655 ft)

Table 2-13
Geophysical Logs Used to Evaluate the Geology of Well ER-20-5#3

Type of Log	Run Number	Date	Interval Logged
6-Arm Caliper/Gamma Ray	1	01/08/1996	234.1 - 955.2 m (768 - 3,134 ft)
4-Arm Caliper/Gamma Ray	1	02/08/1996	950.1 - 1,307.0 m (3,117 - 4,288 ft)
Gamma Ray	1	01/08/1996	234.7 - 953.4 m (770 - 3,128 ft)
Dual Laterolog/ 4-Arm Caliper/Gamma Ray	1	02/07/1996	627.6 - 1,303.6 m (2,059 - 4,277 ft)
Compensated Densilog/ Epithermal Neutron/Gamma Ray	1	02/08/1996	627.6 - 1,306.7 m (2,059 - 4,287 ft)
Digital Full-wave Acoustic/ Gamma Ray	1	02/07/1996	627.6 - 1,303.6 m (2,059 - 4,277 ft)
Spectralog	1	02/07/1996	613.3 - 1,293.3 m (2,012 - 4,243 ft)
Borehole Televiewer/Gamma Ray	1	02/07/1996	740.7 - 1,306.7 m (2,430 - 4,287 ft)
Directional Gyroscope	1	02/13/1996	7.6 - 1,193.0 m (25 - 3,914 ft)

Table 2-14
Laboratory Analyses Performed on Samples from Well ER-20-5#3

Depth [a] meters (feet)	**Sample Type** [b]	**Analyses Performed** [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
618.7 (2,030)	DA	--	✓	--	✓	--	--	--
676.7 (2,220)	DA	--	✓	--	✓	--	--	--
900.7 (2,955)	DA	--	✓	--	✓	✓	--	--
915.9 (3,005)	DA	--	--	--	✓	✓	--	--
972.3 (3,190)	DA	--	--	--	✓	✓	--	--
1185.7 (3,890)	DA	--	--	--	✓	✓	--	--
1207.0 (3,960)	DA	--	--	--	✓	✓	--	--
1255.8 (4,120)	DA	--	--	--	✓	✓	--	--
1295.4 (4,250)	DA	--	--	--	✓	✓	--	--

a Depth represents base of sample interval.
b DA = Drill cuttings that represent lithologic character of interval.
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.
Note: Stratigraphic, lithologic, and alteration assignments for each sample are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.2.2 Geology of Well Cluster ER-20-5

Well Cluster ER-20-5 penetrated 826.9 m (2,713 ft) of Area 20 caldera-burying rocks consisting of ash-flow tuff, bedded tuff, and lava (Figure 2-2). Below 826.9 m (2,713 ft), ER-20-5#3 encountered 467.3 m (1,533 ft) of Area 20 caldera-filling bedded tuff and lava of the Calico Hills Formation, before reaching TD in bedded tuff of the mafic-rich Calico Hills Formation at 1,294.2 m (4,246 ft). Above 437.4 m (1,435 ft), the rocks encountered are vitric or devitrified. Below 437.4 m (1,435 ft) to the base of the Topopah Spring Tuff at 826.9 m (2,713 ft), the less dense units, such as bedded tuffs, are mostly zeolitic, whereas the denser formations, such as the welded ash-flow tuffs, are mostly devitrified. Rocks of the Calico Hills Formation encountered below 826.9 m (2,713 ft) show diverse zones of alteration, including vitric (unaltered), devitrified, zeolitic, silicic, and potassic. The detailed lithologic log for the well cluster is provided in Appendix A. The fluid level in Well ER-20-5#3, before installation of the completion strings, was measured at 627.9 m (2,060 ft) (DOE, 1997) within zeolitic bedded tuff of the rhyolite of Delirium Canyon.

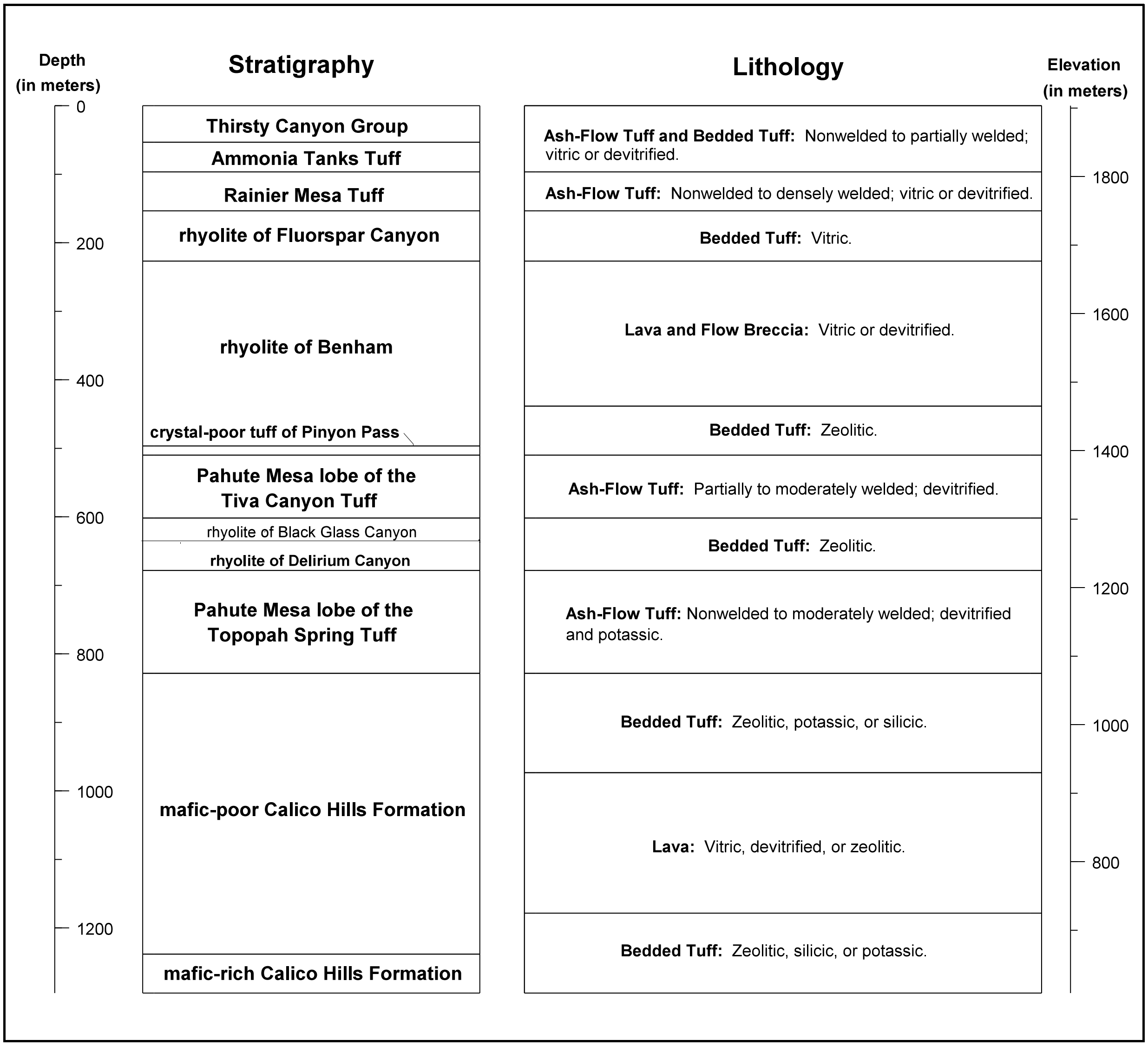

Figure 2-2
Stratigraphic and Lithologic Columns for Well Cluster ER-20-5

2.3 Emplacement Hole U20ag

U20ag is a large-diameter emplacement hole drilled in 1980 to a depth of 670.6 m (2,200 ft). The hole was the site of the MOLBO underground nuclear test conducted in 1982. The test had an announced yield between 20 and 150 kilotons (DOE, 2000) and was conducted at a depth of 638 m (2,093 ft), approximately 23.2 m (76 ft) below the water table, within devitrified lava of the rhyolite of Benham. Table 2-15 provides hole construction information for U20ag.

2.3.1 Geologic Data for U20ag

During the drilling of U20ag, drill cuttings were collected from 24.4 to 670.6 m (80 - 2,200 ft) at 3.0-m (10-ft) intervals, and are the only lithologic samples collected from the hole (Table 2-16). Table 2-17 lists the wireline geophysical logs used during this study to help analyze the geology of the hole. Results from previous laboratory analyses of drill cuttings from 22 depths in U20ag were available, and no additional laboratory analyses were performed for this study (Table 2-18). Existing analyses include x-ray diffraction and carbon-dioxide content. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.3.2 Geology of U20ag

Rocks encountered at U20ag consist entirely of Area 20 caldera-burying units assigned to the Thirsty Canyon, Timber Mountain, and Paintbrush Groups (Figure 2-3). The hole bottomed in devitrified lava of the rhyolite of Benham. Above 333.8 m (1,095 ft), the hole penetrated ash-flow tuff and bedded tuff. Below this depth to the bottom of the hole at 670.6 m (2,200 ft), only rhyolitic lava was encountered. Rocks are vitric or devitrified above 304.8 m (1,000 ft), and vitric, devitrified, or zeolitic below. A detailed lithologic log of U20ag is provided in Appendix A. Fluid level in the open borehole was measured at 614.8 m (2,017 ft) (F&S, 1980) within lava of the rhyolite of Benham.

Table 2-15
Hole Construction Data for Emplacement Hole U20ag

LOCATION DATA		
Coordinates:	Central Nevada State Planar:	N 900,700 ft E 559,400 ft
	Universal Transverse Mercator:	N 4,119,893.8 m E 547,670.8 m
Ground Elevation:	1,900.1 m (6,234 ft)	
DRILLING DATA		
Spud Date:	03/20/1980 (Surface Hole) 04/06/1980 (Main Hole)	
Total Depth (TD):	670.6 m (2,200 ft)	
Date TD Reached:	05/31/1980	
Hole Diameter:	3.1 m (122 in.) from surface to 2.6 m (8.5 ft); 3.0 m (120 in.) from 2.6 to 19.2 m (8.5 - 63 ft); 2.4 m (96 in.) from 19.2 to 670.6 m (63 - 2,200 ft).	
Drilling Techniques:	Dual string with reverse circulation using air and water, and lost circulation material as needed.	
Fluid Depth:	614.8 m (2,017 ft) on 06/21/1980	
CASING DATA		
	2.5 m (98 in.) inner diameter (id) from surface to 18.3 m (60 ft); 1.9 m (74 in.) id from 597.7 to 655.6 m (1,961 - 2,151 ft)	

Source: F&S, 1980.

Table 2-16
Lithologic Samples Available for U20ag

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 24.4 to 670.6 m (80 - 2,200 ft) at 3.0 m (10 ft) intervals. Missing sample at 472.4 m (1,550 ft) depth.

a Sample depth represents base of sample interval.

Table 2-17
Geophysical Logs Used to Evaluate the Geology at U20ag

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	06/06/1980	6.1 to 609.6 m (20 - 2,000 ft)
	2	09/05/1981	9.1 to 596.8 m (30 - 1,958 ft)
	3	09/05/1981	578.5 to 653.5 m (1,898 - 2,144 ft)
Gamma Ray	1	09/05/1981	18.3 to 597.4 m (60 - 1,960 ft)
Electric (wet hole)	1	06/07/1980	614.5 to 670.6 m (2,016 - 2,200 ft)
Electric (dry hole)	1	06/07/1980	15.2 to 611.1 m (50 - 2,005 ft)
Density	1	06/06/1980	15.2 to 669.6 m (50 - 2,197 ft)
Epithermal Neutron Porosity	1	06/08/1980	14.0 to 671.8 m (46 - 2,204 ft)
Magnetometer Survey	1	06/13/1980	21.3 to 671.5 m (70 - 2,203 ft)

Table 2-18
Laboratory Analyses for Samples from U20ag

Depth [a] meters (feet)	Sample Type [b]	Analyses Performed [c]							
		Petrographic		Mineralogic		Chemical			
		GM	TS	MP	XRD	XRF	NAA	ES	CO_2
24.4 (80)	DB1	--	--	--	--	--	--	--	✓
33.5 (110)	DB1	--	--	--	--	--	--	--	✓
70.1 (230)	DB1	--	--	--	--	--	--	--	✓
79.2 (260)	DB1	--	--	--	--	--	--	--	✓
82.3 (270)	DB1	--	--	--	✓	--	--	--	--
88.4 (290)	DB1	--	--	--	--	--	--	--	✓
97.5 (320)	DB1	--	--	--	--	--	--	--	✓
115.8 (380)	DB1	--	--	--	--	--	--	--	✓
134.1 (440)	DA	--	--	--	--	--	--	--	✓
140.2 (460)	DA	--	--	--	✓	--	--	--	--
143.3 (470)	DA	--	--	--	--	--	--	--	✓
189.0 (620)	DA	--	--	--	--	--	--	--	✓
204.2 (670)	DA	--	--	--	✓	--	--	--	--
207.3 (680)	DA	--	--	--	✓	--	--	--	--
249.9 (820)	DB1	--	--	--	--	--	--	--	✓
280.4 (920)	DB1	--	--	--	--	--	--	--	✓
289.6 (950)	DA	--	--	--	✓	--	--	--	--
301.8 (990)	DA	--	--	--	--	--	--	--	✓
307.8 (1,010)	DA	--	--	--	✓	--	--	--	--
320.0 (1,050)	DA	--	--	--	✓	--	--	--	--
329.2 (1,080)	DB1	--	--	--	--	--	--	--	✓
356.6 (1,170)	DA	--	--	--	✓	--	--	--	--

a Depth represents base of sample interval.
b DB1 = Drill cuttings enriched in hard components; DA = drill cuttings that represent lithologic character of interval.
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy; CO_2 = carbon-dioxide content.

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

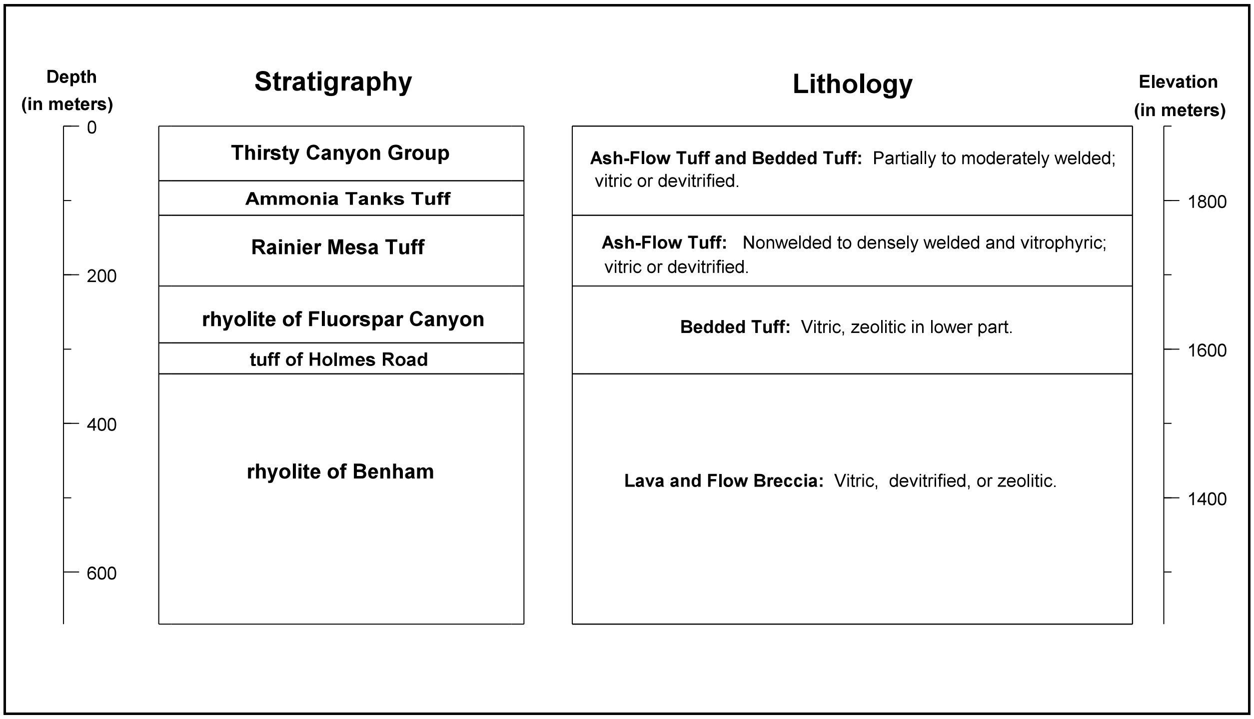

Figure 2-3
Stratigraphic and Lithologic Columns for U20ag

2.4 Emplacement Hole U20ao

U20ao is a large-diameter emplacement hole drilled in 1985 to a depth of 655.3 m (2,150 ft). The hole was the site of the GOLDSTONE underground nuclear test conducted in 1985. The test had an announced yield between 20 and 150 kilotons (DOE, 2000) and was conducted at a depth of 549 m (1,801 ft), approximately 47.5 m (156 ft) above the water table, within devitrified lava of the rhyolite of Benham. Table 2-19 provides hole construction information for U20ao.

2.4.1 Geologic Data for U20ao

During the drilling of U20ao, samples of drill cuttings were collected at 3.0-m (10-ft) intervals from 9.1 to 655.3 m (30 - 2,150 ft), and these are the only lithologic samples available from the hole (Table 2-20). Table 2-21 lists the wireline logs used during this study to help evaluate the geology of the hole. Information from existing x-ray diffraction analyses of drill cuttings from four depths in U20ao was utilized (Table 2-22). No additional laboratory analyses were performed on samples from the hole during this study. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Table 2-19
Hole Construction Data for Emplacement Hole U20ao

LOCATION DATA		
Coordinates:	Central Nevada State Planar:	N 905,600 ft E 556,450 ft
	Universal Transverse Mercator:	N 4,121,383.8 m E 546,766.6 m
Ground Elevation:	1,913.8 m (6,279 ft)	
DRILLING DATA		
Spud Date:	10/08/1984 (Surface Hole) 10/25/1984 (Main Hole)	
Total Depth (TD):	655.3 m (2,150 ft)	
Date TD Reached:	03/03/1985	
Hole Diameter:	3.5 m (136 in.) from surface to 6.1 m (20 ft); 3.0 m (120 in.) from 6.1 to 655.3 m (20 - 2,150 ft).	
Drilling Techniques:	Dual string with reverse circulation using air and water, and lost circulation material as needed.	
Fluid Depth:	596.5 m (1,957 ft) on 07/08/1985	
CASING DATA		
	3.1 m (122 in.) from surface to 5.9 m (19.5 ft).	

Source: F&S, 1985.

Table 2-20
Lithologic Samples Available for U20ao

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 9.1 to 655.3 m (30 - 2,150 ft) at 3.0 m (10 ft) intervals. Missing samples at 12.2 m (40 ft), 173.7 m (570 ft), 350.5 m (1,150 ft), 353.6 m (1,160 ft), and 374.9 m (1,230 ft) depths.

a Individual sample depths represent base of sample interval.

Table 2-21
Geophysical Logs Used to Evaluate the Geology at U20ao

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	11/08/1984	2.4 to 203.9 m (8 - 669 ft)
	2	02/02/1985	1.5 to 539.2 m (5 - 1,769 ft)
	3	03/06/1985	1.5 to 653.8 m (5 - 2,145 ft)
Gamma Ray	1	04/07/1985	18.3 to 654.7 m (10 - 2,148 ft)
Electric (wet hole)	1	04/04/1985	594.4 to 653.8 m (1,950 - 2,145 ft)
	2	05/07/1985	595.0 to 652.3 m (1,952 - 2,140 ft)
Electric (dry hole)	1	04/07/1985	7.6 to 591.3 m (25 - 1,940 ft)
	2	05/08/1985	5.8 to 591.3 m (19 - 1,940 ft)
Big Hole Density	1	04/07/1985	3.4 to 652.6 m (11 - 2,141 ft)
	2	08/17/1985	3.0 to 598.6 m (10 - 1,964 ft)
Special Density	1	04/07/1985	7.6 to 652.3 m (25 - 2,140 ft)
	2	05/08/1985	2.1 to 651.7 m (7 - 2,138 ft)
Epithermal Neutron Porosity	1	04/04/1985	260.3 to 654.4 m (854 - 2,147 ft)
	2	04/07/1985	220.4 to 258.8 m (723 - 849 ft)
	3	08/14/1985	3.0 to 600.2 m (10 - 1,969 ft)

Table 2-22
Laboratory Analyses for Samples from U20ao

Depth [a] meters (feet)	Sample Type [b]	Analyses Performed [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
152.4 (500)	DB1	--	--	--	✓	--	--	--
326.1 (1,070)	DB1	--	--	--	✓	--	--	--
390.1 (1,280)	DB1	--	--	--	✓	--	--	--
417.6 (1,370)	DA	--	--	--	✓	--	--	--

a Depth represents base of sample interval.
b DB1 = Drill cuttings enriched in hard components; DA = drill cuttings that represent lithologic character of interval.
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.4.2 Geology of U20ao

Rocks penetrated at U20ao represent stratigraphic units assigned to the Thirsty Canyon Group, Volcanics of Fortymile Canyon, Timber Mountain Group, and Paintbrush Group, all Area 20 caldera-burying units. Above 425.5 m (1,396 ft), the hole encountered ash-flow tuff and bedded tuff (Figure 2-4). Rhyolitic lava and flow breccia were encountered from 425.5 m (1,396 ft) to the bottom of the hole at 625.1 m (2,150 ft). Rocks above 414.5 m (1,360 ft) are mostly vitric or devitrified. Below 414.5 m (1,360 ft), the rocks encountered are vitric, devitrified, or zeolitic. A detailed lithologic log of U20ao is provided in Appendix A. The fluid level in the open borehole was measured at 596.5 m (1,957 ft) (F&S, 1985) within vitric lava of the rhyolite of Benham.

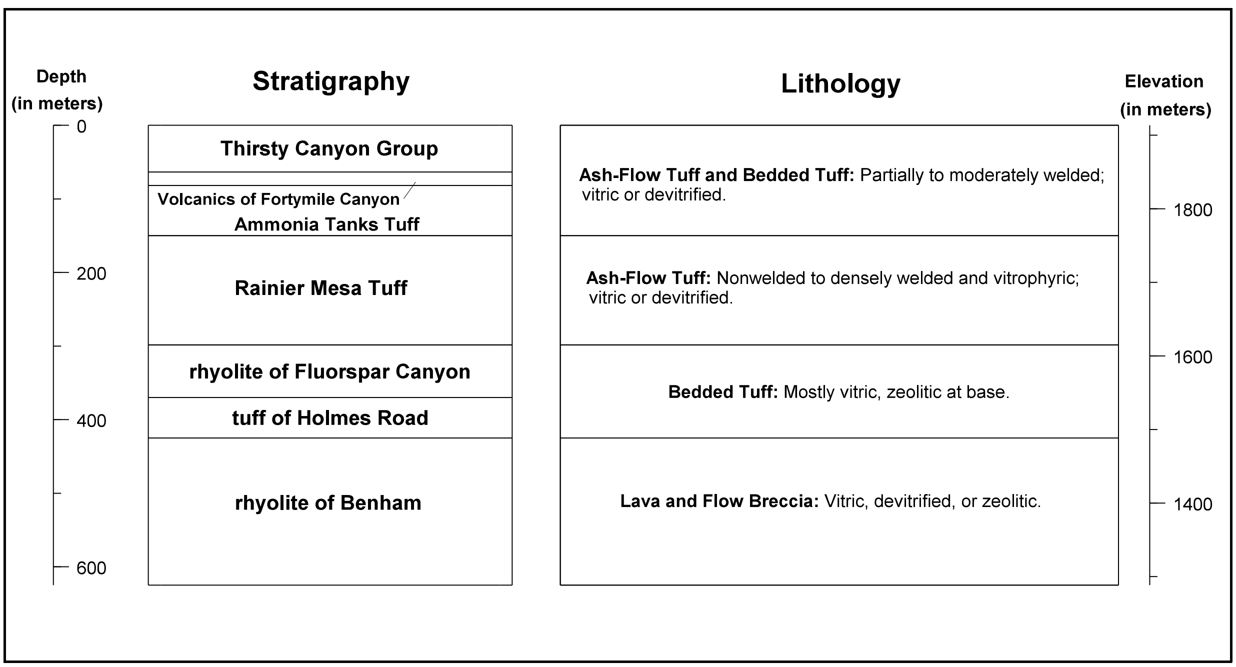

Figure 2-4
Stratigraphic and Lithologic Columns for U20ao

2.5 Emplacement Hole U20as

U20as is a large-diameter emplacement hole drilled in 1986 to a total depth of 640.5 m (2,100 ft). The hole was the site of the BELMONT underground nuclear test conducted in 1986. The test had an announced yield between 20 and 150 kilotons (DOE, 2000) and was conducted at a depth of 605 m (1,985 ft), approximately 8.5 m (28 ft) above the water table within zeolitic bedded tuff of the rhyolite of Benham. Table 2-23 provides hole construction information for U20as.

Table 2-23
Hole Construction Data for Emplacement Hole U20as

LOCATION DATA			
Coordinates:	Central Nevada State Planar:		N 899,201 ft E 559,699 ft
	Universal Transverse Mercator:		N 4,119,437.4 m E 547,763.5 m
Ground Elevation:	1,897.9 m (6,227 ft)		
DRILLING DATA			
Spud Date:	11/25/1985 (Surface Hole) 02/13/1986 (Main Hole)		
Total Depth (TD):	640.5 m (2,100 ft)		
Date TD Reached:	04/12/1986		
Hole Diameter:	4.3 m (168 in.) from 2.4 to 8.2 m (8 - 27 ft); 3.6 m (142 in.) from 8.2 to 22.3 m (27 - 73 ft); 2.4 cm (96 in.) from 22.3 to 640.5 m (73 - 2,100 ft).		
Drilling Techniques:	Dual string with reverse circulation using air and water. Hole sloughing at 235.6 m (773 ft) and again at 384.3 m (1,261 ft).		
Fluid Depth:	613.6 m (2,013 ft) on 06/06/1986 (O'Hagan and Laczniak, 1996)		
CASING DATA:			
	2.5 m (98 in.) id from surface to 21.0 m (69 ft)		

Source: F&S, 1986.

2.5.1 Geologic Data for U20as

During the drilling of U20as, samples of drill cuttings were collected at 3.0-m (10-ft) intervals from 21.3 to 640.1 m (70 - 2,100 ft) (Table 2-24). Table 2-25 lists the wireline logs used during this study to help evaluate the geology of the hole. Information from existing laboratory analyses of drill cuttings from 15 depths in U20as were also available and utilized for this study (Table 2-26). These analyses included grain-mount petrography and x-ray diffraction. Additional laboratory analyses, consisting of thin-section petrography, were performed during this study on drill cuttings from two depths in the hole. Drill cuttings from one of these depths (365.8 m [1,200 ft]) had previously been analyzed by x-ray diffraction. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Table 2-24
Lithologic Samples Available for U20as

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 21.3 to 640.1 m (70 - 2,100 ft) at 3.0 m (10 ft) intervals. Missing sample at 198.1 m (650 ft) depth.

a Sample depth represents base of sample interval.

Table 2-25
Geophysical Logs Used to Evaluate the Geology at U20as

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	04/14/1986	9.8 to 638.6 m (32 - 2,095 ft)
Gamma Ray	1	04/14/1986	6.1 to 638.9 m (20 - 2,096 ft)
Electric (dry hole)	1	05/01/1986	14.9 to 605.6 m (49 - 1,987 ft)
Big Hole Density	1	0507/1986	18.3 to 633.4 m (60 - 2,078 ft)
Special Density	1	05/07/1986	12.2 to 634.0 m (40 - 2,080 ft)
Epithermal Neutron Porosity	1	05/07/1986	12.8 to 637.9 m (42 - 2,093 ft)
Epithermal Neutron Special	1	05/06/1986	9.8 to 634.9 m (32 - 2,083 ft)
Total Magnetic Intensity	1	04/15/1986	30.2 to 640.4 m (99 - 2,101 ft)

Table 2-26
Laboratory Analyses for Samples from U20as

Depth [a] meters (feet)	**Sample Type** [b]	**Analyses Performed** [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
304.8 (1,000)	DB1	--	--	--	✓	--	--	--
310.9 (1,020)	DB1	--	✓	--	--	--	--	--
335.3 (1,100)	DB1	--	--	--	✓	--	--	--
365.8 (1,200)	DB1	--	✓	--	✓	--	--	--
460.2 (1,510)	DB1	--	--	--	✓	--	--	--
472.4 (1,550)	DA	✓	--	--	--	--	--	--
478.5 (1,570)	DA	✓	--	--	✓	--	--	--
478.7 (1,600)	DA	✓	--	--	✓	--	--	--
518.2 (1,700)	DA	✓	--	--	✓	--	--	--
548.6 (1,800)	DA	✓	--	--	--	--	--	--
563.9 (1,850)	DA	--	--	--	✓	--	--	--
579.1 (1,900)	DA	✓	--	--	--	--	--	--
606.6 (1,990)	DA	✓	--	--	✓	--	--	--
624.8 (2,050)	DA	✓	--	--	--	--	--	--
634.0 (2,080)	DA	--	--	--	✓	--	--	--
640.1 (2,100)	DA	✓	--	--	--	--	--	--

a Depth represents base of sample interval.
b DB1 = Drill cuttings enriched in hard components; DA = drill cuttings that represent lithologic character of interval
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.5.2 Geology of U20as

U20as was drilled completely within Area 20 caldera-burying rocks, and reached TD in zeolitic bedded tuff of the rhyolite of Benham at 640.1 m (2,100 ft). Stratigraphic units encountered include, in descending order, units assigned to the Thirsty Canyon, Timber Mountain, and Paintbrush Groups. Figure 2-5 shows that the hole encountered ash-flow tuff and bedded tuff above 370.9 m (1,217 ft), rhyolitic lava and flow breccia from 370.9 to 485.9 m (1,217 - 1,594 ft), and bedded tuff below 485.9 m (1,594 ft). Rocks encountered are mainly vitric or devitrified above 352.0 m (1,155 ft), becoming vitric, devitrified, or zeolitic below. A detailed lithologic log for U20as is provided in Appendix A. Fluid level in the open borehole was measured at 613.6 m (2,013 ft) (O'Hagan and Laczniak, 1996) within zeolitic bedded tuff of the rhyolite of Benham.

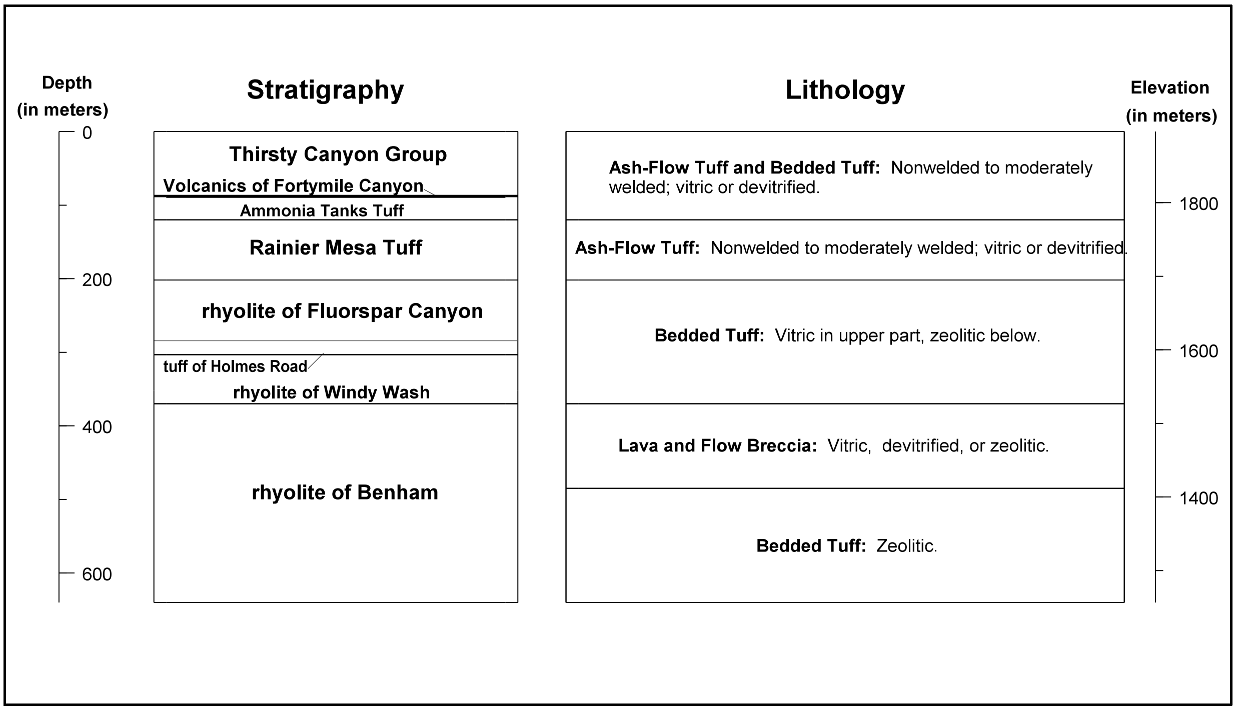

Figure 2-5
Stratigraphic and Lithologic Columns for U20as

2.6 Emplacement Hole U20c

U20c is a large-diameter emplacement hole drilled in 1964 to a depth of 1,463.0 m (4,800 ft). The hole was the site of the BENHAM underground nuclear test conducted in 1968. The test had an announced yield of 1.15 megatons (DOE, 2000), and was conducted in a mined chamber at a depth of 1,402 m (4,600 ft), approximately 762.0 m (2,500 ft) below the water table within zeolitic bedded tuff. Table 2-27 provides hole construction information for U20c.

Table 2-27
Hole Construction Data for Emplacement Hole U20c

LOCATION DATA		
Coordinates:	Central Nevada State Planar:	N 903,296 ft E 556,215 ft
	Universal Transverse Mercator:	N 4,120,681.5 m E 546,697.5 m
Ground Elevation:	1,914.4 m (6,281 ft)	
DRILLING DATA		
Spud Date:	06/26/1964	
Total Depth (TD):	1,463.0 m (4,800 ft)	
Date TD Reached:	04/02/1965	
Hole Diameter:	305 cm (120 in.) from surface to 3.7 m (12 ft). 182.9 cm (72 in.) to TD.	
Drilling Techniques:	182.9 cm (72-in.) flat-bottom bit and reverse circulation method with air, water, soap and infrequent lost-circulation material used from surface to 632.4 m (2,075 ft). Dual-string reverse circulation with air, water, and soap used to TD. 182.9 cm (72-in.) button bit used from 696.75 m (2,286 ft) to TD. Six intermittent cores were center-punched from 1,386.5 m (4,549 ft) to TD.	
Fluid Depth:	639.2 m (2,097 ft) on 02/25/1965 (O'Hagan and Laczniak, 1996)	
CASING DATA		
	121.9 cm (48 in.) id from surface to 1449.3 m (4,755 ft)	

Source: F&S, 1966.

2.6.1 Geologic Data for U20c

Drill cuttings were collected at 1.5-m (5-ft) intervals from 1,112.5 to 1,307.6 m (3,650 - 4,290 ft), and at 3.0-m (10-ft) intervals from 1,307.6 to 1,463.0 m (4,290 - 4,800 ft). Six continuous intervals of conventional core were taken intermittenly from 1,386.5 to 1,463.0 m (4,549 - 4,800 ft). Core intervals ranged from 4.9 to 7.0 m (16 - 23 ft) in length, and the total amount of core recovered was 36.6 m (120 ft). Available lithologic samples are summarized in Table 2-28. Only a few wireline geophysical logs were run at U20c, and only caliper logs were run through the interval above 661.4 m (2,170 ft). Table 2-29 lists the logs used during this study to help evaluate the geology of the hole. No existing laboratory analyses were available from U20c, however during this study, laboratory analyses were performed for five

Table 2-28
Lithologic Samples Available for U20c

Sample Type	Sample Intervals and Recovery [a]		
Drill Cuttings	From 1,112.5 to 1,307.6 m (3,650 - 4,290 ft) at 1.5-m (5-ft) intervals. Missing samples at 1,179.6-m (3,870-ft) and 1,190.2-m (3,905-ft) depths. From 1,307.6 to 1,463.0 m (4,290 - 4,800 ft) at 3.0-m (10-ft) intervals. Missing sample at 1,344.2-m (4,410-ft) depth.		
Conventional Core	**Core Interval**	**Amount Cored**	**Amount Recovered**
	1,386.5 - 1,393.5 m (4,549 - 4,572 ft)	7.0 m (23 ft)	7.0 m (23 ft)
	1,399.3 - 1,404.2 m (4,591 - 4,607 ft)	4.9 m (16 ft)	4.9 m (16 ft)
	1,414.3 - 1,420.7 m (4,640 - 4,661 ft)	6.4 m (21 ft)	6.4 m (21 ft)
	1,429.5 - 1,435.6 m (4,690 - 4,710 ft)	6.1 m (20 ft)	6.1 m (20 ft)
	1,445.1 - 1,451.2 m (4,741 - 4,761 ft)	6.1 m (20 ft)	6.1 m (20 ft)
	1,456.9 - 1,463.0 m (4,780 - 4,800 ft)	6.1 m (20 ft)	6.1 m (20 ft)

a Individual sample depths represent base of sample interval.

Table 2-29
Geophysical Logs Used to Evaluate the Geology at U20c

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	10/14/1964	0 to 907.7 m (0 - 2,978 ft)
	2	12/15/1964	0 to 1,202.7 m (0 - 3,946 ft)
	3	01/01/1965	4.6 to 1,261.9 m (15 - 4,140 ft)
	4	04/06/1965	3.0 to 1,463.0 m (10 - 4,800 ft)
Electric (WELEX)	1	02/22/1965	1,383.8 to 1,462.7 m (4,540 - 4,799 ft)
Electric (Birdwell)	1	02/04/1966	661.4 to 1,371.6 m (2,170 - 4,500 ft)
Big Hole Density	1	02/22/1965	1,386.8 to 1,461.8 m (4,550 - 4,796 ft)

lithologic samples (Table 2-30). These analyses include thin-section petrography, x-ray diffraction, x-ray fluorescence, and emission spectroscopy. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Table 2-30
Laboratory Analyses for Samples from U20c

Depth [a] meters (feet)	**Sample Type** [b]	**Analyses Performed** [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
1,303.0 (4,275)	DA	--	--	--	✓	✓	--	--
1,387.5 (4,552.3)	C	--	✓	--	✓	--	--	--
1,402.1 (4,600)	C	--	--	--	--	--	--	✓
1,418.4 (4,643.7)	C	--	✓	--	✓	--	--	--
1,461.2 (4,794)	C	--	✓	--	--	--	--	--

a Depth represents base of sample interval.
b DA = drill cuttings that represent lithologic character of interval; C = conventional core
c ✓ = analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.6.2 Geology of U20c

Because limited data exist above the 661.4 m (2,170 ft) depth in U20c, the geologic descriptions for this portion of the hole are based on lithologic descriptions from nearby hole UE20c, and correlation of geophysical logs from the two holes. U20c penetrated 937.3 m (3,075 ft) of Area 20 caldera-burying rocks consisting of ash-flow tuff, bedded tuff, and lava, before encountering 525.8 m (1,725 ft) of Area 20 caldera-filling bedded tuff and lava of the Calico Hills Formation (Figure 2-6). The hole reached TD in bedded tuff of the mafic-rich Calico Hills Formation at 1,463.0 m (4,800 ft). Above 617.2 m (2,025 ft), the rocks encountered are vitric or devitrified. Below 617.2 m (2,025 ft) to the base of the mafic-poor Calico Hills Formation lava at 1,333.8 m (4,376 ft), the rocks are vitric, devitrified or zeolitic. The bedded tuff below the Calico Hills lava shows diverse zones of alteration, including zeolitic, silicic, and quartzo-feldspathic (potassic), based on petrographic analysis.

The detailed lithologic log for U20c is provided in Appendix A. The fluid level in the hole was measured at 639.2 m (2,097 ft) (O'Hagan and Laczniak, 1996) within welded ash-flow tuff of the Tiva Canyon Tuff.

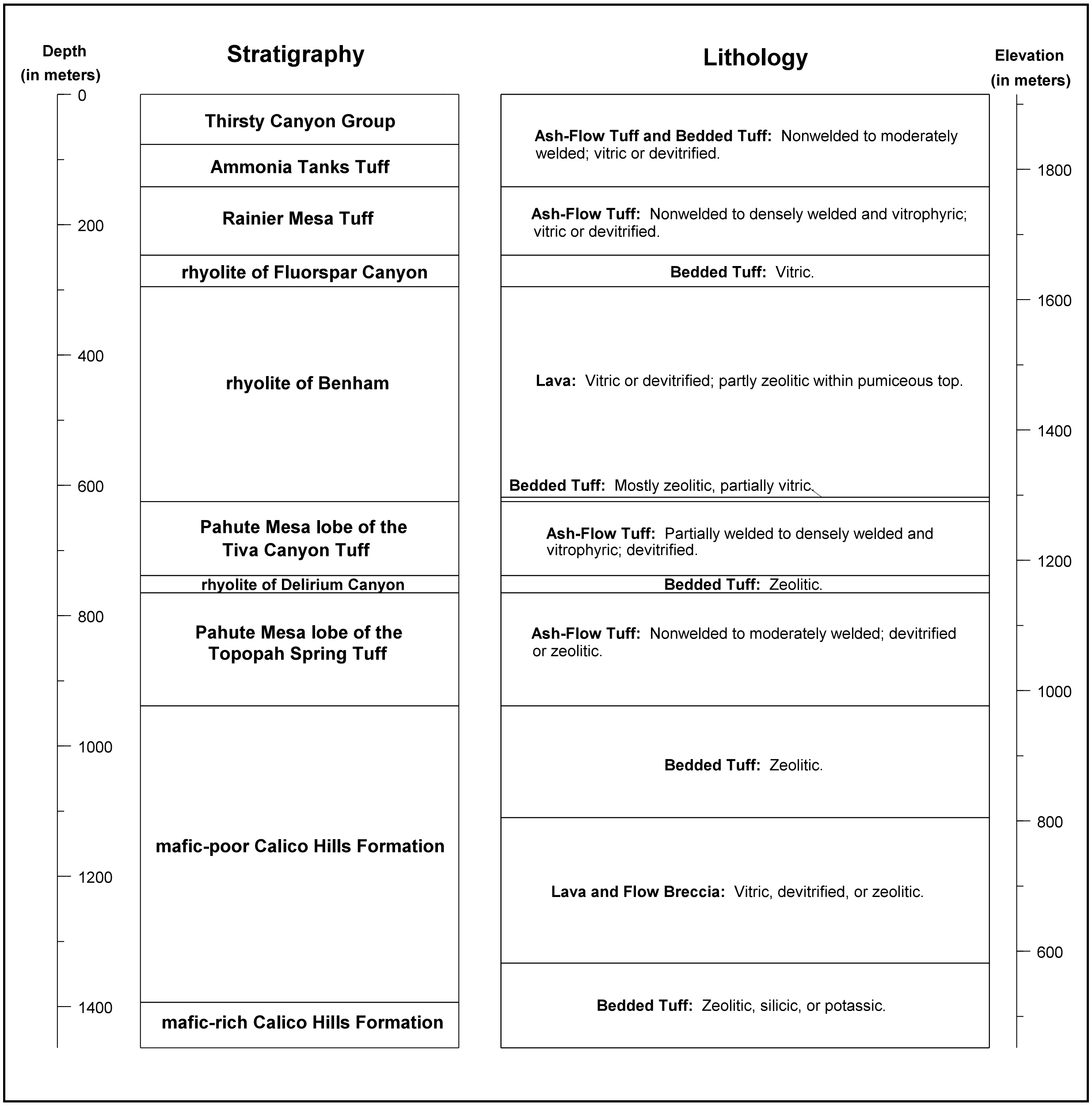

Figure 2-6
Stratigraphic and Lithologic Columns for U20c

2.7 Exploratory Hole UE20c

UE20c is a 24.5-cm (9⅝-in.) diameter exploratory hole drilled in 1964 to evaluate the suitability of the site for the underground testing of nuclear weapons (Santos, 1964). The hole had a planned total depth of 1,828.8 m (6,000 ft), but drilling stopped at 1,630.1 m (5,348 ft) because of severe caving of the borehole. Table 2-31 provides hole construction information for UE20c.

Table 2-31
Hole Construction Data for Exploratory Hole UE20c

LOCATION DATA			
Coordinates:	Central Nevada State Planar:	N 903,204.33 ft E 556,762.61 ft	
	Universal Transverse Mercator:	N 4,120,654.1 m E 546,864.5 m	
Ground Elevation:	1,915.0 m (6,283.0 ft)		
DRILLING DATA			
Spud Date:	02/07/1964		
Total Depth (TD):	1,630 m (5,348 ft)		
Date TD Reached:	03/17/1964		
Hole Diameter:	66 cm (26 in.) from surface to 10 m (33 ft); 44.5 cm (17.5 in.) to 198 m (650 ft); 24.45 cm (9⅝ in.) to TD.		
Drilling Techniques:	44.5 cm (17½ in.) bit with dual string reverse circulation method using air to 30.5 m (100 ft). 31.1-cm (12¼-in.) bit with like method to 198.1 m (650 ft). 44.5 cm (17½ in.) widener to 198.1 m (650 ft). Thirty-five 15.56-cm (6⅛-in.) cores were collected intermittently from 137.2 - 1573.0 m (450 - 5,161 ft) with generally good recovery. Used 24.45-cm (9⅝-in.) widener where cored and same size bit where not cored using dual-string reverse circulation method with air to 635.2 m (2,084 ft) and air, water, and soap to TD.		
Fluid Depth:	648.0 m (2,126 ft) on 02/28/1964 (O'Hagan and Laczniak, 1996)		
CASING DATA	32.04 cm (12.615 in.) id from surface to 198 m (650 ft).		

Source: F&S, 1967.

2.7.1 Geologic Data for UE20c

Both drill cuttings and conventional cores were collected during drilling of UE20c (Tables 2-32 and 2-33). Drill cuttings were collected at 3.0 m (10 ft) intervals from 12.2 to 1,627.6 m (40 - 5,340 ft). Thirty-five conventional cores were taken intermittenly from 137.2 to 1,573.1 m (450 - 5,161 ft). Total core recovery was 84.7 m (278 ft). Because of borehole instability, two caliper logs were the only wireline logs run at UE20c (Table 2-34). Numerous laboratory analyses have been performed for lithologic samples from UE20c (Table 2-35). Prior to this study, a variety of analyses had been performed for samples from 46 depths. During this study, highly precise petrographic analyses were generated for 35 existing thin sections from these samples to replace questionable or less precise analyses. Also, during this study, thin-section petrography, x-ray diffraction, and x-ray fluorescence analyses were performed for samples from five additional depths. Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Table 2-32
Lithologic Samples Available for UE20c: Drill Cuttings

Sample Intervals and Recovery [a]		
Drill cuttings samples at 3.0-m (10-ft) intervals: 12.2 to 1,627.6 m (40 - 5,340 ft)		
Missing samples at:	140.2 m (460 ft)	914.4 m (3,000 ft)
	161.5 m (530 ft)	954.0 m (3,130 ft)
	164.6 m (540 ft)	960.1 m (3,150 ft)
	362.7 m (1,190 ft)	978.4 m (3,210 ft)
	365.8 m (1,200 ft)	1,008.9 m (3,310 ft)
	387.1 m (1,270 ft)	1,039.4 m (3,410 ft)
	524.3 m (1,720 ft)	1,069.8 m (3,510 ft)
	545.6 m (1,790 ft)	1,100.3 m (3,610 ft)
	646.2 m (2,120 ft)	1,130.8 m (3,710 ft)
	713.2 m (2,340 ft)	1,191.8 m (3,910 ft)
	716.5 m (2,350 ft)	1,252.7 m (4,110 ft)
	780.3 m (2,560 ft)	1,295.4 m (4,250 ft)
	795.5 m (2,610 ft)	1,383.8 m (4,540 ft)
	810.8 m (2,660 ft)	1,417.3 m (4,650 ft)
	826.0 m (2,710 ft)	1,420.4 m (4,660 ft)
	841.2 m (2,760 ft)	1,444.8 m (4,740 ft)
	856.5 m (2,810 ft)	1,502.7 m (4,930 ft)
	871.7 m (2,860 ft)	1,505.7 m (4,940 ft)
	887.0 m (2,910 ft)	1,569.7 m (5,150 ft)
	902.2 m (2,960 ft)	1,572.8 m (5,160 ft)
	911.4 m (2,990 ft)	

a Individual sample depths represent base of sample interval.

Table 2-33
Lithologic Samples Available for UE20c: Conventional Cores

Core Interval	Amount Cored	Amount Recovered
137.2 - 138.7 m (450 - 455 ft)	1.5 m (5 ft)	1.1 m (3.5 ft)
198.1 - 199.6 m (650 - 655 ft)	1.5 m (5 ft)	0.9 m (3 ft)
249.9 - 253.0 (820 - 830 ft)	3.0 m (10 ft)	0.0 m (0 ft)
361.2 - 364.2 m (1,185 - 1,195 ft)	3.0 m (10 ft)	3.0 m (10 ft)
411.5 - 413.9 m (1,350 - 1,358 ft)	2.4 m (8 ft)	1.8 m (6 ft)
457.2 - 459.6 m (1,500 - 1,508 ft)	2.4 m (8 ft)	2.3 m (7.5 ft)
523.0 - 525.5 m (1,716 - 1,724 ft)	2.4 m (8 ft)	0.9 m (3 ft)
586.7 - 588.6 m (1,925 - 1,931 ft)	1.8 m (6 ft)	1.8 m (6 ft)
647.7 - 650.1 m (2,125 - 2,133 ft)	2.4 m (8 ft)	1.8 m (6 ft)
712.6 - 715.7 m (2,338 - 2,348 ft)	3.0 m (10 ft)	3.0 m (10 ft)
777.2 - 780.3 m (2,550 - 2,560 ft)	3.0 m (10 ft)	3.0 m (10 ft)
792.5 - 795.5 m (2,600 - 2,610 ft)	3.0 m (10 ft)	3.0 m (10 ft)
807.7 - 810.0 m (2,650 - 2,657.5 ft)	2.3 m (7.5 ft)	2.3 m (7.5 ft)
823.0 - 826.0 m (2,700 - 2,710 ft)	3.0 m (10 ft)	3.0 m (10 ft)
838.2 - 841.2 m (2,750 - 2,760 ft)	3.0 m (10 ft)	3.0 m (10 ft)
853.4 - 856.5 m (2,800 - 2,810 ft)	3.0 m (10 ft)	3.0 m (10 ft)
868.7 - 871.7 m (2,850 - 2,860 ft)	3.0 m (10 ft)	3.0 m (10 ft)
883.9 - 887.0 m (2,900 - 2,910 ft)	3.0 m (10 ft)	3.0 m (10 ft)

Core Interval	Amount Cored	Amount Recovered
899.2 - 902.2 m (2,950 - 2,960 ft)	3.0 m (10 ft)	3.0 m (10 ft)
911.4 - 915.9 m (2,990 - 3,005 ft)	4.6 m (15 ft)	4.6 m (15 ft)
944.9 - 947.9 m (3,100 - 3,110 ft)	3.0 m (10 ft)	3.0 m (10 ft)
975.4 - 978.4 m (3,200 - 3,210 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,005.8 - 1,008.9 m (3,300 - 3,310 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,036.3 - 1,039.4 m (3,400 - 3,410 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,067.7 - 1,070.8 m (3,503 - 3,513 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,097.3 - 1,100.3 m (3,600 - 3,610 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,127.8 - 1,130.8 m (3,700 - 3,710 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,188.7 - 1,190.5 m (3,900 - 3,906 ft)	1.8 m (6 ft)	1.8 m (6 ft)
1,251.2 - 1,253.9 m (4,105 - 4,114 ft)	2.7 m (9 ft)	0.5 m (1.5 ft)
1,292.4 - 1,293.0 m (4,240 - 4,242 ft)	0.6 m (2 ft)	0.6 m (2 ft)
1,293.0 - 1,294.5 m (4,242 - 4,247 ft)	1.5 m (5 ft)	1.5 m (5 ft)
1,382.9 - 1,385.3 m (4,537 - 4,545 ft)	2.4 m (8 ft)	2.4 m (8 ft)
1,444.8 - 1,447.2 m (4,740 - 4,748 ft)	2.4 m (8 ft)	2.4 m (8 ft)
1,504.2 - 1,507.2 m (4,935 - 4,945 ft)	3.0 m (10 ft)	3.0 m (10 ft)
1,570.0 - 1,573.1 m (5,151 - 5,161 ft)	3.0 m (10 ft)	3.0 m (10 ft)

Table 2-34
Geophysical Logs Used to Evaluate the Geology at UE20c

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	02/14/1964	0 to 196.6 m (0 - 645 ft)
	2	04/10/2964	187.8 to 279.5 m (616 - 917 ft)

Table 2-35 (Page 1 of 2)
Laboratory Analyses for Samples from UE20c

Depth [a] meters (feet)	**Sample Type** [b]	**Analyses Performed** [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
363.0 (1,191)	C	--	✓	--	--	--	--	--
412.4 (1,353)	C	--	✓	--	--	--	--	✓
459.3 (1,507)	C	--	✓	--	--	--	--	--
523.6 (1,718)	C	--	✓	--	--	--	--	--
588.3 (1,930)	C	--	✓	--	--	--	--	✓
648.0 (2,126)	C	--	✓	--	--	--	--	--
650.1 (2,133)	C	--	✓	--	--	--	--	--
713.8 (2,342)	C	--	✓	--	--	--	--	--
731.5 (2,400)	DA	--	✓	--	--	--	--	--
778.2 (2,553)	C	--	✓	--	--	--	--	--
780.0 (2,559)	C	--	✓	✓	--	--	✓	--
793.1 (2,602)	C	--	✓	--	--	--	--	--
795.4 (2,609.5)	C	--	✓	✓	--	✓	✓	--
808.3 (2,652)	C	--	✓	--	--	--	--	--
808.9 (2,654)	C	--	✓	--	--	--	--	--
823.6 (2,702)	C	--	✓	--	--	--	--	--
826.0 (2,710)	C	--	✓	✓	--	--	✓	--
840.3 (2,757)	C	--	✓	--	--	--	--	--
853.4 (2,800)	C	--	--	--	--	--	✓	--
854.0 (2,802)	C	--	✓	--	--	--	--	--
871.1 (2,858)	C	--	✓	--	--	--	--	--
884.2 (2,901)	C	--	✓	✓	--	✓	✓	--

Table 2-35 (Page 2 of 2)
Laboratory Analyses for Samples from UE20c

Depth [a] meters (feet)	**Sample Type** [b]	**Analyses Performed** [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
884.5 (2,902)	C	--	✓	--	--	--	--	--
899.8 (2,952)	C	--	✓	--	--	--	--	--
901.3 (2,957)	C	--	--	--	--	--	✓	--
914.7 (3,001)	C	--	✓	--	--	--	--	--
915.9 (3,005)	C	--	✓	✓	--	--	✓	--
947.6 (3,109)	C	--	✓	--	--	--	--	--
947.9 (3,110)	C	--	✓	--	--	--	✓	--
978.1 (3,209)	C	--	✓	--	--	--	--	--
1,005.8 (3,300)	C	--	✓	--	--	--	--	--
1,036.9 (3,402)	C	--	✓	--	--	--	--	--
1,039.4 (3,410)	C	--	✓	--	--	--	✓	--
1,070.5 (3,512)	C	--	✓	--	--	--	--	--
1,097.4 (3,600.5)	C	--	✓	✓	--	--	✓	--
1,098.8 (3,605)	C	--	✓	--	--	--	--	--
1,100.3 (3,610)	C	--	✓	--	--	--	--	--
1,189.6 (3,903)	C	--	--	--	✓	✓	--	--
1,189.9 (3,904)	C	--	✓	--	--	--	--	✓
1,251.2 (4,105)	C	--	✓	--	--	--	--	✓
1,252.7 (4,110)	C	--	--	--	--	--	✓	--
1,294.2 (4,246)	C	--	✓	--	--	--	✓	--
1,383.2 (4,538)	C	--	✓	--	--	--	--	--
1,383.5 (4,539)	C	--	--	--	--	--	✓	--
1,446.3 (4,745)	C	--	✓	--	--	--	--	--
1,446.6 (4,746)	C	--	✓	--	✓	✓	--	--
1,496.6 (4,910)	DB2	--	✓	--	✓	--	--	--
1,505.1 (4,938)	C	--	✓	--	--	--	--	--
1,506.8 (4,943.7)	C	--	--	--	✓	✓	--	--
1,571.2 (5,155)	C	--	✓	--	--	--	--	--
1,573.1 (5,161)	C	--	--	--	✓	✓	--	--

a Depth represents base of sample interval.
b C = Conventional core; DA = drill cuttings that represent lithologic character of interval; DB2 = drill cuttings from interval different from that drilled.
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.7.2 Geology of UE20c

The geology encountered at UE20c (Figure 2-7) is very similar to that encountered at U20c (Figure 2-6). Although both holes bottomed in bedded tuff of the mafic-rich Calico Hills Formation, because UE20c is deeper, it encountered 133.5 m (438 ft) more of the formation. Also, abundant fragments of mudstone, including black silty shale and gray siltstone, are present intermittently in drill cuttings samples from 1,438.6 to 1,630.1 m (4,720 - 5,348ft) in UE20c. The mudstone fragments do not represent lithic fragments from tuffaceous units, and evidence strongly suggests that these sedimentary fragments are not from UE20c. Three conventional cores taken within the interval all consist of bedded tuff. The correlative interval in nearby U20c is bedded tuff, and no other holes at Pahute Mesa have encountered similar rocks. Well ER-19-1, located just west of Rainier Mesa, did encounter intervals of black phyllite, however, the intervals were within Early Paleozoic to Late Proterozoic rocks well below the contact with Tertiary volcanic rocks (Cole, 1997). Petrographic data suggests the shale and siltstone in the UE20c samples are Mississippian Chainman Shale. The nearest occurrence of Mississippian rocks is well outside the Silent Canyon caldera complex along the northern and western margins of Yucca Flat, approximately 25 to 30 km (16 - 19 mi) east of the TYBO-BENHAM area (Barnes et al., 1963; Gibbons et al., 1963; Orkild, 1963). The most plausible explanation for the presence of shale and siltstone within the UE20c samples is that they were introduced into the UE20c circulation system during drilling by equipment that had not been thoroughly cleaned from previous drilling operations. A likely source of the shale and siltstone in UE20c is exploratory hole UE1b. This hole, which was drilled at the same time as UE20c, encountered 163.1 m (535 ft) of Chainman Shale in western Yucca Flat (Cole, 1997).

The detailed lithologic log for UE20c is provided in Appendix A. The fluid level in the open borehole was measured at 648.0 m (2,126 ft) (O'Hagan and Laczniak, 1996) within welded ash-flow tuff of the Tiva Canyon Tuff.

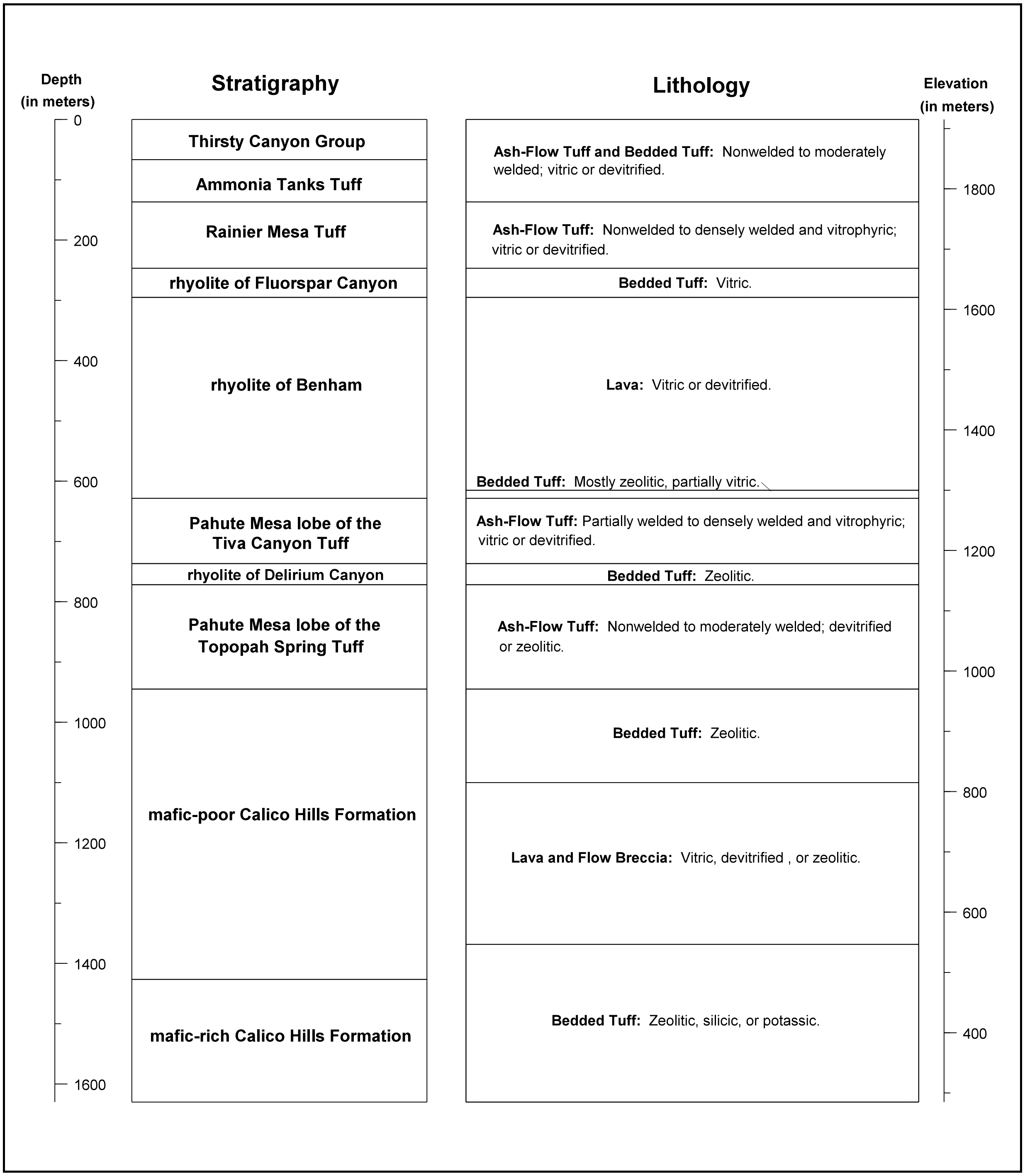

Figure 2-7
Stratigraphic and Lithologic Columns for UE20c

2.8 *Emplacement Hole U20y*

U20y is a large-diameter emplacement hole drilled in 1971 to a temporary depth of 586.7 m (1,925 ft). The hole was deepened to a final depth of 793.1 m (2,602 ft) in 1974. U20y was the site of the TYBO underground nuclear test conducted in 1975. The test had an announced yield in the range of 200 to 1,000 kilotons (DOE, 2000) and was conducted at a depth of 765 m (2,510 ft), approximately 135.0 m (443 ft) below the water table within partially welded ash-flow tuff of the Topopah Springs Tuff. Table 2-36 provides hole construction information for U20y.

Table 2-36
Hole Construction Data for Emplacement Hole U20y

LOCATION DATA			
Coordinates:	Central Nevada State Planar:	N 899,402 ft E 556,046 ft	
	Universal Transverse Mercator:	N 4,119,494.7 m E 546,650.2 m	
Ground Elevation:	1,907.1 m (6,257 ft)		
DRILLING DATA			
Spud Date:	04/12/1971 (Surface Hole) 06/05/1971 (Main Hole)		
Total Depth (TD):	586.7 m (1,925 ft) Temporary TD 793.1 m (2,602 ft) Final TD		
Date TD Reached:	08/31/1971 Temporary TD 12/16/1974 Final TD		
Hole Diameter:	3.0 m (120 in.) from surface to 15.9 m (52 ft); 2.4 m (96 in.) from 15.9 to 793.1 m (52 - 2,602 ft).		
Drilling Techniques:	Vacuum system from surface to 339.8 m (1,115 ft). Hole caved at 78.6 m (258 ft). Dual-string with reverse circulation using air and water from 339.8 to 793.1 m (1,115 - 2,602 ft). Hole caved at 790.6 m (2,594 ft).		
Fluid Depth:	630.0 m (2,067 ft) on 02/18/1975 (O'Hagan and Laczniak, 1996)		
CASING DATA			
	2.5 m (98 in.) id from surface to 15.8 m (52 ft); 1.8 m (72 in.) id from 551.7 to 787.6 m (1,810 - 2,584 ft).		

Source: F&S, 1971.

2.8.1 Geologic Data for U20y

During the drilling of U20y, drill cuttings were collected at 3.0-m (10-ft) intervals from 79.2 to 792.5 m (260 - 2,600 ft) (Table 2-37). Table 2-38 lists the wireline logs used during this study to help evaluate the geology of the hole. Information from existing laboratory analyses of drill cuttings from 19 depths in U20as was also utilized for this study (Table 2-39). These analyses included grain-mount and thin-section petrography, and x-ray diffraction. Additional laboratory analyses, consisting of thin-section petrography, x-ray diffraction, and x-ray fluorescence, were performed during this study on drill cuttings from three additional depths in the hole. Thin-section petrography was also performed on drill cuttings from 460.2 m (1,520 ft) which previously had been analyzed by x-ray diffraction only. Stratigraphic, lithologic, and alteration assignments for each sample are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

Table 2-37
Lithologic Samples Available for U20y

Sample Type	Sample Intervals and Recovery [a]
Drill Cuttings	From 79.2 to 792.5 m (260 - 2,600 ft) at 3.0-m (10-ft) intervals. Missing samples at 118.9-m (390-ft), 621.8-m (2,040-ft), and 789.4-m (2,590-ft) depths.

a Individual sample depths represent base of sample interval.

Table 2-38
Geophysical Logs Used to Evaluate the Geology at U20y

Type of Log	Run Number	Date Run	Interval Logged
Caliper	1	07/19/1971	3.0 to 338.9 m (10 - 1,112 ft)
	2	07/28/1971	0 to 465.1 m (0 - 1,526 ft)
	3	08/12/1971	3.0 to 561.4 m (10 - 1,842 ft)
	4	08/26/1971	3.0 to 585.2 m (10 - 1,920 ft)
Big Hole Density	1	10/22/1971	15.2 to 556.9 m (50 - 1,827 ft)
Epithermal Neutron Porosity	1	01/17/1975	3.0 to 788.2 m (10 - 2,586 ft)

Table 2-39
Laboratory Analyses for Samples from U20y

Depth [a] meters (feet)	Sample Type [b]	Analyses Performed [c]						
		Petrographic		Mineralogic		Chemical		
		GM	TS	MP	XRD	XRF	NAA	ES
341.4 (1,120)	DA	--	✓	--	--	--	--	--
374.9 (1,230)	DA	--	✓	--	--	--	--	--
384.0 (1,260)	DA	✓	--	--	--	--	--	--
426.7 (1,400)	DA	✓	--	--	--	--	--	--
442.0 (1,450)	DA	--	✓	--	✓	--	--	--
454.2 (1,490)	DB1	--	--	--	✓	--	--	--
457.2 (1,500)	DA	✓	--	--	--	--	--	--
460.2 (1,510)	DA	--	✓	--	✓	--	--	--
463.3 (1,520)	DA	--	--	--	✓	--	--	--
466.3 (1,530)	DB1	✓	--	--	✓	--	--	--
472.4 (1,550)	DA	✓	--	--	--	--	--	--
490.7 (1,610)	DA	--	✓	--	--	--	--	--
493.8 (1,620)	DA	--	✓	--	--	--	--	--
521.2 (1,710)	DA	--	✓	--	--	--	--	--
560.8 (1,840)	DA	--	✓	--	--	--	--	--
570.0 (1,870)	DA	--	✓	--	--	--	--	--
640.1 (2,100)	DA	--	--	--	✓	✓	--	--
762.0 (2,500)	DA	--	✓	--	--	--	--	--
768.1 (2,520)	DA	--	✓	--	--	--	--	--
771.1 (2,530)	DA	--	--	--	✓	--	--	--
774.2 (2,540)	DA	--	✓	--	✓	--	--	--
783.3 (2,570)	DA	--	✓	--	✓	✓	--	--

a Depth represents base of sample interval.
b DA = Drill cuttings that represent lithologic character of interval; DB1 = drill cutting that are enriched in hard components
c ✓ = Analysis performed; -- = analysis not performed; GM = grain mount; TS = thin section; MP = electron microprobe; XRD = x-ray diffraction; XRF = x-ray fluorescence; NAA = neutron activation analysis; ES = emission spectroscopy.

Note: Stratigraphic, lithologic, and alteration assignments for each sample analyzed are provided in Appendix B. Analytical data for each analysis are available in Warren et al. (1999).

2.8.2 Geology of U20y

U20y was drilled completely within Area 20 caldera-burying rocks, reaching TD in partially welded ash-flow tuff of the Pahute Mesa lobe of the Topopah Spring Tuff at 793.1 m (2,602 ft). Figure 2-8 shows that the hole encountered ash-flow tuff and bedded tuff above 195.1 m (640 ft), rhyolitic lava from 195.1 to 374.9 m (640 - 1,230 ft), and bedded tuff and welded ash-flow tuff below 374.9 m (1,230 ft). Rocks encountered are mainly vitric and devitrified above 374.9 m (1,230 ft), becoming mostly zeolitic and devitrified below. A detailed lithologic log for U20y is provided in Appendix A. Fluid level in the hole was measured at 630.0 m (2,067 ft) (O'Hagan and Laczniak, 1996) within zeolitic bedded tuff of the rhyolite of Delirium Canyon.

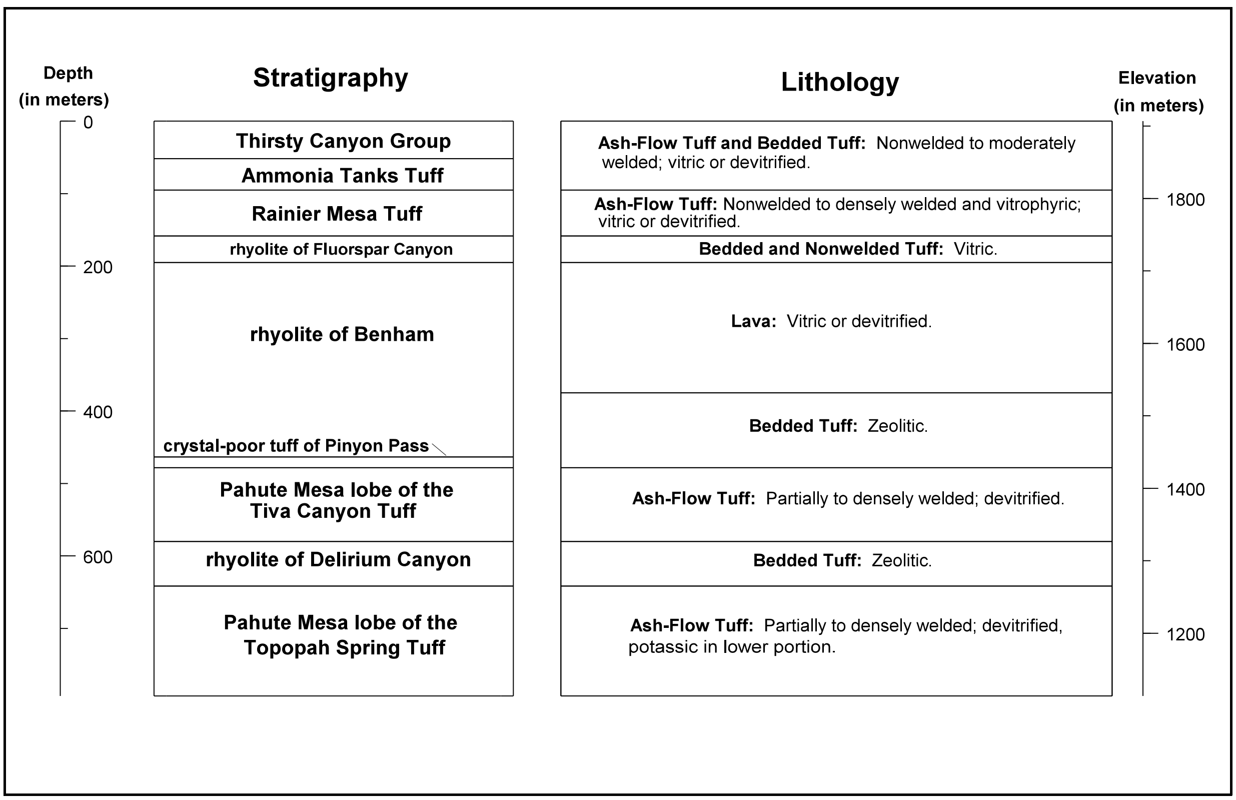

Figure 2-8
Stratigraphic and Lithologic Columns for U20y

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3.0 Geology of the TYBO-BENHAM Area

This section presents results of a detailed subsurface geologic analysis of the TYBO-BENHAM area based mainly on data from the updated geologic descriptions of drill holes presented in Section 2.0. Information from the surrounding region, including drill hole data, surface geology, and information from other subsurface studies, was also incorporated into the analysis to assure that results and conclusions were consistent with regional geologic trends. Section 3.1 describes the nature and extent of stratigraphic units encountered in drill holes in the TYBO-BENHAM area. Both local and regional structural features recognized during the study are discussed in Section 3.2. Section 3.3 describes the type and distribution of alteration minerals in the area. Finally, in Section 3.4, the hydrogeologic implications of the geologic features presented in the previous sections are considered, particularly with regards to modeling groundwater flow and radionuclide migration. Figure 3-1 shows the locations of various geologic features and drill holes in the TYBO-BENHAM region, and is provided as a reference map for all the discussions in Section 3.0.

3.1 Stratigraphic Units

Stratigraphic units encountered in drill holes within the TYBO-BENHAM area are described in this section, in descending order from youngest to oldest. Pairs of west-east and north-south cross sections of stratigraphic and lithologic units are provided for reference in Figures 3-2 through 3-5. A chart showing the relationships of all units was provided in Table 1-5.

3.1.1 Thirsty Canyon Group

The Thirsty Canyon Group was erupted from the Black Mountain caldera west of the TYBO-BENHAM area 9.6 million years ago (Ma) (Sawyer et al., 1994). Three units within this stratigraphic assemblage, all ash-flow sheets, occur in the TYBO-BENHAM area: the Trail Ridge, Pahute Mesa, and Rocket Wash Tuffs. Each of these units has a distinctive magnetic and petrographic signature. The Trail Ridge Tuff, which forms the surface in much of the study area, is moderately crystal-rich and has anomalous reverse magnetic polarity (Sawyer et al., 1994). Pahute Mesa Tuff is strongly zoned, with a crystal-rich top and crystal-poor base, and anomalous reverse magnetic polarity that differs from that of Trail Ridge Tuff. Rocket Wash Tuff is less crystal-rich than Trail Ridge Tuff and has a typical reverse magnetic polarity. The Thirsty Canyon Group is widely exposed at the surface of Pahute

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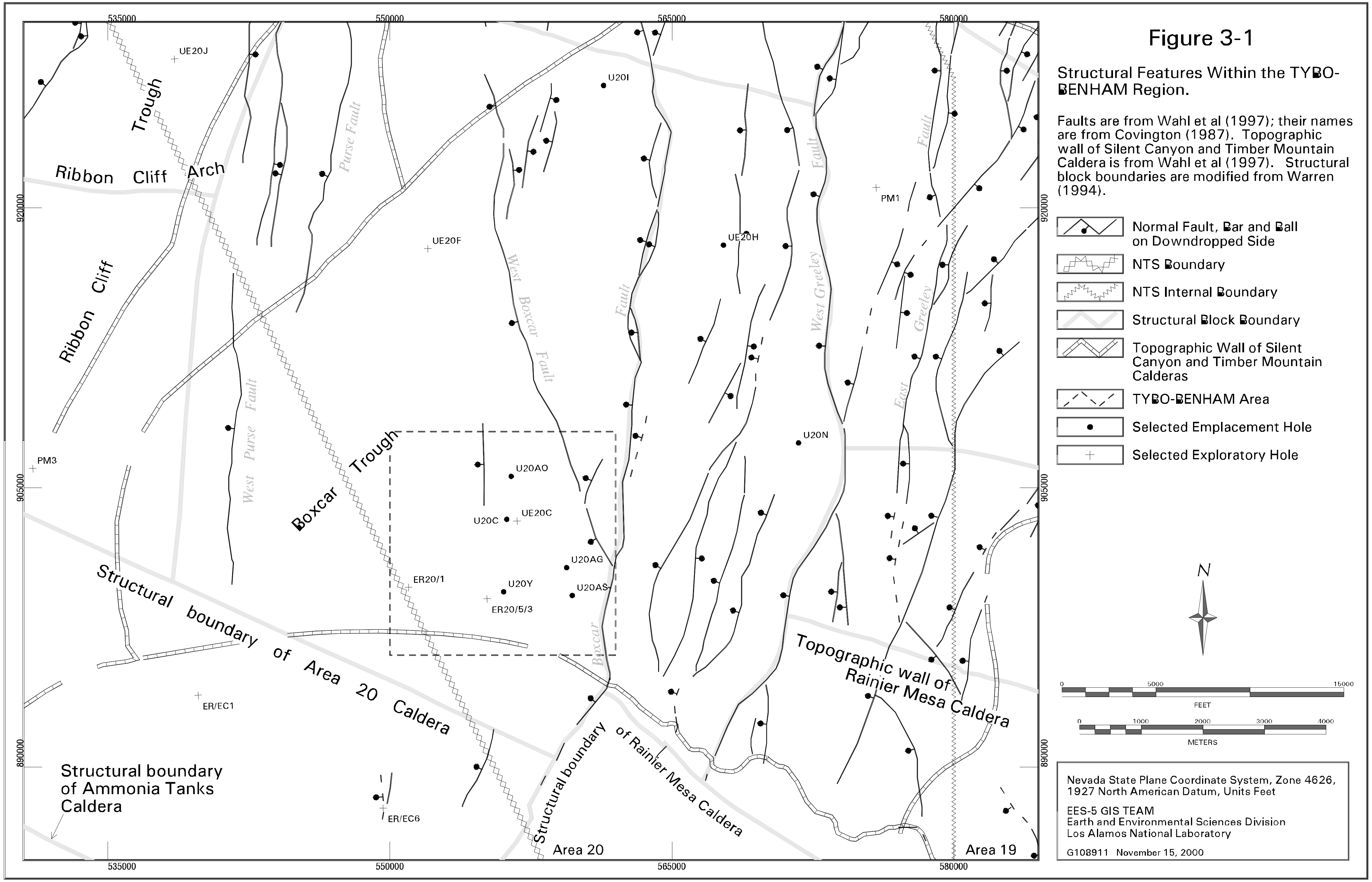

Figure 3-1

Structural Features Within the TYBO-BENHAM Region.

Faults are from Wahl et al (1997); their names are from Covington (1987). Topographic wall of Silent Canyon and Timber Mountain Caldera is from Wahl et al (1997). Structural block boundaries are modified from Warren (1994).

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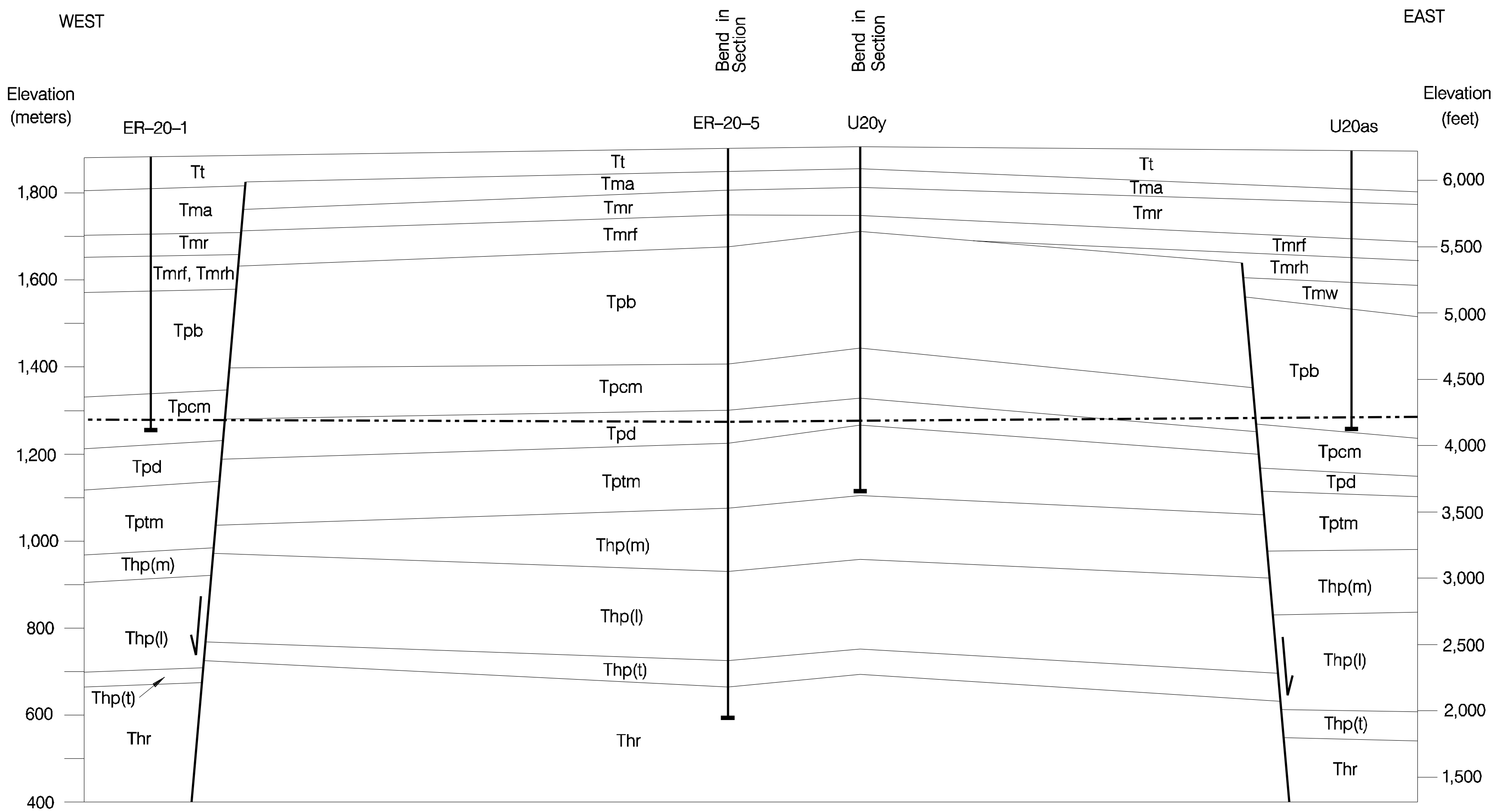


Tt = Thirsty Canyon Group, undivided
Tma = Ammonia Tanks Tuff
Tmr = Rainier Mesa Tuff
Tmrf = rhyolite of Fluorspar Canyon
Tmrh = tuff of Holmes Road

Tmw = rhyolite of Windy Wash
Tpb = rhyolite of Benham
Tpcm = Pahute Mesa lobe of Tiva Canyon Tuff
Tpd = rhyolite of Delirium Canyon (includes rhyolite of Black Glass Canyon in ER–20–5 #3)
Tptm = Pahute Mesa lobe of Topopah Spring Tuff

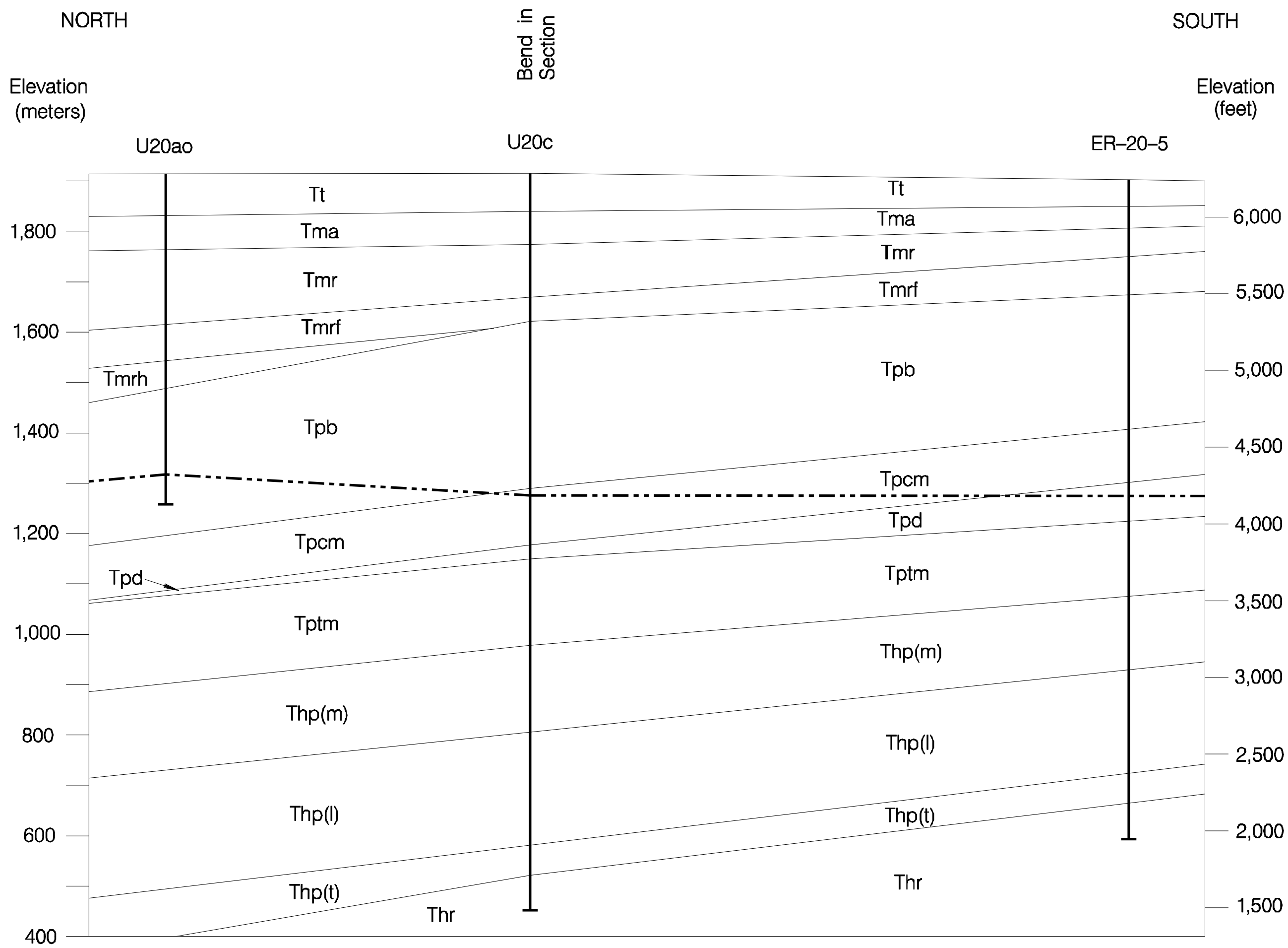
Thp(m) = mafic–poor Calico Hills Formation (main–body subunit)
Thp(l) = mafic–poor Calico Hills Formation (lower subunit)
Thp(t) = mafic–poor Calico Hills Formation (transitional subunit)
Thr = mafic–rich Calico Hills Formation
—·-·— water table

Horizontal Scale = Vertical Scale

See Figure 1–2 for locations of cross sections.

Figure 3-2

West-East Stratigraphic Cross Section Through ER-20-1, ER-20-5, U20y, and U20as



Tt = Thirsty Canyon Group, undivided
Tma = Ammonia Tanks Tuff
Tmr = Rainier Mesa Tuff
Tmrf = rhyolite of Fluorspar Canyon
Tmrh = tuff of Holmes Road
Tpb = rhyolite of Benham
Tpcm = Pahute Mesa lobe of Tiva Canyon Tuff
Tpd = rhyolite of Delirium Canyon (includes rhyolite of Black Glass Canyon in ER-20-5 #3)
Tptm = Pahute Mesa lobe of Topopah Spring Tuff
Thp(m) = mafic-poor Calico Hills Formation (main-body subunit)
Thp(l) = mafic-poor Calico Hills Formation (lower subunit)
Thp(t) = mafic-poor Calico Hills Formation (transitional subunit)
Thr = Mafic-rich Calico Hills Formation
—·-·—· water table

Horizontal Scale = Vertical Scale

See Figure 1-2 for locations of cross sections.

Figure 3-3

North-South Stratigraphic Cross Section Through U20ao, U20c, and ER-20-5

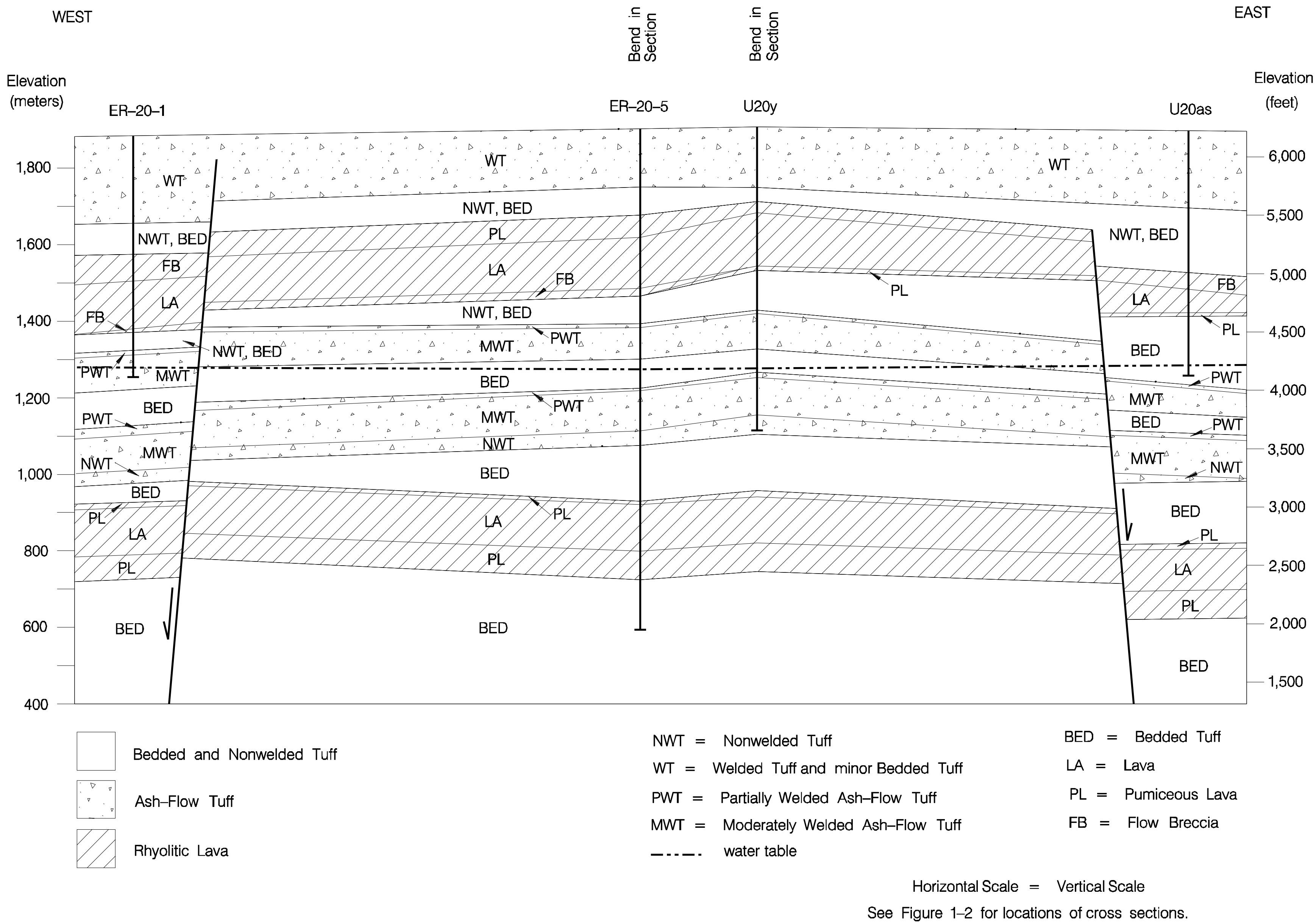


Figure 3-4

West-East Lithologic Cross Section Through ER-20-1, ER-20-5, U20y, and U20as

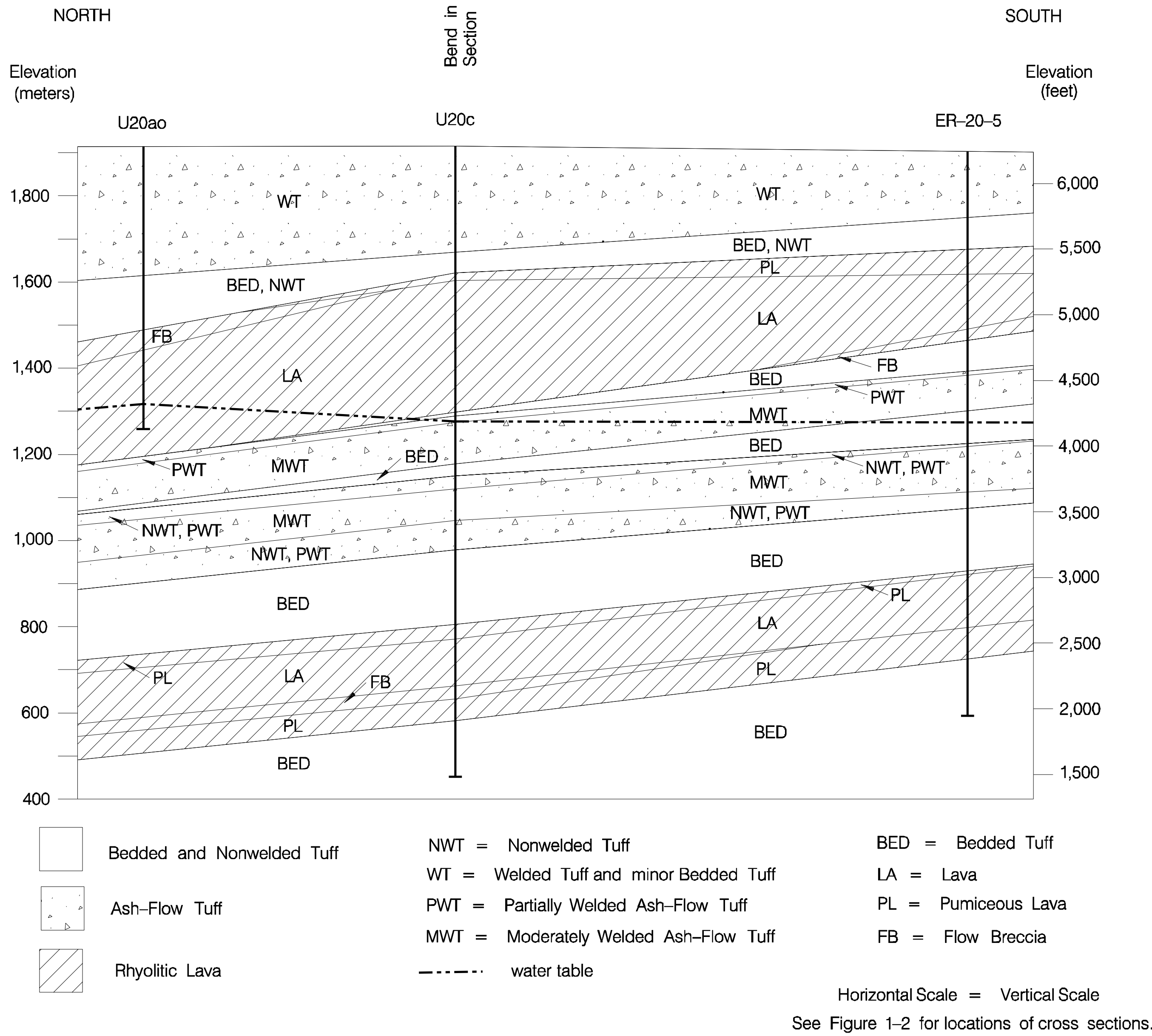


Figure 3-5

North-South Lithologic Cross Section Through U20ao, U20c, and ER-20-5

Mesa, and thus provides extensive structural data within the region, particularly for the upper surface of Pahute Mesa Tuff. Unfortunately, the Thirsty Canyon Group is generally very poorly sampled in drill holes, so no laboratory analyses have been performed, and the uncertainty of stratigraphic data from drill holes within this stratigraphic assemblage is large.

All drill holes in the TYBO-BENHAM area encountered rocks of the Thirsty Canyon Group. Typically, each unit of this group consists of partially to moderately welded ash-flow tuff overlying bedded tuff. Thus, the Thirsty Canyon Group as a whole can be characterized within the study area as consisting lithologically of three partially to moderately welded ash-flow tuff units with intervening bedded tuff. Each of the ash-flow tuff units is about 15.2 to 30.0 m (50 - 100 ft) thick, but the bedded tuffs are considerably thinner. The Thirsty Canyon Group ranges in total thickness within the study area from 51.8 m (170 ft) at U20y to 87.8 m (288 ft) at U20as.

3.1.2 Beatty Wash Formation

Two subunits of the Beatty Wash Formation occur within the TYBO-BENHAM area: rhyolite of Chukar Canyon and the underlying rhyolite of Beatty Wash. The rhyolite of Beatty Wash was erupted from the Timber Mountain Moat south of the TYBO-BENHAM study area 11.2 Ma (Sawyer et al., 1994). It occurs in this region as a pumice fall that is distinctive from the Thirsty Canyon Group above by its conspicuous biotite, and from the Ammonia Tanks Tuff below by a lack of quartz. The rhyolite of Chukar Canyon is a bedded or massive nonwelded tuff distinctive for its brown color, calcareous nature, quartz phenocrysts, and great variety of tiny mafic minerals, a petrographic assemblage typical for alluvia and reworked tuff. Like the Thirsty Canyon Group, samples of drill cuttings from the Beatty Wash Formation are generally very poor, and the unit lies well above depths of importance for hydrologic modeling. Consequently, no laboratory analyses have been performed, and the uncertainty of stratigraphic data for this formation is large. Considering that this unit was recognized at U20as, in the southern portion of the area, and in U20ao, the northernmost hole, it is likely that the Beatty Wash Formation occurs as a thin sheet throughout the TYBO-BENHAM area, though it was not recognized in most holes.

3.1.3 Ammonia Tanks Tuff

Ammonia Tanks Tuff was erupted from the Timber Mountain caldera south of the TYBO-BENHAM area 11.4 Ma (Sawyer et al., 1994). Ammonia Tanks Tuff consists of ash-flow tuff underlain by bedded tuff. The presence of quartz distinguishes Ammonia Tanks Tuff from overlying Beatty Wash Formation, and the presence of sphene and a normal magnetic polarity distinguishes it from underlying Rainier Mesa Tuff. The upper part of the ash flow is mafic-rich, and the lower part is mafic-poor. Within the TYBO-BENHAM area, Ammonia Tanks Tuff ash flow is relatively thin (less than 61 m [200 ft]) and is, thus, generally poorly welded and vitric, resulting in poor samples of drill cuttings. Stratigraphic data within the Ammonia Tanks Tuff are somewhat uncertain, particularly regarding the bedded interval, because no petrographic or chemical analyses are available. There is also some small uncertainty in the position of the lower contact with Rainier Mesa Tuff, as described in Section 3.1.4. Fewer data are available for these and overlying units at Pahute Mesa because they were not as important to the weapons testing program as deeper units, and they also lie well above depths of importance for hydrologic modeling.

3.1.4 Rainier Mesa Tuff

Rainier Mesa Tuff was erupted from the Timber Mountain caldera south of the TYBO-BENHAM area 11.6 Ma (Sawyer et al., 1994), and is found in all holes in the study area. The unit consists of nonwelded to densely welded ash-flow tuff and exhibits a typical welding profile for ash-flow tuff: nowelded and partially welded zones at the top and base, and a moderately to densely welded interior.

Rainier Mesa Tuff is a distinctive compound ash-flow cooling unit that is very well classified throughout the Pahute Mesa subsurface into a mafic-rich upper part and mafic-poor lower part. The absence of sphene and a reversed magnetic polarity distinguish Rainier Mesa Tuff from overlying Ammonia Tanks Tuff, and its lithic-poor, welded, ash-flow lithology distinguishes it from underlying rhyolite of Fluorspar Canyon. The ash-flow tuff of the Rainier Mesa Tuff typically is overlain by bedded tuff, but no Rainier Mesa bedded tuff has been recognized in drill holes in the study area. This lithology can readily be confused with overlying Ammonia Tanks bedded tuff. Also, the bedded tuffs of both units are vitric and friable, and provide poorly representative samples of drill cuttings, as is typical throughout Pahute Mesa subsurface. Thus it is likely that bedded Rainier Mesa Tuff is present but unrecognized in the TYBO-BENHAM area.

The Rainier Mesa Tuff thickens northward from less than 61 m (200 ft) at ER-20-1 and ER-20-5 to almost 152 m (500 ft) at U20ao. Because this unit is relatively thin in the TYBO-

BENHAM area, the lithologic and petrographic distinction between upper and lower parts, dramatically evident where the unit is thick, was recognized only in U20ag and U20ao. Although petrographic and/or chemical analyses could be used to define mafic-rich and mafic-poor Rainier Mesa Tuff, no such analyses are available because the unit lies well above depths of importance for nuclear testing and for hydrologic modeling. Except for structural uncertainties at the top of the unit (related to recognition of Rainier Mesa bedded tuff), structural data for the ash flow of Rainier Mesa Tuff are very accurately defined without need of petrographic or chemical analyses. Within the Western Area 20 structural block of Warren (1994) the unit thickens markedly away from its source within the Timber Mountain caldera, as the base decreases in elevation northward more abruptly than the top (Warren et al., 1985).

3.1.5 Pre-Rainier Mesa Units of the Timber Mountain Group

Three units of the Timber Mountain Group are recognized beneath the Rainier Mesa Tuff in the TYBO-BENHAM area: rhyolite of Fluorspar Canyon, tuff of Holmes Road, and rhyolite of Windy Wash. Rhyolite of Fluorspar Canyon is the only Timber Mountain Group unit below the Rainier Mesa Tuff encountered in all holes of the study area. The underlying tuff of Holmes Road was recognized in four holes, and rhyolite of Windy Wash was identified only in U20as. The thickness of the pre-Rainier Mesa Timber Mountain Group units varies considerably in the area, from approximately 30 m (100 ft) at U20y to more than 152 m (500 ft) at U20as. This variation in thickness is due to infilling of paleotopographic lows. Paleotopography also controlled the distribution of the units, with the older units, tuff of Holmes Road and rhyolite of Windy Wash, occuring where the top of the underlying lava is the lowest, such as at U20as, U20ag, U20ao, and ER-20-1.

In the Pahute Mesa subsurface west of the Boxcar fault, rhyolite of Fluorspar Canyon consists of massive nonwelded and bedded tuff that is petrographically and lithologically similar to the basal, nonwelded portion of mafic-poor Rainier Mesa Tuff, from which it is distinguishable only by a generally much higher content of lithic fragments. Rhyolite of Fluorspar Canyon consists of pale-colored pyroclasts that contain rare biotite as the only mafic mineral. This distinguishes it from underlying tuff of Holmes Road, a brown, nonwelded tuff with great variety of tiny mafic minerals, a petrographic assemblage typical for alluvia and reworked tuffs. Mafic mineral include generally altered biotite, and unaltered hornblende, clinopyroxene, orthopyroxene, sphene, and occasionally olivine. The occurrence of such a lithology reflects the large time gap in eruptive activity between the rhyolite of

Windy Wash (12.3 Ma) and the rhyolite of Fluorspar Canyon (11.6 Ma). Rhyolite of Windy Wash is distinctive by its extremely high content of phenocrysts, which include biotite, hornblende, and sphene. Rhyolite of Fluorspar Canyon was erupted from a source now buried beneath the Timber Mountain caldera south of the TYBO-BENHAM area, and from areas outside this caldera and southwest of the TYBO-BENHAM area 11.6 Ma. Rhyolite of Windy Wash was erupted 12.3 Ma (Sawyer et al., 1994) from a source, probably close to the later-formed rim of the Timber Mountain caldera.

3.1.6 Post-Tiva Canyon Units of the Paintbrush Group

In the TYBO-BENHAM area, rhyolite of Benham is the sole representative of this group of units that crop out along the southern face of Pahute Mesa, coincident with the rim of the Timber Mountain caldera. The rhyolite of Benham was encoutered in all holes of the area, but only five holes completely penetrated the formation. The dominant lithology of the rhyolite of Benham in the TYBO-BENHAM area is lava; however, a thick interval of bedded tuff was penetrated below the lava at U20as, indicating the construction of a tuff cone prior to extrusion of lava (Wagoner and Clark, 1986). The lava shows a typical distribution of lava-flow lithologies, with relatively thin intervals of flow breccia and pumiceous lava surrounding a much thicker interior of stoney and vitrophyric lava. Rhyolite of Benham is readily distinguished from overlying units by its paucity of quartz phenocrysts, and from underlying Tiva Canyon Tuff by its occurrence as rhyolitic lava and associated bedded tuff. The unit has an argon-40/argon-39 ($^{40}Ar/^{39}Ar$) isotopic age date of 12.7 Ma, (Fleck et al., in review) indistinguishable from that of underlying Tiva Canyon Tuff (Sawyer et al., 1994).

The unit is more than 305 m (1,000 ft) thick on the downdropped, western side of the West Boxcar fault, but thins rapidly away from the fault on the upthrown, eastern side. Some lava of this unit crops out east of the Boxcar fault, near the Pahute Mesa Road. Lava of the rhyolite of Benham is thinner where the underlying bedded tuff is the thickest, such as at U20as where only 114.9 m (377 ft) of lava overlies more than 154 m (500 ft) of bedded tuff. At UE20c, 320 m (1,050 ft) of lava overlies only 12.2 m (40 ft) of bedded tuff. This indicates that, as would be expected, the lava flowed away from the prexisting tuff cone and into the surrounding lowlands.

3.1.7 Tiva Canyon Tuff

The Pahute Mesa lobe of Tiva Canyon Tuff occurs in the subsurface throughout the TYBO-BENHAM region west of the West Boxcar fault, but is thin or absent for some distance east of this structure (Figure 3-6). Tiva Canyon Tuff was found in all the holes in the study area that penetrated through the rhyolite of Benham (ER-20-1, ER-20-5, U20c, UE20c, and U20y), although the Tiva Canyon Tuff is absent in Well ER-EC-6, located approximately 2.5 km (1.6 mi) south of the study area (Prothro and Warren, 1999). The unit consists of bedded tuff and partially welded ash-flow tuff overlying a much thicker interval of moderately to densely welded ash-flow tuff. The unit is approximately 110 m (360 ft) thick throughout the study area, though regionally it systematically thickens southwards, presumably towards its source caldera now mostly buried by the Timber Mountain caldera. Tiva Canyon Tuff is distinctive by a nearly complete lack of quartz phenocrysts, presence of sphene, and distinctive ash-flow lithology. The unit is strongly zoned from a crystal-rich top to a crystal-poor base, although a reverse zonation occurs in the TYBO-BENHAM area. Here, an uppermost crystal-poor zone overlies crystal-rich tuff, although chemistries of both zones are similar. This reverse petrographic zonation occurs in outcrop within the Thirsty Canyon NW quadrangle, and may be a general feature of Pahute Mesa lobe of Tiva Canyon Tuff. The zonation may have been overlooked previously due to a paucity of continuous core or because of erosional stripping of this thin, crystal-poor zone, which is generally no more than a few meters thick. The overlying, petrographically identical tuff of Pinyon Pass is regarded as a "regurgitant" of Tiva Canyon magma, and is included within the unit. Tiva Canyon Tuff has an $^{40}Ar/^{39}Ar$ isotopic age of 12.7 Ma (Sawyer et al., 1994).

Petrographic analyses of Tiva Canyon Tuff listed in Table 3-1 suggest that the base of the unit lies 34 $\pm$ 9 m (110 $\pm$ 30 ft) below the bottom of ER-20-1. This estimate is based on a comparison of total felsic phenocryst content for sample ER20/1-2050D with those for samples from U20y and UE20c. At UE20c, the total felsic phenocryst content of 5.21 percent for ER20/1-2050D interpolates in linear fashion to a height above base for the Tiva Canyon Tuff of 48 percent (that is, near the middle of the unit), and at U20y, it interpolates to 65 percent above the base. Using the average value from these two comparisons, 57 percent height above base, yields a base at 662.9 m (2,175 ft) depth in ER-20-1. The combined thickness of 112.2 m (386 ft) calculated by this procedure for tuff of Pinyon Pass and the Pahute Mesa lobe of Tiva Canyon Tuff is consistent with the isopach map for Tiva Canyon Tuff.

Table 3-1
Total Felsic Phenocryst Content of Tiva Canyon Tuff:
Comparison of Sample from Well ER-20-1 with Samples from U20y and UE20c

Drill Hole	Sample Depth [a] meters (feet)	Sample Type [b]	Sample Split ID	Felsic Phenocryst Content (percent) [c]
ER-20-1	624.8 (2,050)	DA	ER20/1-2050D (3	5.21
U120y	493.8 (1,620)	DA	U20Y-1620D (2	15.37
U20y	521.2 (1,710)	DA	U20Y-1710(1	4.82
UE20c	650.1 (2,133)	C	UE20C-2133(A	6.60
UE20-c	713.8 (2,342)	C	UE20C-2342(A	4.02

a Depth represents base of sample interval.
b DA = drill cuttings that represent lithologic character of interval; C = conventional core.
c Values are in volume percent from point count, uncorrected for differential porosity.

3.1.8 Pre-Tiva Canyon, Post-Topopah Spring Units of the Paintbrush Group

Several units occupy the stratigraphic interval between the Tiva Canyon and Topopah Spring Tuffs east of the West Greeley fault, but only bedded tuffs of rhyolite of Black Glass Canyon and rhyolite of Delirium Canyon are presently recognized in the TYBO-BENHAM area. Outside this area, these units occur as rhyolite lava domes with pyroclastic bases. At Pahute Mesa, the combined thickness of these two units increases southward, and so they probably represent distal tephra from domes buried beneath the Timber Mountain caldera. They are distinguished from other units of the same stratigraphic interval as relatively crystal-poor, with hornblende accompanying biotite as a primary mafic mineral. Rhyolite of Delirium Canyon occurs in Well ER-20-5#3 as a relatively quartz-rich subunit near the base of the bedded tuff between the Topopah Spring and Tiva Canyon Tuffs, and rhyolite of Black Glass Canyon as a quartz-free unit near the top. These units are confidently distinguished by sanidine compositions, which are markedly more sodium-rich in rhyolite of Black Glass Canyon. Within the study area, the units range in combined thickness from 27.4 m (90 ft) at U20c to 76.8 m (252 ft) at ER-20-5. Rhyolite of Delirium Canyon has an $^{40}Ar/^{39}Ar$ age of 12.7 Ma (Sawyer et al., 1994).

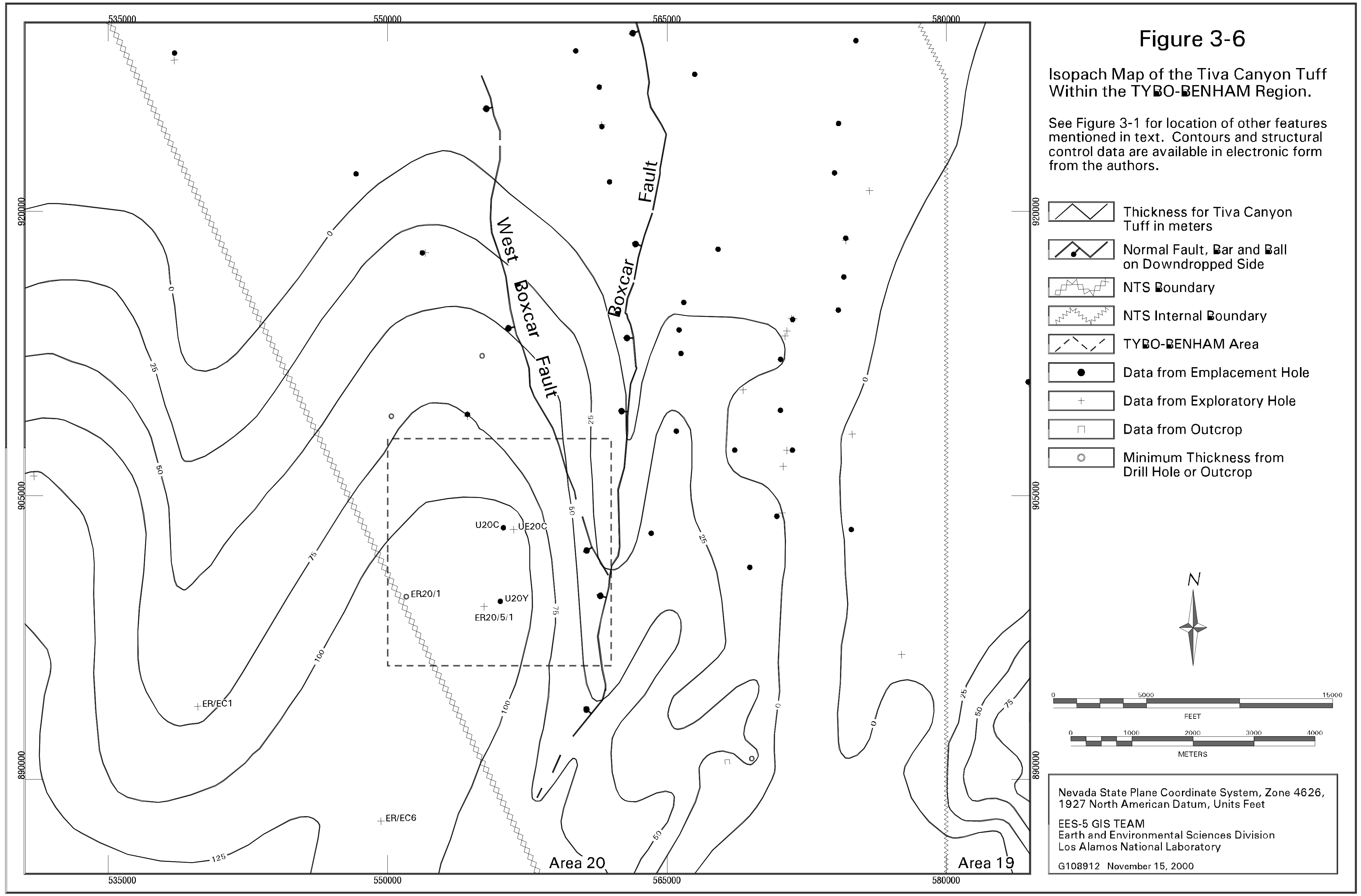


Figure 3-6
Isopach Map of the Tiva Canyon Tuff Within the TYBO-BENHAM Region.
See Figure 3-1 for location of other features mentioned in text. Contours and structural control data are available in electronic form from the authors.
Thickness for Tiva Canyon Tuff in meters
Normal Fault, Bar and Ball on Downdropped Side
NTS Boundary
NTS Internal Boundary
TYBO-BENHAM Area
Data from Emplacement Hole
Data from Exploratory Hole
Data from Outcrop
Minimum Thickness from Drill Hole or Outcrop
N
FEET
METERS
Nevada State Plane Coordinate System, Zone 4626, 1927 North American Datum, Units Feet
EES-5 GIS TEAM
Earth and Environmental Sciences Division
Los Alamos National Laboratory
G108912 November 15, 2000
West Boxcar Fault
Boxcar Fault
U20C
UE20C
ER20/1
U20Y
ER20/5/1
ER/EC1
ER/EC6
Area 20
Area 19
535000
550000
565000
580000
920000
905000
890000

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3.1.9 Topopah Spring Tuff

The distribution of the Pahute Mesa lobe of Topopah Spring Tuff is very similar to that for Pahute Mesa lobe of Tiva Canyon Tuff. Topopah Spring Tuff occurs in the subsurface throughout the TYBO-BENHAM region west of the West Boxcar fault, but is thin or absent east of this structure, where it occurs only as a bedded tuff that is absent where ash-flow tuff occurs. Therefore, bedded Topopah Spring Tuff of the Pahute Mesa subsurface is laterally equivalent to the ash flow, rather than overlying it as at Yucca Mountain (see data for bedded Topopah Spring Tuff in Warren et al., 1999). Topopah Spring Tuff generally thickens southwards, presumably towards its source caldera, which is now mostly buried by the Timber Mountain caldera. The Topopah Spring Tuff is distinctive by a paucity of quartz phenocrysts, lack of sphene, and distinctive ash-flow lithology. Topopah Spring Tuff, zoned from a weakly to moderately crystal-rich top to a crystal-poor base, is much less strongly zoned in the Pahute Mesa subsurface than at Yucca Mountain (Warren et al., 1989). Topopah Spring Tuff has an $^{40}Ar/^{39}Ar$ age of 12.8 Ma (Sawyer et al., 1994).

In the TYBO-BENHAM area, Topopah Spring Tuff shows a typical ash-flow tuff welding profile. The unit has a nonwelded to partially welded upper portion that grades to a thick moderately to densely welded interior that overlies a rather thick, partially to nonwelded base. Cores from UE20c show numerous partially opened fractures within moderately and partially welded Topopah Spring Tuff. Minerals coating and partially filling the fractures include quartz, smectite, feldspar (potassic, sodic, and calcic), and mica (Drellack et al., 1997). Topopah Spring Tuff ranges in thickness from 148.7 m (488 ft) at ER-20-5 to 173.7 m (570 ft) at UE20c.

3.1.10 Mafic-poor Calico Hills Formation

Mafic-poor Calico Hills Formation consists of multiple constructive cycles of rhyolite lava domes with pyroclastic bases, with an age between 12.8 and 12.9 Ma (Sawyer et al., 1994) determined for the overlying Topopah Spring Tuff and underlying mafic-rich Calico Hills Formation, respectively. In the Pahute Mesa subsurface, the distribution of the mafic-poor Calico Hills Formation is very different from that of overlying units. The mafic-poor Calico Hills Formation thins systematically westward from enormous thicknesses (more than 1,000 m [3,280 ft]) along the western, down-dropped side of the West Greeley fault east of the TYBO-BENHAM area (Warren et al., 1985) (Figure 3-7). The unit has a much higher proportion of quartz phenocrysts than the overlying Topopah Spring Tuff, and a much lower

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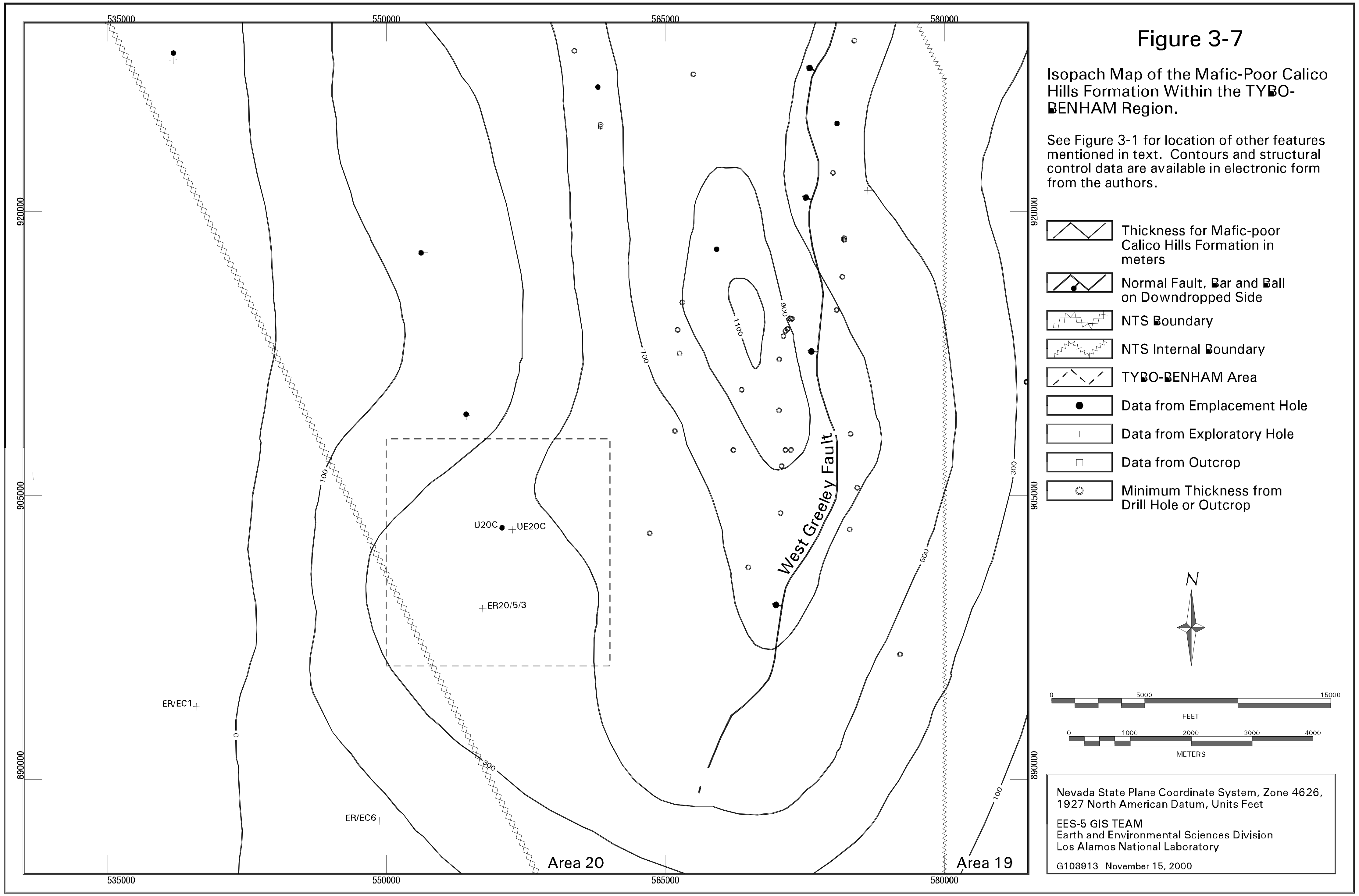

Figure 3-7
Isopach Map of the Mafic-Poor Calico Hills Formation Within the TYBO-BENHAM Region.
See Figure 3-1 for location of other features mentioned in text. Contours and structural control data are available in electronic form from the authors.
Thickness for Mafic-poor Calico Hills Formation in meters
Normal Fault, Bar and Ball on Downdropped Side
NTS Boundary
NTS Internal Boundary
TYBO-BENHAM Area
Data from Emplacement Hole
Data from Exploratory Hole
Data from Outcrop
Minimum Thickness from Drill Hole or Outcrop
N
FEET
METERS
Nevada State Plane Coordinate System, Zone 4626, 1927 North American Datum, Units Feet
EES-5 GIS TEAM
Earth and Environmental Sciences Division
Los Alamos National Laboratory
G108913 November 15, 2000
West Greeley Fault
Area 20
Area 19
U20C
UE20C
ER20/5/3
ER/EC1
ER/EC6
535000
550000
565000
580000
920000
905000
890000

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proportion of felsic phenocrysts and biotite than the underlying mafic-rich Calico Hills Formation.

Evaluation of the large number of precise petrographic analyses, added for the TYBO-BENHAM area to an already robust data set (Warren et al., 1999), indicates that individual flow packages within the Calico Hills Formation can be distinguished by precise petrographic analyses and by mineral chemistries obtained from electron microprobe analyses (Table 3-2). From these data, mafic-poor Calico Hills Formation can be divided into three subunits at the present time, with a fourth subunit suggested by microprobe analyses. The recognition of subunits within the mafic-poor Calico Hills Formation allows for more detailed and confident stratigraphic correlation within this lithologically complex formation.

At the base of the mafic-poor Calico Hills formation lies a transitional subunit, characterized by a significantly higher content of felsic phenocrysts, and somewhat higher content of biotite compared to the rest of the formation. Above the transitional subunit, lies a lower subunit that is quite plagioclase-poor compared to the overlying main-body subunit which composes the remaining portion of the formation in the TYBO-BENHAM area.

The uppermost part of mafic-poor Calico Hills Formation in exploratory hole UE20e#1, located approximately 8 km (5 mi) north of the study area, is represented by a sample from the 522.7-m (1,715-ft) depth that contains sanidine that is significantly more potassium-poor than parts below (Or+Cn data in Table 3-2). If the main body is represented at UE20e#1 by a sample from the 961.6-m (3,155-ft) depth, then the main body might actually comprise additional subunits recognizable by differences in sanidine compositions or biotite contents.

Only three holes in the study area, ER-20-5, U20c, and UE20c, penetrate the Topopah Spring Tuff and encounter mafic-poor Calico Hills Formation. All three holes encounter an upper interval of bedded tuff overlying rhyolitic lava which in turn overlies a lower interval of bedded tuff. Petrographic and electron microprobe data provided in Table 3-2 indicate that the upper interval of bedded tuff in both ER-20-5 and UE20c belong to the main-body subunit of the mafic-poor Calico Hills Formation. This subunit thickens northward in the study area from 145.7 m (478 ft) at ER-20-5 to 172.2 m (565 ft) at U20c.

Table 3-2
Selected Petrographic and Electron Microprobe Analytical Data for Calico Hills Formation in Drill Holes in the TYBO-BENHAM Area and for UE20e-1[a]
(Page 1 of 2)

Sample ID [b]	**Strat** [c]	**Lith** [d]	**Felsic**[e, f] Total %	**Qtz** [f, g] Rel %	**Kspar** [f, h] Rel %	**Plag** [f, i] Rel %	**Biot** [J] ppmV	**Or+Cn** [k] Mol%
Possible upper subunit of mafic-poor Calico Hills Formation								
UE20E1-1715	Thp	LA	2.26	44	39	17	1,080	65
Main body of mafic-poor Calico Hills Formation								
ER20/5/3-2955D	Thp	NWT	2.63	45	16	39	312	-- [L]
UE20C-3109	Thp	NWT	3.01	26	36	38	377	--
UE20C-3110	Thp	NWT	3.18	33	41	26	873	--
UE20C-3209	Thp	NWT	3.3	16	54	30	740	--
UE20C-3300	Thp	NWT	2.45	56	28	16	1,146	--
UE20C-3402	Thp	NWT	1.81	42	32	26	723	--
UE20C-3410	Thp	BED	3.1	33	30	36	97	--
UE20C-3512	Thp	NWT	1.59	40	31	29	353	--
UE20C-3600.5	Thp	NWT	1.88	54	23	24	216	69
UE20C-3605	Thp	NWT	1.69	18	53	29	200	--
UE20E1-3155	Thp	NWT	2.6	28	30	43	140	68
Lower subunit of mafic-poor Calico Hills Formation								
UE20C-3610	Thp	PL	0.81	52	35	13	353	--
UE20C-3904	Thp	LA	2.65	43	47	10	684	--
UE20C-4105	Thp	LA	2.77	27	56	17	523	--
UE20C-4246	Thp	FB	2.76	55	39	6	541	--
Transitional subunit of mafic-poor Calico Hills Formation								
U20C-4552.3	Thp	BED	4.04	29	42	29	699	--
UE20C-4538	Thp	NWT	4.67	58	21	21	747	--
UE20E1-3525.9	Thp	LA	4.54	46	42	12	1,440	--

Table 3-2
Selected Petrographic and Electron Microprobe Analytical Data for Calico Hills Formation in Drill Holes of the TYBO-BENHAM Study Area and for UE20e-1 [a]
(Page 2 of 2)

Sample ID [b]	Strat [c]	Lith [d]	Felsic[e, f] Total %	Qtz [f, g] Rel %	Kspar [f, h] Rel %	Plag [f, i] Rel %	Biot [J] ppmV	Or+Cn [k] Mol%
Transitional subunit of mafic-rich Calico Hills Formation								
U20C-4643.7	Thr	BED	15.2	36	40	24	974	--
UE20C-4745	Thr	NWT	8.98	34	37	29	2,089	--
UE20C-4746RW	Thr	NWT	8.91	56	30	15	1,467	--
U20C-4794	Thr	BED	11.49	32	32	35	2,536	--
UE20C-4938	Thr	NWT	11	46	26	28	1,740	--
UE20E1-3909.3	Thr	NWT	8.81	31	34	36	2,926	--
Main body of mafic-rich Calico Hills Formation								
UE20C-5155	Thr	NWT	15.8	32	40	28	8,017	--
UE20E1-4150	Thr	BED	8.02	19	21	60	6,812	--

a Darkly shaded values generally distinguish subunits of the Calico Hills Formation within the TYBO-BENHAM area; lightly shaded values are often distinctive.
b Numerical values for Sample ID represent basal depth of interval sampled, in feet.
c Stratigraphic unit: Thp = mafic-poor Calico Hills Formation; Thr = mafic-rich Calico Hills Formation.
d Lithology: LA = lava flow; NWT = nonwelded tuff; BED = bedded tuff; PL = pumiceous lava; FB = flow breccia
e Total percent felsic phenocrysts.
f All petrographic analyses are from point count or from more precise methods.
g Quartz as the relative percent of felsic phenocrysts.
h Potassium feldspar as the relative percent of felsic phenocrysts.
i Plagioclase as the relative percent of felsic phenocrysts.
J Volume of biotite phenocrysts in parts per million.
k Microprobe data are median mole percent orthoclase plus celsian end-member contents of sanidine.
L No analysis made.

Data from Table 3-2 also show that the interval of lava in UE20c belongs to the lower subunit of the mafic-poor Calico Hills Formation. Lava was also encountered below the upper interval of bedded tuff in ER-20-5 and U20c. The distribution of lava-flow lithologies is very similar in all three holes. Each hole encountered an upper interval of pumiceous lava that ranges in thickness from 9.1 m (30 ft) at ER-20-5 to 82.6 m (271 ft) at UE20c. Below the pumiceous lava, all three holes encountered an interval of stony and vitrophyric lava of similar thickness (106.7 to 121.9 m [350 - 400 ft]). Underlying this dense lava interior, all three holes penetrated a similar thickness (74.1 to 81.1 m [243 - 266 ft]) of pumiceous lava and flow breccia, although only pumiceous lava was recognized at ER-20-5. The total thickness of lava ranges from 205.4 m (674 ft) at ER-20-5 to 268.5 m (881 ft) at UE20c, indicating an apparent thickening of the lava northward.

Below the lava, ER-20-5, U20c, and UE20c encountered an interval of bedded tuff that is almost identical in appearance and thickness in all three holes. Petrographic and electron microprobe data from U20c and UE20c indicate that the bedded tuff belongs to the transitional subunit that forms the base of the mafic-poor Calico Hills Formation.

The total thickness of the mafic-poor Calico Hills Formation increases northward within the study area from 411.2 m (1,349 ft) at ER-20-5 to 481.6 m (1,580 ft) at UE20c. The excellent correlation from north to south (in the study area) of lithologic units and petrographic/ mineralogic subunits within the mafic-poor Calico Hills Formation, including similar thicknesses, strongly suggests that the lithologic make up of the formation, as described above, is continuous throughout most of the TYBO-BENHAM area.

3.1.11 Mafic-rich Calico Hills Formation

Mafic-rich Calico Hills Formation has been penetrated in only a few widely separated drill holes of Pahute Mesa, all west of the West Greeley fault. Given their strong chemical resemblance and chemical and petrographic gradations with each other, and strong association with the West Greeley fault, mafic-rich and mafic-poor Calico Hills Formation probably have very similar areal distributions. Like the mafic-poor unit, mafic-rich Calico Hills Formation can be divided into subunits based on petrographic character and mineral chemistry. The mafic-rich Calico Hills Formation encountered in drill holes of the TYBO-BENHAM area consists of a transitional subunit overlying a main-body subunit. Table 3-2 shows that the transitional subunit has a lower biotite content than the underlying main-body subunit, and higher felsic phenocryst content than the overlying transitional subunit of the mafic-poor Calico Hills Formation. Mafic-rich Calico Hills Formation has an $^{40}Ar/^{39}Ar$ age of 12.9 Ma (Sawyer et al., 1994).

Only three holes within the study area encountered mafic-rich Calico Hills Formation, and none penetrated completely through the formation. Wells ER-20-5, U20c, and UE20c all bottomed in the mafic-rich Calico Hills Formation, encountering only bedded tuff. UE20c penetrated the deepest, encountering 203.6 m (668 ft) of the formation.

The top of the mafic-rich Calico Hills Formation provides an important structural datum in the TYBO-BENHAM area, which is particularly important for evaluating the possible existence of buried faults within or between U20c and UE20c. The good correlation of petrographic/minerologic subunits within the Calico Hills Formation for samples from similar depths in U20c and UE20c (Table 3-2) demonstrates a lack of any significant faults through or between these holes, as discussed in following sections of this report.

3.2 Structural Geology

Analysis of geologic structure provides important insights for predicting the distribution of hydrogeologic units. Also, faults themselves can act as zones of increased or decreased permeability and thus influence groundwater flow and transport of contaminants. Structural features recognized in the TYBO-BENHAM area are discussed in this section, beginning with features of the immediate TYBO-BENHAM area, which are presented in Section 3.2.1. More regional-scale features recognized during this study are discussed in Section 3.2.2.

3.2.1 Local Structural Features

This section describes three structural features that directly affect structural relations of rocks in the TYBO-BENHAM area. These include a tuff cone and two buried faults. Patterns of surface fracturing from underground weapons testing in the area are also described. Figure 3-8 shows faults and zones of weapons-testing-related surface fracturing in the TYBO-BENHAM area.

3.2.1.1 Tuff Cone

Within the TYBO-BENHAM area, the distribution of lava and tuff of the rhyolite of Benham defines a tuff cone (Wagoner and Clark, 1986) emplaced 12.3 to 12.6 Ma along the downdropped side of the West Boxcar fault. The tuff cone probably represents a single lava flow emplaced upon a pyroclastic base that had been vented along the West Boxcar fault, with the lava flowing northwestward along the western, down-dropped side of the fault. This pile of lava and tuff formed a topographic high in the area that controlled the deposition of many of the overlying units of the Timber Mountain Group. Rhyolite of Windy Wash, tuff of Holmes Road, and rhyolite of Fluorspar Canyon thin dramatically over the feature (see Section 3.1.5). However, Ammonia Tanks Tuff shows very little thinning above this paleotopographic feature, indicating that the feature was effectively buried by intervening Rainier Mesa Tuff (Figures 3-2 and 3-3).

3.2.1.2 Buried Faults

A buried fault that projects east of ER-20-1 and west of ER-20-5 (Figure 3-8) is inferred from the much lower elevation for the top of Rainier Mesa Tuff in ER-20-1 compared to ER-20-5 and U20y (Figure 3-9), and much thicker Ammonia Tanks Tuff in ER-20-1 compared to ER-20-5 and U20y (Figure 3-2). These data indicate that primary movement along the inferred buried fault occurred after emplacement of the Rainier Mesa Tuff and before emplacement of the Ammonia Tanks Tuff, between 11.6 to 11.4 Ma, with an offset of perhaps 20 to 50 m (66 - 164 ft) for the top of Rainier Mesa Tuff. Just below the southern rim of Pahute Mesa, this inferred fault, with 10 to 30 m (33 - 98 ft) of westward-down displacement, is concealed by thin alluvium covering Ammonia Tanks Tuff in outcrop (Byers and Cummings, 1967). This fault trends towards a prominent north-northeast-trending canyon incised in Trail Ridge Tuff at the western edge of the Scrugham Peak quadrangle, which passes about 200 m (656 ft) east of ER-20-1. Northeast of ER-20-1, the buried fault projects towards a north-striking, down-to-the-west fault mapped at the surface west of U20ao (Wahl et al., 1997). The surface fault shows little if any offset of the Trail Ridge Tuff, and its position is estimated from alignment of surface cracks and small-scale displacements produced by underground nuclear explosions in the area.

Structural data for rhyolite of Benham require the presence of a buried down-to-the-east fault between U20y and U20as, as shown in Figure 3-8. Elevations for this unit form a west-east arch from ER-20-1 to U20as (Figure 3-2). This arch cannot be explained as entirely constructional, because the rhyolite of Benham is thickest at the eastern margin of the arch, immediately west of the Boxcar fault. Eastward-down offset of the thin pumiceous lava immediately above the basal pyroclastic sequence is about 80 (263 ft), and offset of the base of the basal pyroclastic sequence is more than 160 m (525 ft), possibly indicating episodic movement along the buried fault during deposition of the rhyolite of Benham (Figure 3-4). Alternatively, the difference in the amount of offset could be constructional, the result of the tuff cone (pyroclastic base) originally being deposited on a relatively flat surface, with deposition of the overlying lava on the sloping western flank of the tuff cone. The top of rhyolite of Benham, so close to its inferred source, is a poor datum to estimate offset, and the difference in elevations of nearly 200 m (656 ft) between U20y and U20as is probably partly constructional. Units younger than rhyolite of Benham uniformly thicken beneath Ammonia Tanks Tuff within a trough formed between the buried fault and the Boxcar fault. It is uncertain if these units are also offset by the buried fault, or serve only to bury the feature.

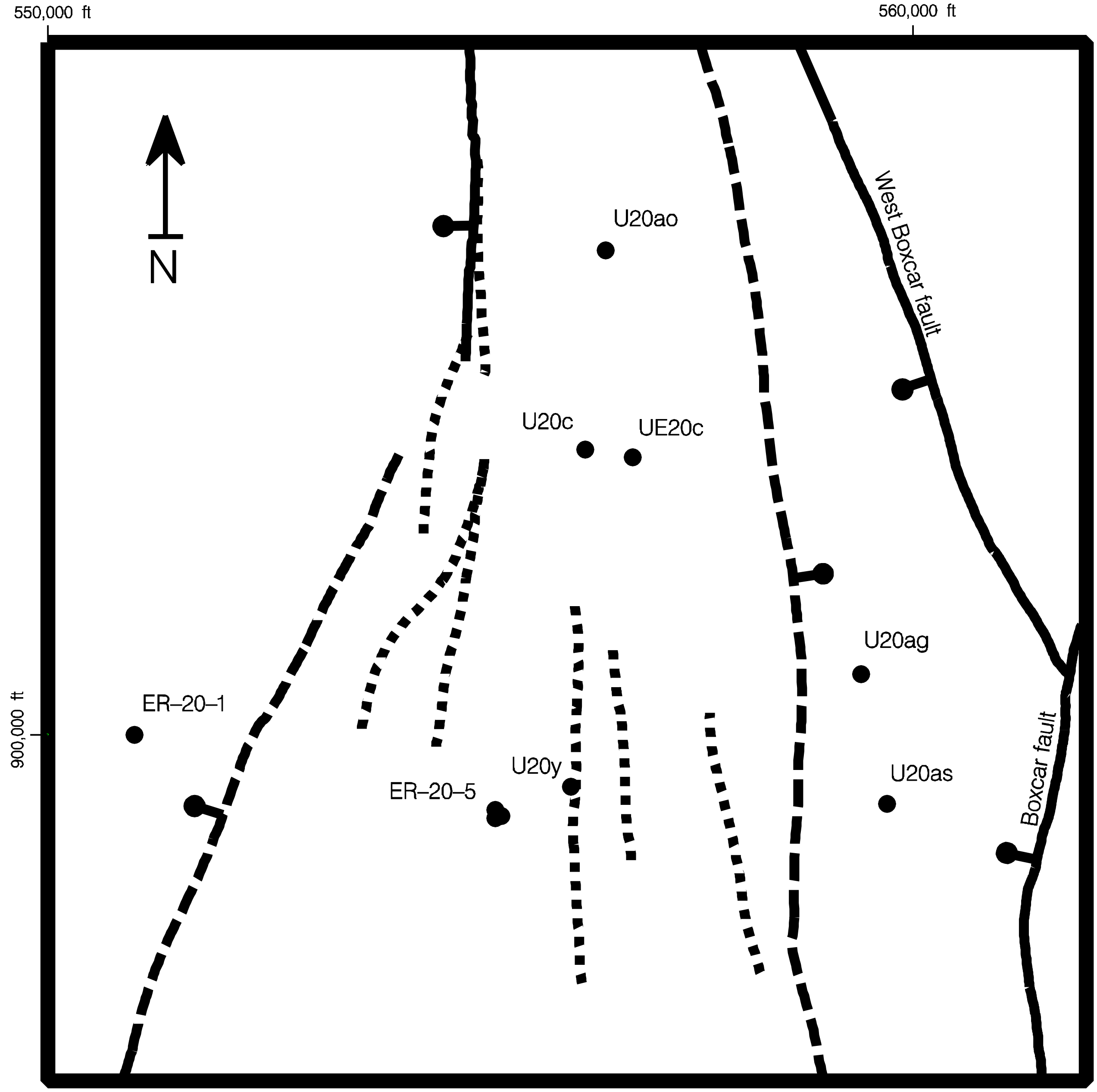
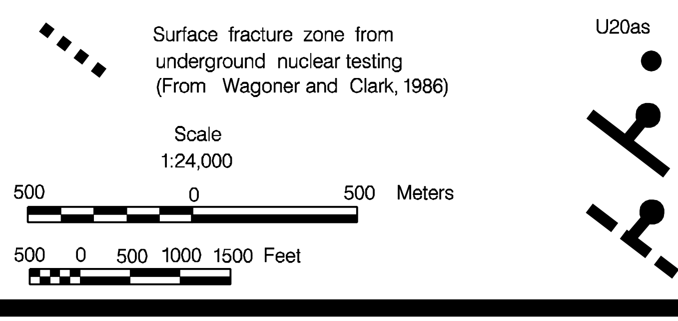


Figure 3–8

Map Showing Locations of Faults and Surface Fracture Zones in the TYBO–BENHAM Area



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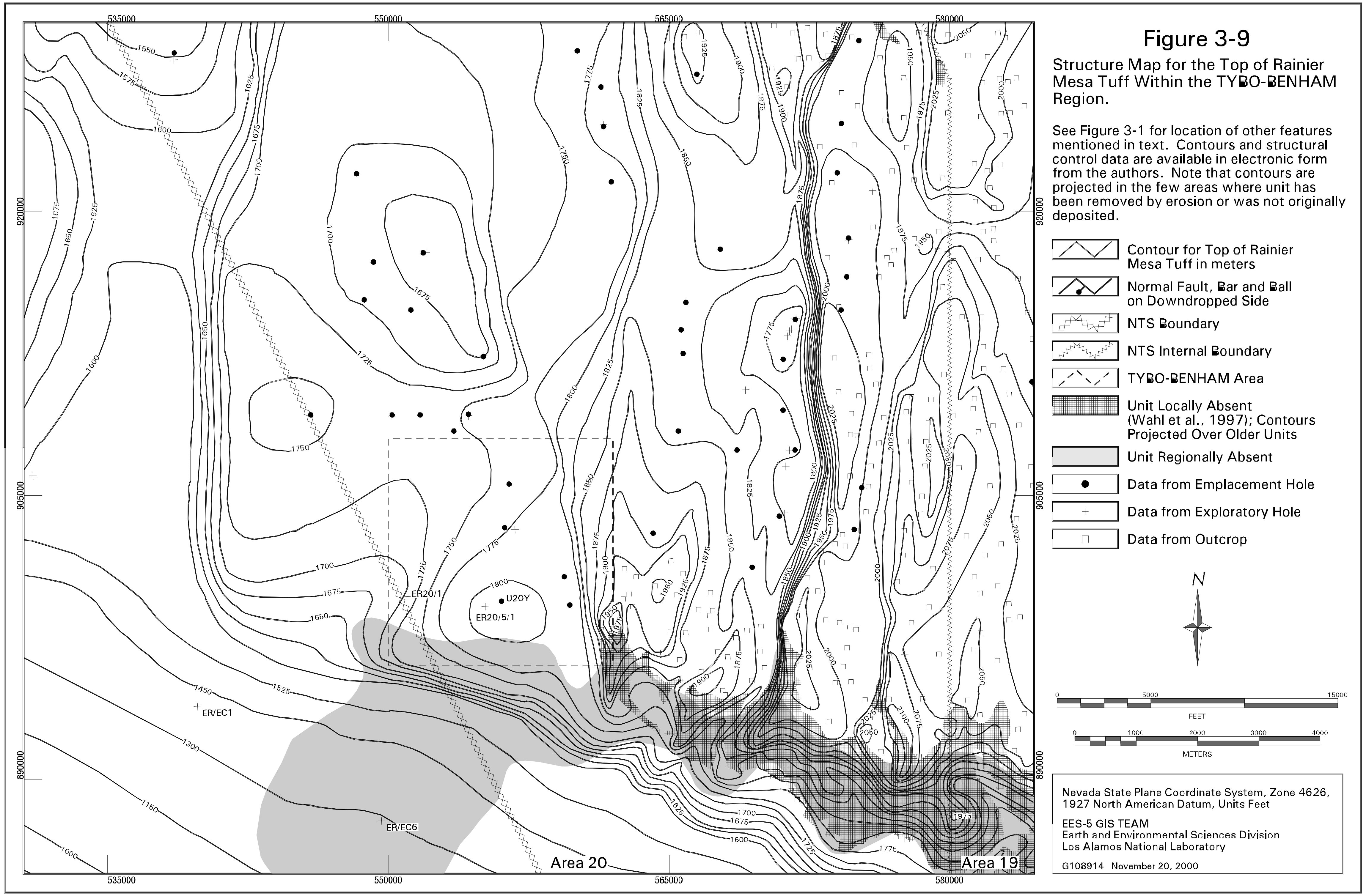

Figure 3-9

Structure Map for the Top of Rainier Mesa Tuff Within the TYBO-BENHAM Region.

See Figure 3-1 for location of other features mentioned in text. Contours and structural control data are available in electronic form from the authors. Note that contours are projected in the few areas where unit has been removed by erosion or was not originally deposited.

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The buried fault is assumed to coincide with the prominent north-trending canyon incised in Trail Ridge Tuff immediately west of the Boxcar fault (Byers and Cummings, 1967). Following the linear projection of this canyon, the buried fault appears to merge with the Boxcar fault just south of Pahute Mesa. To the north on Pahute Mesa, the trace of the fault probably coincides with north- and south-flowing washes, eventually merging with the West Boxcar fault north of the TYBO-BENHAM area.

3.2.1.3 Weapons-Testing-Related Surface Fractures

Several linear, north-trending zones of aligned surface cracks from underground tests in the area are present between U20y and U20as (Figure 3-8). These surface-fracture zones could be the surface expression of buried faults. Based on aligned surface cracks near U20y, Wagoner and Clark (1986) depicted a north-striking, down-to-the-east fault just east of the U20y location. However, this fault and the other nearby surface-fracture zones project northward within very close proximity to U20c and UE20c, where no faults were recognized from detailed stratigraphic correlation of the two holes (Figure 3-10).

3.2.2 Regional Structural Features

Regional structural features recognized during the geologic analysis of the TYBO-BENHAM region are described in this section. These features help place the geology of the TYBO-BENHAM area in a regional context. Also, the hydrologic significance of these features should be considered during development of groundwater flow models of the Pahute Mesa region. Five regional-scale structural features are recognizable in the TYBO-BENHAM region on the basis of structural contours and isopachs of stratigraphic units. From youngest to oldest, these features are (1) an arch crossing the trough listed next and described in Section 3.2.2.2; (2) a trough west of the Purse fault filled with rocks of the Thirsty Canyon Group; 3) a prominent, structurally high, west-northwest-trending ridge displayed by Rainier Mesa Tuff and younger units; (4) a trough west of the Boxcar and West Boxcar faults filled with rocks of the Paintbrush Group; and 5) a half-graben west of the West Greeley fault filled with rocks of the Calico Hills Formation. These features are discussed in the following paragraphs.

3.2.2.1 Ribbon Cliff Arch

The youngest regional structure, here termed the Ribbon Cliff arch, is an east-trending arch that bisects the Ribbon Cliff trough, which is described in Section 3.2.2.2. This arch is clearly defined by structure contours for the top of Pahute Mesa Tuff (Figure 3-11). A

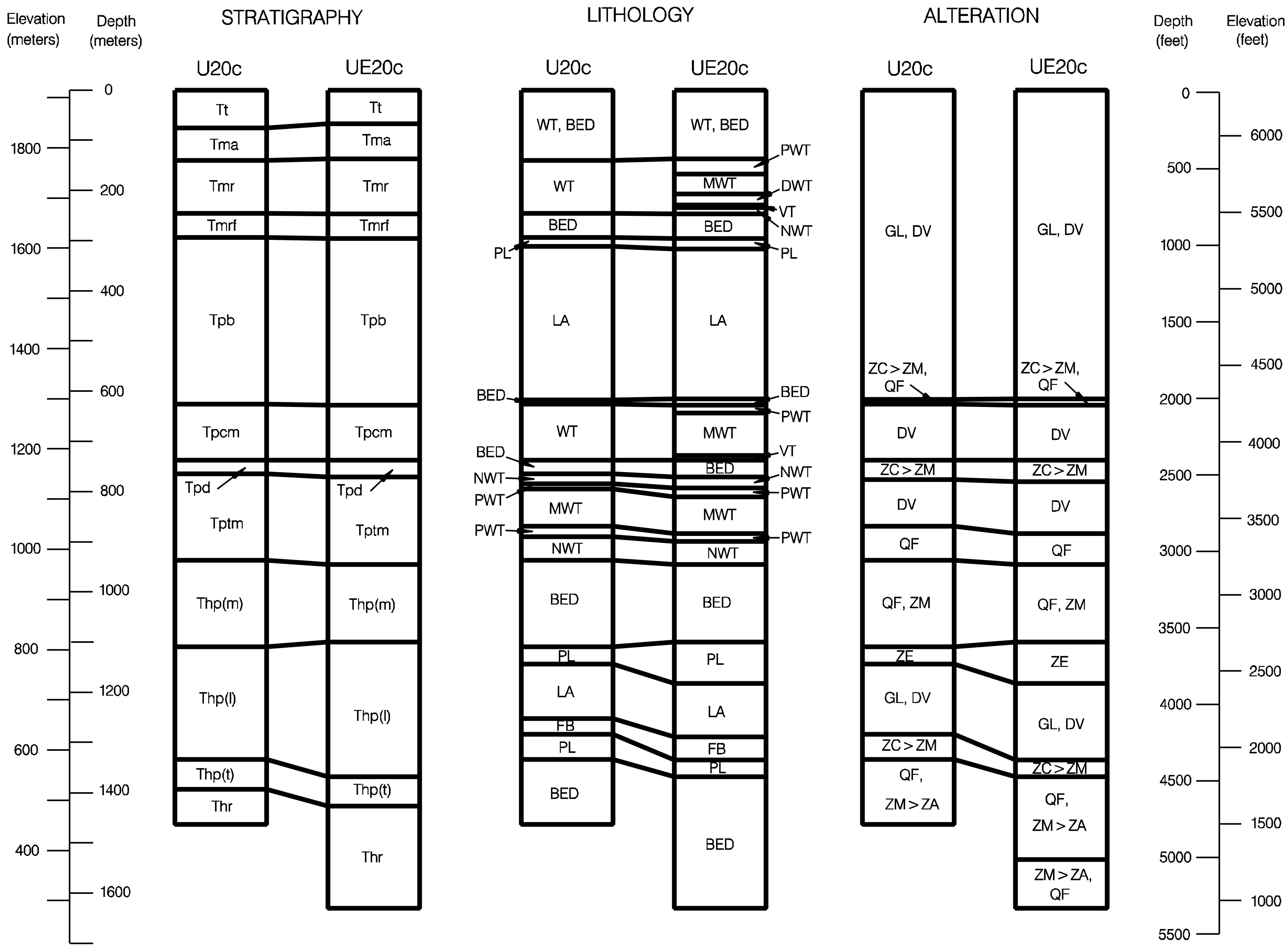

Figure 3–10
Correlation Diagrams for U20c and UE20c

Refer to Figure 3–3 for definitions of stratigraphic symbols; Figure 3–5 for lithologic symbols (DWT=densely welded tuff, VT=vitrophyre); and Figure 3–14 for alteration symbols.

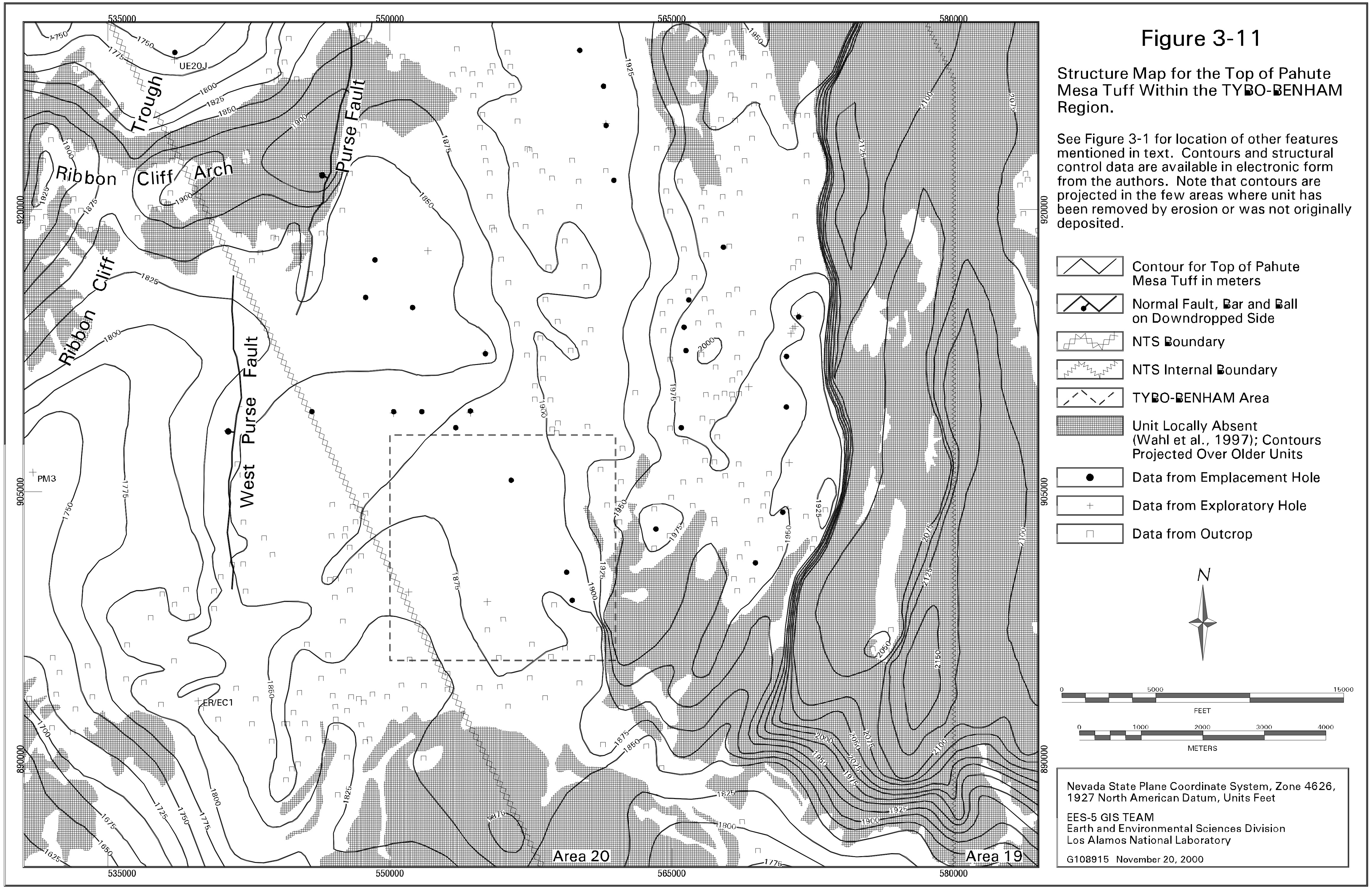

Figure 3-11

Structure Map for the Top of Pahute Mesa Tuff Within the TYBO-BENHAM Region.

See Figure 3-1 for location of other features mentioned in text. Contours and structural control data are available in electronic form from the authors. Note that contours are projected in the few areas where unit has been removed by erosion or was not originally deposited.

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projection of structural data from locations within the Ribbon Cliff trough far distant from the arch indicates an uplift of Pahute Mesa Tuff exceeding 200 m (656 ft) along this arch. Alternatively, the arch might simply represent a ramping of Pahute Mesa Tuff over a topographic high formed of comendite of Ribbon Cliff, rather than uplift. This alternative is unlikely because such a magnitude of ash-flow tuff ramping is unknown, and structure contours for Pahute Mesa Tuff fail to indicate ramping over exposed, older rhyolite of Tannenbaum Hill just southeast of the Ribbon Cliff trough.

Uplift along the Ribbon Cliff arch increases approaching the Black Mountain caldera, from which the Pahute Mesa Tuff was erupted. With these associations, and the common occurrence of caldera resurgence, resurgence of the Black Mountain caldera provides a likely mechanism for creation of the Ribbon Cliff arch.

3.2.2.2 Ribbon Cliff Trough

A north-northeast-trending trough west of the Purse fault, here termed the Ribbon Cliff trough, is clearly defined by structure contours for the top of Pahute Mesa Tuff (Figure 3-11). The axis of the trough is shown as a syncline axis north of exploratory hole UE20j (Christiansen and Noble, 1968). This trough is filled with comendite of Ribbon Cliff and overlying tuffs of the Thirsty Canyon Group. Structural data from U20k demonstrate that Ammonia Tanks Tuff lies at very low elevations within this trough, compared to subsurface data east of the Purse fault, outside the trough (Figure 3-12). Ammonia Tanks Tuff is relatively thin within the Ribbon Cliff trough at Well PM3, indicating that it is a post-Ammonia Tanks, pre- or syn-Ribbon Cliff depression related to either late-stage development of the Ammonia Tanks caldera, or more likely early-stage development of the Black Mountain caldera. The Ribbon Cliff trough is almost certainly the result of westward-down displacement along the Purse and West Purse faults which, along with a series of other north-striking faults in the vicinity of the Purse fault, form the eastern boundary of the trough. The nature of the western boundary has not been investigated.

3.2.2.3 West-Northwest-Trending Ridge

A prominent, structurally high west-northwest-trending ridge that coincides with the southern topographic edge of Pahute Mesa west of the Boxcar fault is displayed by structure contours for Rainier Mesa Tuff and younger units (Figures 3-9, 3-11, and 3-12). The ridge is

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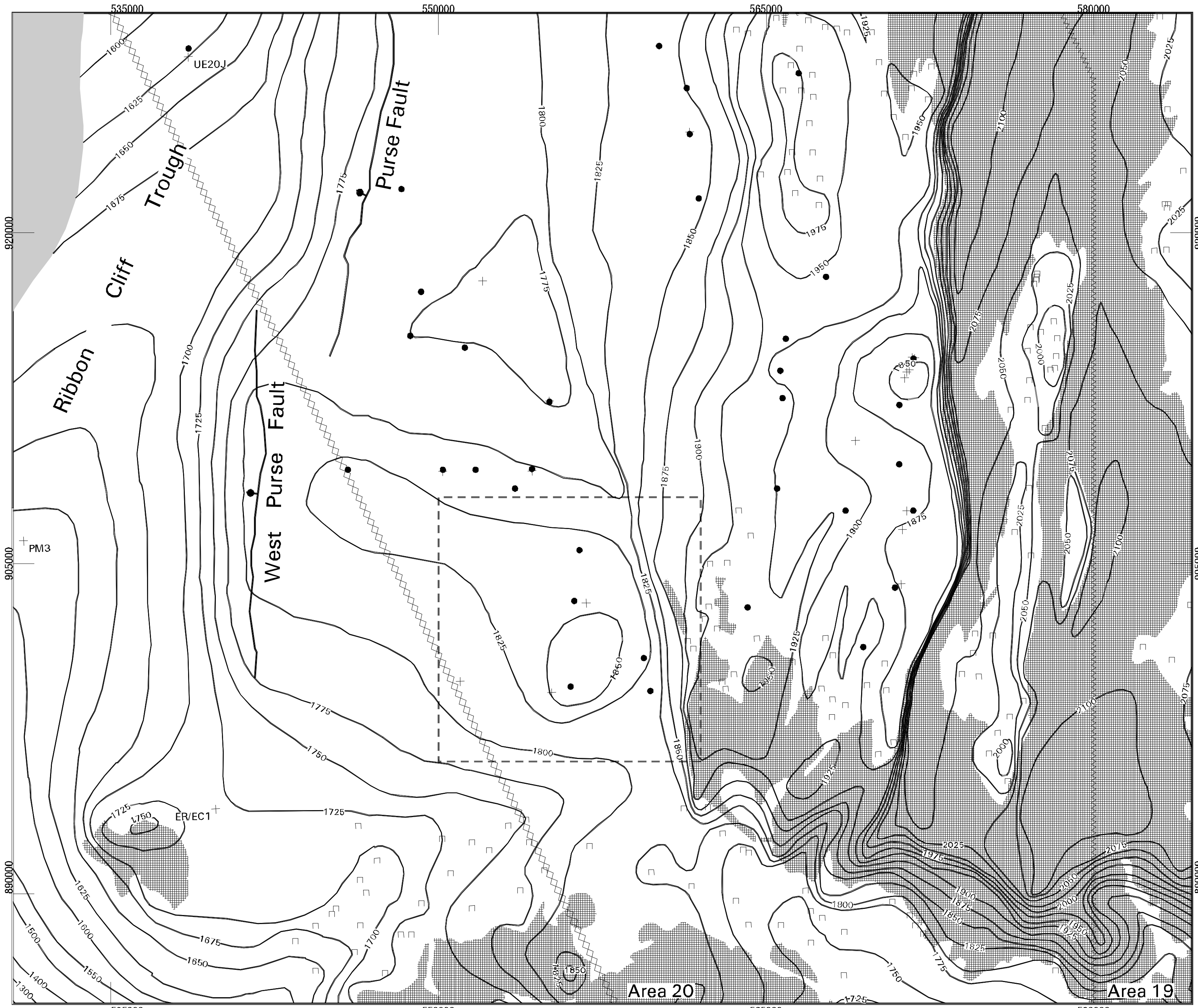

Figure 3-12

Structure Map of the Top of Ammonia Tanks Tuff Within the TYBO-BENHAM Region.

See Figure 3-1 for location of other features mentioned in text. Contours and structural control data are available in electronic form from the authors. Note that contours are projected in the few areas where unit has been removed by erosion or was not originally deposited.

- Contour for Top of Ammonia Tanks Tuff in meters
- Normal Fault, Bar and Ball on Downdropped Side
- NTS Boundary
- NTS Internal Boundary
- TYBO-BENHAM Area
- Unit Locally Absent (Wahl et al., 1997); Contours Projected Over Older Units
- Unit Regionally Absent
- Data from Emplacement Hole
- Data from Exploratory Hole
- Data from Outcrop

N

0 5000 15000 FEET

0 1000 2000 3000 4000 METERS

Nevada State Plane Coordinate System, Zone 4626, 1927 North American Datum, Units Feet

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truncated on the west by the younger Ribbon Cliff trough. The trend of this feature continues east of the Boxcar fault, where it may represent the boundary of the Rainier Mesa caldera, as shown in Figure 3-1. West of the Boxcar fault, this ridge was thought to coincide with the structural wall of the Rainier Mesa caldera (Noble et al., 1991; Warren, 1994), but data from recently drilled Wells ER-EC-1 and ER-EC-6 have disproved this notion (Prothro and Warren, 1999). The ridge coincides with a dramatic southward disappearance of mafic-poor Calico Hills Formation (Figure 3-7), which fills the Area 20 caldera, formed 13.1 Ma (Ferguson et al., 1994). We consider that this abrupt thinning coincides with the southern boundary of the Area 20 caldera, as defined in Figure 3-1.

3.2.2.4 Boxcar Trough

Units of the Paintbrush Group were deposited within a trough, here termed the Boxcar trough, bounded on the east by the Boxcar and West Boxcar faults, as shown by thicknesses for the Tiva Canyon Tuff (Figure 3-6). The western limit of the trough is not well constrained. The trough appears to be fairly symmetric in an east-west direction, without pronounced thickening of regional ash-flow units, such as the Tiva Canyon and Topopah Spring Tuffs, towards the bounding master faults to the east. However, there is pronounced thickening of these ash-flow units to the south, suggesting that the source calderas may lie just south of the TYBO-BENHAM area. Thicknesses on both sides of the West Boxcar fault are similar for Rainier Mesa Tuff (Warren et al., 1985), demonstrating virtually complete burial of this trough by 11.6 Ma.

Structural data indicate that movement occurred along normal faults in the region, including the bounding faults, during and after deposition in the trough. Between the Purse and West Boxcar faults, elevations for the top of Tiva Canyon Tuff (Warren et al., 1985) show a northward to eastward tilt that is far more pronounced than similar tilts for the Rainier Mesa and Ammonia Tanks Tuffs. This is taken as evidence for continued, episodic activity along the West Boxcar fault during post-Tiva Canyon (12.6 Ma) through post-Ammonia Tanks time (11.4 Ma), as inferred by Warren et al. (1985) for all major faults of Pahute Mesa.

In the TYBO-BENHAM area, eastward apparent dips between U20C and UE20C increase with age for the Paintbrush Group (Figure 3-10). The top of Tiva Canyon Tuff shows an eastward apparent dip of 0.7 degrees, compared to 1.9 degrees for the top of Topopah Spring Tuff. Eastward apparent dips between 1.9 and 5.0 degrees are calculated for lithologic contacts between the top and base of Topopah Spring Tuff, averaging 3.3 degrees. The differences between these eastward apparent dips are attributed to episodic rotation resulting from movement along northward-trending faults, with the Boxcar serving as the master fault. Using the average from lithologic contacts, the Topopah Spring Tuff had been rotated at least 2.6 degrees (3.3 minus 0.7 degrees) prior to deposition of the Tiva Canyon Tuff less than a hundred thousand years later.

3.2.2.5 West Greeley Half-Graben

Like the Tiva Canyon and Topopah Spring Tuffs, the Calico Hills Formation was also deposited within a structural depression. However, the geometry of this trough is very different from that of the trough in which the Tiva Canyon and Topopah Spring Tuffs accumulated. Deposition of the Calico Hills Formation occurred within a half-graben bounded on the east by the West Greeley fault (Warren et al., 1985). Thus, unlike the Tiva Canyon and Topopah Spring Tuffs, the Calico Hills Formation thickens systematically eastward towards the bounding fault. The mafic-poor unit alone thickens from less than 488 m (1,600 ft) in the TYBO-BENHAM area to more than 1,009 m (3,310 ft) just west of the West Greeley fault (Figure 3-7).

Analysis of formation dips in drill holes in the TYBO-BENHAM area indicate that movement along the West Greeley fault was synchronous with deposition of the Calico Hills Formation. Eastward apparent dips between U20c and UE20c are markedly higher within the lower subunit of mafic-poor Calico Hills Formation compared to the main body and to the overlying Paintbrush Group (Figure 3-10). Eastward apparent dips between 11.6 and 17.1 degrees are calculated for lithologic contacts within the lower subunit, averaging 13.5 degrees. The difference in apparent dips of these units is attributed to episodic rotation resulting from movement along north-striking faults, with the West Greeley serving as the master fault. The top of the main body of the Calico Hills Formation shows a calculated eastward apparent dip of only 2.4 degrees, similar to that of overlying Topopah Spring Tuff, indicating that the movement mastered by the West Greeley fault post-dated emplacement of the lower subunit but preceded emplacement of the main body of the Calico Hills Formation.

3.3 Alteration in the TYBO-BENHAM Area

Alteration minerals can have significant influence on the hydrologic properties of volcanic rocks. Knowledge of type and distribution of alteration minerals is important for hydrologic modeling in volcanic terrains both for prediction of the movement of water and for prediction of sorptive characteristics of the rocks with regards to radionuclides. Secondary alteration for much of Pahute Mesa, including the TYBO-BENHAM area, has typically been described as simply zeolitic (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Laczniak et al., 1996; Drellack and Prothro, 1997; and Prothro et al., 1998). However, detailed petrographic, mineralogic, and chemical analyses presented in this section show that secondary alteration in the TYBO-BENHAM area is far more complex.

Alteration of volcanic rocks is far more difficult to accurately determine in hand sample than lithology or stratigraphic assignment, and is erroneously assigned in many publications. As an example, compare original descriptions of alteration for Yucca Mountain drill hole USWG1 (Spengler et al., 1981) with alterations assigned from later petrographic and X-ray diffraction (XRD) analyses (Warren et al., 1999). Although XRD analyses provide the single, most definitive means to establish alteration, a petrographic analysis of the same sample is essential in many cases to accurately assess alteration. For example, high-temperature devitrification and complete quartzo-feldspathic alteration yield the same mineral assemblage of approximately 35 percent silica polymorphs (quartz, cristobalite, and tridymite) and 65 percent feldspar; however, entirely different textures and different mafic mineral alterations are observed in petrographic analysis. Following petrographic analysis, microprobe analyses of secondary feldspars reveals details of quartzo-feldspathic alteration that cannot be obtained from routine XRD analysis. Coupled petrographic and XRD analyses were employed to define alteration in key samples from drill holes of the TYBO-BENHAM region. Microprobe analyses are pending, and their results will be included in future revisions of Warren et al. (1999).

Secondary alteration of originally vitric rocks can be controlled locally, by proximity to altering bodies (such as hot ash flows and lava flows) or regionally, by the geothermal gradient beneath the regional water table. Within the southwestern Nevada volcanic field, alteration initially produces zeolites in the progressive sequence, clinoptilolite, mordenite, and analcime (Broxton et al., 1987; Moncure et al., 1981). As alteration progresses, zeolites are replaced by a quartzo-feldspathic assemblage of quartz and secondary feldspar. In the mildest stages of quartzo-feldspathic alteration, feldspar is dominated by almost pure end-member secondary potassium feldspar (adularia) which occurs in the structural state of orthoclase, as opposed to sanidine of phenocrysts within the same rocks. As alteration continues, almost pure end-member plagioclase (albite) becomes increasingly important, although the chemistry of altering fluids may reverse this general order of appearance for the secondary feldspars. At even higher temperatures of hydrothermal alteration, feldspar phenocrysts are converted to secondary feldspar, and mafic minerals (biotite, hornblende, and pyroxene) are converted to illitic clay. Hydrothermal alteration did not occur in any rocks sampled in the TYBO-BENHAM area.

In the TYBO-BENHAM area, the control of secondary alteration appears to be almost entirely local. This contrasts with the generally systematic, downwards increase in alteration intensity within Yucca Mountain (Broxton et al., 1987), which is a manifestation of regional rather than local control. Cross sections that represent alteration in the TYBO-BENHAM area indicate no trends in alteration that are recognizable as regional, even at the deepest levels penetrated (Figures 3-13 and 3-14). Instead, each originally vitric layer seems to reflect the effectiveness of an overlying high-temperature deposit in promoting secondary alteration. Near, or just beneath the water table, originally vitric layers beneath largely devitrified lava of rhyolite of Benham and Tiva Canyon welded ash-flow tuff have altered to an assemblage that is dominantly zeolite (mostly clinoptilolite but with substantial mordenite) with little secondary quartz and feldspar. Within basal, nonwelded Topopah Spring Tuff, alteration is far more advanced, with an assemblage that is almost entirely quartzo-feldspathic, including only minor zeolite, mostly mordenite, and analcime. Within the Calico Hills Formation, alteration intensity decreases downward from predominantly quartzo-feldspathic and mordenite without clinoptilolite, through mordenite-dominant, quartzo-feldspathic, to zeolitic and/or quartzo-feldspathic with relict glass.

Within the lowermost originally vitric layers, beneath largely devitrified lava of the mafic-poor Calico Hills Formation, alteration intensity increases downward through the transitional subunit of mafic-rich Calico Hills Formation. At the top of this layer, alteration is mainly zeolitic, dominated by clinoptilolite over mordenite. Below, alteration is zeolitic, but clinoptilolite and mordenite are equal, and analcime is present. Below, alteration is mainly quartzo-feldspathic, with decreasing zeolite that is increasingly dominated by analcime. The progression of alteration within mafic-rich Calico Hills Formation is that expected for regional control of alteration. But within the lowest layer encountered in UE20c, alteration is predominantly zeolitic, with subequal mordenite and analcime, a reversal of the trend above that might be ascribed to regional control. Table 3-3 summarizes alteration within the TYBO-BENHAM study area, providing relative abundances of alteration minerals in

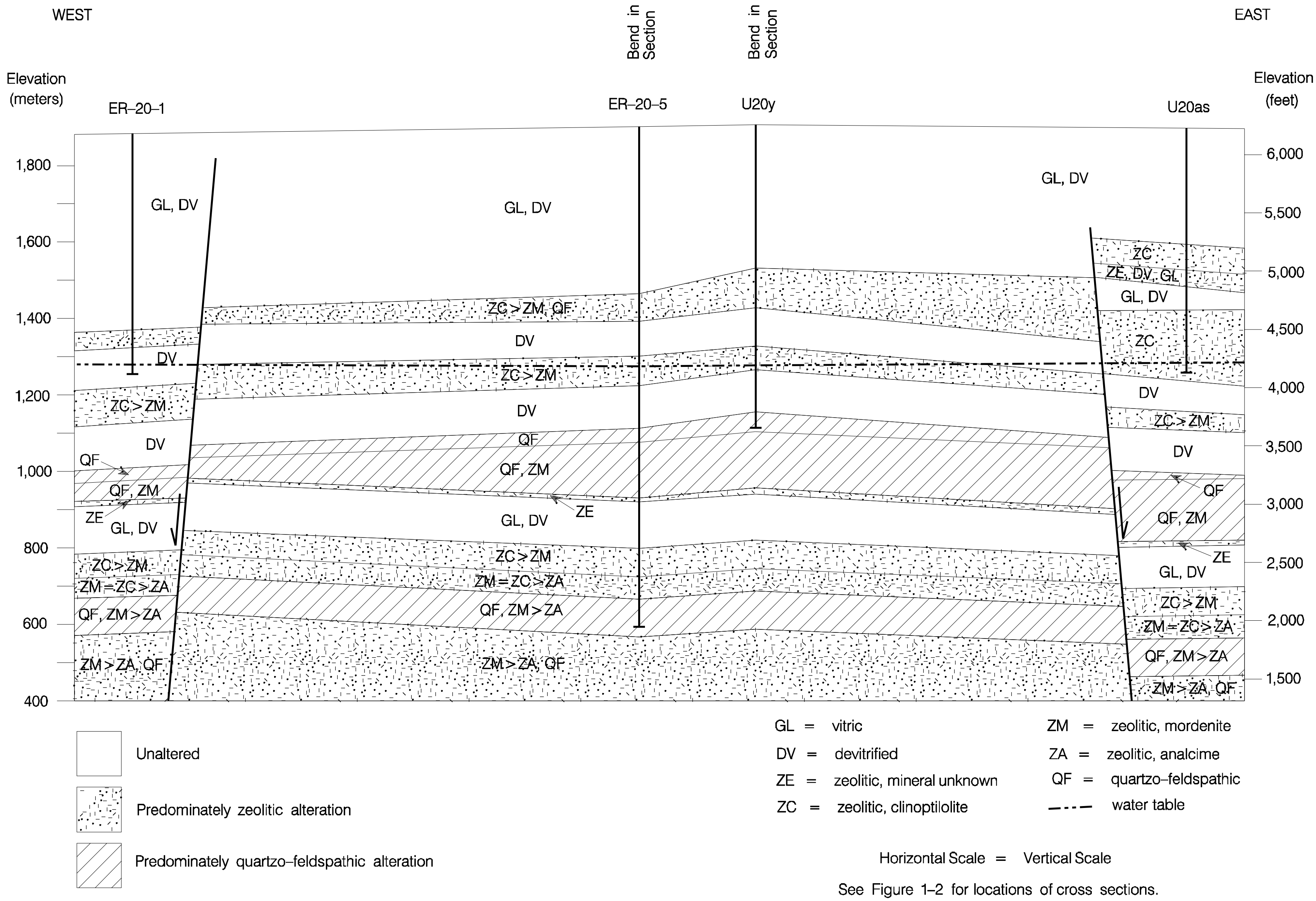


Figure 3-13

West-East Alteration Cross Section Through ER-20-1, ER-20-5, U20y, and U20as

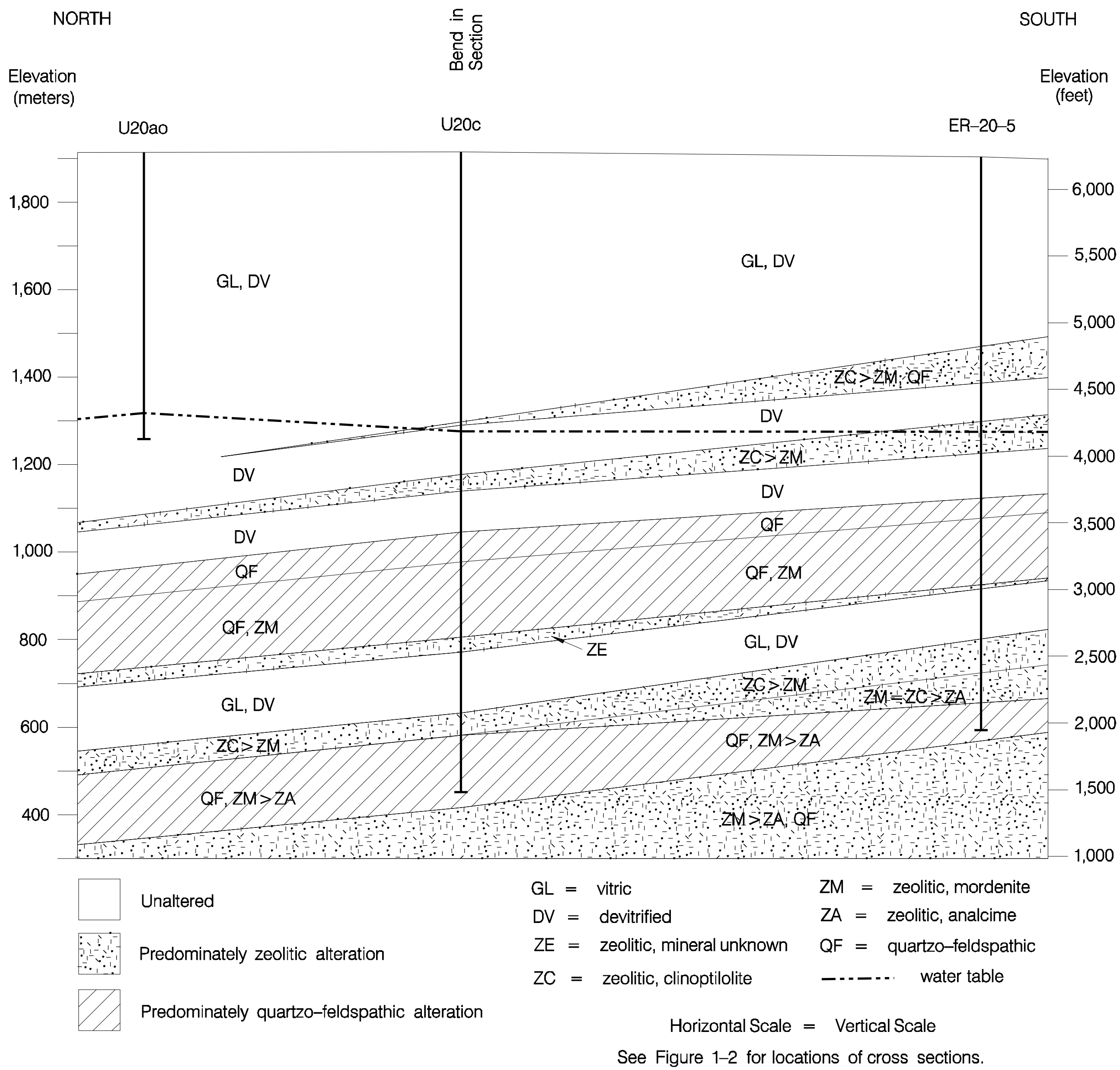


Figure 3-14

North-South Alteration Cross Section Through U20ao, U20c, and ER-20-5

Table 3-3
Relative Abundances for Alteration Minerals in Lithologic Samples from TYBO-BENHAM Area Drill Holes
(Page 1 of 2)

Sample Number [a]	Strati-graphic Unit [b]	Lithologic Unit [c]	Weight Percent from XRD [d]					Calculated Primary [e]		Calculated Secondary [f]	
			FS	QZ	ZC	ZM	ZA	FS	QZ	FS	QZ
Layer beneath lava of rhyolite of Benham											
U20AG-1170D	Tpb	FB	-- [g]	--	75	--	--	--	--	--	--
U20AS-1570D	Tpb	LA	12	2	85	--	--	--	--	--	--
U20AS-1600D	Tpb	NWT	15	2	68	--	--	--	--	--	--
U20AS-1700D	Tpb	NWT	11	2	75	--	--	--	--	--	--
U20AS-1850D	Tpb	BED	15	2	66	--	--	--	--	--	--
U20AS-1990D	Tpb	NWT	27	5	49	--	--	--	--	--	--
U20AS-2080D	Tpb	BED	22	10	58	--	--	--	--	--	--
U20Y-1450D	Tpb	NWT	17	2	51	19	0	13	1	4	1
U20Y-1490D	Tpb	BED	45	5	25	--	--	--	--	--	--
U20Y-1510D	Tpb	BED	30	2.5	40	--	--	21	6	9	0
U20Y-1520D	Tpb	BED	30	2.5	25	--	--	--	--	--	--
U20Y-1530D	Tpcyp	NWT	15	2.5	55	--	--	--	--	--	--
Layer beneath Tiva Canyon Tuff											
ER20/5/3-2030D	Tpd	NWT	13	4	58	17	0	5	2	8	2
ER20/5/3-2220D	Tpd	NWT	22	12	38	24	0	13	5	9	7
Layer beneath Topopah Spring Tuff, including main body of mafic-poor Calico Hills Formation											
U20Y-2530D	Tptm	NWT	40	40	0	--	--	--	--	--	--
U20Y-2540D	Tptm	NWT	40	40	0	--	--	18	7	22	33
U20Y-2570D	Tptm	NWT	36	38	1	8	6	11	3	25	35
ER20/5/3-2955D	Thp	NWT	30	34	0	33	0	11	7	19	27
ER20/5/3-3005D	Thp	NWT	28	36	0	32	0	--	--	--	--
ER20/5/3-3190D	Thp	NWT	25	24	0	49	0	--	--	--	--

Table 3-3
Relative Abundances for Alteration Minerals in Lithologic Samples from TYBO-BENHAM Area Drill Holes
(Page 2 of 2)

Sample Number [a]	Strati-graphic Unit [b]	Lithologic Unit [c]	Weight Percent from XRD [d]					Calculated Primary [e]		Calculated Secondary [f]	
			FS	QZ	ZC	ZM	ZA	FS	QZ	FS	QZ
Layer beneath lava of lower mafic-poor Calico Hills Formation											
ER20/5/3-3890D	Thp	PL	5	2	61	19	1	--	--	--	--
U20C-4275D	Thp	PL	6	4	46	30	0	--	--	--	--
Transitional mafic-poor Calico Hills Formation											
ER20/5/3-3960D	Thp	NWT	14	19	27	27	8	--	--	--	--
Other transitional Calico Hills Formation											
U20C-4552.3	Thp	BED	25	42	0	2	26	24	12	1	30
ER20/5/3-4120D	Thr	NWT	29	35	4	13	15	--	--	--	--
ER20/5/3-4250D	Thr	NWT	36	33	0	17	12	--	--	--	--
U20C-4643.7	Thr	BED	38	38	0	18	1	20	11	18	27
UE20C-4746R	Thr	NWT	38	42	0	8	0.25	10	10	28	32
UE20C-4746W	Thr	NWT	41	41	0	10	0	10	10	31	31
UE20C-4943.7	Thr	NWT	31	40	0	1	22	17	12	14	28
Main body of mafic-rich Calico Hills Formation											
UE20C-5161	Thr	NWT	28	21	0	24	18	20	9	8	12

a Numerical values for Sample Number represent basal depth of interval sampled, in feet.

b Stratigraphic unit: Tpb = rhyolite of Benham; Tpcyp = crystal-poor tuff of Pinyon Pass; Tpd = rhyolite of Delirium Canyon; Tptm = Pahute Mesa lobe of Topopah Spring Tuff; Thp = mafic-poor Calico Hills Formation; Thr = mafic-rich Calico Hills Formation.

c Lithology: FB = flow breccia; LA = lava; NWT = nonwelded tuff; BED = bedded tuff; PL = pumiceous lava.

d X-ray diffraction analysis: FS = feldspar; QZ = quartz; ZC = clinoptilolite; ZM = mordenite; ZA = analcime. Where ZM analysis is not performed, ZC actually represents ZC + ZM.

e Calculated primary QZ and FS are given in weight percent, calculated from volume percent of lithic fragments, assuming that lithics are 35% QZ and 65% FS. To convert from volume to weight percent, all samples with calculated primary QZ and FS are assumed to have a porosity of 40%.

f Calculated values are weight percent from XRD analysis minus calculated primary values.

g -- = Analysis not performed.

lithologic samples from area drill holes. Note that abundances for secondary quartz and feldspar in Table 3-3 are calculated from XRD analyses, which provide total (primary plus secondary) abundances. Non-secondary abundances for quartz and feldspar are subtracted from the total abundances from XRD analyses where petrographic data are available to indicate primary mineral abundances.

Except within the deepest layers penetrated by Well Cluster ER-20-5, alteration is similar laterally within each lithologic layer. It must be noted, however, that lateral variations in alteration were not comprehensively characterized. At ER-20-5, alteration within the lowermost bedded tuff of mafic-poor Calico Hills Formation is zeolite-dominated, but at U20c it is dominated by quartzo-feldspathic minerals. In this case, alteration appears to be more intense within the same layer due to a greater depth. The effect is appreciable, lowering the depth of zeolite-dominated alteration in ER-20-5 about 60 m (197 ft) below the base of the equivalent alteration zone in U20c, but about 90 m (295 ft) higher in elevation.
We conclude that to a first approximation, alteration in the TYBO-BENHAM area is controlled by local, high-temperature deposits, and that depth has an appreciable effect on alteration only at the greatest depths encountered. Local deposits that controlled alteration include rhyolite of Benham, Tiva Canyon Tuff, and Topopah Spring Tuff. Alteration effects are most pronounced beneath Topopah Spring Tuff, with alteration intensity decreasing downwards, away from this heat source. The alteration associated with each local source can be considered to represent an extension of the zone of devitrification within the local source, and clearly occurred during cooling of each unit, a period of as much as a thousand years following emplacement of each unit. Therefore, to a first approximation, zones of alteration tend to follow zones of lithology. Where alteration is not determined, or is poorly determined, for a particular unit in a particular hole, the alteration is best estimated for modeling purposes by assigning alteration well determined within the same lithologic interval in a nearby hole.

3.4 Hydrogeologic Implications

The results of the detailed subsurface geologic analysis of the TYBO-BENHAM area support the general conclusions about the hydrogeology of the area presented in previous reports (DOE, 1997; Drellack and Prothro, 1997). The rocks penetrated by drill holes in the TYBO-BENHAM area can be classified into four hydrogeologic units. Welded ash-flow tuff and lava form welded-tuff and lava-flow aquifers, respectively. Unaltered nonwelded and bedded tuffs form vitric-tuff aquifers, and altered nonwelded and bedded tuffs form tuff confining units. The hydrogeology of the TYBO-BENHAM area as defined by nearby drill holes can be summarized as consisting of four saturated to partially saturated aquifers separated by tuff confining units (Figures 3-15 and 3-16). Only those hydrogeologic units that are at least partially saturated within drill holes of the TYBO-BENHAM area are discussed in this section. For discussions of the hydrogeology below the depth of this investigation and outside of the TYBO-BENHAM area, see Laczniak et al. (1996) and Drellack and Prothro (1997).

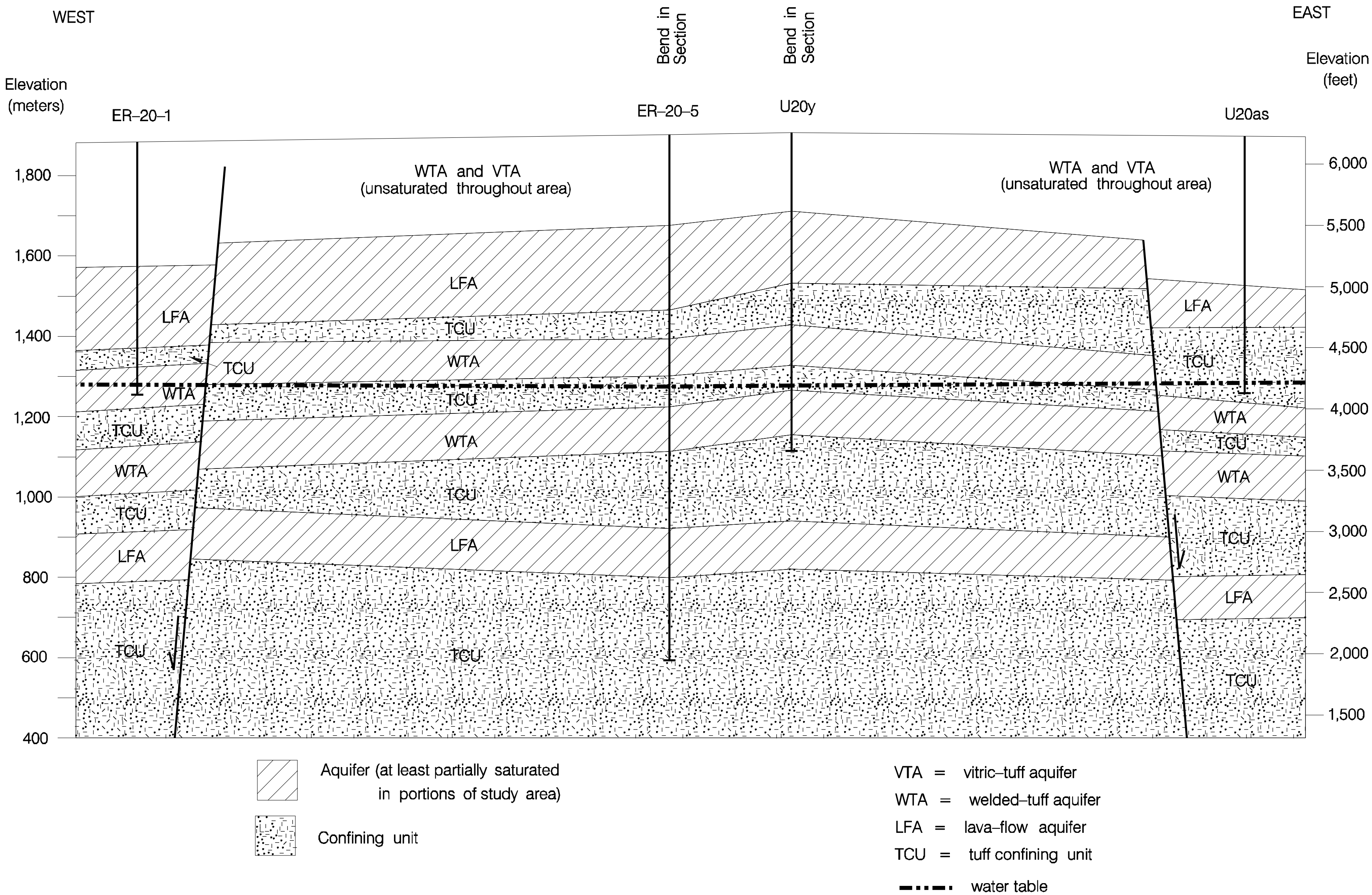
3.4.1 Aquifers in the TYBO-BENHAM Area

Lava of the rhyolite of Benham forms a lava-flow aquifer in the TYBO-BENHAM area. Although the aquifer occurs throughout most of the area, it is generally unsaturated. Only along the West Boxcar fault north of U20as and in the extreme northern portion of the study area around U20ao is the aquifer deep enough to have its lower portion below the water table. The measured fluid level in U20ao is anomalously high compared to nearby holes and the estimated regional water table, and probably represents perched water within the rhyolite of Benham (O'Hagan and Laczniak, 1996).

The Tiva Canyon Tuff is a welded-tuff aquifer throughout the TYBO-BENHAM area. In the southern portion of the area, the aquifer is present above the water table, and is thus unsaturated. However, the northward dip of the unit results in a progressively greater fraction of the aquifer becoming saturated to the north, until it is entirely saturated just north of U20c (Figure 3-16). The entire aquifer is also saturated just west of the West Boxcar and Boxcar faults in the eastern portion of the study area. In the western part of the area near ER-20-1, only the lower portion of the aquifer is saturated.

The Topopah Spring Tuff also forms a welded-tuff aquifer throughout the study area. The aquifer is entirely saturated throughout the TYBO-BENHAM area.

Lava within the mafic-poor Calico Hills Formation forms another lava-flow aquifer within the TYBO-BENHAM area. Detailed correlation of lithologic units within the lava, as well as petrographic/mineralogic subunits within the mafic-poor Calico Hills Formation, strongly suggests that this lava-flow aquifer occurs throughout the area with nearly uniform thickness and character, particularly in a north-south direction. It is completely saturated throughout the TYBO-BENHAM area.



See Figures 1–2 for locations of cross sections.

Figure 3-15

West-East Hydrogeologic Cross Section Through ER-20-1, ER-20-5, U20y, and U20as

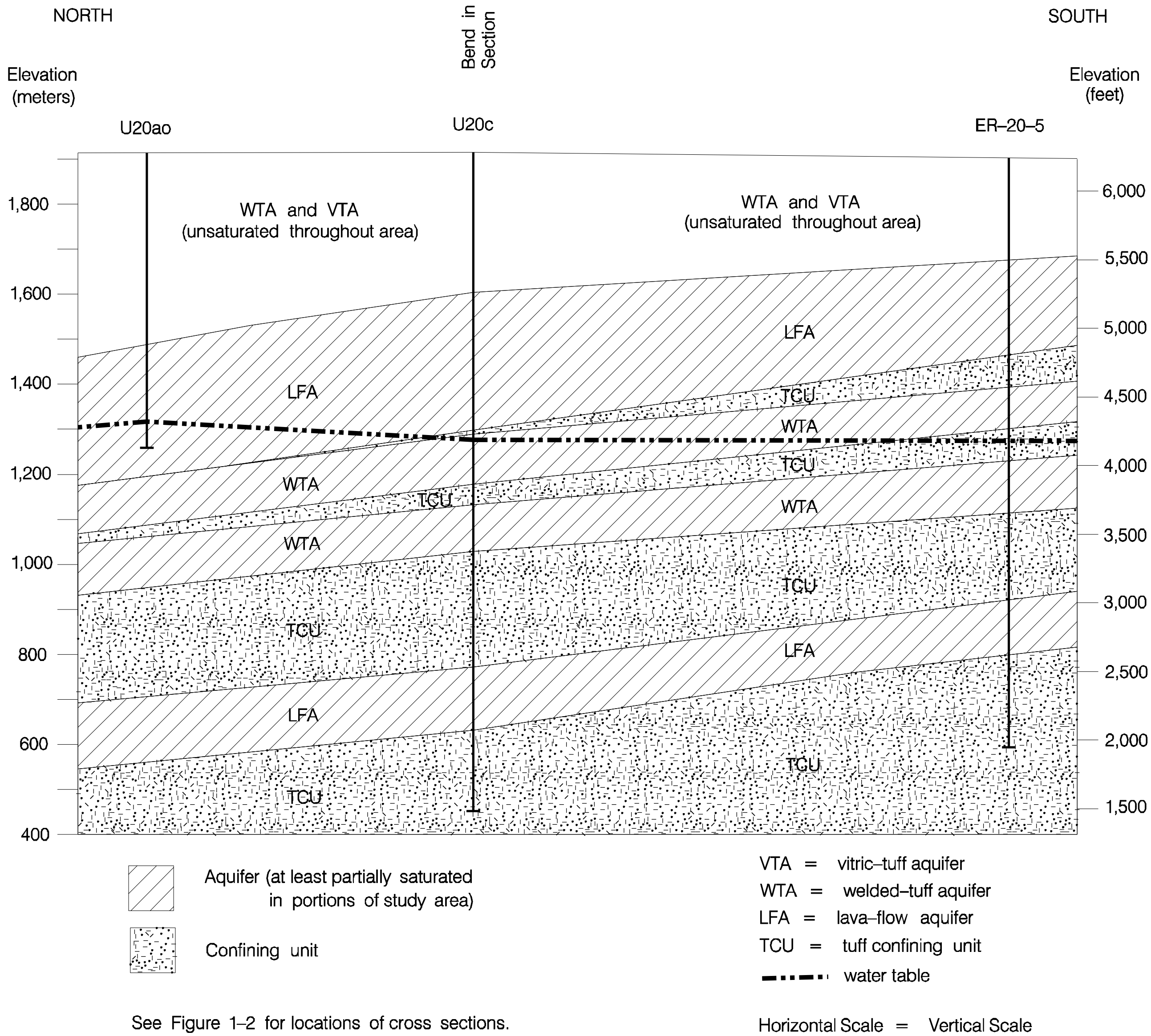


Figure 3-16

North-South Hydrogeologic Cross Section Through U20ao, U20c, and ER-20-5

3.4.2 Confining Units in the TYBO-BENHAM Area

Detailed analysis of the distribution of alteration minerals reveals that secondary alteration within tuff confining units is much more complex than previously described, and appears to be controlled by local heat sources. In addition to the expected occurrence of zeolites such as clinoptilolite and mordenite, higher temperature alteration minerals such as analcime and quartzo-feldspathic minerals are also common. Although this complexity likely has little effect on general hydrologic properties of these rocks, such as permeabilty, it could have considerable effect on their sorption of radionuclides. Because alteration of originally vitric rocks in the TYBO-BENHAM area appears to be controlled by proximity to local heat sources such as overlying ash-flow tuffs and lavas, alteration minerals tend to be distributed in zones that generally follow lithologic units.

3.4.3 Hydrologic Implications of Faulting in the TYBO-BENHAM Area

Faulting can create zones of enhanced permeability within aquifers due to increased fracturing of rocks adjacent to the faults. Therefore, the two buried faults described in Section 3.2.1.2 could form nearly vertical, narrow zones of enhanced permeability within aquifers of the TYBO-BENHAM area. The north to north-northeast strike of these faults, as well as the northward trend of surface fracture zones from underground weapons tests in the area, strongly suggest that fracture permeability is preferentially oriented in a north-south direction in the TYBO-BENHAM area. This may help to explain why water sample data from Well Cluster ER-20-5 indicate a southerly groundwater flow in the area (Thompson, 1998), even though analysis of hydrologic gradients suggests that groundwater flows in a westerly direction (O'Hagan and Laczniak, 1996).

Fracture permeability, including zones of enhanced permeability along faults, has probably been maintained through time in the TYBO-BENHAM area due to episodic fracturing of the rocks. Evidence for this assumption includes (1) episodic movement along faults at Pahute Mesa (Warren et al., 1985), and (2) recent adjustments due to underground weapons testing observed along the Boxcar and West Boxcar faults (Covington, 1987).

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4.0 Summary

The results of a detailed subsurface geologic analysis of the TYBO-BENHAM area support general conclusions about the hydrogeology of the area presented in previous reports (DOE, 1997 and Drellack and Prothro, 1997), and provide additional geologic information important for modeling groundwater flow and radionuclide migration in the area. The detailed work of this study confirms the presence of four shallow aquifers separated by tuff confining units. Correlation of geologic and hydrogeologic units strongly suggests that, as previous studies show, the aquifers underlie the entire area. Confirming the nature and extent of hydrogeologic units within the Calico Hills Formation is particularly important due to the hydrogeologic importance and lithologic complexity of the formation. The use of precise petrographic and mineralogic analyses of samples from area drill holes resulted in the recognition of subunits within the Calico Hills Formation. The identification of these subunits allows more detailed and confident correlation of tuff confining units and lava-flow aquifers within the TYBO-BENHAM area. If found applicable regionally, then this technique could be useful in resolving complex stratigraphic problems in other areas, such as at Well Cluster ER-20-6 where three lava-flow aquifers were encountered within the Calico Hills Formation (DOE, 1998).

Subsurface analysis of the area revealed two previously unrecognized buried faults. These faults could act as zones of enhanced permeability within aquifers. The north to north-northeast strike of these faults, as well as the northward trend of surface fracture zones from underground nuclear weapons tests in the area, strongly suggest that fracture permeability is preferentially oriented in a north-south direction in the TYBO-BENHAM area. This may help to explain why water sample data from ER-20-5 indicate a southerly groundwater flow in the area (Thompson, 1998) even though hydrologic gradients suggest that groundwater flows in a westerly direction (O'Hagan and Laczniak, 1996).

Secondary alteration within tuff confining units was found to be much more complex than previously described, consisting not only of zones of zeolitic alteration but also of zones having substantial quartzo-feldspathic alteration. Although this complexity likely has little effect on general hydrologic properties of these rocks, such as permeability, it could have considerable effect on their sorption of radionuclides. These alteration zones appear to be controlled by proximity to local heat sources, such as overlying ash flows and lava flows, thus alteration zones tend to follow lithologic zones in the TYBO-BENHAM area. The local correspondence of alteration to lithology at Pahute Mesa stands in striking contrast to a regional systematic downwards increase in alteration intensity seen within Yucca Mountain (Broxton et al., 1987).

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Appendix A

Detailed Lithologic Logs for Drill Holes of the TYBO-BENHAM Area

Detailed Lithologic Log for Well ER-20-1

By L. B. Prothro and R. G. Warren, 1999

(Page 1 of 6)

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 18.3 (0 - 60)	18.3 (60)	No Samples	None	**Partially Welded Ash-Flow Tuff**: Geologic samples and geophysical logs were not acquired through this interval. Geology inferred from surface geology and stratigraphy of nearby holes.	Ttt
18.3 - 37.8 (60 - 124)	19.5 (64)	DA	None	**Partially Welded Ash-Flow Tuff**: Lithologic samples and geophysical logs were not acquired from 18.3 to 33.5 m (60 - 110 ft). Geology inferred from surface geology, stratigraphy of nearby holes, and underlying stratigraphy. Sample at 36.6 m (120 ft) is a mixture of vitric to devitrified, peralkaline, partially welded ash-flow tuff fragments, ranging in color from moderate-reddish-brown (10R 4/6) to very-dusky-red (10R 2/2). The tuff fragments have minor to common feldspar phenocrysts, and rare to minor mafic minerals of clinopyroxene and olivine. Some fragments are scoriaceous. Also present are fragments of cement and very-pale-orange, partially zeolitic, nonwelded tuff.	Ttp
37.8 - 53.3 (124 - 175)	15.5 (51)	DB1	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); mostly devitrified, partially vitric; minor light-brown (5YR 5/6) pumice less than 2 mm in size; minor feldspar phenocrysts up to 5 mm in size; minor mafic minerals of olivine and clinopyroxene; rare moderate-reddish-brown (10R 4/6) lithic fragments less than 3 mm in size. Samples contain fragments of cement and peralkaline welded ash-flow tuff from uphole.	Ttr
53.3 - 74.4 (175 - 244)	21.1 (69)	DB2	None	**Bedded Tuff**: Samples consist of fragments of cement and peralkaline welded ash-flow tuff from uphole. Geology inferred from geophysical logs.	Ttr

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
74.4 - 81.7 (244 - 268)	7.3 (24)	DA	None	**Nonwelded Ash-Flow Tuff**: Light-brown (5Y 5/6); vitric; common white (N9) pumice up to 10 mm in size; common felsic phenocrysts of feldspar and lesser quartz; abundant biotite; minor pale-red (10R 6/2) lithic fragments less than 3 mm in size. Samples contain abundant fragments of various tuffaceous lithologies from uphole.	Tmar
81.7 - 93.9 (268 - 308)	12.2 (40)	DA	None	**Partially Welded Ash-Flow Tuff**: Pale-red (10R 6/2); mostly vitric, partially devitrified in upper part, becoming mostly devitrified and partially vitric lower; common very-pale-orange (10YR 8/2) to dark-yellowish-orange (10 YR 6/6) pumice up to 5 mm in size; common felsic phenocrysts of feldspar and lesser quartz; common mafic minerals of biotite and lesser clinopyroxene. Samples contain abundant fragments of various tuffaceous lithologies from uphole.	Tmar
93.9 - 118.9 (308 - 390)	25.0 (82)	DA	None	**Nonwelded Ash-Flow Tuff**: Moderate-yellowish-brown (10YR 5/4); vitric; common to abundant dark-yellowish-orange (10YR 6/6) pumice up to 5 mm in size; minor felsic phenocrysts of feldspar, including chatoyant sanidine, and lesser quartz; minor biotite. Samples contain abundant fragments of various tuffaceous lithologies from uphole.	Tmap
118.9 - 178.0 (390 - 584)	59.1 (194)	DB1	None	**Bedded Tuff:** Samples are a mixture of various tuffaceous lithologies including abundant fragments of white (N9) vitric pumice up to 15 mm in size containing feldspar and quartz phenocrysts, biotite, and sphene. Samples also include loose feldspar and quartz crystals, and abundant fragments of peralkaline welded ash-flow tuff from uphole.	Tmab
178.0 - 199.3 (584 - 654)	21.3 (70)	DA	None	**Nonwelded Ash-Flow Tuff**: Grayish-red (10R 4/2); vitric; abundant white (N9) pumice up to 10 mm in size; minor felsic phenocrysts of feldspar and lesser quartz; minor mafic minerals of biotite and much less clinopyroxene; rare dusky-red (5R 3/4) lithic fragments up to 2 mm in diameter; conspicuous dark-yellowish-orange (10YR 6/6) glass shards.	Tmr

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
199.3 - 201.8 (654 - 662)	2.5 (8)	DA	None	**Partially Welded Ash-Flow Tuff**: Light-brownish-gray (5YR 6/1); devitrified, with vapor-phase mineralization; common light-brownish-gray (5YR 6/1) partially flattened pumice less than 3 mm in size; minor felsic phenocrysts of quartz and feldspar; minor mafic minerals of biotite and much less clinopyroxene; rare dark-reddish-brown (10R 3/4) volcanic lithic fragments less than 3 mm in size; conspicuous moderate-reddish-brown (10R 4/6) devitrified glass shards.	Tmr
201.8 - 210.3 (662 - 690)	8.5 (28)	DA	None	**Moderately Welded Ash-Flow Tuff**: Mottled grayish-red (10R 4/2) and moderate-reddish-brown (10R 4/6); mostly devitrified, partially silicic; minor to common moderate-reddish-brown (10R 4/6) flattened pumice less than 3 mm in size; common felsic phenocrysts of feldspar and lesser quartz; minor mafic minerals of biotite and much less clinopyroxene. Fragments of translucent botryoidal chalcedony are present in samples.	Tmr
210.3 - 218.8 (690 - 718)	8.5 (28)	DA	None	**Densely Welded Ash-Flow Tuff**: Mottled moderate-red (5R 5/4) and grayish-black (N2); vitric; perlitic in part; common felsic phenocrysts of feldspar and quartz; minor mafic minerals of biotite and much less clinopyroxene. Fragments of translucent botryoidal chalcedony are present in samples.	Tmr
218.8 - 223.1 (718 - 732)	4.3 (14)	DA	None	**Moderately Welded Ash-Flow Tuff**: Dark-reddish-brown (10R 3/4); mostly vitric, partially devitrified; minor white (N9) pumice less than 2 mm in size; common felsic phenocrysts of feldspar and quartz; minor mafic minerals of biotite and much less clino-pyroxene; rare dusky-red (5R 3/4) volcanic lithic fragments up to 3 mm in diameter; conspicuous light-brown (5YR 5/6) flattened glass shards.	Tmr
223.1 - 225.6 (732 - 740)	2.5 (8)	DA	None	**Partially Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); vitric; common white (N9) partially flattened pumice up to 10 mm in size; minor felsic phenocrysts of feldspar and quartz; minor mafic minerals of biotite and much less clinopyroxene; conspicuous dark-yellowish-orange (10YR 6/6) glass shards.	Tmr

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
225.6 - 228.6 (740 - 750)	3.0 (10)	DA	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5Y 4/4); vitric; common white (N9) pumice up to 8 mm in size; minor felsic phenocrysts of feldspar and quartz; minor mafic minerals of biotite and much less clinopyroxene; rare dusky-red (5R 3/4) volcanic lithic fragments up to 5 mm in size.	Tmr
228.6 - 280.7 (750 - 921)	52.1 (171)	DB1	None	**Bedded Tuff**: Dark-yellowish-orange (10YR 6/6), grayish-orange (10YR 7/4), and very-pale-orange (10YR 8/2); vitric; minor to common very-pale-orange (10YR 8/2) pumice up to 10 mm in size; rare felsic phenocrysts of quartz and feldspar; rare biotite; minor volcanic lithic fragments of various colors and up to 10 mm in size.	Tmrf
280.7 - 308.5 (921 - 1,012)	27.8 (91)	DA	None	**Nonwelded Tuff**: Pinkish-gray (5YR 8/1) becoming grayish-orange (10YR 7/4) below approximately 295.7 m (970 ft); mostly vitric, partially zeolitic; minor pinkish-gray (5YR 8/1) pumice less than 2 mm in size; rare felsic phenocrysts of feldspar and quartz; rare biotite; rare dark-reddish-brown (10R 3/4) volcanic lithic fragments up to 5 mm in size.	Tmrf
308.5 - 311.2 (1,012 - 1,021)	2.7 (9)	DA	None	**Bedded Tuff**: Pale-reddish-brown (10R 5/4), moderate-brown (5YR 4/4), and pale-yellowish-brown (10YR 6/2); mostly vitric, partially zeolitic; rare to minor white (N9) pumice less than 3 mm in size; rare to minor feldspar phenocrysts; minor mafic minerals of biotite and lesser hornblende and clinopyroxene; rare to abundant volcanic lithic fragments of various colors and less than 2 mm in size. Many of the drill cuttings have a “sandy” texture with conspicuous magnetite and may represent reworked tuff. The spectral gamma ray log shows an increase in uranium and thorium through this interval.	Tmrh
311.2 - 321.3 (1,021 - 1,054)	10.1 (33)	DA	None	**Nonwelded Tuff**: Moderate-yellowish-brown (10YR 5/4); mostly vitric, partially devitrified; common moderate-orange-pink (10R 7/4) and pale-greenish-yellow (10Y 7/4) pumice up to 5 mm in size; minor felsic phenocrysts of feldspar and much less quartz; minor mafic minerals of biotite and lesser hornblende; rare dusky-red (5R 3/4) volcanic lithic fragments up to 3 mm in diameter; rare sphene.	Tpb

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
321.3 - 341.4 (1,054 - 1,120)	20.1 (66)	DA	None	**Flow Breccia**: Mottled yellowish-gray (5Y 8/1) and dark-yellowish-brown (10YR 4/2); mostly zeolitic, partially devitrified and silicic; pumiceous; rare feldspar phenocrysts; minor mafic minerals of biotite and lesser hornblende; common sphene. Fragments of white (N9) translucent botryoidal chalcedony and clusters of large (~4 mm) clear subhedral quartz crystals are present in samples. Interval appears to consist of dark-yellowish-brown (10YR 4/2) devitrified and silicic lava fragments within a yellowish-gray (5Y 8/1) zeolitic and pumiceous matrix.	Tpb
341.4 - 379.8 (1,120 - 1,246)	38.4 (126)	DA	None	**Flow Breccia**: Mottled pale-reddish-brown (10R 5/4), grayish-yellow (5Y 8/4), and light-brownish-gray (5YR 6/1); mostly vitric, partially silicic and zeolitic; perlitic in part; rare feldspar phenocrysts; minor mafic minerals of biotite and lesser hornblende; common sphene. Fragments of white (N9) translucent botryoidal chalcedony are present in samples.	Tpb
379.8 - 474.3 (1,246 - 1,556)	94.5 (310)	DA	None	**Lava**: Mottled light-gray (N7) and pale-brown (5YR 5/2); devitrified; slightly pumiceous towards base of interval; rare feldspar phenocrysts; rare biotite; rare sphene; flow banded.	Tpb
474.3 - 504.1 (1,556 - 1,654)	29.8 (98)	DA	None	**Vitrophyric Lava**: Dark-yellowish-brown (10YR 4/2), lesser moderate-reddish-brown (10R 4/6); vitric; perlitic in part; rare feldspar phenocrysts; rare biotite; rare sphene; rare white (N9) translucent chalcedony as fracture fill.	Tpb
504.1 - 513.6 (1,654 - 1,685)	9.5 (31)	DA	None	**Flow Breccia**: Pale-brown (5YR 5/2); mostly devitrified, partially silicic; pumiceous in part; minor feldspar phenocrysts; common biotite; rare sphene.	Tpb
513.6 - 545.6 (1,685 - 1,790)	32.0 (105)	DA	None	**Nonwelded Tuff**: Pale-reddish-brown (10R 5/4); zeolitic; abundant moderate-orange-pink (10R 7/4) pumice less than 4 mm in size; rare feldspar phenocrysts; minor biotite; rare moderate-brown (5YR 4/4) volcanic lithic fragments up to 5 mm in size; rare sphene.	Tpb

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
545.6 - 560.2 (1,790 - 1,838)	14.6 (48)	DA	None	**Nonwelded Tuff:** Moderate-yellow (5Y 7/6); zeolitic; common moderate-yellow (5Y 7/6) pumice up to 4 mm in size; rare feldspar phenocrysts; rare biotite; rare moderate-brown (5YR 3/4) volcanic lithic fragments up to 3 mm in size.	Tpcyp
560.2 - 572.4 (1,838 - 1,878)	12.2 (40)	DA	TS, XRD, XRF	**Partially Welded Ash-Flow Tuff**: Light-gray (N7); devitrified, minor zeolitic; rare light-brownish-gray (5YR 6/1) recrystallized, partially flattened pumice less than 2 mm in size; rare feldspar phenocrysts; minor biotite; no lithic fragments.	Tpcm
572.4 - 629.4 (1,878 - 2,065) TD	57.0 (187)	DA	TS, XRD, XRF	**Moderately Welded Ash-Flow Tuff:** Grayish-red (10R 4/2) and moderate-reddish-brown (10R 4/6); devitrified; rare pinkish-gray (5YR 8/1) pumice up to 3 mm in size; minor feldspar phenocrysts; minor biotite; rare sphene.	Tpcm

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components; **DB2** = drill cuttings from interval different than that drilled.

b **TS** = thin section; **XRD** = X-ray diffraction; **XRF** = X-ray fluorescence. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = ≤ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = ≥ 20%.
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = ≤ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = ≥ 2%.

d **Ttt** = Trail Ridge Tuff; **Ttp** = Pahute Mesa Tuff; **Ttr** = Rocket Wash Tuff; **Tmar** = mafic-rich Ammonia Tanks Tuff; **Tmap** = mafic-poor Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tmrh** = tuff of Holmes Road; **Tpb** = rhyolite of Benham; **Tpcyp** = crystal-poor tuff of Pinyon Pass; **Tpcm** = Pahute Mesa lobe of the Tiva Canyon Tuff. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of ER-20-1.

Detailed Lithologic Log for Well Cluster ER-20-5

By L. B. Prothro and R. G. Warren, 1999

This lithologic log combines geologic data from ER-20-5#1, ER-20-5#2, and ER-20-5#3 into a single composite lithologic log of the Well Cluster ER-20-5 site. The log is modified from Appendix C of *Completion Report for Well Cluster ER-20-5*, U.S. Department of Energy Report DOE/NV--466, UC-700, March 1997.

Depth Interval [a] meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [b]	**Laboratory Analyses** [c]	**Lithologic Description** [d]	**Stratigraphic Unit** [e]
0 - 9.1 (0 - 30)	9.1 (30)	DA, DB1	None	**Partially Welded Ash-Flow Tuff**: Grayish-brown (5YR 3/2); devitrified; rare dark-gray (N3) pumice; minor feldspar phenocrysts; minor mafic minerals of olivine and much less clinopyroxene; rare moderate-brown (5 YR 3/4) lithic fragments up to 1 mm in diameter.	Ttt
9.1 - 20.1 (30 - 66)	11.0 (36)	DB1	None	**Bedded Tuff**: Samples consist mostly of very-pale-orange(10YR 8/2), light-gray (N7), and white (N9) fragments of vitric pumice. Pumice fragments contain rare feldspar phenocrysts and olivine.	Ttt
20.1 - 45.7 (66 - 150)	25.6 (84)	DA, DB1	None	**Partially Welded Ash-Flow Tuff**: Brownish-black (5YR 2/1) to grayish-black (N2), becoming moderate-brown (5YR 4/4) below 36.6 m (120 ft); devitrified; weakly scoriaceous in part; rare grayish-black (N2) pumice; minor feldspar phenocrysts; rare mafic minerals of olivine and much less clinopyroxene.	Ttp
45.7 - 52.4 (150 - 172)	6.7 (22)	DB1	None	**Bedded Tuff**: Samples are a mixture of vitric pumice and tuffaceous rock fragments; loose crystals of feldspar, olivine, and much less clinopyroxene; and abundant lost circulation material consisting of cottonseed hull fibers.	Ttp
52.4 - 67.7 (172 - 222)	15.3 (50)	DB1	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); vitric; minor to common white (N9) and light-brown (5YR 5/6) to dark-yellowish-orange (10YR 6/6) pumice; minor felsic phenocrysts of feldspar and lesser quartz; minor mafic minerals of biotite (including conspicuously large “booklets” up to 3 mm in size) and clinopyroxene.	Tmap

Depth Interval [a] meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [b]	**Laboratory Analyses** [c]	**Lithologic Description** [d]	**Stratigraphic Unit** [e]
67.7 - 95.7 (222 - 314)	28.0 (92)	DB1	None	**Bedded Tuff:** Samples are a mixture of pumice and various tuffaceous rock fragments, loose crystals of quartz and feldspar, and abundant lost circulation material consisting of cottonseed hull fibers. The pumice fragments dominate the samples and are white (N9), vitric, and contain rare quartz and feldspar phenocrysts, biotite, clinopyroxene, and a trace of sphene.	Tmab
95.7 -106.7 (314 - 350)	11.0 (36)	DB1, DB2	None	**Nonwelded Ash-Flow Tuff**: Lithology not well represented in drill cuttings samples due to poor circulation of drilling fluid. Geology inferred from geophysical logs.	Tmr
106.7 - 112.8 (350 - 370)	6.1 (20)	DA, DB2	None	**Partially Welded Ash-Flow Tuff**: Grayish-red (5Y 4/2); mostly devitrified, partially vitric; minor to common mostly white (N 9) pumice; common felsic phenocrysts of feldspar and quartz; minor biotite, trace of clinopyroxene; rare dusky-red (5R 3/4) lithic fragments up to 2 mm in size. Samples contain abundant fragments of cement and large (>2 cm) pieces of black rubber from cement plug.	Tmr
112.8 - 120.7 (370 - 396)	7.9 (26)	DA	None	**Moderately Welded Ash-Flow Tuff:** Grayish-red (5R 4/2); devitrified; minor grayish-pink (5R 8/2) pumice; common felsic phenocrysts of quartz and feldspar; minor biotite; rare dusky-red (5R 3/4) lithic fragments up to 2 mm in size. Samples contain abundant fragments of cement and large (>2 cm) pieces of black rubber from cement plug.	Tmr
120.7 - 139.6 (396 - 458)	18.9 (62)	DB1	None	**Densely Welded Ash-Flow Tuff**: Grayish-red (10R 4/2) to dark-gray (N3), mottled in part; vitric to devitrified; vitrophyric and weakly perlitic in part; common felsic phenocrysts of feldspar and quartz; common biotite.	Tmr

Depth Interval [a] meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [b]	**Laboratory Analyses** [c]	**Lithologic Description** [d]	**Stratigraphic Unit** [e]
139.6 - 152.4 (458 - 500)	12.8 (42)	DB1	None	**Nonwelded Ash-Flow Tuff**: Samples are mixture of very-pale-orange (10YR 8/2) fragments of vitric pumice, and tuffaceous rock fragments of various colors. Pumice fragments contain rare phenocrysts of feldspar and quartz, and rare biotite. A grayish-orange (10YR 7/4) vitric matrix coats many of the pumice fragments. Loose crystals of feldspar and quartz are also present in the samples.	Tmr
152.4 - 214.0 (500 - 702)	61.6 (202)	DB1	None	**Bedded Tuff**: Samples are a mixture of mostly pumice and tuffaceous rock fragments. Pumice is vitric and ranges in color from grayish-orange (10YR 7/4) and light-brown (5YR 6/4) to white (N9). Feldspar and quartz crystals occur as phenocrysts in the pumice fragments and as loose crystals. Biotite, present mainly as rare small flakes in the pumice, was the only mafic mineral observed.	Tmrf
214.0 - 226.2 (702 - 742)	12.2 (40)	DB1	None	**Bedded Tuff**: Samples are very similar to those from the interval above. Stratigraphy and lithology based on geophysical logs.	Tmrf
226.2 - 284.4 (742 - 933)	58.2 (191)	DA	None	**Pumiceous Lava**: Pale-yellowish-brown (10YR 6/2), becoming black (N1) in part below approximately 265.2 m (870 ft); vitric; frothy and perlitic in part below approximately 265.2 m (870 ft); rare feldspar phenocrysts; common biotite; minor conspicuous sphene; rare fragments of white (N9) translucent chalcedony occur in samples throughout interval.	Tpb
284.4 - 382.2 (933 - 1,254)	97.8 (321)	DA	None	**Lava**: Mottled light-gray (N7) and grayish-red (10R 4/2); devitrified; rare feldspar phenocrysts; common biotite; trace of hornblende; trace of sphene.	Tpb
382.2 - 416.4 (1,254 - 1,366)	34.2 (112)	DA	None	**Lava**: Mottled grayish-black (N2) and light-brown (5YR 5/6); vitric and devitrified; perlitic where vitric; rare feldspar phenocrysts; common biotite; minor conspicuous sphene.	Tpb

Depth Interval [a] meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [b]	**Laboratory Analyses** [c]	**Lithologic Description** [d]	**Stratigraphic Unit** [e]
416.4 - 437.4 (1,366 - 1,435)	21.0 (69)	DA	None	**Flow Breccia:** Mottled grayish-orange (10YR 7/4), pale-yellowish-brown (10YR 6/2) to dark-yellowish-brown (10YR 4/2), and pale-reddish-brown (10R 5/4); devitrified, silicified in part; rare feldspar phenocrysts; common biotite; minor conspicuous sphene.	Tpb
437.4 - 495.3 (1,435 - 1,625)	57.9 (190)	DA	None	**Bedded Tuff:** Pale-reddish-brown (10YR 6/2), grayish-yellow (5Y 8/4), and very-pale-orange (10YR 8/2); zeolitic; minor mostly grayish-yellow (5Y 8/4) pumice; minor feldspar phenocrysts; common biotite; rare to minor moderate-brown (5YR 4/4) lithic fragments up to 4 mm in size; rare sphene.	Tpb
495.3 - 509.3 (1,625 - 1,671)	14.0 (46)	DA	None	**Bedded Tuff**: Pale-yellowish-brown (10YR 6/2); zeolitic; minor to common very-pale-orange (10YR 8/2) pumice; rare feldspar phenocrysts; rare biotite; rare dusky-brown (5YR 2/2) lithic fragments up to 2 mm in size.	Tpcyp
509.3 - 519.4 (1,671 - 1,704)	10.1 (33)	DA	None	**Partially Welded Ash-Flow Tuff**: Light-brownish-gray (5YR 6/1); devitrified, with moderate vapor-phase mineralization; minor light-gray (N7) pumice; rare feldspar phenocrysts; rare biotite; rare moderate-brown (5YR 3/4) lithic fragments up to 1 mm in size; rare sphene.	Tpcm
519.4 - 601.4 (1,704 - 1,973)	82.0 (269)	DA	None	**Moderately Welded Ash-Flow Tuff**: Moderate-brown (5YR 3/4) to approximately 527.3 m (1,730 ft), grayish-red (10R 4/2) from approximately 527.3 to 579.1 m (1,730 - 1,900 ft), and mottled grayish-brown (5YR 3/2) and light-brown (5YR 5/6) below approximately 579.1 m (1,900 ft); devitrified; rare, mostly light-gray (N7) pumice; rare feldspar phenocrysts; rare biotite; minor sphene.	Tpcm

Depth Interval [a] meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [b]	**Laboratory Analyses** [c]	**Lithologic Description** [d]	**Stratigraphic Unit** [e]
601.4 - 678.2 (1,973 - 2,225)	76.8 (252)	DA	TS, XRD	**Bedded Tuff**: Yellowish-gray (5Y 8/4), moderate-reddish-brown (10R 4/6) and dark-yellowish-orange (10YR 6/6); zeolitic; minor to common pumice; rare to minor feldspar phenocrysts; rare to minor biotite; rare to common lithic fragments up to 1 cm in size. Conspicuous chalcedony- and manganese-oxide-filled fractures up to 1 mm in width observed in fragments of drill cuttings samples at approximately 637.0 m (2,090 ft). Laboratory analyses and geophysical logs indicate interval is rhyolite of Black Glass Canyon above 649.8 m (2,132 ft), and rhyolite of Delirium Canyon below.	Tp
678.2 - 684.6 (2,225 - 2,246)	6.4 (21)	DA	None	**Partially Welded Ash-Flow Tuff**: Light-bluish-gray (5B 7/1); devitrified, with vapor-phase mineralization; minor moderate-reddish-brown (10R 4/6) partially flattened pumice; minor feldspar phenocrysts; minor biotite.	Tptm
684.6 - 789.7 (2,246 - 2,591)	105.1 (345)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2) to approximately 717.8 m (2,355 ft), moderate-brown (5 YR 3/4) from 717.8 to 748.3 m (2,355 - 2,455 ft), and light-brown (5YR 5/6) below 748.3 m (2,455 ft); devitrified, becoming partially zeolitic below approximately 748.3 m (2,455 ft); rare flattened pumice; minor felsic phenocrysts of feldspar and a trace of quartz; minor mafic minerals of biotite, with conspicuous clinopyroxene below approximately 763.5 m (2,505 ft).	Tptm
789.7 - 830.6 (2,591 - 2,725) *789.7 - 826.9* *(2,591 - 2,713)*	40.8 (134) *37.2* *(122)*	DA	None	**Nonwelded Ash-Flow Tuff**: Pale-brown (5YR 5/2); potassic (alteration based on laboratory analyses from nearby hole U20y); rare felsic phenocrysts of feldspar and a trace of quartz; minor biotite; rare dark-reddish-brown (10R 3/4) lithic fragments up to 2 mm in size.	Tptm
830.6 - 906.8 (2,725 - 2,975) *826.9 - 902.2* *(2,713 - 2,960)*	76.2 (250) *75.3* *(247)*	DA	TS, XRD, XRF	**Bedded Tuff**: Moderate-reddish-brown (10R 4/6); silicic, zeolitic,and potassic; common grayish-yellow (5Y 8/4) and very-pale-orange (10YR 8/2) pumice; rare felsic phenocrysts of feldspar and quartz; minor biotite; rare dark-reddish-brown (10R 3/4) lithic fragments up to 2 mm in size.	Thp

Depth Interval [a] meters/(feet)	Thickness meters/ (feet)	Sample Type [b]	Laboratory Analyses [c]	Lithologic Description [d]	Stratigraphic Unit [e]
906.8 - 979.0 (2,975 - 3,212) *902.2 - 972.6 (2,960 - 3,191)*	72.2 (237) *70.4 (231)*	DA, SC	XRD, XRF	**Bedded Tuff**: Yellowish-gray (5Y 7/2) to dusky-yellow (5Y 6/4); zeolitic and potassic, silicified in part; very rare felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
979.0 - 988.2 (3,212 - 3,242) *972.6 - 981.8 (3,191 - 3,221)*	9.2 (30) *9.2 (30)*	DA	None	**Pumiceous Lava**: Yellowish-gray (5Y 7/2); zeolitic; very rare felsic phenocrysts of feldspar and quartz; rare biotite; rare manganese-oxide-filled fractures less than 0.5 mm in width.	Thp
988.2 - 1067.4 (3,242 - 3,502) *981.8 - 1,059.2 (3,221 - 3,475)*	79.2 (260) *77.4 (254)*	DA, SC	None	**Lava**: Moderate-yellowish-brown (10YR 5/4) to approximately 999.7 m (3,280 ft) *993.0 m (3,258 ft),* pale-reddish-brown (10R 5/4) to grayish-red (10R 4/2) from approximately 999.7 to 1,039.4 m (3,280 - 3,410 ft) *993.0 - 1,031.7 m (3,258 - 3,385 ft),* and mostly medium-light-gray (N6) below approximately 1,039.4 m (3,410 ft) *1,031.7 (3,385 ft)*; mostly devitrified to partially zeolitic, vitrophyric and silicified in part; rare felsic phenocrysts of feldspar and quartz; rare biotite; flow-banded in part; common chalcedony- and manganese-oxide-filled fractures less than 1 mm in width.	Thp
1,067.4 - 1,113.1 (3,502 - 3,652) *1,059.2 - 1,104.0 (3,475 - 3,622)*	45.7 (150) *44.8 (147)*	DA, SC	None	**Lava**: Light brownish-gray (5YR 6/1) and grayish-black (N2) to approximately 1,082.0 m (3,550 ft) *1,073.5 m (3,522 ft)*, mostly grayish-black (N2) below; partially devitrified (light-brownish-gray fragments) and vitrophyric (grayish-black fragments) to approximately 1,082.0 m (3,550 ft) *1,073.5 m (3,522 ft)*, mostly vitrophyric below; rare feldspar phenocrysts; rare biotite.	Thp
1,113.1 - 1,189.3 (3,652 - 3,902) *1,104.0 - 1,178.1 (3,622 - 3,865)*	76.2 (250) *74.1 (243)*	DA, SC	XRD, XRF	**Pumiceous Lava**: Pale-yellowish-brown (10YR 6/2) and yellowish-gray (5Y 7/2), mottled; zeolitic; rare felsic phenocrysts of feldspar and quartz; rare biotite.	Thp

Depth Interval [a] meters/(feet)	Thickness meters/ (feet)	Sample Type [b]	Laboratory Analyses [c]	Lithologic Description [d]	Stratigraphic Unit [e]
1,189.3 - 1,250.9 (3,902 - 4,104) *1,178.1 - 1,238.1 (3,865 - 4,062)*	61.6 (202) *60.0 (197)*	DA, SC	XRD, XRF	**Bedded Tuff**: Grayish-orange (10YR 7/4) to moderate-yellowish-brown (10YR 5/4); zeolitic; minor pumice; rare felsic phenocrysts of feldspar and quartz; rare biotite; rare moderate-reddish-brown (10R 4/6) lithic fragments up to 2 mm in size.	Thp
1,250.9 - 1,308.8 (4,104 - 4,294) TD *1238.1 - 1294.2 (4062 - 4246) TD*	57.9 (190) *56.1 (184)*	DA, SC	XRD, XRF	**Bedded Tuff**: Moderate-orange-pink (5YR 8/4) to moderate-reddish-brown (10R 4/6); silicic and potassic, and minor zeolitic; minor pumice; minor felsic phenocrysts of feldspar and quartz; minor biotite; rare moderate-reddish-brown (10R 4/6) lithic fragments up to 3 mm in size.	Thr

a Because ER-20-5#3 deviated substantially from the vertical below 789.7 m (2591 ft), true vertical depths and thicknesses are provided in italics below this depth.

b **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components; **SC** = sidewall core.

c **TS** = thin section; **XRD** = X-ray diffraction; **XRF** = X-ray fluorescence. See Appendix B (this report) for details of laboratory analyses.

d Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = ≤ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = ≥ 20%.
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = ≤ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = ≥ 2%.

e **Ttt** = Trail Ridge Tuff; **Ttp** = Pahute Mesa Tuff; **Tmap** = mafic-poor Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tpb** = rhyolite of Benham; **Tpcy** = tuff of Pinyon Pass; **Tpcm** = Pahute Mesa lobe of the Tiva Canyon Tuff; **Tp** = rhyolite of Black Glass Canyon and rhyolite of Delirium Canyon; **Tptm** = Pahute Mesa lobe of the Topopah Springs Tuff; **Thp** = mafic-poor Calico Hills Formation; **Thr** = mafic-rich Calico Hills Formation. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of Well Cluster ER-20-5.

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Detailed Lithologic Log for Emplacement Hole U20ag

By L. B. Prothro and R. G. Warren, 1999

(Page 1 of 5)

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 12.2 (0 - 40)	12.2 (40)	No Sample s	None	**Moderately Welded Ash-Flow Tuff**: No drill hole data. Stratigraphy is inferred from surface exposures. Lower contact is estimated. Base of interval may be bedded tuff.	Ttt
12.2 - 43.0 (40 - 141)	30.8 (101)	DB1	CO_2	**Partially Welded Ash-Flow Tuff**: Pale-brown (5YR 5/2); devitrified, vapor-phase mineralization; minor medium-dark-gray (N 4) and dusky-yellowish-brown (10YR 2/2) recrystallized partially flattened pumice less than 5 mm in size; minor feldspar phenocrysts above 24.4 m (80 ft), becoming rare in abundance below; minor altered olivine; rare dusky-brown (5YR 2/2); volcanic lithic fragments up to 20 cm in size. Interval is probably crystal-rich Pahute Mesa Tuff (Ttpr) above approximately 25.9 m (85 ft), and crystal-poor Pahute Mesa Tuff (Ttpp) below.	Ttp
43.0 - 64.0 (141 - 210)	21.0 (69)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-brown (5YR 3/2) to 45.7 m (150 ft), becoming moderate-brown (5YR 3/4) below; devitrified; rare medium-gray (N 5) and brownish-black (5YR 2/1) flattened pumice less than 5 mm in size; rare feldspar phenocrysts; rare olivine and dark pyroxene; no lithic fragments.	Ttp
64.0 - 73.5 (210 - 241)	9.5 (31)	DB1	CO_2	**Partially Welded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); devitrified, vapor-phase mineralization; minor pale-red (10YR 6/2) and moderate-brown (5YR 3/4) recrystallized, partially flattened pumice less than 4 mm in size; minor feldspar phenocrysts; rare olivine and dark pyroxene; rare grayish-brown (5YR 3/2) volcanic lithic fragments less than 5 mm in size.	Ttr

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
73.5 - 93.3 (241 - 306)	19.8 (65)	DB1	XRD, CO_2	**Partially Welded Ash-Flow Tuff**: Moderate-yellowish-brown (10YR 5/4); mostly vitric, partially devitrified; common white (N 9), brownish-black (5YR 2/1), and dark-yellowish-orange (10Y 6/6) vitric pumice up to 10 mm in size; common felsic phenocrysts of feldspar and quartz; common mafic minerals of biotite and lesser clinopyroxene; rare dark-reddish-brown (10YR 3/4) lithic fragments of devitrified welded tuff up to 10 mm in size.	Tmar
93.3 - 121.3 (306 - 398)	28.0 (92)	DB1	CO_2	**Bedded Tuff**: Samples consist of loose crystals of quartz and feldspar; fragments of white (N 9) vitric pumice up to 20 mm in size containing phenocrysts of quartz, feldspar, biotite, and sphene; and lithic fragments representing a variety of volcanic lithic fragments, including partially welded Ammonia Tanks Tuff (Tma) from up-hole. A white (N 9) vitric matrix partially coats some of the felsic crystals and lithic fragments.	Tmab
121.3 - 126.8 (398 - 416)	5.5 (18)	DB1	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); vitric; minor white (N 9) and light-brown (5YR 5/6) pumice typically less than 4 mm in size; minor felsic phenocrysts of quartz and feldspar; common mafic minerals of biotite and much less clinopyroxene; rare grayish-red (5R 4/2) volcanic lithic fragments less than 2 mm in size.	Tmrr
126.8 - 134.7 (416 - 442)	7.9 (26)	DA	CO_2	**Partially Welded Ash-Flow Tuff**: Pale-reddish-brown (10R 5/4); devitrified, with vapor-phase mineralization; common medium-light-gray (N 6) and light-brown (5YR 5/6) partially flattened, recrystallized pumice less than 5 mm in size; common felsic phenocrysts of feldspar and quartz; abundant mafic minerals of biotite and lesser clinopyroxene; trace of lithic fragments.	Tmrr
134.7 - 164.0 (442 - 538)	29.3 (96)	DA	XRD, CO_2	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; common yellowish-gray (5Y 8/1) flattened pumice less than 4 mm in size; common felsic phenocrysts of feldspar and quartz; common biotite; no lithic fragments.	Tmrr

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
164.0 - 171.3 (538 - 562)	7.3 (24)	DA	None	**Densely Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; common felsic phenocrysts of feldspar and quartz; common biotite; no lithic fragments.	Tmrr
171.3 - 176.8 (562 - 580)	5.5 (18)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; minor yellowish-gray (5Y 8/1) flattened pumice less than 4 mm in size; common felsic phenocrysts of feldspar and quartz; common biotite; no lithic fragments.	Tmrr
176.8 - 185.9 (580 - 610)	9.1 (30)	DB1	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (5R 4/2); devitrified; minor light-gray (N 7) flattened pumice less than 2 mm in size; minor felsic phenocrysts of feldspar and quartz; minor biotite; no lithic fragments.	Tmrp
185.9 -198.7 (610 - 652)	12.8 (42)	DA	CO_2	**Densely Welded Ash-Flow Tuff**: Moderate-brown (5YR 3/4); devitrified; common felsic phenocrysts of feldspar and quartz; rare biotite; no lithic fragments; conspicuous fragments of round lithophysae up to 5 mm in diameter, and mostly filled with crystalline quartz.	Tmrp
198.7 - 208.8 (652 - 685)	10.1 (33)	DB1 - DA	XRD	**Vitrophyric Ash-Flow Tuff**: Mottled brownish-black (5YR 2/1) and moderate-brown (5YR 3/4); mostly vitric, partially devitrified, minor argillic; perlitic; common felsic phenocrysts of feldspar and quartz; minor biotite; no lithic fragments.	Tmrp
208.8 - 216.4 (685 - 710)	7.6 (25)	DB1	None	**Nonwelded Ash-Flow Tuff**: Samples consist of loose crystals of feldspar and quartz; moderate-reddish-orange (10R 6/6) fragments of vitric pumice up to 8 mm in size; various volcanic lithic fragments up to 15 mm in size; and a few flakes of biotite. A moderate reddish-brown (10R 4/6) vitric matrix coats most of the pumice fragments.	Tmrp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
216.4 - 283.5 (710 - 930)	67.1 (220)	DB1	CO_2	**Bedded Tuff**: Samples consist of loose fragments of white (N 9) and very-pale -orange (10YR 8/2) vitric pumice generally less than 5 mm in size, and containing phenocrysts of quartz, feldspar, and biotite; loose felsic crystals of quartz and feldspar; a variety of volcanic lithic fragments less than 5 mm in size; and a very small amount of loose biotite. A white (N 9) and grayish-orange (10YR 7/4) vitric matrix partially coats many of the fragments and crystals.	Tmrf
283.5 - 292.6 (930 - 960)	9.1 (30)	DA	XRD, CO_2	**Nonwelded Tuff**: Very-pale-orange (10YR 8/2); vitric; abundant yellowish-gray (5Y 8/1) vitric pumice generally less than 3 mm in size; minor felsic phenocrysts of feldspar and quartz; rare biotite; rare mostly pale-reddish-brown (10R 5/4) lithic fragments of devitrified volcanic rocks less than 4 mm in size.	Tmrf
292.6 - 304.8 (960 - 1,000)	12.2 (40)	DA, DB1	CO_2	**Bedded Tuff**: Samples consist of loose crystals of quartz and feldspar; fragments of white (N 9) vitric pumice less than 2 mm in size, and containing biotite; and a variety of devitrified lava and welded tuff lithic fragments. Intact fragments of vitric and calcic bedded tuff compose the majority of sample at 301.8 (990 ft).	Tmrh
304.8 - 333.8 (1,000 - 1,095)	29.0 (95)	DA, DB1	XRD, CO_2	**Bedded Tuff**: Very-pale-orange (10YR 8/2) to 320.0 m (1,050 ft), becoming moderate-yellowish-brown (10YR 5/4) below; mostly zeolitic, partially vitric; common to abundant very-pale-orange (10YR 8/2) and grayish-yellow (5Y 8/4) zeolitic to partially vitric pumice up to 5 mm in size; minor to common felsic phenocrysts of feldspar and quartz; common to abundant mafic minerals of biotite, lesser hornblende, and much less clinopyroxene, hornblende increases substantially in abundance below 320.0 (1,050 ft); minor to common volcanic lithic fragments of various colors, and up to 4 mm in size; common partially altered sphene.	Tmrh
333.8 - 353.6 (1,095 - 1,160)	19.8 (65)	DA	None	**Pumiceous Lava**: Grayish-yellow (5Y 8/4); mostly zeolitic, partially vitric; rare feldspar phenocrysts; abundant biotite; no lithic fragments; minor sphene.	Tpb

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
353.6 - 376.7 (1,160 - 1,236)	23.1 (76)	DA	XRD	**Pumiceous Lava**: Yellowish-gray (5Y 7/2) and pale-brown (5YR 5/2); becoming mostly pale-brown (5YR 5/2) below 362.7 m (1,190 ft); mostly zeolitic, partially devitrified and silicic above 362.7 m (1,190 ft), becoming mostly devitrified and silicic, and partially vitric and zeolitic below 362.7 m (1,190 ft); pumiceous and spherulitic, weakly perlitic where partially vitric; rare feldspar phenocrysts; abundant biotite; minor sphene; abundant secondary quartz as crystal aggregates and chalcedony.	Tpb
376.7 - 670.6 (1,236 - 2,200) TD	293.9 (964)	DA	None	**Lava**: Light-gray (N 7) to light-brownish-gray (5YR 6/1); devitrified, partially vitric in some intervals; weakly pumiceous; rare feldspar phenocrysts; abundant biotite; minor sphene. Horizontal to near vertical flow banding observed with downhole camera (Howard, 1981).	Tpb

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components.

b **CO_2** = Carbon dioxide analysis; **XRD** = X-ray diffraction. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = ≤ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = ≥ 20%.
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = ≤ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = ≥ 2%.

d **Ttt** = Trail Ridge Tuff; **Ttp** = Pahute Mesa Tuff; **Ttr** = Rocket Wash Tuff; **Tmar** = mafic-rich Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmrr** = mafic-rich Rainier Mesa Tuff; **Tmrp** = mafic-poor Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tmrh** = tuff of Holmes Road; **Tpb** = rhyolite of Benham. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of U20ag.

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Detailed Lithologic Log for Emplacement Hole U20ao

By L. B. Prothro and R. G. Warren, 1999

(Page 1 of 7)

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 13.7 (0 - 45)	13.7 (45)	DA	None	**Partially Welded Ash-Flow Tuff**: Grayish-brown (5YR 3/2); devitrified, with vapor-phase mineralization; common dark-yellowish-brown (10YR 4/2) and dusky-yellowish-brown (10YR 2/2) scoriaceous pumice up to 10 mm in size; minor feldspar phenocrysts; common olivine, trace dark clinopyroxene; rare dusky-brown (5YR 2/2) volcanic lithic fragments less than 2 mm in size. Description is from a single box of drill cuttings representing the 6.1 to 9.1 m (20 - 30 ft) interval. All other samples for this interval are missing.	Ttt
13.7 - 20.7 (45 - 68)	7.0 (23)	DB1	None	**Bedded Tuff**: Sample consists mostly of white (N9), medium-gray (N5), and grayish-orange (10YR 7/4) fragments of vitric pumice averaging 1 mm in size. Also present, but in much less quantities, are dark-gray (N3) and moderate-reddish-brown (10YR 4/6) volcanic lithic fragments less than 3 mm in size, and crystals of feldspar. The few mafic minerals observed include clinopyroxene, olivine, and biotite. Description is from a single sample representing the 12.2 to 15.2 m (40 - 50 ft) interval.	Ttt
20.7 - 46.9 (68 - 154)	26.2 (86)	DB1	None	**Partially Welded Ash-Flow Tuff**: Grayish-brown (5YR 3/2), mostly devitrified, partially vitric, with vapor-phase mineralization and a scoriaceous appearance to approximately 22.9 m (75 ft); becoming pale-yellowish-brown (10YR 6/2) to dusky-yellowish-brown (10YR 2/2) and devitrified, with vapor-phase mineralization below; minor dusky-brown (5YR 2/2) pumice up to 5 mm in size; minor feldspar phenocrysts; minor mafic minerals of olivine and lesser clinopyroxene; rare very-dusky-red (10R 2/2) lithic fragments less than 2 mm in size.	Ttp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
46.9 - 49.4 (154 - 162)	2.5 (8)	DB2	None	**Bedded Tuff**: Sample consists mostly of a variety of moderately to partially welded, peralkaline, ash-flow tuff fragments that appear not to present the true lithology of this interval; and lesser loose feldspar crystals.	Ttp
49.4 - 54.2 (162 - 178)	4.8 (16)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; minor medium-light-gray (N6) devitrified flattened pumice; minor feldspar phenocrysts; minor mafic minerals of olivine and lesser clinopyroxene; trace grayish-black (N2) volcanic lithic fragments less than 1 mm in size.	Ttr
54.2 - 64.0 (178 - 210)	9.8 (32)	DB1	None	**Nonwelded Ash-Flow Tuff**: Dark-yellowish-brown (10YR 4/2); vitric, calcareous in upper part; common olive-black (5Y 2/1) and pale-yellowish-brown (10YR 6/2) pumice up to 10 mm in size; minor feldspar phenocrysts up to 5 mm in size; minor olivine; common volcanic lithic fragments of various colors, and up to 10 mm in size; very abundant and conspicuous olive-black (5Y 2/1) vesiculated glass shards.	Ttr
64.0 - 70.1 (210 - 230)	6.1 (20)	DB1	None	**Bedded Tuff**: Moderate-yellowish-brown (10YR 5/4), pale-yellowish-brown (10YR 6/2), and dark-yellowish-orange (10YR 6/6); mostly vitric, partially calcareous, argillic at base; minor very-pale-orange (10YR 8/2) to grayish-orange (10YR 7/4) pumice less than 3 mm in size; abundant felsic phenocrysts of feldspar and lesser quartz; common mafic minerals of biotite, hornblende, and clinopyroxene; minor to common volcanic lithic fragments of various colors up to 10 mm in size, but typically less than 2 mm in size.	Tfbr

Lithologic Log for U20ao

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
70.1 - 82.3 (230 - 270)	12.2 (40)	DB1	None	**Bedded Tuff**: Samples consist of loose pumice and lithic fragments, felsic crystals, and mafic minerals. Pumice and lithic fragments are the most abundant constituents, particularly in upper part. Felsic crystals and mafic minerals increase substantially in abundance in lower portion. Pumice fragments are white (N9) to very-pale-orange (10YR 8/2), vitric and generally less than 2 mm in size. Lithic fragments are grayish-red (10R 4/2) devitrified welded tuff and lava less than 2 mm in size. Felsic crystals are mostly feldspar and lesser quartz. Mafic minerals are mostly biotite with lesser hornblende and clinopyroxene. Sphene is present on many of the pumice fragments. Samples are weakly to moderately calcareous.	Tfbw
82.3 - 105.2 (270 - 345)	22.9 (75)	DB1	None	**Partially Welded Ash-Flow Tuff**: Mostly black (N1) to olive-black (5Y 2/1), becoming dark-yellowish-orange (10YR 6/6) at top and base of interval; vitric to 100.6 m (330 ft), becoming mostly devitrified and partially vitric below; minor to common mostly black (N1) and white (N9) pumice up to 7 mm in size, mostly pale-yellowish-orange vitric pumice at top and base of interval; common feldspar phenocrysts of quartz and feldspar; common mafic minerals of biotite and clinopyroxene; minor moderate-orange-pink (10R 7/4) lithic fragments of devitrified moderately welded ash-flow tuff less than 3 mm in size; abundant black (N1) vesiculated glass shards.	Tmar
105.2 - 130.5 (345 - 428)	25.3 (83)	DB1	None	**Partially Welded Ash-Flow Tuff**: Pale-yellowish-brown (10YR 6/2); mostly devitrified, partially vitric; common dark-yellowish-orange (10YR 6/6) vitric to partially devitrified pumice, and pale-yellowish-brown (10YR 6/2) devitrified pumice up to 5 mm in size; minor felsic phenocrysts of feldspar and quartz, including chatoyant sanidine; rare to minor mafic minerals of biotite and lesser clinopyroxene; minor lithic fragments of devitrified moderately welded ash-flow tuff generally less than 3 mm in size; common dark-yellowish-orange (10YR 6/6) vitric to partially devitrified vesiculated glass shards.	Tmap

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
130.5 - 150.6 (428 - 494)	20.1 (66)	DB1	XRD	**Bedded Tuff**: Samples consist of loose felsic crystals of feldspar and quartz less than 2 mm in size, and much less amounts of white (N9) vitric pumice fragments, less than 3 mm in size; lithic fragments of welded ash flow tuff of various colors and less than 5 mm in size; and mafic minerals of clinopyroxene, hornblende, and lesser biotite. Sample at 149.4 m (490 ft) contains abundant fragments of white (N9) to very-pale-orange (10YR 8/2) botryoidal common opal and chalcedony up to 30 mm in size. Fragments of argillic nonwelded tuff up to 2 mm in size are also present in sample at 149.4 m (490 ft).	Tmab
150.6 - 162.2 (494 - 532)	11.6 (38)	DA	None	**Partially Welded Ash-Flow Tuff**: Light-brown (5YR 6/4); devitrified, with vapor-phase mineralization; common dark-yellowish-orange (10YR 6/6) and pinkish-gray (5YR 8/1) devitrified pumice up to 10 mm in size; minor felsic phenocrysts of feldspar and quartz; rare to minor mafic minerals of biotite and lesser clinopyroxene; rare moderate-brown (5YR 3/4) lithic fragments of devitrified phenocryst-poor welded tuff or lava less than 3 mm in size.	Tmrr
162.2 - 231.6 (532 - 760)	69.5 (228)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (5R 4/2) to 201.2 m (660 ft), becoming dark-reddish-brown (10R 3/4) below; devitrified; minor white (N9) to very-light-gray (N8) flattened devitrified pumice; minor feldspar phenocrysts of quartz and feldspar; minor mafic minerals of biotite and lesser clinopyroxene; no lithic fragments. Fragments of medium-gray (N5) to dark-gray (N3) vitric perlite are present in sample 198.1 m (650 ft) (< 5% of sample).	Tmrr
231.6 - 277.4 (760 - 910)	45.7 (150)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (5R 4/2) to 268.2m (880 ft), becoming dark-reddish-brown (10R 3/4) below; devitrified; minor white (N9) to very-light-gray (N8) flattened devitrified pumice; minor feldspar phenocrysts of quartz and feldspar; rare biotite; no lithic fragments.	Tmrp

Lithologic Log for U20ao

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
277.4 - 280.4 (910 - 920)	3.0 (10)	DA	None	**Vitrophyric Ash-Flow Tuff**: Brownish-black (5YR 2/1); vitric; perlitic; abundant felsic phenocrysts of quartz and feldspar; rare biotite; no lithic fragments.	Tmrp
280.4 - 283.5 (920 - 930)	3.1 (10)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; minor white (N9) to very-light-gray (N8) devitrified flattened pumice; minor felsic phenocrysts of quartz and feldspar; rare biotite; no lithic fragments.	Tmrp
283.5 - 286.5 (930 - 940)	3.0 (10)	DA	None	**Densely Welded Ash-Flow Tuff**: Mottled pale-reddish-brown (10R 5/4) and brownish-black (5YR 2/1); vitric; perlitic; common felsic phenocrysts of feldspar and quartz; rare biotite; no lithic fragments.	Tmrp
286.5 - 289.6 (940 - 950)	3.1 (10)	DA	None	**Partially Welded Ash-Flow Tuff**: Pale-reddish-brown (10R 5/4); vitric; common light-gray (N8) vitric partially flattened pumice; minor feldspar phenocrysts of feldspar and quartz; rare biotite; no lithic fragments; minor brownish-black (5YR 2/1) hydroclastic glass shards.	Tmrp
289.6 - 299.0 (950 - 981)	9.4 (31)	DB1	None	**Nonwelded Ash-Flow Tuff**: Samples consist of loose felsic crystals of feldspar and quartz; a wide variety of volcanic lithic fragments up to 15 mm in size; very-pale-orange (10YR 8/2) vitric pumice less than 3 mm in size; and loose mafic minerals of biotite and clinopyroxene.	Tmrp
299.0 - 356.6 (981 - 1,170)	57.6 (189)	DB1	XRD	**Bedded Tuff**: Samples consist of loose felsic crystals of quartz and feldspar; fragments of very-pale-orange (10YR 8/2) vitric pumice generally less than 4 mm in size; and a variety of volcanic lithic fragments up to 20 mm in size. Flakes of black biotite observed in some samples.	Tmrf
356.6 - 370.3 (1,170 - 1,215)	13.7 (45)	DA	None	**Nonwelded Tuff**: Grayish-orange-pink (5YR 7/2); mostly vitric, partially zeolitic; minor pinkish-gray (5YR 8/1) vitric pumice less than 3 mm in size; minor felsic phenocrysts of feldspar and quartz; rare black biotite; rare pale-brown (5YR 5/2) volcanic lithic fragments less than 4 mm in size; minor colorless hydroclastic glass shards.	Tmrf

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
370.3 - 393.2 (1,215 - 1,290)	22.9 (75)	DB1	XRD	**Bedded Tuff**: Samples consist of loose crystals of quartz and feldspar; fragments of white (N9) vitric pumice; and a variety of devitrified volcanic lithic fragments.	Tmrh
393.2 - 402.3 (1,290 - 1,320)	9.1 (30)	DB1	None	**Bedded Tuff**: Light-brown (5YR 6/4); vitric; common very-pale-orange (10YR 8/2) pumice generally less than 3 mm in size; minor felsic phenocrysts of feldspar and quartz; rare very small biotite; rare lithic fragments less than 1 mm in size; trace of sphene.	Tmrh
402.3 - 414.5 (1,320 - 1,360)	12.2 (40)	DB1	None	**Bedded Tuff**: Samples consist of loose crystals of quartz and feldspar; fragments of white (N9) vitric pumice; and a variety of devitrified volcanic lithic fragments.	Tmrh
414.5 - 425.5 (1,360 - 1,396)	11.0 (36)	DA	XRD	**Bedded Tuff**: Mostly yellowish-gray (5Y 8/1), also grayish-orange (10YR 7/4); zeolitic, silicified in part; common grayish-yellow (5Y 8/4) and light-brown (5YR 5/6) zeolitic pumice less than 4 mm in size; rare to minor felsic phenocrysts of feldspar and quartz; rare biotite; minor very-dusky-red (10R 2/2) lithic fragments less than 1 mm in size in upper portion, becoming more lithic-rich near base consisting of common dark devitrified and silicified volcanic lithic fragments; conspicuous dusky-yellowish-brown (10YR 2/2) iron- or manganese-oxide staining.	Tmrh
425.5 - 472.4 (1,396 - 1,550)	46.9 (154)	DA	None	**Flow Breccia**: Mottled grayish-red (10R 4/2) and grayish-yellow (5Y 8/4); mostly devitrified, partially zeolitic, lesser vitric; rare feldspar phenocrysts; common biotite; rare sphene. Chalcedony and common opal occur as vesicle fillings.	Tpb
472.4 - 560.8 (1,550 - 1,840)	88.4 (290)	DA	None	**Lava**: Mottled pale-red (10R 6/2), pale-brown (5YR 5/2), and very-light-gray (N8); mostly devitrified, partially zeolitic and vitric in places; rare to minor feldspar phenocrysts; common biotite; rare sphene.	Tpb
560.8 - 573.0 (1,840 - 1,880)	12.2 (40)	DA	None	**Lava**: Brownish-gray (5YR 4/1); vitric, becoming partially devitrified near base of interval; perlitic; rare feldspar phenocrysts; common biotite; rare sphene.	Tpb

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
573.0 - 591.3 (1,880 - 1,940)	18.3 (60)	DA	None	**Lava**: Pale-brown (5YR 5/2); mostly devitrified, partially vitric; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb
591.3 - 600.5 (1,940 - 1,970)	9.2 (30)	DA	None	**Lava**: Mostly grayish-black (N2), also pale-brown (5YR 5/2); mostly vitric, partially devitrified; perlitic; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb
600.5 - 618.7 (1,970 - 2,030)	18.2 (60)	DA	None	**Lava**: Mostly pale-brown (5YR 5/2), also grayish-black (N2); mostly devitrified, partially vitric; perlitic; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb
618.7 - 635.3 (2,030 - 2,150) TD	6.4 (21)	DA	None	**Lava**: Mostly grayish-black (N2), also grayish-brown (5YR 3/2); mostly vitric, partially devitrified; perlitic; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components; **DB2** = drill cuttings from interval different than that drilled.

b **XRD** = X-ray diffraction. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = $\leq$ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = $\geq$ 20%.
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = $\leq$ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = $\geq$ 2%.

d **Ttt** = Trail Ridge Tuff; **Ttp** = Pahute Mesa Tuff; **Ttr** = Rocket Wash Tuff; **Tfbr** = rhyolite of Chukar Canyon; **Tfbw** = rhyolite of Beatty Wash; **Tmar** = mafic-rich Ammonia Tanks Tuff; **Tmap** = mafic-poor Ammonia tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmrr** = mafic-rich Rainier Mesa Tuff; **Tmrp** = mafic-poor Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tmrh** = tuff of Holmes Road; **Tpb** = rhyolite of Benham. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of U20ao.

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Detailed Lithologic Log for Emplacement Hole U20as

By L. B. Prothro and R. G. Warren

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Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 12.2 (0 - 40)	12.2 (40)	No Samples	None	**Moderately Welded Ash-Flow Tuff**: No drill hole data. Stratigraphy inferred from surface exposures. Lower contact is estimated. Base of interval may be bedded tuff.	Ttt
12.2 - 43.3 (40 - 142)	31.1 (102)	DB1	None	**Partially Welded Ash-Flow Tuff**: Pale-brown (5YR 5/2); devitrified, with vapor-phase mineralization; common dark-gray (N3) partially flattened, recrystallized pumice less than 5 mm in size; minor feldspar phenocrysts; rare mafic minerals of partially altered olivine and clinopyroxene; minor dusky-brown volcanic lithic fragments less than 5 mm in size. No data to approximately 18.3 m (60 ft) . Upper contact is estimated.	Ttp
43.3 - 54.9 (1,042 - 1,080)	11.6 (38)	DA	None	**Moderately Welded Ash-Flow Tuff**: Grayish-red (10R 4/2) becoming moderate-brown (5YR 3/4) at base of interval; devitrified; rare medium-light-gray (N 6) completely flattened, recrystallized pumice; rare feldspar phenocrysts; minor mafic minerals of highly altered olivine and clinopyroxene; no lithic fragments.	Ttp
54.9 - 61.0 (180 - 200)	6.1 (20)	DB1	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); vitric, calcareous; common light-brown (5YR 5/6) pumice less than 10 mm in size; rare feldspar phenocrysts; minor mafic minerals of olivine and lesser clinopyroxene; common moderate-reddish-brown (10R 4/6) volcanic lithic fragments less than 10 mm in size; common black (N1) vesicular glass shards.	Ttr

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
61.0 - 83.8 (200 - 275)	22.8 (75)	DB1	None	**Partially Welded Ash-Flow Tuff**: Grayish-red (10R 4/2), becoming moderate-brown (5YR 4/4) at base of interval; devitrified, with vapor-phase mineralization; common moderate-reddish-brown (10YR 4/6) and grayish-red (10R 4/2) partially flattened, recrystallized pumice less than 3 mm in size; minor feldspar phenocrysts; rare mafic minerals of olivine and clinopyroxene; rare very-dusky-red (10R 2/2) volcanic lithic fragments less than 4 mm in size.	Ttr
83.8 - 87.8 (275 - 288)	4.0 (13)	DB1	None	**Bedded Tuff**: Samples consist of loose crystals of feldspar up to 5 mm in size; very-light-gray (N8) fragments of vitric pumice up to 6 mm in size; a variety of volcanic lithic fragments up to 7 mm in size, including fragments from the overlying interval; and dark crystals of clinopyroxene. A white (N9) vitric matrix coats many of the feldspar crystals and pumice fragments.	Ttr
87.8 - 89.0 (288 - 292)	1.2 (4)	DA	None	**Reworked Tuff**: Dark-yellowish-brown (10YR 4/2); vitric, calcareous; rare dark-yellowish-orange (10YR 6/6) and very-pale-orange (10YR 8/2) vitric pumice up to 8 mm in size but generally less than 2 mm in size; very abundant felsic crystals of quartz and feldspar; minor biotite; common various colored subrounded lithic fragments less than 0.5 mm in size; common black (N 1) vesicular glass shards. Interval is medium-sand-size, angular to subrounded, and moderately sorted.	Tfbr
89.0 - 97.0 (292 - 318)	8 (26)	DB2	None	**Partially or Moderately Welded Ash-Flow Tuff**: Samples consist of a variety of volcanic lithic fragments; vitric pumice fragments; loose crystals of quartz and feldspar; and mafic minerals of biotite and hornblende. Samples do not appear to be representative of the interval. Lithology based on geophysical logs.	Tmap
97.0 - 120.1 (318 - 394)	23.1 (76)	DB1	None	**Bedded Tuff**: Samples consist predominately of white (N 9) vitric pumice fragments up to 20 mm in size and containing crystals of feldspar, quartz, biotite, hornblende, clinopyroxene, and sphene. Also present in samples are various volcanic lithic fragments; and loose crystals of quartz, feldspar, biotite, hornblende, and clinopyroxene.	Tmab

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
120.1 - 132.9 (394 - 436)	12.8 (42)	DB1	None	**Nonwelded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); vitric; common white (N9) and dark-yellowish-orange (10YR 6/6) pumice less than 5 mm in size; minor felsic phenocrysts of feldspar and quartz; minor mafic minerals of biotite and lesser clinopyroxene; rare dusky-red (10R 2/2) lithic fragments less than 2 mm in size. Samples above 125.0 m (410 ft) are approximately 90% loose crystals of quartz and feldspar, and approximately 10% white (N9) vitric pumice and various volcanic lithic fragments. These may represent bedded tuff, possibly bedded Rainier Mesa Tuff (Tmrb), overlying the nonwelded ash-flow tuff described above.	Tmr
132.9 - 163.1 (436 - 535)	30.2 (99)	DA	None	**Partially Welded Ash-Flow Tuff**: Light-brownish-gray (5YR 6/1) to brownish-gray (5YR 4/1), becoming grayish-red (10R 4/2) near base of interval; devitrified; minor very-light-gray (N8) partially flattened pumice less than 4 mm in size; minor felsic phenocrysts of feldspar and quartz; minor biotite; trace of moderate-brown (5YR 3/4) volcanic lithic fragments less than 2 mm in size. Fragments of secondary quartz-aggregates occur in samples below 155.4 m (510 ft), which probably indicates lithophysal development in the lower portion of the interval.	Tmr
163.1 - 187.8 (535 - 616)	24.7 (81)	DA	None	**Moderately Welded Ash-Flow Tuff**: Moderate-brown (5YR 3/4); devitrified; minor light-gray (N7) and yellowish-gray (5YR 8/1) flattened pumice less than 4 mm in size; common felsic phenocrysts of feldspar and quartz; minor biotite; no lithic fragments. Fragments of secondary quartz aggregates occur in samples, which probably indicates lithophysal development. Vitrophyre observed with downhole camera from 185 to 187 m (607 - 614 ft) (Wagoner and Clark, 1986).	Tmr

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
187.8 - 202.7 (616 - 665)	14.9 (49)	DB1	None	**Partially Welded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); vitric; minor white (N9) and grayish-orange (10YR 7/4) partially flattened pumice; minor felsic phenocrysts of feldspar and quartz; minor biotite, trace of clinopyroxene; no lithic fragments; minor dusky-yellowish-brown (10YR 2/2) vesicular glass shards. A cobble bed observed with downhole camera from 199 to 200 m (653 - 656 ft) (Wagoner and Clark, 1986).	Tmr
202.7 - 303.6 (665 - 996)	100.9 (331)	DB1	None	**Bedded Tuff**: Samples consist mostly of loose white (N9) and very-pale-orange (10YR 8/2) fragments of vitric pumice up to 10 mm in size, but generally less than 5 mm in size, and containing rare felsic phenocrysts of quartz and feldspar, and rare biotite. Samples also contain loose crystals of quartz and feldspar, and various volcanic lithic fragments, including moderately welded Tmr from up hole. A white (N9) and very-pale-orange (10YR 8/2) vitric matrix coats many of the pumice fragments. Below 246.9 m (810 ft) interval becomes more conspicuously bedded, and mafic minerals are much smaller in size. This lower interval resembles tuff of Holmes Road (Tmrh) which could be present below 246.9 m (810 ft) as interfingering beds, or could compose the whole section below 246.9 m (810 ft).	Tmrf/Tmrh
303.6 - 352.0 (996 - 1,155)	48.4 (159)	DA, DB1	TS, XRD	**Bedded Tuff**: Moderate-yellowish-brown (10YR 6/6); mostly zeolitic, partially vitric, minor calcite and opal; minor to common very-pale-orange (10YR 8/2) and grayish-yellow (5Y 8/4) zeolitic pumice generally less than 5 mm in size; minor to common felsic phenocrysts of feldspar and quartz; minor very small mafic minerals of biotite and lesser hornblende; minor to abundant lithic fragments of various colors and various volcanic lithologies, but dominated by dark-yellowish-brown (10YR 4/2) fragments up to 10 mm in size of devitrified welded tuff or lava containing common felsic phenocrysts of feldspar and quartz, and rare biotite; rare sphene.	Tmw

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
352.0 - 370.9 (1,155 - 1,217)	18.9 (62)	DA	TS, XRD	**Nonwelded Tuff**: Yellowish-gray (5Y 7/2); zeolitic; common grayish-yellow (5Y 8/4) pumice less than 3 mm in size; common felsic phenocrysts of feldspar and lesser quartz; common biotite; minor moderate-brown (5YR 3/4) lithic fragments of welded tuff up to 8 mm in size, but generally less than 3 mm; minor, very conspicuous sphene.	Tmw
370.9 - 379.8 (1,217 - 1,246)	8.9 (29)	DA	None	**Flow Breccia**: Yellowish-gray (5YR 7/2); mostly zeolitic, partially silicic, clasts of vitric pumiceous lava and devitrified lava are also present; pumiceous; rare feldspar phenocrysts; minor biotite; minor sphene.	Tpb
379.8 - 391.7 (1,246 - 1,285)	11.9 (39)	DA	None	**Flow Breccia**: Mostly light-olive-gray (5YR 6/1), also moderate-yellow (5YR 7/6); mostly vitric, partially zeolitic; weakly perlitic; rare feldspar phenocrysts; minor biotite; rare sphene. Fragments of secondary quartz as chalcedony and crystal aggregates are present in samples.	Tpb
391.7 - 404.2 (1,285 - 1,326)	12.5 (41)	DA	None	**Flow Breccia**: Mottled brownish-gray (5YR 4/1) and grayish-yellow (5Y 8/4); zeolitic and devitrified; rare feldspar phenocrysts; minor biotite; rare sphene. Secondary quartz as chalcedony and crystal aggregates is present in samples. Interval consists of clasts of brownish-gray (5YR 4/1) devitrified lava in a grayish-yellow (5Y 8/4) zeolitic matrix.	Tpb
404.2 - 442.0 (1,326 - 1,450)	37.8 (124)	DA	None	**Lava**: Mottled grayish-red (10R 4/2) and medium-light-gray (N6); devitrified; flow-banded; rare felsic phenocrysts of feldspar and much less quartz; common biotite; rare sphene.	Tpb
442.0 - 476.1 (1,450 - 1,562)	34.1 (112)	DA	GM, XRD	**Lava**: Moderate-greenish-yellow (10Y 7/4), medium-gray (N5), and brownish-gray (5YR 4/1); mostly vitric, also zeolitic and devitrified intervals; weakly perlitic where vitric, vitrophyric at base; rare felsic phenocrysts of feldspar and much less quartz; common biotite; rare sphene. Fragments of secondary quartz as chalcedony and crystal aggregates occur in samples above 457.2 m (1,500 ft). Interval appears to be mostly vitric lava with intercalated intervals of zeolitic and devitrified lava.	Tpb

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
476.1 - 485.9 (1,562 - 1,594)	9.8 (32)	DA	GM, XRD	**Pumiceous Lava**: Light-brown (5YR 6/4) to moderate-brown (5YR 4/4); zeolitic; rare feldspar phenocrysts; common biotite; minor sphene.	Tpb
485.9 - 640.1 (1,594 - 2,100) TD	154.2 (506)	DA, DB1	GM, XRD	**Bedded Tuff**: Pale-reddish-brown (10R 5/4), pale-yellowish-brown (10YR 6/2), and light-brown (5YR 6/4); zeolitic; common to abundant mostly moderate-yellow (5Y 7/6) pumice up to 10 mm in size; rare to minor feldspar phenocrysts; common biotite; rare to common lithic fragments of moderate-brown (5YR 3/4) densely welded devitrified ash-flow tuff and grayish-red (10R 4/2) devitrified lava up to 15 mm in size; rare sphene.	Tpb

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components; **DB2** = drill cuttings from interval different than that drilled.

b **GM** = grain mount; **TS** = thin section; **XRD** = X-ray diffraction. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysicallogs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = ≤ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = ≥ 20%
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = ≤ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = ≥ 2%

d **Ttt** = Trail Ridge Tuff; **Ttp** = Pahute Mesa Tuff; **Ttr** = Rocket Wash Tuff; **Tfbr** = rhyolite of Chukar Canyon; **Tmap** = mafic-poor Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tmrh** = tuff of Holmes Road; **Tmw** = rhyolite of Windy Wash; **Tpb** = rhyolite of Benham. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of U20as.

Detailed Lithologic Log for Emplacement Hole U20c
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Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 75.6 (0 - 248)	75.6 (248)	None	None	**Nonwelded to Moderately Welded Ash-Flow Tuff**: Vitric to devitrified. Geology based on surface geology and descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on surface geology and analysis of the U20c caliper log.	Tt
75.6 - 140.8 (248 - 462)	65.2 (214)	None	None	**Nonwelded to Partially Welded Ash-Flow Tuff and Bedded Tuff**: Vitric. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tma
140.8 - 245.7 (462 - 806)	104.9 (344)	None	None	**Nonwelded to Densely Welded and Vitrophyric Ash-Flow Tuff**: Mostly devitrified, vitric in part. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tmr
245.7 - 294.1 (806 - 965)	48.4 (159)	None	None	**Bedded Tuff**: Vitric. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tmrf

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
294.1 - 311.2 (965 - 1,021)	17.1 (56)	None	None	**Pumiceous Lava**: Mostly vitric, zeolitic in part. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tpb
311.2 - 617.2 (1,021 - 2,025)	306.0 (1004)	None	None	**Lava**: Devitrified. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tpb
617.2 - 625.4 (2,025 - 2,052)	8.2 (27)	None	None	**Bedded Tuff**: Mostly zeolitic, partially vitric. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tpb
625.4 - 737.6 (2,052 - 2,420)	112.2 (368)	None	None	**Partially to Densely Welded and Vitrophyric Ash-Flow Tuff**: Devitrified. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c caliper log.	Tpcm
737.6 - 765.0 (2,420 - 2,510)	27.4 (90)	None	None	**Bedded Tuff**: Zeolitic. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tpd

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
765.0 - 784.9 (2,510 - 2,575)	19.9 (65)	None	None	**Nonwelded Ash-Flow Tuff**: Zeolitic. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tptm
784.9 - 795.5 (2,575 - 2,610)	10.6 (35)	None	None	**Partially Welded Ash-Flow Tuff**: Devitrified. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tptm
795.5 - 868.7 (2,610 - 2,850)	73.2 (240)	None	None	**Moderately Welded Ash-Flow Tuff**: Devitrified. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tptm
868.7 - 890.0 (2,850 - 2,920)	21.3 (70)	None	None	**Partially Welded Ash-Flow Tuff**: Devitrified. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tptm
890.0 - 937.3 (2,920 - 3,075)	47.3 (155)	None	None	**Nonwelded Ash-Flow Tuff**: Zeolitic. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Tptm
937.3 - 1109.5 (3,075 - 3,640)	172.2 (565)	None	None	**Bedded Tuff**: Zeolitic. Geology based on descriptions of lithologic samples from corresponding interval in nearby hole UE20c. Depth interval based on analysis of the U20c electric log.	Thp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
1,109.5 -1,143.6 (3,640 - 3,752)	34.1 (112)	DA	None	**Pumiceous Lava**: Light-olive (10Y 5/4) and dusky-yellow (5Y 6/4) to 1,120.1 m (3,675 ft), dark-yellowish-green (10GY 4/4) from 1,120.1 to 1,136.9 m (3,675 - 3,730 ft), and yellowish-gray (5Y 7/2) below 1,136.9 m (3,730 ft); mostly zeolitic, partially vitric; pumiceous and weakly spherulitic; minor felsic phenocrysts of feldspar and quartz; minor biotite.	Thp
1,143.6 - 1,150.6 (3,752 - 3,775)	7.0 (23)	DA	None	**Lava:** Dusky-yellow (5Y 6/4) and pale-olive (10Y 6/2); vitric; perlitic; minor felsic phenocrysts of feldspar and quartz; minor biotite.	Thp
1,150.6 - 1,156.7 (3,775 - 3,795)	6.1 (20)	DA	None	**Vitrophyric Lava:** Dark-greenish-gray (5GY 4/1) and greenish-black (5GY 2/1); vitric; perlitic; minor felsic phenocrysts of feldspar and quartz; minor biotite.	Thp
1,156.7 - 1,162.8 (3,795 - 3,815)	6.1 (20)	DA	None	**Lava:** Light-olive-gray (5Y 6/1); mostly vitric, partially devitrified, lesser opalline; perlitic; minor felsic phenocrysts of feldspar and quartz; minor biotite.	Thp
1,162.8 - 1,188.1 (3,815 - 3,898)	25.3 (83)	DA	None	**Lava:** Grayish-red (10R 4/2) to 1,175.0 m (3,855 ft) becoming dark-yellowish-brown (10YR 4/2) below; devitrified to 1,175.0 m (3,855 ft), becoming partially vitric below; minor felsic phenocrysts of feldspar and quartz; minor biotite. A dark-greenish-gray (5G 4/1) vitric interval occurs from 1,166.8 to 1,169.5 m (3,828 - 3,837 ft).	Thp
1,188.1 - 1,213.1 3,898 - 3,980	25.0 (82)	DA	None	**Lava**: Dark-gray (N3) and greenish-black (5GY 2/1); vitric; minor felsic phenocrysts of feldspar and quartz; minor biotite.	Thp
1,213.1 - 1,230.2 (3,980 - 4,036)	17.1 (56)	DA	None	**Vitrophyric Lava:** Greenish-black (5G 2/1); vitric; minor felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,230.2 - 1,242.4 (4,036 - 4,076)	12.2 (40)	DA	None	**Lava:** Grayish-black (N2), dark-greenish-gray (5GY 6/1), and brownish-gray (5YR 4/1); mostly vitric, partially devitrified; weakly perlitic; minor felsic phenocrysts of feldspar and quartz; rare biotite.	Thp

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
1,242.4 - 1,252.7 (4,076 - 4,110)	10.3 (34)	DA	None	**Lava:** Greenish-black (5GY 2/1), becoming dark-greenish-gray (5GY 4/1) near base of interval; vitric, becoming partially devitrified near base of interval; minor felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,252.7 - 1,283.2 (4,110 - 4,210)	30.5 (100)	DA	None	**Flow Breccia:** Mottled pale-red (10R 6/2) and grayish-red (10R 4/2); devitrified and silicic; minor felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,283.2 - 1,333.8 (4,210 - 4,376)	50.6 (166)	DA	XRD, XRF	**Pumiceous Lava:** Grayish-orange (10YR 7/4); zeolitic; minor felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,333.8 - 1,392.9 (4,376 - 4,570)	59.1 (194)	C, DA	TS, XRD	**Bedded Tuff:** Grayish-orange (10YR 7/4), light-brown (5YR 5/6), and pale-reddish-brown (10R 5/4); silicic, zeolitic, and potassic; minor grayish-yellow (5Y 8/4); very-pale-orange (10YR 8/2), and pinkish-gray (5YR 8/1) zeolitic pumice less than 3 mm in size; rare to minor felsic phenocrysts of feldspar and quartz; rare biotite; rare dark-reddish-brown (10R 3/4) devitrified volcanic lithic fragments less than 3 mm in size.	Thp
1,392.9 - 1,411.2 (4,570 - 4,630)	18.3 (60)	C, DA	ES	**Bedded Tuff:** Pale-yellowish-brown (10YR 6/2) to 1,400.6 m (4,595 ft) becoming pale-olive (10Y 6/2) below; zeolitic; minor to common moderate-yellowish-green (10GY 6/4) zeolitic pumice up to 1 cm in size; minor felsic phenocrysts of feldspar and quartz; common biotite; minor to common mostly grayish-red (5R 4/2) devitrified volcanic lithic fragments up to 2 cm in size, but typically less than 5 mm. Bedding at 1,403.3 m (4,604 ft) dips 15 to 20 . Two high-angle fractures, one completely filled with manganese-oxide and the other filled with calcite, occur from 1,400.6 to 1,402. m (4,595 - 4,600 ft).	Thr

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
1,411.2 - 1,463.0 (4,630 - 4,800) TD	51.8 (170)	C, DA	TS, XRD	**Bedded Tuff:** Mostly light-brown (5YR 6/4 and 5YR 5/6); lesser moderate-reddish-brown (10R 4/6), moderate-brown (5YR 4/4), and yellowish-gray (5Y 7/2); silicic and potassic, and minor zeolitic; minor to common mostly yellowish-gray (5Y 8/1) and lesser grayish-orange-pink (5YR 7/2) pumice up to 2 cm in size, but typically less than 5 mm; minor to common felsic phenocrysts of feldspar and quartz; common biotite; rare lithic fragments of various colors and volcanic lithologies up to 3 cm in size, but typically less than 5 mm.	Thr

a **DA** = drill cuttings that represent lithologic character of interval; **C** = conventional core.

b **TS** = thin section; **XRD** = X-ray diffraction; **XRF** = X-ray fluorescence; **ES** = Emission Spectroscopy. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = $\leq$ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = $\geq$ 20%
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = $\leq$ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = $\geq$ 2%

d **Tt** = Thirsty Canyon Group, undivided; **Tma** = Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tpb** = rhyolite of Benham; **Tpcm** = Pahute Mesa lobe of the Tiva Canyon Tuff; **Tpd** = rhyolite of Delirium Canyon; **Tptm** = Pahute Mesa lobe of the Topopah Springs Tuff; **Thp** = mafic-poor Calico Hills Formation; **Thr** = mafic-rich Calico Hills Formation. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of U20c.

Detailed Lithologic Log for Exploratory Hole UE20c

By L. B. Prothro and R. G. Warren, 1999

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Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
0 - 12.2 (0 - 40)	12.2 (40)	None	None	**Moderately Welded Ash-Flow Tuff:** Devitrified. No lithologic samples available for this interval. Geology estimated from surface geology and stratigraphy of nearby holes.	Ttt
12.2 - 21.3 (40 - 70)	9.1 (30)	DB1	None	**Nonwelded Ash Flow Tuff:** Pale-yellowish-brown (10YR 6/2); vitric; minor light-olive-gray (5Y 6/1) pumice up to 5 mm in size; rare feldspar phenocrysts; rare hornblende; rare to minor grayish-brown (5YR 3/2) devitrified volcanic lithic fragments less than 4 mm in size. Samples have been substantially rounded by the drilling process.	Tt
21.3 - 46.3 (70 - 152)	25.0 (82)	DB1	None	**Partially Welded Ash-Flow Tuff:** Samples consist mostly of loose crystals of feldspar and volcanic lithic fragments of various lithologies and colors. Loose prismatic crystals of dark pyroxene also occur in samples. Interval appears devitrified with vapor-phase mineralization, and includes dusky-brown (5YR 2/2) devitrified and very scoriaceous pumice fragments.	Tt
46.3 - 67.1 (152 - 220)	20.7 (68)	DB1	None	**Nonwelded Ash-Flow Tuff:** Samples consist mostly of loose crystals of feldspar and volcanic lithic fragments of various lithologies and colors. Loose prismatic crystals of dark pyroxene and fragments of black (N1) glass shards also occur in samples. Interval is probably vitric.	Tt
67.1 - 97.5 (220 - 320)	30.4 (100)	DB1	None	**Nonwelded to Partially Welded Ash-Flow Tuff:** Samples consist of loose fragments of very-pale-orange (10YR 8/2) and dark-yellowish-orange (10YR 6/6) vitric pumice, various tuffaceous lithic fragments, crystals of quartz and feldspar, and mafic minerals of biotite and clinopyroxene. A moderate-yellowish-brown (10YR 5/4) vitric matrix partially coats many crystals and fragments.	Tma

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
97.5 - 136.9 (320 - 449)	39.4 (129)	DB1	None	**Bedded Tuff**: Samples similar to above interval. Division of interval is based partly on bore hole enlargement observed on caliper log.	Tmab
136.9 - 167.0 (449 - 548)	30.1 (99)	DB1, C	None	**Partially Welded Ash-Flow Tuff:** Light-brownish-gray (5YR 6/1); mostly devitrified, partially vitric; common moderate-red (5R 5/4) and grayish-orange (10YR 7/4) recrystallized pumice less than 5 mm in size; common felsic phenocrysts of feldspar and quartz; common biotite, trace of hornblende; rare volcanic lithic fragments less than 3 mm in size.	Tmr
167.0 - 207.3 (548 - 680)	40.3 (132)	DA, C	None	**Moderately Welded Ash-Flow Tuff:** Grayish-red (5R 4/2); devitrified; minor white (N9) flattened pumice up to 3 cm in length; abundant felsic phenocrysts of feldspar and quartz; minor biotite.	Tmr
207.3 - 228.6 (680 - 750)	21.3 (70)	DA	None	**Densely Welded Ash-Flow Tuff:** Dark-reddish-brown (10R 3/4); devitrified; common felsic phenocrysts of feldspar and quartz; minor biotite.	Tmr
228.6 - 234.7 (750-770)	6.1 (20)	DA	None	**VItrophyric Ash-Flow Tuff**: Very-dusky-red (10R 2/2); vitric; common felsic phenocrysts of feldspar and quartz; minor biotite.	Tmr
234.7 - 246.9 (770 - 810)	12.2 (40)	DA	None	**Nonwelded Ash-Flow Tuff**: Pale-reddish-brown (10R 5/4); vitric; minor moderate-orange-pink (10R 7/4) pumice; common felsic phenocrysts of feldspar and quartz; minor biotite.	Tmr
246.9 - 295.7 (810 - 970)	48.8 (160)	DB1	None	**Bedded Tuff:** Samples consist of loose fragments of white (N9) vitric pumice, lithic fragments of various tuffaceous lithologies and colors, felsic crystals of feldspar and quartz, and flakes of biotite which appear to be rare in abundance throughout interval.	Tmrf

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
295.7 - 317.0 (970 - 1,040)	21.3 (70)	DA, DB1	None	**Pumiceous Lava**: Grayish-yellow (5Y 8/4) and light-brownish-gray (5YR 6/1); mostly vitric, zeolitic in part in upper portion of interval; minor felsic phenocrysts of feldspar and much less quartz; common biotite; rare sphene. Fragments of bluish-white (5B 9/1) opal occur in samples near base of interval.	Tpb
317.0 - 603.5 (1,040 - 1,980)	286.5 (940)	DA, C	TS, ES	**Lava:** Grayish-red (10R 4/2); devitrified with vapor-phase mineralization; lithophysal in part with lithophysae up to 3 cm in diameter and lined with vapor-phase minerals; flow-banded; minor felsic phenocrysts of feldspar and much less quartz; common biotite.	Tpb
603.5 - 615.7 (1,980 - 2,020)	12.2 (40)	DA	None	**Vitrophyric Lava:** Dusky-yellowish-brown (10YR 2/2); vitric; perlitic; minor felsic phenocrysts of feldspar and much less quartz; common biotite.	Tpb
615.7 - 627.9 (2,020 - 2,060)	12.2 (40)	DA	None	**Bedded Tuff:** Moderate-reddish-brown (10R 4/6); mostly zeolitic, partially vitric; minor felsic phenocrysts of feldspar and much less quartz; common biotite; rare sphene; rare to minor dark-reddish-brown (10R 3/4) lithic fragments of devitrified welded tuff.	Tpb
627.9 - 643.1 (2,060 - 2,110)	15.3 (50)	DA	None	**Partially Welded Ash-Flow Tuff:** Light-brownish-gray (5YR 6/1); devitrified with vapor-phase mineralization; minor brownish-gray (5YR 4/1) recrystallized, partially flattened pumice generally less than 2 mm in size; minor feldspar phenocrysts; rare biotite; rare brownish-black (5YR 2/1) lithic fragments of devitrified welded tuff up to 5 mm in size. Description is from larger (1 cm) fragments that occur in samples from 649.2 to 658.4 m (2130 - 2160 ft). These fragments appear to have sloughed from the 627.9 to 643.1 m (2,060 - 2,110 ft) interval, and contaminated lower samples.	Tpcm

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
643.1 - 728.5 (2,110 - 2,390)	85.4 (280)	DA, DB2, C	TS	**Welded Ash-Flow Tuff:** Pale-brown (5YR 5/2) to moderate-brown (5YR 4/4), becoming mottled light-brown (5YR 6/4) and grayish-brown (5YR 3/2) in lower portion of interval; devitrified; minor medium-light-gray (N 6) flattened pumice; minor feldspar phenocrysts; common mafic minerals of biotite and lesser clinopyroxene; no lithic fragments observed. Large open fractures coated with manganese oxide occur in lower portion of interval.	Tpcm
728.5 - 737.6 (2,390 - 2,420)	9.1 (30)	DA	None	**Vitrophyric Ash-Flow Tuff:** Brownish-black (5YR 2/1); vitric; minor feldspar phenocrysts; minor biotite; rare sphene.	Tpcm
737.6 - 771.1 (2,420 - 2,530)	33.5 (110)	DA	None	**Bedded Tuff:** Light-brown (5YR 5/6) to 749.8 m (2,460 ft), becoming grayish-orange (10YR 7/4) to moderate-yellow (5Y 7/6) below; zeolitic; rare to minor light-brown (5YR 6/4) and grayish-yellow (5Y 8/4) pumice; rare felsic phenocrysts of feldspar and much less quartz; rare mafic minerals of biotite, clinopyroxene, and orthopyroxene; rare volcanic lithic fragments.	Tpd
771.1 - 792.5 (2,530 - 2,600)	21.3 (70)	DA, C	TS, MP, NAA	**Nonwelded Ash-Flow Tuff:** Grayish-orange (10YR 7/4) to 780.3 m (2,560 ft), becoming moderate-orange-pink (10R 7/4) below; zeolitic; minor light-brown (5YR 5/6), moderate-yellowish-brown (10YR 5/4), and very-pale-orange (10YR 8/2) pumice up to 5 cm, but typically less than 5 mm in size; minor feldspar phenocrysts; minor biotite; rare dusky-brown (5YR 2/2) volcanic lithic fragments.	Tptm
792.5 - 810.8 (2,600 - 2,660)	18.3 (60)	DA, C	TS, MP, XRF, NAA	**Partially Welded Ash-Flow Tuff:** Pale yellowish-brown (10YR 6/2) to pale-reddish-brown (10R 5/4); devitrified; minor light-brown (5YR 5/6), pale-red (10R 6/2), and grayish-orange (10YR 7/4) partially flattened pumice up to 3 cm in size, but typically less than 5 mm; minor feldspar phenocrysts; minor biotite; rare dusky-brown (5YR 2/2) volcanic lithic fragments; numerous thin, discontinuous, partially open fractures.	Tptm

Lithologic Log for UE20c

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
810.8 - 883.9 (2,660 - 2,900)	73.2 (240)	DA, C	TS, MP, NAA	**Moderately Welded Ash-Flow Tuff:** Moderate-brown (5YR 4/4); devitrified; minor pale-reddish-brown (10R 5/4) flattened pumice up to 3 cm in length; minor feldspar phenocrysts; common biotite; rare dark-reddish-brown (10R 3/4) volcanic lithic fragments; numerous large partially open fractures.	Tptm
883.9 - 899.2 (2,900 - 2,950)	15.3 (50)	DA, C	TS, MP, XRF,NAA	**Partially Welded Ash-Flow Tuff:** Light-brown (5YR 6/4); devitrified; minor to common moderate-brown (5YR 4/4) and grayish-orange (10YR 7/4) partially flattened pumice less than 4 mm in size; rare feldspar phenocrysts; rare biotite; rare very-dusky-red (10R 3/4) volcanic lithic fragments less than 4 mm in size; numerous large, partially open fractures.	Tptm
899.2 - 944.9 (2,950 - 3,100)	45.7 (150)	DA, C	TS, MP, NAA	**Nonwelded Ash-Flow Tuff:** Moderate-reddish-brown (10R 4/6) to 908.3 m (2,980 ft), becoming pale-yellowish-brown (10YR 6/2) below; zeolitic; minor to common dark-yellowish-orange (10YR 6/6) and very-pale-orange (10YR 8/2) pumice up to 3 cm, but typically less than 4 mm in size; minor feldspar phenocrysts; minor biotite; rare volcanic lithic fragments of various colors.	Tptm
944.9 - 1,100.0 (3,100 - 3,609)	155.1 (509)	DA, C	TS, MP, NAA	**Bedded Tuff:** Pale-yellowish-brown (10YR 6/2), yellowish-gray (5Y 7/2), and moderate-yellowish-brown (10YR 5/4); zeolitic; minor dark-greenish-yellow (10Y 6/6) and very-pale-orange (10YR 8/2) pumice less than 5 mm in size; rare felsic phenocrysts of feldspar and quartz; rare biotite; minor lithic fragments of various colors and tuffaceous lithologies up to 5 cm in size. Bedding dips between 5 and 10 degrees at 1007.4 m (3,305 ft) and 1037.8 m (3,405 ft), and 30 degrees at 1099.7 m (3,608 ft).	Thp
1,100.0 - 1,182.6 (3,609-3,880)	82.6 (271)	DA, C	TS	**Pumiceous Lava:** Mottled grayish-yellow (5 Y 8/4) and grayish-olive (10 Y 4/2); zeolitic; pumiceous in part; rare felsic phenocrysts of feldspar and quartz; rare biotite.	Thp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
1,182.6 - 1,200.9 (3,880 - 3,940)	18.3 (60)	DA, C	TS, XRD, XRF, ES	**Lava:** Pale-olive (10 Y 6/2), yellowish-gray (5 Y 7/2), and grayish-red (10 R 4/2); mostly vitric, partially devitrified with minor vapor-phase and zeolitic alteration, becoming completely devitrified in places; weakly perlitic and flow banded; rare felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,200.9 - 1,237.5 (3,940 - 4,060)	36.6 (120)	DA, DB1	None	**Lava:** Moderate-reddish-brown (10R 4/6) and grayish-red (10R 4/2); mostly devitrified, partially vitric; rare felsic phenocrysts of feldspar and quartz; rare biotite. A vitric interval occurs from 1,219.2 to 1,225.3 m (4,000 - 4,020 ft).	Thp
1,237.5 - 1,268.0 (4,060 - 4,160)	30.5 (100)	DA, DB1, C	TS, NAA, ES	**Lava:** Drill cuttings samples consists mostly of very small (<1 mm) fragments of medium-gray (N5) and olive-gray (5Y 4/1) vitric lava; lesser amounts of devitrified lava fragments, some of which appear to be from up-hole intervals; loose felsic crystals of feldspar and quartz; and biotite. Core sample from 1,251.2 to 1,253.9 m (4,105 - 4,114 ft) is greenish black (5G 2/1) vitric vitrophyric lava. Drill cuttings sample at 1,261.9 m (4,140 ft) consists mostly of very small fragments of devitrified lava.	Thp
1,268.0 -1,289.3 (4,160 - 4,230)	21.3 (70)	DB1	None	**Vitrophyric Lava:** Samples consist mostly of very small (<1 mm) fragments of olive-gray (5Y 4/1) and black (N1) vitric lava; lesser amounts of devitrified lava fragments; loose felsic crystals of feldspar and quartz; and biotite.	Thp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
1,289.3 - 1,335.0 (4,230 - 4,380)	45.7 (150)	DA, C	TS, NAA	**Flow Breccia:** Mottled grayish-red (5R 4/2) and very-pale-orange (10YR 8/2); mostly devitrified, partially zeolitic near top of interval, becoming mostly zeolitic lower; becomes progressively more pumiceous with depth; rare felsic phenocrysts of feldspar and quartz; rare biotite. Upper portion of interval consists of angular, very-pale-orange (10YR 8/2) zeolitic and devitrified, weakly to very pumiceous lava, clasts within grayish-red (5R 4/2), dense devitrified, flow-banded lava. Interval becomes less dense, more pumiceous, and more zeolitic with depth; and grades into under lying interval of zeolitic pumiceous lava.	Thp
1,335.0 - 1,368.6 (4,380 - 4,490)	33.6 (110)	DA	None	**Pumiceous Lava:** Grayish-orange (10 YR 7/4); zeolitic; rare felsic phenocrysts of feldspar and quartz; rare biotite.	Thp
1,368.6 - 1,426.5 (4,490 - 4,680)	57.9 (190)	DA, DB1, C	TS, NAA	**Bedded Tuff:** Pale-reddish-brown (10R 5/4) and lesser very-pale-orange (10YR 8/2), becoming pale-yellowish-brown (10YR 6/2) near base of interval; zeolitic; minor to common mostly moderate-orange-pink (10R 7/4) pumice up to 2 cm in size, but typically less than 5 mm; rare felsic phenocrysts of feldspar and quartz; rare biotite; minor dark-reddish-brown (10R 3/4) volcanic lithic fragments typically less than 5 mm in size.	Thp

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
1,426.5 - 1,533.1 (4,680 - 5,030)	106.7 (350)	DB1, DB2, C	TS, XRD, XRF	**Bedded Tuff:** Very-pale-orange (10YR 8/2) and moderate-reddish-orange (10R 6/6); silicic, potassic, and minor zeolitic; minor to common very-pale-orange (10YR 8/2) and moderate-orange-pink (10R 7/4) pumice less than 4 mm in size; common felsic phenocrysts of feldspar and quartz; minor to common biotite; rare to minor volcanic lithic fragments of various colors and up to 1 cm in size, but typically less than 3 mm. Drill cuttings below 1,432.6 m (4,700 ft) contain abundant fragments of black shale, gray siltstone, and vitric nonwelded tuff that appear not to be from UE20c. These rocks were likely introduced into the UE20c circulation system during drilling of this interval by equipment brought on location that had not been fully cleaned-out from a previous drilling operation.	Thr
1,533.1 - 1,630.1 (5,030 - 5,348) TD	96.9 (318)	DB1, DB2, C	TS, XRD, XRF	**Bedded Tuff:** Yellowish-gray (5Y 7/2); zeolitic; minor to common pale-greenish-yellow (10Y 8/2) pumice less than 4 mm in size; common felsic phenocrysts of feldspar and quartz; abundant biotite; rare to minor volcanic lithic fragments of various colors and up to 1 cm in size, but typically less than 3 mm. Drill cuttings contain abundant fragments of black shale, gray siltstone, and vitric nonwelded tuff that appear not to be from UE20c. These rocks were likely introduced into the UE20c circulation system during drilling of this interval by equipment brought on location that had not been fully cleaned-out from a previous drilling operation.	Thr

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components; **DB2** = drill cuttings from interval different than that drilled; **C** = conventional core.

b **TS** = thin section; **MP** = electron microprobe; **XRD** = X-ray diffraction; **XRF** = X-ray fluorescence; **ES** = emission spectroscopy; **NAA** = neutron activation analysis. See Appendix A (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = $\leq$ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = $\geq$ 20%
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = $\leq$ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = $\geq$ 2%

d **Tt** = Thirsty Canyon Group, undivided; **Ttt** = Trail Ridge Tuff; **Tma** = Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tpb** = rhyolite of Benham; **Tpcm** = Pahute Mesa lobe of the Tiva Canyon Tuff; **Tpd** = rhyolite of Delirium Canyon; **Tptm** = Pahute Mesa lobe of the Topopah Springs Tuff; **Thp** = mafic-poor Calico Hills Formation; **Thr** = mafic-rich Calico Hills Formation. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of UE20c.

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Detailed Lithologic Log for Emplacement Hole U20y

By L. B. Prothro and R. G. Warren, 1999
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Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
0 - 51.8 (0 - 170)	51.8 (170)	None	None	**Moderately Welded Ash-Flow Tuff**: Geology inferred from geophysical logs, surface exposures, and stratigraphy of nearby holes. Interval probably contains intercalated bedded tuff.	Tt
51.8 - 64.0 (170 - 210)	12.2 (40)	None	None	**Nonwelded Ash-Flow Tuff**: Vitric. Geology inferred from geophysical logs and description of lithologic samples from nearby hole ER-20-5.	Tma
64.0 - 94.5 (210 - 310)	30.5 (100)	DB1	None	**Bedded Tuff**: Samples consist mostly of loose fragments of white (N9), light-gray (N7), and very-pale-orange (10YR 8/2) vitric pumice up to 20 mm in size and containing phenocrysts of feldspar, quartz, biotite, and sphene. Samples also contain considerable amounts of loose crystals of feldspar, quartz, biotite, and hornblende; and a variety of volcanic lithic fragments generally less than 5 mm in size.	Tmab
94.5 - 103.6 (310 - 340)	9.1 (30)	DB1	None	**Nonwelded Ash-Flow Tuff**: Samples consist mostly of loose crystals of feldspar and quartz, and variety of volcanic lithic fragments up to 10 mm in size. Loose fragments of vitric pumice of a variety of colors and generally less than 3 mm in size, and loose crystals of biotite and clinopyroxene are also present in the samples.	Tmr
103.6 - 110.9 (340 - 364)	7.3 (24)	DA	None	**Partially Welded Ash-Flow Tuff**: Moderate-brown (5YR 3/4) and pale-red (10R 6/2); devitrified, with extensive vapor-phase mineralization; minor medium-light-gray (N6) and yellowish-gray (5Y 8/1) recrystallized and partially flattened pumice less than 4 mm in size; minor felsic phenocrysts of quartz and feldspar; rare mafic minerals of biotite and lesser clinopyroxene; rare grayish-red (10R 4/2) lithic fragments less than 5 mm in size.	Tmr

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
110.9 - 126.2 (364 - 414)	15.3 (50)	DA	None	**Moderately Welded Ash-Flow Tuff**: Brownish-gray (5YR 6/1); devitrified; minor yellowish-gray (5Y 8/1) flattened pumice less than 5 mm in size; minor felsic phenocrysts of feldspar and quartz; rare mafic minerals of biotite and lesser clinopyroxene; no lithic fragments.	Tmr
126.2 - 131.1 (414 - 430)	4.9 (16)	DA	None	**Densely Welded Ash-Flow Tuff**: Grayish-red (10R 4/2); devitrified; minor felsic phenocrysts of feldspar and quartz; minor biotite; no lithic fragments.	Tmr
131.1 - 148.7 (430 - 488)	17.6 (58)	DB1	None	**Vitrophyric Ash-Flow Tuff**: Brownish-black (5YR 2/1), becoming moderate-brown (5YR 3/4) at base of interval; vitric; perlitic; common felsic phenocrysts of feldspar and quartz; rare mafic minerals of biotite and lesser clinopyroxene; no lithic fragments.	Tmr
148.7 - 158.5 (488 - 520)	9.8 (32)	DB1	None	**Nonwelded Ash-Flow Tuff**: Samples consist of loose crystals of feldspar and quartz, a variety of volcanic lithic fragments up to 10 mm in size, and fragments of very-pale-orange (10YR 8/2) vitric pumice less than 2 mm in size. Loose crystals of biotite are also present. A moderate-reddish-orange (10R 6/6) vitric matrix partially coats many of the crystals and fragments.	Tmr
158.5 - 170.7 (520 - 560)	12.2 (40)	DB1	None	**Bedded Tuff**: Samples consist of loose fragments of white (N9) and very-pale-orange (10YR 8/2) vitric pumice less than 4 mm in size, lithic fragments of mostly grayish-red (10R 4/2) devitrified lava less than 10 mm in size, and felsic crystals of feldspar and quartz. Small flakes of biotite are present on some pumice fragments. A grayish-orange (10YR 7/4) and light-brown (5YR 5/6) vitric matrix partially coats some pumice and lithic fragments.	Tmrf

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
170.7 - 176.8 (560 - 580)	6.1 (20)	DB1	None	**Nonwelded Tuff**: Pale yellowish-brown (10YR 6/2); mostly vitric, partially silicic; abundant pale-yellowish-brown (10YR 6/2) vitric pumice less than 3 mm in size; minor felsic phenocrysts of feldspar and quartz; rare biotite; rare moderate-reddish-brown (10R 4/6) lithic fragments of devitrified welded ash-flow tuff less than 3 mm in size.	Tmrf
176.8 - 189.0 (580 - 620)	12.2 (40)	DA - DB1	None	**Nonwelded Tuff**: Grayish-orange (10YR 7/4); vitric; minor pale-yellowish-orange (10YR 8/6) vitric pumice up to 2 cm in size; minor felsic phenocrysts of feldspar and quartz; minor biotite; rare grayish-red (10R 4/2) volcanic lithic fragments less than 2 mm in size.	Tmrf
189.0 - 195.1 (620 - 640)	6.1 (20)	DB1	None	**Bedded Tuff**: Dark-yellowish-orange (10YR 6/6); mostly vitric, partially zeolitic; very abundant dark-yellowish-orange (10YR 6/6) partially zeolitic pumice less than 2 mm in size; minor felsic phenocrysts of feldspar and quartz; minor biotite; rare grayish-red (10R 4/2) lithic fragments of devitrified and silicic lava up to 4 mm in size.	Tmrf
195.1 - 224.3 (640 - 736)	29.2 (96)	DB1	None	**Pumiceous Lava**: Light-olive-gray (5Y 6/1) and pale-yellowish-brown (10YR 6/2); vitric; pumiceous; rare feldspar phenocrysts; abundant biotite; minor sphene.	Tpb
224.3 - 329.2 (736 - 1080)	104.9 (344)	DA	None	**Lava**: Mottled very-light-gray (N8) and moderate-reddish-brown (10R 4/6) devitrified; minor feldspar phenocrysts; common biotite; show flow-banding.	Tpb
329.2 - 362.7 (,1080 - 1,190)	33.5 (110)	DA - DB1	TS	**Vitrophyric Lava**: Dusky-yellowish-brown (10YR 2/2) and dark-reddish brown (10R 3/4); vitric, partially devitrified from 341.4 to 350.5 m (1,120 - 1,150 ft); perlitic; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
362.7 - 374.9 (1,190 - 1,230)	12.2 (40)	DA	TS	**Pumiceous Lava**: Moderate-brown (5YR 4/4); vitric, becoming mostly devitrified and partially vitric at base of interval; rare feldspar phenocrysts; minor biotite; rare sphene.	Tpb
374.9 - 463.3 (1,230 - 1,520)	88.4 (290)	DA	GM, TS, XRD	**Bedded Tuff**: Moderate-yellowish-brown (10YR 5/4), light-brown (5YR 6/4); grayish-yellow (5Y 8/4), and moderate-reddish-brown (10R 4/6); mostly zeolitic, partially opalline and potassic in part, partially argillic at base of interval; minor to common light-brown (5YR 6/4), grayish-yellow (5Y 8/4), and white (N9) zeolitic pumice generally less than 2 mm in size; rare to minor felsic phenocrysts of feldspar and much less quartz; common biotite; rare to minor dark-reddish-brown (10R 3/4) and very-dusky-red (10R 2/2) lithic fragments of devitrified welded tuff and lava up to 1 cm in size; minor sphene.	Tpb
463.3 - 478.5 (1,520 - 1,570)	15.2 (50)	DA	GM, XRD	**Nonwelded Tuff**: Pale brown (5YR 5/2); zeolitic, minor argillic and opaline; common very-pale-orange (10YR 8/2) zeolitic pumice up to 5 mm in size; rare feldspar phenocrysts; rare biotite; rare dusky-brown (5YR 2/2) devitrified volcanic lithic fragments up to 1 cm in size.	Tpcyp
478.5 - 487.7 (1,570 - 1,600)	9.2 (30)	DB1	None	**Partially Welded Ash-Flow Tuff**: Yellowish-gray (5Y 8/1); devitrified, with vapor-phase mineralization; minor yellowish-gray (5Y 8/1) recrystallized pumice up to 2 mm in size; rare feldspar phenocrysts; rare biotite; rare moderate-brown (5YR 4/4) devitrified volcanic lithic fragments up to 4 mm in size.	Tpcm
487.7 - 560.2 (1,600 - 1,838)	72.5 (238)	DA	TS	**Moderately Welded Ash-Flow Tuff**: Mostly grayish-red (10R 4/2), moderate-brown (5YR 4/4) at top and base of interval; mostly devitrified, partially silicic below 545.6 m (1,790 ft); minor light-gray (N7) flattened pumice up to 3 mm in size; rare feldspar phenocrysts; rare biotite; no lithic fragments.	Tpcm

Depth Interval meters/(feet)	Thickness meters/ (feet)	Sample Type [a]	Laboratory Analyses [b]	Lithologic Description [c]	Stratigraphic Unit [d]
560.2 - 579.1 (1,838 - 1,900)	18.9 (62)	DA	TS	**Densely Welded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); devitrified; rare feldspar phenocrysts; rare biotite.	Tpcm
579.1 - 585.2 (1,900 - 1,920)	6.1 (20)	DA, DB1	None	**Bedded Tuff**: Pale-reddish-brown (10R 5/4), light-brown (5YR 6/4), pale-yellowish-brown (10YR 6/2) to moderate-yellowish-brown (10YR 5/4), and dark-yellowish-orange (10YR 6/6); zeolitic; pumice mostly absent; rare to minor feldspar phenocrysts; rare biotite; rare to common welded and nonwelded tuffaceous and lava lithic fragments up to 3 mm in size.	Tpd
585.2 - 640.7 (1,920 - 2,102)	55.5 (182)	DA, DB1	None	**Bedded Tuff**: Grayish-yellow (5Y 8/4), grayish-orange (10YR 7/4), very-pale-orange (10YR 8/2), and light-brown (5YR 6/4); zeolitic; rare to minor pumice up to 2 mm in size; rare feldspar phenocrysts, rare to minor biotite; minor to common mostly grayish-red (10R 4/2) to very-dusky-red (10R 2/2) devitrified welded tuff lithic fragments up to 1 cm in size, becoming rare in abundance below approximately 606.5 m (1,990 ft).	Tpd
640.7 - 654.1 (2,102 - 2,146)	13.4 (44)	DA	XRD, XRF	**Partially Welded Ash-Flow**: Light-brownish-gray (5YR 6/1), becoming light-brown (5YR 5/6) at base of interval; devitrified; rare light-brownish-gray (5YR 6/1) pumice generally less than 2 mm in size; rare feldspar phenocrysts; minor biotite; rare moderate-brown (5YR 3/4) lithic fragments of densely welded ash-flow tuff up to 4 mm in size.	Tptm
654.1 - 726.6 (2,146 - 2,384)	72.5 (238)	DA	None	**Moderately Welded Ash-Flow Tuff**: Pale-brown (5YR 5/2) to approximately 695.0 m (2,280 ft), becoming mostly moderate-brown (5YR 3/4) below; devitrified; rare to minor pale-brown (5YR 5/2) and moderate-brown (5YR 3/4) flattened pumice up to 3 mm in size; rare feldspar phenocrysts; minor biotite; rare grayish-brown (5YR 3/2) tuffaceous lithic fragments up to 5 mm in size.	Tptm
726.6 - 751.6 (2,384 - 2,466)	25.0 (82)	DA	None	**Densely Welded Ash-Flow Tuff**: Moderate-brown (5YR 4/4); devitrified; rare feldspar phenocrysts; rare biotite.	Tptm

Depth Interval meters/(feet)	**Thickness** meters/ (feet)	**Sample Type** [a]	**Laboratory Analyses** [b]	**Lithologic Description** [c]	**Stratigraphic Unit** [d]
751.6 - 793.1 (2,466 - 2,602) TD	41.5 (136)	DA	TS, XRD, XRF	**Partially Welded Ash-Flow Tuff**: Pale-brown (5YR 5/2); potassic, minor zeolitic and opaline; minor pale-brown (5YR 5/2) pumice up to 7 mm in size; rare feldspar phenocrysts; minor biotite; rare grayish-brown (5YR 3/2) lithic fragments of lava and densely welded tuff up to 1 cm in size.	Tptm

a **DA** = drill cuttings that represent lithologic character of interval; **DB1** = drill cuttings enriched in hard components.

b **GM** = grain mount; **TS** = thin section; **XRD** = X-ray diffraction; **XRF** = X-ray fluorescence. See Appendix B (this report) for details of laboratory analyses.

c Descriptions are based mainly on visual examination of lithologic samples using a 10x- to 40x-zoom binocular microscope and geophysical logs. Additional data from laboratory analyses have been incorporated into the descriptions. Colors describe wet sample color, and are based on the Geological Society of America Rock-Color Chart.
Abundances for felsic phenocrysts, pumice fragments, and lithic fragments: **trace** = only one or two individuals observed; **rare** = ≤ 1%; **minor** = 5%; **common** = 10%; **abundant** = 15%; **very abundant** = ≥ 20%
Abundances for mafic minerals: **trace** = only one or two individuals observed; **rare** = ≤ 0.05%; **minor** = 0.2%; **common** = 0.5%; **abundant** = 1%; **very abundant** = ≥ 2%

d **Tt** = Thirsty Canyon Group, undivided; **Tma** = Ammonia Tanks Tuff; **Tmab** = bedded Ammonia Tanks Tuff; **Tmr** = Rainier Mesa Tuff; **Tmrf** = rhyolite of Fluorspar Canyon; **Tpb** = rhyolite of Benham; **Tpcy** = tuff of Pinyon Pass; **Tpcm** = Pahute Mesa lobe of the Tiva Canyon Tuff; **Tpd** = rhyolite of Delirium Canyon; **Tptb** = bedded Topopah Springs Tuff; **Tptm** = Pahute Mesa lobe of the Topopah Springs Tuff. See Table 1-5 (this report) for additional information regarding stratigraphic relationships in the vicinity of U20y.

Appendix B

List of Laboratory Analyses Available for Drill Holes of the TYBO-BENHAM Area

List of Laboratory Analyses Available for Drill Holes of the TYBO-BENHAM Area

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
ER-20-1	570.0	1,870.0	DA	Tpcm	PWT	MG	SR/ZC	TS, XRD, XRF
ER-20-1	624.8	2,050.0	DA	Tpcm	MWT	MG/GR	SR	TS, XRD, XRF
ER-20-5 #3	618.7	2,030.0	DA	Tpg	NWT	ZC	ZM/OP	TS, XRD
ER-20-5 #3	676.7	2,220.0	DA	Tpd	NWT	ZC/ZM	OP/KF	TS, XRD
ER-20-5 #3	900.7	2,955.0	DA	Thp	NWT	QC/ZM/KF	OP	TS, XRD, XRF
ER-20-5 #3	915.9	3,005.0	DA	Thp	NWT	QC/ZM/KF	--	XRD, XRF
ER-20-5 #3	972.3	3,190.0	DA	Thp	NWT	ZM/KF/QC	--	XRD, XRF
ER-20-5 #3	1,185.7	3,890.0	DA	Thp	PL	ZC	ZM/OP/ZA	XRD, XRF
ER-20-5 #3	1,207.0	3,960.0	DA	Thp	NWT	ZM/ZC	QC/KF/ZA	XRD, XRF
ER-20-5 #3	1,255.8	4,120.0	DA	Thr	NWT	QC/KF	ZA/ZM/ZC	XRD, XRF
ER-20-5 #3	1,295.4	4,250.0	DA	Thr	NWT	KF/QC	ZM/ZA	XRD, XRF
U20ag	24.4	80.0	DB1	Ttpr	PWT	DV/VP	CC	CO_2
U20ag	33.5	110.0	DB1	Ttpp	PWT	DV/VP	CC	CO_2
U20ag	70.1	230.0	DB1	Ttr	PWT	DV/VP	--	CO_2
U20ag	79.2	260.0	DB1	Tmar	PWT	GL/DV	CC	CO_2
U20ag	82.3	270.0	DB1	Tmar	PWT	GL/DV	--	XRD
U20ag	88.4	290.0	DB1	Tmar	PWT	GL/DV	--	CO_2
U20ag	97.5	320.0	DB1	Tmab	BED	GL	--	CO_2
U20ag	115.8	380.0	DB1	Tmab	BED	GL	CC	CO_2
U20ag	134.1	440.0	DA	Tmrr	PWT	DV/VP	--	CO_2
U20ag	140.2	460.0	DA	Tmrr	MWT	DV	--	XRD
U20ag	143.3	470.0	DA	Tmrr	MWT	DV	--	CO_2
U20ag	189.0	620.0	DA	Tmrp	DWT	DV	--	CO_2
U20ag	204.2	670.0	DA	Tmrp	VT	GL/DV	AR	XRD

See notes a through f on Page B-7

Laboratory Analyses - TYBO-BENHAM Area Drill Holes

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
U20ag	207.3	680.0	DB1	Tmrp	VT	GL/DV	--	XRD
U20ag	249.9	820.0	DB1	Tmrf	BED	GL	--	CO_2
U20ag	280.4	920.0	DB1	Tmrf	BED	GL	--	CO_2
U20ag	289.6	950.0	DA	Tmrf	NWT	GL	--	XRD
U20ag	301.8	990.0	DA	Tmrh	BED	GL	CC	CO_2
U20ag	307.8	1,010.0	DA	Tmrh	BED	ZC	GL	XRD
U20ag	320.0	1,050.0	DA	Tmrh	BED	ZC	GL	XRD
U20ag	329.2	1,080.0	DB1	Tmrh	BED	ZC	GL/CC	CO_2
U20ag	356.6	1,170.0	DA	Tpb	PL	ZC	QC	XRD
U20ao	152.4	500.0	DB1	Tmab	BED	GL	--	XRD
U20ao	326.1	1,070.0	DB1	Tmrf	BED	GL	--	XRD
U20ao	390.1	1,280.0	DB1	Tmrh	BED	GL	--	XRD
U20ao	417.6	1,370.0	DA	Tmrh	BED	ZC	--	XRD
U20as	304.8	1,000.0	DB1	Tmw	BED	ZC	--	XRD
U20as	310.9	1,020.0	DB1	Tmw	BED	ZC	GL/CC/OP	TS
U20as	335.3	1,100.0	DB1	Tmw	BED	ZC	--	XRD
U20as	365.8	1,200.0	DB1	Tmw	BED	ZC	--	TS, XRD
U20as	460.2	1,510.0	DB1	Tpb	LA	GL	ZC	XRD
U20as	472.4	1,550.0	DA	Tpb	LA	GL	DV	GM
U20as	478.5	1,570.0	DA	Tpb	LA	ZC	--	GM, XRD
U20as	487.7	1,600.0	DA	Tpb	NWT	ZC	AR	GM, XRD
U20as	518.2	1,700.0	DA	Tpb	NWT	ZC	AR	GM, XRD
U20as	548.6	1,800.0	DA	Tpb	NWT	ZC	--	GM
U20as	563.9	1,850.0	DA	Tpb	BED	ZC	AR	XRD
U20as	579.1	1,900.0	DA	Tpb	NWT	ZC	--	GM

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
U20as	606.6	1,990.0	DA	Tpb	NWT	ZC	AR/KF	GM, XRD
U20as	624.8	2,050.0	DA	Tpb	NWT	ZC	--	GM
U20as	634.0	2,080.0	DA	Tpb	BED	ZC	--	XRD
U20as	640.1	2,100.0	DA	Tpb	NWT	ZC	--	GM
U20c	1,303.0	4,275.0	DA	Thp	PL	ZC/ZM	OP	XRD, XRF
U20c	1,387.5	4,552.3	C	Thp	BED	QC/ZA/KF	ZM	TS, XRD
U20c	1,402.1	4,600.0	C	Thr	BED	ZE	--	ES
U20c	1,418.4	4,643.7	C	Thr	BED	QC/KF	ZM/ZA	TS, XRD
U20c	1,461.2	4,794.0	C	Thr	BED	QC/KF/ZA	CC	TS
UE20c	363.0	1,191.0	C	Tpb	LA	SR/MG	--	TS
UE20c	412.4	1,353.0	C	Tpb	LA	MG/VP/GR	--	TS, ES
UE20c	459.3	1,507.0	C	Tpb	LA	SR/MG/GR	--	TS
UE20c	523.6	1,718.0	C	Tpb	LA	GR	--	TS
UE20c	588.3	1,930.0	C	Tpb	LA	MG	--	TS, ES
UE20c	648.0	2,126.0	C	Tpcm	DWT	AX/GR	--	TS
UE20c	650.1	2,133.0	C	Tpcm	DWT	MG	GR	TS
UE20c	713.8	2,342.0	C	Tpcm	MWT	MG/GR/SR	--	TS
UE20c	731.5	2,400.0	DA	Tpcm	WT	DV	--	TS
UE20c	778.2	2,553.0	C	Tptm	NWT	ZC	--	TS
UE20c	780.0	2,559.0	C	Tptm	NWT	ZC	--	TS, MP, NAA
UE20c	793.1	2,602.0	C	Tptm	NWT	MG/SR	--	TS
UE20c	795.4	2,609.5	C	Tptm	PWT	MG/SR	--	TS, MP, XRF, NAA
UE20c	808.3	2,652.0	C	Tptm	PWT	MG/GR	--	TS
UE20c	808.9	2,654.0	C	Tptm	PWT	MG/GR	--	TS
UE20c	823.6	2,702.0	C	Tptm	MWT	MG/GR	SR	TS

Laboratory Analyses - TYBO-BENHAM Area Drill Holes

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
UE20c	826.0	2,710.0	C	Tptm	MWT	MG/GR	--	TS, MP, NAA
UE20c	840.3	2,757.0	C	Tptm	MWT	MG/GR	SR	TS
UE20c	853.4	2,800.0	C	Tptm	MWT	MG/GR	SR	NAA
UE20c	854.0	2,802.0	C	Tptm	MWT	MG/GR	SR	TS
UE20c	871.1	2,858.0	C	Tptm	MWT	MG/GR	SR	TS
UE20c	884.2	2,901.0	C	Tptm	PWT	MG/SR/GR	--	TS, MP, XRF, NAA
UE20c	884.5	2,902.0	C	Tptm	PWT	MG	SR	TS
UE20c	899.8	2,952.0	C	Tptm	NWT	ZC	--	TS
UE20c	901.3	2,957.0	C	Tptm	NWT	ZC	--	NAA
UE20c	914.7	3,001.0	C	Tptm	NWT	ZC/QC	--	TS
UE20c	915.9	3,005.0	C	Tptm	NWT	ZC	--	TS, MP, NAA
UE20c	947.6	3,109.0	C	Thp	NWT	ZC	--	TS
UE20c	947.9	3,110.0	C	Thp	NWT	ZC	QZ	TS, NAA
UE20c	978.1	3,209.0	C	Thp	NWT	ZC/QC	--	TS
UE20c	1,005.8	3,300.0	C	Thp	NWT	ZC/QC	--	TS
UE20c	1,036.9	3,402.0	C	Thp	NWT	ZC	--	TS
UE20c	1,039.4	3,410.0	C	Thp	BED	ZC	CH	TS, NAA
UE20c	1,070.5	3,512.0	C	Thp	NWT	ZC/QC	--	TS
UE20c	1,097.4	3,600.5	C	Thp	NWT	ZE	KF	TS, MP, NAA
UE20c	1,098.8	3,605.0	C	Thp	NWT	ZC/QC	--	TS
UE20c	1,100.3	3,610.0	C	Thp	PL	ZC/QC	--	TS
UE20c	1,189.6	3,903.0	C	Thp	LA	AX/GR	VP/ZC	XRD, XRF
UE20c	1,189.9	3,904.0	C	Thp	LA	AX/GR	--	TS, ES
UE20c	1,251.2	4,105.0	C	Thp	LA	GL	--	TS, ES
UE20c	1,252.7	4,110.0	C	Thp	LA	GL	--	NAA

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
UE20c	1,294.2	4,246.0	C	Thp	FB	MG	SR	TS, NAA
UE20c	1,383.2	4,538.0	C	Thp	PWT	MG	--	TS
UE20c	1,383.5	4,539.0	C	Thp	NWT	ZE	--	NAA
UE20c	1,446.3	4,745.0	C	Thr	NWT	ZC/QC	--	TS
UE20c	1,446.6	4,746.0	C	Thr	NWT	QC/KF	ZM	XRD, XRF
UE20c	1,446.6	4,746.0	C	Thr	NWT	QC/KF	ZM	XRD, XRF
UE20c	1,446.6	4,746.0	C	Thr	NWT	QC/KF	ZM	TS
UE20c	1,496.6	4,910.0	DB2	Mc	AR	AR/KA/PY	CC/CH	TS, XRD
UE20c	1,496.6	4,910.0	DB2	Mc	SLT	AR/KA/PY	CC/CH	TS, XRD
UE20c	1,505.1	4,938.0	C	Thr	NWT	ZC/QC	CC	TS
UE20c	1,506.8	4,943.7	C	Thr	NWT	QC/KF/ZA	ZM	XRD, XRF
UE20c	1,571.2	5,155.0	C	Thr	NWT	ZC/CH	--	TS
UE20c	1,573.1	5,161.0	C	Thr	NWT	ZM	ZA	XRD, XRF
U20y	341.4	1,120.0	DA	Tpb	LA	GL/SR	--	TS
U20y	374.9	1,230.0	DA	Tpb	PL	MS	--	TS
U20y	384.0	1,260.0	DA	Tpb	NWT	ZC	--	GM
U20y	426.7	1,400.0	DA	Tpb	NWT	ZC	--	GM
U20y	442.0	1,450.0	DA	Tpb	NWT	ZC	ZM/OP/KF	TS, XRD
U20y	454.2	1,490.0	DB1	Tpb	BED	KF/ZC	OP	XRD
U20y	457.2	1,500.0	DA	Tpb	NWT	ZC	--	GM
U20y	460.2	1,510.0	DA	Tpb	BED	ZC/KF	OP	TS, XRD
U20y	463.3	1,520.0	DA	Tpb	BED	AR/ZC/KF	OP	XRD
U20y	466.3	1,530.0	DB1	Tpcyp	NWT	ZC	AR/OP	GM, XRD
U20y	472.4	1,550.0	DA	Tpcyp	NWT	ZC	--	GM
U20y	490.7	1,610.0	DA	Tpcm	MWT	MG/AX/GR	--	TS

Drill Hole	Sample Depth [a] (meters)	Sample Depth [a] (feet)	Sample Type [b]	Stratigraphic Unit [c]	Lithologic Unit [d]	Alteration [e]	Minor Alteration [e]	Laboratory Analyses Performed [f]
U20y	493.8	1,620.0	DA	Tpcm	MWT	MG	GR/CC	TS
U20y	521.2	1,710.0	DA	Tpcm	MWT	MG	GR	TS
U20y	560.8	1,840.0	DA	Tpcm	MWT	MG/MS	--	TS
U20y	570.0	1,870.0	DA	Tpcm	DWT	DV	--	TS
U20y	640.1	2,100.0	DA	Tptm	PWT	MG	KA	XRD, XRF
U20y	762.0	2,500.0	DA	Tptm	PWT	ZC	--	TS
U20y	768.1	2,520.0	DA	Tptm	PWT	ZC	--	TS
U20y	771.1	2,530.0	DA	Tptm	PWT	DV	ZE	XRD
U20y	774.2	2,540.0	DA	Tptm	PWT	DV	ZE	TS, XRD
U20y	783.3	2,570.0	DA	Tptm	PWT	MG	ZM/ZA/OP/ CC/ZC	TS, XRD, XRF

a Depth represents base of sample interval. See Section 2.0 of this report and Warren et al. (1999) for sample intervals.

b **DA** = drill cuttings that represent lithologic character of interval
DB1 = drill cuttings enriched in hard components
DB2 = drill cuttings from interval different than that drilled
C = conventional core

c **Ttpr** = crystal-rich Pahute Mesa Tuff
Ttpp = crystal-poor Pahute Mesa Tuff
Ttr = Rocket Wash Tuff
Tmar = mafic-rich Ammonia Tanks Tuff
Tmab = bedded Ammonia Tanks Tuff
Tmrr = mafic-rich Rainier Mesa Tuff
Tmrp = mafic-poor Rainier Mesa Tuff
Tmrf = rhyolite of Fluorspar Canyon
Tmrh = tuff of Holmes Road
Tmw = rhyolite of Windy Wash
Tpb = rhyolite of Benham
Tpcyp = crystal-poor tuff of Pinyon Pass
Tpcm = Pahute Mesa lobe of Tiva Canyon Tuff
Tpg = rhyolite of Black Glass Canyon
Tpd = rhyolite of Delirium Canyon
Tptm = Pahute Mesa lobe of Topopah Spring Tuff
Thp = mafic-poor Calico Hills Formation
Thr = mafic-rich Calico Hills Formation
Mc = Chainman Shale

d **BED** = bedded tuff
NWT = nonwelded tuff
PWT = partially welded ash-flow tuff
MWT = moderately welded ash-flow tuff
DWT = densely welded ash-flow tuff
VT = vitrophyric ash-flow tuff
WT = welded tuff
PL = pumiceous lava
LA = lava
FB = flow breccia
AR = argillite
SLT = siltstone

e **--** = minor alteration not identified or not present
GL = vitric
OP = opalline
AR = argillic
ZE = zeolitic
ZC = zeolitic (clinoptilolite)
ZM = zeolitic (mordenite)
ZA = zeolitic (analcime)
QZ = silicic
QC = silicic (chalcedony)
CC = calcite
KF = potassic
KA = kaolinitic
PY = pyritic
CH = chloritic
DV = devitrified
VP = devitrified (vapor-phase)
GR = devitrified (granophyric)
SR = devitrified (spherulitic)
AX = devitrified (axiolitic)
MG = devitrified (microgranophyric)
MS = devitrified (microspherulitic)

f **GM** = grain mount
TS = thin section
MP = electron microprobe
XRD = X-ray diffraction
XRF = X-ray fluorescence
NAA = neutron activation analysis
ES = emission spectroscopy
CO_2 = carbon dioxide content

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