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A Hydrostratigraphic System for Modeling Groundwater Flow and Radionuclide Migration at the Corrective Action Unit Scale, Nevada Test Site and Surrounding Areas, Clark, Lincoln, and Nye Counties, Nevada

January 2009

Prepared for:

U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office

Prepared by:

Lance B. Prothro, Sigmund L. Drellack, Jr., and Jennifer M. Mercadante

Underground Test Area and Boreholes Programs and Operations
Environmental Restoration
National Security Technologies, LLC
Las Vegas, Nevada

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ABSTRACT

Underground Test Area (UGTA) corrective action unit (CAU) groundwater flow and contaminant transport models of the Nevada Test Site (NTS) and vicinity are built upon hydrostratigraphic framework models (HFMs) that utilize the hydrostratigraphic unit (HSU) as the fundamental modeling component. The delineation and three-dimensional (3-D) modeling of HSUs within the highly complex geologic terrain that is the NTS requires a hydrostratigraphic system that is internally consistent, yet flexible enough to account for overlapping model areas, varied geologic terrain, and the development of multiple alternative HFMs. The UGTA CAU-scale hydrostratigraphic system builds on more than 50 years of geologic and hydrologic work in the NTS region. It includes 76 HSUs developed from nearly 300 stratigraphic units that span more than 570 million years of geologic time, and includes rock units as diverse as marine carbonate and siliciclastic rocks, granitic intrusives, rhyolitic lavas and ash-flow tuffs, and alluvial valley-fill deposits.

The UGTA CAU-scale hydrostratigraphic system uses a geology-based approach and two-level classification scheme. The first, or lowest, level of the hydrostratigraphic system is the hydrogeologic unit (HGU). Rocks in a model area are first classified as one of ten HGUs based on the rock's ability to transmit groundwater (i.e., nature of their porosity and permeability), which at the NTS is mainly a function of the rock's primary lithology, type and degree of post-depositional alteration, and propensity to fracture.

The second, or highest, level within the UGTA CAU-scale hydrostratigraphic system is the HSU, which is the fundamental mapping/modeling unit within UGTA CAU-scale HFMs. HSUs are 3-D bodies that are represented in the finite element mesh for the UGTA groundwater modeling process. HSUs are defined systematically by stratigraphically organizing HGUs of similar character into larger HSUs designations. The careful integration of stratigraphic information in the development of HSUs is important to assure individual HSUs are internally consistent, correlatable, and mappable throughout all the model areas.

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List of Acronyms and Abbreviations

3-D	three-dimensional
AA	alluvial aquifer
BN	Bechtel Nevada
CA	carbonate aquifer
CAU	corrective action unit
CHZCM	Calico Hills zeolitic composite unit
CCU	clastic confining unit
CM	composite unit
DOE/NV	U.S. Department of Energy, Nevada Operations Office
ft	foot (feet)
GCU	granite confining unit
HFM	hydrostratigraphic framework model
HGU	hydrogeologic unit
HSU	hydrostratigraphic unit
IICU	intra-caldera intrusive confining unit
IT	IT Corporation
LCA	lower carbonate aquifer
LCA3	lower carbonate aquifer–thrust plate
LCA3–1	lower carbonate aquifer–thrust plate–1
LCCU	lower clastic confining unit
LCCU1	lower clastic confining unit 1–thrust plate
LCCU2	lower clastic confining unit 2–thrust plate
LFA	lava-flow aquifer
LTCU	lower tuff confining unit
m	meter(s)
MT	magnetotelluric
NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office
NSTec	National Security Technologies, LLC
NTS	Nevada Test Site
OSBCU	Oak Spring Butte confining unit
PCU	playa confining unit
PM–OV	Pahute Mesa–Oasis Valley
RM–SM	Rainier Mesa–Shoshone Mountain
TCU	tuff confining unit

List of Acronyms and Abbreviations, continued

TMCM	Timber Mountain composite unit
TM-LVTA	Timber Mountain lower vitric-tuff aquifer
TM-WTA	Timber Mountain welded-tuff aquifer
TSA	Topopah Spring aquifer
UCCU	upper clastic confining unit
UCCU1	upper clastic confining unit–thrust plate
UGTA	Underground Test Area
USGS	U.S. Geological Survey
VTA	vitric-tuff aquifer
WTA	welded-tuff aquifer
WTP	Weapons Testing Program
YF–CM	Yucca Flat-Climax Mine

1.0 INTRODUCTION

The Environmental Restoration Project of the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NNSA/NSO) initiated the Underground Test Area (UGTA) Sub-Project to investigate the extent of groundwater contamination at the Nevada Test Site (NTS) and surrounding areas due to past underground nuclear testing. The UGTA investigation focuses on modeling the geology and hydrology of the NTS to estimate the direction and rate at which contaminants are transported by groundwater flow. A crucial step in this investigation was the construction of three-dimensional (3-D) hydrostratigraphic framework models (HFMs), one for each of the former underground nuclear testing areas, which are geographically organized into four corrective action units (CAUs) (Figure 1-1). These models are used to develop groundwater flow and contaminant transport models for each of the CAUs. The construction of HFMs required the development of a hydrostratigraphic system that organized rock units within the model area into hydrostratigraphic units (HSUs) according to their water-bearing qualities and in such a way that they could be accurately depicted in three dimensions within the HFMs.

HFMs for all four UGTA CAUs have been constructed, and the HSUs delineated for each model area now form a single CAU-scale hydrostratigraphic system for the entire NTS and vicinity. This system provides a consistent yet flexible framework for defining and modeling HSUs at the NTS and in surrounding areas. The system builds on more than 50 years of geologic and hydrologic work in the NTS region. It includes 76 HSUs developed from nearly 300 stratigraphic units (Warren et al., 2003) that span more than 500 million years of geologic time, and includes rock units as diverse as marine carbonate and siliciclastic rocks, granitic intrusives, rhyolitic lavas and ash-flow tuffs, and alluvial valley-fill deposits.

1.1 Objectives

The purpose of the UGTA CAU-scale hydrostratigraphic system is to provide a systematic and consistent method for organizing stratigraphic rock units in the NTS area into HSUs based on similar groundwater flow properties. Because HSUs are the building blocks for the HFMs on which flow and transport models are built, understanding the hydrostratigraphic system on which HSUs are based is critical for proper grid and mesh development, flow and transport parameterization, evaluation of model results, and model review. Thus, the objective of this report is to provide UGTA participants, including project scientists and modelers, peer reviewers, and stakeholders, a comprehensive overview of the CAU-scale hydrostratigraphic

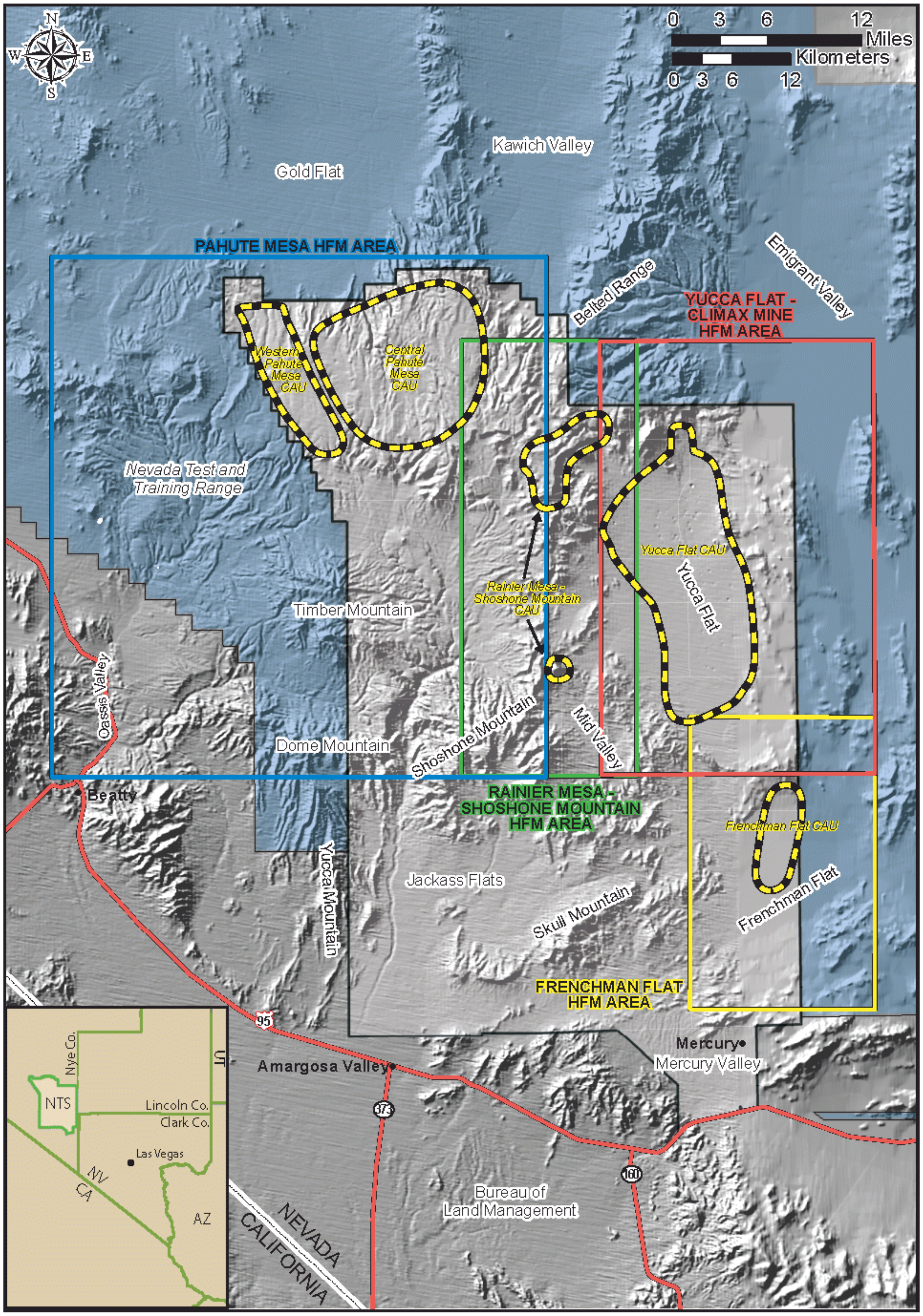

Figure 1-1
Map Showing Locations of All UGTA HFM Areas

system that has previously been described only in the context of each individual HFM. The report is also intended to be a general reference resource for the hydrostratigraphic system and units utilized in the HFMs. More detailed information on the HSUs can be found in the HFM documentation reports for each CAU (Bechtel Nevada [BN], 2002; 2005; 2006; National Security Technologies, LLC [NSTec], 2007).

It should be noted that the UGTA Sub-Project is ongoing, and that new HSUs may be developed in the future in response to new data and modeling requirements. Thus, the HSUs described in this report are those developed at the time of publication, which generally coincides with the completion of Phase I activities. It is likely that new HSUs will be developed as UGTA Phase II activities progress, and if so, they will be defined using the process of HSU development described here.

1.2 Geologic Setting

Geologically, the NTS area is very complex. The region includes diverse rock types that have been distributed by a variety of depositional processes, including extensive volcanic activity, followed by widespread alluvial deposition. It has undergone compressional and extensional structural events, causing extensive faulting and folding. This geologic complexity makes the delineation and 3-D correlation of HSUs very challenging. This section gives a brief overview of the geologic setting of the NTS region, and is intended to provide the reader with an appreciation of the diverse and complex geology of the NTS. More detailed discussions of the structure and stratigraphy of the UGTA CAU-scale model areas, including references, are found in their respective HFM documentation reports (BN, 2002; 2005; 2006; NSTec, 2007).

The NTS lies within the northern portion of the Basin and Range physiographic province, which is characterized by narrow, generally north-trending mountain ranges separated by valleys filled with alluvium (Figure 1-2). The oldest rocks in the NTS area are more than 200 million years old, and consist of Proterozoic and Paleozoic sedimentary and metasedimentary rocks of mostly marine origin. These rocks include limestone, dolomite, sandstone, siltstone, shale, quartzite, and argillite that are as much as 10,000 meters (m) (32,800 feet [ft]) thick in the NTS region (Cole and Cashman, 1999; Slate et al., 1999). This thick sedimentary section can be subdivided as follows: Upper Proterozoic to Middle Cambrian siliciclastic rocks, a thick sequence of Middle Cambrian to Upper Devonian carbonate rocks, Upper Devonian to Pennsylvanian siliciclastic rocks, and Pennsylvanian to Middle Permian carbonate rocks. More than 100 million years ago, these rocks were compressed by tectonic forces, resulting in the formation of folds and thrust faults (e.g., Belted Range and CP thrust faults) (Cole and Cashman, 1999).

Figure 1-2
Color Relief Map Showing Locations of the Basin and Range Physiographic and Great Basin Hydrographic Provinces (Province boundaries from Fiero, 1986)

During the Cretaceous period (about 100 million years ago), granitic bodies intruded these deformed rocks (Naeser and Maldonado, 1981). Two granitic bodies are exposed at the surface at the NTS: the Gold Meadows stock located just north of Rainier Mesa, and the Climax stock at the north end of Yucca Flat (Gibbons et al., 1963; Barnes et al., 1963). Except for Cretaceous granitic rocks, no rocks of Mesozoic- or lower Cenozoic-age are present at the NTS (Frizzell and Shulters, 1990).

The next youngest rocks at the NTS are relatively minor deposits of sedimentary and volcanic rocks of middle to upper Oligocene age (Frizzell and Shulters, 1990). During the middle Miocene, between approximately 15 and 9 million years ago, extensive eruptions of volcanic material resulted in the accumulation of a thick blanket of volcanic deposits across much of the NTS, and the formation of large calderas in the western and northwestern portions of the NTS and adjacent areas (Sawyer et al., 1994). Volcanic rocks include thick sequences of bedded ash- and pumice-fall deposits and reworked tuff, laterally extensive sheets of welded ash-flow tuff, and intercalated occurrences of rhyolitic and basaltic lava. The thickness and extent of the volcanic rocks vary, partly because of the irregularity of the surface on which they were deposited, and partly because of the presence of topographic barriers and windows between the depositional areas and the source calderas to the west and northwest.

Extensional forces began to stretch and down-fault the rocks of the NTS region during the Miocene, resulting in the formation of an extensive system of normal faults (Sawyer et al., 1994). In the eastern and southern portions of the NTS, basins formed along large normal and strike-slip faults generally after the main phase of volcanic activity. These basins, which include Yucca Flat and Frenchman Flat, were filled with alluvial debris eroded from the adjacent highlands during basin development. The thickness of alluvial deposits in these basins exceeds 1,067 m (3,500 ft) (Drellack and Thompson, 1990; NNSA/NSO, 2005b).

Geologic structures (faults and folds) are also an important factor in the distribution of HSUs in the NTS region. Structures define the geometric configuration of the area, including the distribution, thickness, and orientation of units. Synvolcanic structures, including caldera faults and some normal faults, had a strong influence on depositional patterns of many of the units, which display abrupt and dramatic lithologic and thickness changes across caldera margins (Byers et al., 1976; Ferguson et al., 1994).

A generalized geologic map of the NTS area is given in Figure 1-3. Figure 1-4 is a more detailed geologic map that illustrates the geologic complexity of the NTS area. A comprehensive list of the stratigraphic units in the NTS area is provided in Plate 1.

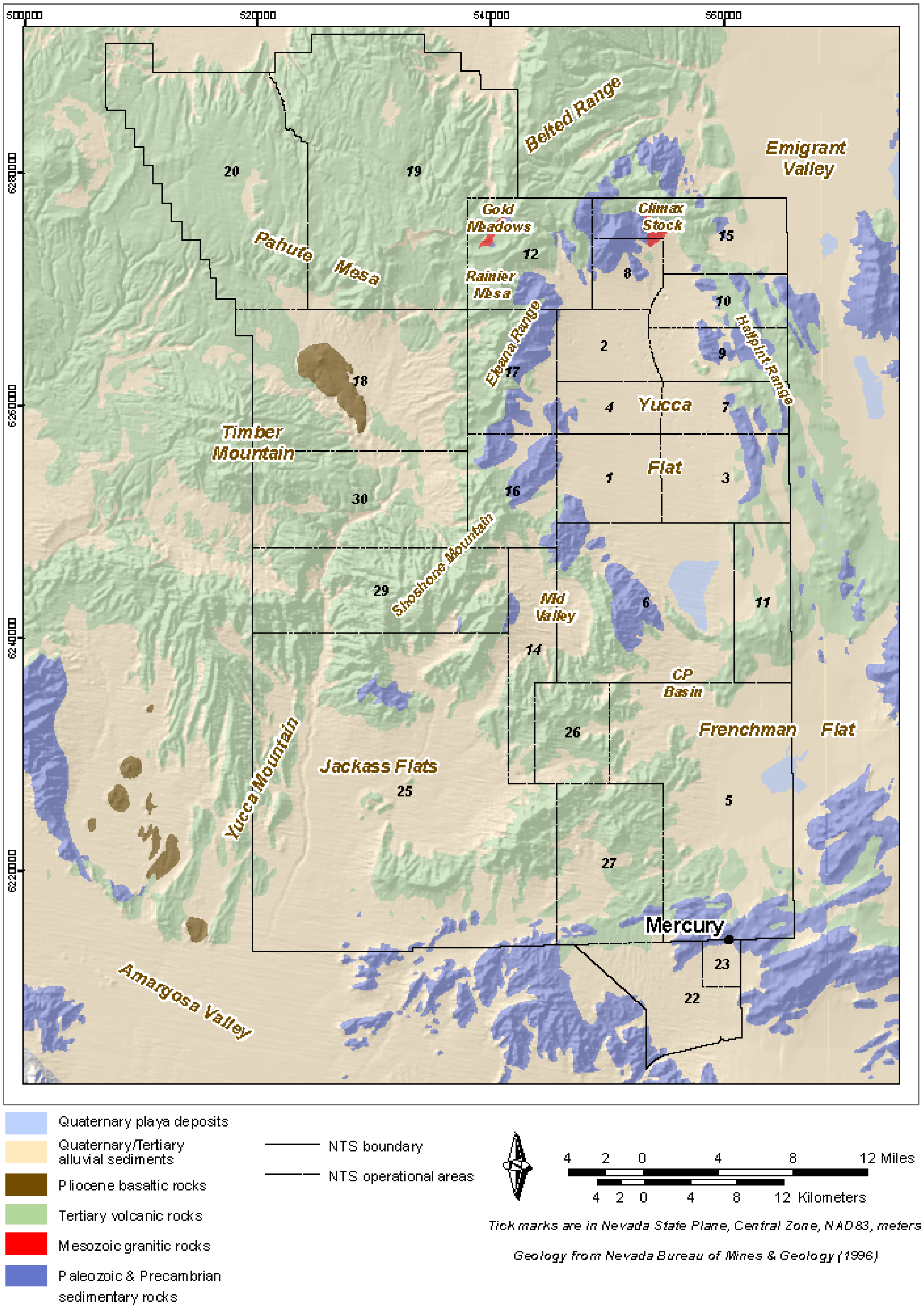

Figure 1-3
Generalized Geologic Map of the Nevada Test Site Area

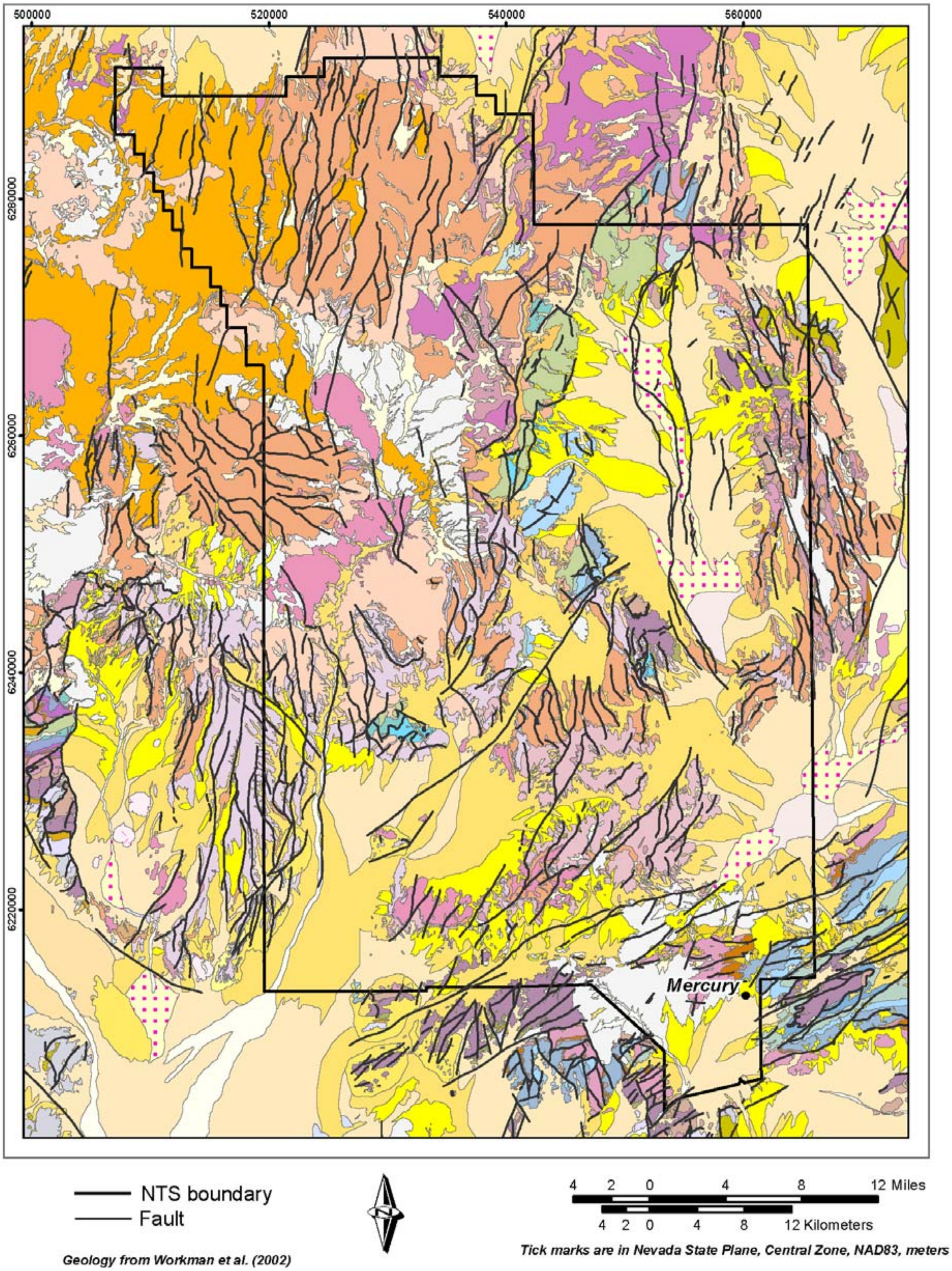

Figure 1-4
Detailed Geologic Compilation Map of the Nevada Test Site Area

1.3 Hydrologic Setting

The hydrologic character of the NTS and vicinity reflects the region's arid climatic conditions and complex geology (D'Agnese et al., 1997). The hydrology of the NTS has been extensively studied for over 50 years (U.S. Department of Energy, Nevada Operations Office [DOE/NV], 1996) and numerous scientific reports and large databases are available to project scientists.

The NTS is located within the southern portion of the Great Basin (Figure 1-2), a hydrographic province characterized by internal drainage of surface water within numerous hydrologically closed topographic basins that are generally related to the basin-and-range style topography of the region (Laczniak et al., 1996). Examples of hydrologically closed basins at the NTS are Yucca Flat and Frenchman Flat. Streams in the region are ephemeral, flowing as runoff in response to precipitation events or snowmelt.

The NTS also lies within the Death Valley regional groundwater flow system, one of the major hydrologic subdivisions of the southern Great Basin (Waddell et al., 1984; Laczniak et al., 1996). The Death Valley regional groundwater flow system is subdivided into groundwater sub-basins, three of which occur within the boundaries of the NTS (Figure 1-5). Recharge areas for the Death Valley groundwater system are the higher mountain ranges of central and southern Nevada, where there can be significant precipitation and snow-melt. Groundwater flow is generally from these upland areas to natural discharge areas in the south and southwest.

Groundwater at the NTS is also derived from underflow from basins up-gradient of the area (Harrill et al., 1988). The direction of groundwater flow is influenced locally by structure, rock type, or other geologic conditions. Existing water-level data (Reiner et al., 1995; IT Corporation [IT], 1996b) and results of modeling groundwater flow (IT, 1996a; D'Agnese et al., 1997) indicate that the general groundwater flow direction within major water-bearing units beneath the NTS is to the south and southwest (Figure 1-5).

The groundwater-bearing rocks at the NTS have been classified into several aquifers and confining units, of which the most important is the lower carbonate aquifer (LCA), a thick sequence of Paleozoic carbonate rock. This unit is present throughout the subsurface of central and southeastern Nevada, and is considered to be a regional aquifer (Winograd and Thordarson, 1975; Laczniak et al., 1996; IT, 1996a).

Groundwater discharge at the NTS is minor, consisting of small springs that drain perched water lenses, and artificial discharge at a limited number of water supply wells. Springs that emanate from local perched groundwater systems are the only natural sources of perennial surface water

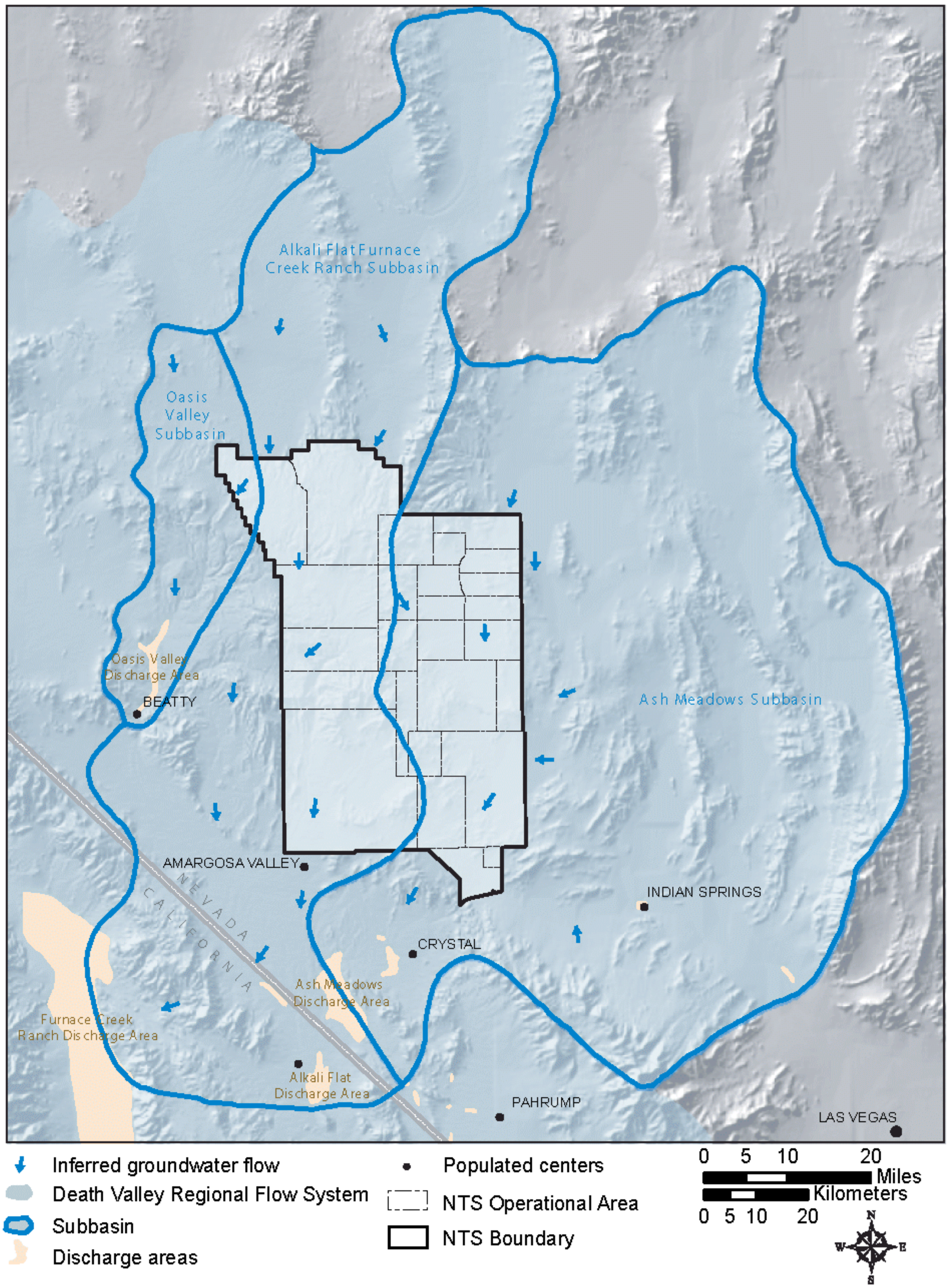

Figure 1-5
Groundwater Sub-Basins of the Nevada Test Site and Vicinity
(Modified from Waddell et al. [1984] and Laczniak et al. [1996]**)**

in the region. Spring discharge rates are low, ranging from 0.014 to 2.2 liters/second (0.22 to 35 gallons/minute) (Hansen et al., 1997). Most water discharged from springs travels only a short distance from the source before evaporating or infiltrating into the ground.

In general, the static water level across the NTS is deep, but measured depths vary depending on the land elevation from which each well was drilled. The depth to groundwater in wells at the NTS varies from about 210 m (690 ft) below the land surface under the Frenchman Flat playa in the southeastern NTS, to more than 610 m (2,000 ft) below the land surface in the northwestern NTS, beneath Pahute Mesa (IT, 1996b; Reiner et al., 1995). Water-level elevations range from 730 m (2,400 ft) at Frenchman Flat to 1,450 m (4,760 ft) on Pahute Mesa. Perched groundwater (isolated lenses of water lying above the regional groundwater level) occurs locally throughout the NTS, mainly within volcanic rocks.

1.4 UGTA Hydrostratigraphic Framework Models

The hydrostratigraphic system forms the foundation of all UGTA CAU-scale HFMs on which flow and transport models are developed. HFMs are computer models that establish and depict the three-dimensional relationships of HSUs and structural features within a CAU model area. The HFMs are constructed using EarthVision® software. Model input data include a digital elevation model of the land surface, elevations of the tops of HSUs based on drill hole intercepts and surface exposures, HSU isopach (i.e., thickness) and unit extent maps, and locations and orientations of faults (BN, 2002; 2005; 2006; NSTec, 2007). Fault data are used to construct a fault-tree model, which effectively subdivides the model area into numerous fault blocks. HSUs are assigned a stratigraphic order, and EarthVision® then "stacks" the HSUs from lowest to highest, according to their ordering within each fault block, using geology-based geometric "rules" that honor the input data within each block, but also consider data from adjacent fault blocks. The resulting 3-D computer model can be rotated in any direction, sliced vertically and horizontally, and individual layers (i.e., HSUs) can be added or removed. This allows for a thorough review and evaluation of the model.

The base HFM is the HFM for a particular CAU that is thought to best represent the subsurface geology. There is one base model per CAU. However, because of the complexity of the geology at the NTS, more than one interpretation of the subsurface geology is possible in some areas. To address non-unique aspects of hydrologically significant interpretations within the base HFMs, alternative HFMs were developed that incorporated different interpretations than those in the base HFMs. This allows for the exploration of how groundwater flow might differ if the alternative HFM is closer to the true configuration of the subsurface geology than the base model. Only those portions of the base model affected by the alternative interpretations were modified to produce an alternative HFM.

The boundaries of all the UGTA CAU-scale model areas, which correspond to the boundaries of the HFMs, are shown in Figure 1-1. Examples of UGTA CAU-scale HFMs are provided in Figures 1-6 and 1-7. Figure 1-6 is a 3-D cut-away view of the Yucca Flat–Climax Mine (YF–CM) HFM (BN, 2006). Figure 1-7 shows a two-dimensional profile through the Pahute Mesa-Oasis Valley (PM-OV) HFM (BN, 2002).

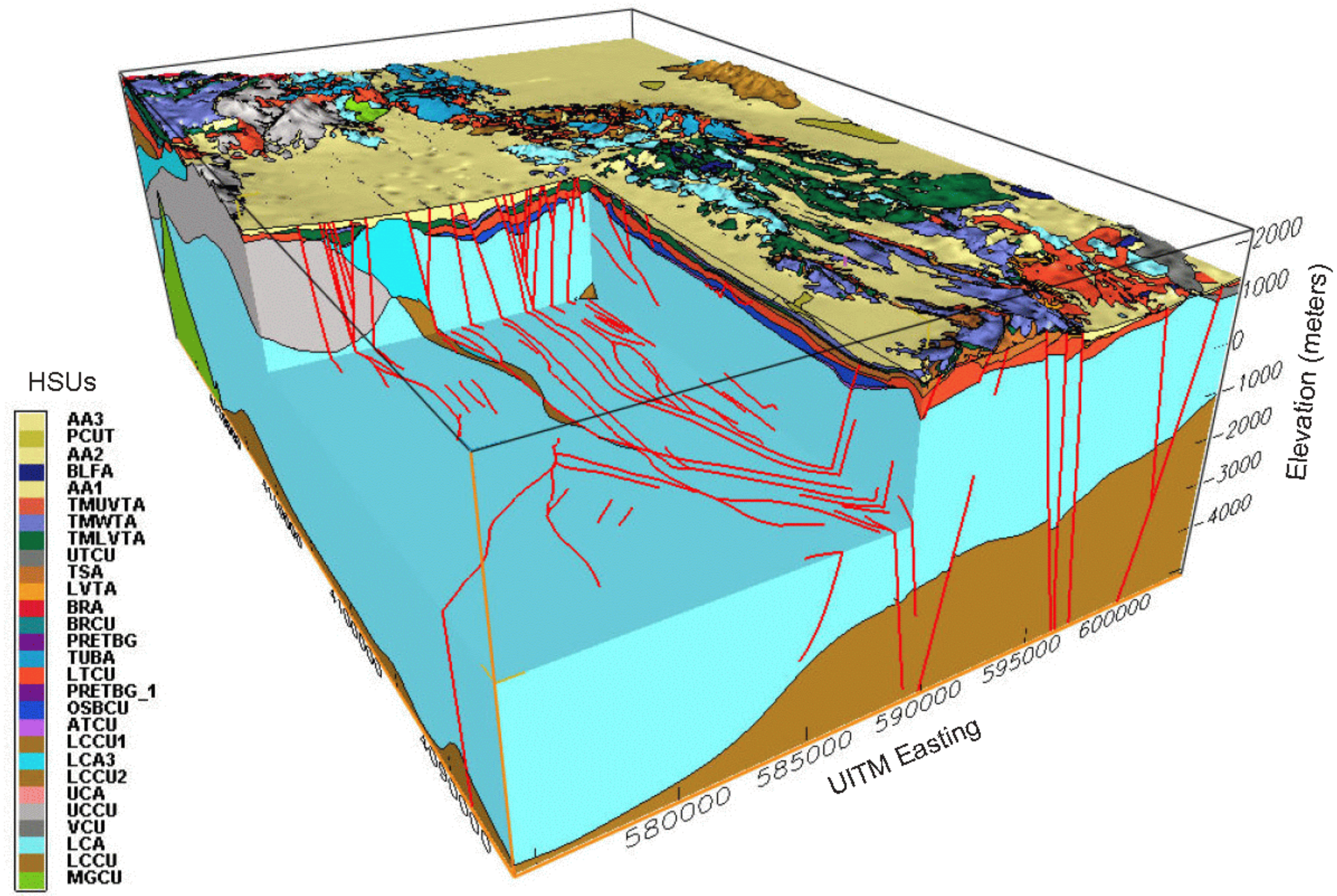

Figure 1-6
Cut-Away View of the Yucca Flat-Climax Mine HFM
(View is to the northeast)

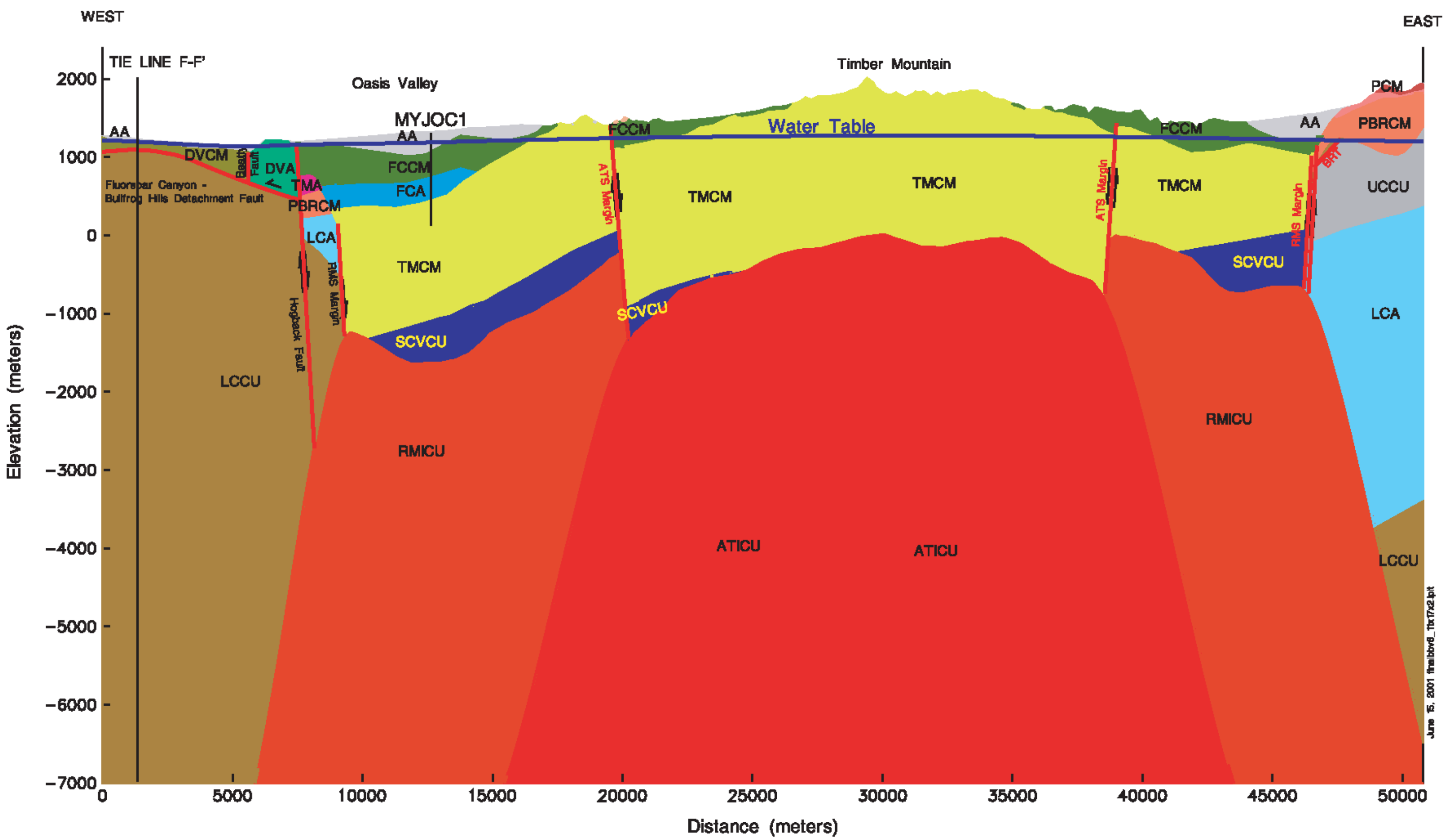

Figure 1-7
West-East Profile through the Pahute Mesa-Oasis Valley HFM (Profile B-B' in BN, 2002)

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2.0 Data Sources

Geoscientists have been working in the NTS area for more than 50 years, and many sources of geologic and hydrologic information and data are available. Specific data sources for the Frenchman Flat area are discussed in BN (2005), for the PM–OV area in BN (2002), for the YF–CM area in BN (2006), and for the Rainier Mesa–Shoshone Mountain (RM–SM) area in NSTec (2007). Typical data sources available for characterization work at the NTS are described in the following subsections. The development of a CAU-scale hydrostratigraphic system in such a complex geologic setting as the NTS region would be impossible without the large body of geologic, geophysical, and hydrologic data now available from both Weapons Testing Program (WTP) and UGTA Sub-Project investigations.

2.1 Geologic Mapping

Geologists working for the U.S. Geological Survey (USGS) have been mapping in the NTS area since the 1950s, and have produced numerous high quality geologic quadrangle maps at a scale of 1:24,000 (Figure 2-1). This early detailed geologic mapping established the basic stratigraphic and structural frameworks that have survived decades of scientific evaluation and are still used today. The geologic quadrangle maps are an extremely valuable resource, and the UGTA Sub-Project is fortunate to have access to such basic, high quality geologic data. Larger scale geologic compilation maps include Frizzell and Shulters (1990), Slate et al. (1999), and Workman et al. (2002).

2.2 Drill Hole Data

More than 4,000 boreholes have been drilled on and around the NTS for various purposes (Figure 2-2), including water production and monitoring wells, emplacement holes and post-shot holes for underground nuclear tests, exploratory holes, and holes for underground instrumentation (Raytheon Services Nevada, 1990). In addition to typical stratigraphic and lithologic information, data from geophysical logs, geologic samples, and hydrologic testing in the boreholes have added information about the character of the geologic units penetrated. Most of these data have been compiled, analyzed, and organized into databases (Warren et al., 2003; BN, 2002; Drellack and Thompson, 1990; Wagoner and Richardson, 1986; and various unpublished BN, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory databases; see references in Section 5.0). During development of the UGTA Phase I regional model, some of these data were compiled, analyzed, and organized into databases for import into modeling software applications (circa 1996). For the CAU-scale modeling

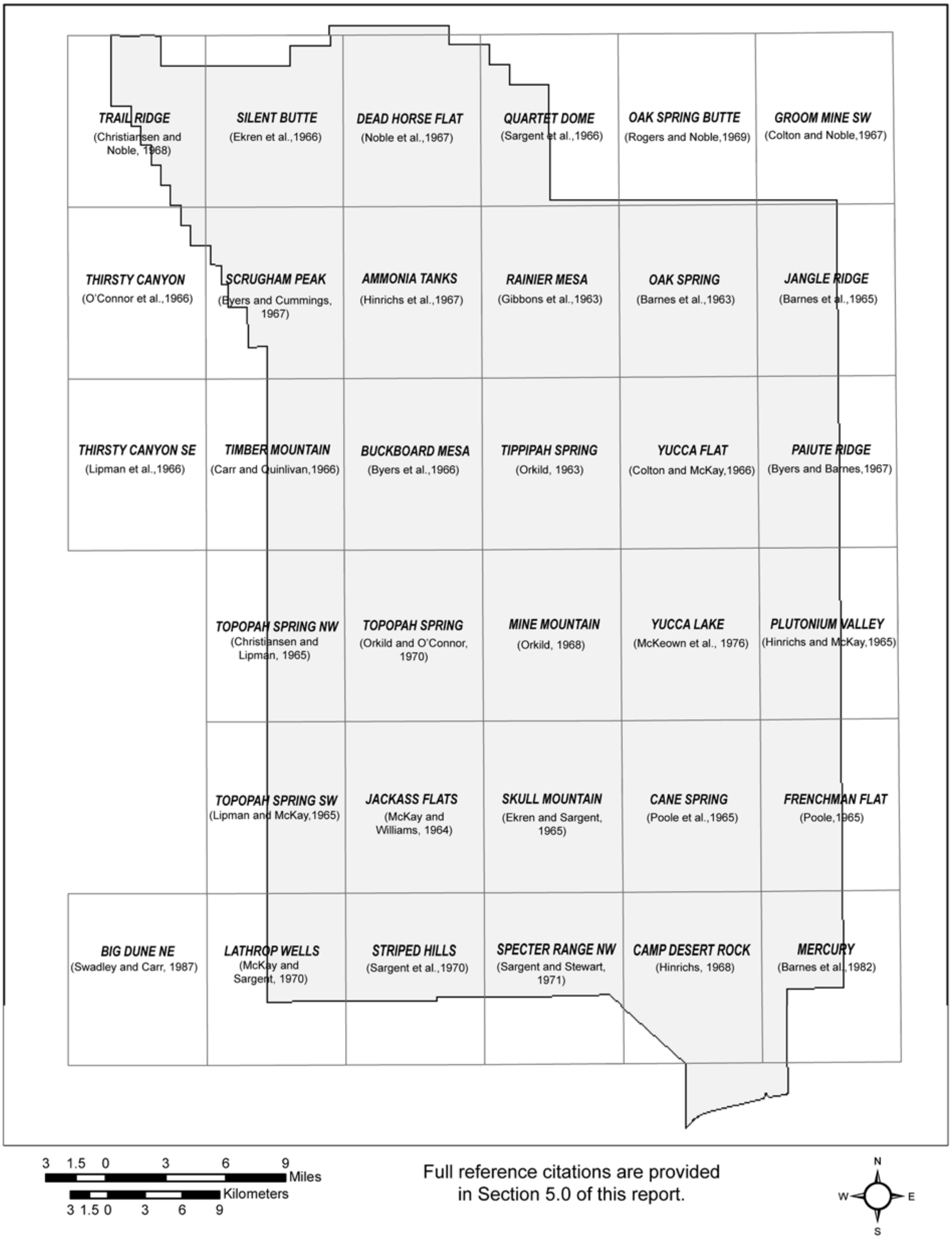


Figure 2-1
Locations of Geologic Quadrangle Maps Covering the Nevada Test Site Area

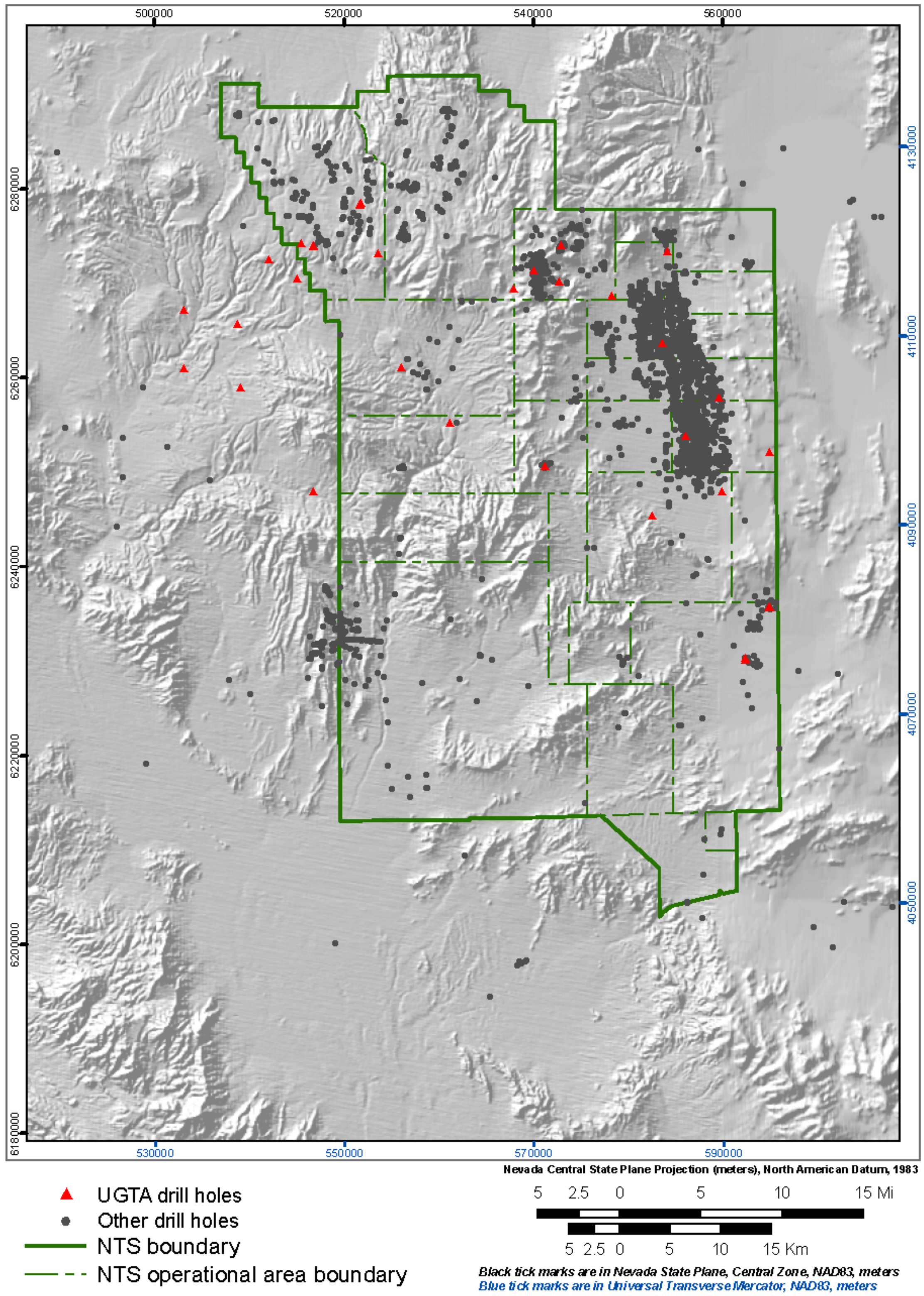


Figure 2-2
Distribution of Boreholes on the Nevada Test Site and Surrounding Areas That Have Been Drilled or Utilized by DOE Activities

initiatives, a much more intensive data compilation and evaluation effort was implemented (BN, 2002; 2005; 2006; NSTec, 2007). Boreholes providing input for the CAU-scale models are listed in Appendix A of the respective HFM documentation reports. The boreholes provide information on the geologic and hydrologic character and distribution of subsurface units.

Although much of the drill-hole information is typically referred to as data, it should be noted that such information, particularly stratigraphic and lithologic information, is produced through a rigorous interpretive process based on an integrated analysis of drill cuttings, rock core, geophysical logs, and nearby surface exposures. Results from laboratory analyses such as petrography, x-ray diffraction, and x-ray fluorescence are also commonly integrated into the stratigraphic interpretation.

2.3 Tunnel Data

Six large and several smaller tunnel complexes were constructed at Rainier Mesa for underground nuclear testing, starting in the 1950s and continuing through the early 1990s, when the current nuclear testing moratorium began (Figure 2-3). In addition, the U16a Tunnel complex at Tippipah Point in NTS Area 16 was also used to conduct similar tests in the 1960s and early 1970s (Figure 2-4). Tunnel complexes were also constructed for nuclear tests in granite in Area 15.

Most of these tunnel complexes have in common a history of intense geologic study. For most tunnel tests, extensive geologic, geomechanical, and geophysical studies were made of the test bed to support engineering design, containment design, and containment evaluation. Expanded summaries for each of the main tunnel complexes in Areas 12 and 16 are provided in NSTec (2007).

2.4 Geophysical Investigations

Numerous geophysical investigations have been conducted at the NTS since the 1950s and include gravity, magnetic, resistivity, and seismic. Most of the geophysical surveys were conducted in active testing areas such as Yucca Flat and Rainier Mesa in support of the WTP. Many of the geophysical surveys were designed to address very specific and local geological issues related to a specific underground test and thus are of limited use in constructing CAU-scale HFMs. These data include mainly tunnel and borehole velocity, gravity, and resistivity measurements (Carroll, 1986; 1990; 1994; Carroll and Kibler, 1983; Kososki et al., 1978; Hearst and Burkhard, 1989). More recent geophysical data were collected specifically for the UGTA

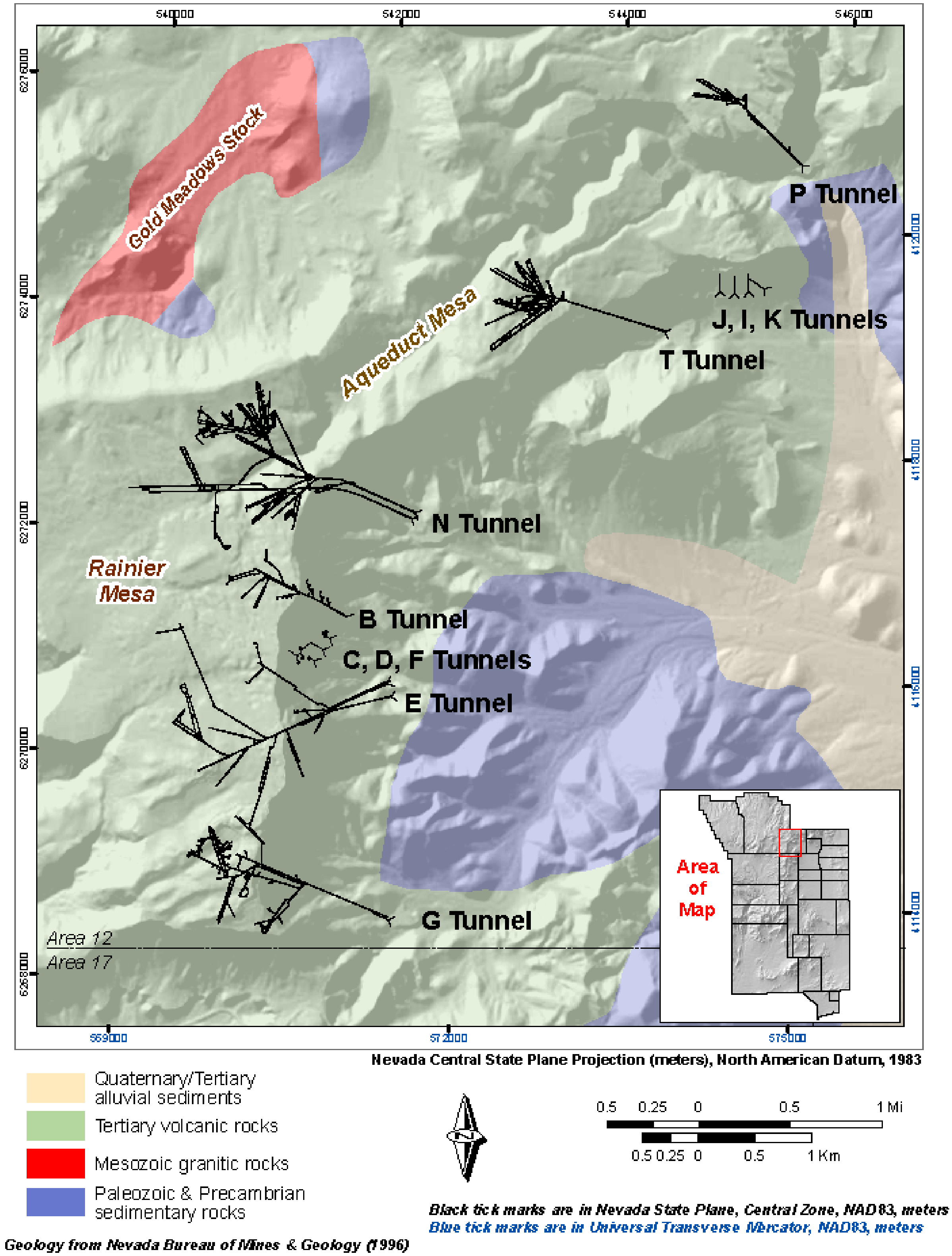


Figure 2-3
Generalized Geologic Map of the Rainier Mesa Area Showing Locations of Area 12 Tunnel Complexes in which Nuclear Tests were Conducted

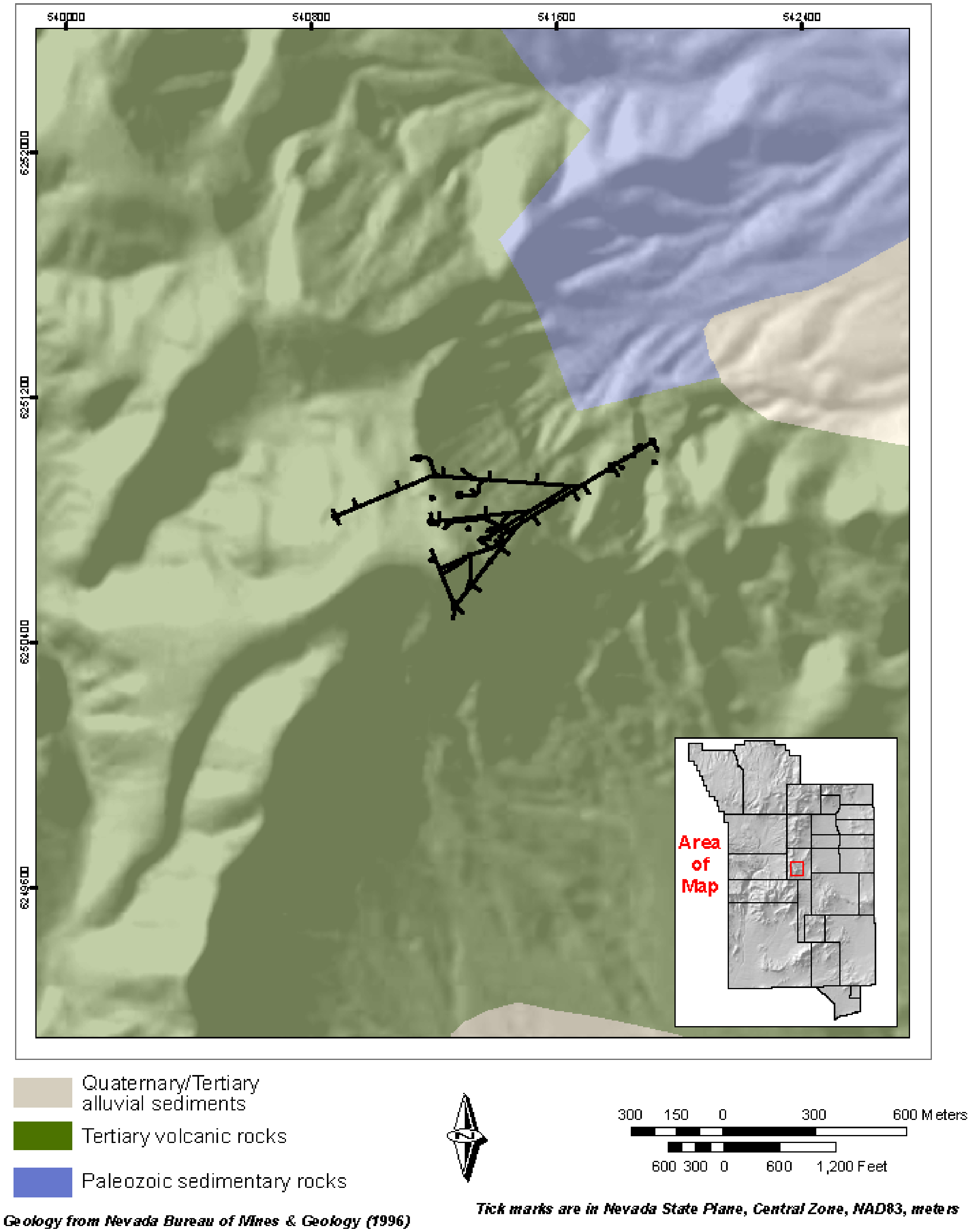


Figure 2-4
Generalized Geologic Map of the Shoshone Mountain Area Showing Location of the U16a Tunnel Complex

modeling efforts. Information from geophysical investigations was integrated with surface geology and drill hole data to help in the interpretation of the distribution of HSUs and develop structural models. Some of the geophysical methods and studies considered during the construction of UGTA HFMs are itemized below.

A. The collection and analysis of **gravity data** have been an integral part of geologic investigations at the NTS since the early 1960s (McCafferty and Grauch, 1997; Grauch et al., 1997; Healey et al., 1987; Jachens and Moring, 1990; Ponce et al., 1988; Ponce et al., 1999). Gravity data have been used to help define basin architecture, locate buried faults, and estimate depth to pre-Tertiary rocks buried by volcanic rocks and alluvium. Gravity data played a critical role in the recognition and characterization of buried calderas such as the Silent Canyon caldera complex (Healey, 1968) and, more recently, the Redrock Valley caldera (NSTec, 2007).

B. **Ground magnetic surveys** were conducted during special geologic and geophysical studies within the former testing areas of Yucca Flat, Pahute Mesa, and Rainier Mesa, mainly in support of the WTP (Bath et al., 1983; Orkild et al., 1983). The surveys were typically used to identify buried faults by determining the configuration of the near-surface volcanic rocks. Other ground magnetic surveys were conducted in support of individual underground tests, for example, to help locate faults in areas with thin alluvial cover.

C. Numerous **aeromagnetic surveys** and related investigations have been conducted at the NTS in the past several decades mainly in support of the WTP (Kirchoff-Stein et al., 1989; McCafferty and Grauch, 1997; Ponce, 1999). Aeromagnetic data were used to help define the subsurface shape of the Climax and Gold Meadows granitic stocks (Bath et al., 1983; Phelps et al., 2004). Aeromagnetic data have also been used at the NTS to delineate buried structures by identifying linear magnetic anomalies within buried volcanic rocks. However, subsurface structural interpretations of aeromagnetic data at the NTS are generally poorly constrained due mostly to the great thickness of alluvium within the basins, and the presence of both normally and reversely magnetized volcanic units (e.g., the Ammonia Tanks and Rainier Mesa tuffs).

D. Since 2003, the USGS has been conducting natural-source **magnetotelluric (MT) surveys** for the UGTA Sub-Project to better constrain pre-Tertiary stratigraphy and structures buried beneath thick sequences of alluvium and volcanic rocks. MT data from Yucca Flat proved particularly useful in constraining the extent and thickness of the upper clastic confining unit (UCCU) HSU beneath the basin (BN, 2006; Asch et al., 2006). This improved stratigraphic understanding led to a revised and better constrained structural model of the pre-Tertiary rocks beneath Yucca Flat.

E. **Half-refraction surveys** were conducted in Yucca Flat for the WTP in an attempt to map the pre-Tertiary surface near selected test locations (App, 1983). Seismic refraction surveys were conducted in many drifts and boreholes in the Rainier Mesa and Shoshone Mountain tunnel complexes, primarily for determination of the velocity of the medium as input to ground shock calculations for underground explosions (Carroll, 1986; 1994; Carroll and Kibler, 1983). Data from some of these surveys were also used to characterize regions of damage following underground tests (Carroll, 1983).

F. **Two-dimensional seismic reflection surveys** have been conducted in two portions of the RM–SM model area. In Yucca Flat, approximately 225 kilometers (140 miles) of two-dimensional seismic surveys have been conducted. Most of these data were acquired between 1970 and 1985 in support of the WTP at the NTS (App, 1983; Burkhard, 1983). A seismic survey consisting of three lines was conducted in Mid Valley (McArthur and Burkhard, 1986) to evaluate the area for underground nuclear testing. Seismic reflection surveys in Yucca Flat and Mid Valley were successful in imaging the general geology above the pre-Tertiary surface, including the contact between the alluvium and underlying volcanic rocks, the distribution of welded volcanic rocks, and the major faults that offset these units. Due to a variety of geologic and geophysical factors, the seismic reflection method has been mostly unsuccessful in imaging pre-Tertiary stratigraphy and structure beneath basins at the NTS (Burkhard, 1983).

G. A high resolution **3-D seismic reflection survey** was conducted in Frenchman Flat in 2001. The purpose of the survey was to better constrain structural interpretations and distributions of HSUs beneath the underground nuclear testing areas in Frenchman Flat. This endeavor was quite successful and contributed substantially to the constructions of the Phase II Frenchman Flat HFM (BN, 2005).

3.0 The UGTA CAU-Scale Hydrostratigraphic System

Maxey (1964) was the first to propose that a category of HSUs be formally recognized so that "geohydrologic" units, such as aquifers and confining units, could be clearly set apart from other rock groupings such as lithologic and rock-stratigraphic units, as well as to clarify usage in hydrogeologic applications. Maxey (1964) proposed that HSUs be defined as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system." Although recognizing that some of the same criteria (e.g., lithology) used to define rock-stratigraphic units are still "basic factors" in defining HSUs, a set of different parameters was necessary for HSU designation. These included geology-related parameters such as the distribution and characteristics of primary and secondary porosity and permeability, as well as parameters related to the dynamics of the hydrological regime such as movement, storage, and release of water, and water-well construction methods and locations.

Seaber (1988) argued that parameters related to the dynamics of the hydrologic regime are not material properties, and that inclusion of such parameters in the definition of HSUs severely reduces the regional applicability of such a categorical system. Consequently, Seaber (1988) proposed a redefinition of an HSU based on the characteristics of a rock's interstices, and defined an HSU as "a body of rock distinguished and characterized by its porosity and permeability." The stated purpose of Seaber (1988) was to "promote uniform and unambiguous methods to be used in partitioning any type of body of rock into hydrostratigraphic units, based on their inherent, mappable porosity and permeability." Like rock-stratigraphic units, HSUs should be recognizable, mappable, traceable, and reproducible.

The UGTA CAU-scale hydrostratigraphic classification system includes hydrostratigraphic concepts consistent with portions of both Maxey (1964) and Seaber (1988), and is built using the abundant geologic and hydrologic data available for the NTS region. Consistent with the proposal of Seaber (1988), the UGTA CAU-scale hydrostratigraphic system organizes volumes of rock into HSUs based mainly on the nature of their porosity and permeability. However, 3-D model development requires that rock- and time-stratigraphic information and concepts be carefully integrated into the system, as recognized by Maxey (1964), to assure that HSUs correctly correlate throughout the various HFMs.

As mentioned previously, the construction of UGTA CAU-scale HFMs required a hydrostratigraphic classification system that consistently defines the lateral and vertical distributions of HSUs within a very complex geologic setting. To achieve this requirement, the

UGTA CAU-scale hydrostratigraphic system uses a two-level classification scheme, in which hydrogeologic units (HGUs) are organized into HSUs that form the unit volumes, or layers, within the HFMs.

3.1 Hydrogeologic Units

The hydrogeologic framework established by Winograd and Thordarson (1975) delineated the various aquifers and aquitards within the NTS region. Like most post-1975 hydrologic studies in the NTS vicinity (e.g., Laczniak et al., 1996), the UGTA CAU-scale hydrostratigraphic system uses most of the aquifer and aquitard designations of Winograd and Thordarson (1975). The UGTA CAU hydrostratigraphic system, however, follows Maxey (1964), USGS (1991), and, Laczniak et al. (1996), and uses the term "confining unit" for all non-aquifer rocks, including aquitards.

Within the UGTA CAU-scale hydrostratigraphic system, HGUs categorize aquifers and confining units according to the nature of their porosity and permeability; thus, the UGTA HFMs follow Seaber's (1988) proposed definition of an HSU. Rocks in the model area are classified as one of ten HGUs based on the rock's ability to transmit groundwater (Table 3-1), which is mainly a function of the rock's primary lithology, type and degree of post-depositional alteration, and propensity to fracture (Winograd and Thordarson, 1975; BN, 2002; 2005; 2006; NSTec, 2007).

The most important factor affecting how groundwater flows through a body of rock is the rock's original primary lithology, which exerts a strong influence on the other two important processes, post-depositional alteration and fracturing. Hard, dense, rigid rocks such as welded ash-flow tuff, the interior portion of lava, and carbonate generally have low matrix porosity and permeability, but tend to fracture readily in response to tectonic forces and, as in the case of welded tuffs and lavas, also as a result of contraction during cooling. In addition, the low primary porosity and matrix permeability of these rocks tend to inhibit significant secondary alteration, such as zeolitization and argillization, which typically changes the hydrologic character of the rocks. These rocks are considered aquifers and have been shown to be prolific water producers at the NTS.

Less dense rocks, such as alluvium and bedded and nonwelded tuff, typically do not support extensive fracture systems and thus usually have low fracture-related permeability. However, some low density rocks, such as nonwelded tuff and alluvium, can have relatively high matrix

Table 3-1
Hydrogeologic Units of the Nevada Test Site
(Adapted from Winograd and Thordarson [1975]; IT [1996a]; and Laczniak et al. [1996])

Hydrogeologic Unit	Typical Lithologies	Hydrologic Significance
Alluvial aquifer (AA) (AA is also an HSU)	Unconsolidated to partially consolidated gravelly sand, eolian sand, and colluvium	Has characteristics of a highly conductive aquifer, but less so where lenses of clay-rich paleocolluvium or zeolitic alteration are present.
Welded-tuff aquifer (WTA)	Welded ash-flow tuff; vitric to devitrified	Degree of welding greatly affects interstitial porosity (i.e., less porosity as degree of welding increases) and permeability (i.e., greater fracture permeability as degree of welding increases).
Vitric-tuff aquifer (VTA)	Bedded tuff; ash-fall and reworked tuff; vitric	Constitutes a volumetrically minor HGU. Generally does not extend far below the static water level due to tendency of tuff to become zeolitic under saturated conditions, which drastically reduces permeability. Significant interstitial porosity (i.e., 20 to 40 percent). Generally insignificant fracture permeability.
Lava-flow aquifer (LFA)	Rhyolite, basalt and dacite lava flows; includes flow breccia (commonly at base)	Generally occurs as small, moderately thick (rhyolite) to thin (basalt) local flows. Hydrologically complex, showing a wide range of transmissivity values. Fracture density and interstitial porosity differ with lithologic variations.
Playa confining unit (PCU)	Silt and clay	Near-surface confining unit at Yucca and Frenchman Lakes and within lower portion of alluvial section in the deepest portions of Frenchman Flat.
Tuff confining unit (TCU)	Zeolitic bedded tuff with interbedded, but less significant, zeolitic, nonwelded to partially welded ash-flow tuff	May be saturated but measured transmissivity values are very low. May cause semi-perched conditions.
Intra-caldera intrusive confining unit (IICU)	Highly altered, highly injected/intruded country rock and granitic material	Assumed to be impermeable. Conceptually underlies each of the calderas in the southwest Nevada volcanic field. Developed for the PM–OV model to designate basement beneath calderas as different from basement outside calderas.
Granite confining unit (GCU)	Quartz monzonite	Saturated at depth but because of low intergranular porosity and permeability, plus the lack of inter-connecting fractures, is considered a confining unit.
Clastic confining unit (CCU)	Argillite, siltstone, quartzite	Siliciclastic rocks are relatively impermeable; coarser-grained siliciclastic rocks are fractured, but with fracture porosity generally sealed due to secondary mineralization.
Carbonate aquifer (CA)	Dolomite, limestone	Transmissivity values differ greatly and are directly dependent on fracture frequency.

porosity and permeability, and these units are also considered aquifers where they are unaltered. The high matrix porosity and permeability of these rocks, particularly glassy nonwelded tuffs, make them susceptible to post-depositional alteration processes such as zeolitization, which can significantly reduce the permeability of altered rocks. Nonwelded tuff units that have undergone zeolitic or argillic alteration are considered confining units because of their very low permeability and generally poorly fractured character.

The UGTA CAU-scale hydrostratigraphic system differs in nomenclature from most of the previous, more regional studies and framework models (e.g., Winograd and Thordarson, 1975; Laczniak et al., 1996; and Belcher, 2004), which designated their main mapping/modeling units as HGUs. In the UGTA CAU-scale HFMs, the main modeling units are called HSUs, and HGUs are components of HSUs. Because lithologic composition typically exerts such a strong influence on a rock's porosity and permeability attributes, the UGTA CAU-scale hydrostratigraphic system, like those of Winograd and Thordarson (1975) and Laczniak et al. (1996), uses lithologic modifiers to designate HGUs.

3.1.1 Alluvial HGUs

Within the NTS area, alluvial deposits include two HGUs. The alluvial aquifer (AA; also an HSU) consists mainly of gravelly sand and sandy gravel eroded from the surrounding mountains during basin development, and deposited on alluvial fans by debris flow and sheet-flood processes (Figure 3-1). Similar deposits that filled the low moat area of the Timber Mountain caldera complex are also included in this HGU. Based on water production records from several water wells completed within the alluvial sediments at the NTS (e.g., Water Wells WW5c, WW5b,WWUE5c [Gillespie et al., 1996]), the AA is typically a fairly good aquifer.

Another HGU that is commonly associated with alluvial deposits is the playa confining unit (PCU). The PCU consists of silt and clay deposited in playa lakes that occupy the modern topographic low points of Yucca and Frenchman Flat (Figure 3-2). Older PCU deposits occur within the lower portions of the alluvial section beneath Frenchman Flat (BN, 2005).

3.1.2 Volcanic HGUs

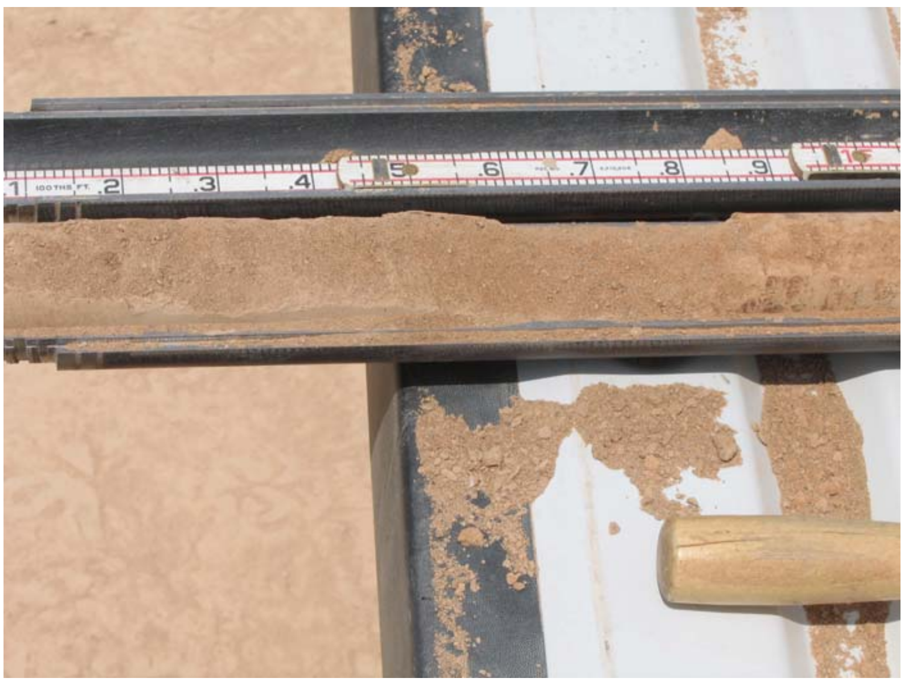
The volcanic rocks within the NTS and vicinity are categorized into four HGUs based on primary lithologic properties, degree of fracturing, and secondary mineral alteration. In general, the altered volcanic rocks, which are typically zeolitized and support few fractures (Prothro, 2008), act as tuff confining units (TCUs) (Figure 3-3), and the unaltered rocks form aquifers. The aquifer units are further divided into welded-tuff aquifers (WTAs) and vitric-tuff aquifers

A. View of a mined face. (Red arc is approximately 3.3 m [10 ft] across at widest point.)

B. Closer view of alluvium (Jackleg drill is approximately 2.1 m [7 ft] long.)

Figure 3-1
Photographs of Alluvium from the U1a Complex

A. Geophysical Logging Truck on Yucca Lake Playa



B. Playa Material Obtained During Drilling on the Yucca Lake Playa

Figure 3-2
Photographs of Yucca Lake Playa

Figure 3-3
Exposure of Tuff Confining Unit Rocks in Area 12 (Tuff of Tolicha Peak)

(VTAs) (depending on degree of welding) and lava-flow aquifers (LFAs) (Figures 3-4, 3-5, and 3-6). Denser rocks, such as welded ash-flow tuff and lava flows, tend to fracture more readily and, therefore, have relatively high permeability (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Laczniak et al., 1996; IT, 1996a; Prothro and Drellack, 1997).

An additional igneous HGU, designated as the intra-caldera intrusive confining unit (IICU) was initially defined for the PM-OV model (BN, 2002). Conceptually, an IICU underlies each of the calderas in the southwest Nevada volcanic field. Although modeled as single intrusive masses, the exact nature of the rocks beneath the calderas is unknown, as no drill holes penetrate these rocks. It is assumed that these rocks range from highly altered, highly injected or intruded country rock to granite. The IICUs are considered to behave as confining units due to low primary porosity and low permeability where measured at other localities (such as in the granitic rocks of Climax stock [Walker, 1962]). Most fractures are probably filled with secondary minerals. The Climax stock in extreme northern Yucca Flat (Houser et al., 1961; Walker, 1962; Maldonado, 1977) and the Gold Meadows stock just north of Rainier Mesa (Snyder, 1977) may serve as analogs to the IICUs, though the effects of the greater depth of the IICUs cannot be addressed by these analogs.

3.1.3 Pre-Tertiary HGUs

The hydrogeology of the pre-Tertiary sedimentary rocks at the NTS follows the framework developed by Winograd and Thordarson (1975), which was used in the Phase I regional modeling effort (IT, 1996a; 1996b; 1996c) and subsequent CAU-scale models (BN, 2002; 2005; 2006; NSTec, 2007). Within the UGTA model areas, pre-Tertiary rocks are categorized as aquifer or confining unit HGUs based on lithology. The siliciclastic rocks, such as quartzite, siltstone, and shale, are classified as clastic confining units (Figure 3-7). The granitic intrusive rocks are classified as confining units (Figure 3-8). Carbonate rocks, such as limestone and dolomite, are classified as carbonate aquifers (Figure 3-9).

3.2 Hydrostratigraphic Units

The highest level within the UGTA CAU-scale hydrostratigraphic system is the HSU. HSUs are the main modeling unit within UGTA CAU-scale HFMs, and serve as 3-D bodies that are represented in the finite element mesh for the UGTA groundwater modeling process (IT, 1996d). HSUs are defined systematically by stratigraphically organizing HGUs of similar character into the larger HSU designations. HSUs typically consist of a single HGU (e.g., 100 percent TCU). However, some HSUs may consist of several HGUs, but are defined so that a single general type of HGU dominates (e.g., mostly WTA with minor VTA). In some places, thick stratigraphic intervals representing substantial volumes of rock contain a poorly understood distribution of differing HGUs (e.g., LFA and TCU). These large intervals with uncertain distributions of

Figure 3-4
Exposure of Welded-Tuff Aquifer in Area 16 (Redrock Valley Tuff)

Figure 3-5
Exposure of Vitric-Tuff Aquifer in Area 19 (Calico Hills Formation)

Figure 3-6
Close-up View of Lava-Flow Aquifer in Area 20 (rhyolite of Benham)
(Note contorted flow-banding [red arrow])

Figure 3-7
Exposure of Clastic Confining Unit in Area 16 (Eleana Formation/Chainman Shale)

Scale is in inches.
Core was moistened to better reveal details.

Figure 3-8
Photograph of Drill Core of Granite Confining Unit (Cretaceous Quartz Monzonite)

Figure 3-9
Exposure of Carbonate Aquifer in the Halfpint Range, Area 3 (Nopah Formation)

HGUs are called composite unit (CM) HSUs, and were originally developed as part of the PM–OV HFM (BN, 2002). This CM designation is similar to that of Maxey (1964) who recognized rock volumes that are a combination of aquifers and confining units. A more detailed discussion of CMs is provided in Section 3.2.2.5.

Currently, the UGTA CAU-scale hydrostratigraphic system consists of 76 HSUs, which are listed and described in Appendix A. Several additional HSUs were delineated for alternative models only. Because of the complex geologic setting of the NTS region, particularly the presence of dramatically different geologic domains (e.g., calderas and extensional basins), the cumulative number of HSUs has necessarily increased as each new CAU HFM was developed. However, the process used to develop and define HSUs for each HFM area has remained the same, resulting in a hydrostratigraphic system that maintains its integrity and is internally consistent without regard to model area. Table 3-2 shows the correlation of HSUs for the four CAU-scale HFMs. The information in Table 3-2 is also provided in graphical form in Plate 2.

Because the UGTA CAU-scale hydrostratigraphic system organizes rock units into HSUs according to the nature of a rock's porosity and permeability, the system and component HSUs are readily adaptable to groundwater flow models. However, radioactive contaminant transport modeling is also an important part of UGTA modeling efforts. Fortunately, HSUs are also adaptable to contaminant transport models.

An important aspect of UGTA transport models is the affinity of certain radionuclides to sorb onto specific minerals in the rocks (Tompson et al., 1999; Pawloski et al., 2000; Zavarin et al., 2004). These "reactive" minerals include clays, zeolites, hematite, carbonate, and certain mafic minerals such as biotite. Because mineralogic composition is a basic component of lithologic and stratigraphic designations and assignments, the hydrostratigraphic system can form the basis for developing reactive mineral models for transport modeling.

The volcanic rocks at the NTS are particularly conducive to development of reactive mineral models from HSUs. The presence of alteration minerals such as clays and zeolites is the main geologic characteristic used to distinguish TCUs from volcanic aquifers, which are composed mostly of non-reactive felsic minerals (i.e., WTA and LFA) and unaltered volcanic glass (i.e, VTA). Stratigraphic assignments of volcanic units are based on phenocryst mineralogy, including the amount of biotite present, and most volcanic units at the NTS can be characterized as either mafic-rich or mafic-poor according to their biotite content, which is typically an important attribute of a unit's stratigraphic identity. Carbonate is rarely present in volcanic rocks at the NTS, and occurs mainly within pre-Tertiary limestone and dolomite units where it

Table 3-2
Correlation of Hydrostratigraphic Units Among the Four UGTA HFMs at the Nevada Test Site

Hydrostratigraphic Unit	RM-SM Model [1, 2]	YF-CM Model [1, 3]	Phase II FF Model [1, 4]	PM-OV Model [1, 5]	DVRFM [1, 6]	UGTA Phase 1 [1,7]
Alluvial aquifer	AA	AA2, AA1 [8]	AA3, AA2, AA1 [7]	AA	YAA	AA [9]
Playa confining unit	NP [10]	PCU	PCU2T	NP	YACU	ND, AA
Basalt lava-flow aquifer		BLFA	BLFA	YVCM	LFU	
Older altered alluvial aquifer		NP	OAA, OAA1 [8]	NP	ND [12]	
Older playa confining unit			PCU1U, PCU1L [7]			
Younger volcanic composite unit		NP (BLFA) [14]	NP (BLFA)	YVCM	YVU	VU
Thirsty Canyon volcanic aquifer		NP	NP	TCVA	TMVA	TMA, VU
Detached volcanic aquifer				DVA	ND	VU
Detached volcanic composite unit				DVCM		
Fortymile Canyon composite unit	FCCM			FCCM	TMVA	TMA [9], VA [9], TC
Fortymile Canyon aquifer	NP			FCA		VU
Tannenbaum Hill lava-flow aquifer				THLFA		TMA
Tannenbaum Hill composite unit				THCM		
Timber Mountain upper vitric-tuff aquifer	TM-UVTA [11]	TM-UVTA	ND	TMA [8]		TMA, VA, TC
Timber Mountain welded-tuff aquifer	TM-WTA	TM-WTA	TM-WTA			
Timber Mountain lower vitric-tuff aquifer	TM-LVTA	TM-LVTA	TM-LVTA	PVTA	TMVA, PVA	
Fluorspar Canyon confining unit	NP	NP	NP	FCCU	ND (TMVA)	
Windy Wash aquifer				WWA		
Timber Mountain composite unit	TMCM			TMCM	TMVA	
Rainier Mesa breccia confining unit	RMBCU			ND (TMCM)		
Sub-caldera volcanic confining unit	SCVCU			SCVCU	OVU	BCU
Benham aquifer	NP			BA	ND (PVA)	TC
Upper Paintbrush confining unit		NP (LTCU)		UPCU	ND	
Tiva Canyon aquifer	TCA	NP [15] (TSA)		TCA, PCM [16]	PVA	TMA, VA, TC
Paintbrush composite unit	NP	NP		PCM		

Table 3-2
Correlation of Hydrostratigraphic Units Among the Four UGTA HFMs at the Nevada Test Site (continued)

Hydrostratigraphic Unit	RM-SM Model [1, 2]	YF-CM Model [1, 3]	Phase II FF Model [1, 4]	PM-OV Model [1, 5]	DVRFM [1, 6]	UGTA Phase 1 [1,7]
Paintbrush vitric-tuff aquifer	PVTA	NP (TM-LVTA)	TM-LVTA	PVTA	PVA	TMA, VA, TC
Upper tuff confining unit	UTCU	UTCU	UTCU	UPCU, LPCU		
Paintbrush lava-flow aquifer	NP	NP	NP	PLFA		
Lower Paintbrush confining unit	NP (LTCU)	NP (LTCU)	NP (LTCU)	LPCU		
Topopah Spring aquifer	TSA	TSA	TSA	TSA, PCM [15]		
Lower vitric-tuff aquifer	LVTA	LVTA	LVTA	PVTA	CHVA, CHVU	
Calico Hills vitric-tuff aquifer	CHVTA	ND (TM-LVTA, LVTA)	ND (TM-LVTA, LVTA)	CHVTA		TC
Calico Hills vitric composite unit	NP	NP	NP	CHVCM		
Calico Hills zeolitic composite unit				CHZCM		
Calico Hills confining unit	NP (LTCU)	NP (LTCU)	NP (LTCU)	CHCU		
Inlet aquifer	NP	NP	NP	IA		TC, VA
Wahmonie confining unit			WCU	NP	WVU	BCU [9]
Crater Flat composite unit			NP	CFCM	CHVA, CHVU	TC, VU
Crater Flat confining unit	NP (LTCU)	NP (LTCU)	NP (LTCU)	CFCU		
Yucca Mountain Calico Hills lava-flow aquifer	YMCHLFA	NP	NP	ND (YMCFCM)	CHVU	VA, TC, VU
Yucca Mountain Crater Flat composite unit	NP			YMCFCM	ND	
Kearsarge aquifer	KA			KA	CFPPA	
Upper tuff confining unit 2	UTCU2	ND (LTCU or TM-LVTA)	NP (LTCU)	CHCU	CFBCU	
Stockade Wash aquifer	SWA		NP	ND (CFCU, BFCU)		
Lower vitric-tuff aquifer 2	LVTA2			ND		
Bullfrog confining unit	BFCU	ND (LTCU)	UTCU/LTCU	BFCU		TCB
Upper tuff confining unit 1	UTCU1			CFCU, BFCU		

Table 3-2
Correlation of Hydrostratigraphic Units Among the Four UGTA HFMs at the Nevada Test Site (continued)

Hydrostratigraphic Unit	RM-SM Model [1, 2]	YF-CM Model [1, 3]	Phase II FF Model [1, 4]	PM-OV Model [1, 5]	DVRFM [1, 6]	UGTA Phase 1 [1,7]
Belted Range aquifer	BRA	BRA	NP	BRA	BRU	TBA, VA, TC
Lower vitric-tuff aquifer 1	LVTA1	ND (TM-LVTA)	ND (TM-LVTA)	NP		
Pre-Belted Range composite unit	OSBCU	OSBCU	LTCU/LTCU1	PBRCM		BAQ, BCU
Belted Range confining unit	BRCU	BRCU	NP (LTCU)	NP (PBRCM [8])		TBA, VA, TC
Pre-Grouse Canyon Tuff lava flow aquifer	ND (BRA)	PRETBG	NP			
Tub Spring aquifer	TUBA	TUBA		ND (BRA)	OVU [9]	
Pre-Grouse Canyon Tuff lava flow aquifer 1	NP	PRETBG1 [7]		NP (PBRCM [8])		
Lower tuff confining unit	LTCU	LTCU	LTCU, LTCU1 [7]	CFCU, BFCU, PBRCM		VCU, BCU
Oak Spring Butte confining unit	OSBCU	OSBCU [12]		ND (PBRCM [8])		
Redrock Valley aquifer	RVA	ND (OSBCU [12])				
Redrock Valley breccia confining unit	RVBCU	NP	NP			
Lower tuff confining unit 1	LTCU1	ND (LTCU/ OSBCU)	LTCU, LTCU1 [7]			
Twin Peaks aquifer (RM–SM alternative model only)	TPA	NP (OSBCU)	NP	PBRCM		VCU, BCU
Argillic tuff confining unit	ATCU	ATCU	ND (LTCU)	ND (PBRCM)	VSU, OVU	BCU
Volcaniclastic confining unit	NP	VCU	VCU	NP	VSU	
Black Mountain intrusive confining unit		NP	NP	BMICU	ICU	VU
Ammonia Tanks intrusive confining unit	ATICU			ATICU		BCU, TMA
Rainier Mesa intrusive confining unit	RMICU			RMICU		
Claim Canyon intrusive confining unit	NP			CCICU		VA
Calico Hills intrusive confining unit	CHICU			CHICU		BCU, I
Silent Canyon intrusive confining unit	SCICU			SCICU		BCU, LCCU

Table 3-2
Correlation of Hydrostratigraphic Units Among the Four UGTA HFMs at the Nevada Test Site (continued)

<table>
<tr><th>Hydrostratigraphic Unit</th><th>RM-SM Model [1, 2]</th><th>YF-CM Model [1, 3]</th><th>Phase II FF Model [1, 4]</th><th>PM-OV Model [1, 5]</th><th>DVRFM [1, 6]</th><th>UGTA Phase 1 [1,7]</th></tr>
<tr><td>Redrock Valley intrusive confining unit</td><td>RVICU</td><td>NP</td><td rowspan="3">NP</td><td>NP</td><td rowspan="2">ICU</td><td>BCU</td></tr>
<tr><td>Mesozoic granite confining unit</td><td>MGCU</td><td>MGCU</td><td>MGCU</td><td>I</td></tr>
<tr><td>Lower clastic confining unit 1–thrust plate</td><td>LCCU1</td><td>LCCU1</td><td>LCCU1</td><td>LCCU_T1</td><td>NP (LCCU1)</td></tr>
<tr><td>Lower carbonate aquifer-thrust plate</td><td>LCA3</td><td>LCA3</td><td>LCA3</td><td>LCA3</td><td>LCA_T1</td><td>LCA3</td></tr>
<tr><td>Upper clastic confining unit–thrust plate</td><td>UCCU1</td><td>NP</td><td rowspan="4">NP</td><td rowspan="4">NP</td><td rowspan="2">NP</td><td rowspan="3">NP</td></tr>
<tr><td>Lower carbonate aquifer–thrust plate 1 (RM-SM alternative model only)</td><td>LCA3-1</td><td>NP</td></tr>
<tr><td>Lower clastic confining unit 2–thrust plate</td><td>LCCU2</td><td>LCCU2</td><td>LCCU_T1</td></tr>
<tr><td>Upper carbonate aquifer</td><td>UCA</td><td>UCA</td><td>UCA</td><td>LCA3</td></tr>
<tr><td>Upper clastic confining unit</td><td>UCCU</td><td>UCCU</td><td>UCCU</td><td>UCCU</td><td>UCCU</td><td>UCCU</td></tr>
<tr><td>Lower carbonate aquifer</td><td>LCA</td><td>LCA</td><td>LCA</td><td>LCA</td><td>LCA</td><td>LCA</td></tr>
<tr><td>Lower clastic confining unit</td><td>LCCU</td><td>LCCU</td><td>LCCU</td><td>LCCU</td><td>LCCU</td><td>LCCU</td></tr>
</table>

1 If correlative to more than one HSU, all HSUs are listed.
2 See NSTec (2007) for explanation of RM-SM HSU nomenclature.
3 See BN (2006) for explanation of YF-CM model nomenclature.
4 See BN (2005) for explanation of Frenchman Flat HSU nomenclature.
5 See BN (2002) for explanation of PM-OV HSU nomenclature.
6 See Belcher (2004) for explanation of the Death Valley Regional Flow Model.
7 See IT (1996a) for explanation of the UGTA Phase I HSU nomenclature.
8 Subdivisions, though hydrogeologically equivalent, are necessary to satisfy operational requirements of the EarthVision® modeling software.
9 Not subdivided.
10 Not present.
11 Subdivided only in Yucca Flat and Mid Valley.
12 Not differentiated.
13 Subdivided only in areas with sufficient drill hole control.
14 Parentheses implies a less than 1:1 correlation.
15 The welded Tpc (TCA) was lumped with the TSA in Mid Valley in the YF–CM model.
16 Paintbrush units differentiated in the SCCC area, but lumped in the vicinity of Yucca Mountain.

composes the majority of the mineralogy. Thus, it has been relatively easy to create reactive mineral models used in contaminant transport modeling from the previously defined UGTA HSUs (Stoller-Navarro Joint Venture, 2005; 2007; 2008).

3.2.1 Methodology for Delineating Hydrostratigraphic Units

The delineation of HSUs in the NTS region, particularly at the CAU scale, is complicated by the large number of stratigraphic units, great variety of rock types, and complex depositional and structural histories. Fortunately for the UGTA CAU-scale modeling project, the delineation of the various aquifers and confining units (i.e., HGUs) at the NTS was generally established prior to the UGTA Sub-Project by Winograd and Thordarson (1975). Thus, the development of the CAU-scale hydrostratigraphic system began with most of the HGUs already established on which to begin defining and mapping HSUs for HFM construction.

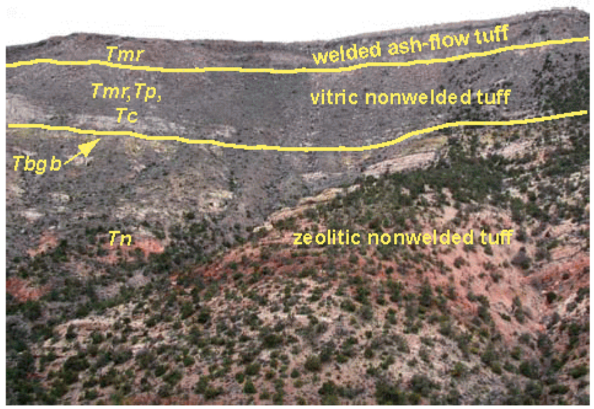
The process for delineating HSUs begins with the collection and review of geologic and geophysical information of a particular area to determine the various rock types present. Using mainly the geologic quadrangle maps and drill hole information, all the rock types are categorized as one of the ten HGUs of the UGTA CAU-scale hydrostratigraphic system (Table 3-1). These are based mainly on each rock type's primary lithology, type and degree of post-depositional alteration, and propensity to fracture, which typically relate directly to the nature of a rock's interstices (i.e., porosity and permeability). For example, all occurrences of welded ash-flow tuff in an area are categorized as WTAs because these brittle rocks typically have relatively low matrix porosity and permeability, but tend to be fractured as a result of cooling and tectonic forces. In contrast, all zeolitic tuffs in the area are categorized as TCU HGUs because the nature of their interstices is rather unique and considerably different from WTAs, consisting of relatively high total porosity but low permeability. TCUs also tend to be poorly fractured.

Once the rocks of an area have been categorized into HGUs, stratigraphic information is used to organize the various HGUs into internally consistent, correlatable, and mappable unit volumes, or HSUs. HSUs are typically designated by a stratigraphic name followed by an HGU category. For example, the Paintbrush vitric-tuff aquifer HSU is composed of vitric (i.e., glassy and unaltered) nonwelded tuffs of the Paintbrush Group stratigraphic unit. Where an HSU includes HGUs of more than one stratigraphic unit, a relative position name is sometimes used in place of a stratigraphic name. The lower tuff confining unit (LTCU), for example, consists of a rather monotonous sequence of zeolitic nonwelded tuffs in the lower portion of the volcanic section that includes numerous stratigraphic units, but which all consist of TCU HGUs. Figure 3-10 illustrates the delineation of HSUs using geologic quadrangle maps. The delineation of HSUs in a drill hole is illustrated in Figure 3-11. Additional examples of the delineation of HSUs in UGTA wells are provided in Appendix B.

The importance of integrating stratigraphic information in the delineation of HSUs cannot be overstated. The complex geologic setting of the NTS region coupled with the higher resolution of CAU-scale HFMs necessitates the careful integration of stratigraphic information to assure that HSUs properly correlate throughout each of the four HFMs. Also, because several HFM areas overlap, it is important that the integration of stratigraphic information was consistently applied during development of each HFM. Plate 2 illustrates the correlation between stratigraphy and hydrostratigraphy for various domains across all four UGTA HFMs. For comparison and correlation to important regional models and studies, Plate 2 also includes correlation columns for the Death Valley Regional Flow Model (Belcher, 2004) and the foundation hydrogeologic work of Winograd and Thordarson (1975). These regional studies applied more general stratigraphic information in delineating their main mapping/modeling units, which they referred to as HGUs. Although appropriate for such regional hydrologic studies, it is insufficient for the smaller-scale CAU models, particularly in such a complex geologic setting.

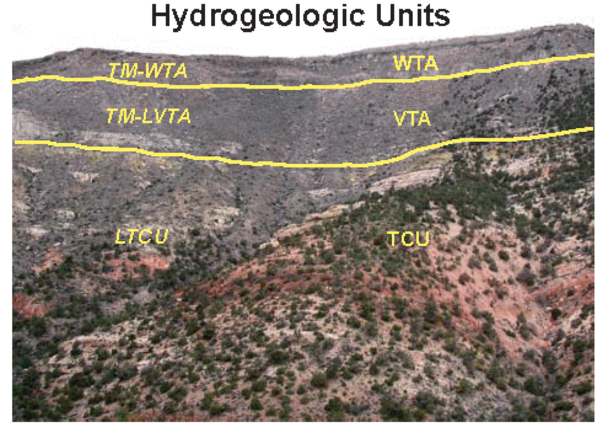
The importance of accurately integrating detailed rock- and time-stratigraphic information into the development of the UGTA CAU-scale hydrostratigraphic system is illustrated in simplified form in Figure 3-12. In the southwestern portion of Pahute Mesa, two WTAs separated by a TCU are present between approximately 1,000 and 1,300 m (3,280 and 4,260 ft) elevation (BN, 2002). The two welded ash-flow tuff units (Tiva Canyon Tuff and Topopah Spring Tuff) that form these two WTAs are very similar in appearance and basic mineralogy. Because ash-flow tuffs typically form extensive sheet-like deposits, these WTAs should form continuous tabular-shaped bodies beneath this portion of Pahute Mesa, unless disrupted by faulting. Thus, it is critical that these two HGUs are correlated to the correct stratigraphic position between the various drill holes in the area so that they can be correctly assigned as separate, mappable HSUs.

Figure 3-12A illustrates the problem of using hydrogeologic information only. As shown here, important questions arise as to the proper relationships between the WTAs encountered in drill holes PM-3 and UE-20c. This is important because the nature of ash-flow tuff geometry suggests that one of the WTAs in UE-20c probably correlates with the WTA in PM-3, thus forming a continuous flow path between the two holes. By integrating stratigraphic information, Stratigraphic and Lithologic Units



View looking west at east face of Rainier Mesa.

Hydrostratigraphic and Hydrogeologic Units

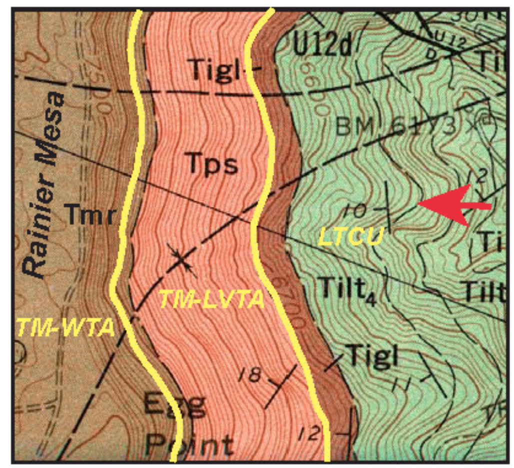


EXPLANATION

Stratigraphic Units	Hydrgeologic Units
Tmr = Rainier Mesa Tuff	WTA = welded-tuff aquifer
Tp = Paintbrush Group	VTA = vitric-tuff aquifer
Tc = Crater Flat Group	TCU = tuff confining unit
Tbgb = bedded Grouse Canyon Tuff	
Tn = Tunnel Formation	

Hydrostratigraphic Units

TM-WTA = Timber Mountain welded-tuff aquifer
TM-LVTA = Timber Mountain lower vitric-tuff aquifer
LTCU = lower tuff confining unit



Portion of Geologic Quadrangle Map (from Gibbons et al., 1963)

Red arrow shows view direction of photographs.
Tps = Tp & Tc; Tigl = Tbg; Tilt$_4$ = Tn

Figure 3-10
Illustration of the Delineation and Mapping of HSUs Based on Surface Exposures and Geologic Quadrangle Maps

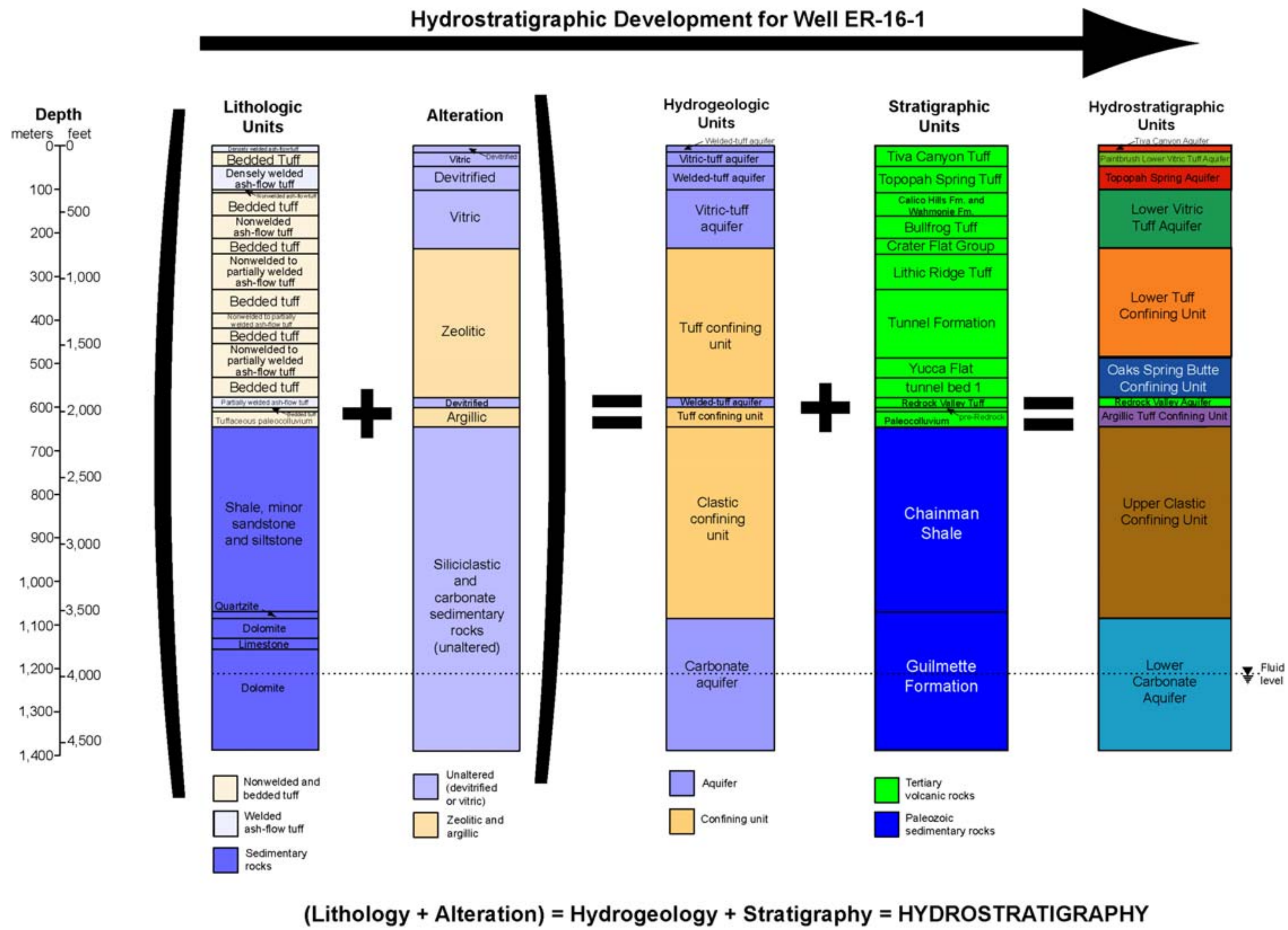
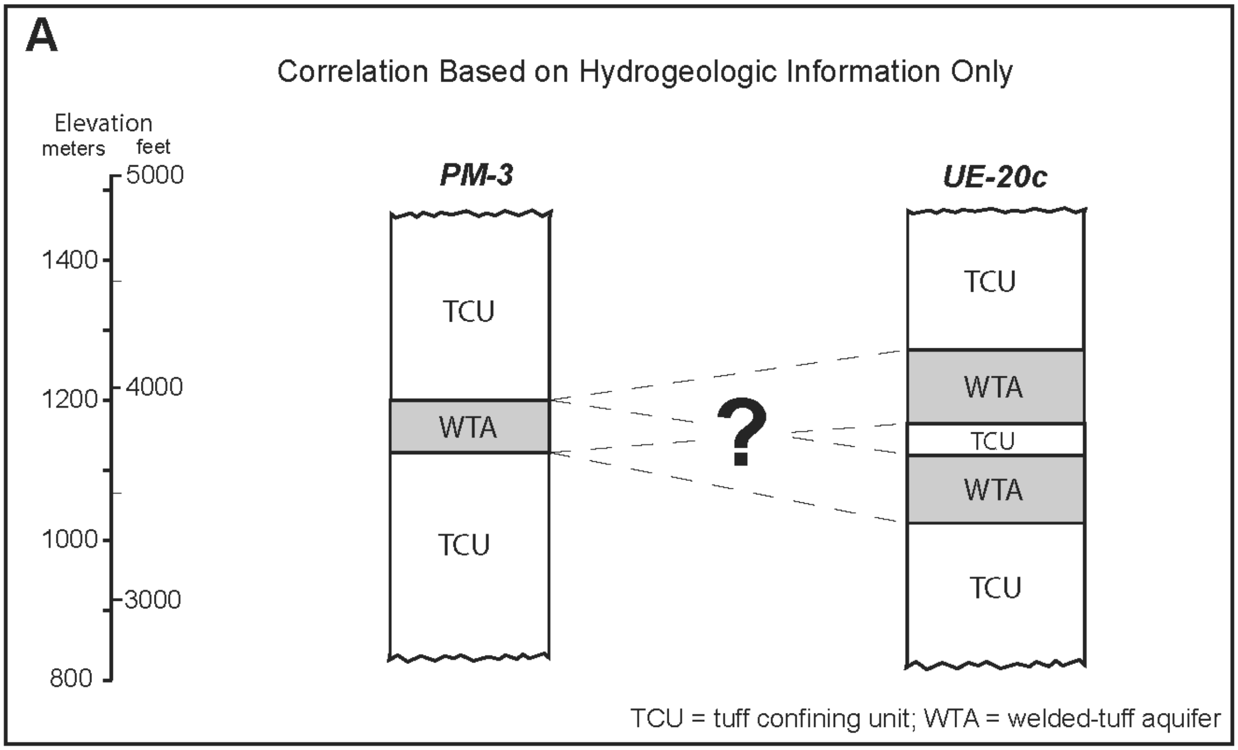


Figure 3-11
Illustration of the Delineation of HSUs Based on Drill Hole Data
(Geology from NNSA/NSO, 2006c)



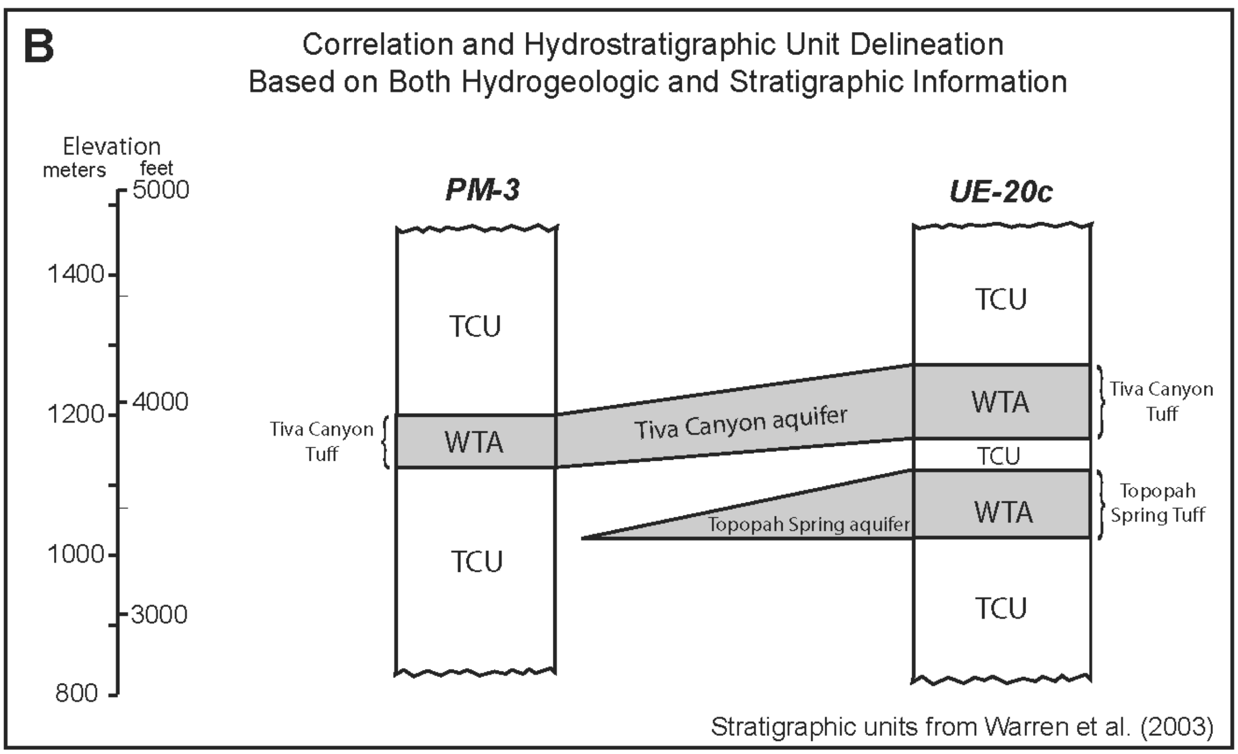


Figure 3-12
Schematic Cross Sections that Illustrate the Importance of Integrating Stratigraphic Information in the Correlation and Delineation of HSUs

however, it is revealed that the two WTAs in UE-20c are, from higher to lower, the Tiva Canyon Tuff and the Topopah Spring Tuff, both stratigraphic formations of the Paintbrush Group (Warren et al., 2003). The WTA in PM-3 is the Tiva Canyon Tuff, and thus the upper WTA in UE-20c correlates to the WTA in PM-3 and forms the Tiva Canyon aquifer HSU (Figure 3-12B). Consequently, the lower WTA in UE-20c, designated the Topopah Spring aquifer HSU, must end (i.e., pinch-out) somewhere between the two holes. These important relationships could not be confidently deciphered without the integration of the detailed stratigraphic information.

Relying too heavily on stratigraphic information, and not incorporating lithologic and alteration information when defining HSUs, however, can also lead to poor or questionable correlations and HSU assignments. For example, the Grouse Canyon Tuff stratigraphic unit forms conspicuous exposures of densely welded ash-flow tuff (i.e., WTA) in the vicinity of Rainier Mesa, near its source area (Gibbons et al., 1963; Barnes et al., 1963). Yet at its distal edges, beneath most of Yucca Flat, the Grouse Canyon Tuff consists only of vitric and zeolitic nonwelded ash-flow tuff and bedded tuff, forming either a VTA or a TCU (BN, 2002). Problems are obvious in accurately modeling groundwater flow within, for example, a “Grouse Canyon” HSU, if only stratigraphic information were utilized for establishing the HSU. A similar situation occurs with the Tub Spring Tuff, which also consists of densely welded ash-flow tuff (i.e., WTA) in the extreme northern portions of Yucca Flat (Barnes et al., 1963; 1965), but is mostly zeolitic bedded tuff (i.e., TCU) in other portions of the basin (BN, 2006).

3.2.2 Hydrostratigraphic Complexities

The complex geologic setting of the NTS region naturally results in complex hydrostratigraphic relationships that can be difficult to represent realistically in CAU-scale HFMs, particularly in areas of sparse data control and with certain constraints imposed by software requirements. The following sections discuss several of these complexities.

3.2.2.1 Changes in Lithofacies

Changes in lithologic features within certain volcanic deposits in the NTS region can result in distinct lithofacies with significantly different hydrologic properties, as illustrated in the examples of the Grouse Canyon and Tub Spring tuffs above. If of significant thickness and extent, these lithofacies are typically categorized as separate HGUs and are included in different HSUs. For example, ash-flow tuff deposits typically have several associated lithofacies related to the degree of welding that occurred after emplacement of the ash-flow tuff (Smith, 1960). Figure 3-13 schematically shows a typical welding profile of an ash-flow tuff deposit. As shown here, the degree of welding tends to decrease outward both vertically and laterally from the

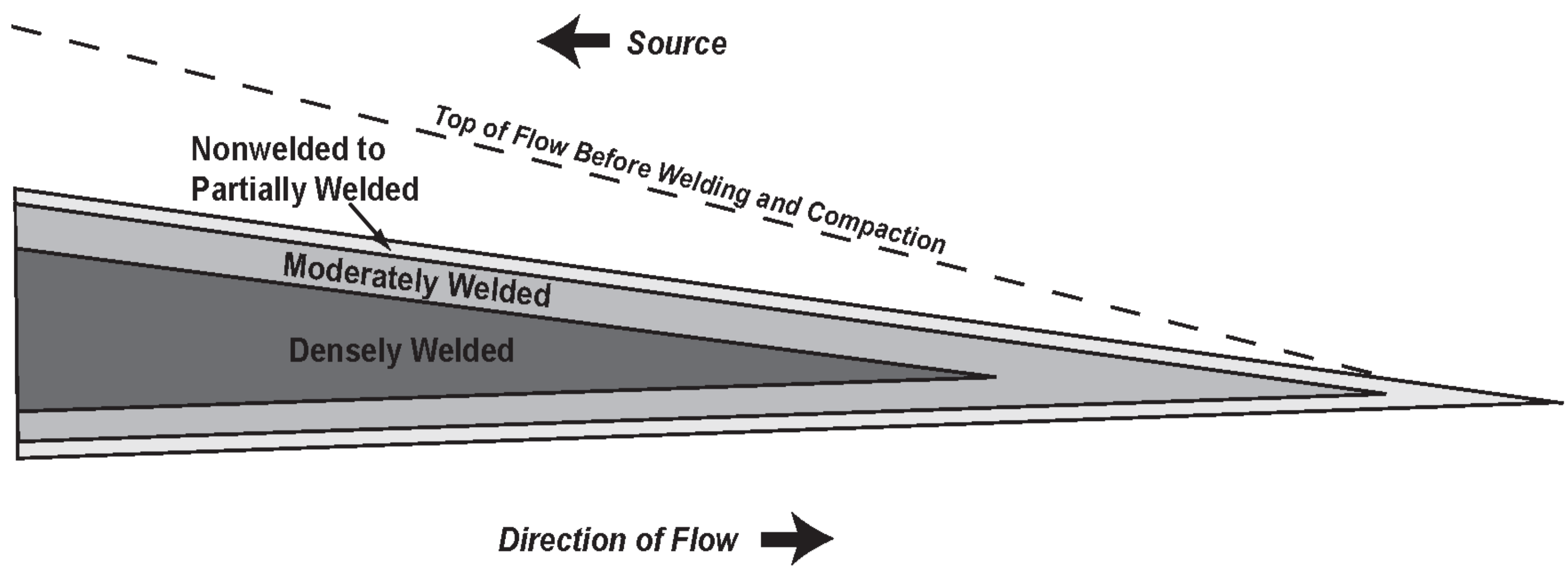


Figure 3-13
Simplified Schematic Cross Section through an Ash-Flow Tuff Showing Zones of Welding
(Modified from Lipman and Christiansen,1964)

center of the flow. Thus, an ash-flow tuff deposit can include a welded lithofacies that forms a WTA in the interior portions of the flow unit that is surrounded by a nonwelded to poorly welded lithofacies that forms either a VTA or, if zeolitized, a TCU.

A specific example of how an ash-flow tuff and associated lithofacies are modeled in UGTA CAU-scale HFMs is provided by the Rainier Mesa Tuff, which occurs as a typical ash-flow tuff deposit in many areas of the NTS (Byers et al., 1976) (Figure 3-14). Surface exposures and drill hole data indicate that where the Rainier Mesa Tuff is less than approximately 76 m (250 ft) thick, typically near the distal edges of the deposit, the ash-flow deposit is poorly welded and commonly vitric. In these areas, all of the Rainier Mesa Tuff is categorized as a VTA and included as part of the Timber Mountain lower vitric-tuff aquifer (TM-LVTA) HSU (Figure 3-15). In locations where the Rainier Mesa Tuff is more than 76 m (250 ft) thick, typically closer to its source, all but the bottom 30 m (100 ft) is classified as the Timber Mountain welded-tuff aquifer (TM-WTA), and the bottom 30 m (100 ft) of nonwelded ash-flow tuff is generally included in the TM-LVTA. Note that in some places the TM-WTA may contain up to 20 percent VTA to accommodate the nonwelded top of the Rainier Mesa Tuff, which typically is thin and not easily mapped for a CAU-scale model.

Because of the relatively consistent nature of the welding process, the distribution of lithofacies related to the degree of welding in ash-flow tuffs is relatively easy to predict. The distribution of lithofacies in other lithologic units, however, can be more complex and difficult to predict, even in areas of good data control. An example is rhyolitic lava flows that can have complex distributions of lithofacies (Prothro and Drellack, 1997). Similar to ash-flow tuff deposits, individual rhyolite lava flows typically have a dense interior that forms a fractured aquifer, in this case an LFA. The outer portions of individual flows can be quite complex, however, consisting of various mixtures of vitric, devitrified, and zeolitic flow breccia and pumiceous and perlitic lava. Depending on their lithology and degree of alteration, these outer lithofacies may form VTAs, TCUs, or LFAs. Where confidently identified, mostly in Pahute Mesa drill holes, rhyolite lava lithofacies are categorized hydrogeologically and included in the appropriate HSUs.

3.2.2.2 Lateral Stratigraphic Terminations

Many rock units terminate laterally within the HFMs. These lateral terminations can be gradual or abrupt. An example of gradual thinning and the eventual pinching out of a unit is probably best observed in ash-flow tuffs where the welded portions of ash-flow tuffs (i.e., WTA) typically thin and pinch out toward the distal ends of the deposit (Figure 3-16).

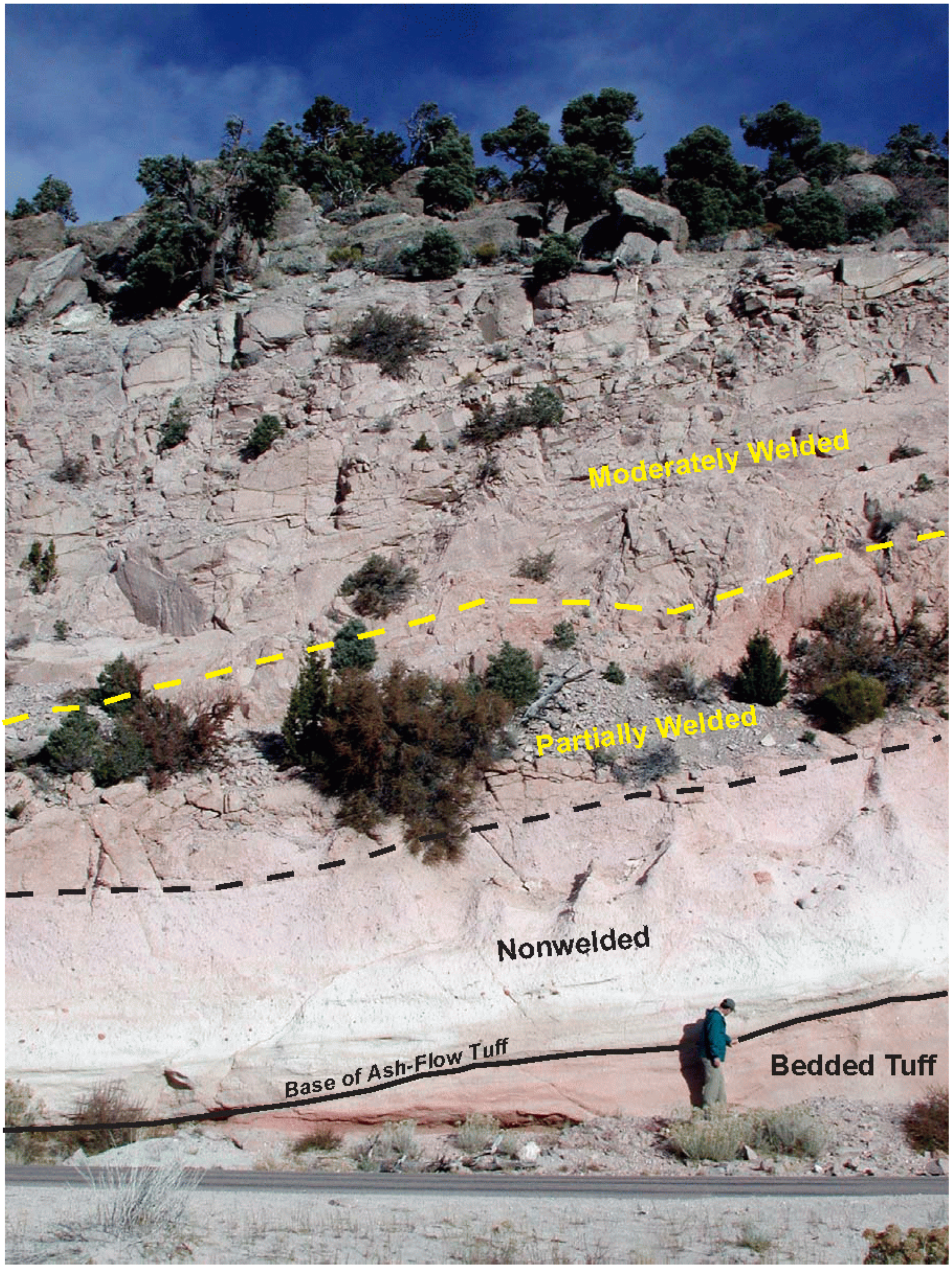


Figure 3-14
Exposure of Ash-Flow Tuff Lithofacies in the Basal Portion of the Rainier Mesa Tuff, Pahute Mesa, Area 19

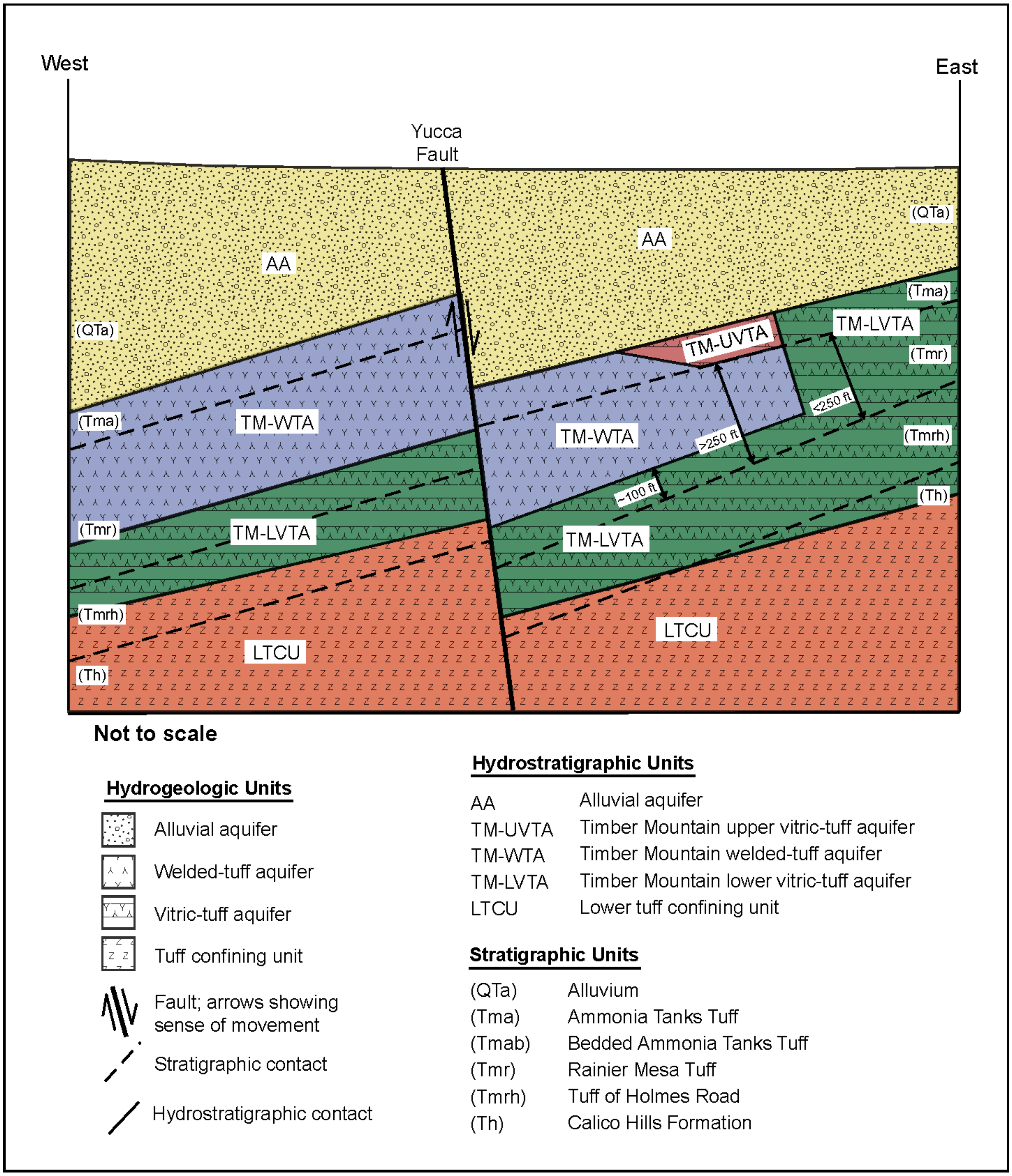


Figure 3-15
Schematic West-East Cross Section across Yucca Flat Illustrating the Delineation of HSUs with Respect to Lithofacies within the Rainier Mesa Tuff
(From BN, 2006)

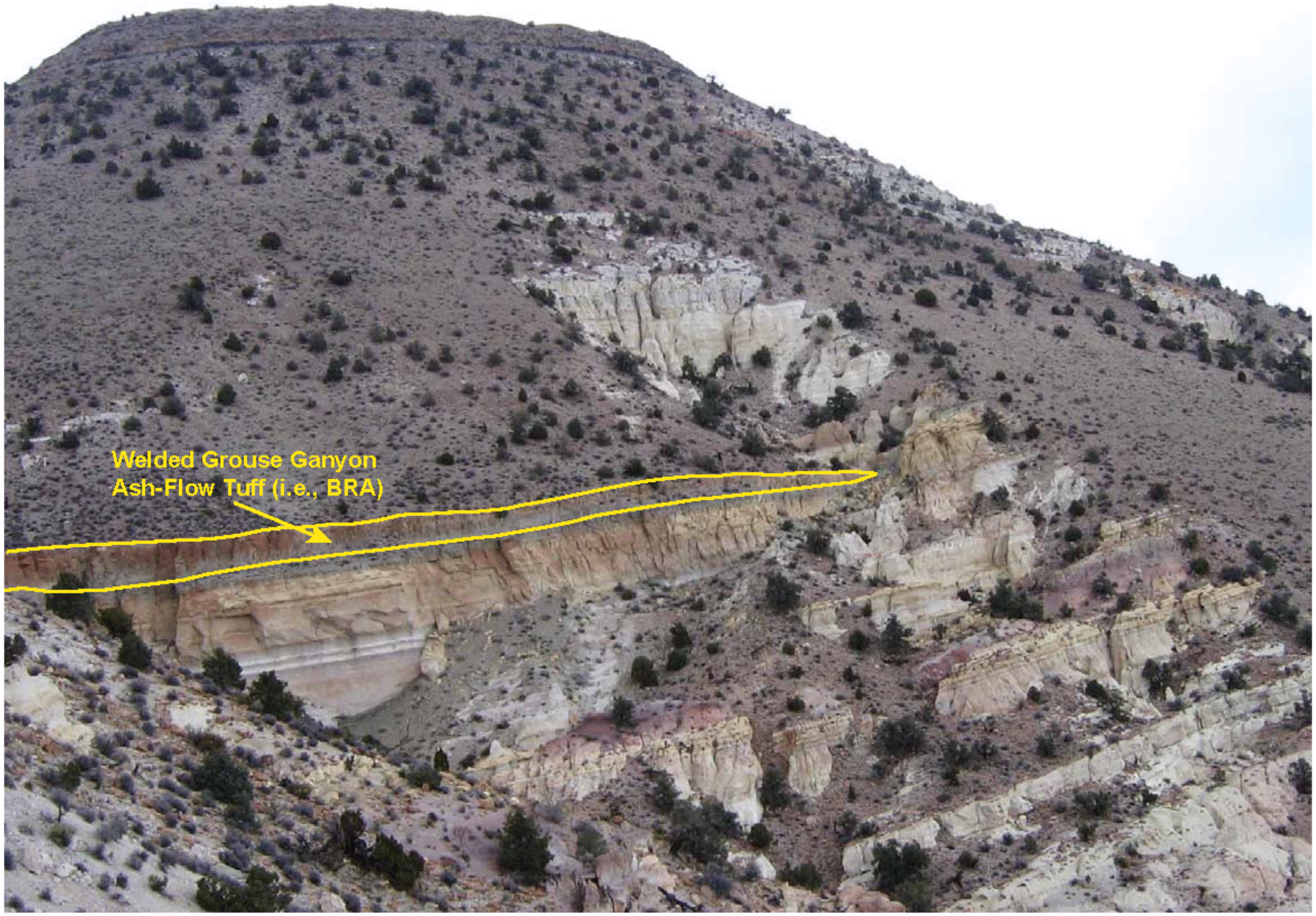


Figure 3-16
Exposure of Welded Grouse Canyon Tuff Showing Lateral Pinch-Out of the Unit (Area 17)

Abrupt lateral stratigraphic terminations are best illustrated by rhyolitic lava flows (i.e., LFAs). These extrusive igneous rocks flow out of vents and onto the ground surface; they typically form bulbous deposits with rather abrupt lateral terminations due to their high viscosity (Cas and Wright, 1987). Subsequent volcanic or alluvial activity may bury the lava-flow deposits, creating an embedded unit that terminates laterally in an abrupt fashion.

In addition to the obvious challenge of determining the locations of buried lateral terminations in areas of sparse data control, requirements of EarthVision®, the software used to construct the HFMs, presents additional challenges to modeling hydrostratigraphic relationships related to lateral terminations. Many HSUs, particularly those composed of WTA, terminate and are effectively embedded within intervals of rock having consistent HGU character, most often TCU. Outside the lateral limits of an embedded HSU, the enclosing rocks are typically grouped within the same HSU because they are hydrologically similar and consist of the same HGU. However, where the embedded HSU is present, EarthVision® requires that the overlying unit be designated a separate HSU from the rocks beneath the embedded HSU even though they may consist of the same HGU, and are included within the same HSU beyond the lateral limits of the embedded HSU. As a consequence, the lateral limits of the overlying HSU are the same as that of the embedded HSU.

Figure 3-17 schematically illustrates a simple case involving the lateral termination of the Topopah Spring aquifer (TSA) in southern Yucca Flat. East of the limits of the TSA, all the units between the TM-LVTA and the Oak Spring Butte confining unit (OSBCU) consist of zeolitic tuff (i.e., TCU) and are grouped within the LTCU HSU. Where the TSA is present, however, the zeolitic rocks above the TSA are designated the UTCU, and the zeolitic rocks below the TSA retain the name LTCU. Where multiple laterally terminating HSUs occur, such as the northern portion of the RM-SM HFM area, the hydrostratigraphic relationships can become quite complex (Figure 3-18).

3.2.2.3 Post-Depositional Alteration

Post-depositional alteration, especially zeolitization, exerts a major influence on the hydrologic properties of rocks in the NTS region, and its presence or absence is one of the defining characteristics of HGUs (Winograd and Thordarson, 1975; Laczniak et al., 1996). Within much of the NTS region, an upper level of pervasive zeolitization can be identified at depth within volcanic rocks (Drellack and Thompson, 1990). The vitric (i.e., glassy) constituents of all nonwelded tuff and similar low density volcanic rocks below this depth are typically altered. Alteration products include mainly zeolite in the upper levels, with quartzo-feldspathic mineral

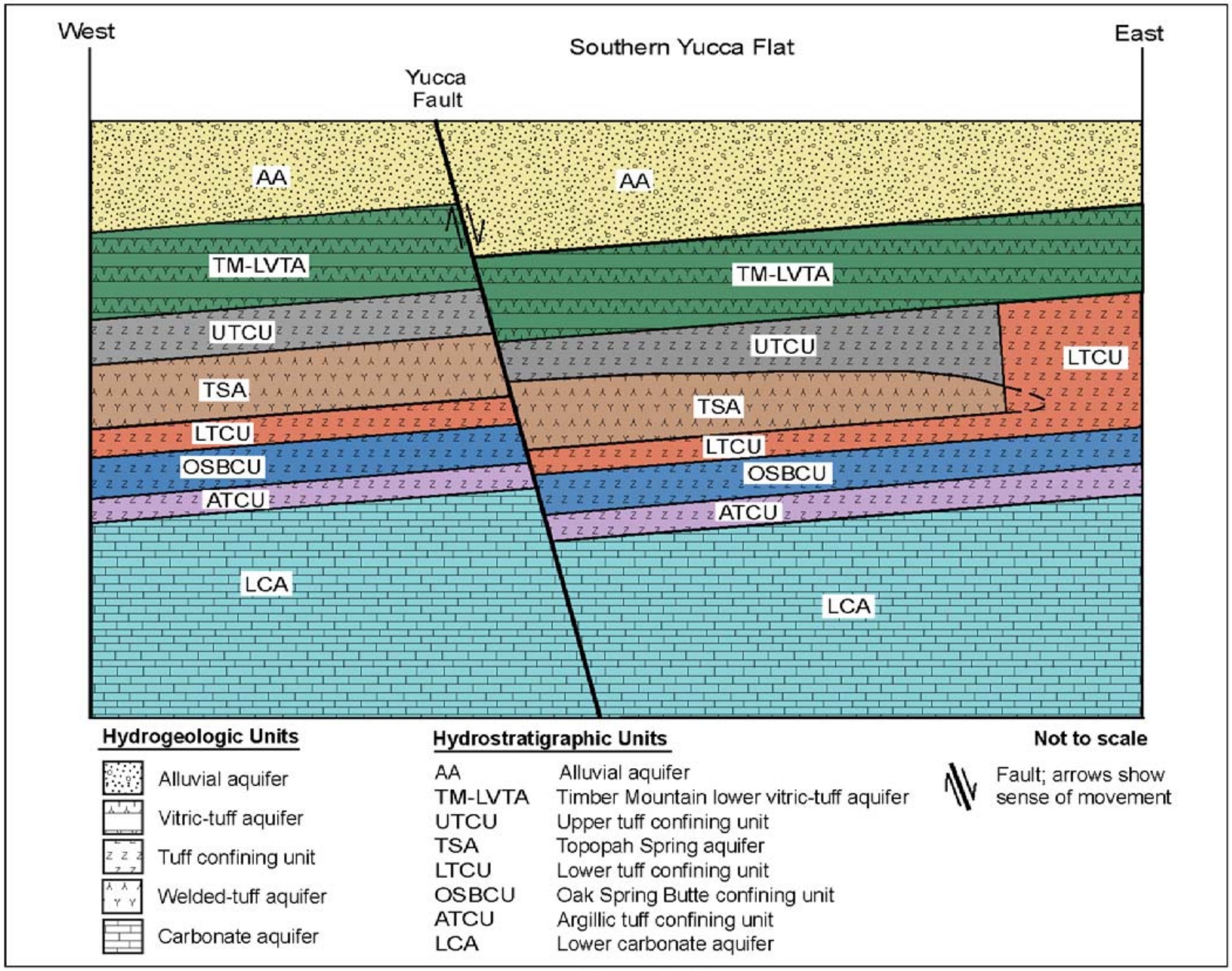


Figure 3-17
Schematic Hydrostratigraphic Cross Section through Southern Yucca Flat Showing Relationships Among the TCUs and the Topopah Spring Aquifer
(From BN, 2006)

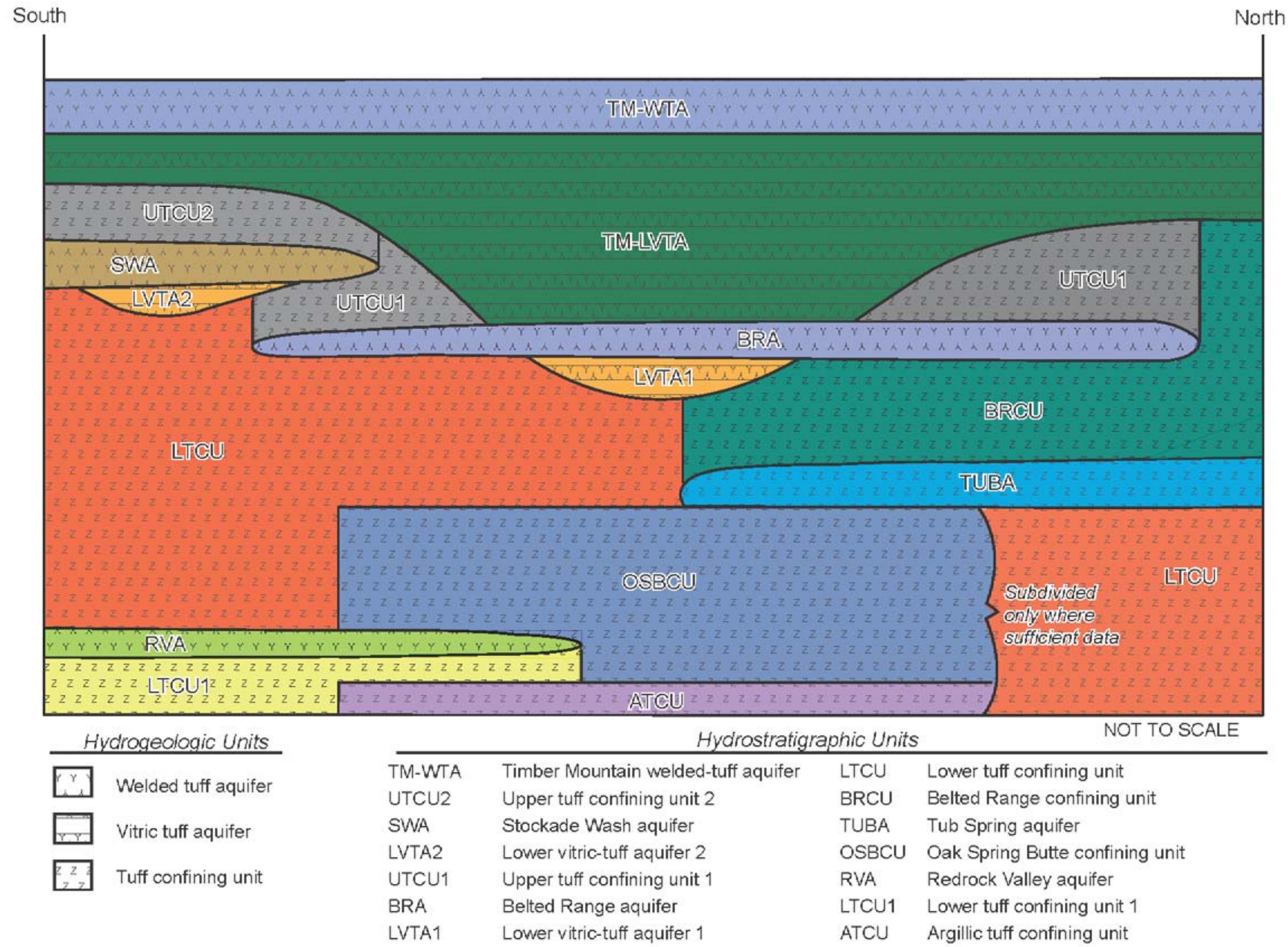


Figure 3-18
Schematic Hydrostratigraphic Cross Section through Northern Half of the Rainier Mesa-Shoshone Mountain Model Area Showing the Relationships Among the TCU and WTA HSUs
(From NSTec, 2007)

assemblages becoming more dominant lower, and clay dominating near the base of the volcanic sequence (Prothro, 2005). In all the UGTA CAU-scale HFMs, the top of pervasive zeolitization always defines the top of a TCU HSU. Because zeolitization is strongly influenced by lithology and the position of the water table (Hoover, 1968), the top of zeolitization is usually independent of stratigraphy, and commonly cuts across stratigraphic boundaries (Figure 3-19). Therefore, the tops of many confining unit HSUs cannot be defined by stratigraphic boundaries.

3.2.2.4 Thrust Plates

Mesozoic thrust faulting associated with both the east-directed Belted Range system and the slightly younger, west-directed CP thrust fault results in hydrostratigraphic complexities within the upper portion of the pre-Tertiary section at the NTS (Cole and Cashman, 1999). As a result of this thrusting, thrust plates of older stratigraphic units have been transported up from depth along thrust faults and emplaced over younger units (Figure 3-20). Where these thrust plates are separated from correlative rocks by underlying younger rocks of different hydrologic character, the thrusted rocks are delineated as a separate HSU to distinguish them from lower correlative and unthrusted rocks.

The Belted Range thrust system is particularly complex. This thrust system has brought Precambrian and late Cambrian siliciclastic rocks of the lower clastic confining unit (LCCU) up and over Paleozoic carbonate rocks of the LCA, which themselves have been emplaced over younger siliciclastic rocks of the UCCU by imbricate thrust faulting that occurred structurally below and generally in front of the Belted Range thrust fault (Cole and Cashman, 1999) (Figure 3-21). Thrusted Precambrian and late Cambrian siliciclastic rocks of the LCCU are designated as LCCU1 to distinguish them from the deeper and unthrusted LCCU. Similarly, the thrusted carbonate rocks are designated LCA3 to distinguish them from the deeper and unthrusted LCA.

The LCA3 designation is also used to distinguish Paleozoic carbonate rocks of the LCA that have been thrust westward over the UCCU along the CP thrust fault beneath the western portion of Yucca Flat. As a result, LCA3 occurs as two separate thrust plates associated with two different thrust faults, but are designated the same HSU because they both consist of Paleozoic carbonate rocks and have similar structural relationships (i.e., thrusted over UCCU).

Precambrian and late Cambrian siliciclastic rocks of the LCCU are interpreted to have been emplaced over LCA rocks along the CP thrust fault at depth beneath Yucca Flat (BN, 2006). These thrusted LCCU rocks are designated LCCU2 to distinguish them from deeper unthrusted

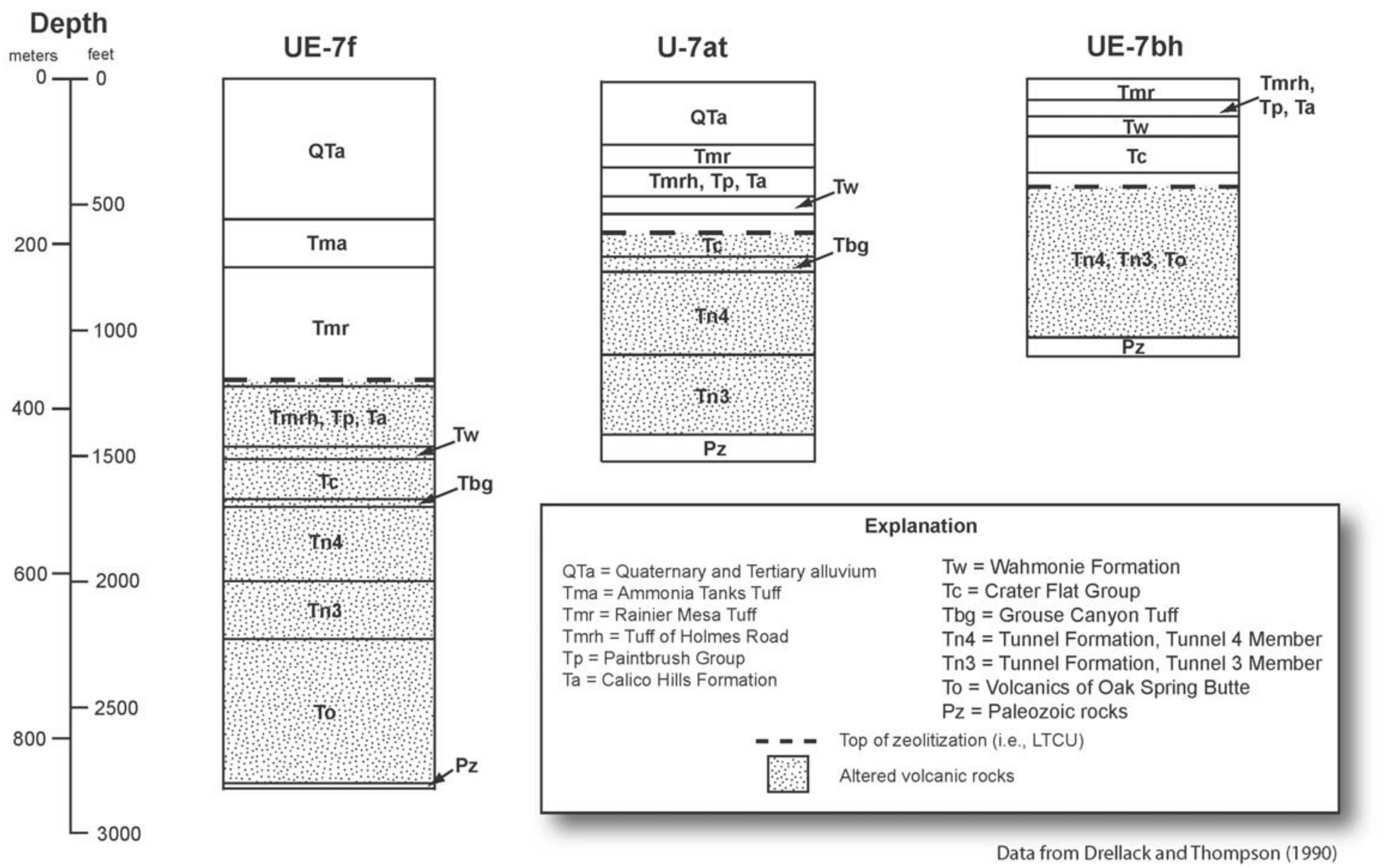


Figure 3-19
Stratigraphic Columns for Three Drill Holes in Yucca Flat Showing the Stratigraphic Variability in the Top of Zeolitization (i.e., TCU)

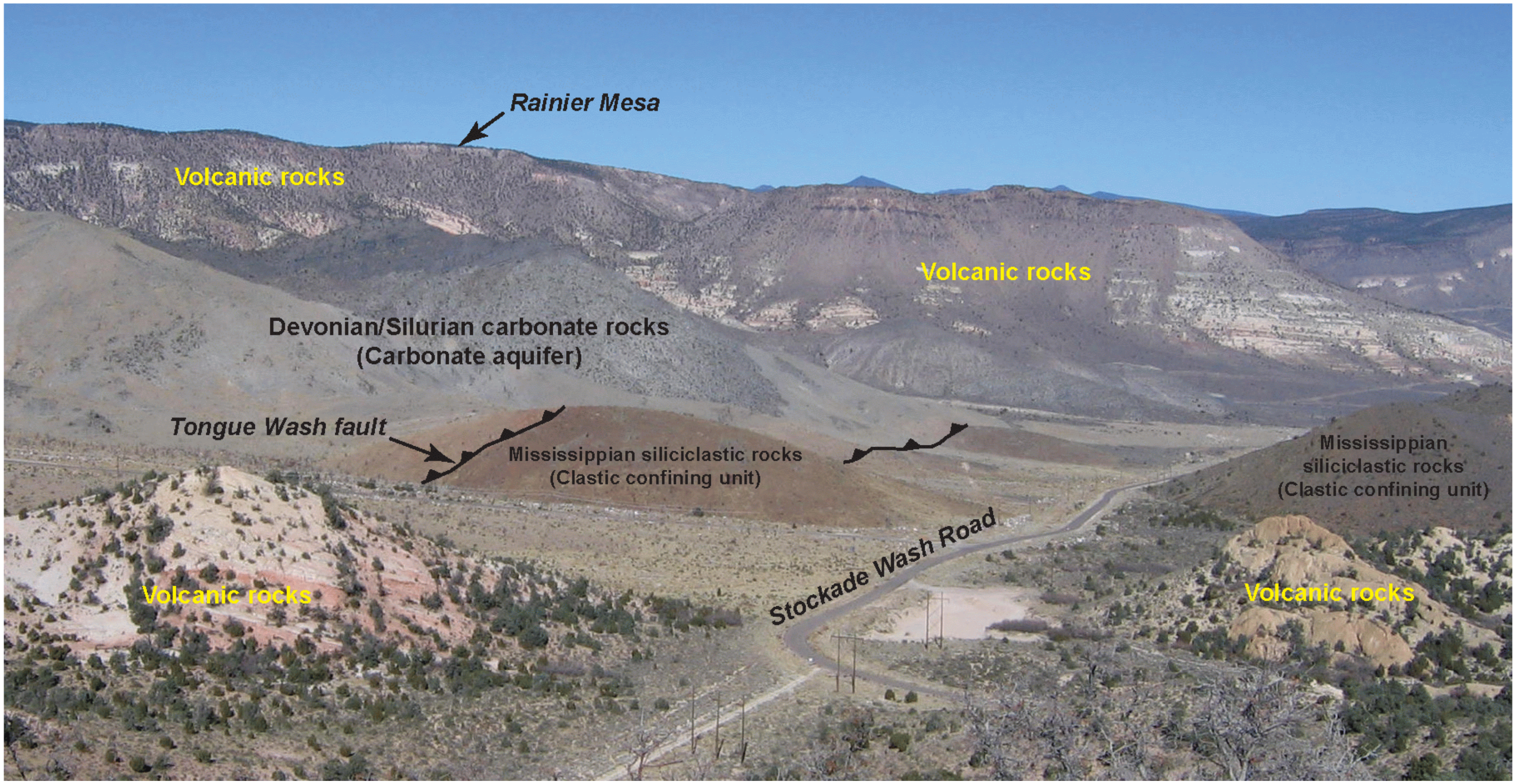


Figure 3-20
Photograph of Devonian/Silurian Carbonate Rocks Emplaced Over Mississippian Siliciclastic Rocks along the Tongue Wash Fault, East Flank of Rainier Mesa
(View is north; fault teeth on upper plate)

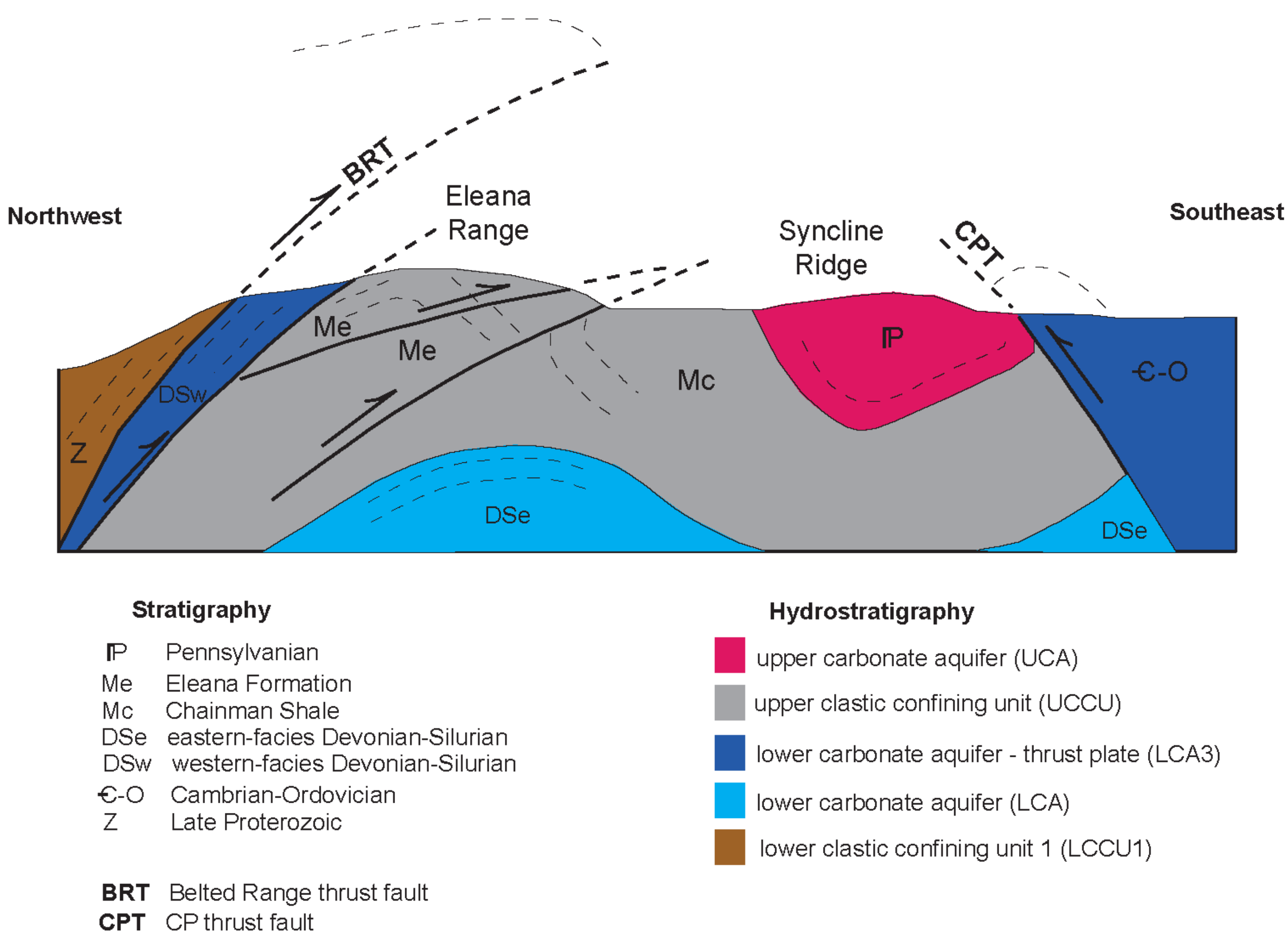


Figure 3-21
Schematic Northwest-Southeast Cross Section through the Eleana Range and Syncline Ridge Showing Thrust Fault Relationships
(Modified from Cole and Cashman, 1999)

LCCU. Complex imbricate thrust faulting related to the Belted Range thrust fault and observed in UGTA Well ER-12-1 necessitated the delineation of a UCCU1 HSU and another LCA3 HSU designated LCA3-1.

3.2.2.5 Composite Units

The CM designation was originally developed as part of the PM–OV HFM to address the uncertainty associated with complex volcanic intervals composed of poorly understood distributions of differing HGUs (BN, 2002). The most common CM HSU consists of a stratigraphic interval containing multiple LFA HGUs intercalated within TCU or VTA. Because subsurface control is insufficient to confidently correlate and map the lateral extent of individual LFAs, they are grouped together with the associated TCU HGUs into a single HSU. The upper and lower boundaries of CM HSUs typically correspond to stratigraphic boundaries. For example, the Calico Hills zeolitic composite unit (CHZCM) consists of several individual rhyolite lava flows (i.e., LFAs), assigned stratigraphically to the Calico Hills Formation, that are intercalated within zeolitic tuff (i.e., TCUs) also assigned to the Calico Hills Formation (DOE/NV, 1998). Consequently, the top and bottom of the CHZCM correspond to the stratigraphic top and bottom of the Calico Hills Formation. Some CM HSUs, such as the Fortymile Canyon composite unit, may also contain WTA along with LFA and TCU. The composite unit was assigned an abbreviation of CM to avoid confusion with the more common confining unit HGU, which is abbreviated CU.

A unique CM HSU is the Timber Mountain composite unit (TMCM). The CM designation was applied to the TMCM to address uncertainties associated with the occurrence and distribution of open fractures within a very thick sequence of predominantly welded ash-flow tuffs (i.e., WTAs) that accumulated within the Timber Mountain caldera complex (BN, 2002). The intra-caldera setting, surface exposures, and information from deep drill holes suggest that fracture permeability within the TMCM may be significantly reduced in places by secondary mineralization and poorly developed cooling and tectonic fractures. Consequently, groundwater-flow properties of the TMCM may be considerably different than those for WTA-dominated HSUs in areas outside of the Timber mountain caldera complex (e.g., Timber Mountain aquifer, Tiva Canyon aquifer, and Topopah Spring aquifer).

3.2.3 Uncertainty

As can be inferred from above discussions of the hydrogeologic complexities of the NTS region, geologic interpretations, such as those associated with HSU delineation and modeling, contain varying amounts of uncertainty, some of which can be quite large. This geologic complexity is offset somewhat by the shear amount of geologic study that has occurred in the NTS region during the past 50 years. This has resulted in a very good understanding of the basic geologic setting of the NTS region. The geologic data generated by scientists from the federal government, national laboratories, federal contractors, and academia is of high quality. In weapon testing areas, such as Yucca Flat and Pahute Mesa, the quantity of geologic data, particularly subsurface data, is probably greater than in other areas in the Great Basin. However, the geologic complexity of the NTS region means that geologic uncertainty increases both laterally and vertically away from the subsurface control, and this uncertainty can increase very rapidly in many places. In most areas of the NTS region, uncertainty increases with increasing depth to a point in every HFM where the geology, including HSUs, are highly conceptualized.

With regard to the UGTA CAU-scale hydrostratigraphic system, the least uncertainty is probably associated with HGU designations in outcrop and drill holes. Assigning HGU designations to rocks exposed at the surface and encountered in drill holes is a relatively straightforward process, and is typically done with a relatively high degree of confidence. HGU classification of rock units is based on basic lithologic information (e.g., carbonate versus shale, nonwelded tuff versus welded tuff, vitric tuff versus zeolitic tuff) which usually can be accurately determined macroscopically from field hand samples and drill cuttings.

Uncertainty increases somewhat when assigning HGUs to specific HSUs because determining stratigraphic information, which is essential for proper HSU delineation, is typically more difficult than determining lithologic information. However, detailed stratigraphic studies conducted at the NTS have resulted in a large and robust data set and knowledge base for the stratigraphic units in the NTS area. HSU contacts in drill holes can usually be determined with relative precision, sometimes within 0.3 m (1 ft), using mainly drill cuttings and geophysical logs.

The uncertainty associated with modeling HSU volumes increases with increasing distance, both horizontally and vertically, from data control such as outcrop and drill holes. Typically, buried HSUs in areas of sparse drill hole control are only conceptualized, and thus have relatively high degrees of uncertainty regarding their precise extent, thickness, and depth below the surface (for example, the intra-caldera intrusive confining units). The least uncertain of these characteristics is probably extent. General knowledge of the geologic setting will typically allow for a reasonable approximation of the presence of an HSU in a particular area. Thickness of an HSU in areas of sparse control can usually be approximated from the geologic setting and stratigraphic and lithologic composition of the HSU. However, faulting contemporaneous with volcanic activity (e.g., calderas) and alluvial deposition (e.g., Yucca Flat) can result in dramatic thickness differences across short distances. If fault location and amount of displacement are poorly constrained, then the thicknesses of some HSUs may be highly uncertain. Because of the intense faulting in the NTS region from both tectonic and volcanic processes (i.e., caldera development), depths to buried HSUs in areas of poor control can have uncertainties on the order of hundreds of meters.

For more detailed information on the uncertainty associated with each HSU, the reader is referred to the full descriptions of the HSUs presented in the HFM reports (BN, 2002; 2005; 2006; NSTec, 2007). However, it is very difficult to quantify and fully explain geologic uncertainty associated with HSU delineation and modeling in such a complex geologic setting as the NTS region. Geologic uncertainty associated with HSUs is better addressed and incorporated into flow and transport models, as well as HFMs, by a close synergistic relationship between geologists and flow and transport modelers during all phases of model construction and evaluation.

4.0 SUMMARY

Four 3-D CAU-scale HFMs have been constructed for the UGTA Sub-Project to support groundwater flow and contaminant transport modeling. All four overlapping models were constructed using the same hydrostratigraphic system, which required careful evaluation of the complex stratigraphy of the NTS region and incorporation of the lithologic variations that affect rock hydrologic properties. The HSUs of each CAU-scale model area are described in the documentation package for each, but this document provides a comprehensive overview of the NTS-wide, CAU-scale hydrostratigraphic system, and may serve as a general reference resource for the HSUs used in all the UGTA HFMs.

The construction of HFMs required the development of a hydrostratigraphic system that consistently defines the lateral and vertical distributions of rock units according to their water-bearing qualities and in such a way that they can be accurately depicted in three dimensions within the HFMs. To achieve this requirement within the very complex geologic setting of the NTS, the UGTA CAU-scale hydrostratigraphic system uses a two-level classification scheme in which HGUs are organized into HSUs that form the unit volumes, or layers, within the HFMs.

The UGTA hydrostratigraphic units were defined using principles described by Maxey (1964) and Seaber (1988), and incorporating the very large database of geologic and hydrogeologic data available for the NTS primarily in the form of surface geologic maps and lithologic, geophysical, and hydrologic data from thousands of boreholes. The NTS regional volcanic stratigraphy of Warren et al. (2003) defines more than 300 stratigraphic units, and more than 20 pre-Tertiary stratigraphic units have been mapped (Slate et al., 1999). The basic hydrogeologic framework for the NTS established by Winograd and Thordarson (1975) and updated by Laczniak et al. (1996) delineated many of the aquifers and aquitards within the NTS region, which were the basis for the ten HGUs used as the basis for the HSUs.

The process used to define the current 76 UGTA HSUs is described, including how various types of geologic complexity (facies changes, lateral stratigraphic terminations, alteration, etc.) were addressed. Several examples with graphic depictions are provided to illustrate the “rules” used to define the HSUs of the UGTA framework for the NTS region. All 76 HSUs are listed in this report, including their presence or absence within each of the four CAU-scale HFMs.

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APPENDIX A

Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models
(Compiled from BN, 2002; 2005; 2006; NSTec, 2007)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Alluvial aquifer (AA)	AA	Qay, QTc, Qs, QTa, QTu, Qb, Tgy, Tgc, Tgy, Tt	Consists mainly of alluvium that fills extensional basins including Yucca Flat, Frenchman Flat, Gold Flat, Crater Flat, Kawich Valley, and Sarcobatus Flat. In the northwest also includes generally older Tertiary gravels, tuffaceous sediments, and nonwelded tuffs (where thin) that partially fill other basins such as Oasis Valley and the moat of the Timber Mountain caldera complex.
Playa confining unit (PCUT)	PCU	Qp	Clayey silt and sandy silt. Forms the surface and near-surface playas (dry lake beds) at Frenchman Flat, Yucca Flat, and Papoose Lake.
Basalt lava-flow aquifer (BLFA)	LFA	Tyb, Tybp	Subsurface occurrences of Pliocene basalt in Yucca Flat and northern Frenchman Flat.
Older altered alluvial aquifer (OAA and OAA1)	AA	QTa	Older, denser, zeolitic alluvium recognized only in northern Frenchman Flat. OAA and OAA1 are equivalent except for position: the OAA is above the BLFA, and the OAA1 is stratigraphically beneath the BLFA.
Older playa confining unit (PCU1U and PCU1L)	PCU	QTp	Deep, subsurface playa deposits in the deepest portion of Frenchman Flat. Recognized in Well ER-5-4#2 and 3-D seismic data. The PCU1U and PCU1L are similar except for position.
Younger volcanic composite unit (YVCM)	LFA, WTA, VTA	Typ, Tgy, Ts, Tyb, Tyr	A minor unsaturated HSU that consists of Pliocene to late Miocene basaltic rocks such as those at Thirsty Mountain and Buckboard Mesa. Also includes welded and nonwelded ash-flow tuff of the Volcanics of Stonewall Mountain. Mainly occurs in the northwestern portion of the Pahute Mesa-Oasis Valley (PM–OV) model area.
Thirsty Canyon volcanic aquifer (TCVA)	WTA, LFA, lesser VTA	Tth, Ttg, Tts, Ttt, Ttp, Ttc	Consists mainly of welded ash-flow tuff and lava of the Thirsty Canyon Group. Unit is very thick within the Black Mountain caldera. Also is present east and south of the caldera, including the northwestern moat area of the Timber Mountain caldera complex and the northern portion of the Oasis Valley basin.
Detached volcanics aquifer (DVA)	WTA, LFA	Tf, Tma, Tmr	Consists of welded ash-flow tuff and lava assigned to the Ammonia Tanks Tuff and units of the Volcanics of Fortymile Canyon. Although, like the DVCM, the DVA also overlies the Fluorspar Canyon-Bullfrog Hills detachment fault, it is considered a separate HSU because of the preponderance of welded-tuff and lava-flow aquifers that compose the HSU and much smaller degree of alteration present.
Detached volcanics composite unit (DVCM)	WTA, LFA, TCU	Tf through Tq	Consists of a very complex distribution of lavas and tuffs that form a relatively thin, highly extended interval above the Fluorspar Canyon-Bullfrog Hills detachment fault in the southwestern portion of the PM–OV model area.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Fortymile Canyon composite unit (FCCM)	LFA, TCU, lesser WTA	Tfu, Tfs, Tfd, Tfr, Tfb, Tfl, Tff	Consists of a complex and poorly understood distribution of lava and associated tuff of the Volcanics of Fortymile Canyon. Generally confined within the moat of the Timber Mountain caldera complex, where the unit forms a ring around Timber Mountain. Unit is also present in areas southwest of the Timber Mountain caldera complex.
Fortymile Canyon aquifer (FCA)	WTA, LFA	Tff, Tfbc	Composed mainly of welded ash-flow tuff and rhyolitic lava, and is generally less than 305 m (1,000 ft) thick. Occurs in the subsurface in the southwestern portion of the Timber Mountain caldera complex.
Tannenbaum Hill lava-flow aquifer (THLFA)	LFA	Tmat	Composed entirely of rhyolitic lava of the rhyolite of Tannenbaum Hill. Exposed at the surface just outside the northwestern structural boundary of the Timber Mountain caldera complex. Tannenbaum Hill lava occurring inside the caldera complex is grouped with the TMCM.
Tannenbaum Hill composite unit (THCM)	Mostly TCU, lesser WTA	Tmat	Zeolitic tuff and lesser welded ash-flow tuff of the rhyolite of Tannenbaum Hill that occurs stratigraphically below Tannenbaum Hill lava and above the rhyolite of Fluorspar Canyon. Distribution is similar to the THLFA.
Timber Mountain upper vitric-tuff aquifer (TM-UVTA)	VTA, minor WTA	Tma, Tmab	Typically saturated only in the deepest structural basins (i.e., Yucca Flat and Mid Valley). This HSU comprises only the nonwelded to partially welded Ammonia Tanks Tuff, which stratigraphically overlies the TM-WTA in Yucca Flat and Mid Valley.
Timber Mountain welded-tuff aquifer (TM-WTA)	WTA minor VTA	Tma, Tmab, Tmrb, Tmr	Consists mainly of out-flow sheets of Ammonia Tanks and Timber Mountain welded ash-flow tuff. Also includes minor bedded tuff (Tmab and Tmrb) that occurs between Ammonia Tanks and Timber Mountain ash-flow tuffs. This is an extensive HSU that occurs in many parts of the NTS region. Typically saturated only in the deeper portions of Yucca Flat, Frenchman Flat, and Mid Valley. Equivalent to the TMA in the PM–OV model area.
Timber Mountain lower vitric-tuff aquifer (TM-LVTA)	VTA	Tma, Tmab, Tmr, Tmrh, Tp, Th, Tw, Tc; may also include Tbgb and Tn	Typically includes the nonzeolitized, nonwelded lower portion of the Rainier Mesa Tuff and post-Tunnel Formation units. However, in places this HSU encompasses all vitric (i.e., non-zeolitized), nonwelded and bedded units below the welded Rainier Mesa Tuff and above the upper level of pervasive zeolitization. Typically occurs above the level of saturation because vitric, nonwelded tuffs tend to zeolitize under saturated conditions.
Fluorspar Canyon confining unit (FCCU)	TCU	Tmrf	Consists of zeolitic, nonwelded tuff of the rhyolite of Fluorspar Canyon that generally occurs beneath the THCM, and thus has a similar distribution.
Windy Wash aquifer (WWA)	LFA	Tmw	Minor HSU consisting of the lava-flow lithofacies of the rhyolite of Windy Wash. Occurs along the western (down-thrown) side of the West Greeley fault in Area 20.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Timber Mountain composite unit (TMCM)	WTA; lesser TCU and LFA	Tmay, Tmaw, Tma, Tmc, Tmat, Tmr	Consists mainly of intra-caldera, strongly welded ash-flow tuff of the Timber Mountain Group, and is confined within the Timber Mountain caldera complex. Although consisting mainly of strongly welded tuff, which is assumed to be considerably fractured and thus behave as an aquifer, the TMCM is designated a composite unit because of the potential for hydrothermal alteration within this deep intra-caldera setting. Alteration would have significantly altered the hydraulic properties of the rocks, particularly filling fractures with secondary minerals such as quartz.
Timber Mountain aquifer (TMA)	Mostly WTA, minor VTA	Tma, Tmab, Tmr, Tmrb	Consists mainly of extra-caldera welded ash-flow tuffs of Ammonia Tanks Tuff and Rainier Mesa Tuff. These rocks are the extra-caldera equivalent of the rocks comprising the TMCM. Unit occurs mostly north and west of the Timber Mountain caldera complex. The TMA in the PM–OV model area is equivalent to the TM-WTA.
Rainier Mesa breccia confining unit (RMBCU)	TCU/AA	Tmc	Breccia deposits formed by sloughing of the caldera wall during formation of the Rainier Mesa caldera. Consists of angular clasts of volcanic rocks older than the Rainier Mesa Tuff, within an argillic, tuffaceous matrix. Modeled as a wedge-shaped volume adjacent to the structural wall of the Rainier Mesa caldera. Delineated within the Rainier Mesa-Shoshone Mountain (RM–SM) model only.
Sub-caldera volcanic confining unit (SCVCU)	TCU	Tm, Tp, Tc, and older, undifferen-tiated tuffs	A highly conjectural unit that is modeled as consisting of highly altered volcanic rocks that occur stratigraphically between the Rainier Mesa Tuff and basement rocks (ATICU and RMICU) within the deeper portions of the Timber Mountain caldera complex.
Benham aquifer (BA)	LFA	Tpb	Lava-flow lithofacies of the rhyolite of Benham. Occurs north of the Timber Mountain caldera complex and beneath the southwestern portion of Pahute Mesa.
Upper Paintbrush confining unit (UPCU)	TCU	Pre-Tmr tuffs, Tp	Includes all zeolitic, nonwelded and bedded tuffs between the rhyolite of Benham lava (i.e., Tpb) and welded tuff of the Tiva Canyon Tuff (i.e., TCA). Unit occurs in the vicinity of southwestern Area 20.
Tiva Canyon aquifer (TCA)	WTA	Tpc	The welded ash-flow tuff lithofacies of the Tiva Canyon Tuff.
Paintbrush composite unit (PCM)	WTA, LFA, TCU	Tp	Consists mostly of units of the Paintbrush Group that occur in the southern portion of the PM-OV model area in the vicinity of the Claim Canyon caldera. Unit is dominated by thick, strongly welded Tiva Canyon Tuff within the Claim Canyon caldera. Outside the caldera this unit is more variable, consisting of welded and nonwelded tuff and rhyolitic lava assigned to various formations of the Paintbrush Group. Stratigraphically equivalent units of the Paintbrush Group that occur beneath Pahute Mesa have been grouped into seven separate HSUs.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Paintbrush vitric-tuff aquifer (PVTA)	VTA	Pre-Tmr tuffs, Tp	Typically includes all vitric, nonwelded and bedded tuff units below the Rainier Mesa Tuff to the top of a Paintbrush lava (e.g., Tpb or Tpe) but may extend to base of Paintbrush Tuff in eastern Area 19 where Tpe or Tpr lavas are not present. May also include the vitric pumiceous top of the Tpe lava. Unit occurs in the northern portion of the PM-OV model area beneath Pahute Mesa. In the RM–SM model, PVTA is restricted to vitric, nonwelded and bedded tuff that occurs between the TCA and the TSA.
Upper tuff confining unit (UTCU)	TCU	Tmr (lowermost), Tmrh, Tp	Defined to encompass the zeolitized bedded tuffs which stratigraphically overlie the Topopah Spring aquifer (TSA). Although some geologic units of the UTCU are laterally continuous with those of the LTCU, the UTCU is limited areally to extreme southern Yucca Flat and Mid Valley where the welded Topopah Spring Tuff is an important aquifer present between the two tuff confining units (UTCU and LTCU).
Paintbrush lava-flow aquifer (PLFA)	LFA	Tpd, Tpe, Tpr	Lava-flow lithofacies of the rhyolite of Delirium Canyon (Tpd), rhyolite of Echo Peak (Tpe), and rhyolite of Silent Canyon (Tpr). Also includes moderately to densely welded ash-flow tuff of Tpe. Unit occurs only beneath Pahute Mesa.
lower Paintbrush confining unit (LPCU)	TCU	Tpe, Tpp, Tpt	Includes all zeolitic nonwelded and bedded tuffs between TCA and TSA. Unit occurs in the northern portion of the PM-OV model area beneath Pahute Mesa.
Topopah Spring aquifer (TSA)	WTA	Tpt	The welded ash-flow lithofacies of the Topopah Spring Tuff.
Lower vitric-tuff aquifer (LVTA)	VTA	Th (formerly Tac)	Relatively thin vitric-tuff aquifer unit below the TSA. Grouped with the TM-LVTA where the Topopah Spring welded ash-flow tuff is not present.
Calico Hills vitric-tuff aquifer (CHVTA)	VTA	Th (Tac)	Structurally high, vitric, nonwelded tuffs of the Calico Hills Formation. Present beneath the eastern portion of Area 19. May become partly zeolitic in the lower portions.
Calico Hills vitric composite unit (CHVCM)	VTA, LFA	Th	Structurally high, lava and vitric nonwelded tuff of the Calico Hills formation. Present beneath the western portion of Area 19. May become partly zeolitic in the lower portions.
Calico Hills zeolitic composite unit (CHZCM)	LFA, TCU	Th	Complex 3-D distribution of rhyolite lava and zeolitic nonwelded tuff of the Calico Hills Formation. Present beneath most of eastern and central Area 20.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Calico Hills confining unit (CHCU)	Mostly TCU, minor LFA	Th (Tac)	Consists mainly of zeolitic nonwelded tuff of the Calico Hills Formation. Present beneath the western portion of Area 20.
Inlet aquifer (IA)	LFA	Tci	Lava-flow lithofacies of the rhyolite of Inlet. Occurs as two thick, isolated deposits beneath Pahute Mesa in the northern portion of the PM–OV model area.
Wahmonie confining unit (WCU)	TCU, minor LFA	Twu, Twm, Twl, Twls	Mixture of lava flows, debris flows, lahars, ash-flows, and air-falls of the Wahmonie Formation. Typically zeolitic, argillic, or hydrothermally altered. Grades or interfingers laterally with the LTCU.
Crater Flat composite unit (CFCM)	Mostly LFA, intercalated with TCU	Tcpj, Tcps, Tcg	Includes welded tuff and lava flow lithofacies of the tuff of Jorum (Tcpj), the rhyolite of Sled (Tcps), and the andesite of Grimy Gulch (Tcg). Occurs in central Area 20 in the northern portion of the PM–OV model area.
Crater Flat confining unit (CFCU)	TCU	Tc	Includes all zeolitic, nonwelded and bedded units below the Calico Hills Formation (Th) to the top of the Bullfrog Tuff (Tcb). Occurs mainly in Area 19 in the northern portion of the PM–OV model area.
Yucca Mountain Calico Hills lava-flow aquifer (YMCHLFA)	LFA	Th	Minor HSU in the southwest corner of the RM–SM model area. Consists mainly of rhyolitic lava flows of the Calico Hills Formation.
Yucca Mountain Crater Flat composite unit (YMCFCM)	LFA, WTA, TCU	Tc, Th	Includes all units of the Crater Flat Group and Calico Hills Formation that occur in the southern portion of the PM–OV model area in the vicinity of Yucca Mountain. Stratigraphically equivalent units that occur in other model areas have been grouped into nine separate HSUs.
Kearsarge aquifer (KA)	LFA	Tcpk	Minor HSU that consists of the lava-flow lithofacies of rhyolite of Kearsarge. Unit is present as a small isolated occurrence in the northeastern portion of the PM–OV model area.
Upper tuff confining unit 2 (UTCU2)	TCU	Tp(b), Tc	Defined to encompass the zeolitized bedded tuffs which stratigraphically overlie the Stockade Wash welded-tuff aquifer (SWA). Although some geologic units of the UTCU2 are laterally continuous with those of the UTCU1, the UTCU2 is limited areally to the Rainier Mesa area where the welded Stockade Wash Tuff is present within zeolitic bedded tuff confining units (defined here as UTCU2 and UTCU1).
Stockade Wash aquifer (SWA)	WTA	Tcbs	Consists of partially welded ash-flow tuff of the Stockade Wash Lobe of the Bullfrog Tuff. Distribution limited to the central portion of the RM–SM model area.
Lower vitric-tuff aquifer 2 (LVTA2)	VTA	Tc, Tn	Relatively thin VTA unit below the SWA. Grouped with the TM-LVTA or LVTA where the SWA welded ash-flow tuff is not present.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Bullfrog confining unit (BFCU)	TCU	Tcb	Major confining unit in the Pahute Mesa area. Unit consists of thick intra-caldera, zeolitic, mostly nonwelded ash-flow tuff of the Bullfrog Tuff.
Upper tuff confining unit 1 (UTCU1)	TCU	Th, Tc	Defined to encompass the zeolitized bedded tuffs which stratigraphically overlie the BRA. Although some geologic units of the UTCU1 are laterally continuous with those of the LTCU and/or the UTCU2, the UTCU1 is limited areally to the northern portion of the RM–SM model area where the welded Grouse Canyon Tuff is present between the two tuff confining units (UTCU1 and LTCU).
Belted Range aquifer (BRA)	LFA and WTA, with lesser TCU	Tb, Tbg, Tbs, Tbq	Consists of welded ash-flow tuff and lava of the Belted Range Group (Tb) above the Grouse Canyon Tuff (Tbg), but may also include the lava flow lithofacies of the comendite of Split Ridge (Tbgs) and the comendite of Quartet Dome (Tbq) where present. Occurs in the northern portions of the RM-SM and Yucca Flat–Climax Mine (YF–CM) model areas.
Lower vitric-tuff aquifer 1 (LVTA1)	VTA	Tbgu, Tn4	Relatively thin vitric-tuff aquifer unit below the BRA. Grouped with the TM-LVTA or LVTA where the BRA welded ash-flow tuff is not present.
Pre-Belted Range composite unit (PBRCM)	TCU, WTA , LFA	Tr, Tn, Tq, Tu, To, Tk, Te	Laterally extensive and locally very thick HSU in the PM–OV model area that includes all the volcanic rocks older than the Belted Range Group. Consists of a poorly understood distribution of volcanic aquifers and confining units.
Belted Range confining unit (BRCU)	TCU	Tn, Tn4, Tn3	Includes all zeolitized tuffs above the welded Tub Spring Tuff (i.e., TSA). Limited to the northern NTS.
Pre-Grouse Canyon Tuff lava-flow aquifer (PRETBG)	LFA	Tbq, Tuo	Defined to include all the comendite lava flows emplaced before the Grouse Canyon Tuff but after the Tub Spring Tuff. Limited to the northern portions of the YF-CM model area.
Tub Spring aquifer (TUBA)	LFA	Tub	Comprises only the welded Tub Spring Tuff and is limited to the northeastern NTS.
Pre-Grouse Canyon Tuff lava-flow aquifer 1 (PRETBG1)	LFA	Tue	Defined to include all the comendite lava flows emplaced before the Tub Spring Tuff but after the older Tunnel beds (Ton). Limited to the northern portion of the YF–CM model area.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Lower tuff confining unit (LTCU)	TCU	Tmrh, Tp, Th, Tw, Tc, Tn, Tub, Ton2, To, Tlt	Generally includes all older zeolitized tuffs in the central and eastern NTS area. Stratigraphically the LTCU may include all units from the base of the Rainier Mesa Tuff to the top of the Paleozoic rocks. The strongly argillized older tuffs and paleocolluvium that immediately overlie pre-Tertiary rocks may also be included. The uppermost zeolitized bedded tuffs overlying the TSA in central and eastern NTS form a separate HSU (the UTCU). Subdivided into the LTCU, OSBCU, and ATCU where there is sufficient drill-hole control.
Oak Spring Butte confining unit (OSBCU)	TCU	Ton2, To, Toy, Ton1, Tor, Tot	Typically includes all volcanic rocks below the Tub Spring Tuff (Tub) to the top of pervasive argillization (i.e., ATCU), if present. Where not delineated, the units of the OSBCU are grouped within the LTCU.
Redrock Valley aquifer (RVA)	WTA	Tor, Tot	Includes only the welded lithofacies of the Redrock Valley Tuff in central and northern NTS. Where not strongly welded, lumped with the OSBCU or the LTCU.
Redrock Valley breccia confining unit (RVBCU)	TCU/AA	Not defined	Very limited areal extent; wedge-shaped volume inside the structural margin of the Redrock Valley caldera. Breccia blocks within an argillic matrix.
Lower tuff confining unit 1 (LTCU1)	TCU	To	Zeolitic bedded tuffs below the welded Redrock Valley Tuff. Separates overlying RVA from pre-Tertiary units and/or ATCU.
Twin Peaks aquifer (TPA)	WTA	Tot	Includes only the welded lithofacies of the tuff of Twin Peaks in central and northern NTS. Where not strongly welded, is lumped with the OSBCU or the LTCU. Defined only for the “No Redrock Valley Caldera” alternative; otherwise lumped with the RVA.
Argillic tuff confining unit (ATCU)	TCU	To, Tlt	Includes the argillic, lowermost Tertiary volcanic units and paleocolluvium that immediately overlie the pre-Tertiary rocks.
Volcaniclastic confining unit (VCU)	TCU	Tgp, Tgw	Older Tertiary-age sedimentary rocks of variable lithologies. Present in the southeastern corner of the YF–CM model area, but is a significant HSU in the Frenchman Flat model area. Similar to AA in the YF–CM model, but name retained to correlate with the Frenchman Flat model in the area of overlap.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Black Mountain intrusive confining unit (BMICU)	IICU	Not defined	Although modeled as single intrusive masses beneath each of the Black Mountain, Ammonia Tanks, Rainier Mesa, Claim Canyon, and Silent Canyon calderas, and the Calico Hills area, the actual nature of these units is unknown. They may consist exclusively of igneous intrusive rocks, or older volcanic and pre-Tertiary sedimentary rocks that are intruded to varying degrees by igneous rocks ranging in composition from granite to basalt.
Ammonia Tanks intrusive confining unit (ATICU)	IICU	Not defined	
Rainier Mesa intrusive confining unit (RMICU)	IICU	Not defined	
Claim Canyon intrusive confining unit (CCICU)	IICU	Not defined	
Calico Hills intrusive confining unit (CHICU)	IICU	Not defined	
Silent Canyon intrusive confining unit (SCICU)	IICU	Not defined	
Redrock Valley intrusive confining unit (RVICU)	IICU	Not defined	
Mesozoic granite confining unit (MGCU)	GCU	Kg	Consists of granitic rocks that form the Gold Meadows and Climax stocks in the northern part of the NTS.
Lower clastic confining unit 1–thrust plate (LCCU1)	CCU	Cc, Cz, Czw, Zs	Late Proterozoic to Early Cambrian siliciclastic rocks that occur within the hanging wall of the Belted Range thrust fault.

Table A-1
Hydrostratigraphic Units of UGTA CAU-Scale Hydrostratigraphic Framework Models (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Units [b]	General Description
Lower carbonate aquifer–thrust plate (LCA3)	CA	Dg through Cc	Cambrian through Devonian, mostly carbonate, rocks that occur in the hanging wall of the Belted Range and CP thrust faults. Typically separated from correlative rocks within LCA by intervening younger rocks such as those composing the UCCU.
Upper clastic confining unit–thrust plate (UCCU1)	CCU	PMc, MDe	Occurs as a thin imbricate thrust sheet of Mississippian CCU associated with the Belted Range thrust fault. Defined only for an alternative in the RM-SM HFM.
Lower carbonate aquifer–thrust plate–1 (LCA3-1)	CA	Dg through Cc	Occurs as a thin imbricate thrust sheet of CA associated with the Belted Range thrust fault. Defined only for an alternative in the RM–SM HFM.
Lower clastic confining unit 2–thrust plate (LCCU2)	CCU	Lower Cc, Cz, CZw, Zs, Zj	Late Proterozoic to early Cambrian siliciclastic rocks that occur within the hanging wall of the CP thrust fault.
Upper carbonate aquifer (UCA)	CA	PPt	Includes the Tippipah Limestone, which stratigraphically overlies the Chainman Shale at Syncline Ridge.
Upper clastic confining unit (UCCU)	CCU	PMc, MDe	As much as 2,745 m (9,000 ft) thick. Typically forms footwalls of Mesozoic thrust faults in NTS region. Limited areal extent (western Yucca Flat and portions of CP Basin).
Lower carbonate aquifer (LCA)	CA	Dg through Cc	Cambrian through Devonian, mostly limestone and dolomite. Important regional aquifer underlying most of southern Nevada.
Lower clastic confining unit (LCCU)	CCU	Cc, Cz, Czw, Zs, Zj	Late Proterozoic through Early Cambrian siliciclastic rocks. Significant regional confining unit. Composite thickness about 2,870 m (9,400 ft). May present barrier to deep regional groundwater flow where structurally high (e.g., northeastern Yucca Flat).

a See Table 3-1 for definitions of HGUs.
b See Plate 1 for definitions of stratigraphic unit map symbols.

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APPENDIX B

Examples of HSU Delineation in UGTA Wells

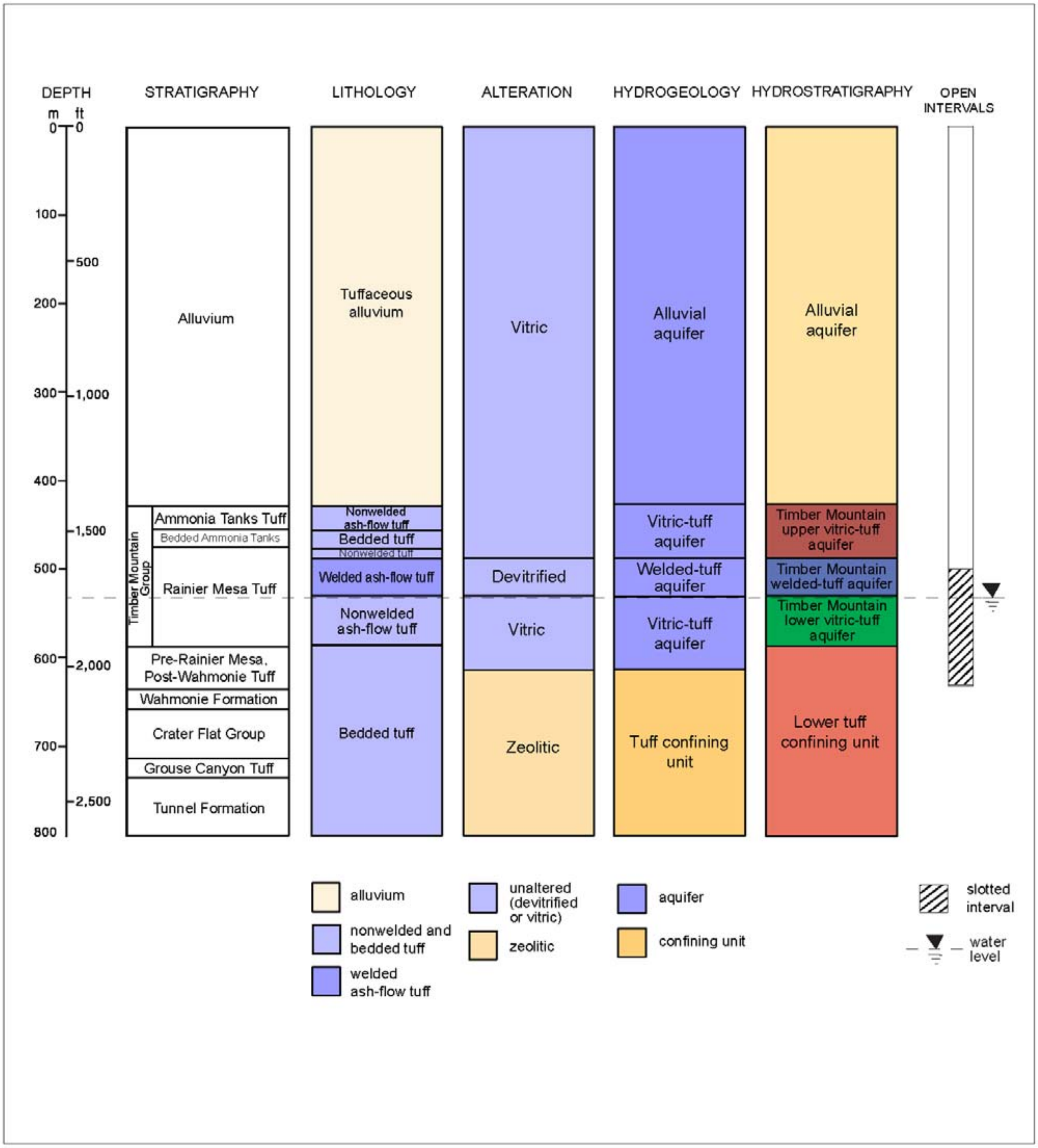

Figure B-1
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-2-1

Modified from NNSA/NSO, 2004h

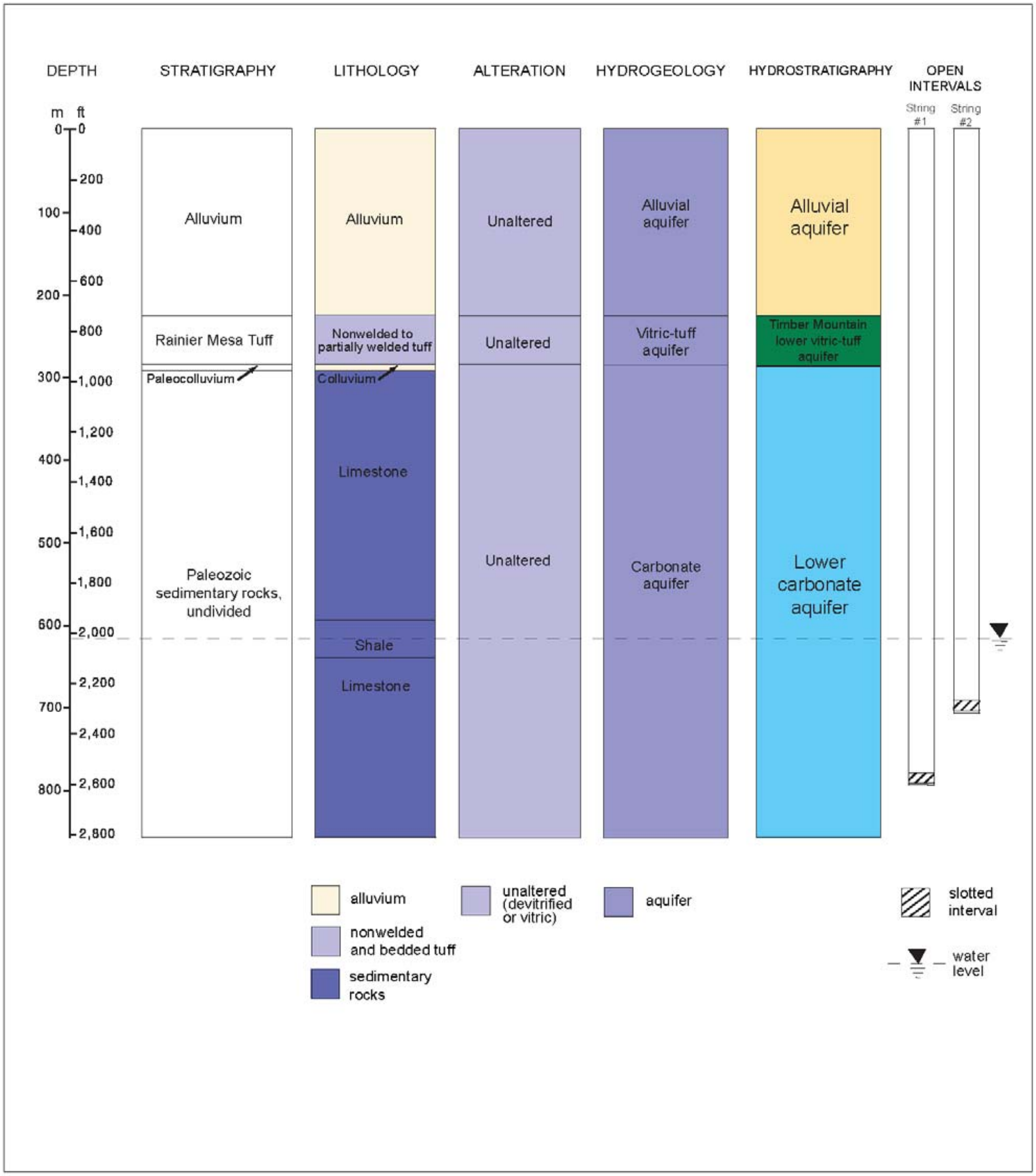

Figure B-2
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-3-1

(Data from DOE/NV, 1995a)

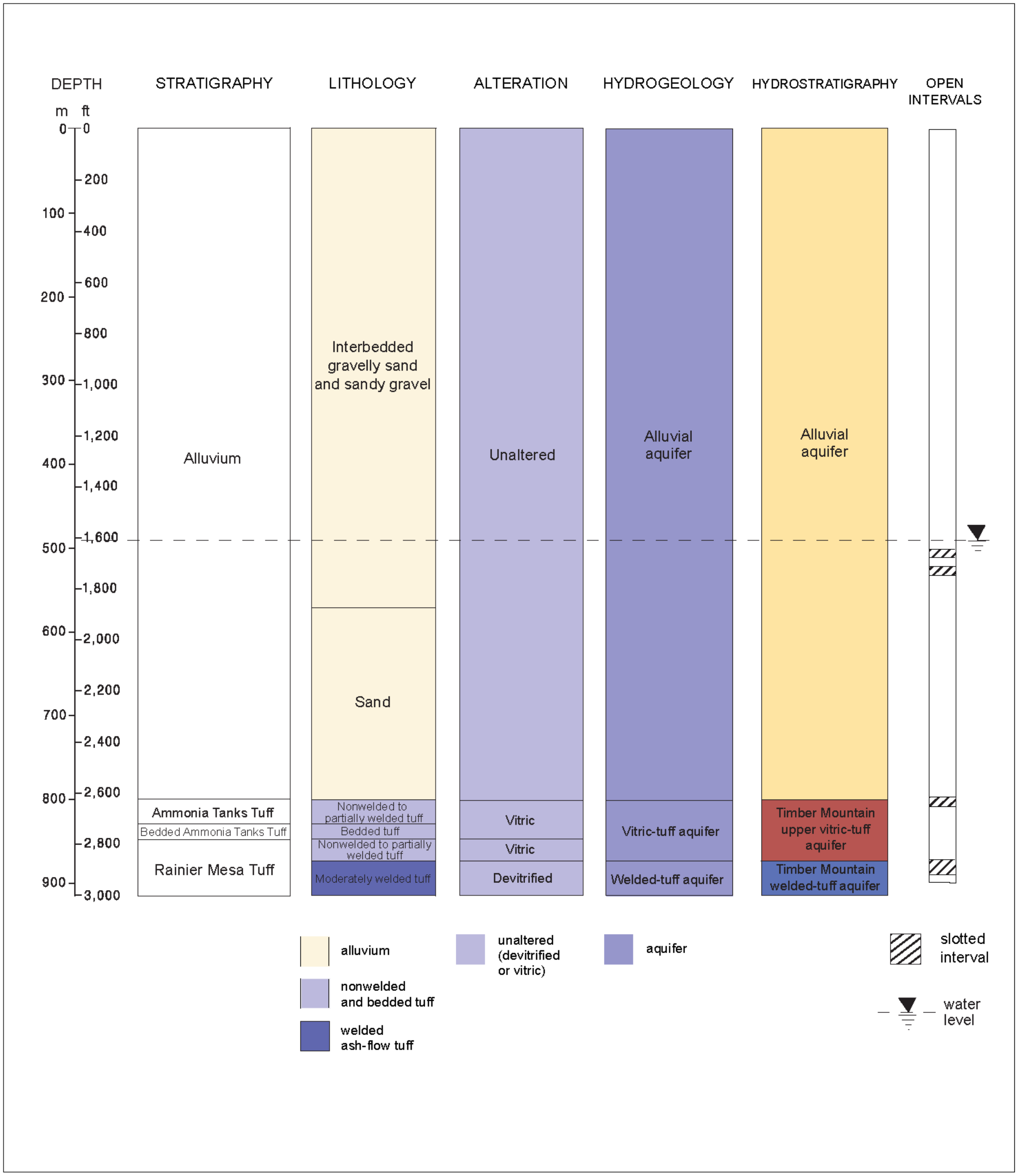

Figure B-3
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-3-2

(Data from DOE/NV, 1995b)

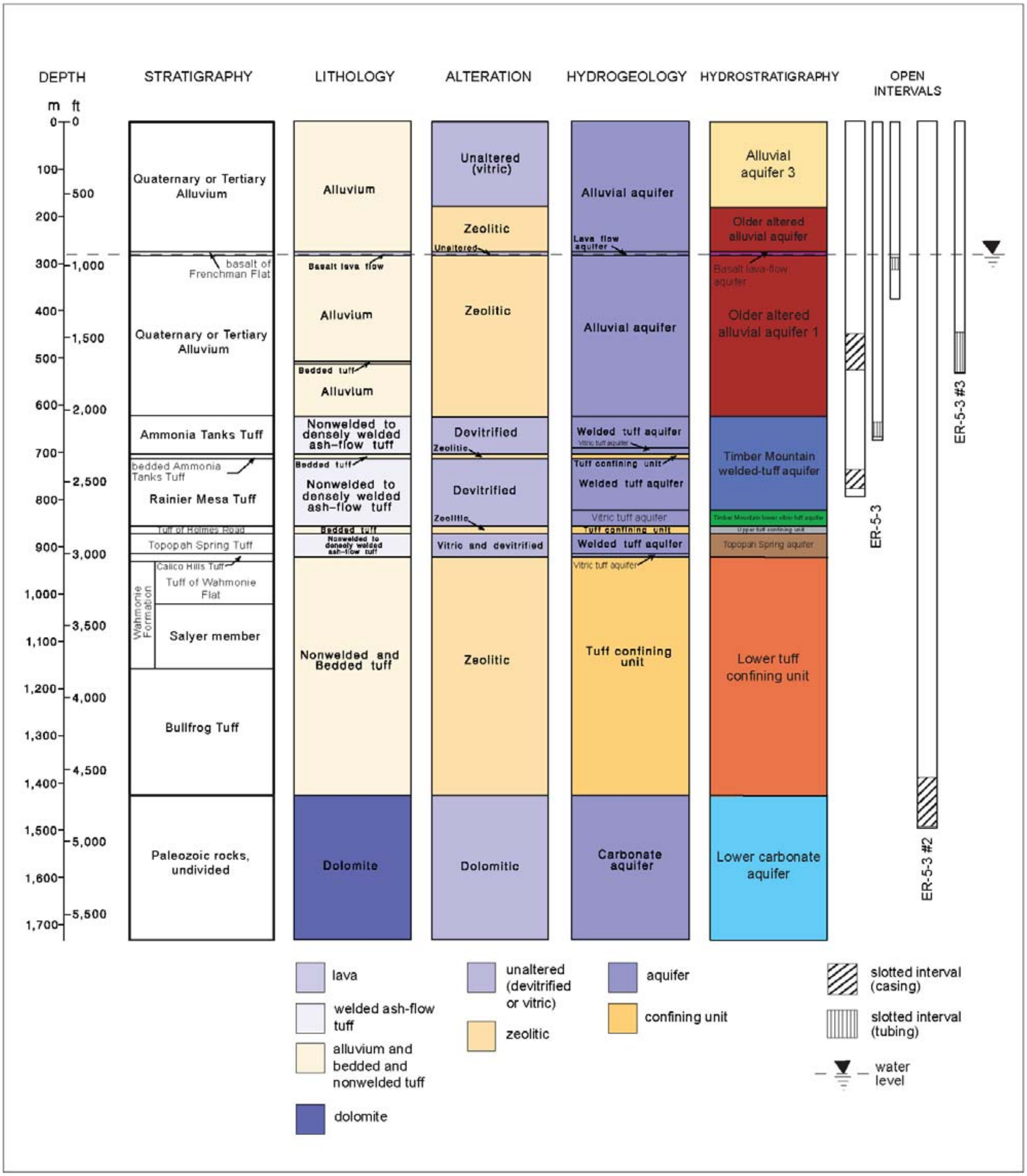

Figure B-4
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for Well Cluster ER-5-3
(Modified from NNSA/NSO, 2005a)

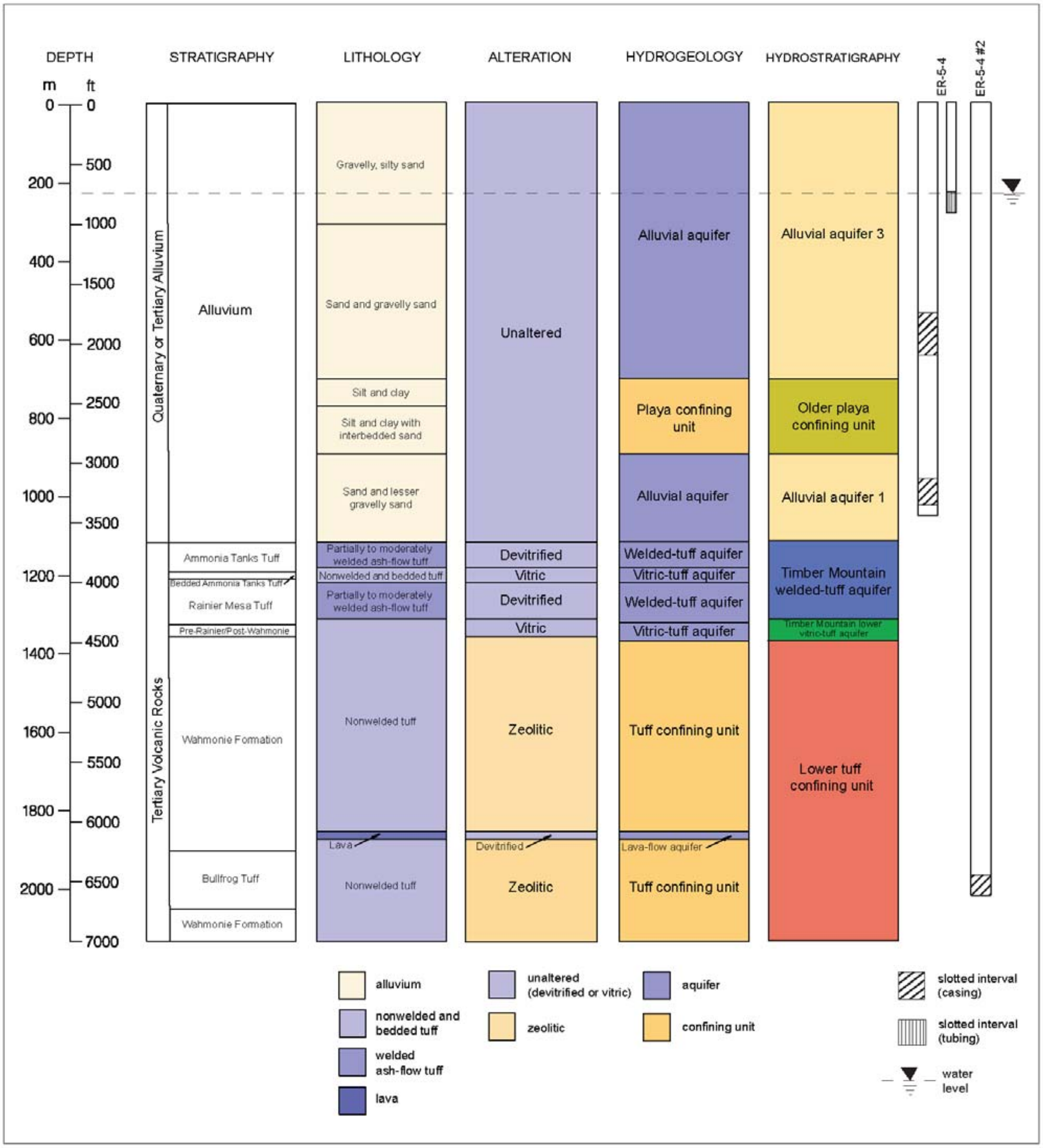

Figure B-5
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well Cluster ER-5-4

(Modified from NNSA/NSO, 2005b)

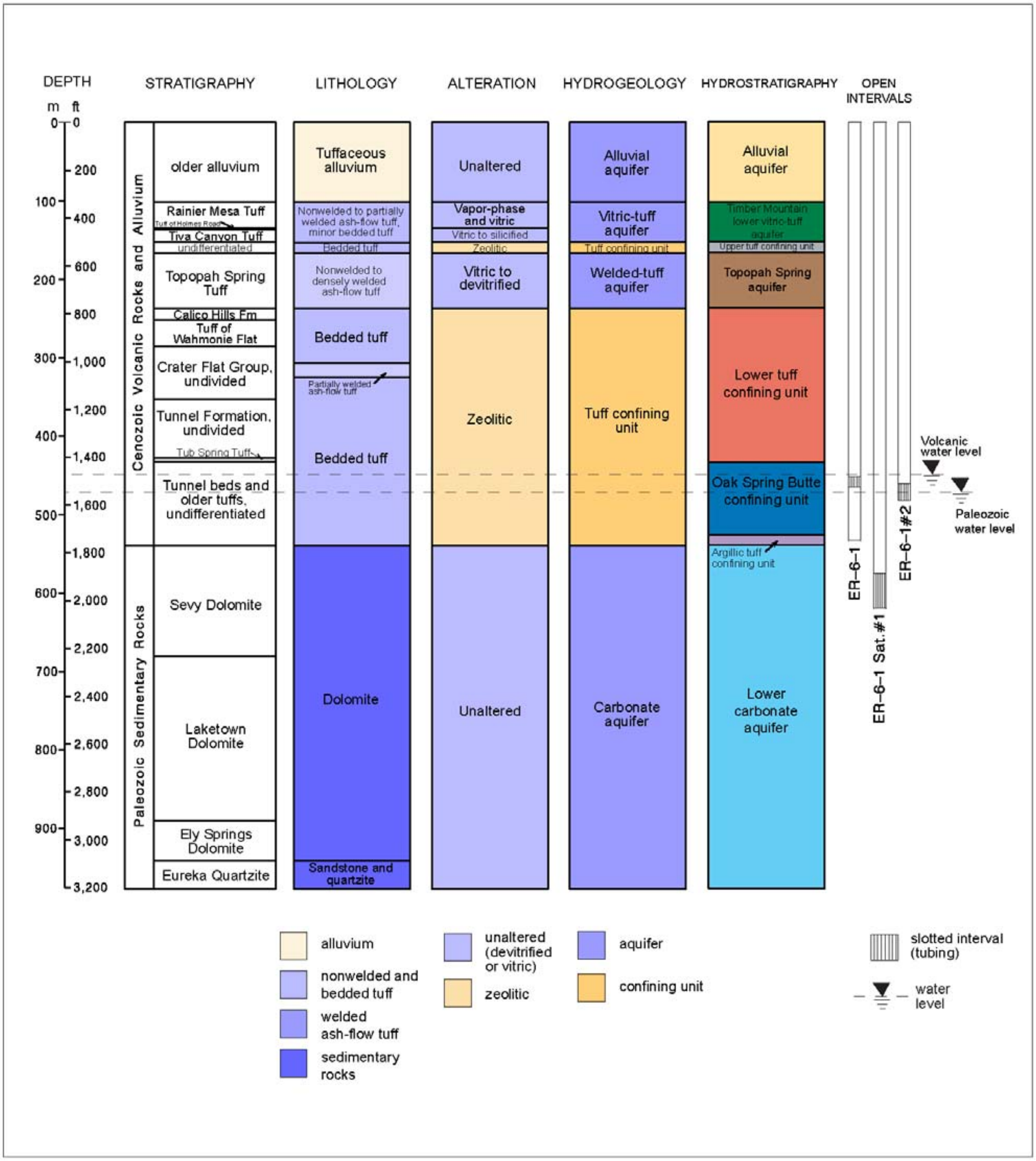

Figure B-6
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well Cluster ER-6-1

(Modified from NNSA/NSO, 2004f)

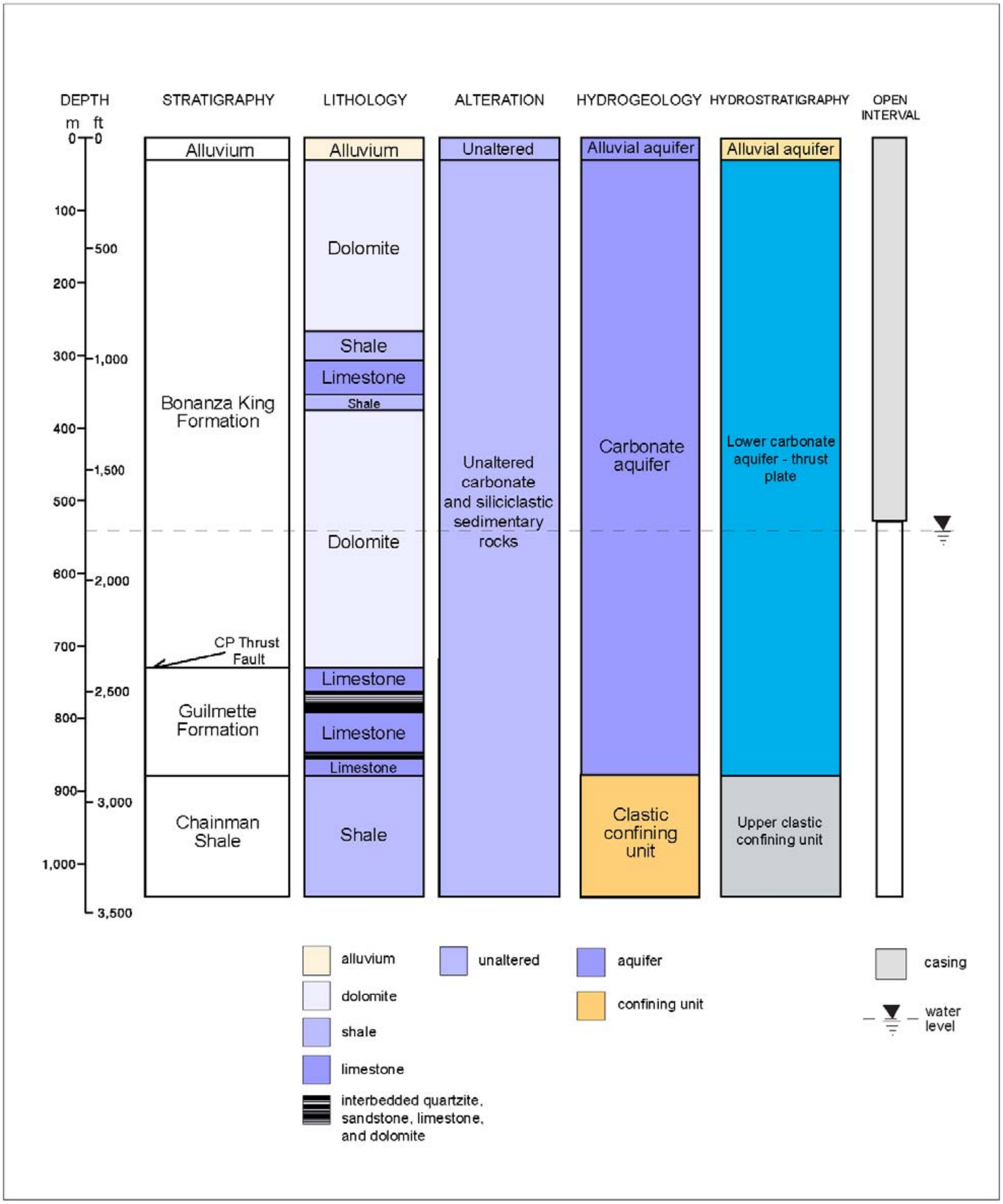

Figure B-7
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-6-2
(Modified from NNSA/NSO, 2008)

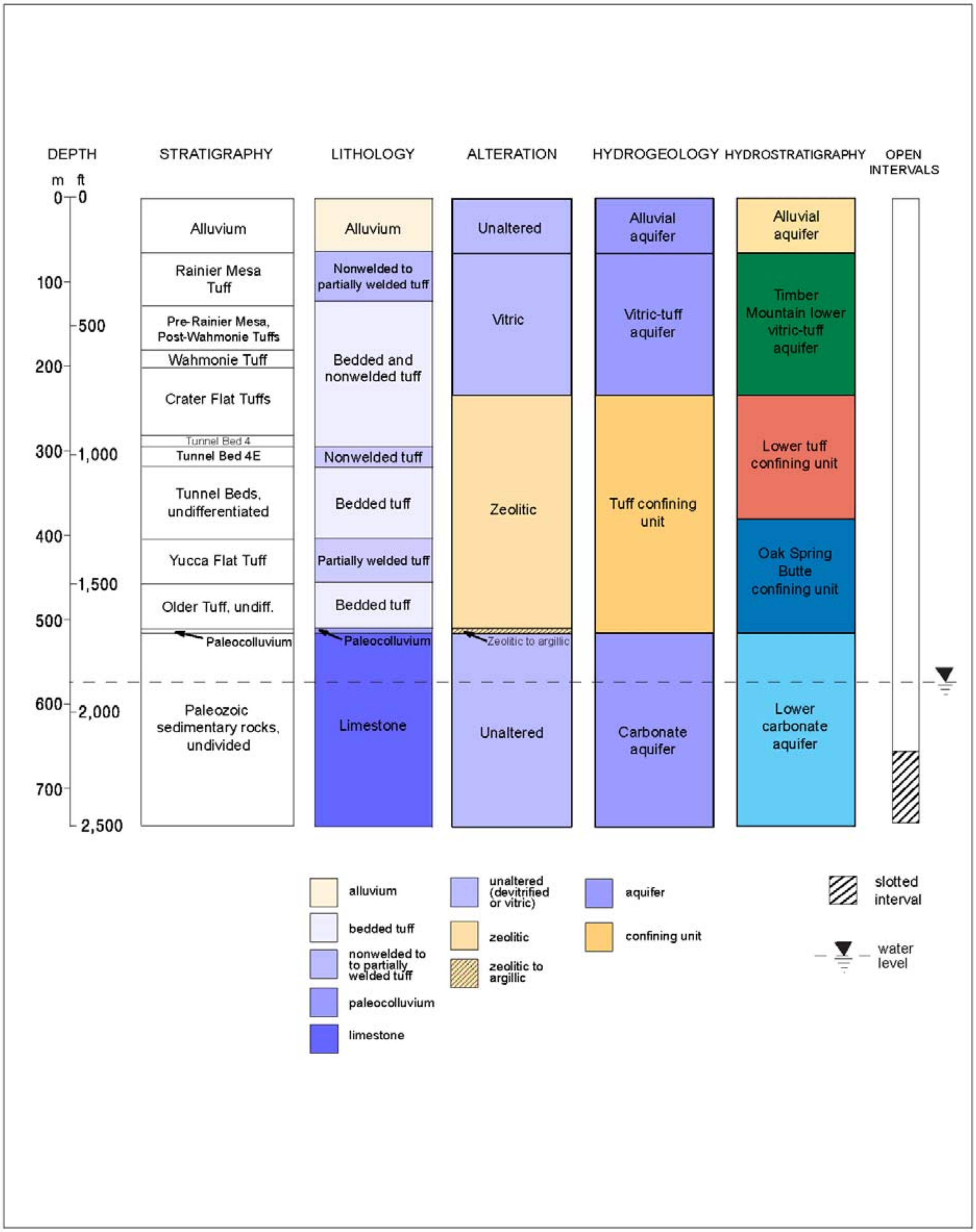

Figure B-8
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-7-1
(Modified from NNSA/NSO, 2004g)

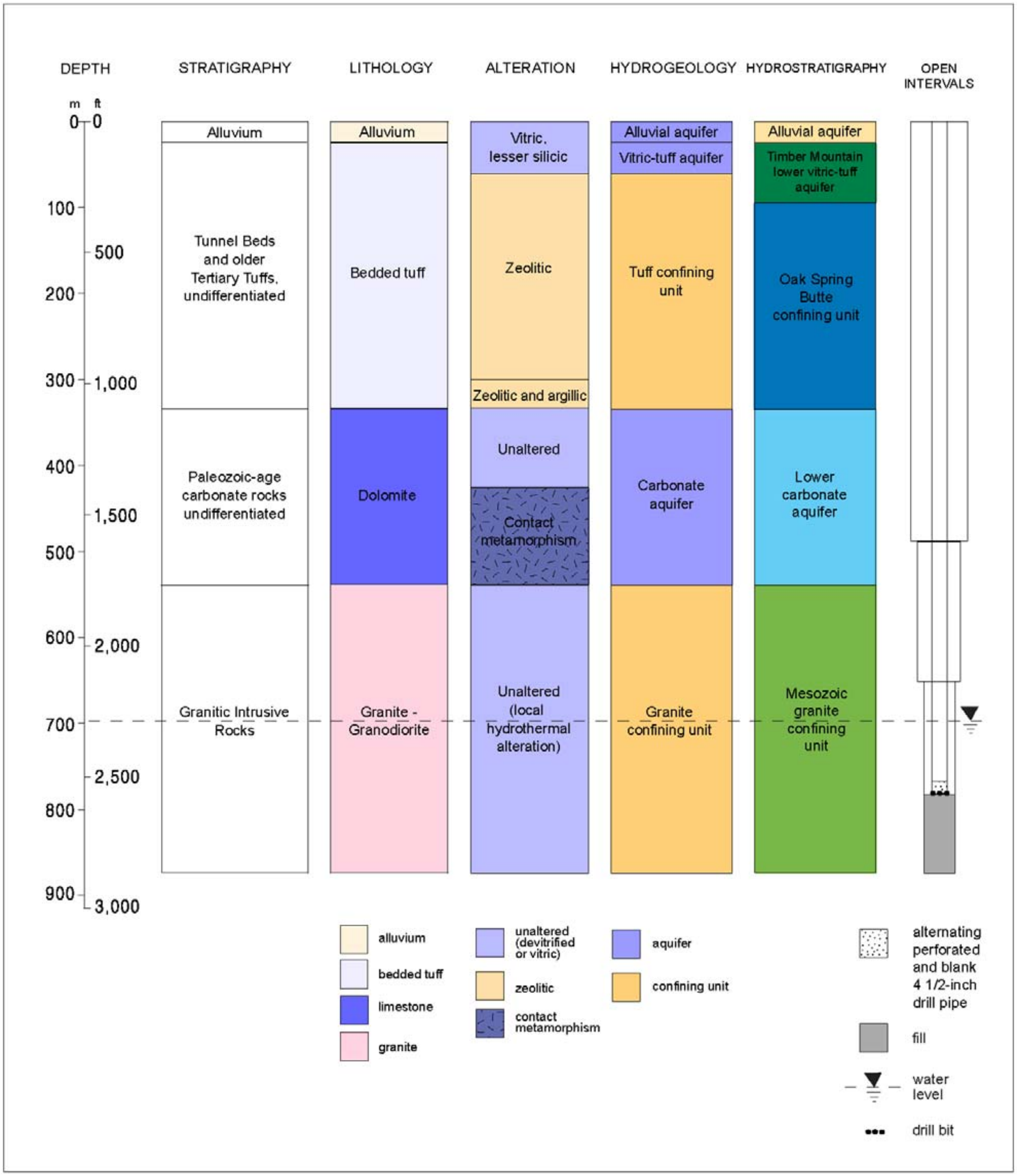

Figure B-9
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-8-1

(Modified from NNSA/NSO, 2004d)

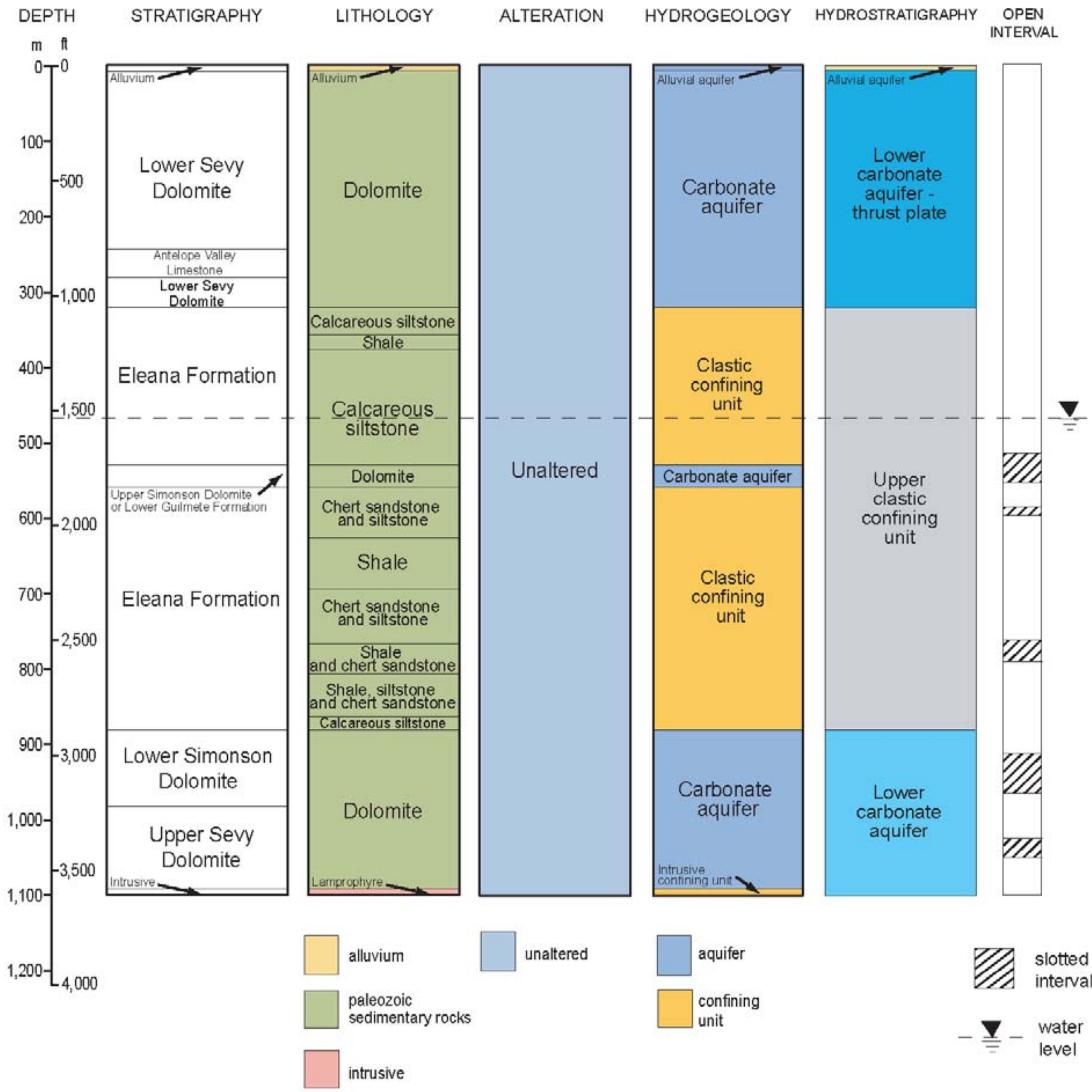

Figure B-10
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-12-1

(Data from Russell et al., 1996)

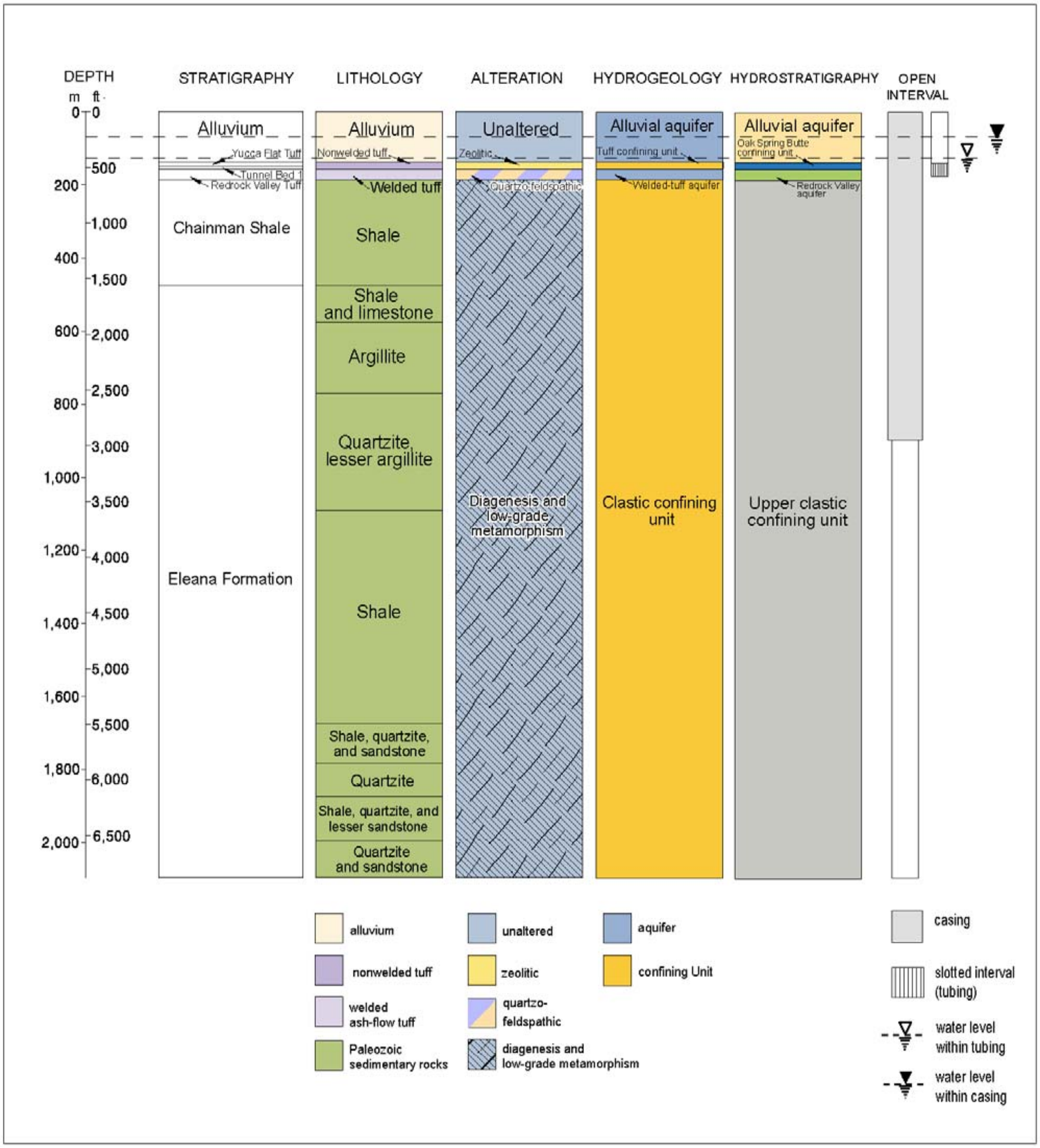

Figure B-11
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-12-2

(Modified from NNSA/NSO, 2004e)

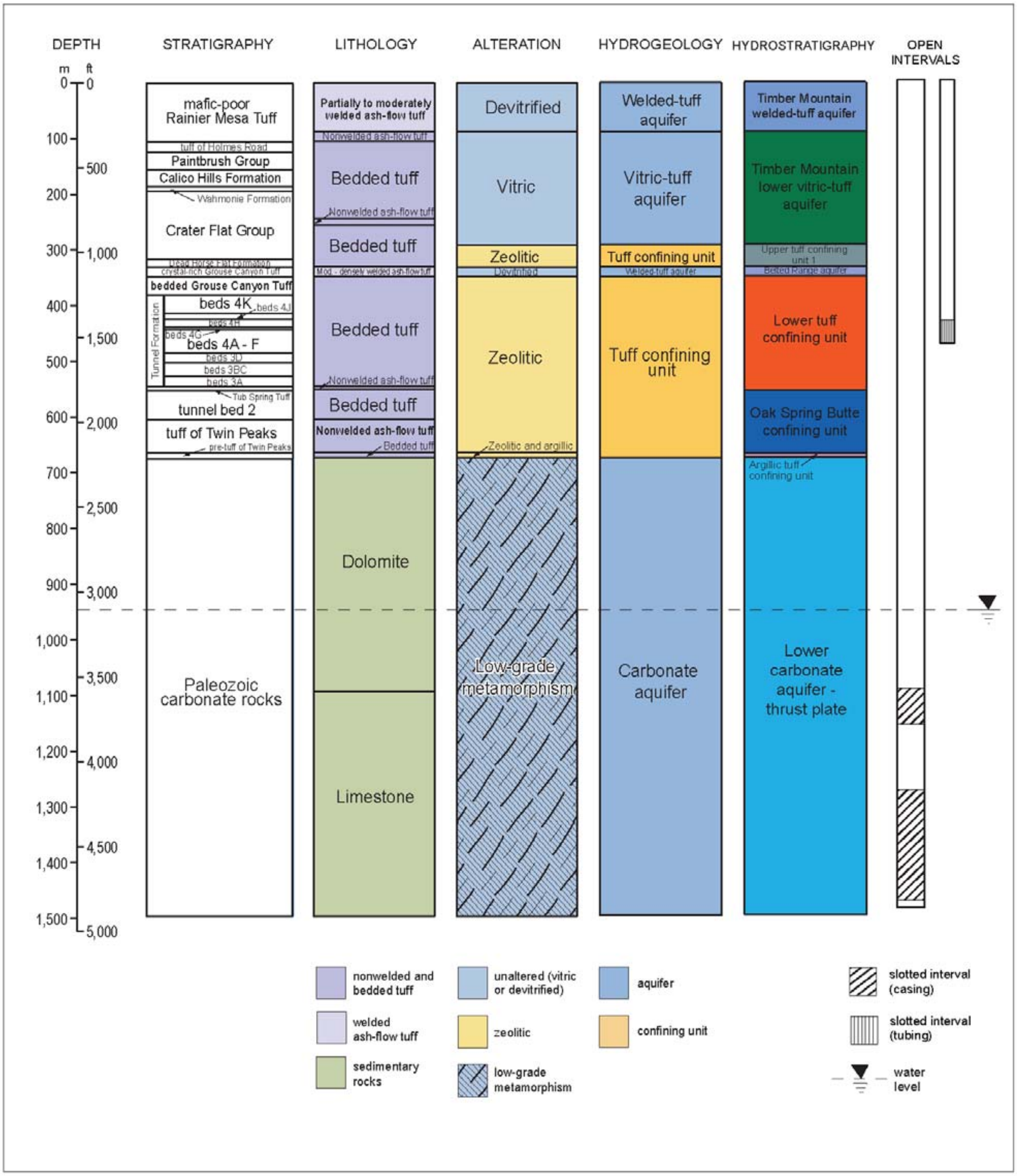

Figure B-12
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-12-3
(Modified from NNSA/NSO, 2006a)

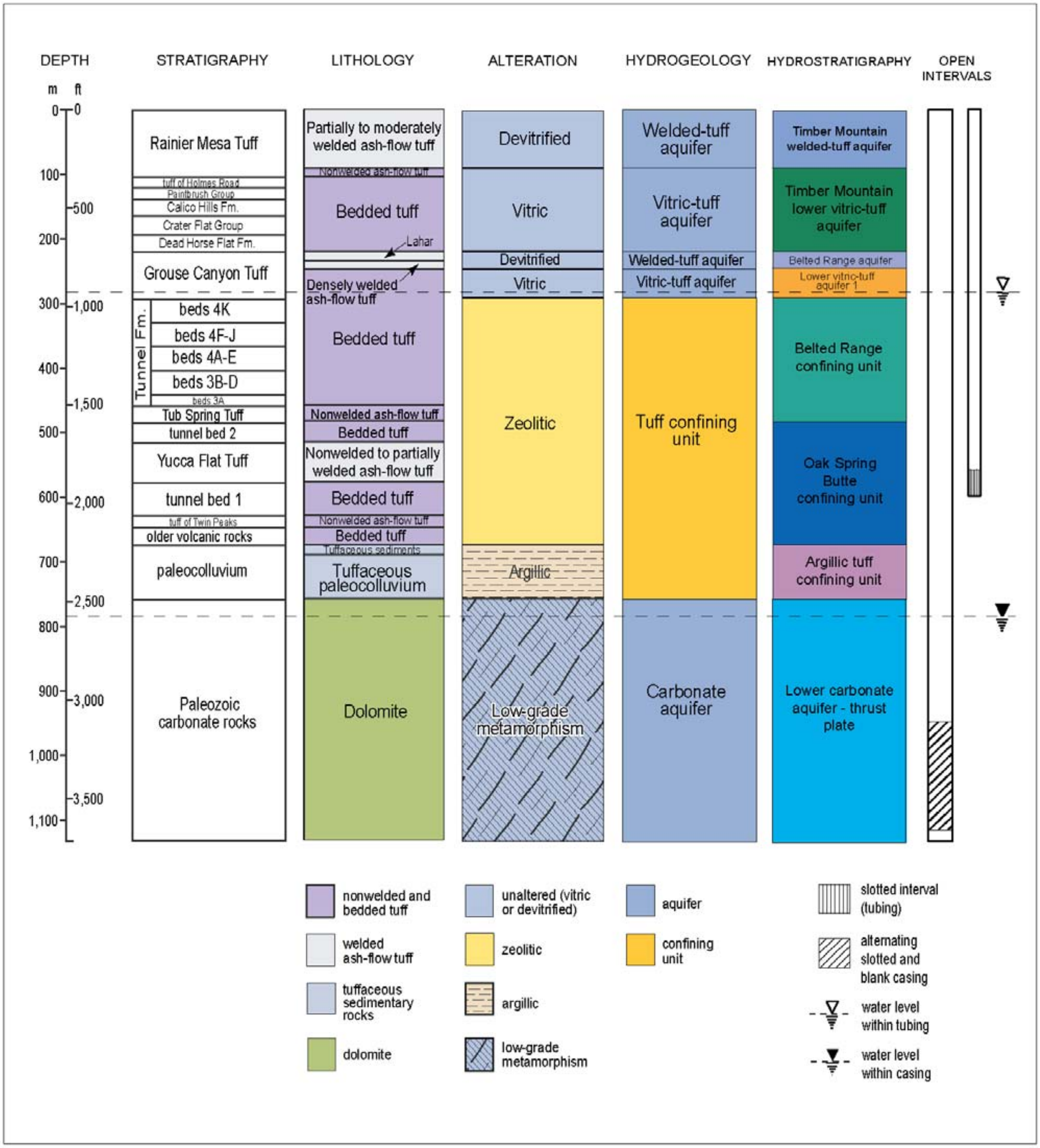

Figure B-13
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-12-4
(Modified from NNSA/NSO, 2006b)

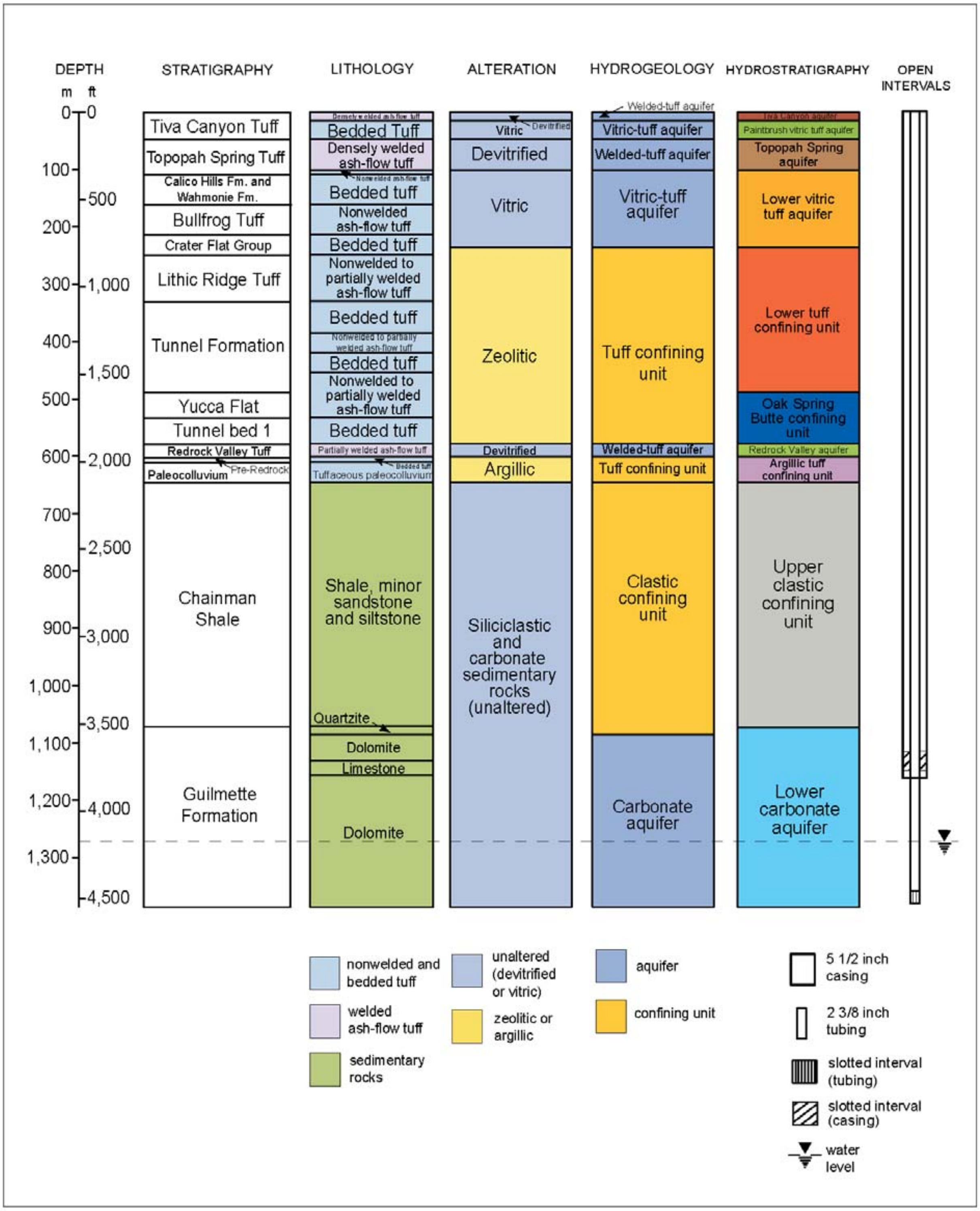

Figure B-14
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-16-1

(Modified from NNSA/NSO, 2006c)

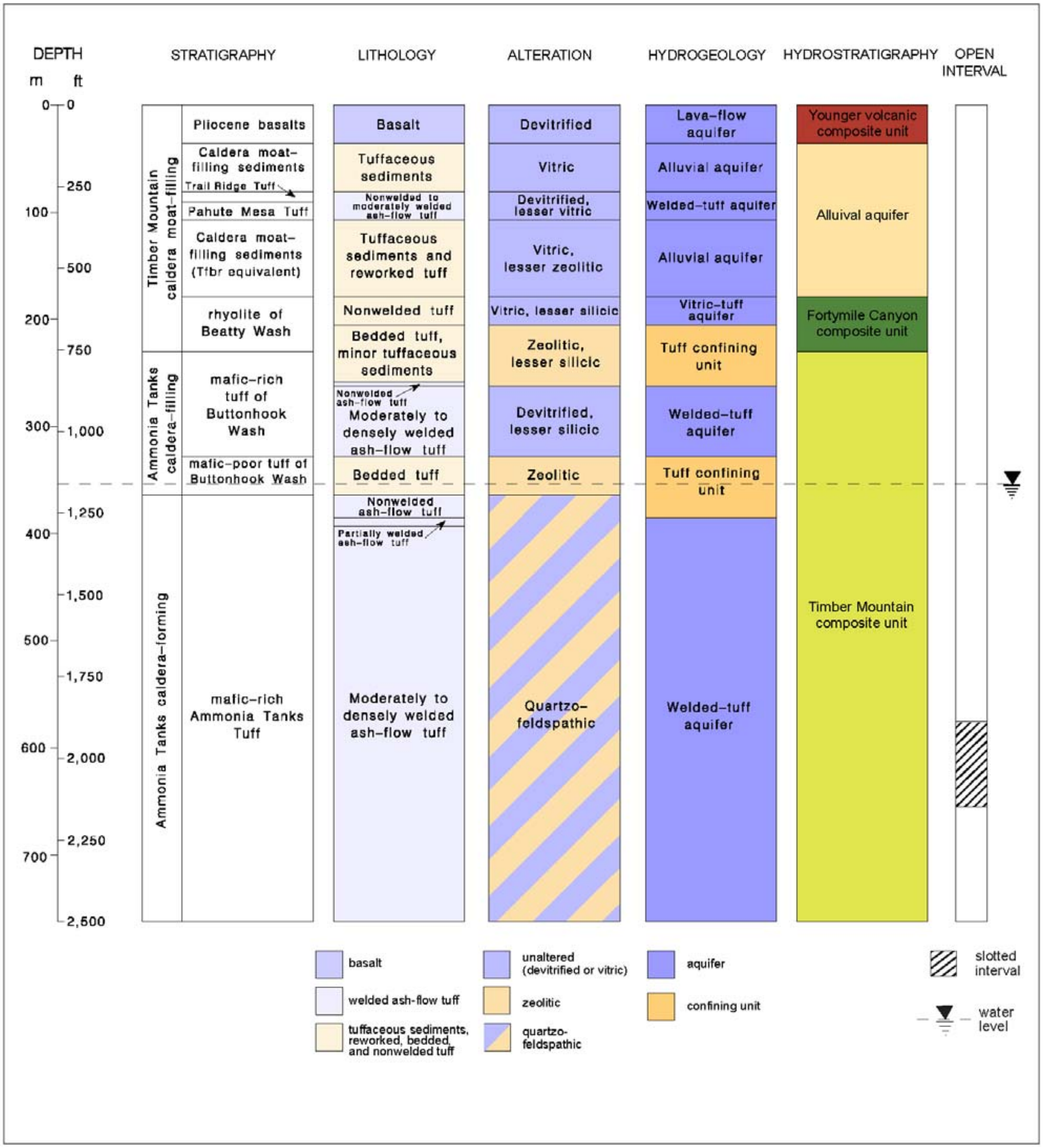

Figure B-15
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-18-2

(Modified from NNSA/NSO, 2003)

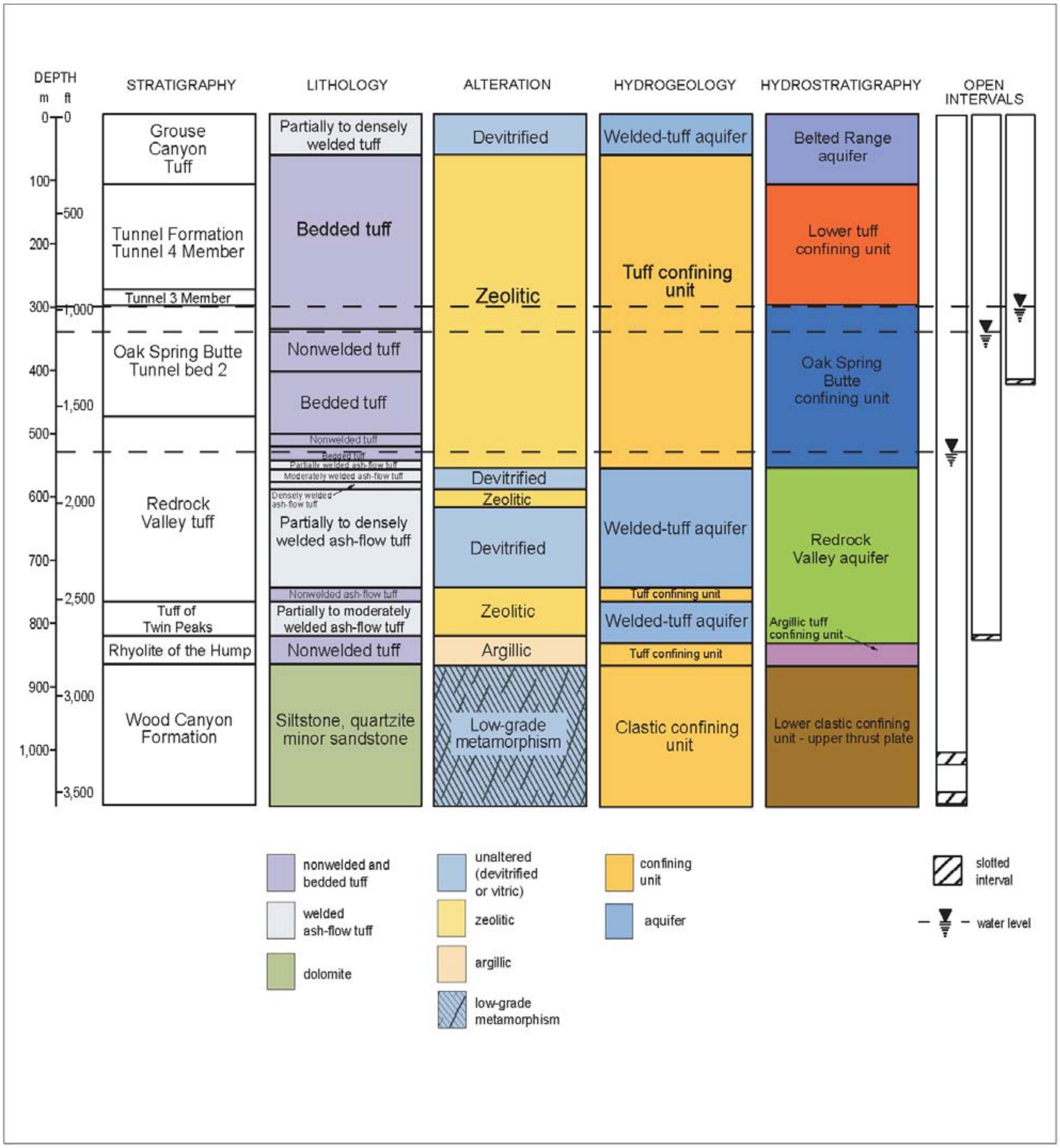

Figure B-16
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-19-1

(Data from DOE/NV, 1995c)

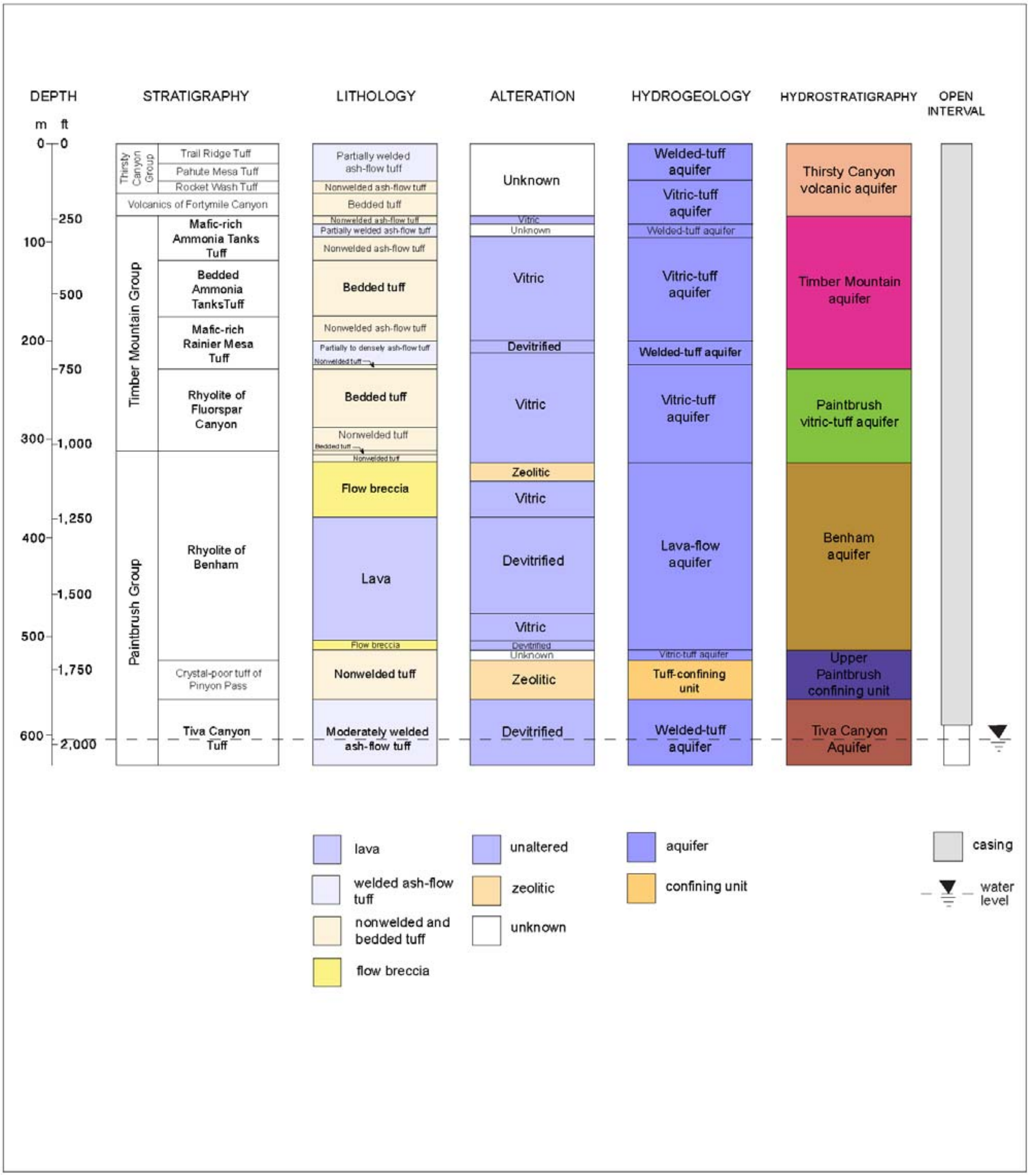

Figure B-17
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-20-1

(Data from BN, 2002)

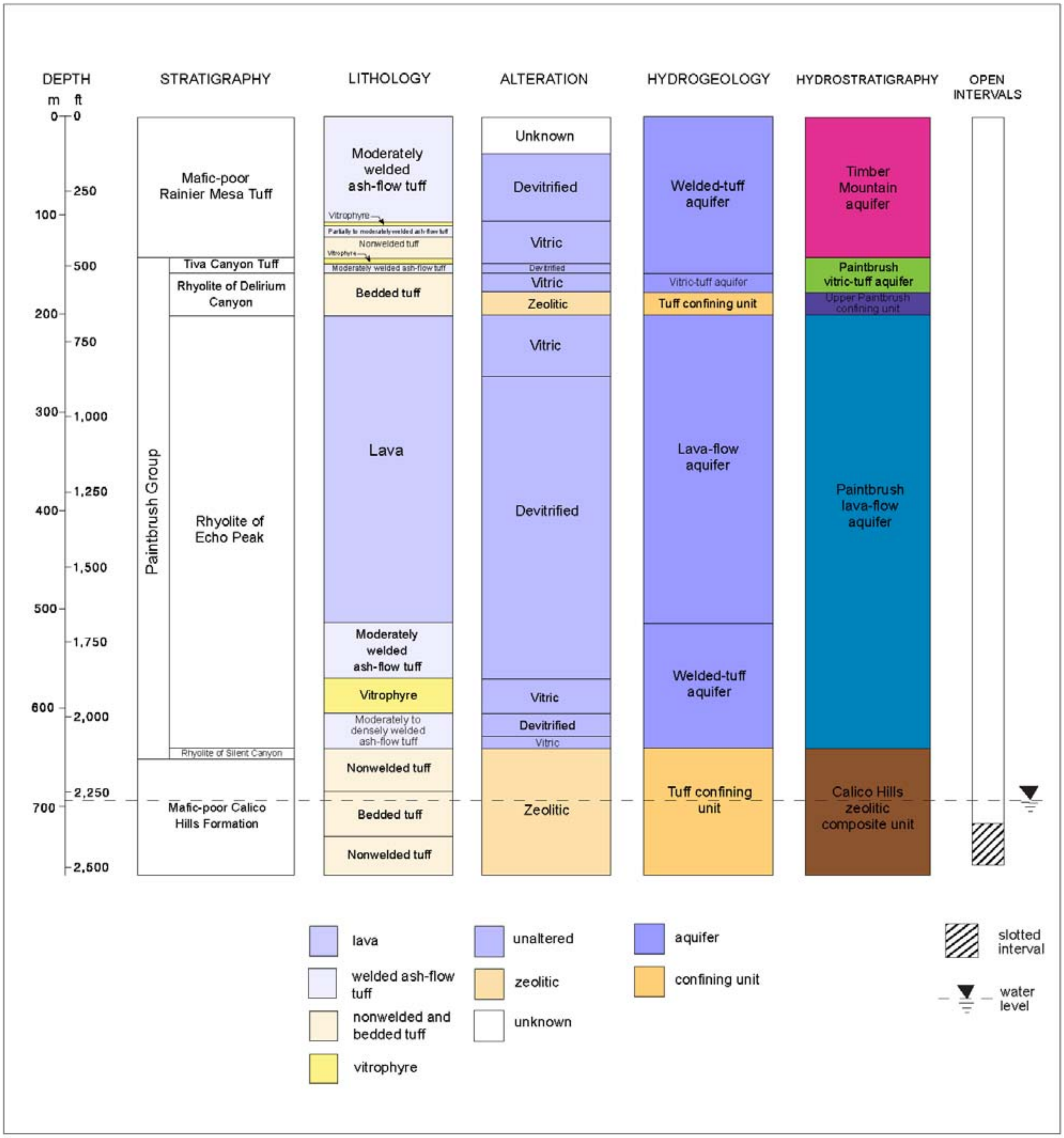

Figure B-18
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-20-2 Sat #1
(Data from BN, 2002)

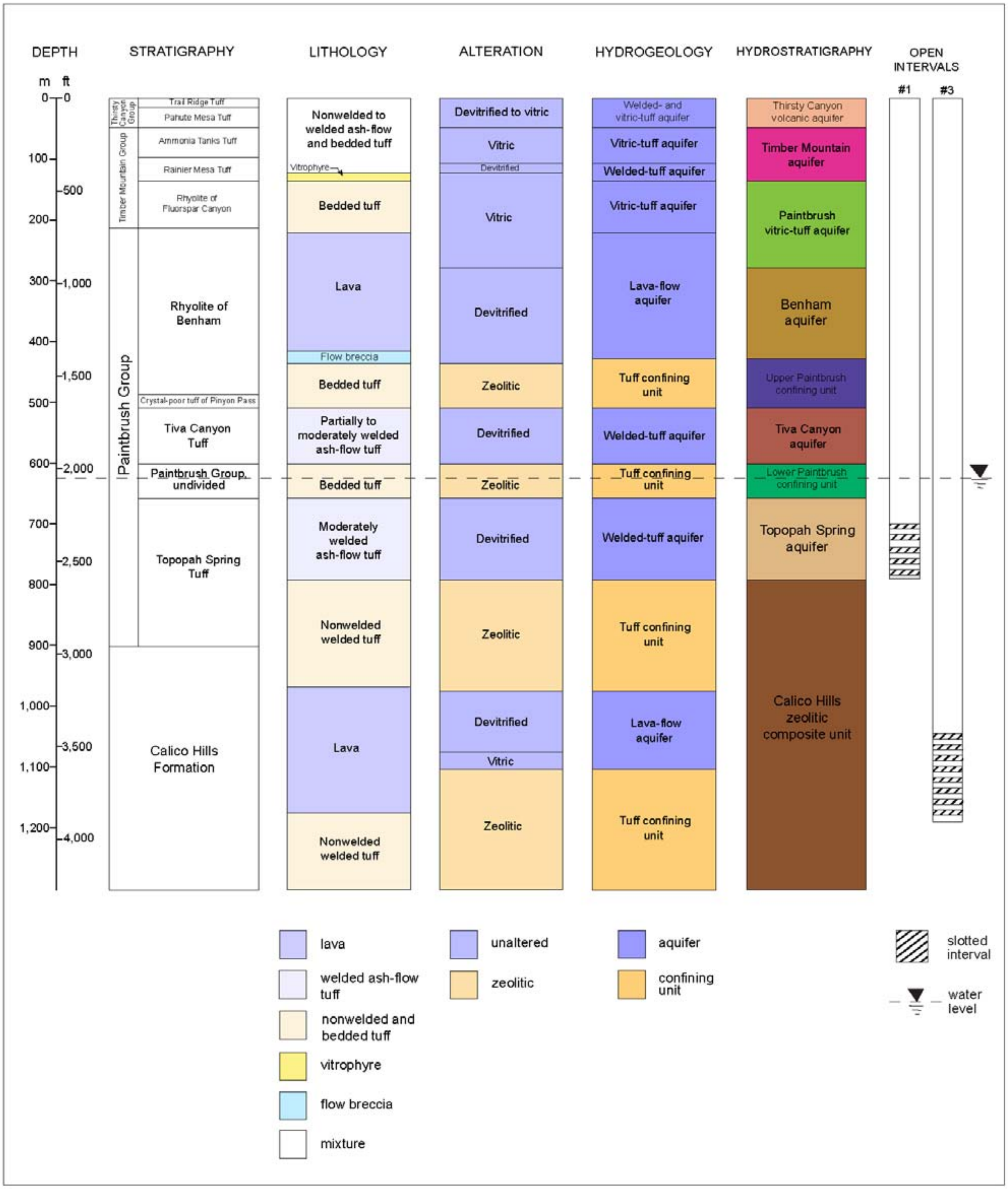

Figure B-19
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-20-5

(Data from DOE/NV, 1997)

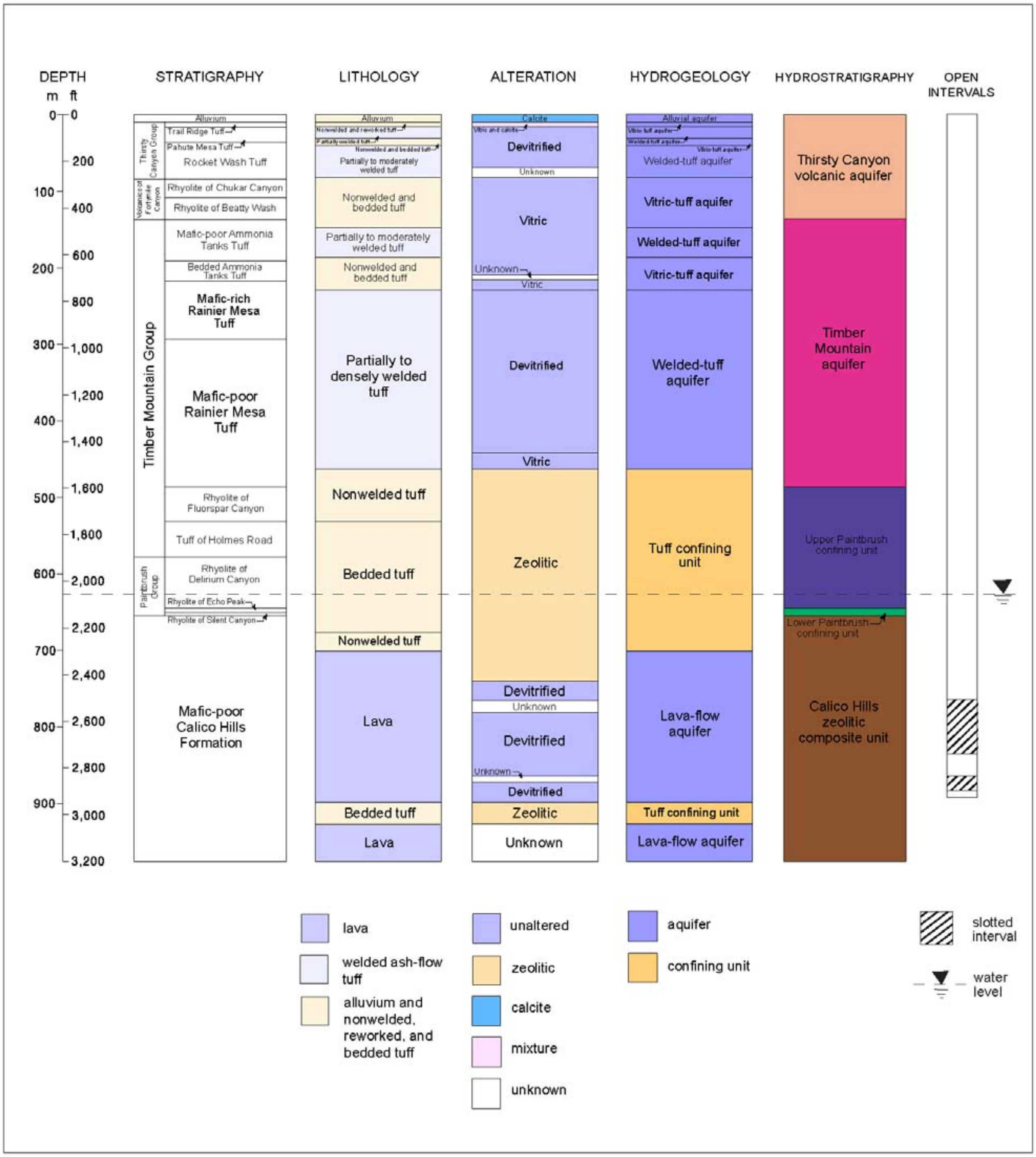

Figure B-20
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-20-6 #1

(Data from DOE/NV, 1998)

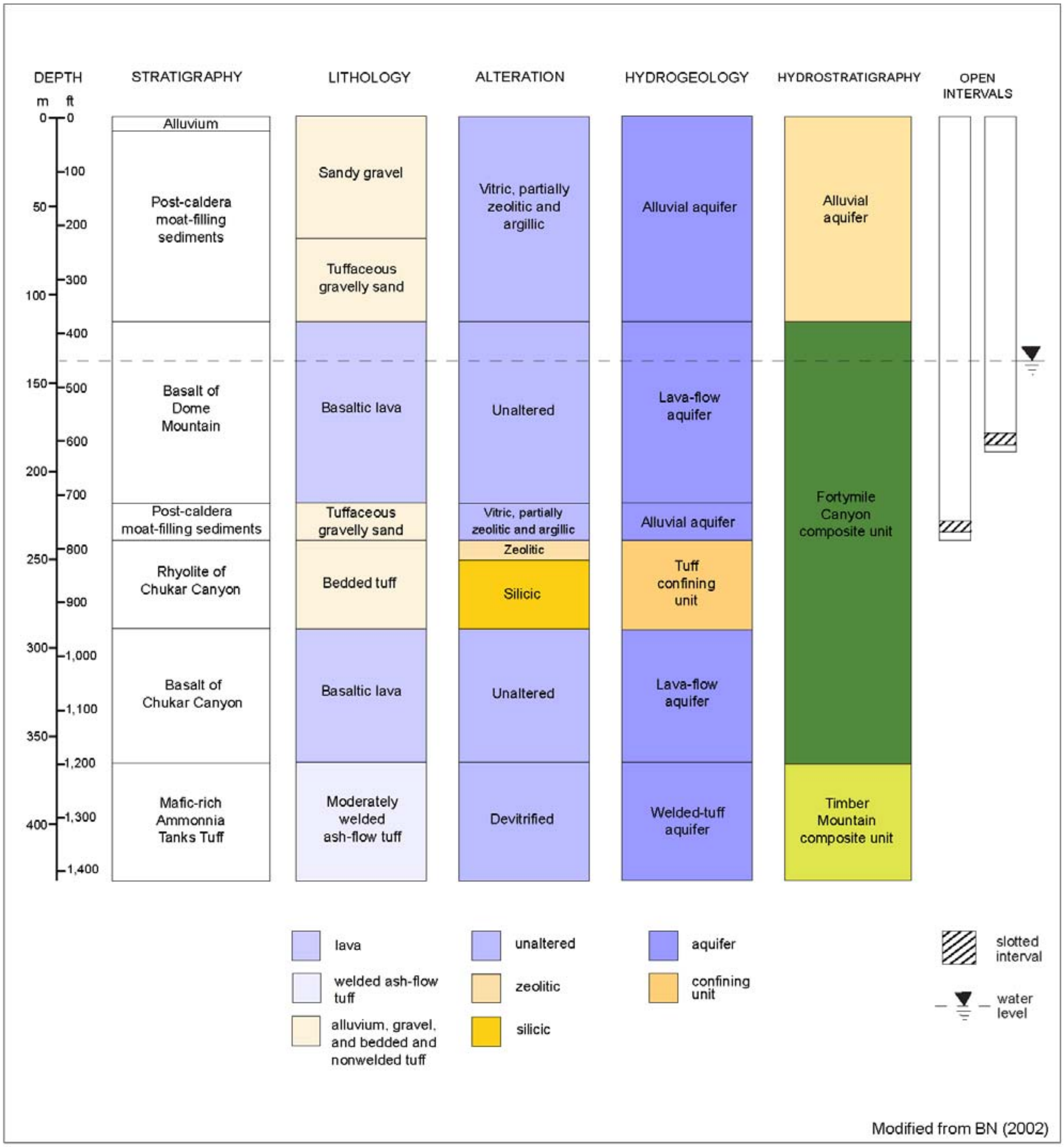

Figure B-21
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-30-1

(Data from DOE/NV, 1995d)

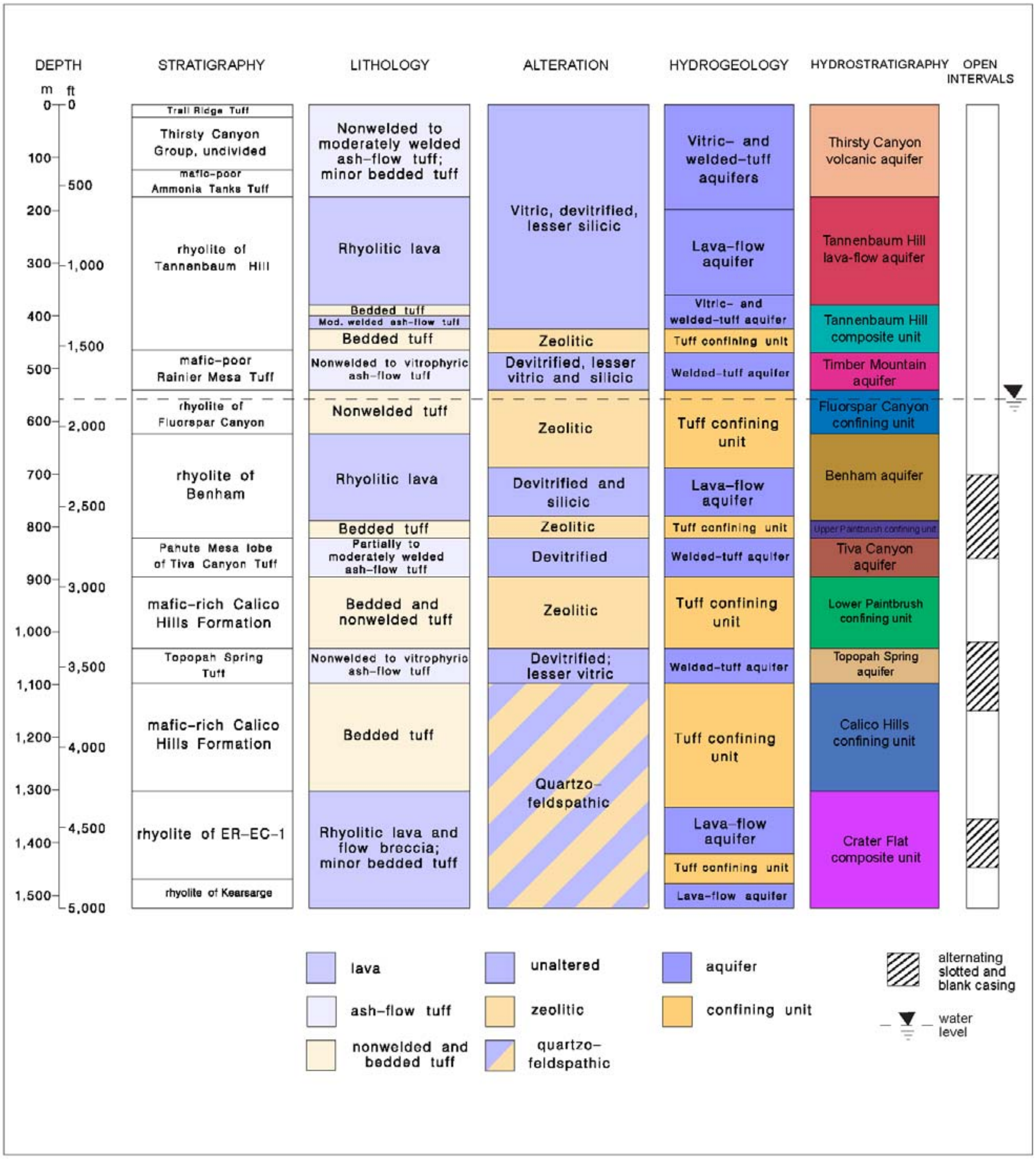

Figure B-22
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-1

(Modified from DOE/NV, 2000b)

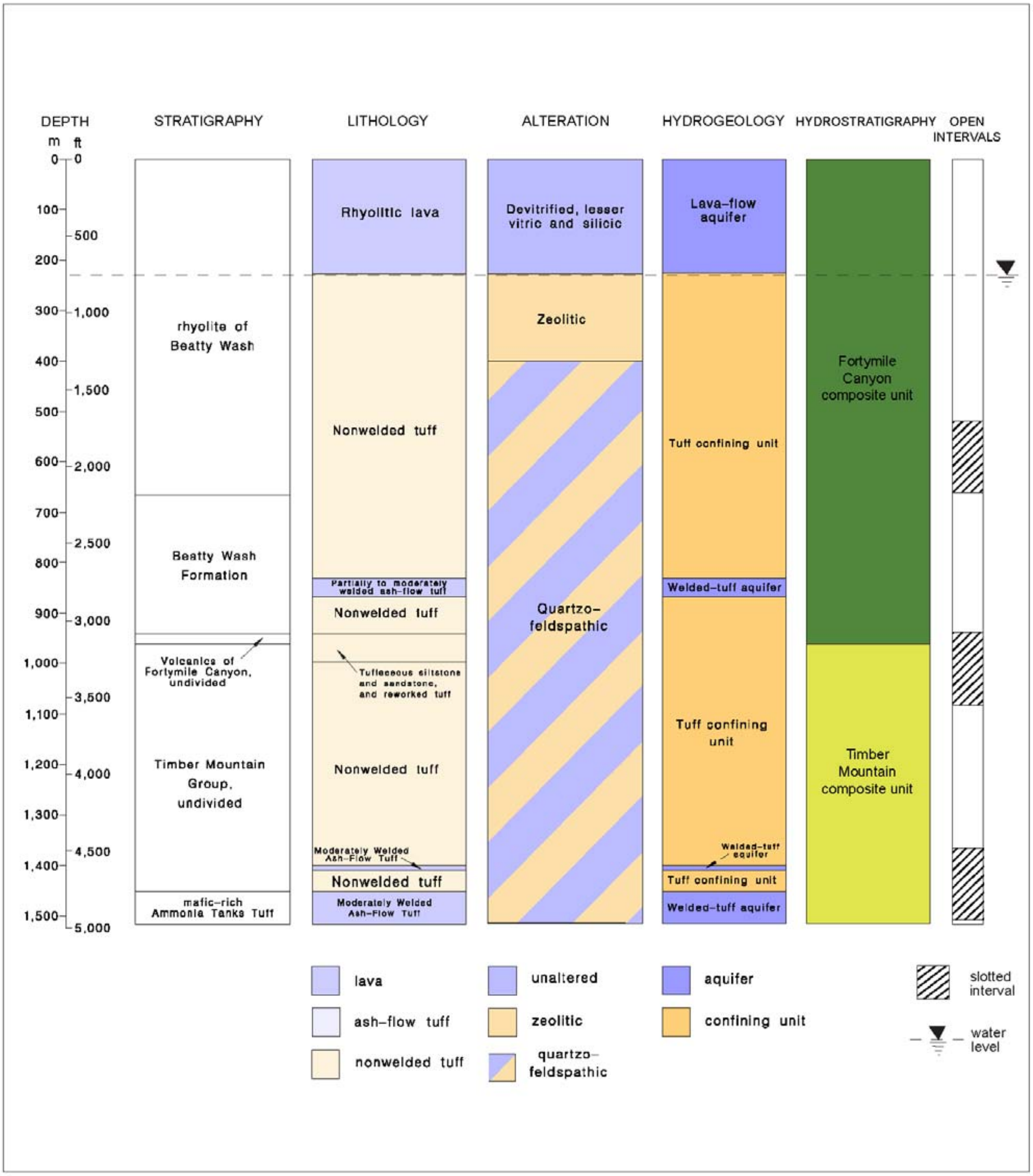

Figure B-23
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-2A
(Modified from DOE/NV, 2002)

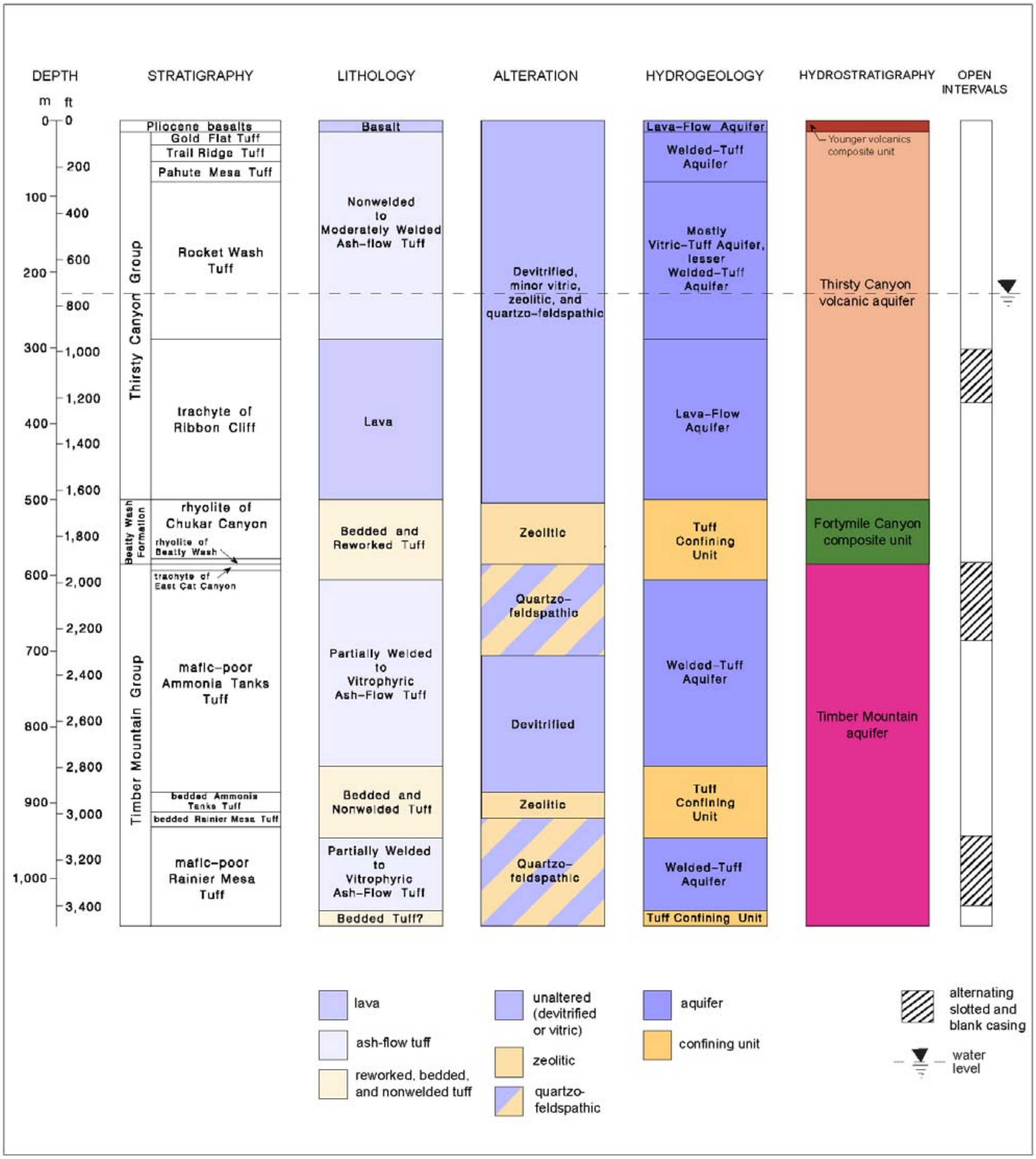

Figure B-24
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-4

(Modified from DOE/NV, 2000c)

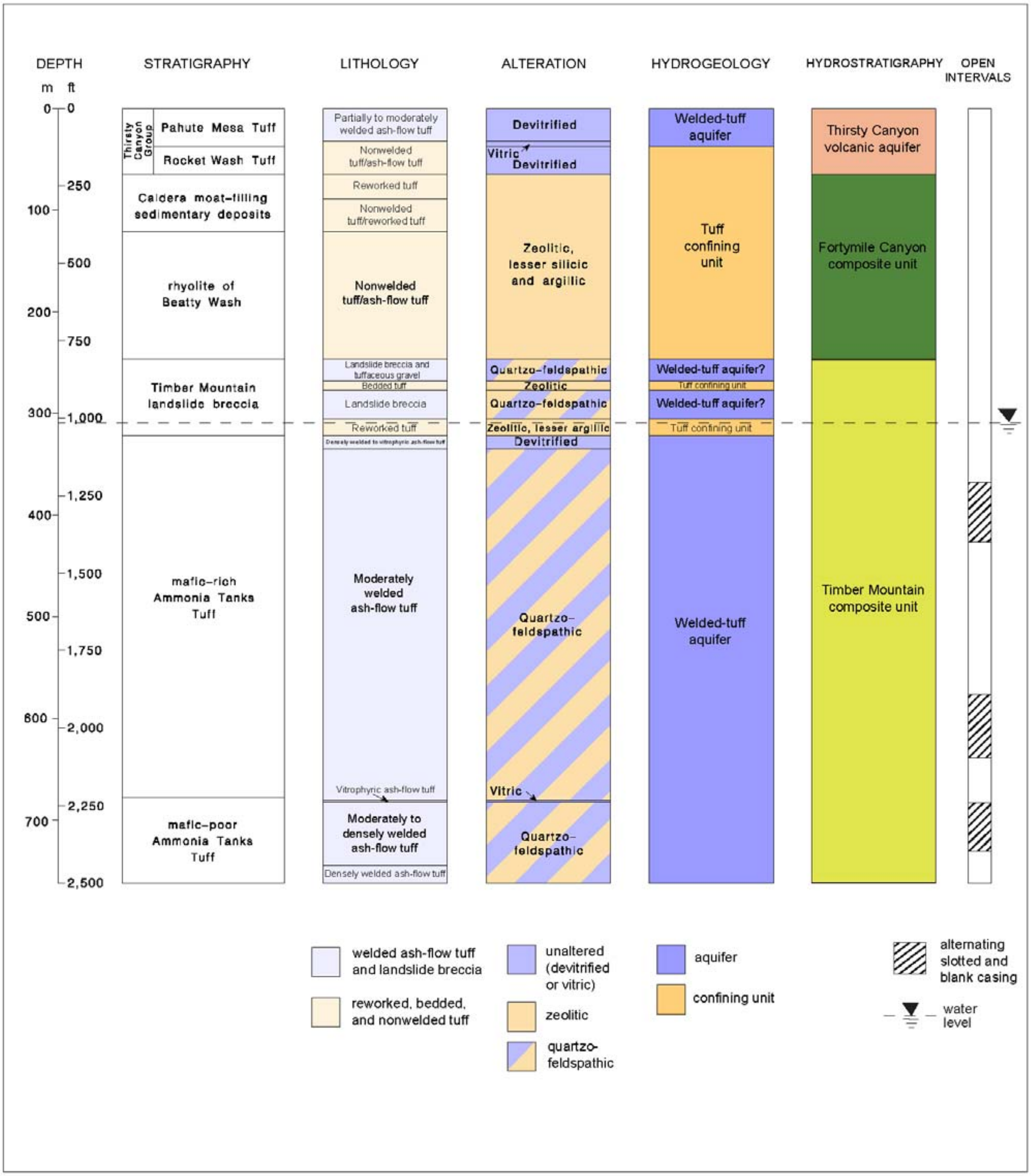

Figure B-25
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-5
(Modified from NNSA/NSO, 2004a)

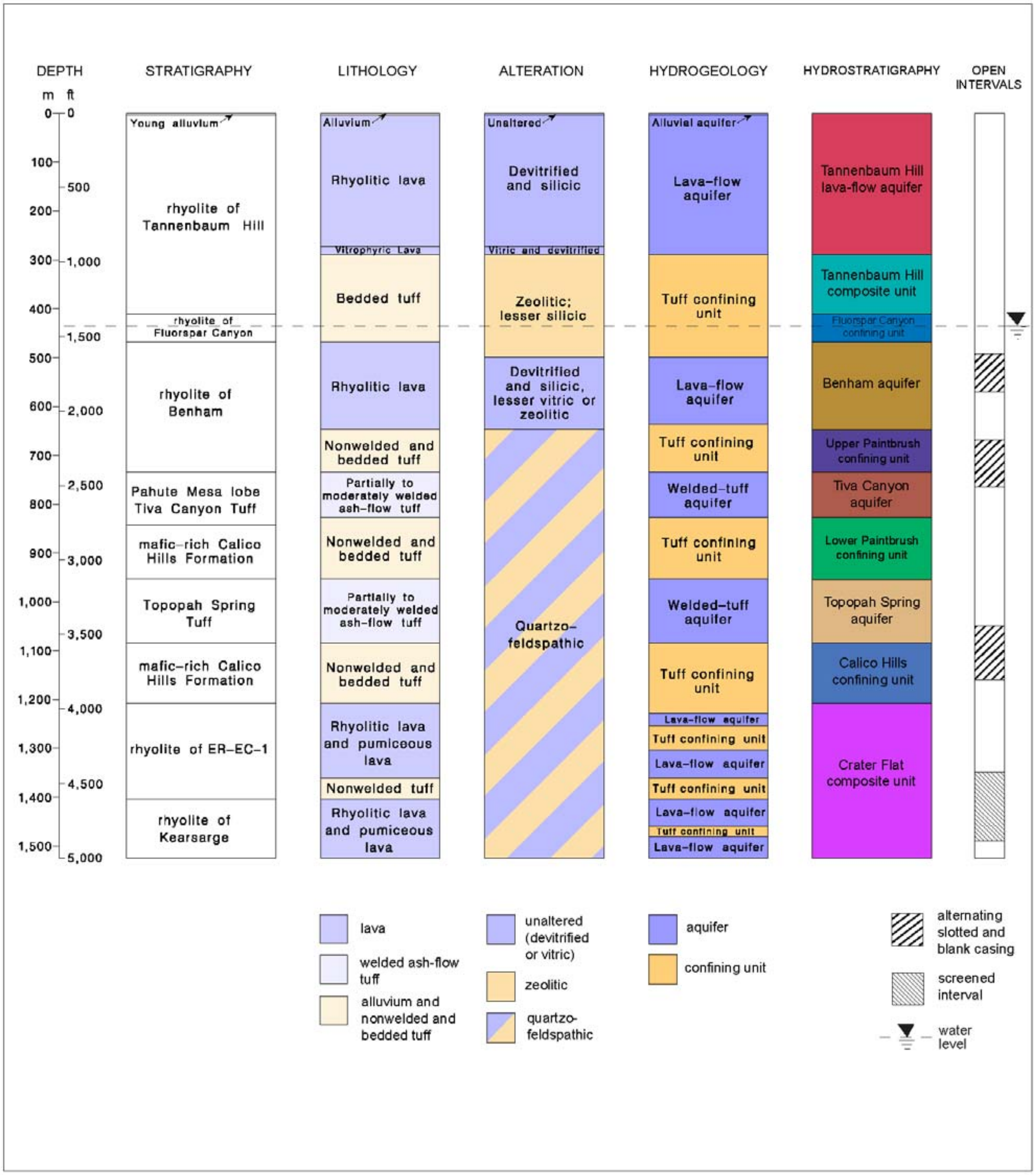

Figure B-26
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-6

(Modified from DOE/NV, 2000a)

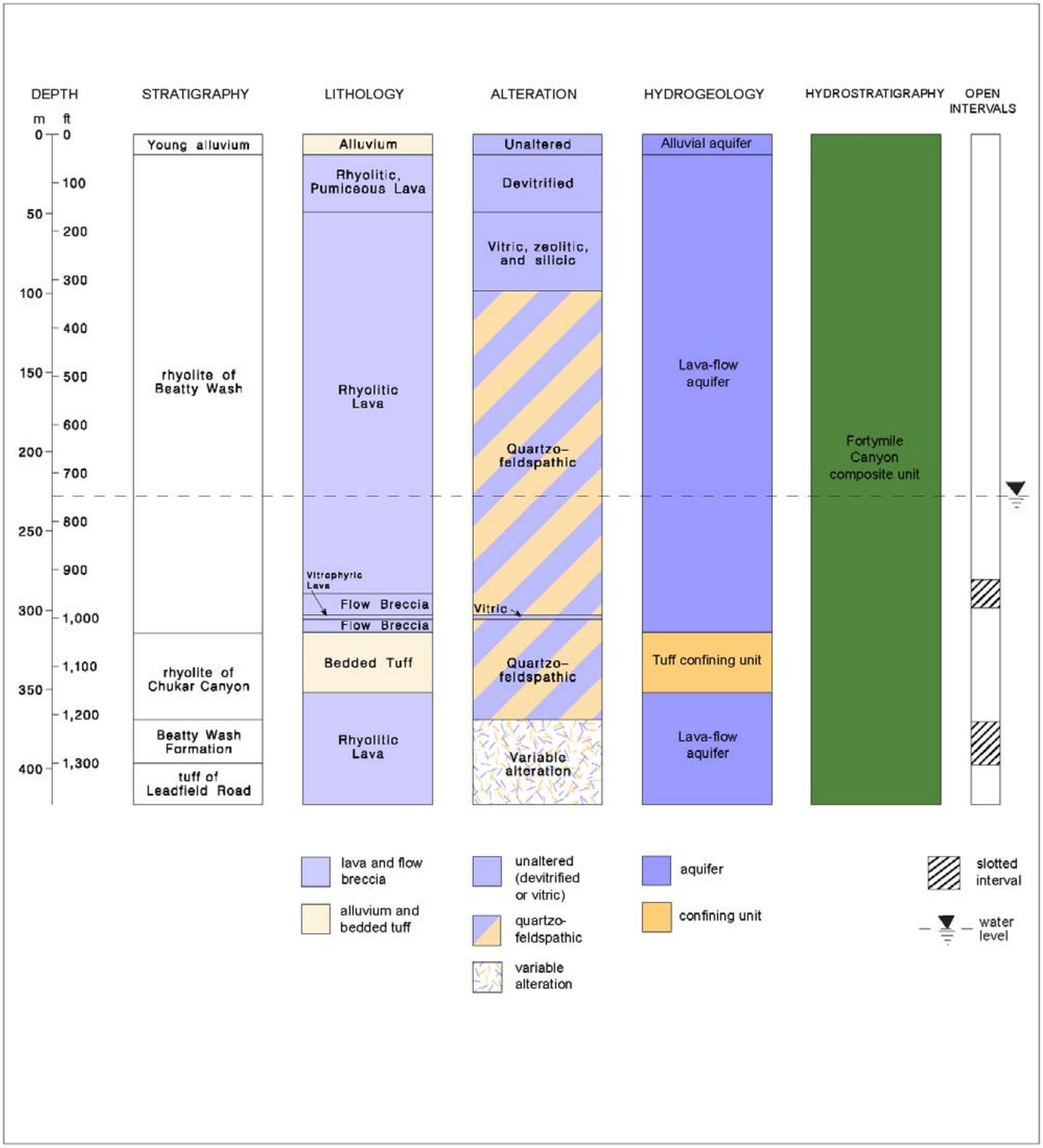

Figure B-27
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-7
(Modified from NNSA/NSO, 2004c)

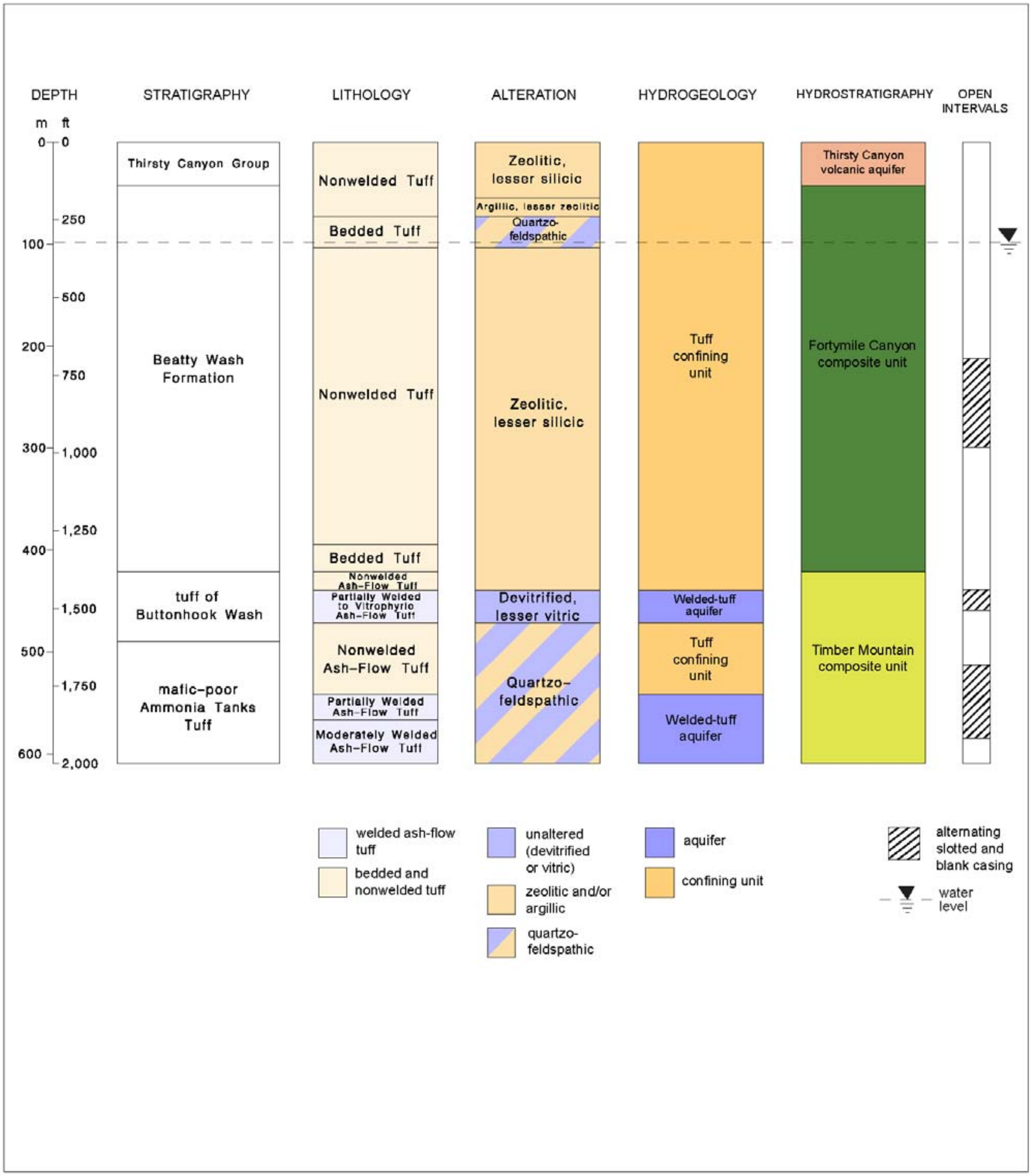

Figure B-28
Graphical Presentation Showing Stratigraphy, Lithology, Alteration, and Hydrogeologic Units for UGTA Well ER-EC-8

(Modified from NNSA/NSO, 2004b)

Plate 1

Stratigraphic Units of the NTS Region

PLATE 1
Stratigraphic Units of the Nevada Test Site Region

Era	Period	Epoch	*after Slate et al. (1999)*		*after Ferguson et al. (1994)*	
Cenozoic	Quaternary	Holocene Pleistocene	**QT** Qay Qey Qed Qp QTc QTu Qai Qeo QTa Qbu Qbl	**Quaternary and Tertiary Alluvium** Young alluvial deposits Young eolian sand deposits Eolian dune sand deposits Playa deposits Colluvium Undifferentiated surficial deposits Intermediate alluvial deposits Old eolian sand deposits Old alluvial deposits Youngest basalt Basalt of central Crater Flat	Qa Qb Qe QTe QTp QTa	**Quaternary and Tertiary Alluvium** alluvium basalt eolian deposits eolian sand playa deposits alluvium
	Tertiary	Pliocene	Typ Tgy Tgc	Basalt of Thirsty Mountain and other areas Basin-fill sediments, undivided Caldera moat-filling sediments	Typ Tyb Tgy	Pliocene basalts post-Thirsty Canyon basalts Tertiary alluvium
		Miocene	**Ts** Tsc Tsp Tsf	Stonewall Flat Tuff Civet Cat Canyon Member Spearhead Member Rhyolite of Stonewall Mountain	**Ts** Tsc Tsp Tsr	**Volcanics of Stonewall Mountain** Civet Cat Canyon Member Spearhead Member rhyolite lava
				Not defined	**Ty** Tyb Tyo Tyr	**Younger Tertiary Units** post-Thirsty Canyon basalts rhyolite of Obsidian Butte rhyolite tephra
			Tt Ttb Tth Ttg Tts Ttt Ttp Ttc Txy	**Thirsty Canyon Group** Basalt of Black Mountain Trachyte of Hidden Cliff Gold Flat Tuff Trachytic rocks of Pillar Spring and Yellow Cleft Trail Ridge Tuff Pahute Mesa and Rocket Wash Tuffs Comendite of Ribbon Cliff Younger landslide, gravity-slide and talus breccia	**Tt** Tth Ttg Tts Tty Ttt Ttp Ttpr Ttpp Ttr Ttl Ttc	**Thirsty Canyon Group** Trachyte of Hidden Cliff Gold Flat Tuff lavas of Pillar Spring syenite of Yellow Cleft Trail Ridge Tuff Pahute Mesa Tuff crystal-rich crystal-poor Rocket Wash Tuff tuff of Scotch comendite of Ribbon Cliff
			Tf Tfs Trs Tft Tfn Tgb Tfr Tfd Tfb Tff	**Volcanics of Fortymile Canyon** Rhyolite of Shoshone Mountain Rhyolite of Springdale Mountain Intermediate-age basalt Trachyte of Donovan Mountain Bedded tuff and sedimentary rocks Rhyolite of Rainbow Mountain Lava flows of Dome Mountain Betty Wash Formation Rhyodacite of Fleur-de-lis-Ranch	**Tf** Tfs Tfn Tfu Tfr Tfd Tfm Tfb Tfbr Tfbc Tfbw Tfl Tff Tft	**Volcanics of Fortymile Canyon** rhyolite of Shoshone Mountain latite of Donovan Mountain rhyolite of Boundary Butte volcanics of Rainbow Mountain lavas of Dome Mountain rhyolite of Max Mountain Betty Wash Formation rhyolite of Chukar Canyon tuff of Cutoff Road rhyolite of Betty Wash tuff of Leadfield Road rhyolite of Fleur-de-lis-Ranch post-Timber Mountain Group basalts
			Tm Tmi Tmay Tmaw Tma Tmc Tmat Tmtc Tmr Tmrf Tgs	**Timber Mountain Group** Intrusive rocks of Timber Mountain Trachyte of East Cat Canyon Tuff of Buttonhook Wash Ammonia Tanks Tuff Caldera-collapse beccia of Timber Mountain caldera Rhyolite of Tannenbaum Hill Rhyolites of Twisted Canyon Rainier Mesa Tuff Rhyolite of Fluorspar Canyon Sedimentary rocks and landslide deposits	**Tm** Tmay Tmac Tmaw Tma Tmar Tmap Tmab Tmat Tmo Tmc Tmr Tmrb Tmrf Tmrh Tmt Tmp Tml Tmw Tmb	**Timber Mountain Group** trachyte of East Cat Canyon tuff of Crooked Canyon tuff of Buttonhook Wash Ammonia Tanks Tuff mafic-rich mafic-poor bedded Ammonia Tanks Tuff rhyolite of Tannenbaum Hill basalt of Oasis Valley rhyolite of Buried Canyon Rainier Mesa Tuff bedded Rainier Mesa rhyolite of Fluorspar Canyon tuff of Holmes Road basalt of Tierra (UE19c) rhyolite of Pinnacles Ridge rhyolite of The Loop rhyolite of Windy Wash rhyolite of Water Pipe Butte
			Tp Tpw Tpr Tpc Tpcc Tpy Tpm Tpp Tpt	**Paintbrush Group** Rhyolite of Windy Wash Rhyolite of Comb Peak Tiva Canyon Tuff Caldera-collapse breccia of Claim Canyon caldera Yucca Mountain Tuff Middle Paintbrush Group rhyolites Pah Canyon Tuff Topopah Spring Tuff	**Tp** Tpk Tpb Tps Tpv Tpcy Tpc Tpcr Tpcm Tpcp Tpy Tpg Tpd Tpe Tpz Tpp Tpm Tpr Tpt Tptr Tptm Tptp	**Paintbrush Group** rhyolite of Comb Peak rhyolite of Benham rhyolite of Scrugham Peak rhyolite of Vent Pass tuff of Pinyon Pass Tiva Canyon Tuff crystal-rich Pahute Mesa lobe crystal-poor Yucca Mountain Tuff rhyolite of Black Glass Canyon rhyolite of Delirium Canyon rhyolite of Echo Peak rhyolite of Zigzag Hill Pah Canyon Tuff rhyolite of Chocolate Mountain rhyolite of Silent Canyon Topopah Spring Tuff crystal-rich Pahute Mesa lobe crystal-poor
			Tac	**Calico Hills Formation**	**Th** Thp Thr	**Calico Hills Formation** mafic-poor mafic-rich
			Tw Twi Tws Tgp Txo	**Wahmonie Formation** Intrusive rocks of Wahmonie Salyer Formation Pre-basin-range sedimentary rocks, undivided Older landslide and talus breccia	**Tw** Twu Twm Twl Twlb Twls	**Wahmonie Formation** upper member middle member lower member tuff of Wahmonie Flat Salyer Formation
			Tc Tcp Tcg Tcb Tcr Tct	**Crater Flat Group** Prow Pass Tuff Latite of Grimy Gulch Bullfrog Tuff Rhyolite of the Crater Flat Group Tram Tuff	**Tc** Tci Tcp Tcpj Tcps Tcpk Tcg Tcb Tcbl Tcblr Tcblp Tcbr Tcbs Tcby Tcbp Tct Tcl	**Crater Flat Group** rhyolite of Inlet Prow Pass Tuff tuff of Jorum rhyolite of Sled rhyolite of Kearsarge andesite of Grimy Gulch Bullfrog Tuff lithic-rich mafic-rich mafic-poor tuff of Rickey Stockade Wash Lobe Yucca Mountian Lobe rhyolite of Prospectors Pass Tram Tuff lower tuff
			Tb Tbd Tbdb Tbg Tbgs Tfq Tob	**Belted Range Group** Deadhorse Flat Formation Comendite of Basket Valley Grouse Canyon Tuff Comendite of Split Ridge Comendite of Quartet Dome Older basalt	**Tb** Tbd Tbdb Tbgm Tbg Tbgb Tbgs Tbq	**Belted Range Group** Deadhorse Flat Formation comendite of Basket Valley trachyte of Muenster Grouse Canyon Tuff bedded Grouse Canyon Tuff comendite of Split Ridge comendite of Quartet Dome
			Trl Trr Trd	Lithic Ridge Tuff Rhyolite of Picture Rock Dikes of Tram Ridge	**Tr** Trl Trr	**Tram Ridge Group** Lithic Ridge Tuff Rhyolite of Picture Rock
			Tn	**Tunnel Formation**	**Tn** Tn4 Tn4K Tn4J Tn4H Tn4G Tn4F Tn4E Tn4CD Tn4AB Tn3 Tn3D Tn3BC Tn3A	**Tunnel Formation** Tunnel 4 Member beds 4K beds 4J beds 4H beds 4G beds 4F beds 4E beds 4CD beds 4AB Tunnel 3 Member beds 3D beds 3BC beds 3A
			Tq Tqu Tqs Tqh Tqt Tqe Tqe Tqm	**Volcanics of Quartz Mountain** Upper rhyolite Tuff of Sleeping Butte Middle rhyolite Tuff of Tolicha Peak Lower rhyolite Volcanic rocks of Gold Flat, undivided Dacite of Mount Helen	**Tq** Tqg Tqs Tqsu Tqsp Tqsr Tqsq Tqp Tqh Tqt Tqb Tqc Tqd Tqm Tqw	**Volcanics of Quartz Mountain** rhyolite of Guiding Light Mesa tuff of Sleeping Butte upper plagioclase-rich cyrstal-rich quartz-rich pyroxene bearing rhyolite of Quartz Mountain hornblende bearing rhyolite of Quartz Mountain tuff of Tolicha Peak biotite bearing rhyolite of Quartz Mountain rhyolite of Coyote Cuesta Dacite of Triangle Mtn Dacite of Mount Helen tuff of Wilson's Camp
			Tuo Tub Tue	Comendite of Ocher Ridge Tub Spring Tuff Comendite of Emigrant Valley	**Tu** Tuc Tuo Tub	**Volcanics of Big Dome** tuff of Cache Cave Draw rhyolite of Ochre Ridge Tub Spring Tuff
			Ton Toy Tor Tot	Older tunnel beds Tuff of Yucca Flat Redrock Valley Tuff Tuff of Twin Peaks	Ton2 Toy Ton1 Tor Tot Toa Tob Tow	**Volcanics of Oak Spring Butte** tunnel bed 2 Yucca Flat Tuff tunnel bed 1 Redrock Valley Tuff tuff of Twin Peaks tuff of Argillite Wash basalt of Whiterock Spring tuff of Whiterock Spring
			Tkr Tka Tkl	Rhyolite of Belted Peak Rhyolite of Wheelbarrow Peak Latite of Kawich Valley	**Tk** Tkr Tkj Tkb Tkc Tki Tkw Tky Tkl	**Volcanics of Kawich Valley** rhyolite of White Ridge rhyolite of Johnnies Water rhyolite of Belted Peak rhyolite of Cliff Spring rhyolite of Indian Spring rhyolite of Wheelbarrow Peak trachyte of Kawich Valley latite of Kawich Valley
			Tep Tes Tem	Pahranagat Formation Shingle Pass Tuff Monotony Tuff	**Te** Tec Tep Tes Tea Tem	**Volcanics of Central Nevada** tuff of Cathedral Ridge Pahranagat Lakes tuff Shingle Pass Tuff tuff of Antelope Springs Monotony Tuff
				Not defined	**Tl** Tlt Tln	**Paleocolluvium** tuffaceous nontuffaceous
			Tgo	Older sedimentary rocks, undivided	Tgp Tgw	Rocks of Pavits Spring Rocks of Winapi Wash
Mesozoic	Cretaceous		**Kg** TKg Kgg Kgc	**Cretaceous Plutonic Rocks** Gabbro dikes Gold Meadows Stock Climax Stock	**Kg** Kgg Kgc	**Cretaceous Plutonic Rocks** Gold Meadows Stock Climax Stock
Paleozoic	Permian Penn. Miss. Dev. Silurian Ordovic. Camb.		**Pz** PIPt IPMsc MDe MDu Dg Dsf Ds DSsl DSlm Sr Oes Oe Op Oa On Og Cn Cb Cbb Cbp Cc Cz CZw	**Paleozoic Sedimentary Rocks** Tippipah Limestone Scotty Wash Quartzite and Chainman Shale Eleana Formation Mississippian and Devonian rocks, undivided Guilmette Formation Slope-facies carbonate rocks Simonson Dolomite Sevy Dolomite and Laketown Dolomite Lone Mountain Dolomite Roberts Mountain Formation Ely Springs Dolomite Eureka Quartzite Pogonip Group Antelope Valley Limestone Ninemile Formation Goodwin Formation Nopah Formation Bonanza King Formation Banded Mountain Member Papoose Lake Member Carrara Formation Zabriske Quartzite Wood Canyon Formation	**Pz** PIPt IPMc Mej Mg MDe Dg Ds Dv DSd Sl SOs Oe Op Oa On Og Cn Cnd Cb Cc Cz CZw	**Paleozoic Sedimentary Rocks** Tippipah Limestone (Bird Spring Formation) Chainman Shale Captain Jack Formation Gap Wash Formation Eleana Formation Guilmette Formation Simonson Dolomite Sevy Dolomite transitional beds Laketown Dolomite Ely Springs Dolomite Eureka Quartzite Pogonip Group Antelope Valley Limestone Ninemile Formation Goodwin Formation Nopah Formation Dunderburg Shale Bonanza King Formation Carrara Formation Zabriske Quartzite Wood Canyon Formation
Precambrian	Protero-zoic		**P€** Zs Zj Yk Yb Yc Xmi	**Precambrian Rocks** Stirling Quartzite Johnnie Formation Kingston Peak Formation Beck Spring Dolomite Crystal Spring Formation Metamorphic and instrusive rocks	**P€** Zs Zj Zn Xm	**Precambrian Rocks** Stirling Quartzite Johnnie Formation Noonday Dolomite Gneisses and Schists

Plate 2

Correlation of Stratigraphic and Hydrostratigraphic Units for the Four UGTA Hydrostratigraphic Framework Model Areas

Plate 2
Correlation of Hydrostratigraphic Units for UGTA CAU-scale HFMs
(Refer to Figure P-1 for locations of hydrostratigraphic sections, and Tables 3-2 and A-1 for explanations of hydrostratigraphic unit symbols)

Not to scale

* HSU defined for specific alternative models

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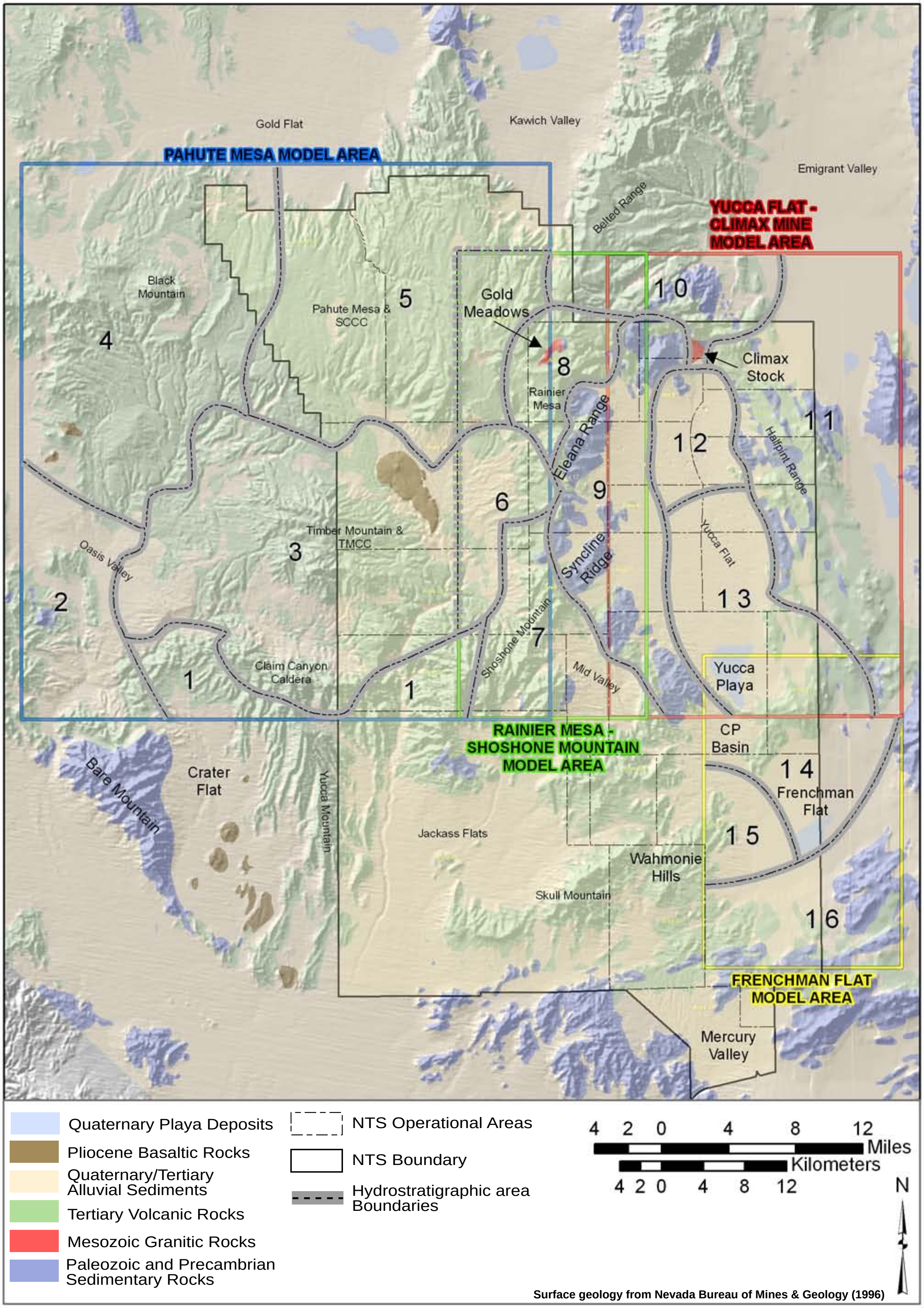

Figure P-1
Generalized Geologic Map Showing the Regions Represented by the Hydostratigraphic Columns in Plate 2