DOE/NV/11718--1064

A Hydrostratigraphic Framework Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Clark, Lincoln and Nye Counties, Nevada

Prepared for
U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Las Vegas, Nevada

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September 2005

This manuscript was prepared by Bechtel Nevada under Contract No. DE-AC08-96NV11718 with the U.S. Department of Energy.

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ABSTRACT

A new, revised three-dimensional (3-D) hydrostratigraphic framework model for Frenchman Flat was completed in 2004. The area of interest includes Frenchman Flat, a former nuclear testing area at the Nevada Test Site, and proximal areas. Internal and external reviews of an earlier (Phase I) Frenchman Flat model recommended additional data collection to address uncertainties. Subsequently, additional data were collected for this Phase II initiative, including five new drill holes and a 3-D seismic survey. These were integrated using EarthVision® to develop the new 3-D hydrostratigraphic framework model.

The model area is large (approximately 570 square kilometers) and geologically complex. A diverse set of geological and geophysical data collected over the past 40 years was utilized to develop a structural model and hydrostratigraphic classification system for the basin. The model consists of 73 faults and 17 hydrostratigraphic units. Formation of the basin appears to be related to the termination of the left-lateral Rock Valley fault system. Northeast-striking faults of the Rock Valley system in the southern portion of Frenchman Flat turn north and then northwest as the faults of the system flare out into an extensional imbricate fan along the eastern and northern margins of the basin. This has resulted in the basin being dropped down on the south, east and north, and filled with more than 2,740 meters of mostly Tertiary volcanic rocks and alluvium.

Forty-eight stratigraphic units in the model area were grouped into 17 hydrostratigraphic units based on their propensity toward aquifer or aquitard characteristics. The authors divided the alluvial section into 5 hydrostratigraphic units, including 3 aquifers and 2 confining units. The volcanic rocks are organized into 8 hydrostratigraphic units that include 4 aquifers and 4 confining units. The underlying pre-Tertiary rocks were divided into 4 hydrostratigraphic units, including 2 aquifers and 2 confining units. The model depicts the thickness, extent, and geometric relationships of these hydrostratigraphic units ("layers" in the model) along with the major structural features that control them (e.g. faults).

Some of the more significant differences between this hydrostratigraphic model and the Phase I model include a better constrained structural model that does not include a series of large-displacement north-striking faults through the center of the basin and the testing areas. The depth of the lower carbonate aquifer is also better constrained and deeper in the vicinity of the testing areas in the current model. The current model also contains more hydrostratigraphic units based on new data and is consistent with the hydrostratigraphic classification system developed for the adjacent Yucca Flat CAU.

The complexity of the model area and the non-uniqueness of some of the interpretations incorporated into the base model made it necessary to address alternative interpretations for some of the major features in the model. Four of these alternatives were developed so they could be modeled in the same fashion as the base model.

This work was done in support of the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office in support of the Environmental Restoration Division's Underground Test Area Project.

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List of Acronyms and Abbreviations

° C	degrees Celsius
° F	degrees Fahrenheit
3-D	three-dimensional
AA	Alluvial aquifer; valley fill aquifer
AA1	Alluvial aquifer 1
AA2	Alluvial aquifer 2
AA3	Alluvial aquifer 3
BLFA	Basalt lava-flow aquifer
BN	Bechtel Nevada
CAU	Corrective Action Unit
CSMAT	controlled-source audio-frequency magnetotelluric
DEM	Digital Elevation Model
DOE	U.S. Department of Energy
ERMA®	Environmental Resources Management Applications System
FFACO	*Federal Facility Agreement and Consent Order*
ft	feet (foot)
gal/min	gallons per minute
HGU	hydrogeologic unit
HSU	hydrostratigraphic unit
IT	International Technologies Corporation
km	kilometer(s)
km^2	square kilometers
LANL	Los Alamos National Laboratory
LCA	lower carbonate aquifer
LCA3	lower carbonate aquifer - thrust plate
LCCU	lower clastic confining unit
LFA	lava-flow aquifer
LLNL	Lawrence Livermore National Laboratory
lpm	liters per minute
LTCU	lower tuff confining unit
LTCU1	lower tuff confining unit 1
LVTA	lower vitric tuff aquifer
m	meter(s)
Ma	Mega anna (i.e., million years ago)
mi	mile(s)
mi^2	square miles
MT	magnetotelluric
NAD	North American Datum

List of Acronyms and Abbreviations *(continued)*

NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
NTS	Nevada Test Site
OAA	older alluvium aquifer
OAA1	older alluvium aquifer 1
PCU2T	playa confining unit
PCU1U	older playa confining Unit 1 Upper
PCU1L	older playa confining Unit 1 Lower
RWMS	Radioactive Waste Management Site
SEM	scanning electron microscope
SNJV	Stoller-Navarro Joint Venture
SWNVF	Southwestern Nevada Volcanic Field
TCU	tuff confining unit
TD	total depth
TMA	Timber Mountain aquifer
TM-WTA	Timber Mountain welded-tuff aquifer
TM-LVTA	Timber Mountain lower-vitric aquifer
TSA	Topopah Spring aquifer
TWG	Technical Working Group
UCCU	upper clastic confining unit
UGTA	Underground Test Area
USGS	U.S. Geological Survey
UTCU	upper tuff confining unit
UTM	Universal Transverse Mercator
VCU	volcaniclastic confining unit
WCU	Wahmonie confining unit
WTP	weapons testing program
YMP	Yucca Mountain Project
XRD	x-ray diffraction
XRF	x-ray fluorescence

1.0 INTRODUCTION

The Environmental Restoration Division of the U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office (NNSA/NSO) initiated the Underground Test Area (UGTA) 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 the geology and hydrology of the NTS to estimate the direction and rate at which contaminants are transported by groundwater flow. This report describes the hydrostratigraphic framework model constructed for the Frenchman Flat area. This model will be used to develop models of groundwater flow and contaminant transport for the underground nuclear testing areas in Frenchman Flat.

1.1 Background Information for Hydrostratigraphic Framework Model Task

A regional three-dimensional (3-D) computer groundwater model (IT Corporation [IT], 1996a) was developed in the initial stages of the UGTA project to identify any immediate risk, and to provide a basis for developing more detailed models of specific nuclear testing areas designated as Corrective Action Units (CAU). The CAU-specific models, of which four are planned, geographically cover each of the six former NTS underground nuclear testing areas (Figure 1-1). CAU-specific groundwater-flow and contaminant-transport models will be used to determine contaminant boundaries based on the maximum extent of contaminant migration at specified regulatory limits. The models will also be used to refine a monitoring network to ensure public health and safety.

Construction of CAU-specific groundwater-flow and contaminant-transport models requires a hydrostratigraphic framework that depicts the character and extent of hydrostratigraphic units in three dimensions. CAU-specific framework models will provide modelers the ability to test a range of potential groundwater flow and contamination scenarios by allowing them to apply flow and transport algorithms and to vary parameters for each hydrostratigraphic unit. Thus, the framework model must reflect reality as well as it is known, but also must be suitable for mathematical manipulation. This report provides information about how the hydrostratigraphic framework model for the Frenchman Flat CAU was developed, presents a description of the model, and provides documentation of data sources used to produce the model. This document addresses only the hydrostratigraphic framework model. Separate data documentation packages containing detailed descriptions of the hydrologic modeling process, and other pertinent flow and transport information, have also been developed.

The Frenchman Flat hydrostratigraphic framework model was developed by a multi-disciplinary team of scientists from the Bechtel Nevada (BN) Geotechnical Sciences group and Stoller-Navarro Join Venture (SNJV; the SNJV personnel were employed by the consortium, IT Corporation/Science Applications International Corporation/Geotrans at the beginning of this project). The team also received valuable input from scientists at the Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the U.S. Geological Survey (USGS), and the NNSA/NSO, and guidance from the NNSA/NSO UGTA Technical Working Group (TWG).

The model presented here consists of a base model and several alternatives. Because of the geologic complexity of the model area and non-unique interpretations incorporated into the base model, different geologic interpretations were developed for some of the more significant features in the model. These alternative models are intended to be tested by hydrologic modeling to evaluate the hydrologic impact of different geologic interpretations.

1.2 Document Organization

This section contains background information for the development of the Frenchman Flat hydrostratigraphic framework model, including location, setting, and previous work. Section 2.0 provides descriptions of the processes, methods, and data used to construct the model, including discussions of data obtained within the last five years specifically for the Frenchman Flat UGTA model. Section 3.0 presents a discussion of the structural elements of the model, and Section 4.0 describes all the hydrostratigraphic units included in the model. Alternative models are described in Section 5.0, Section 6.0 presents a document summary, and relevant references are listed in Section 7.0.

1.3 Objectives

The primary objective of the Frenchman Flat hydrostratigraphic modeling effort was to produce a 3-D hydrostratigraphic framework model that depicts the geometric relationships of hydrostratigraphic units (HSUs) and structural features in the Frenchman Flat model area. The effort also included development of alternative scenarios. The Frenchman Flat hydrostratigraphic framework model and alternative scenarios will be used to model groundwater flow and contaminant transport for the Frenchman Flat CAU.

1.4 Location and Setting

The hydrostratigraphic framework model for the Frenchman Flat area encompasses more than 570 square kilometers (km^2) (220 square miles [mi^2]) in the southeastern part of the NTS (Figure 1-1). The model area is located approximately 113 kilometers (km) (70 miles [mi])

northwest of Las Vegas, Nevada, and includes lands managed by the U.S. Air Force (Nevada Test and Training Range; formerly known as the Nellis Air Force Range) and a co-use area of the Desert National Wildlife Refuge and the Nevada Test and Training Range, in addition to the southeastern portion of the NTS. The model area lies mostly in southern Nye County, Nevada, but also includes portions of southwestern Lincoln and northwestern Clark Counties, Nevada. The model area encompasses the Frenchman Flat CAU defined in the Federal Facility Agreement and Consent Order (FFACO; 1996 as amended), and additional areas surrounding the CAU that include important rock outcrop and drill hole data that help constrain geologic interpretations. The model area includes the Frenchman Flat topographic basin and portions of the adjacent highlands. The model area also includes portions of Yucca Flat and CP basins, located north and northwest of Frenchman Flat. The model has a north-south dimension of 30.0 km (19.1 mi) and an east-west dimension of 19.1 km (11.9 mi), and includes geologic units as deep as 5 km (3.1 mi) below mean sea level. Boundaries for the Frenchman Flat model area are listed in Table 1-1.

Table 1-1
Boundaries of the Frenchman Flat Model Area

	Central Nevada State Planar Coordinates (NAD 27; feet)[a, b]	**Universal Transverse Mercator (Zone 11)** (NAD 83; meters)
Northern Boundary, Along Northing	N 805,460	N 4,091,000
Southern Boundary, Along Northing	N 707,676	N 4,061,000
Western Boundary, Along Easting	E 679,585	E 584,500
Eastern Boundary, Along Easting	E 742,227	E 603,500

a NAD = 1927 North American Datum
b N = North; E = East

1.4.1 Underground Nuclear Tests in Frenchman Flat

The Frenchman Flat CAU includes the locations of all ten of the underground nuclear tests conducted in Frenchman Flat. All the tests are assumed to have generated contaminated groundwater because the tests were conducted in the saturated zone or within 100 meters (m) (325 feet [ft]) of the water table (DOE, 1999). The tests were conducted in two areas located in the northern and the central parts of Frenchman Flat (Figure 1-2). Seven underground nuclear tests were conducted in the northern part of the basin. One of these tests was located within the Tertiary volcanic rocks, below the alluvium, and the other six were conducted within the

alluvium. Three tests were conducted in alluvium in the central part of the basin. Table 1-2 lists the underground nuclear tests conducted in Frenchman Flat, along with the designation of the emplacement hole, announced yield, depth of burial, location of the water table, and geologic unit at the working point (explosion point).

1.4.2 Climate

Frenchman Flat is located within the northern portion of the Mojave desert (DOE, 2004). Annual precipitation for Frenchman Flat is approximately 12 centimeters (5 inches) (DOE, 1998). Precipitation in the area is sporadic, typically falling as small amounts of rain or snow during isolated, short-duration winter and summer storms. Severe weather can occur in the region, usually in the form of summer thunderstorms with intense lightning, strong winds, and localized heavy rainfall. Daily temperatures range from -3 to 12 degrees Celsius (° C) (27 to 54 degrees Fahrenheit [° F]) in January, and from 17° to 36° C (63° to 97° F) in July (DOE, 1998).

1.4.3 Physiography

Frenchman Flat is an intermontane basin located in the northern portion of the Basin and Range physiographic province (Figure 1-3). The basin is bounded on the north by Massachusetts Mountain and French Peak, on the east by the Ranger Mountains and Buried Hills, on the south by the Spotted Range, and on the west by the Wahmonie Hills (Figure 1-2). The sparsely vegetated valley floor slopes gently toward a central playa (dry lake bed). Ground level elevations range from 938 m (3,078 ft) above sea level at the playa, to over 1,463 m (4,800 ft) in the nearby surrounding mountains.

1.4.4 Geologic Setting

Frenchman Flat is a Cenozoic-age basin formed in response to basin-and-range extension. Rocks exposed in the highlands around the margins of Frenchman Flat include Paleozoic sedimentary rocks and Cenozoic volcanic and tuffaceous sedimentary rocks (Hinrichs and McKay, 1965; Poole, 1965; Poole et al., 1965; Hinrichs, 1968; McKeown et al., 1976; Barnes et al., 1982). Paleozoic sedimentary rocks are exposed along the south and east margins of Frenchman Flat (Figure 1-4 and Plate 1), and consist mostly of carbonate rocks ranging in age from Cambrian to Mississippian. The Paleozoic rocks show contractional deformation most likely related to generally east-directed thrusting during the Mesozoic. However, contractional

Table 1-2
List of Underground Nuclear Tests Conducted in Frenchman Flat [a]

Emplacement Hole Designation	Test Name	Date of Test	Yield (kilotons)	Depth of Burial (meters [feet])	Static Water Level Depth (meters [feet])	Working Point Geology [b]	Estimated Alluvium Thickness (meters [feet])
Northern Test Area							
U-5i	DERRINGER	9/12/1966	7.8	255 (837)	335 (1,100)	Alluvium	305 (1,000)
U-5k	MILK SHAKE	3/25/1968	<20	265 (868)	286 (939)	Alluvium	500 (1,640)
U-11b	PIN STRIPE	4/25/1966	<20	269 (970)	349 (1,146)	Volcanic Rocks	58 (190)
U-11c	NEW POINT	12/13/1966	<20	239 (785)	299 (980)[c]	Alluvium	478 (1,570)
U-11e	DIANA MOON	8/27/1968	<20	242 (794)	305 (1,000)[c]	Alluvium	366 (1,200)
U-11f	MINUTE STEAK	9/12/1969	<20	265 (868)	302 (990)[c]	Alluvium	427 (1,400)
U-11g	DIAGONAL LINE	11/24/1971	<20	264 (867)	301 (988)[c]	Alluvium	341 (1,120)
Central Test Area							
U-5a	WISHBONE	2/18/1965	<20	175 (574)	NA [d]	Alluvium	590 (1,935)
U-5b	DILUTED WATERS	6/16/1965	<20	193 (632)	213 (700)[c]	Alluvium	400 (1,312)
U-5e	CAMBRIC	5/14/1965	0.75	295 (967)	213 (700)	Alluvium	576 (1,890)

a Sources: DOE (2000b) and Marsh (1992)
b Drellack, 1997
c Estimated
d Not Available

deformation has been overprinted by extensive extensional deformation related to basin-and-range extension during the Cenozoic. The Paleozoic rocks dip generally south and east away from Frenchman Flat.

Volcanic rock exposures include Miocene-age tuffs of generally rhyolitic composition erupted from large calderas located 40 km (25 mi) northwest of Frenchman Flat. These rocks dominate the highlands north and northwest of Frenchman Flat and dip south and southeast into the basin. The highlands bordering Frenchman Flat on the west are composed of intermediate-composition tuffs, lavas, and debris flows from the Wahmonie volcanic center located west of Frenchman Flat. These rocks are also Miocene in age, and generally dip southeastward into the basin. Numerous normal faults related to basin-and-range extension offset the volcanic rocks.

Tuffaceous sedimentary rocks occur within a rather narrow, linear, northeast-trending depositional area that generally corresponds to the topographic axis of the basin (Prothro and Drellack, 1997). These rocks are exposed along the southern margin of the basin, where they consist of a diverse assemblage of fluvial and lacustrine sandstone and mudrock, freshwater limestone, conglomerate, and volcanic tuff. The tuffaceous sedimentary rocks appear to be partly coeval with the older volcanic rocks, and thus likely interfinger with the volcanic rocks beneath northern portion of Frenchman Flat. Tuffaceous sedimentary rocks exposed along the southern margin of Frenchman Flat dip north into the basin.

Drilling and geophysical data from Frenchman Flat indicate that many of the rock units exposed along the margins of the basin are present beneath Frenchman Flat, but have been buried by thick aprons of alluvial debris shed from the exposed highlands during basin development. At its deepest point the basin is filled with approximately 1,500 m (5,000 ft) of Miocene to Quaternary alluvium that overlies approximately 1,300 m (4,300 ft) of Tertiary volcanic and tuffaceous sedimentary rocks.

Frenchman Flat lies within the Walker Lane Belt, a northwest-trending zone of complex structural deformation consisting of basin-and-range extensional fault blocks, strike-slip faults, and detachment faults (Stewart, 1998). The basin is just north of the Las Vegas Valley shear zone, a west-northwest-trending zone of right-lateral strike-slip faulting. The Rock Valley fault zone is located southwest of the basin. This zone is a system of left-lateral strike-slip faulting that trends northeast into the southern portion of the model area.

1.4.5 Hydrologic Setting

Frenchman Flat is located within the Great Basin hydrographic province (Figure 1-3). The Great Basin is characterized by internal drainage, and consists of numerous hydrographically closed topographic basins, such as Frenchman Flat and Yucca Flat. Streams in the Frenchman Flat vicinity are ephemeral, flowing only in response to precipitation events. Runoff is conveyed through normally dry washes toward the topographically lowest part of the basin, and collects on the Frenchman Flat playa. The Frenchman Flat model area also includes portions of the Yucca Flat playa, northwest of Frenchman Flat. Although there are 24 known springs or seeps on the NTS (Hansen et al., 1997), no springs or seeps occur within the boundaries of the Frenchman Flat model area (Figure 1-5).

The NTS, including the Frenchman Flat model area, is located 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). Groundwater in the NTS region is conveyed within several groundwater flow-system sub-basins within the Death Valley regional flow system (Figure 1-6). The Frenchman Flat model area is located within the Ash Meadows sub-basin. 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 located to the south and southwest. Potentiometric data indicate that the groundwater flow direction in the Frenchman Flat area is to the south-southwest, toward discharge areas in Amargosa Valley and Death Valley.

The depth to groundwater in Frenchman Flat ranges from 282.6 m (927 ft) in the northern portion of the basin at Well ER-5-3, to 215.7 m (708 ft) at Well ER-5-4 #2 in the central portion of Frenchman Flat. At Well TW6-C at the southern end of Yucca Flat, the depth to groundwater is 470.6 m (1,544 ft). In CP Basin groundwater occurs at 256.6 m (842 ft) below the ground surface at Well WW6-4A. These depths correspond to elevations (above mean sea level) of 734.6 m (2,410 ft) in northern Frenchman Flat, 738.8 m (2,424 ft) in central Frenchman Flat, 724.5 m (2,377 ft) at the southern end of Yucca Flat, and 842.5 m (2,764 ft) in CP Basin.

Six water supply wells within the Frenchman Flat model area provide both potable and non-potable water to the NTS. These wells include Water Wells 5b, 5c,and UE-5c in Frenchman Flat, WW6-4 and WW6-4a in CP Basin, and TWC6 at the southern end of Yucca Flat.

1.5 Previous UGTA Work

Results from the Value of Information Analysis conducted for the Frenchman Flat area (IT, 1997) indicated that existing geologic data were sufficient to develop a CAU-specific hydrostratigraphic framework model for Frenchman Flat. The process of building a 3-D hydrostratigraphic model of Frenchman Flat began in October 1997, and an interim report containing supporting documentation for the completed model, hereafter referred to as the Phase I Frenchman Flat model, was issued in August 1998 (IT, 1998).

Technical reviews of the Phase I Frenchman Flat model were conducted by the UGTA TWG modeling subcommittee and an outside technical peer-review panel (IT, 1999b). These reviewers' major concerns regarding the Phase I hydrostratigraphic framework model were that existing data were inadequate to define the hydrostratigraphic framework, and that the model contained several uncertainties. Recommendations for resolving these concerns included performing additional data-collection activities such as drilling and seismic reflection, and assessing uncertainties in the model through the use of alternative models. As a result of the reviews, the Frenchman Flat Corrective Action Investigation Plan (DOE, 2000a) and a Phase II data acquisition initiative was conducted that included the completion of 5 new drill holes, a 3-D seismic reflection survey, and other studies referenced throughout this report. In addition, alternative models were developed to address uncertainties associated with hydrologically significant interpretations in the base model.

Rebuilding of the Phase I hydrostratigraphic framework model for Frenchman Flat using the new Phase II data began in October 2003. The methods used to rebuild the Phase I Frenchman Flat model were similar to those used to construct the UGTA Pahute Mesa - Oasis Valley framework model (BN, 2002). This effort included the use of EarthVision® modeling software which was not available during construction of the initial Frenchman Flat Phase I model.

1.6 Summary of Differences Between the Initial Phase I Frenchman Flat Model and the Phase II Model

The initial Phase I Frenchman Flat model and the current Phase II model differ in six main attributes: areal extent of the model; structural framework; depth of the basin; number of HSUs; extent of the volcanic aquifers; and the development of alternative models. The following paragraphs describe the differences between the two models for each attribute.

1.6.1 Areal Extent

The northern boundary of the Phase II model is 4.37 km (2.7 mi) farther north than the northern boundary of the Phase I model. This provides more overlap between the Frenchman Flat

framework model and the Yucca Flat framework model (currently under construction). The extension of the northern boundary of the Phase II model makes the Phase II model 83 km^2 (32 mi^2) larger in areal extent than the Phase I model.

1.6.2 Structural Framework

The initial Frenchman Flat Phase I base model incorporated a conceptual structural model developed by Grauch and Hudson (1995) that was based primarily on interpretation of gravity and aeromagnetic data. The Phase II model uses a new structural model based on a rigorous analysis of all the geologic and geophysical data, including data from the Phase II data acquisition. As a result, the structural models for the Phase I and Phase II Frenchman Flat hydrostratigraphic framework models, although similar in the general concept of basin development, differ considerably in detail. Both structural models depict a series of basin-forming faults that flare out of the Rock Valley fault zone. However, the Phase I structural model depicted these faults as north-trending, down-to-the-west normal faults that produced a series of east-tilted half grabens beneath the central portion of Frenchman Flat. The Phase II structural model confines the basin-forming faults to the east side of Frenchman Flat, and models the faults as curving to the northwest. This results in a single, deep, east-tilted half graben beneath the central portion of Frenchman Flat, and a structural platform beneath the northern portion of the basin. The Phase II model also includes a detachment fault beneath the northern portion of Frenchman Flat. This structural feature was not part of the Phase I model.

1.6.3 Basin Depth

Data collected during the Frenchman Flat Phase II data acquisition clearly show that the Frenchman Flat basin is deeper than originally depicted in the Phase I framework model. In the vicinity of underground nuclear test locations in the central portion of Frenchman Flat, pre-Tertiary rocks, which form the regional aquifer, are more than 1,000 m (3,000 ft) deeper in the Phase II model. Beneath northern Frenchman Flat, in the vicinity of Well Cluster ER-5-3, pre-Tertiary rocks are approximately 380 m (1,250 ft) deeper in the Phase II model.

The greater depth to pre-Tertiary rocks in the Phase II model results in greater thicknesses of the overlying alluvial and volcanic deposits. Alluvial deposits in the Phase II framework model are more than 100 m (330 ft) thicker in northern portion of the basin, and more than 800 m (2,600 ft) thicker beneath central Frenchman Flat. Likewise, Tertiary-age volcanic rocks are 300 m (980 ft) thicker beneath northern Frenchman Flat and 600 m (1,970 ft) thicker beneath the central portion of the basin.

1.6.4 Number of Hydrostratigraphic Units

The Phase II hydrostratigraphic framework model for Frenchman Flat includes 17 HSUs versus 9 HSUs in Phase I model. The increase in the number of HSUs in the Phase II model is mainly the result of subdividing original Phase I HSUs based on new information from the Phase II data acquisition initiative. These subdivisions provide more detail in the model, as well as consistency with the hydrostratigraphic system under development for Yucca Flat where much more subsurface data is available.

1.6.5 Extent of Volcanic Aquifers

Phase II data from Well Cluster ER-5-4 (see Section 2.3.4.2) and the 3-D seismic survey (Section 2.3.5.9) clearly indicate that the volcanic aquifers in the Phase II model (i.e., Timber Mountain welded-tuff aquifer [TM-WTA], Timber Mountain vitric-tuff aquifer [TM-LVTA], and Topopah Spring aquifer [TSA]) are more extensive than the hydrostratigraphically equivalent Timber Mountain aquifer (TMA), that was originally modeled in the Phase I model. The volcanic aquifers in the Phase II model extend from outcrops in the hills north of Frenchman Flat southward to the central portion of the basin, pinching out south of Well Cluster ER-5-4. In the Phase I model the TMA was confined to the northern portion of Frenchman Flat, and thus was not present beneath the central portion of the basin.

1.6.6 Alternative Models

Although alternative interpretations were considered and described narratively in the Phase I model, they were not developed as independent models. The Phase II model also provides for four alternative models. Each alternative model contains a different interpretation of a non-unique or poorly constrained interpretation of a certain aspect of the base model that was judged to be hydrologically significant. Eight other alternative interpretations were judged to be better assessed during flow and transport modeling instead of developing separate framework models.

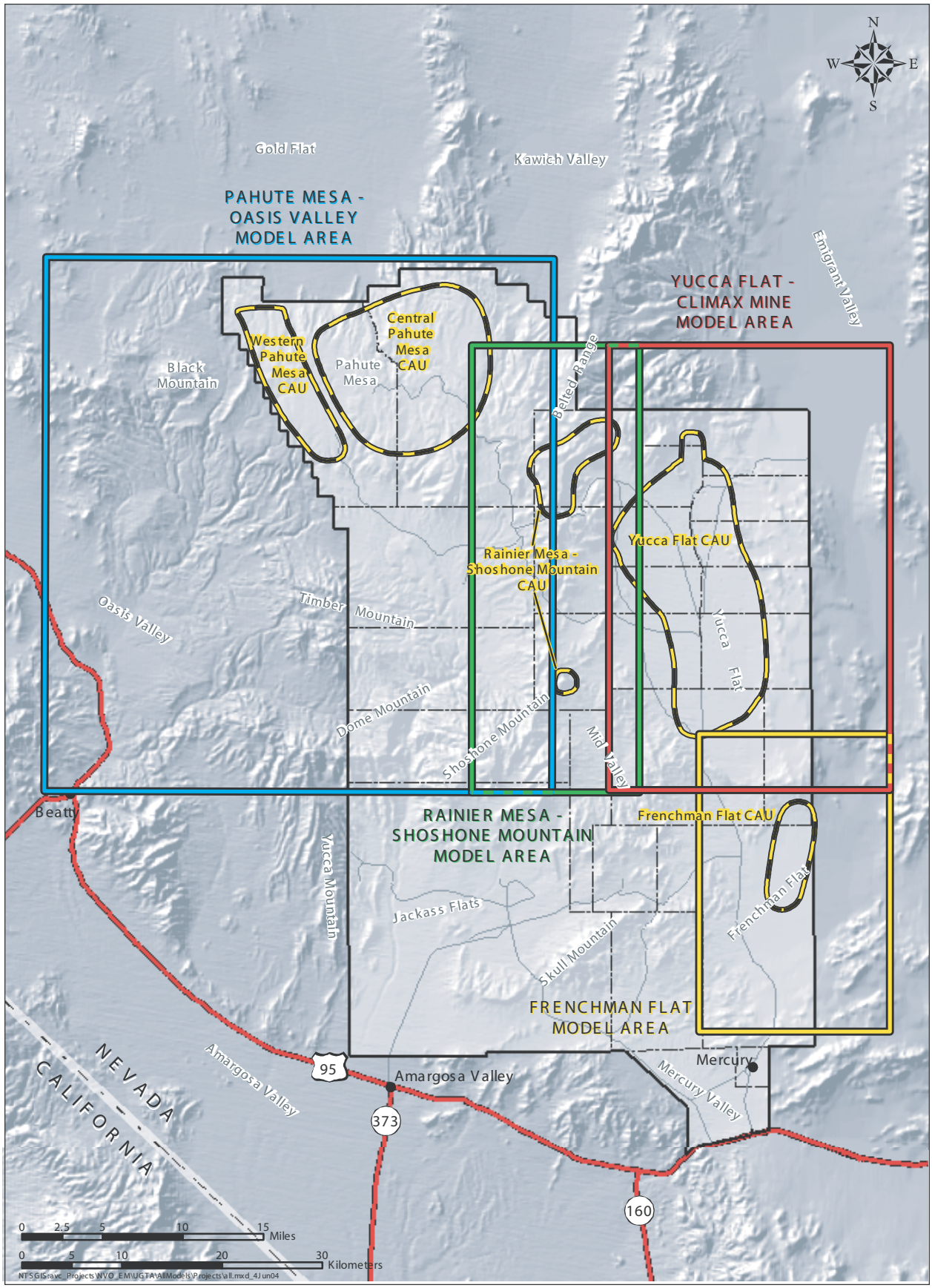

Figure 1-1
UGTA Corrective Action Unit (CAU) and Model Area Boundaries

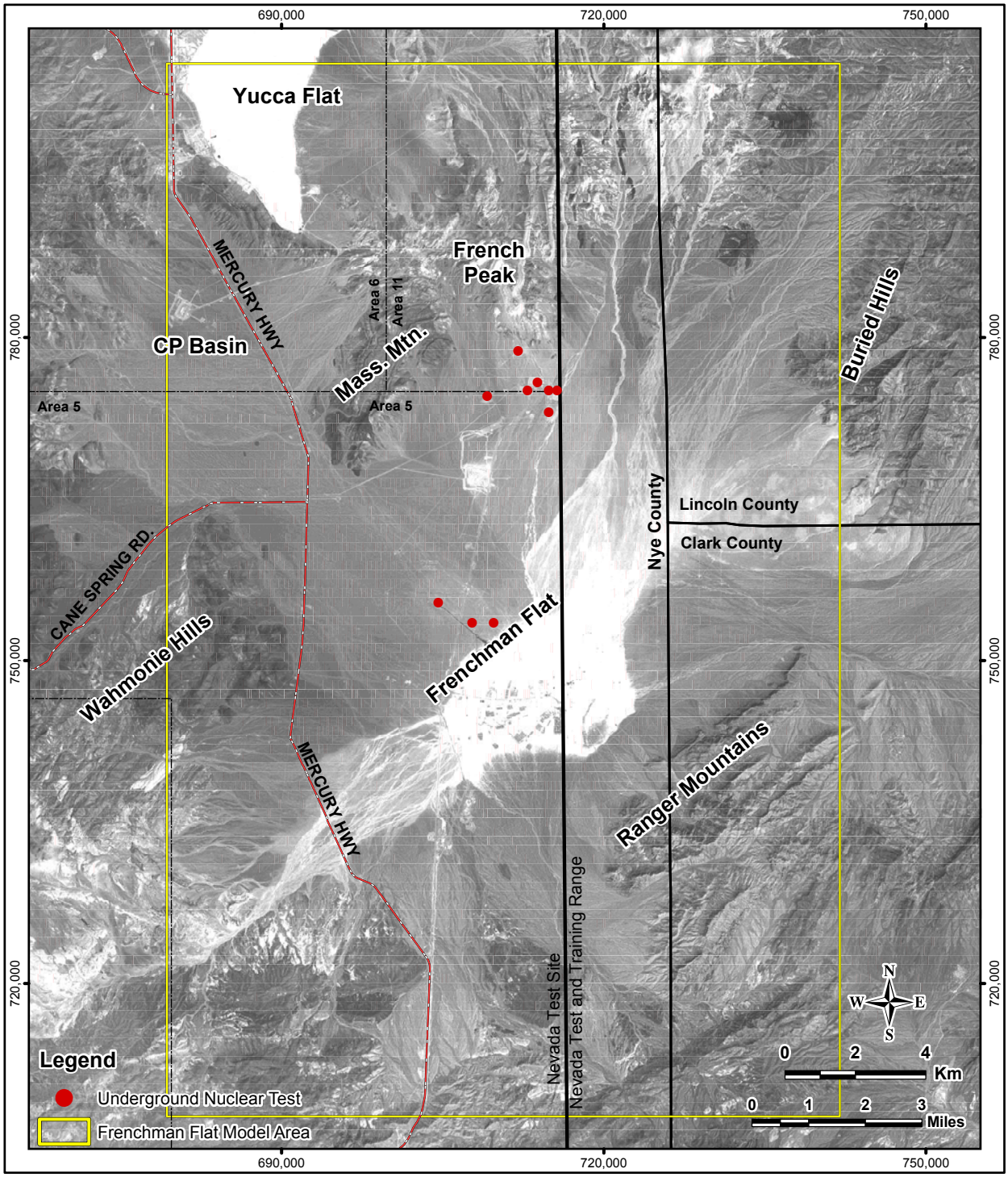

Figure 1-2
Satellite Image of the Frenchman Flat Area Showing Physiographic Features and Locations of Underground Nuclear Tests

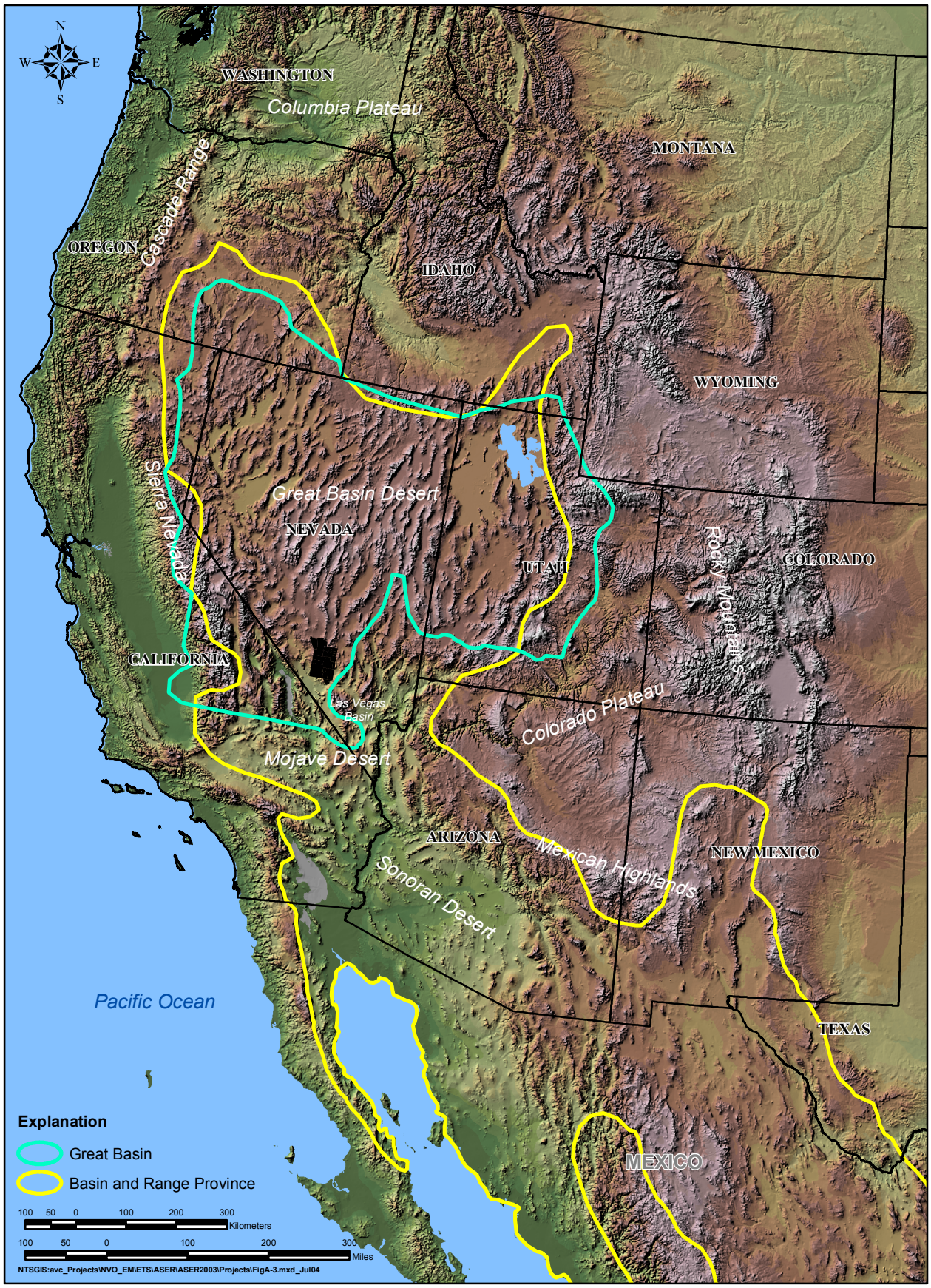

Figure 1-3
Color Relief Map Showing Locations of
the Basin and Range Physiographic and Great Basin Hydrographic Provinces

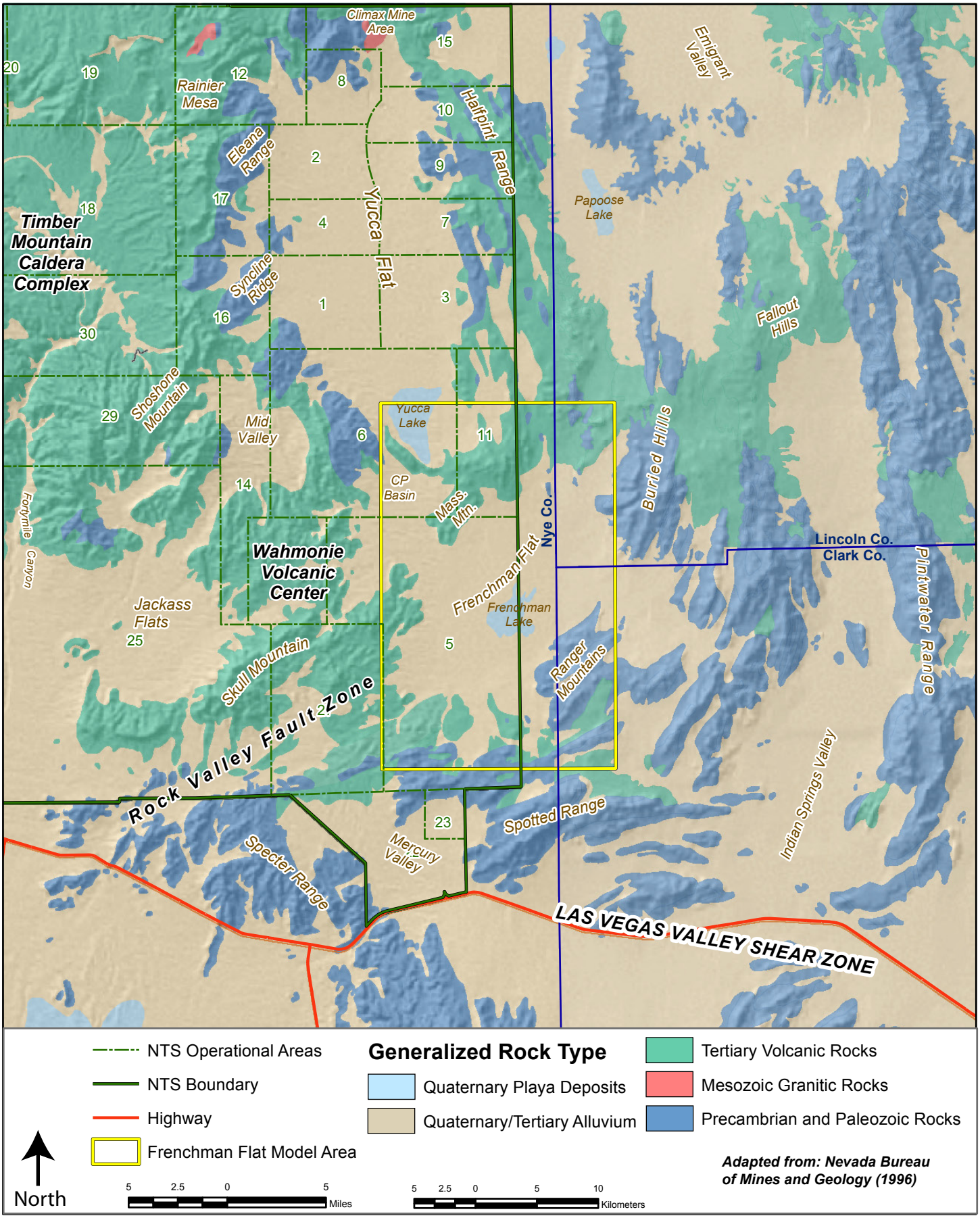

Figure 1-4
Generalized Geologic Map of the Frenchman Flat Region

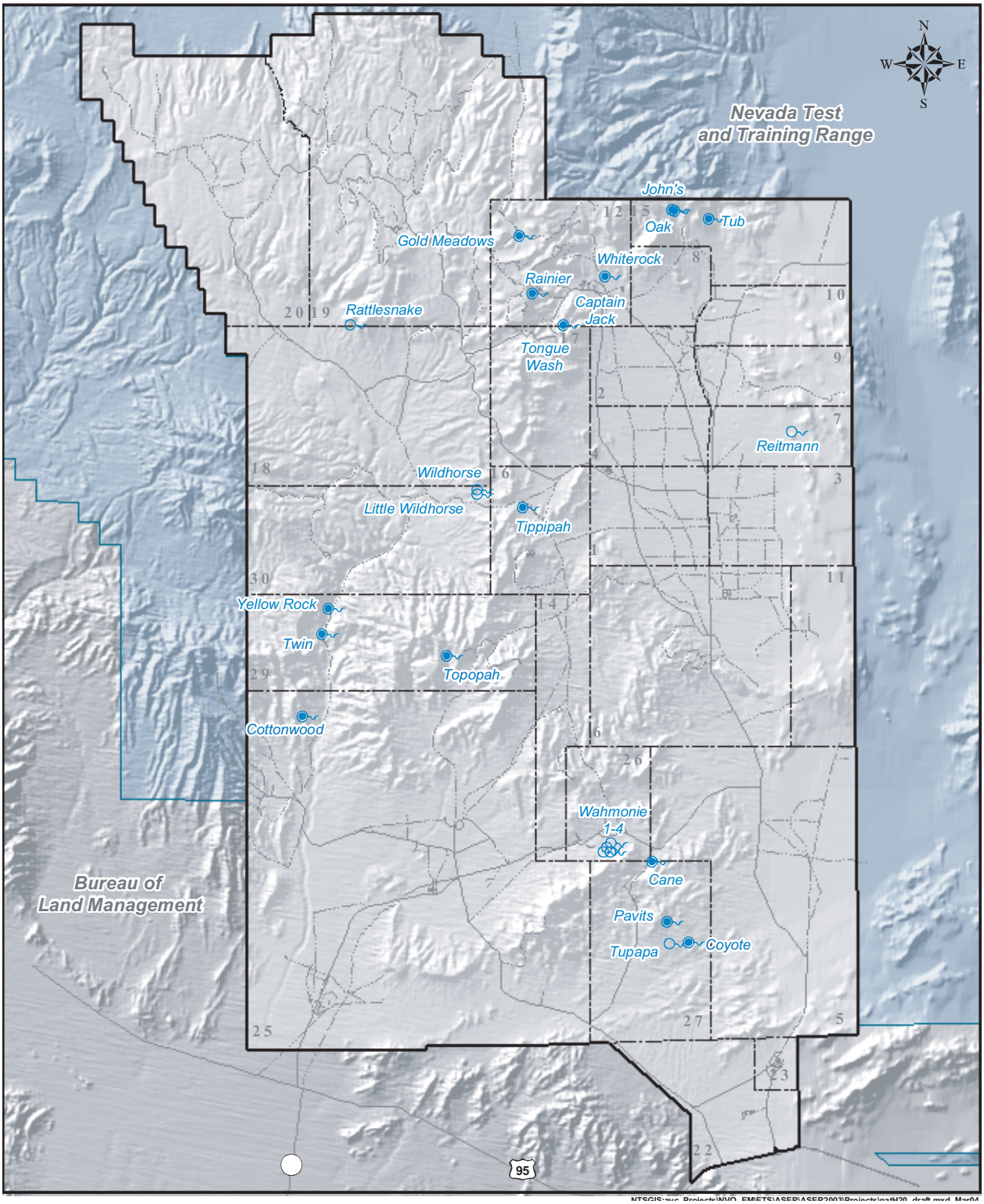

Figure 1-5
Natural Springs and Seeps on the Nevada Test Site
(After Hansen et al., 1997)

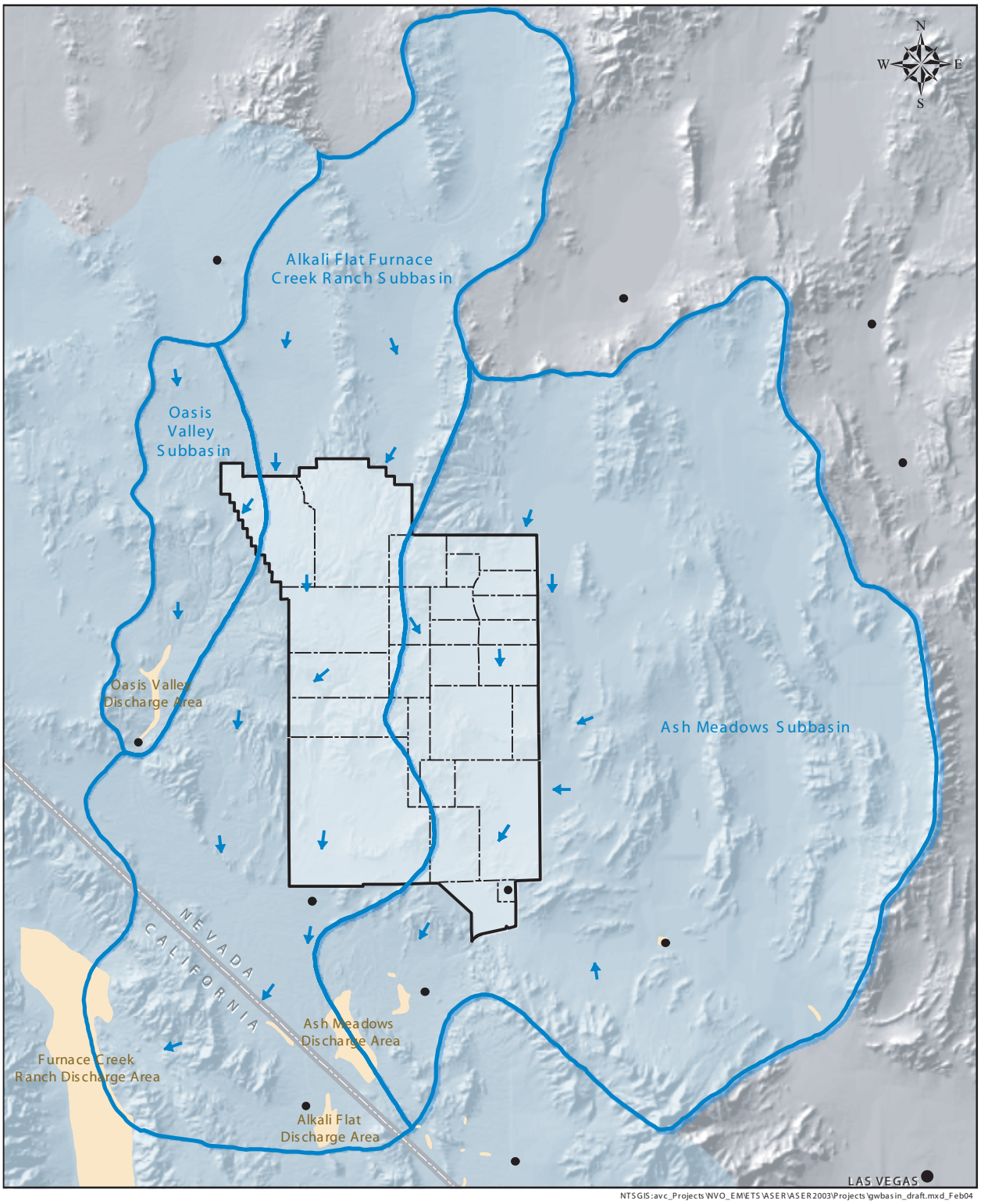

Figure 1-6
Groundwater Subbasins of the Nevada Test Site and Vicinity
(Modified from Waddell et al., 1984 and Laczniak et al., 1996)
Arrows show general direction of inferred groundwater flow.
Black dots represent populated areas.

2.0 METHODOLOGY

This section describes the process, methods, and data utilized to construct the Frenchman Flat hydrostratigraphic framework model. Because much of the initial model-building work was accomplished during Phase I (IT, 1998), some activities performed during Phase I are also included in this section.

2.1 Model Construction Process

A summary of the general work flow for model construction is provided below. The summary lists in general chronological order individual tasks accomplished to build the final framework model. More in-depth discussions of some of the major portions of the model-building process are provided in following subsections.

Phase I (Fiscal Year [FY] 1997 and FY 1998)

- Establish and define the boundaries of the model area.
- Assemble stratigraphic, lithologic, and alteration data for all drill holes within the model area.
- Assemble other existing geologic data and interpretive products, including geologic maps, cross sections, and geophysical investigations:
  - » Relevant hydrostratigraphic cross sections originally prepared during the UGTA Phase I regional modeling effort.
  - » Special-purpose maps, cross sections, and other data originally prepared in support of the DOE weapons testing program (WTP).
- Build upon existing databases to create an expanded stratigraphic drill hole database for the Frenchman Flat model.
- Develop a hydrostratigraphic classification system and HSU drill hole database for the Frenchman Flat model using stratigraphic, lithologic, and alteration data.
- Integrate the USGS structural model.
- Construct interpretive geologic cross sections, pseudo drill holes (i.e., control points), and structure-contour maps for selected HSUs.
- Input data and interpretive products into Environmental Resources Management Applications System® (ERMA®) modeling software.

- Resolve relational problems and modify the hydrostratigraphic framework model as necessary.

- Subject draft model to an internal review process.

- Revise draft model.

- Document the data used, their sources, interpretative approach, methods, etc.

- Submit hydrostratigraphic framework model and documentation to the UGTA hydrologic modelers.

- Submit model and documentation for internal and external reviews.

<u>Phase II: Data Acquisition (FY 2001 and FY 2002)</u>

- Drill five new wells.

- Conduct a 3-D seismic survey.

- Revise geophysical analyses (gravity and aeromagnetic data).

<u>Phase II: Data Assessment and Model Building (this report, FY 2004 and FY 2005)</u>

- Convert the 1998 ERMA® model to the EarthVision® modeling platform.

- Revise model area boundaries.

- Conduct pre-emptive review.

- Compile data.

  » Re-evaluate all existing data.
  » Integrate new data.

- Develop new conceptual structural model.

- Enhance the existing Phase I hydrostratigraphic classification system (i.e., subdivide the alluvial and volcanic aquifer units) and revise HSU drillhole database.

- Input data into EarthVision® and build revised framework model.

- Resolve relational problems and modify the framework model as necessary.

- Subject draft base model to an internal review process.

- Revise draft base model.

- Develop alternative scenarios.
- Subject alternative models to internal review process.
- Revise alternative models.
- Compile documentation package.
- Submit model to hydrologic modelers.

2.2 Determination of Model Area Boundaries

The Frenchman Flat model area is a north-south oriented, 19.1- by 30.0-km (11.9- by 19.1-mi) rectangular area encompassing more than 570 km^2 (220 mi^2). Vertically, the model extends from the ground surface to 5 km (3.1 mi) below mean sea level (Figure 2-1). The base of the model is below the top of the Precambrian sedimentary rocks that underlie the regional aquifer. This deep confining unit is considered to be the hydrologic basement ("LCCU" in Figure 2-1). Geographic coordinates that define the boundaries for the Phase II Frenchman Flat model area are given in Table 1-1.

The model area boundaries were constrained by the needs of the hydrologic modelers and by the limitations and benefits of using computer modeling software. The model area had to be large enough to encompass all potential regulatory boundaries and any subsequent or derivative flow and transport models. However, the area covered by the Frenchman Flat 3-D hydrostratigraphic framework model may not necessarily be the same as that covered in the final flow and transport model. The hydrostratigraphic framework model area encompasses all of the underground testing areas (i.e., radiological source areas) in northern and central Frenchman Flat. The model includes all relevant geologic features, including known and inferred geologic structures. It also encompasses plausible flow paths from the source areas, based on the initial Frenchman Flat model (IT, 1998), on the regional flow models (IT, 1999c), and on known hydrologic features (e.g., a possible flow path to Paleozoic-age rocks along the eastern portion of the model, or along the Rock Valley fault system in the southwest). The original northern boundary of the Phase I Frenchman Flat model, which coincided with the southern boundary of the Yucca Flat model area, was moved northward 4.37 km (2.7 mi) for the Phase II model. This creates an overlap with the southern portion of the Yucca Flat model area, and provides a larger hydrologic buffer on the north side of the Frenchman Flat model (Figure 1-1).

The model area had to be of a size that does not overload computing capabilities. Both software and hardware limitations, and desired level of detail in the model were considered. For ease of manipulation, the model area was kept rectangular in shape, which resulted in the inclusion of

CP Basin in the northwest corner of the Phase II model. The CP Basin, located northwest of the Cane Spring fault, was not included in the Phase I model.

2.3 Data, Interpretive Products, and Other Information Used in Model Construction

Despite the presence of clusters of drill holes in portions of the model area (Drellack, 1997; Wagoner and Richardson, 1986) subsurface information in portions of the model area is sparse, particularly at deeper stratigraphic levels. However, geoscientists have been working in the NTS region for more than 40 years (Byers et al., 1989), and many sources of geologic and geophysical information and data relevant to the Frenchman Flat area are available. For example, most of the geologic units in the model are exposed at the surface within the NTS region, allowing direct observation of rock properties and characteristics. Drill hole and surface geophysical data are also available for these units. Other data for the adjacent Yucca Flat CAU area were also available (Gonzales et al., 1998), as well as published maps and geologic reports, and unpublished geologic and geophysical data originally collected in support of other NTS programs (e.g., WTP, Yucca Mountain Project [YMP], and Area 5 Radioactive Waste Management Site [RWMS]). Data also became available from five new boreholes and several new geophysical studies conducted in the study area. Ground surface elevations were imported from a digital elevation model (DEM) data set (IT, 1999a). This newer DEM was compiled from the most recent USGS 7½-minute quadrangle maps. Surface and near-surface geologic information was derived from USGS geologic maps of the area.

Some of the more important sources of data and information used to construct the model are listed below and discussed in more detail in following subsections.

- Six USGS geologic quadrangle maps (Table 2-1)
- Lincoln County geologic map (Tschanz and Pampeyen, 1970)
- Gravity and magnetic investigations (Carr et al., 1975; Healey et al., 1987; Hudson, 1992 and 1997; Ponce et al., 1988; Wahl, 1995; Phelps and Graham, 2002; Phelps et al., 2005)
- Frenchman Flat alluvium study (Pawloski, 1996)
- Area 5 (RWMS) studies (Blout et al., 1995; Case, et al., 1984; RSN, 1994; REECo, 1993a, 1993b; BN, 2005; Shott et al., 1995, 1998; Snyder et al., 1994, 1995; Sully et al., 1993)
- A reconnaissance study of the Tertiary sediments in the Frenchman Flat area (Prothro and Drellack, 1997)
- USGS DEM data (IT, 1999a) were used as the basis for the final digital model. The original 90-m grid data were resampled to a 250-m grid for use in this model.
- Drill hole data (Drellack, 1997)

- Well Cluster ER-5-3 (DOE, 2005a)
- Well Cluster ER-5-4 (DOE, 2005b)
- Seismic surveys (National Geophysical Company, Inc., 1966; Pullammanappallil and Louie, 1994; Prothro, 2002)
- Alluvium mineralogy study (Warren et al., 2002; Zavarin et al., 2002 and 2004)

2.3.1 Other Models

Several organizations have produced, or are in the process of producing, geologic and hydrologic models of various sizes and degrees of complexity for areas that adjoin or include portions of the UGTA Frenchman Flat area. The UGTA models that served as a starting point for the Frenchman Flat model have already been mentioned: the UGTA Phase I Regional Model (IT, 1996a, 1996b, 1996c, 1996d) and the initial Frenchman Flat Phase I hydrostratigraphic framework model (IT, 1998). The initial work on the Phase I Yucca Flat model (Gonzales et al., 1998) provided information for the northern portion of the Frenchman Flat model which overlaps the southern end of the Yucca Flat model area. The Death Valley regional groundwater flow model (D'Agnese et al., 1997; Workman et al., 2002; Sweetkind et al., 2001; Faunt, 1998; Faunt et al., 1999) was developed by the USGS at the request of a multi-organizational consortium which includes the National Park Service, the Bureau of Land Management, the State of Nevada, and NNSA/NSO for the YMP. The developers of the Frenchman Flat 3-D hydrostratigraphic framework model benefitted from access to these other models, and incorporated data and working concepts from them as necessary.

2.3.2 Existing Geological and Geophysical Maps

USGS geologists have been mapping in the NTS area since the 1950s, and have produced numerous geologic quadrangle maps at a scale of 1:24,000. Table 2-1 lists the six USGS geologic quadrangle maps that include portions of the Frenchman Flat model area. Data from other surface geologic maps at larger scales were also utilized (Table 2-2). Table 2-3 lists some of the special-purpose geological and geophysical maps that were studied and referred to during model construction.

Table 2-1
Geologic Quadrangle Maps (Scale 1:24,000) Used in Construction of the Frenchman Flat Hydrostratigraphic Framework Model

Quadrangle Name	Reference
Mercury	Barnes et al., 1982
Camp Desert Rock	Hinrichs, 1968
Plutonium Valley	Hinrichs and McKay, 1965
Yucca Lake	McKeown et al., 1976
Frenchman Flat	Poole, 1965
Cane Spring	Poole et al., 1965

Table 2-2
Special Purpose Geologic Maps Used in Construction of the Frenchman Flat Hydrostratigraphic Framework Model

Map Title and Scale	Reference
Digital Geologic Map of the Nevada Test Site and Vicinity, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California (1:120,000)	Slate et al., 1999
County Digital Geologic Maps (1:250,000)	Nevada Bureau of Mines and Geology, 1996
Geologic Map of Nevada (1:500,000)	Stewart and Carlson, 1978
Geologic Map of the Death Valley Groundwater Basin and Surrounding areas, Nevada and California (1:250,000)	Workman et al., 2002

Table 2-3
Miscellaneous Special Purpose Maps Used in Construction of the Frenchman Flat Hydrostratigraphic Framework Model

Map Title and Scale	Reference
Geologic Surface Effects of Underground Nuclear Testing, Buckboard Mesa, Climax Stock, Dome Mountain, Frenchman Flat, Rainier/Aqueduct Mesa, and Shoshone Mountain, NTS, Nevada	Grasso, 2003
Lineaments Identified in Northern Frenchman Flat, Nye, Lincoln, and Clark Counties, Nevada (1:24,000)	Miller et al., 1993
Preliminary Aeromagnetic Map of the Nevada Test Site and Vicinity, Nevada (1:100,000)	Kirchoff-Stein et al., 1989
Digital Aeromagnetic Map of the Nevada Test Site Area, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California (1:100,000)	Ponce, 1999
Complete Bouguer Gravity Map of the Nevada Test Site and Vicinity, Nevada (1:100,000)	Healey et al., 1987
Isostatic Gravity Map of the Nevada Test Site and Vicinity, Nevada (1:100,000)	Ponce et al., 1988
Digital Isostatic Gravity Map of the Nevada Test Site Area, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California (1:100,000)	Ponce et al., 1999
Maps of the Thickness of Cenozoic Deposits and the Isostatic Residual Gravity over Basement for Nevada (1:1,000,000)	Jachens and Moring, 1990

2.3.3 Drill Hole Data

Nearly 80 holes have been drilled in the Frenchman Flat area for various purposes, including construction of water wells and monitoring wells, emplacement holes for underground nuclear tests, and exploratory holes (RSN, 1990; Drellack, 1997). Most of these holes were drilled for the DOE in support of NTS programs, and data from most of these were held primarily in NTS agency files. During development of the UGTA Phase I regional model (IT, 1996a, 1996b, 1996c, 1996d) and the initial Phase I Frenchman Flat model (IT, 1998), most of these data were compiled, analyzed, and organized into databases for import into modeling software applications. Holes providing input for the Frenchman Flat framework model are listed in Appendix A and shown on Plate 2. The holes provide information on the geologic and hydrologic character and distribution of subsurface units. However, approximately half the holes listed in Appendix A are shallow alluvium holes and thus provide limited information. The principal holes that provide the most useful information are shown in Figure 2-2 and on Plate 1.

Although much of the geologic information provided in Appendix A is typically referred to as data, it should be remembered that such information is a result of a rigorous interpretive process based on an integrated analysis of drill cuttings, rock core, geophysical logs, and surrounding surface exposures. Results from laboratory analyses such as petrography, x-ray diffraction, and x-ray fluorescence were also integrated into the stratigraphic interpretation when available.

2.3.4 Phase II Well Drilling Initiative

Five new wells were drilled and completed as part of the Phase II data acquisition initiative for the Frenchman Flat CAU, and provide important information and constraints for the framework model. The wells were intended to provide confirmatory information for the Frenchman Flat hydrogeologic model, and new detailed information about the geology, hydrogeology, and water chemistry in the immediate vicinity of the two underground nuclear testing areas within Frenchman Flat. Well Cluster ER-5-3 is located near the northern group of underground tests in Frenchman Flat, and Well Cluster ER-5-4 is located near the southern group of underground tests in central Frenchman Flat. The purpose and expectations of this drilling initiative are spelled out in the *Frenchman Flat Hydrogeologic Investigation Wells Drilling and Completion Criteria* and its addendum (IT, 2000, 2001). Data from these wells, combined with the 3-D seismic data, were important in the development of the modified structural model for Frenchman Flat. Information about the well clusters is summarized in the two subsections below.

2.3.4.1 Well Cluster ER-5-3

Well Cluster ER-5-3 is located in Frenchman Flat near the northern Frenchman Flat underground nuclear test area (Figure 2-2). The well cluster consists of three boreholes drilled on the same drill pad. The wells were drilled as part of the hydrogeologic investigation well program of Phase II Data Acquisition for Frenchman Flat. The primary purpose of constructing Well Cluster ER-5-3 was to obtain information to help characterize the hydrogeology near a group of underground nuclear test locations in this part of Frenchman Flat. Material for this discussion was abstracted from *Completion Report for Well Cluster ER-5-3* (DOE, 2005a).

Three boreholes were drilled at this site in the attempt to penetrate saturated alluvium, the volcanic aquifer, and the tuff confining unit, and to reach total depth (TD) in the lower carbonate aquifer. Because of borehole instability problems the first borehole, Well ER-5-3, was terminated in the tuff confining unit before reaching the planned depth of 1,158.2 m (3,800 ft). Well ER-5-3#2, was then drilled to the depth of 1,732.2 m (5,683 ft) and reached TD within the lower carbonate aquifer. Well ER-5-3#3 was drilled to a TD of 548.6 m (1,800 ft) and completed in the saturated alluvium.

The unconfined water level, which is within the alluvial section at Well Cluster ER-5-3, is approximately 282.5 m (927 ft) below ground surface. Based on this preliminary fluid depth and the as-built surface elevation of 1,016.3 m (3,334.3 ft), the fluid level elevation at Well Cluster ER-5-3 is 733.8 m (2,407.3 ft). The potentiometric water level for Well ER-5-3#2 (completed within Paleozoic-age carbonate rocks) is at a depth of 289.9 m (951 ft) below the ground surface. See also IT (2002) and SNJV (2004) for additional information on hydrologic studies made at this well cluster. No radionuclides above background levels were encountered during drilling of Well Cluster ER-5-3 (DOE, 2005a).

The wells penetrated Quaternary/Tertiary alluvium to the depth of 622.4 m (2,042 ft), with a 8.5-m (28-ft) thick basalt flow encountered within the alluvium. Tertiary-age tuffs were penetrated to the depth of approximately 1,425.9 m (4,678 ft), where the top of Paleozoic rocks was tagged in Well ER-5-3#2. Geologic data from the well suggest that the contact between the Tertiary-age Bullfrog Tuff and Paleozoic-age dolomite is a fault, which is consistent with interpretation of 3-D seismic data in the area that shows a west-dipping normal fault cutting Well ER-5-3#2 very near the 1,425.9-m (4,678-ft) depth. The depth to the top of Paleozoic rocks is 329 m (1,078 ft) deeper than predicted by the Phase I model. See Appendix B-1 for a graphical representation of the geology and hydrogeology of Well ER-5-3#2.

The welded ash-flow tuffs that occur in the upper portion of the volcanic section above 914.4 m (3,000 ft) form welded-tuff aquifers. Severe lost circulation and borehole instability experienced while drilling these welded tuff intervals suggest that they are highly fractured and thus would likely form substantial aquifers in the vicinity of the well cluster. The volcanic rocks below 914.4 m (3,000 ft) consist mostly of poorly welded zeolitic tuffs that form a 511.5-m (1,678-ft) thick tuff confining unit at the well cluster site. The dolomite encountered below the volcanic section, at 1,425.9 m (4,678 ft), is the top of the regional carbonate aquifer.

2.3.4.2 Well Cluster ER-5-4

Well Cluster ER-5-4 is located in central Area 5 of the NTS (Figure 2-2), approximately 1.6 km (1.0 mi) northwest of the Frenchman Lake playa, and 5.7 km (3.6 m) south of Well Cluster ER-5-3. Well Cluster ER-5-4 consists of 2 boreholes drilled 30.5 m (100 ft) apart on the same drill pad. The wells were drilled as part of the hydrogeologic investigation well program, Phase II Data Acquisition for Frenchman Flat. The primary purpose of constructing Well Cluster ER-5-4 was to obtain information to help characterize the hydrogeology near a group of underground nuclear test locations in central Frenchman Flat. Material for this discussion was abstracted from *Completion Report for Well Cluster ER-5-4* (DOE, 2005b).

Well ER-5-4, the first well of the cluster, was drilled to a depth of 1,137.5 m (3,732 ft) in 2001. The completion design of the well allows for access to the alluvial aquifer at three depths. Well ER-5-4#2 was drilled in 2002 to a depth of 2,133.6 m (7,000 ft). The well was completed in zeolitized, non-welded tuff (tuff confining unit) with a slotted interval at 1,976.9 to 2,029.3 m (6,486.0 to 6,657.7 ft).

The geologic units encountered at Well Cluster ER-5-4, in descending order, are 1,120.4 m (3,676 ft) of Quaternary and Tertiary alluvium, 242.6 m (796 ft) of generally unaltered nonwelded and welded ash-flow tuff of Tertiary age, and 770.5 m (2,528 ft) of mostly zeolitic nonwelded tuff, also of Tertiary age. Data from an imaging log indicate bedding dips of about 30 degrees to the east-southeast, which is consistent with dips determined from the seismic data. The wells encountered thicker alluvium and volcanic rocks than expected, and the deeper well, Well ER-5-4#2, at 2,133.6 m (7,000 ft), did not reach the older Tertiary sedimentary rocks or Paleozoic rocks as predicted. The pre-drill estimate for the depth to Paleozoic rocks ranged from 1,158 to 1,524 m (3,800 to 5,000 ft) depending on the exact position of the borehole relative to a large inferred buried fault in the Phase I model. See Appendix B-2 for a graphical representation of the geology and hydrogeology of Well ER-5-4#2.

The water level in both wells is approximately 221.6 m (727 ft) below ground surface. No radionuclides above background were encountered in the groundwater produced from either well in the cluster (DOE, 2005b).

2.3.5 Geophysical Data and Investigations

Numerous geophysical investigations have been conducted in Frenchman Flat since the 1960s, including seismic, resistivity, magnetic, and gravity surveys. Most recently, in FY 2001 and 2002, the UGTA Phase II data acquisition initiative for Frenchman Flat included a high resolution 3-D seismic survey of the two Frenchman Flat testing areas (see Appendix D), and analysis of existing gravity data in Frenchman Flat using 3-D inversion methods (Phelps and Graham, 2002). Also, a magnetotelluric (MT) survey was conducted in the Yucca Flat vicinity in 2003 as part of the Phase I data acquisition initiative for Yucca Flat. The two southern-most MT transects included measurements within the Frenchman Flat model area. The USGS collected additional gravity data in FY 2003 in the northwestern portion of the model area, including CP Basin and Massachusetts Mountain (Phelps et al., 2005).

Data and interpretations for all the geophysical investigations conducted in Frenchman Flat were reviewed during model construction and, where appropriate, integrated into the hydrostratigraphic framework model. Information from geophysical investigations was

integrated with surface geology and drill hole data to develop a structural model of the basin and determine the distribution of HSUs. The geophysical data were also utilized during development of alternative scenarios. Each of the geophysical methods conducted in Frenchman Flat and used during model construction is discussed below.

2.3.5.1 Gravity Data

Gravity methods have been used in the Frenchman Flat vicinity since the 1960s to define the overall shape of the basin, determine approximate locations of major faults, and estimate the depth to pre-Cenozoic rocks (Poole, 1965; Healey, 1965; Carr et al., 1975; Miller and Healey, 1986; Grauch and Hudson, 1995; Wahl, 1995; Phelps and Graham, 2002; Phelps et al., 2005). The data indicate that Frenchman Flat is a northeast-oriented oval-shaped basin narrower at its southwest end. Strong gravity gradients are observed around the margins of the basin, particularly along the southeast and northeast margins, suggesting large basin-forming faults in these areas (Carr et al., 1975; Grauch and Hudson, 1995; Phelps and Graham 2002). Estimates of the maximum depth to pre-Cenozoic rocks range from 1,219.2 to 1,676.4 m (4,000 to 5,500 ft) in the earlier investigations (Poole, 1965; Carr et al., 1975; Miller and Healey, 1986; Wahl, 1995).

Phelps and Graham (2002) used an iterative gravity inversion method with a density model of the Cenozoic rocks that varies with depth (based on density data from Well Clusters ER-5-3 and ER-5-4), to estimate the maximum depth of the basin (i.e., depth to pre-Cenozoic rocks) at 2,400 m (7,874 ft). This estimate is consistent with recently acquired data from deep drilling at Well ER-5-4#2 and from the 3-D seismic reflection survey (see Section 2.3.5.4). Phelps and Graham (2002) used data from 3,746 gravity measurements in and around Frenchman Flat, including 642 made in the basin itself and 233 made on surrounding pre-Cenozoic outcrops. Phelps and Graham (2002) verified the general shape of the basin as determined in the earlier investigations, and found no indication that major horst and graben structures are present beneath the basin (Figure 2-3). However, a northwest-trending, down-to-the-southwest gradient appears to separate the deeper basin occupying the southwestern two thirds of Frenchman Flat from a structural platform beneath the northeast portion of the basin. This feature is also quite evident in the maximum horizontal gradient map (Grauch and Hudson, 1995) and in the 3-D seismic data.

High-spatial-frequency gravity measurements were made in Frenchman Flat in 2001 as part of the 3-D seismic reflection survey effort. A total of 2,991 measurements were made within a 22.5-km^2 (14-mi^2) area covering northern and central Frenchman Flat to provide near-surface, gravity-derived, static corrections to the seismic data. A Bouguer gravity map constructed from

this data set indicated that the data are consistent with gravity data from previous investigations (Healey et al., 1987).

Additional gravity measurements were made in 2003 by the USGS in the northwest portion of the model area, including CP Basin and Massachusetts Mountain (Phelps et al., 2005). These data indicated that CP Basin is deepest on its eastern side, adjacent to the Cane Spring Fault. However, the gravity data did not indicate substantial vertical offset along the fault. These new data also indicated that the substantial negative gravity anomaly at Massachusetts Mountain (an area with few controlling data points ([Wahl, 1995; Phelps and Graham, 2002]), was not as pronounced when the new data points from this survey were taken into consideration.

The various gravity investigations conducted in and around Frenchman Flat provided valuable information during construction of the Frenchman Flat hydrostratigraphic model. The overall shape of the basin observed in the gravity data was honored in developing a structural model for Frenchman Flat. Areas with strong gravity gradients provided information on the approximate locations of major basin-forming faults. Gravity data also provided information for estimating the depth to pre-Cenozoic rocks in areas of little or no subsurface control. Figure 2-4 shows the locations of gravity measurements in the Frenchman Flat vicinity.

2.3.5.2 Ground Magnetic Data

Ground magnetic surveys were conducted as part of a special geologic and geophysical study of northern Frenchman Flat (Carr et al., 1975). These data were collected along 11 transects (Figure 2-4) and used by Carr et al. (1975) to determine the edges of several basalt lava flows intercalated within the alluvium in northern Frenchman Flat. Basalt was encountered in drill holes UE-5i and UE-5k (Dixon et al., 1967; Byers and Miller, 1966), and subsequently in UGTA Well Cluster ER-5-3 (DOE, 2005a). These data were utilized to establish the extent and thickness of buried basalt flow aquifers within the Frenchman Flat hydrostratigraphic framework model.

2.3.5.3 Aeromagnetic Data

Numerous aeromagnetic surveys have been flown over the Frenchman Flat vicinity (Carr et al., 1975; Grauch and Hudson, 1995; McCafferty and Grauch, 1997; Phelps et al., 2005). Carr et al. (1975) used aeromagnetic data to identify and evaluate the subsurface extent of magnetic anomalies caused by basalt flows and the presence of Rainier Mesa Tuff beneath the northern portion of Frenchman Flat.

Grauch and Hudson (1995) used aeromagnetic data to evaluate the distributions of volcanic rocks beneath the basin and identify buried faults. Several north-trending linear magnetic boundaries were observed beneath Frenchman Flat that Grauch and Hudson (1995) interpreted to be buried, down-to-the-west normal faults. This interpretation of the aeromagnetic data formed an important component of the structural model of the original Frenchman Flat Phase I hydrostratigraphic framework model. However, these faults are not observed in the gravity data or 3-D seismic data, and thus likely result from other geological or geophysical effects. The current Phase II model does not include these aeromagnetic-inferred faults.

The USGS collected additional aeromagnetic data in the northwestern portion of the model area in 2003 (Phelps et al., 2005). This area includes CP Basin, the southern end of Yucca Flat, and the extreme northwest portion of Frenchman Flat.

Aeromagnetic data were the least useful of all the geophysical data utilized in the Frenchman Flat area. This is due mostly to the great thickness of alluvium within the basin and the presence of both positively and negatively magnetized units within the volcanic rocks of the area.

2.3.5.4 Natural Source Magnetotelluric Survey

In the fall of 2003, the USGS conducted a natural-source MT survey in the Yucca Flat vicinity to better characterize pre-Tertiary stratigraphy and structure beneath Yucca Flat. Fifty-two MT recording stations were arranged along six generally west-to-east profiles extending across Yucca Flat (Figure 2-5). The two southern-most MT profiles extend into the Frenchman Flat model area, and information from these profiles was incorporated into the Frenchman Flat model. The southern-most transect stretches from Mid Valley on the west, crosses CP Basin, and ends just north of Massachusetts Mountain. The other transect extends from west to east across Yucca Lake in extreme southern Yucca Flat.

BN geologists analyzed the MT data sets and found that MT stations across CP Basin delineate the Cane Spring fault and indicate that the fault forms the eastern boundary of the basin. MT data show that rocks east of the fault consist of a relatively thin section of Tertiary volcanic rocks overlying structurally high pre-Tertiary carbonate. Rocks west of the fault consist of thicker alluvium and volcanic rocks directly overlying a thick section of low resistivity rocks that are interpreted to represent Mississippian siliciclastic rocks. The siliciclastic rocks appear to be confined in extent to the eastern portion of CP Basin adjacent to the Cane Spring fault. However, a relatively thin (e.g. 100-m [330-ft]) section of Mississippian siliciclastic rocks could be present beneath the western portion of the basin. Such a section would be too thin to be resolved by the MT method.

Data from the survey lines that cross the Yucca Flat playa indicate that the alluvium around the playa is much less resistive than alluvium in other parts of Yucca Flat, as expected for fine-grained playa deposits. High resistivity values to a depth of 3,000 m (9,842 ft) beneath southern Yucca Flat indicate that pre-Tertiary rocks beneath the southern portion of the basin probably consist mostly of carbonate.

2.3.5.5 Controlled-Source Audio-Frequency Magnetotelluric Survey

A vector controlled-source audio-frequency magnetotelluric (CSMAT) survey was conducted in Frenchman Flat in 1990 to help characterize the subsurface geology in the vicinity of the Area 5 RWMS (Zonge, 1990). Two lines of vector CSMAT data were gathered in the northern portion of Frenchman Flat using two transmitter sites located in the southern portion of the valley. Several single-receiver stations were located in the southern portion of Frenchman Flat (Figure 2-5).

The CSMAT data provided information on the depth to the water table and on the depth and character of the Paleozoic rocks beneath the northwestern portion of Frenchman Flat. The water table is clearly visible along the southern line and the eastern half of the northern line, and appears relatively flat in an east-west direction. The thickness of unsaturated alluvium is slightly greater along the northern line, which is consistent with the higher surface elevation in that area.

The top of a deep resistive layer that likely corresponds to the top of pre-Tertiary rocks is observed at approximately 1,000 m (3,280 ft) depth beneath the western portion of the northern line and at approximately 1,300 m (4,270 ft) depth beneath the eastern portion of the line. This deep resistor is not observed on the southern line, which indicates that the top of pre-Tertiary rocks is below the depth of investigation (1,500 m [4,920 ft]). These observations are generally consistent with the depth to top of pre-Tertiary rocks as determined from other data such as gravity and seismic, and from Well ER-5-3#2. Gravity and 3-D seismic data indicate the top of pre-Tertiary rocks at between 1,250 and 1,750 m (4,100 to 5,740 ft) in the area, with pre-Tertiary rocks deepening to the south and east. Well ER-5-3#2, located approximately 670 m (2,200 ft) north of the western portion of the northern line, encountered the top of pre-Tertiary dolomite at 1,425.9 m (4,678 ft). The relatively high resistivity (100 to 400 ohm-meters) of the deep resistive layer along the northern line indicates that it likely consists of carbonate rocks, which is consistent with data from Well ER-5-3#2, and that the carbonate aquifer is present below the northwestern portion of the basin.

2.3.5.6 Other Resistivity Surveys

Electrical resistivity surveys were conducted around the Frenchman Lake playa in 1962 in support of the Small Boy series of above-ground nuclear tests (Scott, 1962; Scott and Black, 1962). Information from these early resistivity surveys was utilized during model construction to help determine the thickness of the Frenchman Flat playa deposit and the depth to the LCA in the vicinity of the Frenchman Lake playa. Data from the resistivity surveys indicate that the depth to higher resistivity units such as welded volcanic rocks and Paleozoic sedimentary rocks is more than 304.8 m (1,000 ft) which, with respect to the Paleozoic rocks, is consistent with gravity data (Phelps et al., 2005). The data also indicate that the playa deposits are greater than 91.4 m (300 ft) thick, which is consistent with nearby drill hole data. Figure 2-5 shows the locations of these early resistivity measurements.

2.3.5.7 Seismic Refraction Surveys

Two programs of seismic refraction surveys have been conducted in Frenchman Flat. The first was conducted (in conjunction with the reflection survey described in Section 2.3.5.8) in 1966 in the northern portion of the basin (National Geophysical Company, Inc., 1966) to help characterize the subsurface geology of the area for underground nuclear testing. It consisted of 8 lines, each approximately 1,500 m (4,921 ft) long, and all oriented in a general east-west direction (Figure 2-6). The refraction data are of limited use due to the shallow depth of investigation of these relatively short lines. However, the data do seem to confirm the presence of a higher velocity alluvium at relatively shallow depths (213.3 to 243.8 m [700 to 800 ft]) beneath much of the northern portion of the basin.

Another seismic refraction survey was conducted in 1982, and consisted of 2 northwest-southeast oriented lines that ran from CP Basin into the western portions of Frenchman Flat (Figure 2-6). These long lines provided useful structural information to a depth of 3 km (9,842 ft). Interpretation of the seismic data indicates that the Cane Spring fault has a maximum throw of 500 m (1,600 ft) down to the northwest, and a minimum dip of 72 degrees to the northwest (Pullammanappilli and Louie, 1994). The data also indicate that a down-to-the-east fault is present along the western side of Frenchman Flat. In addition, the data show velocity horizons along the western side of Frenchman Flat, which likely correspond to geologic units, dip eastward into the basin.

2.3.5.8 2-D Seismic Reflection Survey

A 2-dimensional seismic reflection survey was conducted in the northern and central portions of Frenchman Flat in 1966 (in conjunction with the first refraction survey series described in Section 2.3.5.7). This reconnaissance survey consisted of six seismic reflection lines, five

oriented east-west and one oriented generally north-south (Figure 2-6). Although the original seismic profiles could not be located for interpretation during construction of the Frenchman Flat hydrostratigraphic model, the model developers reviewed an informal report (National Geophysical Company, Inc., 1966) that summarizes the results of the survey. The report indicates that the survey was of limited success. The pre-Tertiary rocks were not imaged and there is no mention of any volcanic horizons being identified. Faults cutting the alluvial section were identified but could not be correlated between lines due to the large line spacing. Some of the east-west lines were said to indicate "steep" east dips along the western portions of the lines. This is consistent with later geophysical and geologic data that show rocks beneath the western portion of Frenchman Flat dipping east into the basin.

2.3.5.9 3-D Seismic Reflection Survey

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 hydrostratigraphic units beneath the underground nuclear testing areas in Frenchman Flat. The survey area covered 35.8 km^2 (13.8 mi^2) in the northern and central portions of Frenchman Flat (Figure 2-6). Approximately 4.5 million seismic traces were acquired within the survey area. These were stacked (i.e., grouped) into 153,855 traces within a 15.2-m by 15.2-m (50-ft by 50-ft) bin spacing (i.e., grid). Appendix D provides additional details regarding the acquisition parameters, processing, and interpretation of the Frenchman Flat 3-D seismic survey. The horizons and faults mapped from these data were converted from time to depth and integrated directly into the hydrostratigraphic framework model.

Results from the 3-D seismic survey provided valuable information on the structure and hydrostratigraphy beneath the northern and central portions of the basin. Three seismic horizons were mapped in detail. These included from shallowest to deepest: 1) the base of the alluvium, which corresponds hydrostratigraphically with the base of the alluvial aquifers and playa confining units; 2) the base of the welded volcanic rocks, which generally corresponds to the base of the volcanic aquifers and top of the volcanic confining units; and 3) the top of the Paleozoic rocks, which is interpreted to correspond to the top of the lower carbonate aquifer. In addition, two separate zones of poor seismic reflectivity in the alluvium were tentatively mapped, and are interpreted to represent older playa deposits (i.e., playa confining units) based on correlation of the seismic data with information from Well ER-5-4. Mapping of the seismic horizons, along with information from Well ER-5-4#2, showed that welded volcanic rocks were more extensive beneath the basin than originally thought. It also provided much better constraints on the depth to the Paleozoic rocks, particularly in the northern portion of the basin where these rocks occur higher in the section.

Important structural information was obtained from the seismic data. Of particular importance was the recognition of a previously unknown buried fault zone that strikes northwest beneath the northern portion of Frenchman Flat. This fault zone offsets the Paleozoic and volcanic rocks as much as 610 m (2,000 ft) along a series of down-to-the-southwest faults.

2.3.6 Alluvium Studies

Alluvial deposits that fill Frenchman Flat are particularly important in the Frenchman Flat model. Nine of the ten underground nuclear tests conducted in Frenchman Flat were emplaced within the alluvium, and initial modeling during Phase I showed that radionuclides from these tests did not migrate out of the alluvium during the 1,000-year transport simulations (IT, 1999c). In the Phase I Frenchman Flat hydrostratigraphic framework model, the alluvium was modeled as a single HSU. However, an early objective of the Phase II modeling effort was to subdivide the alluvium into multiple HSUs to allow for more realistic and versatile modeling of these important deposits. Information utilized for subdividing the alluvium came from various sources, including two alluvium investigations. Pawloski (1996) sought to define an apparent older, denser alluvium recognized in Frenchman Flat by early investigators. Warren et al. (2002) focused on characterizing the mineralogic and chemical nature of the alluvium in Frenchman Flat, primarily at Well ER-5-4. These two studies are described in more detail in the following subsections. Information from Well Clusters ER-5-3 and ER-5-4 (Sections 2.4.5.1 and 2.4.5.2) and geophysical data, including 3-D seismic (Section 2.4.7.9 and Appendix D) and surface magnetics (Section 2.4.7.2), also provided important information on the alluvium.

2.3.6.1 Differentiation of the Older Alluvium

Because of apparent variability of the alluvium in Frenchman Flat mentioned by earlier investigators (Carr et al., 1975 and Miller and Healey, 1986), Pawloski (1996) conducted an investigation of the alluvium in northern Frenchman Flat using existing literature, lithologic logs, and geophysical data to determine if the alluvial deposits could be subdivided on the basis of hydrogeologic characteristics. Pawloski (1996) focused on characterizing the nature and extent of an interval of dense alluvium recognized by Carr et al., (1975) and Miller and Healey (1986), that might possess hydrologic properties that are slightly different from the rest of the alluvial section. Although Pawloski (1996) confirmed that this subunit can be distinguished on the basis of bulk density, porosity, and velocity, it appeared to be discontinuous and of local extent, having been encountered in only a few holes in northern Frenchman Flat. Information from Pawloski (1996) was used during construction of the Phase II model to help designate and model a separate older alluvial aquifer beneath northern Frenchman Flat.

2.3.6.2 Reactive Secondary Mineral Study for Alluvium in North Central Frenchman Flat

Hydrologic source term modeling has shown that radionuclide transport is highly sensitive to the abundance and availability of certain reactive minerals. Detailed chemical, mineralogic, and micrographic analyses were used to characterize the 1,137.5-m (3,732-ft) thick sequence of alluvium at Well ER-5-4 (Warren et al., 2002). Analysis methods for this study included x-ray diffraction (XRD), x-ray fluorescence (XRF), scanning electron microscope (SEM), quantitative petrography, and electron microprobe. The objective of the study was to provide detailed information regarding the distribution of reactive minerals in the thick alluvial section in north-central Frenchman Flat. The task also supported a geostatistical characterization study by LLNL (Carle et al., 2002).

As summarized in Warren et al. (2002), important findings include:

- The alluvium within Well ER-5-4 can be subdivided into 12 lithologically, chemically, and/or mineralogically distinctive layers.
- The alluvial deposits have not been significantly altered since deposition.
- Though the layers in Well ER-5-4 are recognized within nearby holes UE-5n and RNM-1, they do not relate well to more distant parts of Frenchman Flat (e.g. Well ER-5-3).
- Detritus from the Wahmonie Formation is dominant at Well ER-5-4, indicating a source to the west.
- Minerals within the alluvium are partitioned among three components: crystals, lithic fragments, and matrix. Only those reactive minerals within the matrix are expected to interact with groundwater.
- Clays are present as coatings on crystals and lithic fragments, which limits their reactivity to groundwater.
- Authigenic iron and manganese oxides occur both as phenocrysts and in the matrix.
- Carbonate minerals (secondary calcite) are common in the matrix of the deeper layers.
- Zeolite minerals, on the other hand, occur mostly in lithic fragments and in shards, and consequently are largely unavailable for interaction with groundwater.

Warren et al. (2002) provided information used to subdivide the alluvium in the hydrostratigraphic framework model, and to characterize the nature and distribution of the older alluvial aquifer beneath northern Frenchman Flat. Mineralogic information from Well ER-5-3