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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

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indicates that the tuffaceous matrix of the older alluvial deposits has been altered to zeolite. This may explain the physical differences between the older and younger alluvium observed by Pawloski (1996) and earlier investigators. The lack of zeolitic alteration within older alluvium in Well ER-5-4 provides a lateral constraint (i.e. southern limit) on the distribution of the older alluvial aquifer, and supports the conclusion of Pawloski (1996) that the older, denser alluvium in northern Frenchman Flat is limited in extent.

Detailed analytical results of lithologic samples from Well ER-5-4 reported in Warren et al. (2002) are consistent with lithologic descriptions from the well (DOE, 2005b) that describe a relatively thick interval of clay and silt within the coarser-grained alluvial section. Based on the lithology and correlation with seismic data, the interval 704.7 to 869.1 m (2,312 to 2,940 ft) was modeled separately and designated as an older playa confining unit.

2.4 Pre-Emptive Review

Before the Phase II Frenchman Flat hydrostratigraphic model was constructed, the UGTA TWG initiated a pre-emptive review process. The purpose of this review was to provide a forum for the TWG to evaluate the model and model-building process at various stages during construction of the Phase II model. The pre-emptive review subcommittee consisted of scientists from LANL, LLNL, SNJV, and the USGS. Pre-emptive reviews for the Frenchman Flat model were conducted on October 30, 2003, and March 3, 2004. Data sets, current status of the model, alternative interpretations, and the path forward were assessed from both technical and programmatic perspectives. Comments and suggestions from the subcommittee members were addressed as appropriate.

2.5 Model Construction

Prior to the actual digital construction of the 3-D framework model, two important tasks had to be completed. First, a structural model of the area had to be developed that included the locations and orientations of all the relevant faults in the model area. Fault information was imported into EarthVision®, a 3-D computer modeling program, to form a fault-tree model that depicts all the model faults in 3-D space. The fault-tree model formed the framework on which the hydrostratigraphic model was built. A detailed discussion of the structural model is provided in Section 3.0 of this report.

Although the framework of the Frenchman Flat hydrostratigraphic model is the fault-tree, the foundation of the model is the hydrostratigraphic classification system. This system was developed through a rigorous analysis of stratigraphic and lithologic data in and around Frenchman Flat, and consists of 17 HSUs that form 3-D volumetric layers in the model. A detailed description of the hydrostratigraphic system developed for the Frenchman Flat model is provided in Section 4.0 of this report.

2.5.1 Use of Computer Software to Construct the Model

Computer software designed to handle large amounts of data and interpretive products is used to present the hydrostratigraphic framework for the use of the flow-and-transport modelers. The size of the study area, the large amount of data to be manipulated, and the complexity of the geologic setting of the NTS and vicinity demand sophisticated algorithms for production of realistic interpretations. As the field of computer modeling rapidly grows, new software becomes available which improves the efficiency and results of the modeling process. Thus, the UGTA hydrostratigraphic modeling efforts for Frenchman Flat were initiated in 1997 using ERMA® software, but the data were migrated in 2002 to EarthVision®, an improved system, for continuation of the modeling process. See IT (1998) and IT (1996a) for descriptions of modeling done with ERMA® software.

EarthVision® software (Version 7.5, by Dynamic Graphics) accepts spatially located data such as the elevation of the tops of stratigraphic units in boreholes, outcrop traces, locations and orientations of faults, and other data such as seismic profiles and geophysically derived surfaces. The software then applies geology-based geometric "rules" to determine the most likely 3-D interpretation of the geology in the model area that honors the input data. After the data and interpretive products are input, the computer's interpretation can be adjusted to suit the geologist's concept, to incorporate additional information, or to test alternate hypotheses. It is possible to easily and thoroughly evaluate a geologic model built in EarthVision® and examine relationships of the individual elements. Because the interpretive rules are geology-based, the model automatically satisfies many fundamental geometric requirements for geologic structure and, therefore, requires much less work to check and adjust than in the previously used modeling software (i.e., ERMA®). EarthVision® can be used to produce maps and profiles to illustrate the structure and distribution of HSUs for any portion of the model.

The final hydrostratigraphic framework model will be provided in digital form to UGTA flow-and-transport modelers who will use the framework model to model groundwater flow and contaminant movement within the Frenchman Flat study area. The plates, maps, profiles, and other figures included with this documentation report are intended to provide only general illustrations of the physical framework, structure, and distributions of the HSUs to aid the reader. The flow-and-transport modelers will receive the complete, digital, 3-D model (Figure 2-1).

2.5.2 Model Input

As mentioned previously, the Phase I Frenchman Flat model (IT, 1998) was used as the initial starting point for the Phase II model. However, considerable re-building of the original model was required to incorporate new data acquired during Phase II data collection and to expand the hydrostratigraphic classification system to include more HSUs. A new fault-tree model was developed for the Phase II model based on a revised structural model of the basin resulting from interpretation of Phase II data, particularly from new drill holes and the 3-D seismic survey. Fault locations were digitized from maps and imported into EarthVision® along with information regarding fault dip and offset. Locations of faults determined from 3-D seismic data were imported directly into EarthVision®.

Input regarding HSUs included a drill hole database consisting of elevation tops for HSUs (Appendix A), surface (i.e., outcrop) HSU maps derived from surface geologic maps, unit extent maps for each HSU, and a digital elevation model of the ground surface. The unit extent and outcrop maps were digitized and imported into EarthVision®. Surfaces interpreted from 3-D seismic data were input directly into EarthVision®. The pre-Tertiary surface derived from inversion of gravity-data (Section 2.3.5.1), was imported to help guide the construction of this surface in areas of limited data.

2.5.3 Quality Control and Model Review

The Phase II model was checked and modified as necessary by the SNJV and BN team members during model construction. This was an iterative process utilizing the capabilities of EarthVision® to cut profiles anywhere through the model, then interactively view individual or groups of HSU layers in 3-D, and visually compare various data sets such as drill hole tops and surface-grid points with HSU layers in the model. Traditional 2-D products such as structure contour maps and thickness maps were also produced from the model, and these were used to further evaluate the model. Modifications were made to address geometric conflicts, assure that geologic conventions were honored, assure conformation to drill hole, outcrop, and geophysical data, and incorporate geologic interpretations in areas of limited data. The various versions of the model produced during this process are electronically archived at the offices of SNJV in Las Vegas, Nevada. The final Frenchman Flat model, including alterative scenarios and electronic data sets, resides on workstations and electronic archival media at the offices of SNJV in Las Vegas, Nevada.

Computer-generated assessments of the final base model were conducted to statistically analyze and compare input data sets with computer-generated surfaces and grid points. These assessments show that computer-generated HSU surfaces tie well with the drill hole data

(Figure 2-7), with associated errors typically less than 5 m (16.4 ft). Error associated with outcrop data is greater due to the complexity of the topographic surface, but is still considered to be relatively small.

Reviews of the model and alternatives were conducted within the UGTA pre-emptive review process as described in Section 2.4. A draft model documentation package (i.e., a draft of this report) was reviewed by a select group of pre-emptive review subcommittee members from LANL, LLNL, and USGS, and this final version of the package incorporates their comments.

2.5.4 Alternative Models

As briefly summarized in Sections 1.3.4 and discussed in more detail in Sections 3.0 and 4.0, the Frenchman Flat model area is geologically complex. Many of the major features within the valley are buried, and drill hole data are relatively sparse. Portions of the model are thus necessarily simplified, and represent non-unique solutions to the 3-D distribution of HSUs.

To address non-unique aspects of hydrologically significant interpretations within the base model, alternative interpretations were developed for portions of the base model. Ideas for alternative scenarios were conceived and evaluated during construction of the base model. The alternative models were constructed after the base model was completed, generally using the same model construction techniques. Each alternative model is equally bound by all the data and interpretation methods used for development of the base model. However, each alternative model is of limited geographic extent, and thus, affects only a portion of the base model. The alternatives can be thought of as fully functional, but geologically different, pieces of the base model that can be swapped into and out of the base model to test if the alternative interpretations can affect flow and transport.

An electronic copy of the base model was used in developing each alternative, and only those areas of the base model affected by the alternative interpretation were modified to produce the alternative model. Ultimately, four scenarios were selected for further development as alternative models, and eight scenarios were identified as alternative interpretations that would be better addressed later during hydrologic modeling. The UGTA pre-emptive review subcommittee participated in the development of alterative interpretations by reviewing the interpretations throughout the model construction process, including the final alternative interpretations. The process for addressing alternative interpretations is described in more detail, along with the interpretations themselves, in Section 5.0.

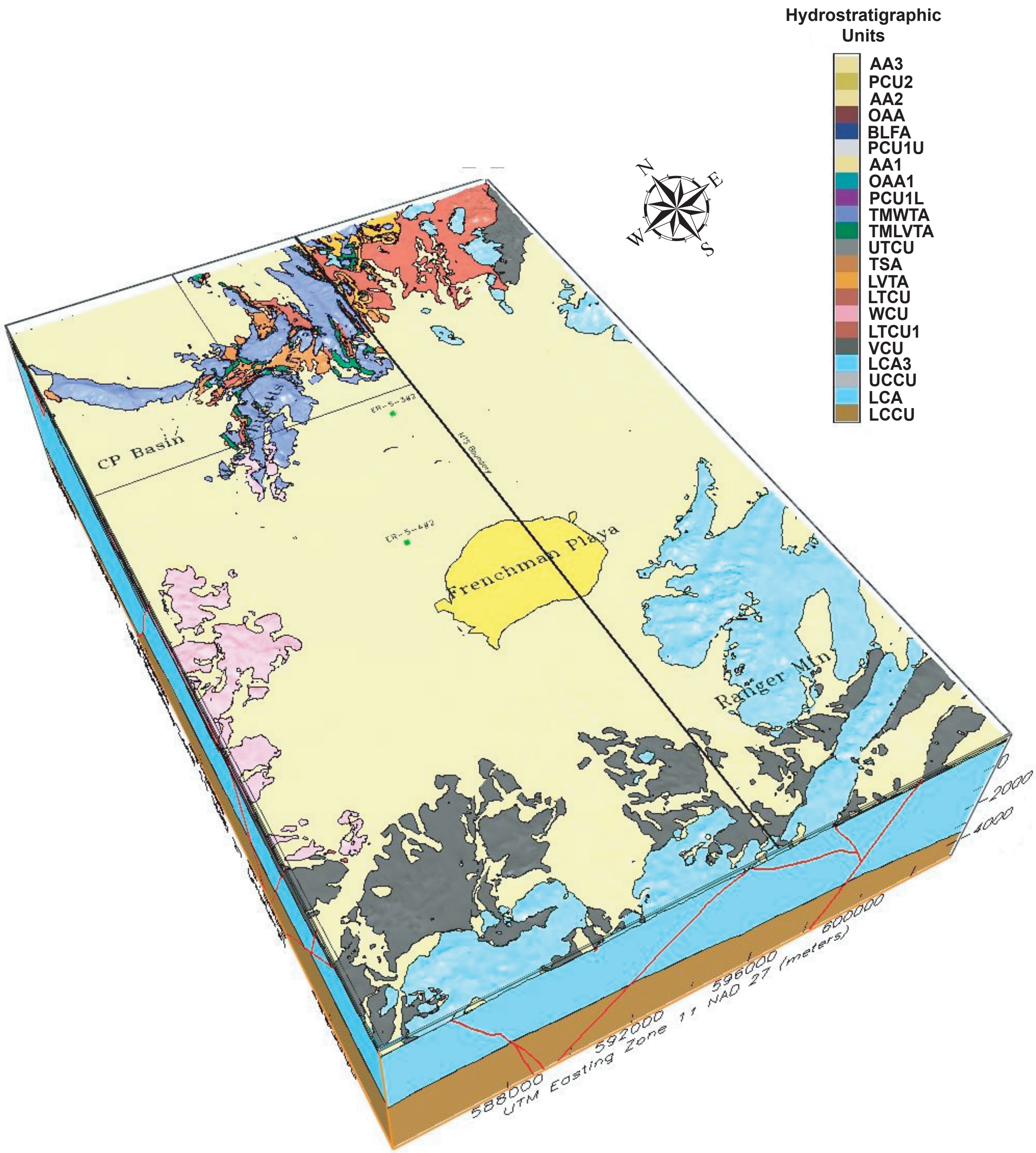

Figure 2-1
3-D Display from EarthVision® of the Model Volume

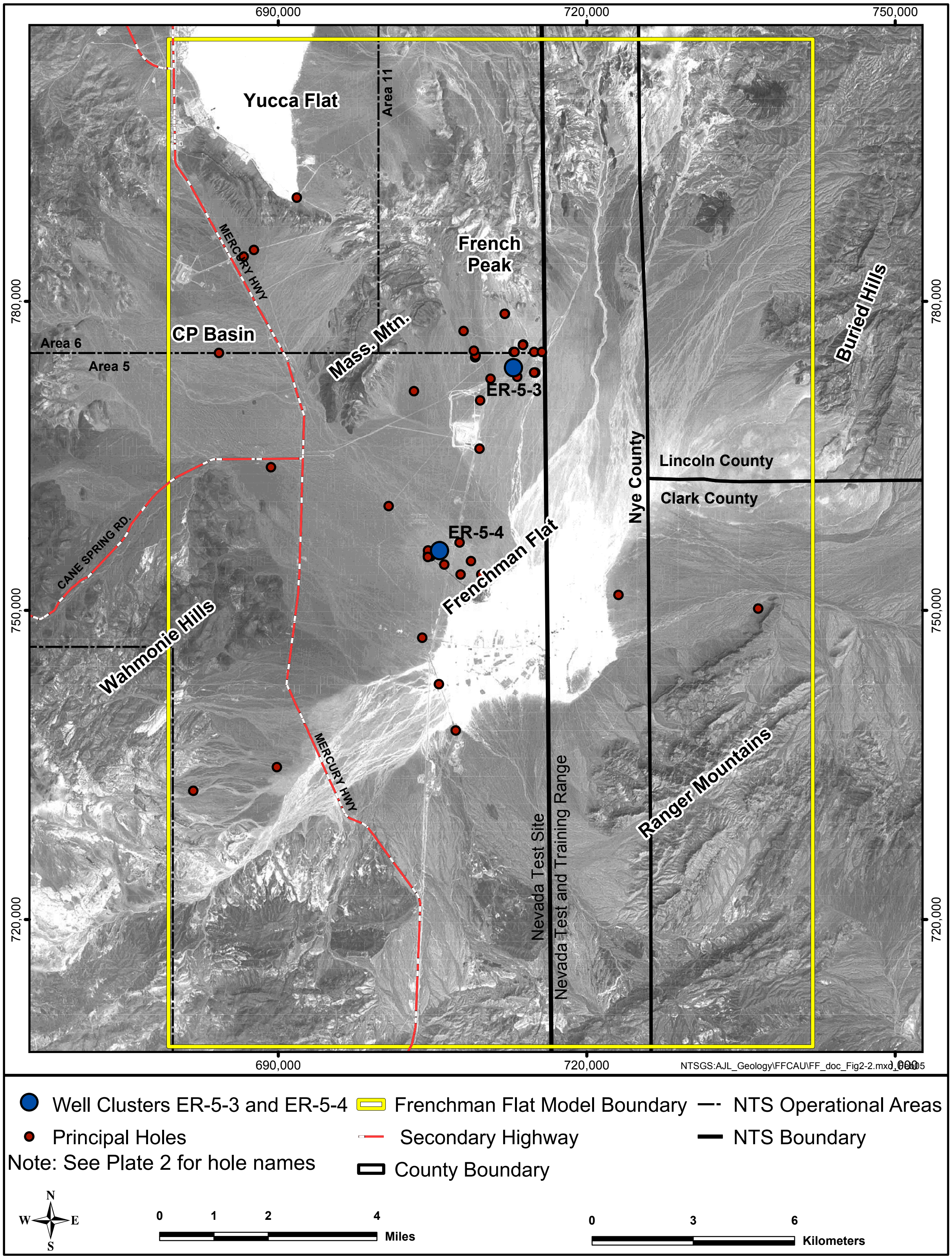

Figure 2-2
Locations of Drill Holes in the Frenchman Flat Model Area

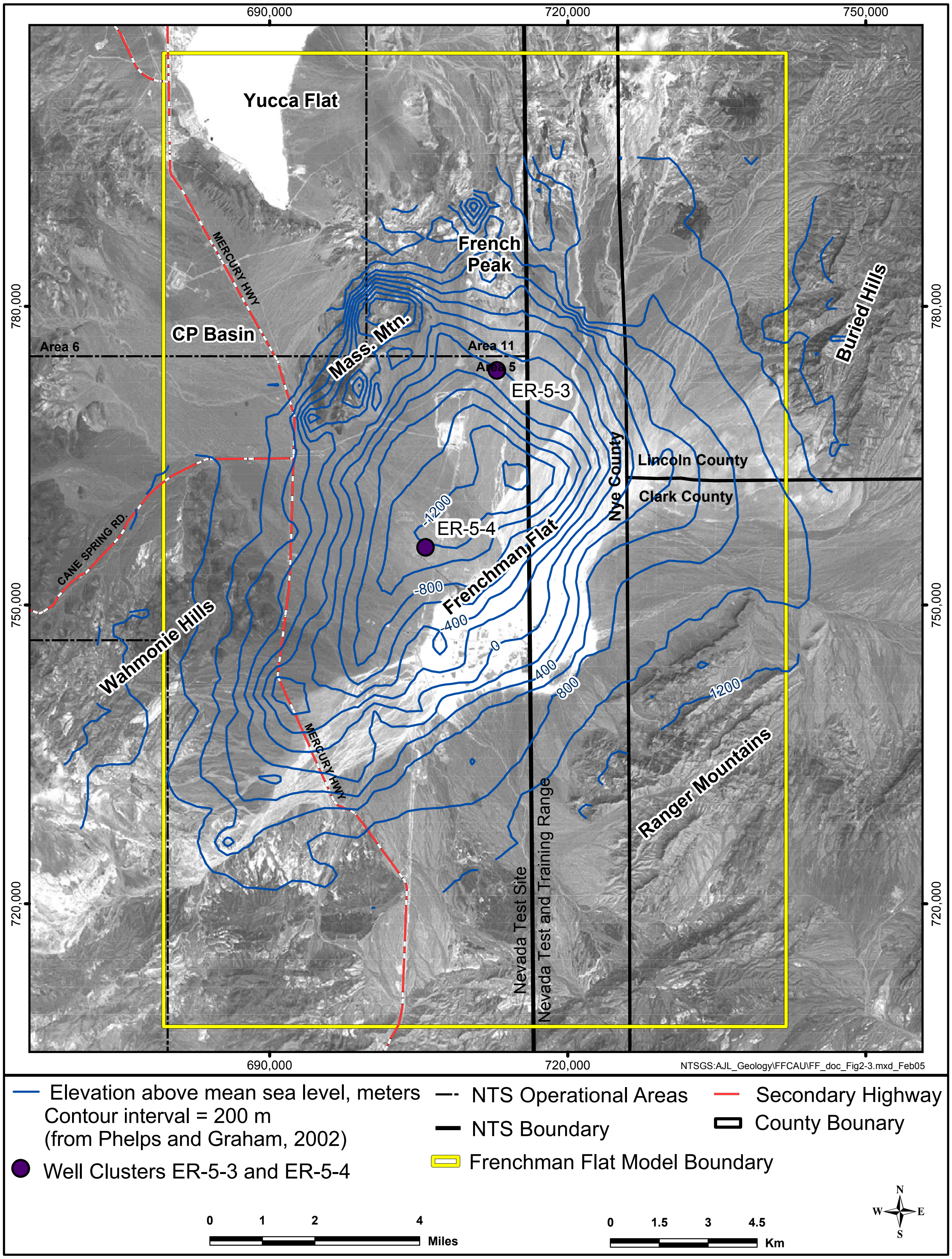

Figure 2-3
Elevation of Pre-Cenozoic Rocks Beneath Frenchman Flat Based on the Gravity Inversion Method

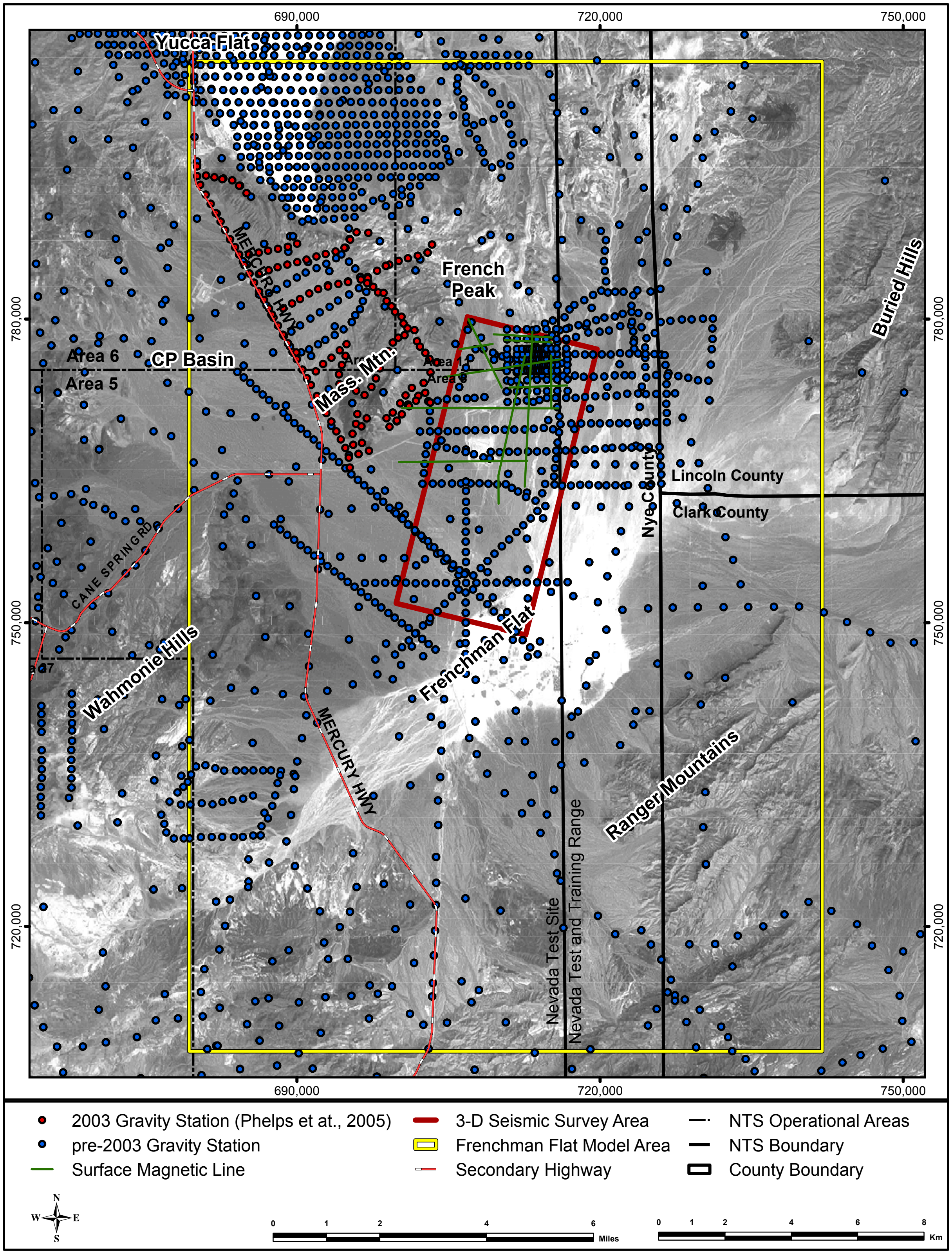

Figure 2-4
Locations of Gravity Stations and Surface Magnetic Lines in the Frenchman Flat Model Area

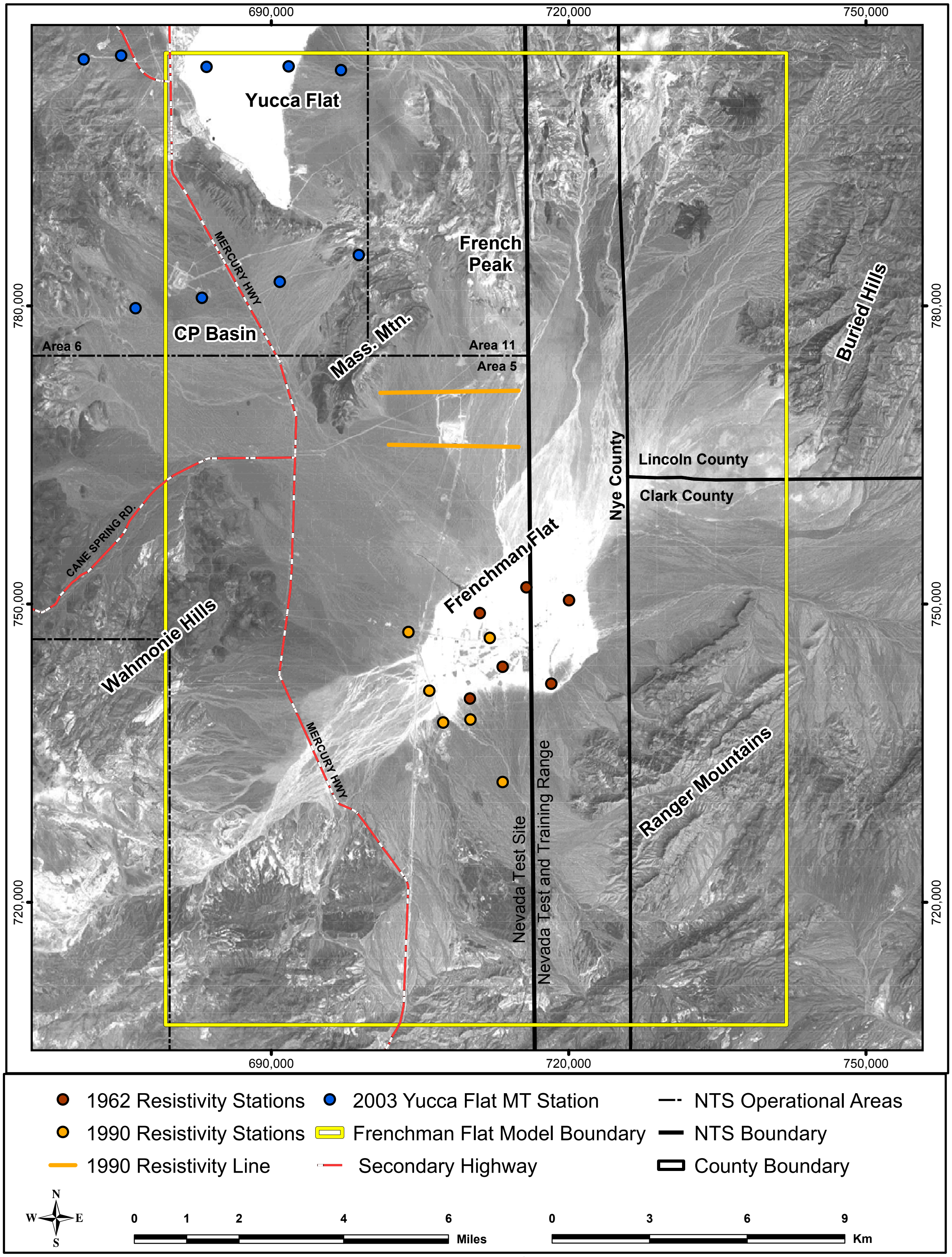

Figure 2-5
Locations of Resistivity Reciever Stations and Lines in the Frenchman Flat Model Area

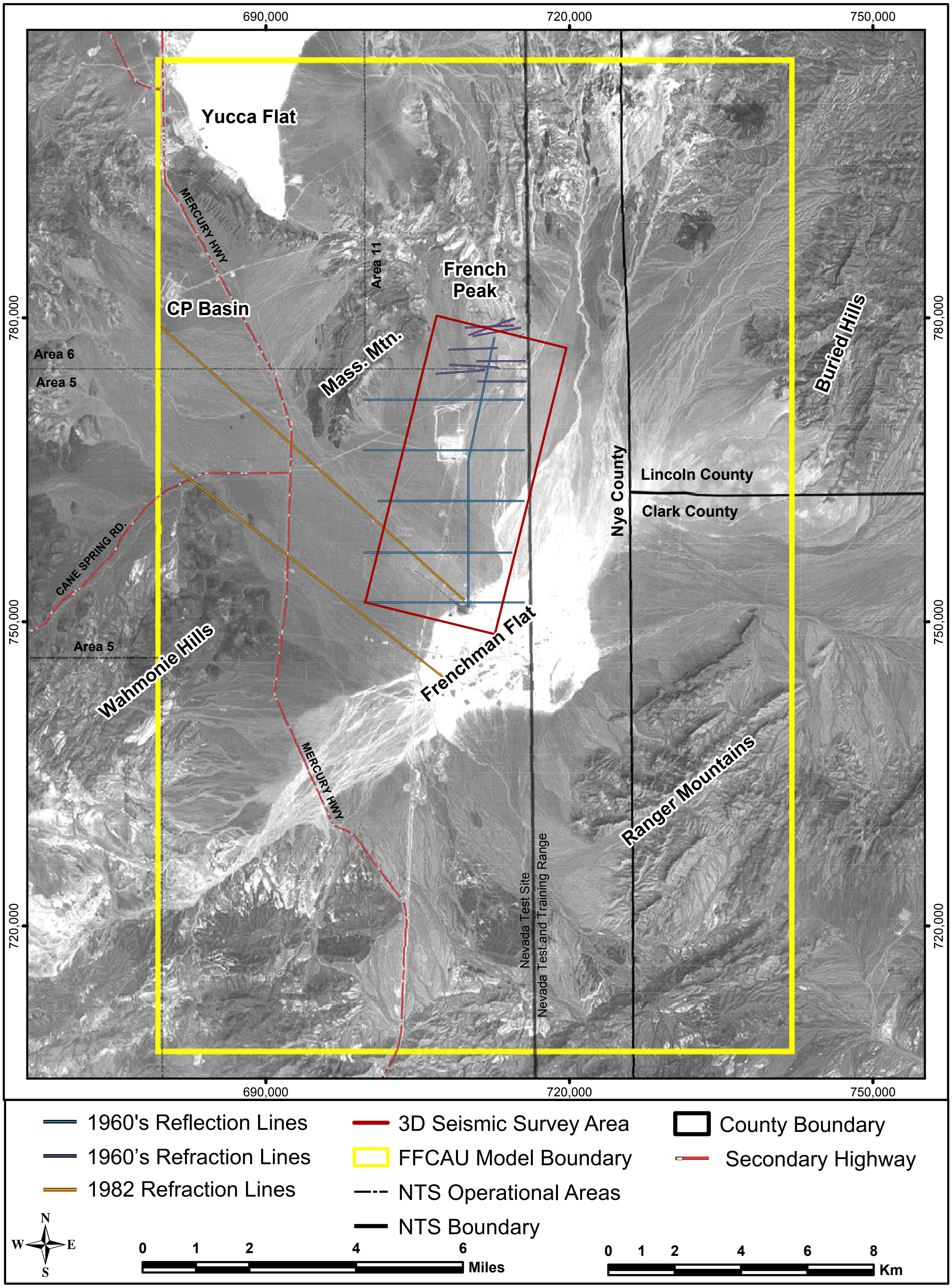

Figure 2-6
Locations of Seismic Surveys in the Frenchman Flat Model Area

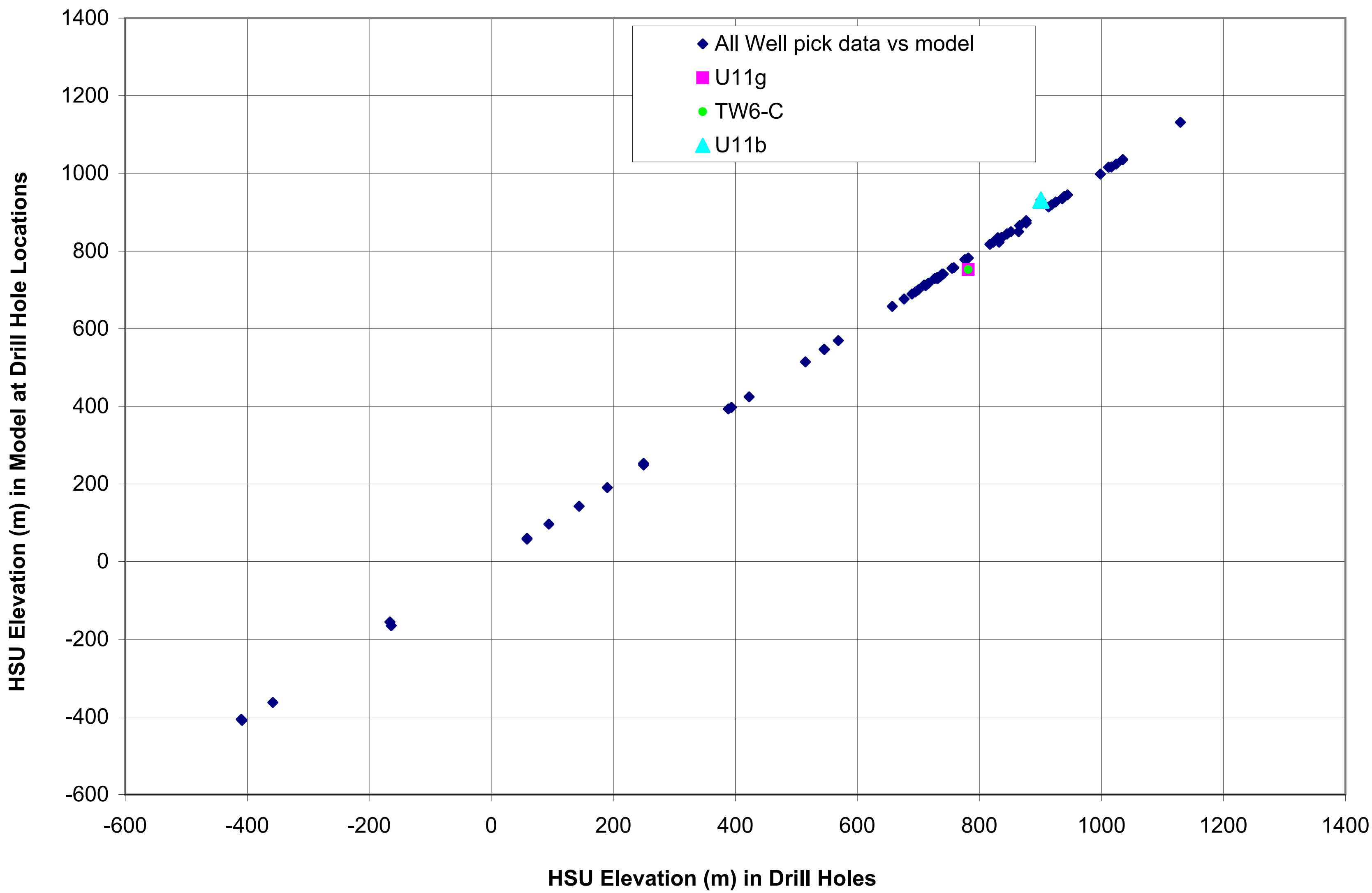

Figure 2-7

Model Assessment Chart Comparing HSU Tops in Drill Holes with HSU Tops Generated by EarthVision® in the Base Model

3.0 STRUCTURAL MODEL

Geologic structures define the geometric configuration of the HSUs in the Frenchman Flat model area, including their distribution, thickness, and orientation, and thus are an important part of the hydrogeologic regime of the area. Basin-forming structures, including normal faults and some strike-slip faults, had a strong influence on depositional patterns of alluvial deposits and the extent, thickness, and structural elevation of volcanic deposits. Some faults place units with different hydrologic properties in juxtaposition, which may have significant hydrologic consequences. Also, the structures may themselves act as either conduits of groundwater flow, if they are characterized by open fractures, or barriers to flow, if associated with fine-grained gouge or increased alteration of nearby rocks. This section describes the structural elements of the model area, and includes discussions of how they were identified and spatially defined for the hydrostratigraphic framework model.

3.1 Structural Overview

The interpretation of the structural geology in the Frenchman Flat vicinity is difficult because complex pre-Tertiary contractional deformation has been overprinted by more recent extensional deformation. In addition, most of the major structural features are buried by thick deposits of volcanic rocks and alluvium. Fortunately, as described in Section 2.0, a rather large data set is available for Frenchman Flat that includes surface geologic exposures, drill hole data, and a variety of geophysical data. Recently acquired data, including deep drilling, 3-D seismic, and a new gravity inversion analysis, have proven valuable in better constraining the structural model of the basin.

3.1.1 Pre-Tertiary Structure

The pre-Tertiary rocks around the margins of Frenchman Flat show complex contractional structural relationships that include both east- and west-vergent thrusting and over-folding. South and east of Frenchman Flat the southeast-vergent Spotted Range thrust fault places Cambrian rocks over rocks as young as Mississippian (Barnes et al., 1982, Cole and Cashman, 1999). Northwest of CP Basin, Cambrian rocks have been thrust over Upper Mississippian and Pennsylvanian rocks along the west-vergent CP thust fault (McKeown et al., 1976; Caskey, 1991 and Cole and Cashman, 1999). The pre-Tertiary structural geology beneath Frenchman Flat however, is unknown. Only one hole within the basin (Well ER-5-3#2) was drilled into pre-Tertiary rocks, and very few coherent reflections were observed within the pre-Tertiary rocks in the seismic data (Prothro, 2002; Appendix D).

Very little is also known about the pre-Tertiary structural geology beneath CP Basin. Analysis by BN geologists of the USGS MT measurements across CP Basin (Section 2.3.5.4) suggest that Mississippian rocks are thick but of limited extent beneath the basin. One interpretation of the MT data is that the Mississippian rocks dip very steeply beneath the eastern portion of the basin. Or Mississippian rocks may be present beneath the western portion of CP Basin, but not thick enough to be resolved by the MT method.

The timing of pre-Tertiary contractional deformation in the Frenchman Flat region is poorly constrained. Deformation must have occurred after the Pennsylvanian (less than 286 million years ago [Ma]) because rocks of this age are deformed within the footwall of the CP thrust fault northwest of CP Basin (McKeown et al., 1976; Caskey, 1991; and Cole and Cashman, 1999). Contractional deformation in the NTS region is probably older than Middle Cretaceous because approximately 100-Ma granite intrudes contractional structures in the northern portion of the NTS (Barnes et al., 1963; Gibbons et al., 1963; and Naeser and Maldonado, 1981).

3.1.2 Development of Frenchman Flat Basin

Gravity data show Frenchman Flat to be a northeast-oriented, tear-drop shaped basin, with its narrower end on the southwest (Figure 3-1). Steep gravity gradients along the south and east margins suggest the presence of major basin-forming faults in these areas. Structural attitudes of rocks exposed around the margins of Frenchman Flat also suggest that major basin-forming faults are located beneath the southern and eastern portions of the basin. Pre-Tertiary rocks are exposed extensively along the southern and eastern margins of the basin and generally dip east and southeast away from the basin. Along the western and northern margins of the basin thick sections of much younger volcanic rocks are exposed that generally dip southeast into the basin. Beneath the central portion of the basin, at Well ER-5-4#2, these volcanic rocks occur at depths ranging from 1,120.4 m to more than 2,133.6 m (3,676 to more than 7,000 ft) (DOE, 2005b). Dip-meter analysis of the borehole image log from Well ER-5-4 #2 and 3-D seismic data indicate that the volcanic rocks beneath the central portion of the basin dip approximately 30 degrees to the east-southeast (Prothro, 2002). This orientation is consistent with interpretations of seismic refraction (Pullammanappallil and Louie, 1994), 2-D seismic reflection (National Geophysical Company, Inc., 1966), and CSMAT data (Zonge, 1990), all of which indicate an eastward tilt to units beneath the basin. In addition, 3-D seismic reflection data do not indicate any large faults offsetting the volcanic rocks beneath the central portion of the basin. Together, the surface geology, geophysical, and drill hole data provide strong evidence that Frenchman Flat is an east-southeast-tilted, half-graben-type basin with the main basin-forming faults located along its southern and eastern margins (Figure 3-2).

Integration of Frenchman Flat site-specific geologic information with regional geologic information strongly suggests that the development of Frenchman Flat is related to movement along the Rock Valley fault zone located southwest of the model area. The Rock Valley fault zone is a system of east-northeast-striking, left-lateral faults that appear to be an offshoot of the Walker Lane-Las Vegas Valley shear zone. Several faults of the Rock Valley system are mapped at the surface in the southwestern portion of the model area (Barnes et al., 1982; Hinrichs, 1968), but appear to be covered by alluvium in the southern portion of the basin, indicating that the fault system continues northeastward beneath the southern portion of Frenchman Flat (see Plate 1). However, pre-Tertiary rocks exposed along the east side of Frenchman Flat are not disrupted by east-northeast-striking faults, which suggests that the Rock Valley fault zone terminates in the vicinity of Frenchman Flat. Pre-Tertiary rocks and associated high-angle normal faults exposed south and east of Frenchman Flat generally strike east-northeast, south of the basin but curve and strike in a more northerly direction east of the basin. It is likely that the faults of the Rock Valley system follow this same trend beneath the southern and eastern portions of the basin. This would place the Rock Valley faults in the same general location and orientation as the steep gravity gradients, and suggests that the Rock Valley faults form the major basin-forming faults along the south and east sides of Frenchman Flat.

Complicating this general structural model is the recognition of a previously unknown northwest-striking, down-to-the-southwest fault zone beneath the northern portion of the basin. This fault zone, which was identified with 3-D seismic reflection data, displaces the Paleozoic rocks as much as 600 m (2,000 ft), resulting in a structural platform beneath the northern portion of the basin (Figure 3-2; Appendix D, Figures D.4-22 and D.4-24). Though subtle, this structural feature is also observed on the gravity data (Figure 2-3). Due to the large amount of displacement associated with this fault zone it is interpreted to be related to basin development and therefore is also likely related to the large basin-forming faults interpreted to be present along the south and east margins of the basin. If this is the case, then the faults of the Rock Valley system must not only curve to the north but also continue to curve to the northwest forming a fan-shaped fault pattern. This fan-shaped pattern of basin-forming faults results in the overall tear-drop shape of the basin as observed in the gravity data.

The beginning of the main period of basin development for Frenchman Flat is well constrained. No sedimentary units are recognized within the volcanic section between the Crater Flat Group (13.25 Ma) and Ammonia Tanks Tuff (11.45 Ma). In addition, 3-D seismic reflection data show no stratigraphic relationships within this portion of the volcanic section characteristic of growth-faulting, such as increasing stratigraphic dip with depth or consistent directional thickening of volcanic units. Basalt flows intercalated within alluvium in drill holes UE-5i and UE-5k have been dated at 8.6 and 8.4 Ma, respectively (RSN, 1994), indicating that basin development had begun well before approximately 8.5 Ma in northern Frenchman Flat. However, at UE-5i, 3.0 m (10 ft) of colluvium consisting of subangular to rounded gravel-sized clasts of mostly tuff and lesser quartzite (Dixon et al., 1967), occurs between the Ammonia Tanks Tuff and an overlying ash-flow tuff related to the Thirsty Canyon Group (9.14 to 9.4 Ma). Additionally, at Well ER-5-4 a thin ash-bed related to the Thirsty Canyon Group (Warren et al., 2002) occurs within the alluvium 293.5 m (963 ft) above the top of the Ammonia Tanks Tuff (DOE, 2005b). These stratigraphic relationships further constrain the onset of major basin development to some time after the eruption of the Ammonia Tanks Tuff (11.45 Ma) and before the end of the eruptive cycles of the Thirsty Canyon Group (9.14 Ma). Quaternary fault scarps in southern Frenchman Flat (Poole, 1965) and recent earthquake activity in the Frenchman Flat area, including the along Rock Valley fault zone (Anderson et al., 1993 and Fischer et al., 1972), suggest basin development may continue into the present.

Although the main period of basin development in Frenchman Flat occurred after the eruption of the Ammonia Tanks Tuff (11.45 Ma), the distribution of the older Tertiary units indicates that a Frenchman Flat proto-basin may have existed prior to, and contemporaneous with, the initial eruptions of the southwestern Nevada volcanic field (SWNVF). A thick, diverse assemblage of rocks ranging in age from approximately 18 to 13.25 Ma is exposed in a rather narrow band that coincides with the Rock Valley fault zone in the southwestern portion of Frenchman Flat (Prothro and Drellack, 1997). This assemblage consists of sedimentary rocks deposited in fluvial and lacustrine environments, and intercalated volcanic rocks associated with the initial eruptions of the SWNVF. The presence of these rocks along the fault zone may indicate that movement along the Rock Valley fault prior to the development of the main basin produced a depositional center aligned with the trace of the fault system. The fault trace appears to continue north-eastward beneath the southern portion of Frenchman Flat. The occurrence of more than 610 m (2,000 ft) of Wahmonie Formation in Well ER-5-4#2 (DOE, 2005b) may indicate that as late as 13.0 Ma, volcanic units were continuing to fill this pre-existing proto-basin.

In summary, the formation of Frenchman Flat appears to be directly related to the northeastern termination of the Rock Valley fault zone within an extensional imbricate fan. The formation of this fan structure has resulted in a series of oblique-slip faults that flare out to the north and northwest from the Rock Valley fault zone. These faults drop the basin down along the south, east, and north, forming an east-tilted half-graben-type basin beneath the central portion of Frenchman Flat and a structural platform beneath the northern portion. The main period of basin development appears to have begun between 11.45 and 9.14 Ma, and may continue into the present.

3.2 Structural Elements

The primary structural elements within the Frenchman Flat model are high-angle faults. Other structural features in the model include thrust and detachment faults. These structural elements are described in the following subsections.

3.2.1 Thrust Faults

No thrust faults are exposed within the boundaries of the model area. However, as mentioned in Section 3.1.1, the CP and Spotted Range thrust faults are exposed just northwest and southeast of the model area, and their orientations suggest that both faults are likely present at depth within the model area.

The southeast-vergent Spotted Range thrust fault places carbonate rocks of Cambrian age over carbonate rocks as young as Mississippian (Barnes et al., 1982). Because the fault juxtaposes rocks of similar hydrologic character (i.e., carbonate aquifer over carbonate aquifer) where mapped at the surface southeast of the model area, and because of uncertainty about the nature and location of the fault at depth within the model area, the Spotted Range fault was not delineated within the framework model.

The CP thrust fault is exposed in the hills just west of the northwest corner of the model area. This west-vergent fault places mostly carbonate rocks of Cambrian age over Mississippian- and Pennsylvanian-age units that include fine-grained siliciclastic (i.e., clastic confining unit) and carbonate rocks (McKeown et al., 1976; Caskey, 1991 and Cole and Cashman, 1999). Because the fault juxtaposes rocks with significantly different hydrologic character, the CP thrust fault was modeled at depth within the framework model.

Very little is known about the CP thrust fault within the model area. No drill holes penetrate the fault and geophysical methods have been mostly unsuccessful in delineating it. However, MT data have proven successful in Yucca Flat in estimating the thickness and extent of Mississippian-age fine-grained siliciclastic rocks that compose the footwall of the CP thrust fault in the vicinity of the northwest portion of the Frenchman Flat model area. MT measurements across CP Basin show that Mississippian siliciclastic rocks are thick, but of limited lateral extent beneath the basin. These rocks occur at a depth of approximately 1,300 m (4,300 ft) and appear to be confined to the east side of the basin adjacent to the Cane Spring fault. MT data east of the Cane Spring fault do not indicate the presence of fine-grained siliciclatic rocks above 3,000 m (9,800 ft). In addition, information from Well ER-5-3#2 (DOE, 2005a) and from a CSMAT survey (Zonge, 1990) in northern Frenchman Flat indicate that no pre-Tertiary fine-grained siliciclastic rocks occur above approximately 1,500 m (5,000 ft) in the northern portion of Frenchman Flat.

Because MT data suggest that fine-grained Mississippian rocks are present within the footwall of the CP thrust beneath CP Basin, the CP thrust fault was modeled beneath CP Basin. However, because no fine-grained pre-Tertiary rocks are indicated above approximately 1,500 m (5,000 ft) east of CP Basin in northern Frenchman Flat, the CP thrust fault was not modeled beneath Frenchman Flat. The CP fault may be present beneath Frenchman Flat, but if so, it occurs at depths greater than 1,500 m (5,000 ft). If it is shallower, the fault likely places carbonate rocks over other carbonate rocks, and thus, like the Spotted Range thrust fault, juxtaposes rocks of similar hydrologic character.

Beneath CP Basin the CP thrust fault is modeled as a southeast-dipping fault that is rooted in the northeast-striking Cane Spring fault. The thrust fault places carbonate rocks in the hanging wall over the steeply-dipping siliciclastic and carbonate rocks that compose the footwall. Because the CP thrust fault is poorly constrained in the model area, but may have a profound influence on the distribution of pre-Tertiary hydrostratigraphic units, an alternative interpretation of the thrust fault was developed (Section 5.5). This alternative models a more extensive and continuous sheet of Mississippian siliciclastic rocks within the footwall of the thrust fault beneath CP Basin.

3.2.2 High-Angle Faults

The most common structural feature in the model are high-angle normal faults related to basin-and-range extension and basin formation. Although an early pre-volcanic extensional event that included the development of low-angle faults has been documented in the NTS region (Cole and Cashman, 1999), no such faults have been mapped in the model area and thus are not included in the model. Seventy-three high-angle faults are included in the framework model. Each fault is typically modeled as a single fault plane that dips approximately 75 degrees, and extends to the base of the model. Some faults, however, terminate against other faults. Almost all of the high-angle faults are modeled with a component of dip-slip displacement, and most are probably best classified as normal faults. However, the apparent strong influence of strike-slip faulting on basin development likely results in many high-angle faults also having a component of strike-slip movement. Some faults, such as the Cane Spring fault and the main basin-forming faults along the southern margin of the basin, may have significant horizontal motion, and thus may best be classified as strike-slip faults.

The locations of the high-angle faults were determined on the basis of surface traces and geophysical evidence. Only the main surface faults were included in the model, and were digitized from surface geology maps (Hinrichs and McKay, 1965; Poole, 1965; Poole et al., 1965; Hinrichs, 1968; McKeown et al., 1976; Barnes et al., 1982; Workman et al., 2002). These faults typically have offsets greater than 61 m (200 ft) and appear to provide the main control on the structural fabric and outcrop patterns in the model area. Geophysically inferred high-angle faults include almost all the faults confidently identified in the 3-D seismic data. Other faults were inferred from seismic refraction and gravity data. The major basin-forming faults along the south and east sides of Frenchman Flat are inferred from gravity data and regional structural analysis. Therefore, the exact location, dip, and offset of these faults are poorly constrained, and the relative uncertainty of these features is thus higher than for most other faults in the model.

3.2.3 Detachment Fault

Evidence from 3-D seismic and drill hole data suggests that a detachment fault is present beneath the northern portion of Frenchman Flat (Prothro, 2002; Appendix D). Seismic reflections from the welded volcanic rocks (i.e. Ammonia Tanks Tuff, Rainier Mesa Tuff, and Topopah Spring Tuff) show a southeast-trending anticlinal feature within the volcanic rocks in the extreme northern portion of Frenchman Flat, between Drill Hole UE-11b and Well ER-5-3#2 (see Appendix D). However, the anticlinal form does not extend downward to the top of the Paleozoic rocks, which are clearly expressed on the seismic data in this area. This large-scale disharmonic folding is common along listric normal faults, where such folds are referred to as rollover anticlines (Twiss and Moores, 1992). Rollover anticlines form in the hanging walls of concave-upward, listric normal faults as a result of the hanging wall strata tilting downward and deforming to maintain contact with the footwall of the fault. The disparity in depth to the volcanics between drill holes UE-11b and UE-11g ext 1 (338.6 vertical meters [1,111 ft] in 1,036.3 horizontal meters [3,400 ft]) and the shallow dip of the reflections of the volcanics here, indicate that the high-angle portion of the detachment fault is present between these two wells and that the dip of the fault shallows rapidly with depth to the south. It is likely that the detachment fault runs near the base of the Tertiary rocks and is rooted in the northwest-striking structural zone described previously. Because of the uncertainty of this interpretation and the potential hydrologic consequences associated with such an interpretation, an alternative model was developed that did not include the detachment fault, but modeled volcanic rocks as dipping steeply southward from UE-11b and nearby surface exposures to the deeper intercepts in drill holes located to the south (Section 5.3).

3.3 Comparison with Phase I Model

The structural models for the Phase I and II Frenchman Flat HSU framework models are similar in the general concept of basin development but differ considerably in detail. The structural model for the Phase I Frenchman Flat hydrostratigraphic framework model (IT, 1998) was developed by Grauch and Hudson (1995) in support of the UGTA hydrologic modeling project. It was based mainly on interpretation of gravity and aeromagnetic data, and like the Phase II model, depicted a series of basin-forming faults flaring 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 resulted in a series of east-tilted half grabens beneath the central portion of Frenchman Flat. This structural pattern is not reflected in the overall shape of the basin as indicated with the gravity data, and no such faults are observed in the 3-D seismic data beneath the central portion of the basin. As described previously, a large northwest-striking fault zone was observed on the seismic data in the northern portion of Frenchman Flat, suggesting that the larger basin-forming faults beneath Frenchman Flat strike northwest. This fault pattern provides a better fit with the gravity data.

Information from the 3-D seismic survey and from Wells ER-5-3#2 and ER-5-4#2 shows that the basin is deeper than modeled in the Phase I model. The maximum depth to pre-Tertiary rocks beneath Frenchman Flat in the Phase I model was 1,480 m (4,850 ft), versus 2,790 m (9,150 ft) in the Phase II model, which incorporates the more recent gravity, seismic, and drill hole data.

The Phase II model also includes a detachment fault beneath the northern portion of Frenchman Flat. This structural feature was not included in the Phase I model. However, a Phase II alternative model was developed that removes the detachment fault which is more consistent with the original Phase I model.

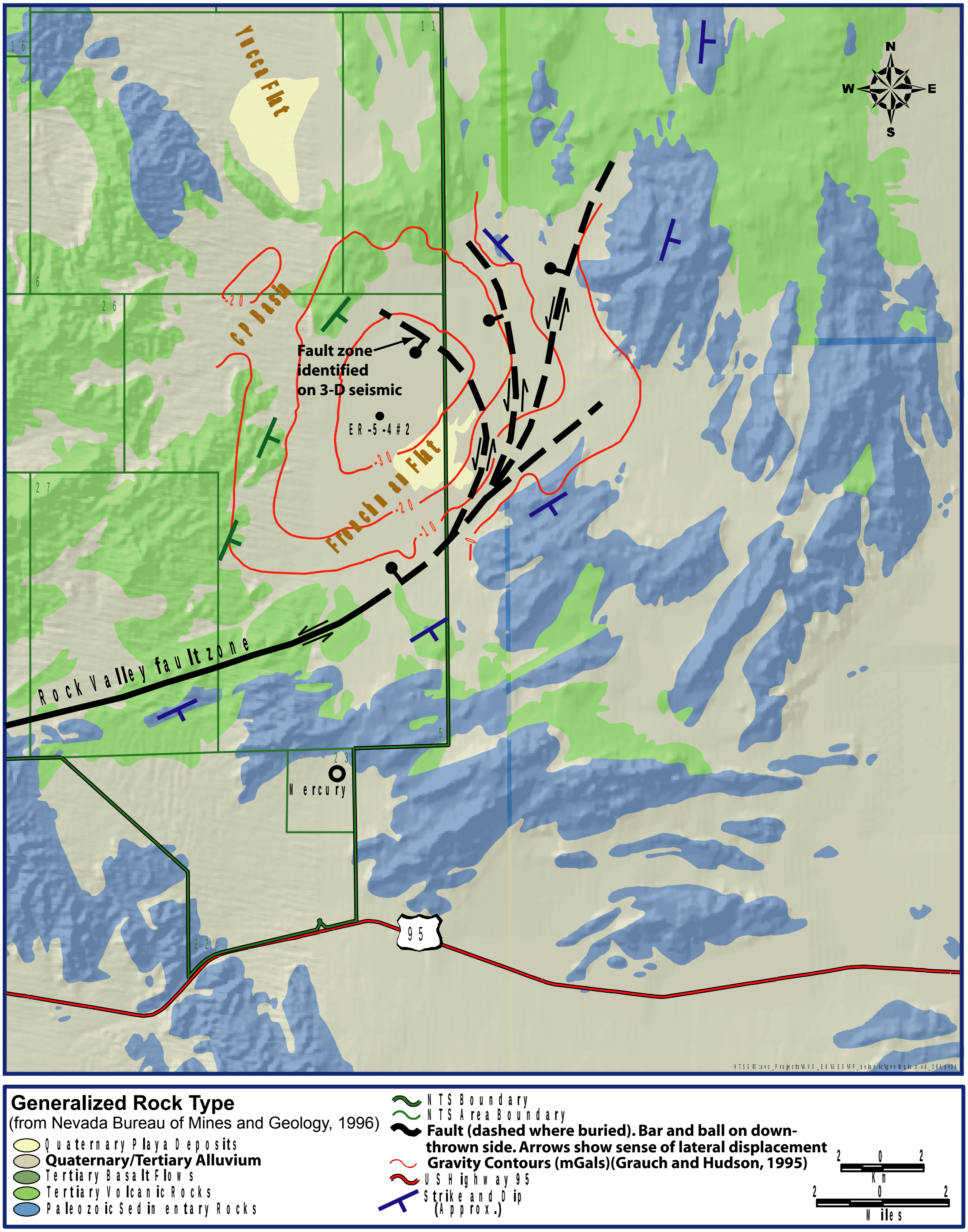

Figure 3-1
Generalized Geologic Map of Frenchman Flat and Vicinity Showing the Conceptual Structural Model of the Basin

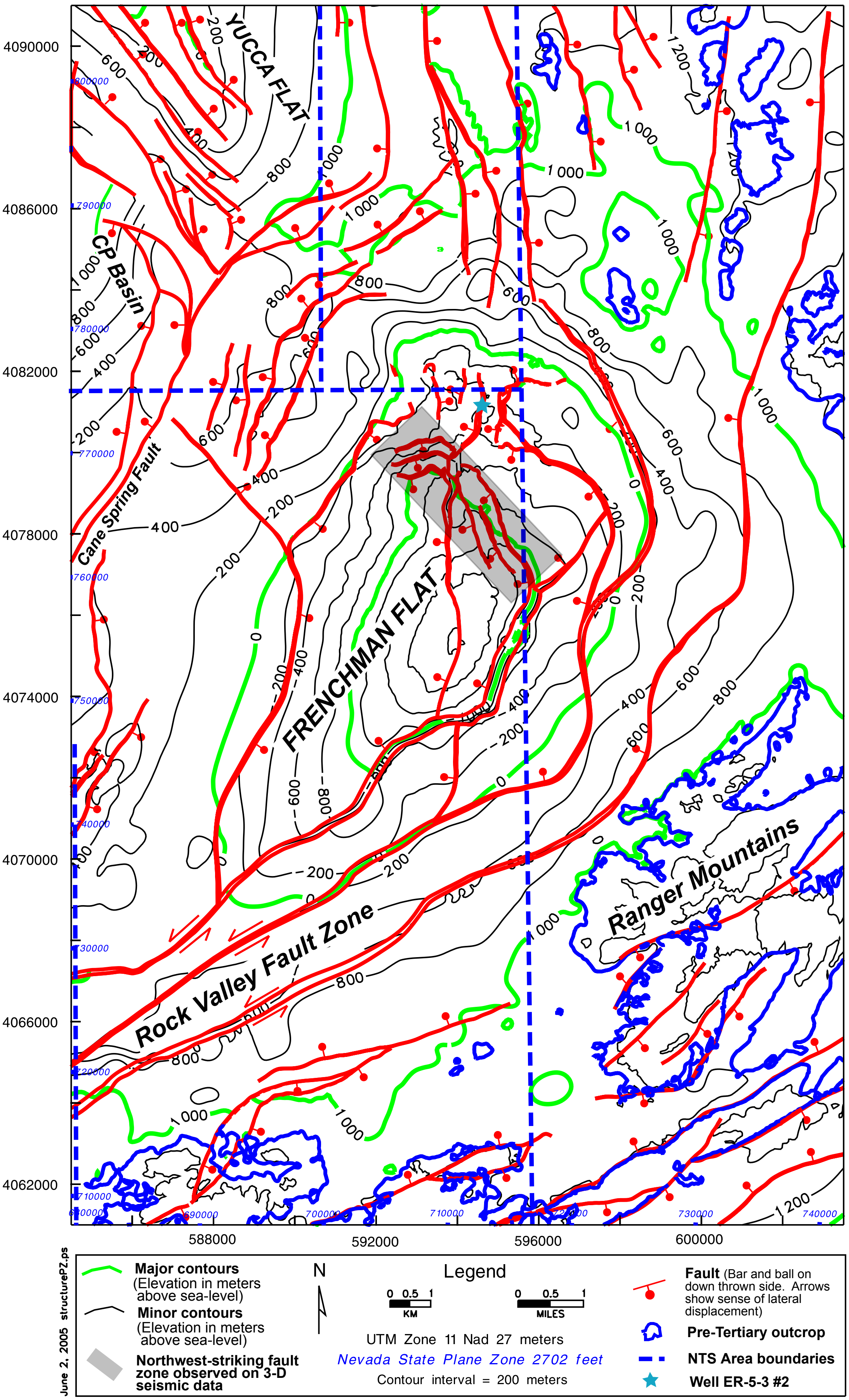

Figure 3-2

Structure Map for the Top of Pre-Tertiary Rocks in the Frenchman Flat Model Area (Map generated from the EarthVision® model)

4.0 HYDROSTRATIGRAPHY

As introduced in Section 2.5, a hydrostratigraphic classification system for depicting the hydrologic character of complexly interfingering rocks of a wide range of lithologic and hydrologic characteristics was developed for use in the digital framework model for the Frenchman Flat area. The hydrogeologic framework for Frenchman Flat and vicinity established by Winograd and Thordarson (1975) provided the basis for developing the hydrostratigraphic system presented in this section.

4.1 Development of the Hydrostratigraphic Classification System

The development of the hydrostratigraphic classification system for the Frenchman Flat model area involved a three-step process. The first step was acquiring a thorough understanding of the character and three-dimensional distribution of the rocks, both lithologically and stratigraphically, within the model area. This critical first step was accomplished through a rigorous analysis of published surface geologic maps and descriptions, and drill hole and geophysical data.

In the second step, rocks in the Frenchman Flat area were classified as one of eight hydrogeologic units (HGUs) based on the rock's ability to transmit groundwater, which is mainly a function of a rock's primary lithology, type and degree of post-depositional alteration, and propensity to fracture. 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, brittle rocks such as welded tuff, lava, and carbonate generally have low primary 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 permeability of these rocks tend to inhibit significant secondary alteration such as zeolitization 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 units such as alluvium, nonwelded tuff, and shale typically do not support extensive fracture systems and thus usually have low fracture-related effective porosity. However, some low density rocks such as nonwelded tuffs and alluvium can have relatively high primary effective porosity and these units are also considered aquifers where they are unaltered. The high primary effective porosity of these rocks, particularly nonwelded tuffs, makes them susceptible to post-depositional alteration precesses such as zeolitization, which can significantly reduce the effective porosity of altered rocks. Nonwelded tuffs that have undergone zeolitic alteration are considered confining units because of their very low effective porosity.

The third step in the development of the Frenchman Flat hydrostratigraphic classification system was to group individual HGUs of similar character into larger HSUs to facilitate mapping and 3-D model construction. A critical component of this step was the careful integration of Frenchman Flat stratigraphy. The integration of stratigraphic concepts is important to assure individual HGUs grouped within HSUs, and the HSUs themselves, properly correlate within the model. HSUs, therefore, can be thought of as groupings of contiguous stratigraphic units that have a particular hydrogeologic character, such as aquifer or confining unit. An HSU may consist of several HGUs, but is defined so that a single general type of HGU dominates (e.g., mostly welded-tuff and lava-flow aquifers, or mostly tuff confining units). HSUs serve as "layers" for the UGTA groundwater modeling process (IT, 1996c).

Sections 4.2 and 4.3 describe the stratigraphy and the HGUs of the Frenchman Flat area. Each of the 17 HSUs in the Frenchman Flat hydrostratigraphic framework model is described in Section 4.4.

4.2 Stratigraphy of the Frenchman Flat Model Area

To define appropriate HSUs to serve as layers in the framework model, the modelers had to start from a well understood stratigraphic system. Refinement of the stratigraphy of the NTS area, including Frenchman Flat, was a continuous process during the decades in which geoscientists associated with the WTP worked to understand the complex volcanic setting (Byers et al., 1989). The need to develop detailed geologic models in support of the UGTA program continued this process. The recognition of smaller and smaller distinct volcanic units permitted a greater understanding of the three-dimensional configuration of these rocks. Efforts to better understand the structure and stratigraphy of the pre-Tertiary sedimentary rocks have also continued throughout the UGTA program.

The stratigraphic section for the Frenchman Flat area consists of Paleozoic-age siliciclastic and carbonate rocks, Tertiary-age lacustrine and fluvial sedimentary rocks, Tertiary-age volcanic rocks, and Tertiary- and Quaternary-age alluvium (Hinrichs and McKay, 1965; Poole, 1965; Poole et al., 1965; Hinrichs, 1968; McKeown et al., 1976; Barnes et al., 1982) (Figure 4-1).

Paleozoic rocks are exposed in the mountains bordering Frenchman Flat on the northeast, east, and south. These rocks range in age from Cambrian to Mississippian. In northern Frenchman Flat, middle to upper Miocene-age volcanic rocks, that originated from vents located to the northwest of the basin, unconformably overlie Ordovician-age carbonate and siliciclastic rocks (Hinrichs and McKay, 1965; Prothro and Drellack, 1997). Southward, these volcanic units, including the Ammonia Tanks Tuff, Rainier Mesa Tuff, Topopah Spring Tuff, and Crater Flat Group, thin considerably and ultimately pinch out. The Crater Flat Group and older tuffs interfinger with coeval sedimentary rocks to the south and southeast (Poole, 1965; Poole et al., 1965; Hinrichs, 1968; Barnes et al., 1982; Prothro and Drellack, 1997). Upper to middle Miocene tuffs, lavas, and debris flows from the Wahmonie volcanic center, located west of Frenchman Flat, dominate the volcanic section beneath the western portion of the valley. To the south and southeast, most of the volcanic units are absent, and Oligocene to middle Miocene sedimentary and tuffaceous sedimentary rocks, which unconformably overlie the Paleozoic-age rocks in southern Frenchman Flat, dominate the Tertiary section (Hinrichs, 1968; Barnes et al., 1982; Prothro and Drellack, 1997). In most of the basin, upper Miocene to Holocene alluvium covers the older sedimentary and volcanic rocks (Hinrichs and McKay, 1965; Poole, 1965; Poole et al., 1965; Hinrichs, 1968; McKeown et al., 1976; Barnes et al., 1982; Slate, 1999).

Table 4-1 lists the Quaternary and Tertiary stratigraphic units of the Frenchman Flat model area. Table 4-2 lists the pre-Tertiary units.

4.3 Hydrogeologic Units of the Frenchman Flat Model Area

The data documentation package prepared for the previous CAU-scale hydrostratigraphic framework model (Pahute Mesa - Oasis Valley area; see BN, 2002) included a separate section that addressed expected hydraulic properties of the HGUs included in the model. However, separate data documentation packages have been developed specifically for Frenchman Flat hydrology, transport parameter, and source term data (for example, SNJV, 2004b, 2005a, 2005b), which address the ranges of parameter values hydrologic modelers will use as they explore groundwater flow and contaminant transport using this hydrostratigraphic framework model. This document thus does not include a section specifically addressing hydraulic properties, but the following paragraphs and Table 4-3 provide general information to aid in the reader in understanding the hydrologic character of each HGU.

All the rocks of the Frenchman Flat model area are classified as one of the following eight HGUs: playa confining unit, alluvial aquifer, welded-tuff aquifer, vitric-tuff aquifer, lava-flow

Table 4-1
Quaternary and Tertiary Stratigraphic Units of the Frenchman Flat Model Area

Stratigraphic Assemblages and Major Units [a]	Volcanic Sources [b]
Quaternary and Tertiary Sediments	
Young playa deposits (Qp)	
Young alluvium (Qay)	
Quaternary - Tertiary colluvium (QTc)	
Intermediate alluvium (Qai)	Not applicable
Quaternary-Tertiary alluvium (QTa)	
Pliocene Basalts (Tybf)	
Older playa deposits (QTp)	
Tertiary alluvium (QTa)	
Thirsty Canyon Group (Tt)	**Black Mountain Caldera**
Pahute Mesa Tuff (Ttp)	
Timber Mountain Group (Tm)	**Timber Mountain Caldera Complex**
Ammonia Tanks Tuff (Tma)	Ammonia Tanks Caldera
bedded Ammonia Tanks Tuff (Tmab)	
Rainier Mesa Tuff (Tmr)	Rainier Mesa Caldera
Tuff of Holmes Road (Tmrh)	
Paintbrush Group (Tp)	
Tiva Canyon Tuff (Tpc)	**Claim Canyon Caldera**
Topopah Spring Tuff (Tpt)	Unknown
Calico Hills Formation (Th; formerly Tac)	Unknown
Wahmonie Formation (Tw)	
Upper Member (Twu)	**Wahmonie Volcanic Center**
Middle Member (Twm)	
Lower Member (Twl)	
Tuff of Wahmonie Flat (Twlb)	
Salyer Member (Twls)	
Crater Flat Group (Tc)	**Silent Canyon Caldera Complex**
Prow Pass Tuff (Tcp)	
Bullfrog Tuff (Tcb)	Area 20 Caldera
Tram Tuff (Tct)	
Belted Range Group (Tb)	
Grouse Canyon Tuff (Tbg)	Grouse Canyon Caldera
Tunnel Formation (Tn)	Unknown
Older volcanics (Tqo)	Unknown
Older Tuffaceous Sedimentary Rocks [c]	
Rocks of Pavits Spring (Tgp) [d]	Unknown
Rocks of Winapi Wash (Tgw) [e]	Not Applicable