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

a Compiled from Slate et al. (1999) and Ferguson et al. (1994). Letters in parentheses are stratigraphic unit map symbols.
b Sources, where known, from Sawyer et al. (1994)
c Prothro and Drellack, 1997
d Proposed symbol: Tg after Wahl et al., 1997
e Informal unit, after Yount (1996). Formerly the Horse Spring Formation

Table 4-2
Pre-Tertiary Stratigraphic Units of the Frenchman Flat Model Area
(Stratigraphic and lithologic units adapted from Cole, 1992)

Map Unit	Stratigraphic Unit Map Symbol	Stratigraphic Thickness Feet	Stratigraphic Thickness Meters	Dominant Lithology
Tippipah Limestone	PIPt	3,500	1,070	Limestone
Chainman Shale Eleana Formation	Mc MD	4,000	1,220	Shale, argillite, and quartzite
Guilmette Formation	Dg	1,400	430	Limestone
Simonson Dolomite	Ds	1,100	330	Dolomite
Sevy Dolomite	DSs	690	210	Dolomite
Laketown Dolomite	Sl	650	200	Dolomite
Ely Springs Dolomite	Oes	340	105	Dolomite
Eureka Quartzite	Oe	400	125	Quartzite
Antelope Valley Limestone	Oa	1,530	466	Limestone
Ninemile Formation	On	335	102	Limestone
Goodwin Limestone	Og	685	209	Limestone
Nopah Formation	Cn	2,050	620	Limestone
Bonanza King Formation	Cb	4,350	1,330	Limestone/dolomite
Carrara Formation	Cc	925	280	Limestone/shale/siltstone
Zabriskie Quartzite	Cz	200	60	Quartzite
Wood Canyon Formation	CZw	2,300	700	Micaceous quartzite
Stirling Quartzite	Zs	2,900	890	Quartzite
Johnnie Formation	Zj	3,000	914	Quartzite/siltstone/limestone

Table 4-3
Hydrogeologic Units of the Frenchman Flat Model
Adapted from Winograd and Thordarson (1975); IT (1996a); and Laczniak et al. (1996)

Hydrogeologic Unit	Typical Lithologies	Hydrologic Significance
Playa Confining Unit (PCU)	Clayey-silt, sandy-silt	Near-surface confining unit at Frenchman Lake and at base of alluvium in deepest portion of Frenchman Flat. May also limit, or redirect, recharge where present at surface.
Alluvial aquifer (AA) (AA is also an HSU in the Frenchman Flat framework model.)	Unconsolidated to partially consolidated gravelly sand, eolian sand, and colluvium;	Has characteristics of a highly conductive aquifer, but less so where lenses of clay-rich paleocolluvium, zeolitic alteration, or playa deposits are present.
Welded-tuff aquifer (WTA)	Welded ash-flow tuff; vitric to devitrified	Degree of welding greatly affects interstitial porosity (i.e., less porosity as degree of welding increases) and permeability (i.e., greater fracture permeability as degree of welding increases).
Vitric-tuff aquifer (VTA)	Bedded tuff; ash-fall and reworked tuff; vitric	Constitutes a volumetrically minor HGU. Generally does not extend far below the static water level due to tendency of tuffs to become zeolitic under saturated conditions, which drastically reduces permeability. Significant interstitial porosity (i.e., 20 to 40 percent). Generally insignificant fracture permeability.
Lava-flow aquifer (LFA)	Basalt and dacite lava flows	Generally as thin local flows. Hydrologically complex; wide range of transmissivities; fracture density and interstitial porosity differ with lithologic variations.
Tuff confining unit (TCU)	Zeolitic bedded tuff with interbedded, but less significant, zeolitic, nonwelded to partially welded ash-flow tuff	May be saturated, but measured transmissivities are very low. May cause accumulation of perched and/or semi-perched water in overlying units.
Clastic confining unit (CCU)	Argillite, siltstone, quartzite	Clay-rich rocks are relatively impermeable; coarser-grained siliceous rocks are fractured, but with fracture porosity generally sealed due to secondary mineralization.
Carbonate aquifer (CA)	Dolomite, limestone	Transmissivity values vary greatly, and are directly dependent on degree of fracturing and dissolution.

aquifer, tuff confining unit, clastic confining unit, and the carbonate aquifer. These are summarized in Table 4-3 and described in the following paragraphs.

4.3.1 Alluvial HGUs

Two alluvial HGUs are recognized in the Frenchman Flat model area: the alluvial aquifer (AA; also an HSU) and the playa confining unit. The AA consists mainly of gravelly sand and sandy gravel eroded from the surrounding mountains during the main period of basin development, and deposited on alluvial fans by debris flow and sheet-flood processes. Deposits of finer-grained eolian sand are intercalated within the coarser alluvial deposits. The playa confining unit consists of fine-grained sand, silt, and clay deposited as playa lake sediments in the topographic low point of the basin. Descriptions for these two HGUs are included in the subsections for the similarly named HSUs (Sections 4.4.1, 4.4.2, and 4.4.3).

4.3.2 Volcanic HGUs

The volcanic rocks within the study area are categorized into four HGUs based on primary lithologic properties, degree of fracturing, and secondary mineral alteration. In general, the altered volcanic rocks, which are typically zeolitized, act as confining units, and the unaltered rocks form aquifers. The aquifer units can be further divided into welded-tuff and vitric-tuff aquifers, depending on degree of welding, and lava-flow aquifers. Denser rocks, such as welded ash-flow tuffs and lava flows, tend to fracture more readily, and therefore have relatively high permeability (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Laczniak et al., 1996; IT, 1996a; Prothro and Drellack, 1997).

4.3.3 Pre-Tertiary HGUs

The hydrogeology of the pre-Tertiary sedimentary rocks at the NTS follows the framework developed by Winograd and Thordarson (1975), and used in the Phase I regional modeling effort (IT, 1996a, 1996b, 1996c, 1996d) and subsequent CAU-scale models (BN, 2002; Gonzales et al., 1998). Within the study area, pre-Tertiary rocks are categorized as aquifer or confining unit HGUs based on lithology. The siliceous clastic rocks, such as quartzite, siltstone, and shale, are classified as clastic confining units. Carbonate rocks such as limestone and dolomite are classified as carbonate aquifers (Winograd and Thordarson, 1975; Laczniak et al., 1996).

4.4 Hydrostratigraphic Units for the Frenchman Flat Model

The following paragraphs describe all the HSUs in the Frenchman Flat hydrostratigraphic framework model. They are generally listed in descending order from the top of the model to the bottom. However, some HSUs are laterally rather than vertically contiguous, and not all units are present in all parts of the model area. A summary of the characteristics of each of the

17 HSUs of the Frenchman Flat model is given in Table 4-4. Table 4-5 shows the correlation of Frenchman Flat HSUs with HSUs of other hydrostratigraphic framework models of the region.

The geometric configuration of the HSUs as defined in the model is represented as 3-D perspective views and 2-D plan maps and profiles in various figures throughout this report. Contour maps showing the depth to the top of selected aquifer HSUs are introduced as necessary to aid in the description of these HSUs. The correlation of stratigraphic units and hydrostratigraphic units of the Frenchman Flat model area is depicted graphically in Figure 4-2. Figure 4-3 is a HSU surface map (see also Plate 2) and Figure 4-4 is a HSU "basement" sub-crop map. Profiles A-A' through E-E', which illustrate the relationships of the HSUs and structures in various vertical planes, can be found in Appendix C.

4.4.1 Alluvial Aquifer (AA, AA3, AA2, AA1)

This HSU consists of Quaternary- and Tertiary-age basin-filling alluvium such as that mapped at the surface in the central portions of Frenchman Flat and CP Basin (Qay, Qa, and QTa in Slate et al., 1999) (Figure 1-4; Plate 1 and Figure 4-3). Although the AA is considered the highest (i.e., youngest) HSU in the model, stratigraphically, it consists of alluvial debris as young as recent alluvium found in active drainages, and as old as tuffaceous gravels that may correlate time-stratigraphically with the volcanic units of the Thirsty Canyon Group, approximately 9 Ma (Sawyer et al., 1994).

The alluvium in Frenchman Flat is a friable to moderately consolidated, poorly sorted mixture of detritus derived from volcanic and Paleozoic-age sedimentary rocks, ranging in particle size from clay to boulders. Sediment deposition is largely in the form of alluvial fans which coalesce to form discontinuous, gradational, and poorly sorted deposits. Eolian sand, basalt lava flows, and playa deposits are also present within the alluvium section. Basalt lava flows and playa deposits have been designated as separate HSUs in the Frenchman Flat base model and are discussed in following subsections.

The alluvial aquifer is an important aquifer in Frenchman Flat because many of the underground nuclear tests were conducted in this unit, and it is thick and extensive within much of the model area (Figure 4-5). Significant saturated thicknesses are present in the central portion of the model area (Profiles B-B' and C-C'). Where saturated, the unit is considered an aquifer, as

Table 4-4
Hydrostratigraphic Units of the Frenchman Flat Hydrostratigraphic Framework Model

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Unit Map Symbols [b]	General Description	Transport Parameter Category [d]
alluvial aquifer (AA, AA3, AA2, AA1) [c] (this term is also used to designate a hydrogeologic unit)	AA	Qay, QTc, Qai, QTa, Tt	Consists mainly of alluvium that fills extensional basins. Also includes generally older Tertiary gravels and very thin air-fall tuffs. AA, AA1, AA2, and AA3 are equivalent hydrogeologically except for position relative to other HSUs embedded within the alluvial section (see Figures 4-7 and 4-10).	AA
playa confining unit (PCU2T)	PCU	Qp	Clayey silt and sandy silt. Forms the Frenchman Flat playa (dry lake).	TCU
basalt lava-flow aquifer (BLFA)	LFA	Tybf	Several (possibly dissected) basalt flows are recognized in the middle of the alluvial section of the northeastern Frenchman Flat. Related to other basalt flows in Nye Canyon.	LFA
older altered alluvial aquifer (OAA, and OAA1)	AA	QTa	Older, denser, zeolitized alluvium recognized only in northern Frenchman Flat. OAA and OAA1 are equivalent except for position: the OAA is above the BLFA, and the OAA1 is stratigraphically beneath the BLFA (see Figure 4-10).	TCU 50% AA 50%
older playa confining unit (PCU1U and PCU1L)	PCU	QTp	Deep, subsurface playa deposits in the deepest portion of Frenchman Flat. Recognized in Well ER-5-4#2 and with 3-D seismic data. The PCU1U and PCU1L are similar except for position (see Figure 4-7).	TCU
Timber Mountain welded-tuff aquifer (TM-WTA)	Mostly WTA, minor VTA	Tma, Tmab, Tmr	Consists mainly of welded ash-flow tuffs of Ammonia Tanks Tuff and Rainier Mesa Tuff. Unit occurs mostly in north and central Frenchman Flat. Prolific aquifer when saturated.	WTA 90% VTA 10%
Timber Mountain lower vitric-tuff aquifer (TM-LVTA)	VTA	Tma, Tmab, Tmr, Tmrh, Tp, Th	Defined to include all unaltered (nonzeolitic) nonwelded and bedded tuffs below the welded Tmr and above the level of pervasive zeolitization. The presence of the welded Tpt (see TSA) complicates this general description.	VTA
upper tuff confining unit (UTCU)	TCU	Tmr (lower most), Tmrh, Tp	Relatively thin TCU above the TSA. Grouped with the LTCU where the TSA is not present.	TCU 90% VTA 10%
Topopah Spring aquifer (TSA)	WTA	Tpt	The welded ash-flow lithofacies of the Topopah Spring Tuff in Massachusetts Mountain / French Peak area and north-central Frenchman Flat.	WTA 80% VTA 20%

Table 4-4
Hydrostratigraphic Units of the Frenchman Flat Hydrostratigraphic Framework Model (continued)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) [a]	Stratigraphic Unit Map Symbols [b]	General Description	Transport Parameter Category [d]
lower vitric-tuff aquifer (LVTA)	VTA	Th	Relatively thin VTA unit below the TSA. Grouped with the TM-LVTA where TSA is not present.	VTA
lower tuff confining unit (LTCU and LTCU1)	TCU, minor WTA	Th, Tw, Tc, Tn, To	Generally includes all the zeolitic nonwelded and bedded tuffs in southeastern NTS. May include all units from base of Tmr to top of Paleozoic-age rocks. The Tw stratigraphic interval grades or interfingers laterally (westward) into the WCU (see below). Zeolitic bedded tuffs stratigraphically below the WCU (e.g. Tc, Tn, and To) are classified as the LTCU1 in order to address the operation requirements of the EarthVision® modeling software.	TCU 95% WTA 5%
Wahmonie confining unit (WCU)	TCU, minor LFA	Tw (Twu, Twm, Twl, Twls)	Mixture of lava flows, debris flows, lahars, ash-flows, and air-falls. Typically zeolitic, argillic, or hydrothermally altered. Grades or interfingers laterally with the LTCU.	TCU 80% AA 10% CA 5%
volcaniclastic confining unit (VCU)	TCU, minor AA and CA	Tgp, Tgw	Older Tertiary sedimentary rocks of variable lithologies including silt, clay, limestone, gravel and tuffaceous units. Present in southeastern half of Frenchman Flat.	TCU 85% AA 10% CA 5%
lower carbonate aquifer-thrust plate (LCA3)	CA	Dg through Cc	Cambrian through Devonian, mostly limestone and dolomite, rocks that occur in the hanging wall of the Belted Range thrust fault. Present only in the northwest corner (CP Basin) of the model area.	CA
upper clastic confining unit (UCCU)	CCU	Mc, MDe	Late Devonian through Mississippian siliciclastic rocks. Present only in the northwest corner (CP Basin) of the model area, northwest of Cane Spring fault and southwest of Topgallant fault.	CCU
lower carbonate aquifer (LCA)	CA	Dg through Cc	Cambrian through Devonian mostly limestone and dolomite. Regional carbonate aquifer present throughout the model area.	CA
lower clastic confining unit (LCCU)	CCU	Cc, Cz, Czw, Zs, Zj	Late Proterozoic through Early Cambrian siliciclastic rocks. Hydrologic “basement” present at great depth in the model area.	CCU

a See Table 4-3 for definitions of HGUs.

b See Tables 4-1 and 4-2 for definitions of stratigraphic unit map symbols.

c These subdivisions are equivalent hydrogeologically but are necessary to satisfy operational requirements of the EarthVision® Software.

d Indicator of HSU hydraulic properties, provided for flow-and-transport modelers.

Table 4-5
Correlation of Hydrostratigraphic Units of the Frenchman Flat Model and Earlier Models

Hydrostratigraphic Unit	Symbol Used in this Report	Correlation with Phase I FF Model [a, b]	Correlation with UGTA Phase I Regional Model [c]	Correlation with Yucca Flat Model [d]	Correlation with Pahute Mesa - Oasis Valley Model [e]
Alluvial Aquifer	AA3, AA2, AA1 [f]	AA [g]	AA [g]	AA	AA
Playa confining unit	PCU2T			PCU	NP
Basalt lava-flow aquifer	BLFA			BLFA	YVCM
Older altered alluvial aquifer	OAA, OAA1 [f]			NP [h]	NP
Older playa confining unit	PCU1U, PCU1L [f]			NP	NP
Timber Mountain welded-tuff aquifer	TM-WTA	TMA [g]	VA [g]	TM-WTA	TMA
Timber Mountain lower vitric-tuff aquifer	TM-LVTA			TM-LVTA	PVTA
Upper tuff confining unit	UTCU			UTCU (YF-UCU)	UPCU, LPCU
Topopah Spring aquifer	TSA			TSA	TSA
Lower vitric-tuff aquifer	LVTA			LVTA	PVTA
Lower tuff confining unit	LTCU and LTCU1 [f]	TCU	BCU [g]	LTCU (YF-LCU)	CFCU, BFCU, PBRCM [i]
Wahmonie confining unit	WCU	WCU		NP	NP
Volcaniclastic confining unit	VCU	VCU		NP	NP
Lower carbonate aquifer-thrust plate	LCA3	NP	LCA3	LCA3	LCA3
Upper clastic confining unit	UCCU	NP	UCCU	UCCU	UCCU
Lower carbonate aquifer	LCA	PreT [g]	LCA	LCA	LCA
Lower clastic confining unit	LCCU		LCCU	LCCU	LCCU

a If correlative to more than one HSU, all HSUs are listed.
b See IT, 1998 for explanation initial FF model (1998) nomenclature.
c See IT (1996a) for explanation of the UGTA Phase I HSU nomenclature.
d Preparation of documentation material for final Yucca Flat model is in progress. See Gonzales et al. (1998) for explanation of the Yucca Flat HSU nomenclature.
e See BN, 2002 for explanation of Pahute Mesa/Oasis Valley HSU nomenclature.
f Subdivisions, though hydrogeologically equivalent, are necessary to satisfy operational requirements of the EarthVision® modeling software.
g Not subdivided.
h Not present.
i PBRCM may include embedded ash-flow tuffs.

inferred from high hydraulic conductivity and specific capacity values from NTS wells completed within the AA (e.g., Water Wells 5a, 5b, and 5c in Frenchman Flat [Classen, 1973; IT, 1996b]; Well A, Well 3 [IT, 1996b]). However, the more tuffaceous intervals may have zeolitic alteration that could locally reduce the unit's ability to transmit water. The AA is over 1,220 m (4,000 ft) thick in the vicinity of Well Cluster ER-5-4 (DOE, 2005b) located near the central portion of the valley.

Lithologic and physical properties data from drill holes near the Area 5 RWMS indicate that the alluvium is relatively homogenous (REECo, 1993a, 1993b; BN, 2005). Hydrologic data show that the alluvium is isotropic with respect to hydrologic properties as well (Sully et al., 1993). Thus, no subdivisions of the alluvial aquifer were included in the initial Phase I hydrogeologic model for Frenchman Flat (IT, 1998). Pawloski (1996) also concluded that the limited data available suggested that Frenchman Flat alluvium is homogeneous on a basin-wide scale. However, she recommended that during the modeling process this unit should be tested to determine if the localized zones of dense alluvium identified in northern Frenchman Flat have any influence on groundwater flow. As more information became available as a result of Phase II data acquisition, subdividing the alluvium became possible. These subdivisions, particularly the older altered alluvium, are discussed separately in the following subsections.

The AA is subdivided into three EarthVision® model layers: AA1, AA2, and AA3. These subdivsions are equivalent hydrogeologically except for position relative to other HSUs imbedded within the alluvial section. Such subdivisions are necessary to satisfy operational requirements of the of the EarthVision® software, only, and do not represent geologically significant boundaries.

4.4.2 Playa Confining Unit (PCU2T, PCU1U, and PCU1L)

Three separate playa confining units are defined in the Frenchman Flat model: a younger unit that includes the youngest deposits at the surface (PCU2T) and two older, buried units (PCU1U and PCU1L). The playa deposits are mainly clayey silt, but may also contain intercalated beds of sand and pumice. The playa deposits behave as an aquitard due to the abundance of silt and clay (Winograd and Thordarson, 1975).

Frenchman Lake is a prominent playa near the center of Frenchman Flat. The playa deposits that compose the Frenchman Lake playa are designated PCU2T in the hydrostratigraphic framework model (Figure 4-6). The PCU2T is approximately 150 m (500 ft) thick. The relationship of the PCU2T to the older playa confining units (i.e., PCU1U and PCU1L) with the alluvial aquifer is shown in Figure 4-7.

Beneath the central portion of Frenchman Flat, two zones of low reflectivity within the alluvium section are observed in the 3-D seismic data (see Appendix D). The upper of these two zones is penetrated by Well ER-5-4#2 where it corresponds to fine-grained sand, silt, and clay that is interpreted to represent an earlier period of playa deposition. The lower zone is not penetrated by any drill holes, and is define strictly on a similar seismic character to the upper zone. This lower zone is also interpreted to represent older playa deposits.

The buried playa deposits are designated hydrostratigraphically as older playa confining units due to the fine-grained nature of playa deposits. Because the two deposits are separated by coarser alluvium, they are designated as separate EarthVision® layers in the framework model. The upper of the two older playa confining units is designated PCU1U, and its extent is shown in Figure 4-8. The lower older playa confining unit is designated PCU1L, and its extent is shown in Figure 4-9. The hydraulic characteristics of both the PCU1U and PCU1L are assumed to be similar to the modern playa deposit (PCU2T) that is exposed at Frenchman Lake.

4.4.3 Older Alluvial Aquifer (OAA and OAA1)

Pawloski (1996) conducted an investigation using existing literature, lithologic logs, and geophysical data to determine if these deposits could be subdivided on the basis of hydrogeologic characteristics, as described in Section 2.3.6.1. One of the units she examined was a dense alluvium recognized by Carr et al. (1975), Miller and Healey (1986), and others, which might possess hydrologic properties that are slightly different from those of 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, she found that it apparently is discontinuous and of local extent, having been identified in only a few drill holes in northern Frenchman Flat.

Analysis of recent XRD data from Well Cluster ER-5-3 has shown that this “older, denser” alluvium has undergone low-grade zeolitic alteration (DOE, 2005a). The original vitric constituents in the alluvial matrix have been altered to the zeolite clinoptilolite. Such alteration has a tendency to lower overall hydraulic conductivity of the formation. This assumption is substantiated by the lower than expected water production while drilling this interval at Well Cluster ER-5-3. The distribution of the older alluvium aquifer (OAA) is shown in Figure 4-6. The distribution of the older alluvium aquifer 1 (OAA1) is shown in Figure 4-9.

The OAA1, which occurs below the basalt lava-flow aquifer, and the OAA, which is above the BLFA, are hydrogeologically equivalent (Figure 4-10). It was necessary to subdivide them to satisfy operational requirements of the EarthVision® modeling software, only, and does not represent a geologically significant boundary.

4.4.4 Basalt Lava-Flow Aquifer (BLFA)

Basalt was encountered within the alluvial section beneath the northern portion of Frenchman Flat in drill holes UE-5i (Dixon et al., 1967), UE–5k (Byers and Miller, 1966), and at Well Cluster ER-5-3 (DOE, 2005a). The thickness of basalt ranges from 9.1 m (30 ft) at Well Cluster ER-5-3 to 25.9 m (85 ft) at UE-5i. The depth to the basalt ranges from 268.2 m (880 ft) at UE-5i to 289.6 m (950 ft) at UE-5k, which places the basalt near the water table, particularly at Well Cluster ER-5-3 and UE-5k (Figure 4-11). Ages of the basalt in UE-5i (8.6 Ma) and UE-5k (8.4 Ma) are similar (RSN, 1994). Surface magnetic data appear to show that the basalt is not a single continuous flow, but instead occurs as three separate and isolated flows (Carr et. al, 1975).

Because dense volcanic rocks like basalt tend to be highly fractured at the NTS, the basalt beneath northern Frenchman Flat likely has hydraulic properties considerably different than that of the encasing alluvium. Therefore, the basalt was modeled as a separate HSU called the basalt lava-flow aquifer (BLFA). This HSU includes all three of the basalt occurrences beneath northern Frenchman Flat. Figure 4-8 shows the distribution of the BLFA; the relationship of the BLFA to the various alluvial aquifers is shown in Figure 4-10.

Due to uncertainty related to the exact extent of the BLFA and to the potential hydrologic significance of its position near the water table, an alternative model was developed that includes a more extensive and continuous occurrence of BLFA. This alternative model is described in more detail in Section 5.2.

4.4.5 Timber Mountain Hydrostratigraphic Units

The Timber Mountain HSUs include, stratigraphically, the Rainier Mesa Tuff and younger Ammonia Tanks Tuff, both formations of the Timber Mountain Group (Figure 4-2). Lithologically, the Timber Mountain HSUs consist mostly of welded ash-flow tuff and lesser amounts of vitric (i.e., unaltered) nonwelded ash-flow tuff and bedded tuff. These rocks were erupted from the Rainier Mesa and Ammonia Tanks calderas, and deposited as outflow sheets and ash-fall deposits in areas outside of the margins of the calderas.

The unaltered volcanic rocks of the Frenchman Flat model area are divided into two Timber Mountain HSUs. The hydrology of this part of the geologic section is complicated by the presence of one or more ash-flow tuffs units that are quite variable in properties both vertically and laterally. The Timber Mountain Group includes ash-flow tuffs that can be either welded-tuff aquifers or vitric-tuff aquifers, depending on the degree of welding. Where the Rainier Mesa Tuff is less than about 76 m (250 ft) thick the formation is typically poorly welded, and the

entire unit is classified as the Timber Mountain lower vitric-tuff aquifer (TM-LVTA). In locations where the Rainier Mesa Tuff is more than 76 m (250 ft) thick, all but the bottom 30 m (100 ft) is classified as the Timber Mountain welded-tuff aquifer (TM-WTA), and the bottom 30 m (100 ft) of nonwelded ash-flow tuff is generally included in the TM-LVTA. The overlying Ammonia Tanks Tuff is included with the TM-WTA when either the Ammonia Tanks Tuff or Rainier Mesa Tuff is sufficiently thick to be welded. Otherwise, the Ammonia Tanks Tuff is considered to be a vitric-tuff aquifer, and is included in the TM-LVTA. The relationship of these HSUs is depicted in Figure 4-12.

The thicknesses of the TM-WTA and TM-LVTA in the north-central portion of the model area are well constrained where they are extensively exposed and numerous drill holes penetrate them. In this area the volcanic aquifers are approximately 260 m (850 ft) thick. West and east of this data corridor, the thickness of the HSUs is poorly constrained due to burial by thick alluvium and absence of drill hole penetrations. At Well Cluster ER-5-4, more than 196 m (644 ft) of the TM-WTA was encountered (DOE, 2005b).

The designation of these units as aquifers is based on the predominance of densely welded tuff (which is assumed to be fractured and transmissive) and vitric, nonwelded and bedded tuff. This designation is consistent with water production data from Well ER-5-3, where the TM-WTA produced 1,893 liters per minute (lpm) (500 gallons per minute [gpm]) of water during drilling of welded Ammonia Tanks Tuff (DOE, 2005a), and up to 10,220 lpm (2,700 gpm) near the bottom of the welded Rainier Mesa Tuff. Note that this water production was during air-foam drilling, and the formation was reported to be highly fractured. Additional hydrologic data for outflow sheets of welded Ammonia Tanks and Rainier Mesa Tuff outside of the model area in the vicinity of Yucca Flat indicate these units are significant aquifers where saturated (IT, 1996c).

4.4.5.1 Timber Mountain Welded-Tuff Aquifer (TM-WTA)

The TM-WTA is not an extensive HSU, being generally confined to the north-central and northwestern portions of the model area, and west of the basin-forming faults. Additionally, in Frenchman Flat the Ammonia Tanks and Rainier Mesa Tuffs are saturated only in the deeper portions of the basin. The distribution of the TM-WTA is shown in Figure 4-13, and its relationship to other volcanic HSUs is shown in Figure 4-14. Figure 4-15 shows the depth below ground surface of the top of the HSU.

The extent of the TM-WTA is not well constrained (Figure 4-13). The unit occurs north and south of the Well Clusters ER-5-3 and ER-5-4. Extensive outcrops and numerous drill-hole

penetrations in northern Frenchman Flat provide unambiguous evidence that the HSU is extensive in the northern portion of the model area, north of Well Cluster ER-5-4. The presence of more than 198 m (650 ft) of TM-WTA at Well Cluster ER-5-3 (DOE, 2005a) indicates that the HSU is an important aquifer within the northern portion of the valley.

4.4.5.2 Timber Mountain Lower Vitric-Tuff Aquifer (TM-LVTA)

The TM-LVTA includes all unaltered bedded, ash-fall, reworked tuff, and nonwelded ash-flow tuff units present above the level of pervasive zeolitization in Frenchman and Yucca Flats. However, where welded Topopah Spring Tuff, which forms the Topopah Spring aquifer (TSA), is present, unaltered nonwelded tuffs below the TSA are grouped within a separate HSU called the lower vitric tuff aquifer (LVTA). Welded tuffs are included in the TM-WTA (described in Section 4.4.5.1). Stratigraphically, the TM-LVTA typically includes formations and members of the Timber Mountain and Paintbrush Group, but may also include units within the Calico Hills Formation, and Wahmonie Formation. Older units are generally zeolitized, and are therefore categorized as confining units and placed with the LTCU.

The TM-LVTA has a slightly larger distribution than the TM-WTA. Some TM-LVTA rocks are present beneath the alluvium throughout most of the northern and central portions of Frenchman Flat, though this unit is absent in areas where it has been removed by erosion over major structural highs. These include the western (Wahmonie Hills area) and eastern portions of Frenchman Flat. The TM-LVTA is also absent from portions of northern Frenchman Flat where stratigraphically equivalent rocks are zeolitic, and classified as a separate HSU called the upper tuff confining unit (UTCU; Section 4.4.6). The distribution of the TM-LVTA is shown in Figure 4-16, and its relationship with other volcanic HSUs is shown in Figure 4-14. The depth to the top of the TM-LVTA is shown in Figure 4-17.

In Frenchman Flat the TM-LVTA units are saturated in the deep central portion of the basin. The TM-LVTA exhibits significant interstitial porosity, ranging from about 20 to 40 percent. However, because these lithologies tend to be poorly to moderately indurated, fractures are not common. So, even though interstitial porosity may be high, transmissivities are not great.

4.4.6 Upper Tuff Confining Unit (UTCU)

The zeolitized nonwelded tuffs that overlie the Topopah Spring Tuff in north-central Frenchman Flat are designated as the upper tuff confining unit (UTCU). Stratigraphically, the UTCU includes units from the base of the welded Rainier Mesa Tuff to the top of welded Topopah Spring Tuff. The areal extent of the UTCU is limited in Frenchman Flat, where it occurs only beneath the northern portion of the basin. The extent of this HSU is not well constrained, but it

appears to overlie the area of detachment faulting, and thus may be related to this feature. The unit is not present in Well ER-5-4#2 due to stratigraphically equivalent rocks being unaltered, and thus assigned to the TM-LVTA. The UTCU is also absent from the hills north of Frenchman Flat, where equivalent rocks are also unaltered, and assigned to the TM-LVTA. Where the TSA (Section 4.4.7) is not present, but zeolitic rocks equivalent to the UTCU are present, the zeolitic rocks are assigned to the lower tuff confining unit (LTCU; Section 4.4.10). The UTCU is also present in the southern portion of the Yucca Flat basin immediately above the TSA. The distribution of the UTCU in the Frenchman Flat model area is shown in Figure 4-18, and its relationship with other volcanic HSUs is shown in Figure 4-14.

The hydrologic properties of the two tuff confining units (the UTCU and the LTCU) are considered to be essentially identical. The UTCU at Well ER-5-3#2 produced water at a very low rate (DOE, 2005a; see also IT, 2002 and SNJV, 2004a) and behaved as a viable aquitard that separates the overlying TM-WTA from the TSA.

4.4.7 Topopah Spring Aquifer (TSA)

The TSA consists of a single welded-tuff aquifer composed of welded ash-flow tuff of the Yucca/Frenchman Flat lobe of the Topopah Spring Tuff (Figure 4-2). The unit is saturated and has a distribution similar to that of the TM-WTA. The relationship of the TSA to the other volcanic HSUs is shown in Figure 4-13.

The TSA is limited in areal extent. It is up to 50 m (165 ft) thick in northern Frenchman Flat, but thins to the north and east in the Halfpint Range, and to the south in Frenchman Flat. The distribution of the TSA is shown in Figure 4-19, and the depth to the top of the unit is shown in Figure 4-20.

The TSA is typically well fractured and therefore highly transmissive. Overall, the hydraulic properties of the TSA are similar to those of the TM-WTA. (Section 4.4.5.1).

4.4.8 Lower Vitric-Tuff Aquifer (LVTA)

The LVTA includes all unaltered bedded, ash-fall, reworked tuff, and nonwelded ash-flow tuff units below the TSA and above the level of pervasive zeolitization in Frenchman and Yucca Flats. The LVTA is only differentiated where the TSA is present; these rocks would otherwise be included in the TM-LVTA (Figure 4-2; Section 4.4.5.2). Overlying welded tuffs are included in the TSA welded-tuff aquifer (Section 4.4.7). Stratigraphically, the LVTA may include formations and members of the Paintbrush Group, Calico Hills Formation, Wahmonie

Formation, Crater Flat Group. Older units are generally zeolitized, and are therefore categorized as confining units and assigned to the LTCU.

The LVTA has a distribution similar to the TSA (Figure 4-19). However, the LVTA is not present beneath portions of northern Frenchman Flat because equivalent units are zeolitic and thus assigned to the LTCU. The distribution of the LVTA is shown in Figure 4-21, and the depth to the top of the unit is shown in Figure 4-22.

In Frenchman Flat the LVTA units are saturated in the deep central portion of the basin. The LVTA exhibits significant interstitial porosity, ranging from about 20 to 40 percent. However, because these lithologies tend to be poorly to moderately indurated, fractures are not common. So, even though interstitial porosity may be high, transmissivities are not great.

4.4.9 Wahmonie Confining Unit (WCU)

One of the unique aspects of the Frenchman Flat model area is its proximity to the Wahmonie volcanic center. The highlands associated with this volcanic center form the western boundary of the Frenchman Flat physiographic basin. The Wahmonie Formation, including the Salyer Member, consists mainly of rhyodacitic and dacitic lava flows, flow breccia, ash-flow tuff, ash-fall tuff, and reworked tuff (Poole et al., 1965). The lava and breccia flows are interpreted to be restricted in areal extent, but the ash-flow and ash-fall tuffs likely have a much wider distribution. Lavas and flow breccia are probably more abundant in the western third of Frenchman Flat, whereas ash-fall and reworked tuffs are likely the primary Wahmonie units found in the central and eastern parts of the basin (Warren, 1995).

As with the overlying and underlying bedded tuffs, the Wahmonie nonwelded tuff units tend to become zeolitized where saturated, and thus behave hydrologically as a confining unit. Closer to the volcanic source, the rocks are argillized due to hydrothermal alteration (Warren, 1995) and thus are not hydraulically conductive. However, some of the lava flows may remain vitric to devitrified, and thus be transmissive. Evidence for perched and/or semiperched water within these units along the westernmost portion of Frenchman Flat has been presented by several authors (West and Garber, 1961; Carroll, 1963; Poole et al., 1963; Healey et al., 1967; Carr et al., 1975).

The Wahmonie Formation is divided into two HSUs based on distance from its source area. Wahmonie rocks in the central and eastern parts of the basin (east of Water Well UE-5c) are included within the LTCU (Section 4.4.10). West of Well UE-5c (closer to the Wahmonie center), the heterogenous group of Wahmonie rocks is classified as a “leaky” confining unit and

designated as the Wahmonie confining unit (WCU). The distribution of the WCU is shown on Figure 4-23. The boundaries of the WCU are very poorly constrained, and thus are conceptual in nature. The relationship of the WCU to other HSUs is shown in Figure 4-24.

4.4.10 Lower Tuff Confining Unit (LTCU)

The LTCU is an important hydrogeologic layer over much of the NTS because it separates the volcanic aquifer units from the underlying regional lower carbonate aquifer (LCA). Almost all zeolitized tuff units in Yucca and Frenchman Flat are grouped within the LTCU, which comprises mainly zeolitized nonwelded tuff. In the lower part of the section several zeolitized and devitrified nonwelded to partially welded ash-flow tuff units such as Bullfrog Tuff, Yucca Flat Tuff, and Redrock Valley Tuff, are also included. Stratigraphically, the LTCU may include all the Tertiary volcanic strata from the top of the Paleozoic rocks to the base of the Rainier Mesa Tuff (Figure 4-2). The strongly argillized older tuff and paleocolluvium that directly overlie the Paleozoic rocks in some places are also included. However, the older Tertiary sedimentary rocks in southern Frenchman Flat, and the Wahmonie Formation in the western Frenchman Flat are not included in the LTCU. These two units are differentiated as separate HSUs and are described separately (Sections 4.4.9 and 4.4.11).

The zeolitic bedded tuffs stratigraphically beneath the WCU in the western portion of the Frenchman Flat model are labeled LTCU1 (Figure 4-24). This subdivision was necessary to address operational requirements of the EarthVision® modeling software. The relationship of the LTCU to other volcanic HSUs is shown in Figure 4-14. The LTCU and the LTCU1 are hydrogeologically equivalent except for their position relative to the WCU.

The LTCU is generally present in the northern and western two-thirds of the model area. It is absent over the major structural highs, where the volcanic rocks have been removed by erosion. Areas where the LTCU is absent include the “Paleozoic bench” south of the Rock Valley fault in southern Frenchman Flat, and east of the main basin-forming faults in eastern Frenchman Flat. The distribution of the LTCU is shown in Figure 4-25.

The LTCU is saturated in much of Frenchman Flat, however, measured transmissivities are very low.

4.4.11 Volcaniclastic Confining Unit (VCU)

The Tertiary sedimentary rocks that are exposed south and southwest of Frenchman Flat are divided into two formations: Rocks of Winapi Wash (Yount, 1996) and the younger, more extensive, Rocks of Pavits Spring (Prothro and Drellack, 1997) (Figure 4-2). These units consist of a diverse assemblage of interbedded volcanic and sedimentary rocks deposited primarily in lacustrine and fluvial environments. Specific lithologies include ash-flow tuff, ash-fall tuff, and reworked tuff; shale; tuffaceous sandstone and argillaceous sandstone; siltstone and mudstone; conglomerate; and lesser limestone (Hinrichs, 1968; Barnes et al., 1982). The Tertiary sedimentary rocks are probably present beneath most of southern and central Frenchman Flat, but pinch out in the northern portion of the basin.

The Tertiary sedimentary rocks as a whole are believed to behave as a confining unit because of their tuffaceous component, which has a tendency to become zeolitized below the water table, and the abundance of fine-grained clastic rocks (Prothro and Drellack, 1997). However, the presence of rocks that tend to act as aquifers such as limestone and coarser clastic rocks, might justify their classification as a “leaky” confining unit. Winograd and Thordarson (1975) included these rocks with their “tuff aquitard.” For the UGTA Frenchman Flat model, the Tertiary sedimentary rocks are grouped into a distinct HSU, the VCU. The VCU potentially is a significant HSU in southern Frenchman Flat because of its intervening position between overlying saturated rocks and the LCA. The distribution of the VCU is shown in Figure 4-26.

4.4.12 Lower Carbonate Aquifer - Thrust Plate (LCA3)

Cambrian-age through Devonian-age, mostly carbonate, rocks that form the hanging wall of the CP thrust fault are assigned to the LCA3. Deformation related to the west-vergent CP thrust fault has placed these older LCA rocks over younger rocks of the UCCU, and over stratigraphically equivalent LCA rocks. Thus, the rocks of LCA3 are stratigraphically equivalent, and probably hydrogeologically similar to the LCA, but are structurally separated from the LCA by the thrust fault (Section 3.2.1; Profiles A-A’ and D-D’). The position of these rocks above the UCCU requires that they be distinguishable in the model from the regional aquifer (LCA). The interpreted extent of the LCA3 in the Frenchman Flat model area is shown in Figure 4-27. The depth to the top of the LCA3 is shown in Figure 4-28.

Subsurface control for the LCA3 is poor and no drill holes penetrate this HSU or the CP thrust fault. Remnants of this thrust plate are mapped just outside of the model area in CP Hills north-northwest of CP Basin. An alternate interpretation was provided for the CP thrust fault and the LCA3 (Section 5.5).

4.4.13 Upper Clastic Confining Unit (UCCU)

Upper Devonian-age and Mississippian-age siliciclastic rocks in the NTS vicinity are assigned to the Eleana Formation and the Chainman Shale (Cashman and Trexler, 1991, 1994; Trexler et al., 1996). The Eleana Formation as originally defined by Poole et al. (1961) was partitioned by Cashman and Trexler (1991) on the basis of lithofacies variations and sediment source. The shaley lithofacies in the Frenchman Flat model area are now grouped in the Chainman Shale, while the section farther east, bearing the non-shaley quartzite, sandstone, and conglomeratic lithofacies, retains the original formation name. The Mississippian and Devonian Eleana Formation and the Mississippian Chainman Shale form the UCCU (Figure 4-2), the extent of which is shown on Figure 4-29. The subsurface control for this HSU is also poor, with no drill hole penetration within the model area. The UCCU crops out just northwest of the model area, in the CP Hills (Plate 1; Figure 4-3). The Frenchman Flat model depicts the UCCU as present only in CP Basin. It is bounded by the Cane Spring fault on the southeast and by the southern extent of the Topgallant fault on the northeast. The subsurface configuration of this unit and its relation to proximal HSUs are depicted in Profiles A-A' and D-D'.

4.4.14 Lower Carbonate Aquifer (LCA)

The LCA consists of thick sequences of Middle Cambrian-age through Upper Devonian-age carbonate rocks (Figure 4-2). This HSU serves as the regional aquifer for most of southern Nevada, and locally may be as thick as 5,000 m (16,400 ft) (Winograd and Thordarson, 1975; Cole, 1992). The unit consists mostly of dolomite and interbedded limestone but contains thin shale, quartzite, and calcareous clastic units (Burchfiel, 1964). The LCA outcrops mainly within the southeast portion of the Frenchman Flat model. There are also small exposures of carbonate rocks in the northeastern corner of the model (Figure 4-3 and Plate 1). The extent of this unit is shown in Figure 4-30. The depth to the top of the LCA is shown in Figure 4-31.

Transmissivities of LCA rocks differ from place to place, apparently reflecting the observed differences in fracture and fault densities and characteristics (Winograd and Thordarson, 1975).

4.4.15 Lower Clastic Confining Unit (LCCU)

Proterozoic-age to Middle Cambrian-age rocks in the NTS region are largely quartzite and silica-cemented siltstone. This section includes the Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, and the lower half of the Carrara Formation (Winograd and Thordarson, 1975). These units make up the LCCU, which is considered to be the regional hydrologic basement (Winograd and Thordarson, 1975; Laczniak et al., 1996; IT, 1996a). The base of the Frenchman Flat model terminates within the LCCU. The composite thickness of the LCCU is about 2,870 m (9,400 ft). Although these rocks are brittle and commonly fractured,

secondary mineralization seems to have greatly reduced formation permeability (Winograd and Thordarson, 1975). Where it is in a structurally high position, the LCCU may act as a barrier to deep regional groundwater flow. The present structural interpretation for the Frenchman Flat model depicts the LCCU at great depth (Profile C-C'). The interpreted extent of the LCCU in the Frenchman Flat model area is shown in Figure 4-32.

4.5 Relationship of Hydrostratigraphic Units and the Water Table

The EarthVision® base framework model was electronically "sliced" along a surface that represents the water table (IT, 1996a) to reveal the distribution of HSUs at the water table (Figure 4-33). Within much of the model area where LCA is structurally high, such as in the northern, eastern, and southern portions, the water table is within the LCA. West of Frenchman Flat the water table is within the WCU, which is exposed at the surface in the Wahmonie Hills along the western margin of the model area. Within much of the Frenchman Flat basin, the water table is within the AA, however, in northern Frenchman Flat beneath the northern testing area, the water table is below the AA and within the OAA, BLFA, and TM-WTA. The water table occurs within volcanic HSUs below the AA in Yucca Flat and most of CP Basin.

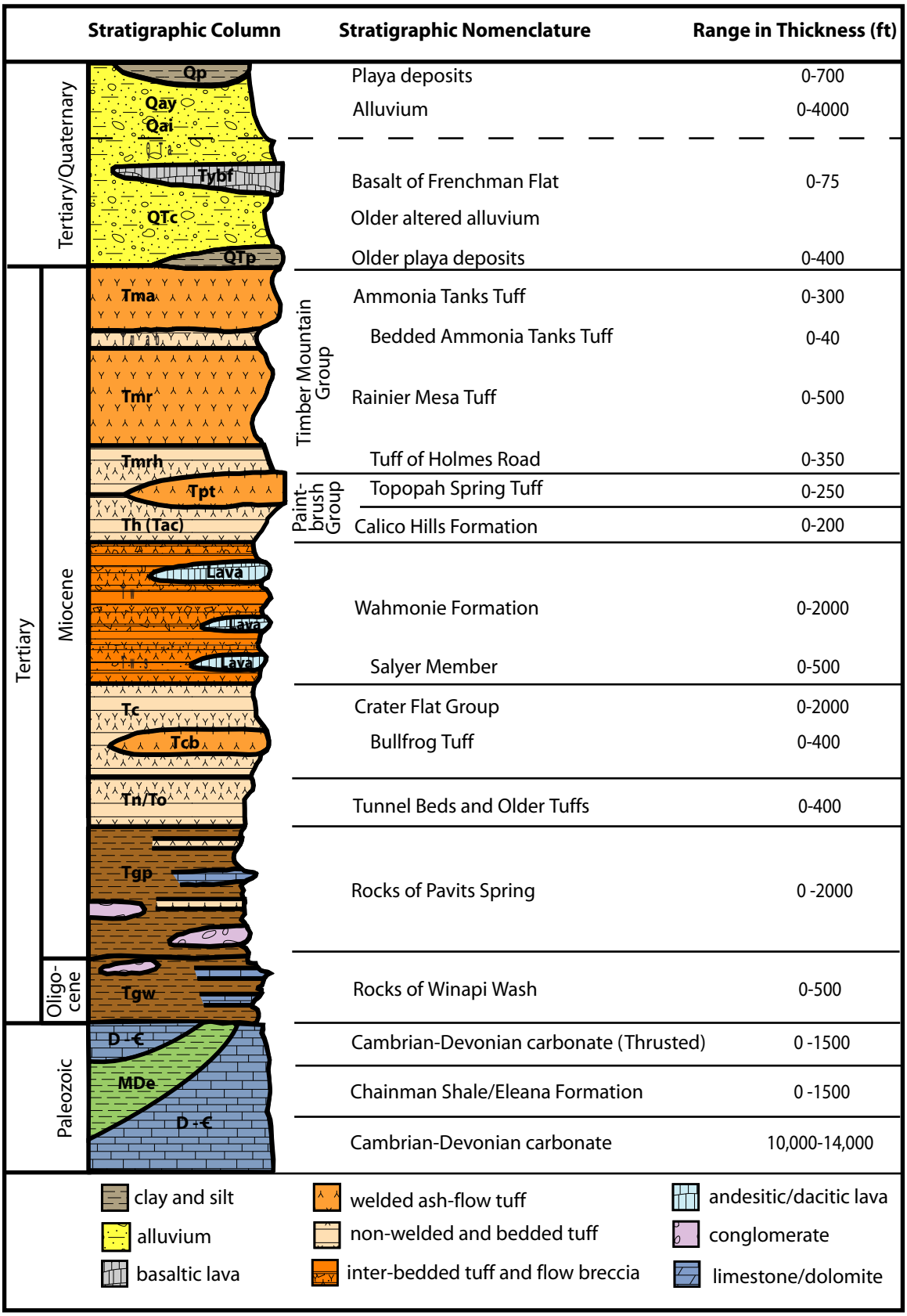
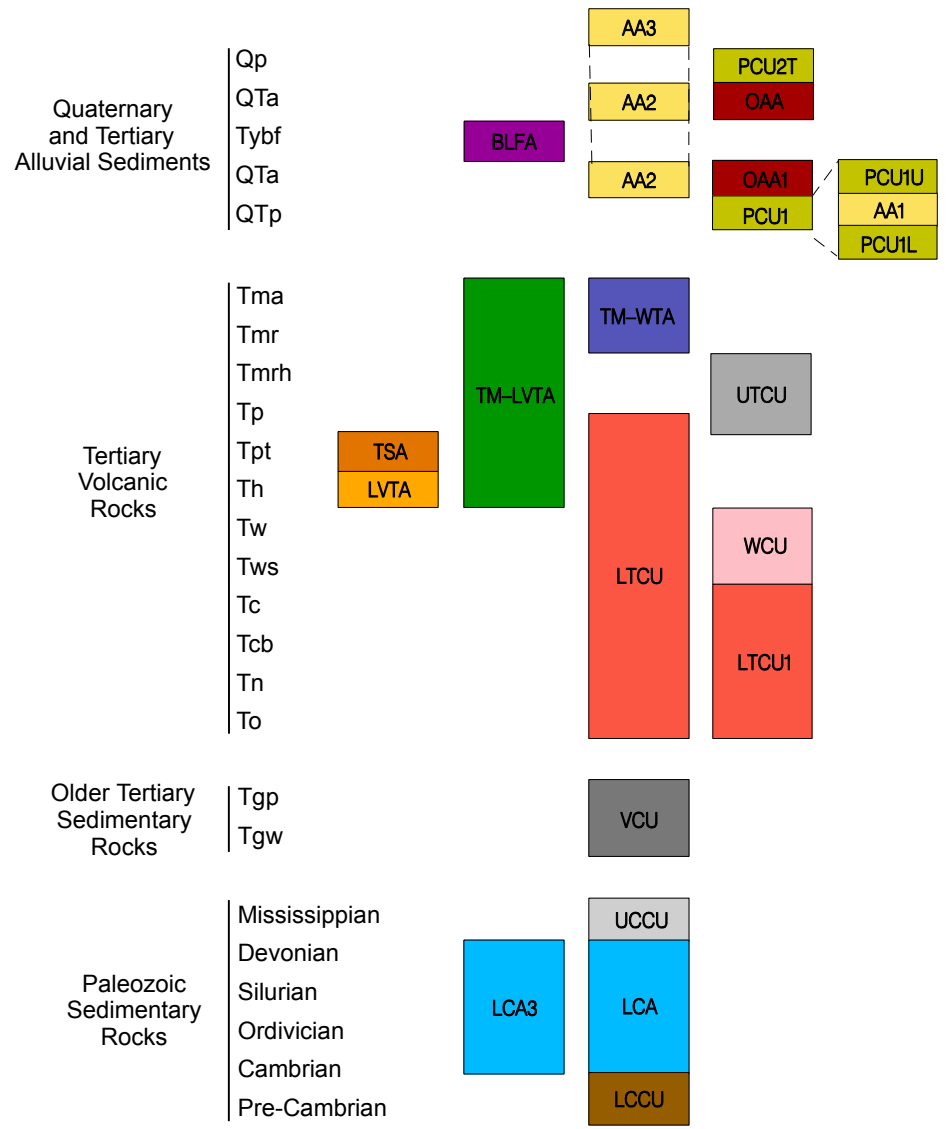


Figure 4-1
Simplified Stratigraphic Section for Frenchman Flat



See Table 4-1 for definitions of stratigraphic symbols

Definitions of Hydrostratigraphic Symbols

AA3	Alluvial Aquifer 3
PCU2T	Playa Confining Unit 2T
AA2	Alluvial Aquifer 2
BLFA	Basalt Lava Flow Aquifer
OAA1	Older Altered Alluvium
PCU1U	Playa Confining Unit 1 Upper
PCU1L	Playa Confining Unit 1 Lower
AA1	Alluvial Aquifer 1
TM-WTA	Timber Mountain-Welded Tuff Aquifer
TM-LVTA	Timber Mountain-Lower Vitric Tuff Aquifer
UTCU	Upper Tuff Confining Unit
TSA	Topopah Spring Aquifer
LVTA	Lower Vitric Tuff Aquifer
LTCU	Lower Tuff Confining Unit
WCU	Wahmonie Confining Unit
LTCU1	Lower Tuff Confining Unit 1
VCU	Volcaniclastic Confining Unit
LCA3	Lower Carbonate Aquifer 3
UCCU	Upper Clastic Confining Unit
LCA	Lower Carbonate Aquifer
LCCU	Lower Clastic Confining Unit

Figure 4-2
Correlation of Stratigraphic and Hydrostratigraphic Units of the Frenchman Flat Model Area

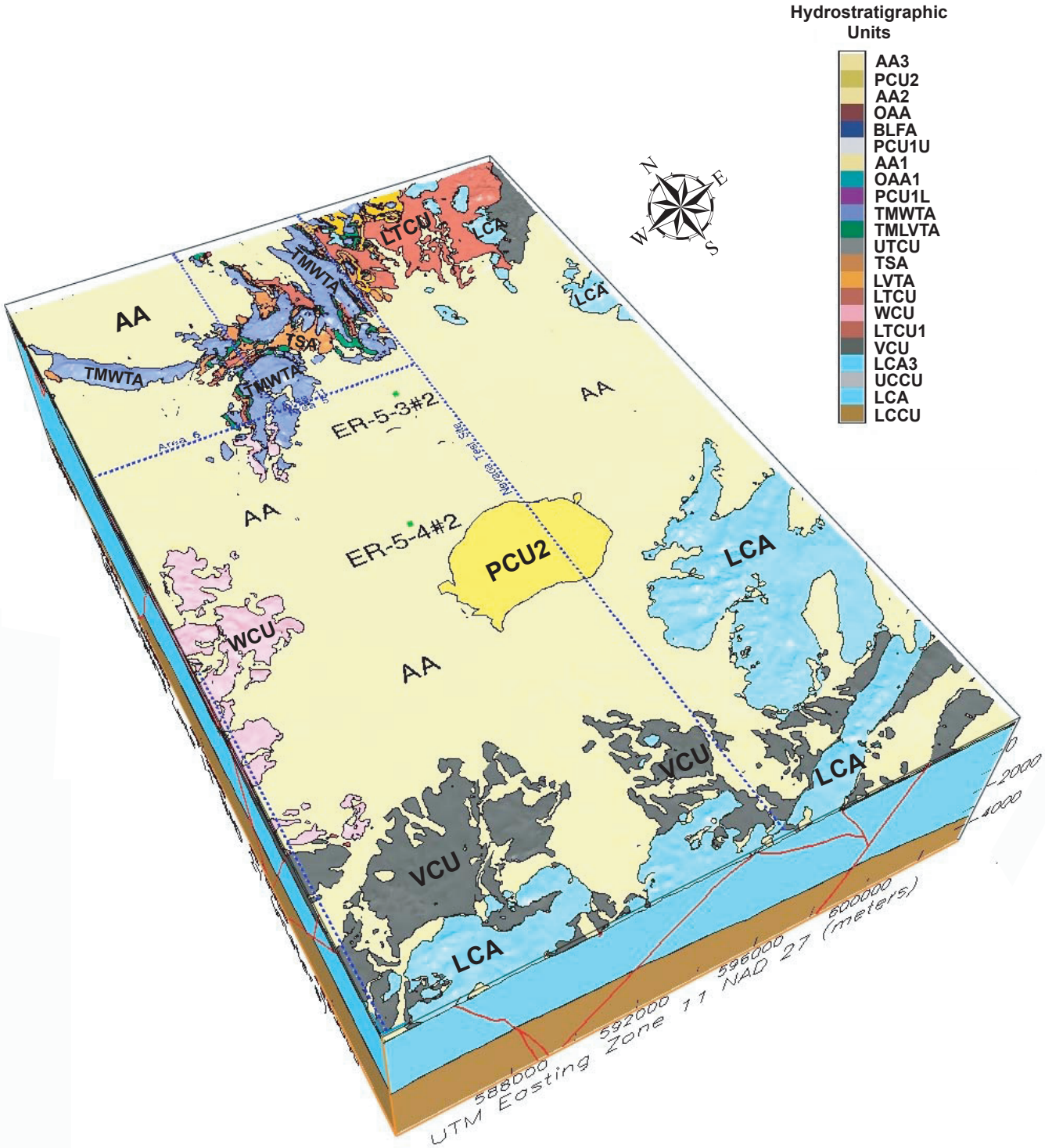


Figure 4-3
Block Model View Showing Hydrostratigraphic Units at the Surface within the Frenchman Flat Model Area

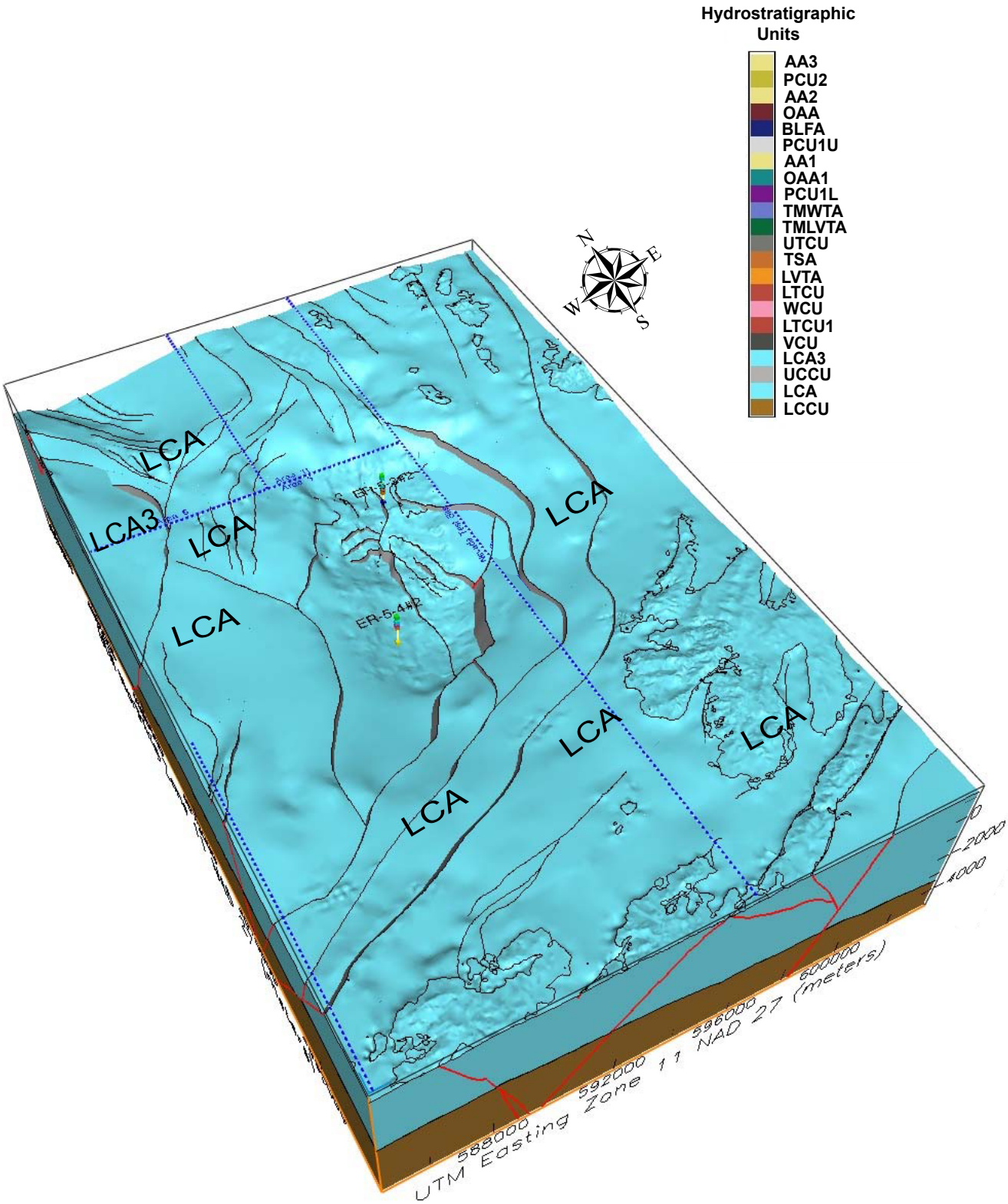


Figure 4-4
Block Model View Showing Basement Subcrop for the Frenchman Flat Model Area

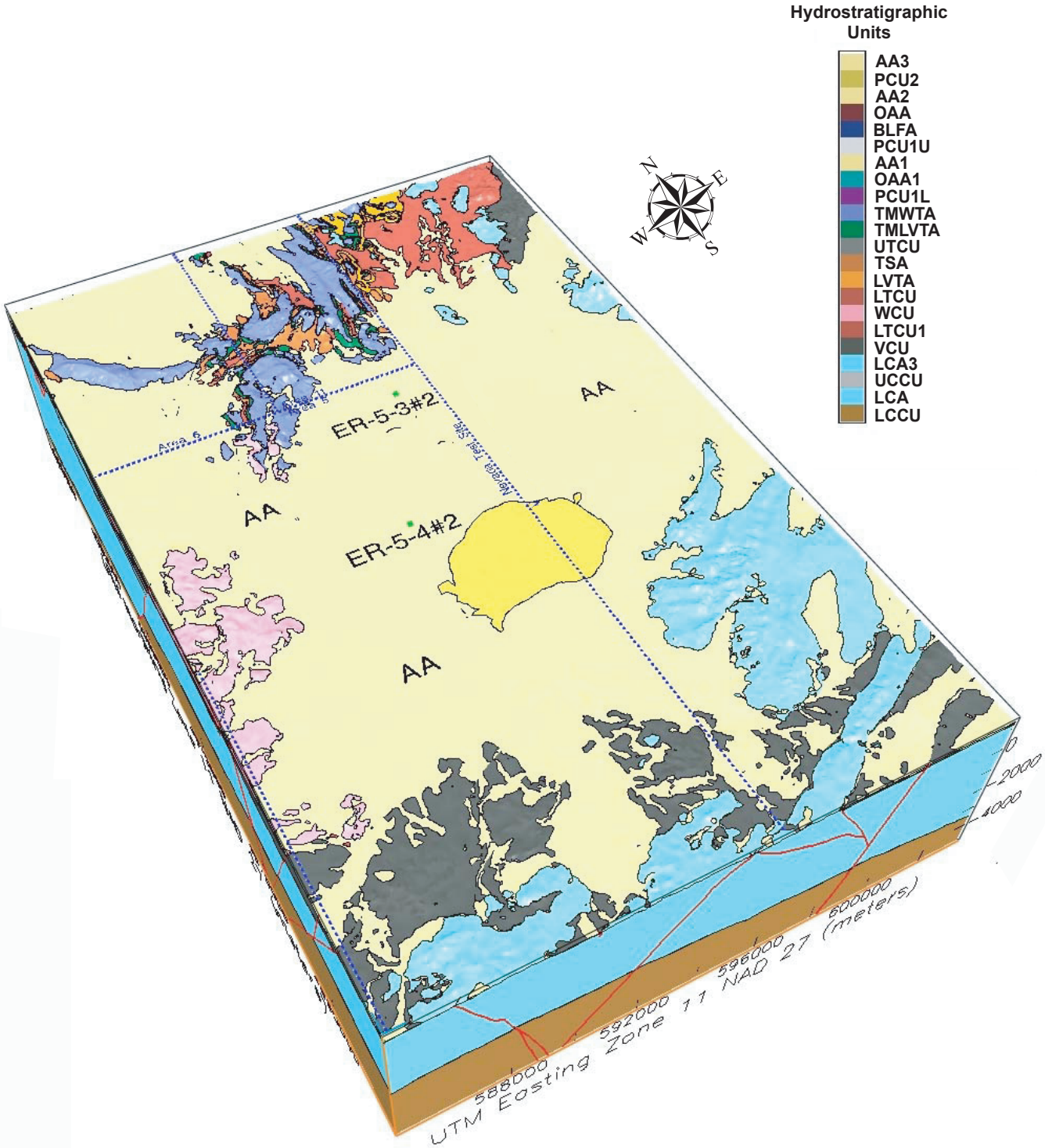


Figure 4-5
Block Model View Showing Extent of the Alluvial Aquifer (AA) within the Frenchman Flat Model Area

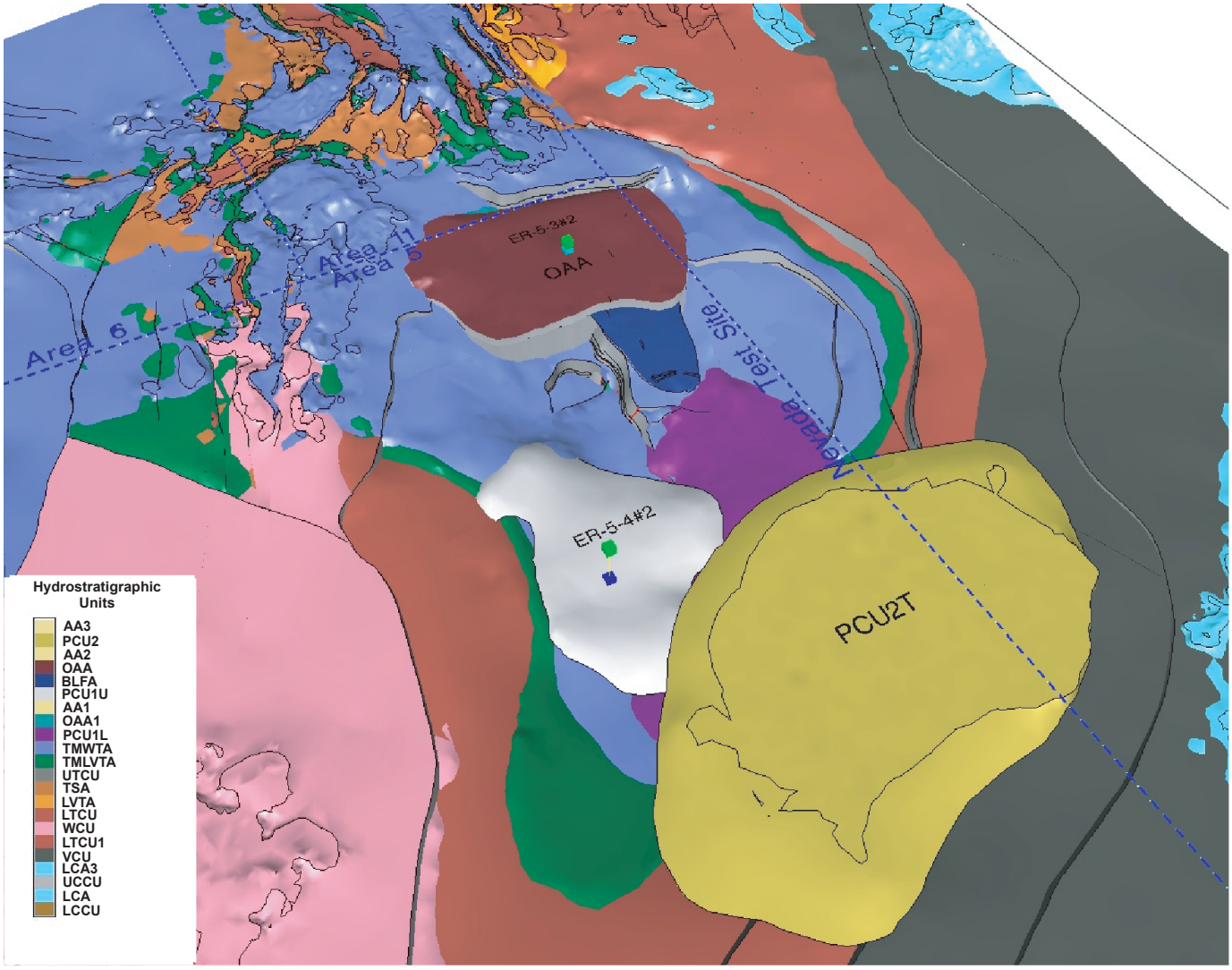
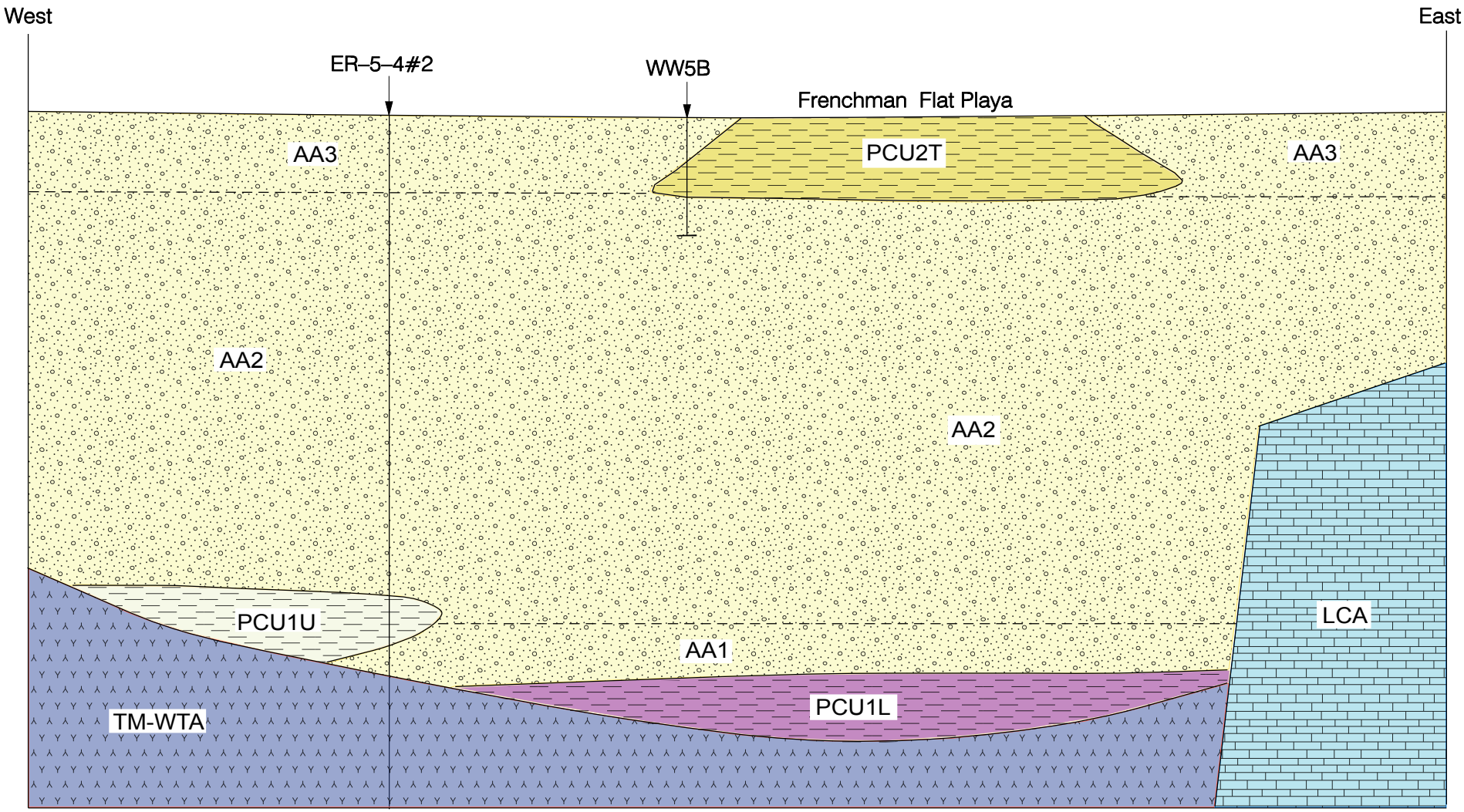


Figure 4-6
Perspective View Showing Extent of the Playa Confining Unit (PCU2T) and the Older Alluvial Aquifer (OAA) within the Frenchman Flat Model Area



Not to scale

Hydrogeologic Units

- Playa confining unit
- Alluvial aquifer
- Welded tuff aquifer
- Carbonate aquifer

Hydrostratigraphic Units

PCU2T	Playa confining unit 2	PCU1U	Playa confining unit 1 upper
AA3	Alluvial aquifer 3	PCU1L	Playa confining unit 1 lower
AA2	Alluvial aquifer 2	TM-WTA	Timber Mountain welded tuff aquifer
AA1	Alluvial aquifer 1	LCA	Lower carbonate aquifer

— — — Subdivising of the AA unit into 3 subunits, AA1, AA2, AA3, is necessary due to software limitations, and does not represent differences in the properties of the AA unit.

Figure 4-7
Schematic West-East Hydrostratigraphic Cross Section Through Central Frenchman Flat Showing Relationships of the Playa Confining Units and the Alluvial Aquifers.