State of California
California Natural Resources Agency
California Department of Water Resources
Northern Region Office

Geology of the Northern Sacramento Valley, California

June 2014
Updated: September 22, 2014

Prepared by the California Department of Water Resources
Northern Region Office Groundwater and Geologic Investigations Section

Edmund G. Brown Jr. Governor State of California	John Laird Secretary for Natural Resources California Natural Resources Agency	Mark W. Cowin Director California Department of Water Resources

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Cover photos by: Jon Mulder, Larry Snell, and Debbie Spangler

Clockwise from center: The Tehama Formation on the west side of the Sacramento Valley, Table Mountain near Oroville, stream drainages in the Sacramento Valley, Butte Creek Canyon looking northeast, the Tuscan formation on the east side of the valley.

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Acronyms and Abbreviations

a	annum (year)
amsl	above mean sea level
Ar40/Ar39	argon 40/argon 39 dating
DOGGR	Division of Oil, Gas, and Geothermal Resources
DSOD	Division of Safety of Dams
DWR	California Department of Water Resources
ft-bgs	feet below ground surface
ft-msl	feet mean sea level
K-Ar	potassium-argon age-dating
Lm	lithic metamorphic sediment
Ls	lithic sedimentary sediments
Lv	lithic volcanic sediments
Ma	mega-annum (million years)
NODOS	North-of-the-Delta Offstream Storage Investigation
USGS	United States Geological Survey

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Executive Summary

This study describes the complex geology of the northern Sacramento Valley, focusing on the Late Cenozoic geologic formations and structures that compose or influence the valley's fresh groundwater aquifer formations. The California Department of Water Resources (DWR) acquired geologic data from groundwater observation well drilling operations that were conducted in the valley over the last 15 years. Using the observation well drilling data, DWR evaluated and classified the lithology of the subsurface sediments, implemented petrographic sand provenance analyses on lithologic sediment samples, and reviewed associated geophysical logs from each bore hole. In addition, DWR conducted an extensive literature review of published and unpublished data and then integrated the data to produce this geologic report, map, and cross sections that describe the geology of the northern Sacramento Valley.

Results from the lithologic logging, petrographic analyses, and data review show that the heterogeneous sediments of the northern Sacramento Valley's most productive groundwater-bearing geologic formations, the Tehama Formation and the Tuscan Formation, intermix in the subsurface in various areas near the center of the valley. The results also show that toward the westward and eastward extents of the valley, the sediments of the formations become more unified in composition due to the proximity of their respective sediment source areas. However, because of the depositional environment of the geologic formations, sediment sizes within the formations can be discontinuous and intermittent in places, resulting in variable groundwater aquifer zones within the geologic formations.

Additional data are needed to further define the northern Sacramento Valley aquifer system. Drilling and installing groundwater observation wells in areas of little or no data can provide the information needed to determine the extent and variability of the valley's groundwater aquifers. Groundwater level data supplied by the observation wells can provide valuable information for monitoring aquifer conditions, for determining the change in groundwater levels over time, and for assessing the ability of groundwater to move through the geologic aquifer sediments. In addition, a textural analysis of formational sediments using lithologic cuttings and/or driller's well logs could be performed to better identify aquifer production zones.

In summary, the geology of the northern Sacramento Valley is diverse and has a widely varied historical sequence of earth-shaping events. It includes periods of time when much of the area was below sea level, multiple and distinct periods of volcanic activity, several periods of mountain building, and intermingled periods of massive erosion and deposition. Analyses of the data illustrate the heterogeneity of the groundwater-bearing geologic formations in the subsurface, and the intermixing of formational sediments toward the center of the northern Sacramento Valley, resulting in a region with great geologic and hydrogeologic complexity.

Section 1. Introduction

The natural beauty of the northern Sacramento Valley is a result of complex geologic processes that have shaped the valley, mountains, and the unseen subsurface sediments over millions of years. This study describes the geologic processes and tectonic forces that formed, and are continuing to form, the surface and subsurface geology of the northern Sacramento Valley. The main emphasis of the study focuses on the late Cenozoic geologic formations and structures that compose or influence the valley's fresh-water aquifer formations. Understanding the characteristics that make up these geologic formations is important to our basic understanding of the groundwater-bearing aquifer zones of the geologic formations themselves.

Previous published and unpublished geologic data were reviewed and analyzed to provide background information and context for the study area. In addition, the California Department of Water Resources (DWR) acquired data from groundwater observation well drilling operations, which supplement the previous information about the geology of the northern Sacramento Valley. Using the observation well drilling data, DWR evaluated and classified the lithology of the subsurface sediments, facilitated petrographic analyses on lithologic sediment samples, and reviewed associated geophysical logs from each bore hole. DWR then integrated the previous and current data to produce this geologic report, map, and cross sections that describe the geology of the northern Sacramento Valley.

The report includes the main text, four plates, and three appendices. The main text contains four key sections: Section 2 describes the methods of investigation; Section 3 describes the study area; Section 4 contains a discussion of the geology, which includes the geologic history, formations, and structures; and Section 5 discusses the geologic cross sections and results of the petrographic analysis.

The four plates consist of a geologic map (Plate 1), six geologic cross sections (Plates 2 and 3), and a correlation of mapped lithologic units (Plate 4).

The three appendices consist of diagrams of the groundwater observation well data which include a lithologic log, geophysical log, and the well construction as-built for each observation well shown on the cross sections (Appendix A); the petrographic analysis report, titled *Northern Sacramento Valley Sand Provenance Study Final Memorandum Report* (Appendix B); and a description of the geologic units that are shown on the geologic map and cross sections (Appendix C).

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Section 2. Methods of Investigation

This section describes the procedures used in producing the geologic map, the geologic cross sections, the groundwater observation well geologic logs and well construction diagrams, and the petrographic sand provenance analysis.

2.1. Geologic Map

The "Geologic Map of the Late Cenozoic Deposits of the Northern Sacramento Valley California" shown on Plate 1, is a modified digital reproduction of the U.S. Geological Survey (USGS) Miscellaneous Field Studies Map MF-1790 five-sheet map set "Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California" by Helley and Harwood (1985). Jon Mulder, of DWR, created the geologic map by scanning the five-sheet set, geo-referencing the scanned images, and digitizing the lithologic contacts and other geologic information. Once the map was digitized, colorization and symbology were added, and the map was checked for quality control. The accuracy of the digitized lines is within the same range as the accuracy of the originally drafted lines on the paper map. In general, the width of the contact lines on the paper copy ranges up to about 65 feet. Minor topological mistakes (such as identical rock units on both sides of a lithologic contact or unclosed polygons) and omissions (such as unidentified lithologic units) have been corrected to the best of the authors' geologic expertise.

The geologic map on Plate 1 was also compared with the original Mylar and colored field sheets of the five-sheet map set, and other local and regional maps, such as "Geologic Map of the Battle Creek Fault Zone and Adjacent Parts of the Northern Sacramento Valley, California" (Helley et al. 1981), "Geologic Map of the Chico Monocline and Northeastern Part of the Sacramento Valley, California" (Harwood et al. 1981), and "Geologic Map of the Red Bluff 30' X 60' Quadrangle, California" (Blake et al. 1999).

Structural geology was digitized from "Structure Contour Map of the Sacramento Valley, California, Showing Major Late Cenozoic Structural Features and Depth to Basement" (Plate 1 of Harwood and Helley 1987a). Geological fault information was digitized both from Helley and Harwood (1985) and from Harwood and Helley (1987a).

"Description of Geologic Units" depicted on Plates 1 through 3 is from Harwood and Helley (1987a), and is included as Appendix C. "Correlation of Map and Cross Section Units" and "List of Map and Cross Section Units" that are shown on Plate 4 were modified from Helley and Harwood (1985).

2.2. Geologic Cross Sections

Six geologic cross sections were constructed to illustrate the subsurface geology of the northern Sacramento Valley. Plate 2 shows three cross sections that are oriented in a generally east-west direction (labeled A-A’, B-B’, and C-C’) and one cross section that is oriented in an approximately northeast-southwest direction (D-D’). Plate 3 shows two cross sections that are oriented in a generally north-south direction (E-E’ and F-F’). Because cross section F-F’ traverses a great distance, it is shown on the plate in two parts, with the southernmost part of the cross section illustrated below the northern part of the cross section. Table 1 lists the end-point coordinates for cross sections A-A’ through F-F’.

Table 1. End-Point Coordinates for Cross Sections A-A’ through F-F’

Section	Western point (easting, northing)*	Eastern point (easting, northing)*
A-A’	560260, 4411983	593158, 4427968
B-B’	557795, 4394578	607083, 4398603
C-C’	554033, 4372879	625129, 4370384
D-D’	565932, 4332520	613278, 4382340
Section	**Northern point (easting, northing)***	**Southern point (easting, northing)***
E-E’	601730, 4413718	602891, 4345841
F-F’	570703, 4436960	579891, 4340027

*Universal Transverse Mercator (UTM), North American Datum (NAD) of 1983, Zone 10, Meters

The geologic cross sections are shown both with and without vertical exaggeration. The fully illustrated cross section is shown with a vertical scale exaggeration of 1 inch equals 1,000 feet and a horizontal scale of 1 inch equals 5,280 feet (1 mile). The vertical exaggeration was selected both to help illustrate the geologic formations and to facilitate the measurement of various features on the cross sections. A one-to-one scale version of each cross section is provided below the vertically exaggerated cross sections to show the actual relationship of the geologic formations.

Various sources of data were used to identify the subsurface geology. Lithologic cutting descriptions and geophysical data from groundwater observation well drilling were used to identify sediments in the subsurface; observation well diagrams for these wells are shown in Appendix A. Geophysical data from the California Department of Conservation’s Division of Oil, Gas, and Geothermal Resources’ (DOGGR’s) natural gas well drilling were also used for reference in identifying formational boundaries; natural gas well geophysical logs can be found on the DOGGR website listed in the “References” section (California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, 2011). In addition, sand-provenance testing and the associated petrographic analysis were performed on selected sediment samples that came from the groundwater observation well lithologic cutting samples; the full petrographic analysis report is presented in Appendix B.

2.2.1. Cross Section Construction

The process to construct the cross sections began with developing a working base map on which to plot the surface geologic data. The base map was developed by compiling USGS 7.5-minute topographic maps of the study area and superimposing geologic contacts and structural features on them. In addition, the locations of the groundwater observation wells were plotted on the base map. Lithologic and geophysical data that were obtained during the drilling of these observation wells were extremely valuable in the interpretation of the subsurface geology on the cross sections.

Six cross section lines were drawn through areas where the most subsurface data existed that would help illustrate the cross sections. After a draft version of the cross sections was constructed, lithologic samples from certain groundwater observation wells were petrographically analyzed for mineralogical composition and determination of sand provenance, or the original geologic source area of the subsurface samples. The results from this analysis were used to make the final geologic contact designations. Further discussion of the sand provenance analysis is presented in Section 2.2.4, and the full report is presented in Appendix B.

Additional sources of geologic data were also used to develop the cross sections. These sources include:

- Geophysical logging data from the online database of DOGGR (California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, 2011).
- Subsurface cross sections produced by L. E. Redwine (1972).
- Subsurface mapping of the lower Princeton Submarine Valley produced by L. E. Redwine (1972).
- Surface, subsurface, and structural mapping produced by the USGS (Harwood and Helley 1987a).

2.2.2. Geologic Contacts and Formations

Data from published and unpublished studies, natural gas exploration wells, groundwater observation wells, and petrographic sand-provenance characterization were used to determine the subsurface geologic contacts. The particular reference or data source used to determine the geologic contact locations is numerically annotated and correspondingly labeled as numbers 1-7 on Plates 2 and 3. A question mark denotes contacts or portions of contacts where no reference data were available and where the contact location was inferred. The numeric geologic references are described below and are listed in the legend on Plates 2 and 3 (for complete reference information, see the “References” section at the end of this report).

Numeric geologic references for Plates 2 and 3:

1. *Late Cenozoic Tectonism of the Sacramento Valley, California* (Harwood and Helley1987a).

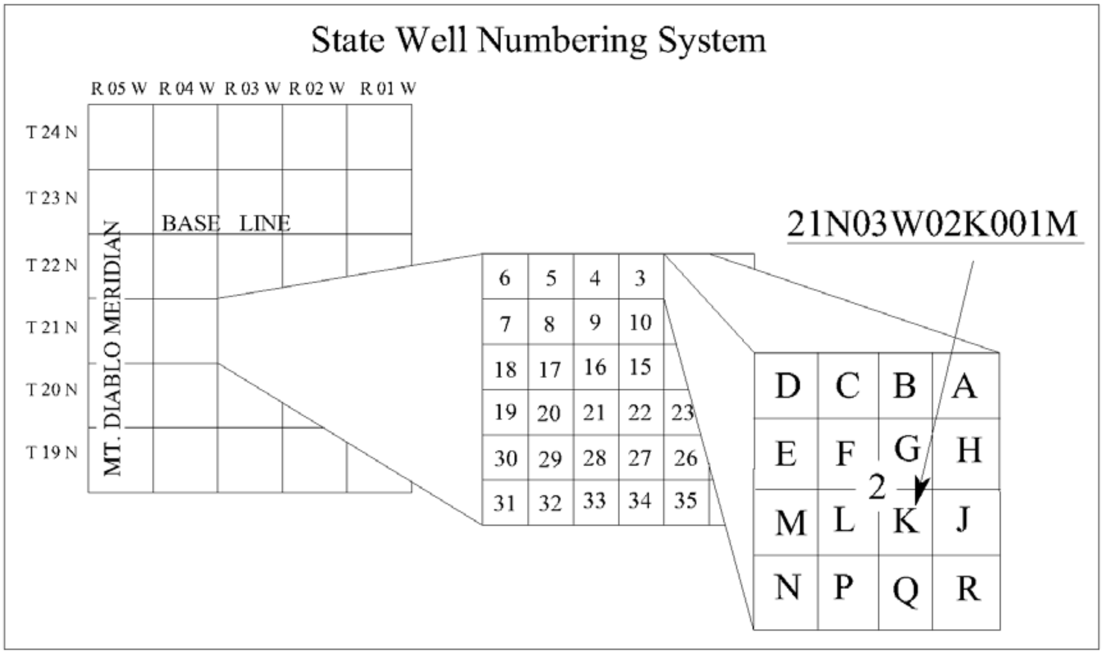
2. “Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California” (Helley and Harwood 1985).
3. “The Tertiary Princeton Submarine Valley System beneath the Sacramento Valley, California” (Redwine 1972).
4. Drill cutting lithology derived from the drilling of groundwater observation wells in the northern Sacramento Valley. (The data summary is included in the observation well diagrams in Appendix A.)
5. *Northern Sacramento Valley Sand Provenance Study Final Memorandum Report* (Appendix B).
6. Geophysical resistivity log signature.
7. Lithologic data provided by DOGGR.

2.2.3. Groundwater Observation Well Diagrams and Identification

Numerous groundwater observation wells were drilled and installed in the northern Sacramento Valley from around 1995 to 2010. DWR Northern Region Office staff provided oversight during the drilling and construction operations of many of the observation wells and were able to collect lithologic cuttings and geophysical logs during the drilling process. Lithologic samples were taken at 10-foot intervals, and geophysical logs were run in the open test hole prior to constructing the observation wells. The lithologic descriptions of the samples and the geophysical logs were vital for a better understanding of the area’s subsurface geology. Diagrams that show the lithologic descriptions, the geophysical logs, and the well construction as-builts for the groundwater observation wells that were sampled for petrographic analyses are included in Appendix A.

The groundwater observation wells are identified according to the State’s well numbering system. The numbering system is based on the Public Land Survey System, which includes the township, range, and section where each well is located. Each section is further subdivided into 16 40-acre tracts, which are assigned a letter designation. Within each 40-acre tract, wells are numbered sequentially; the final letter of the well number refers to the baseline and meridian of the public land grid in which the well lies. “M” refers to the Mount Diablo baseline and meridian; “S” refers to the San Bernardino baseline and meridian; and “H” refers to the Humboldt baseline and meridian. Figure 1 shows an example of the location and identification of State Well No. 21N03W02K001M.

Figure 1. State Well Numbering System



2.2.4. Petrographic Sand Provenance Analysis

A petrographic sand provenance analysis was implemented to determine or confirm the original geologic source areas of subsurface lithologic sediment samples taken during groundwater observation well drilling. The results confirm distinct source areas for the geologic formations on the east and west sides of the valley. Near the center of the valley, the analysis identified multiple source areas, indicating areas of intermixing and reworking of sediments.

The petrographic sand provenance analysis was performed by petrographers Raymond Ingersoll, Ph.D., with the University of California, Los Angeles, and Martin Steinpress, with Brown and Caldwell. Samples of sand grains from groundwater observation well cuttings were submitted for a petrographic sand provenance characterization to determine the mineralogical content and source area of the individual samples. The location and depth of the samples were unknown to the petrographers at the time of their analysis to prevent operator bias. In addition, control tests were performed on samples from known geologic formations to verify test results.

These sand-sized grains were glued together with epoxy to form an artificial “rock.” A thin slice was cut from the “rock,” mounted to a microscope slide, and polished to create a thin-section slide that could be viewed under a microscope. Using the same systematic procedure for each slide, the rock type (volcanic, metamorphic, or sedimentary) was recorded for a predetermined number of grains visible under the microscope.

A constituent composition percentage was calculated to determine the predominant rock type or types for each slide and, accordingly, each sample. Once the predominant rock type for the sample was determined, each sample was correlated to the original formation from which it came. This tool proved useful in confirming the geologic formation determinations made by the field geologists and in determining the geologic contacts depicted on the cross sections.

The differing compositions of lithic sediments were then graphed on pie charts showing the major composition types at each sample location. The pie charts illustrate the percentage of the three major mineralogical composition types found in the northern Sacramento Valley: lithic metamorphic sediments (Lm) are shown in blue, lithic volcanic sediments (Lv) are shown in pink, and lithic sedimentary sediments (Ls) are shown in yellow. The pie charts are shown on the cross sections at the corresponding depth and location from which the sample was taken. A plan view, location map (a map that shows a surface from above) is illustrated on the cross sections showing the location from where the sand samples were taken. Table 2 lists the observation well State well number of the wells that were sampled for petrographic analysis, and the cross section(s) on which the well is shown.

A complete description of the petrographic study methodology is discussed in Appendix B.

Table 2. Observation Well Identification for Petrographic Analysis and Cross Section Location

State well number of observation well	Cross section location
16N02W04J001M	D-D’; F-F’
17N01E24A002M	E-E’
19N01E35B002M	C-C’; D-D’; E-E’
19N02E07K002M	C-C’; D-D’; E-E’
19N02E13Q002M	C-C’
19N04W14M002M	C-C’
21N02W33M001M	F-F’
21N03W01R002M	B-B’; F-F’
21N04W12A001M	B-B’
22N02W18C001M	F-F’
22N02E30C002M	B-B’; E-E’
24N01W04M001M	A-A’
24N02W29N003M	A-A’; F-F’
24N03W29Q001M	A-A’

Section 3. Description of the Study Area

The following sections describe the location of the study area and the general climate of the area in sections 3.1 and 3.2. Section 3.3, “Hydrology and Hydrogeology,” summarizes the general flow direction of the major streams and rivers, as well as the general direction of groundwater movement in the northern Sacramento Valley.

3.1. Location

The northern Sacramento Valley lies in the northernmost region of the Central Valley and encompasses all or part of Butte, Colusa, Glenn, Sutter, and Tehama counties. The study area extends north to south from the city of Red Bluff to the Sutter Buttes, and east to west from the Coast Ranges and Klamath Mountains to the Sierra Nevada and Cascade Range, shown in Figure 2. The elevation of the northern Sacramento Valley floor increases northward, ranging from around 40 feet mean sea level (ft-msl) near the Sutter Buttes to about 240 ft-msl near Red Bluff. The elevation of the surrounding mountains ranges from 10,456 ft-msl at Lassen Peak in the Cascade Range to an average peak elevation of about 6,500 ft-msl in the Coast Ranges. Prominent features in the northern Sacramento Valley are the Orland Buttes (1,038 ft-msl) and the Sutter Buttes (2,132 ft-msl), which provide the only significant topographic relief on the northern Sacramento Valley floor.

3.2. Climate

The northern Sacramento Valley has a Mediterranean-type climate characterized by hot, dry summers and cool, wet winters. The majority of precipitation falls in the winter months; summer months are hot and dry with no significant rainfall. The average annual rainfall on the valley floor is about 21 inches, with around 90 percent of the precipitation falling from October to April. Typical precipitation from May through September is less than 2 inches.

3.3. Hydrology and Hydrogeology

The major sources of surface water in the northern Sacramento Valley are the watersheds of the Sacramento River and the Feather River. The Sacramento River flows into Lake Shasta from its headwaters near Mount Shasta. It then flows southward through the valley until it bends west around the Sutter Buttes, flowing to its confluence with the Feather River near Verona and the San Joaquin River in the Sacramento-San Joaquin River Delta.

The headwaters of the Feather River originate from several tributaries in the Cascade Range and Sierra Nevada. The main stem of the Feather River flows westward along the general boundary between the Cascade Range and the Sierra Nevada, where it flows into Lake Oroville. Exiting the lake, the

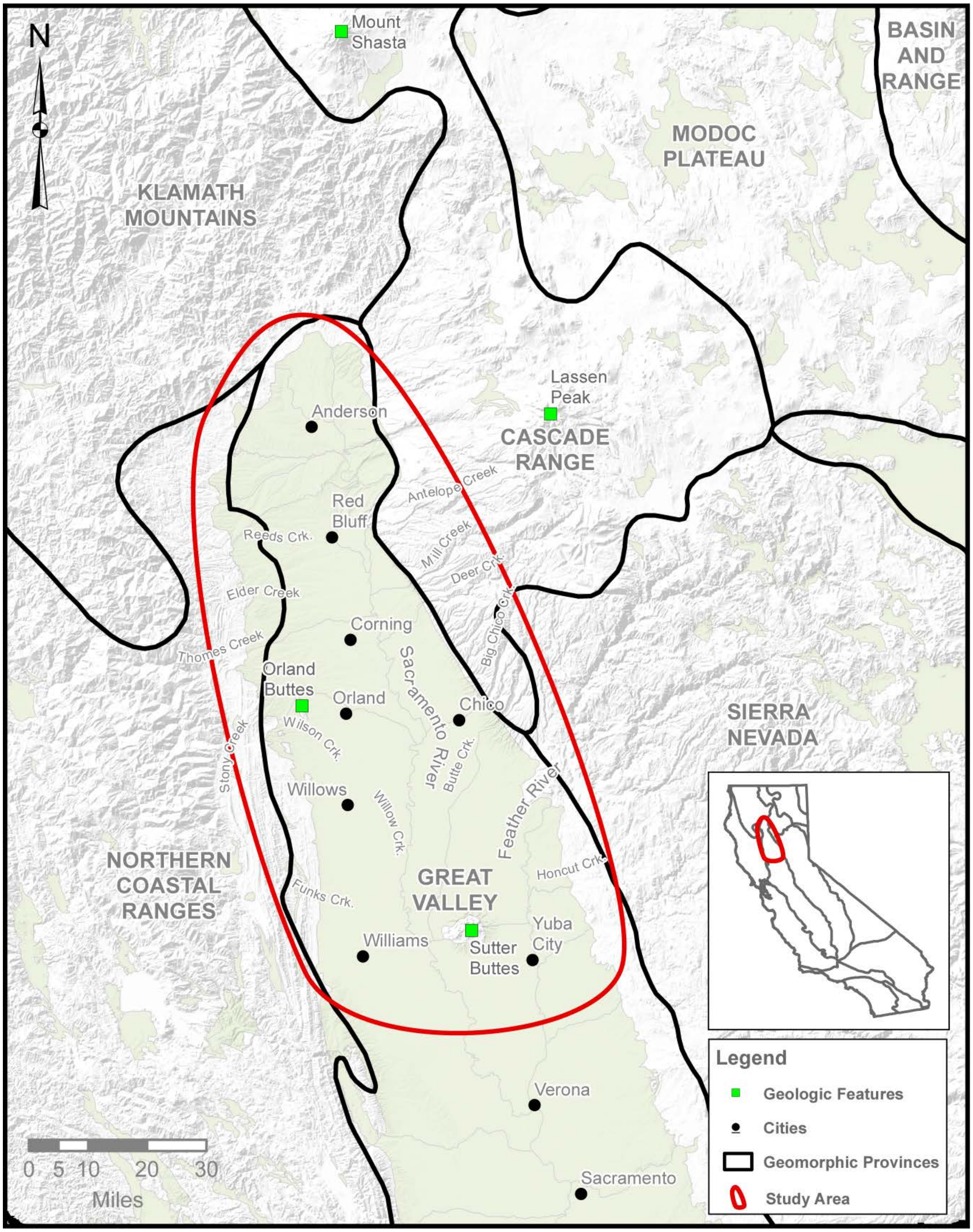
Feather River flows in a southerly direction, east of the Sutter Buttes, where it joins the Sacramento River about 20 miles north of Sacramento near Verona.

Numerous perennial and ephemeral streams flow from the mountain ranges surrounding the northern Sacramento Valley, across the valley floor, and into the Sacramento and Feather rivers. The majority of streams originating on the west side of the valley are ephemeral, and the majority of streams flowing from the east side are perennial. Some of the notable streams flowing from the west side of the valley are Cottonwood Creek, Reeds Creek, Elder Creek, Thomes Creek, Stony Creek, Wilson Creek, Willow Creek, and Funks Creek. Significant creeks flowing from the east side of the valley are Battle Creek, Antelope Creek, Mill Creek, Deer Creek, Big Chico Creek, Butte Creek, and Honcut Creek.

Groundwater occurs in the heterogeneous gravel and sand layers of the Tehama, Tuscan, and Laguna formations, and in the shallower alluvial layers of the Riverbank and Modesto formations, and the Stony Creek fan alluvium. The general trend of groundwater flow on the west side of the valley is in a southeasterly direction toward the Sacramento River. On the east side of the valley, groundwater flows generally in a south-southwesterly direction toward the Sacramento River. On the southeast side of the valley, groundwater flows in a southeasterly or southwesterly trend towards the Feather River.

Barriers to groundwater flow include geologic structures such as the Red Bluff Arch, the Corning domes, the Sutter Buttes, and the buried Colusa dome. In the northern part of the valley, the Red Bluff Arch acts as a groundwater divide separating the Sacramento Valley groundwater basin from the Redding groundwater basin. South of Corning, the surface expression of the Corning domes influences the flow patterns of Stony Creek and Thomes Creek. Stony Creek flows southeast of the domes, with regional flow to the confluence of the Sacramento River, whereas Thomes Creek flows northeast of the domes, against regional flow to the Sacramento River (Blake et al. 1999). In the southern part of the valley, groundwater mounds up on the north side of the Sutter Buttes before it flows westward around the Buttes and between the buried Colusa dome and southward.

Figure 2. Location Map of the Northern Sacramento Valley Study Area



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Section 4. Geology of the Northern Sacramento Valley

This section discusses the geologic setting, formations, and structures in the northern Sacramento Valley. The discussion provides an overview of the regional setting for each geologic time period, describes the geologic formations shown on the six cross sections (Plates 2 and 3), and describes geologic structures that are shown on the cross sections as well as on the geologic map (Plate 1). A stratigraphic correlation of the mapped units that are shown on Plates 1, 2, and 3 is presented on Plate 4.

The geologic setting, formations, and structures are summarized and organized by the chronology of the two most recent geologic eras, the older Mesozoic era and the current Cenozoic era. The Mesozoic era is subdivided into three geologic periods: the Triassic, Jurassic, and Cretaceous; and the Cenozoic era is also subdivided into three geologic periods: the Paleogene, the Neogene, and the Quaternary. The latter three geologic periods are further subdivided into seven geologic epochs: the Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene. The geologic time interval for the era, periods, and epochs is shown in Table 3.

Table 3. Geologic Time Scale for the Mesozoic and Cenozoic Eras

Era	Period	Epoch
Cenozoic (65 Ma to 1.8 Ma)	Quaternary (1.8 Ma to present)	Holocene (11,000 a to present)
		Pleistocene (1.8 Ma to 11,000 a)
	Neogene (23 Ma to 1.8 Ma)	Pliocene (5 Ma to 1.8 Ma)
		Miocene (23 Ma to 5 Ma)
	Paleogene (65 Ma to 23 Ma)	Oligocene (38 Ma to 23 Ma)
		Eocene (54 Ma to 38 Ma)
		Paleocene (65 Ma to 54 Ma)
Mesozoic (245 Ma to 65 Ma)	Cretaceous (146 Ma to 65 Ma)	
	Jurassic (208 Ma to 146 Ma)	
	Triassic (245 Ma to 208 Ma)	

Notes:
Ma = Mega annum, or million years.
a = annum, or year.

4.1. Regional Overview

The northern Sacramento Valley has a diverse and complex geologic history. Convergence of the Pacific and North American plates has created tectonic stresses that caused the present-day northern Sacramento Valley to go through many changes. From the Mesozoic era through the mid-Cenozoic era, the present-day northern Sacramento Valley was inundated with Pacific Ocean waters, and the Pacific shoreline oscillated back and forth from the eastern side to the western side of the area. From the mid-

Cenozoic era to present, the Pacific shoreline migrated westward to its current position west of the California Coast Ranges, exposing the valley as it looks today.

Tectonic forces between the Pacific and North American plates also initiated mountain-building events, which in turn have formed the present-day northern Sacramento Valley. Throughout the Mesozoic and Cenozoic eras, these mountain-building events formed the ancestral Sierra Nevada, Klamath, Cascade Range, contemporary Sierra Nevada, and Coast Range mountains, and subsequently the Sacramento Valley. These mountains are the source areas for the erosion and deposition of sediments that make up the geologic formations of the northern Sacramento Valley.

The valley's current form is described as an elongated, asymmetrical, structural basin that contains marine and non-marine sediments up to 5 miles thick (Graham 1981). At the base of the marine sediments is the basement bedrock, which was formed in the Triassic period. Overlying the basement bedrock is a thick succession of marine sediments that were deposited during the Mesozoic and early Cenozoic eras. The marine sediments are overlain by a relatively thin veneer, about a half-mile thick, of non-marine, or continentally derived, sediments that were deposited during the mid- to late Cenozoic era. This thin veneer of continental, fresh-water-bearing sediments is the focus of this study.

Further discussion of the geologic setting, formations, and structure is provided in the following sections. An overview of the chronology of geologic formations, geologic structures, and tectonic forces that formed the key geologic features in the northern Sacramento Valley is shown in Figure 3.

Figure 3. Overview of the Geochronology of the Northern Sacramento Valley

GEOCHRONOLOGY
of the
NORTHERN SACRAMENTO VALLEY, CALIFORNIA

	CENOZOIC ERA							MESOZOIC ERA		
	QUATERNARY		NEOGENE		PALEOGENE			Cretaceous 65 Ma to 146 Ma	Jurassic 146 Ma to 208 Ma	Triassic 208 Ma to 245 Ma
	Holocene (Recent) Present to 11,000 a*	Pleistocene 11,000 a to 1.8 Ma**	Pliocene 1.8 Ma to 5 Ma	Miocene 5 Ma to 23 Ma	Oligocene 23 Ma to 38 Ma	Eocene 38 Ma to 54 Ma	Paleocene 54 Ma to 65 Ma			
GEOLOGIC FORMATIONS	[1]Surficial alluvium, stream channel and basin deposits	[8]Modesto Formation (0.14 Ma to 0.42 Ma) and Riverbank Formation (0.13 Ma to 0.45 Ma)	[1]Laguna, Tuscan, and Tehama, Formations, Nomlaki Tuff	[2]Lovejoy Basalt and Upper Princeton Valley fill	?	[2]Ione Formation & Lower Princeton Submarine Valley fill	?	[17]Great Valley Sequence, Franciscan Formation and Coast Range Ophiolite (Late Jurassic to Cretaeceous)		[4]Undivided volcanic and marine sedimentary rocks
	[4]Stony Creek Fan alluvium (Holocene to Late Pleistocene)		[4]Sutter Formation (Pliocene to Miocene)							
		[5, 16]Tuff Breccia and volcanic sediments of the Sutter Buttes (<1.36 Ma to 1.56 Ma)								
		[9]Red Bluff Formation (0.45 Ma to 1.08 Ma)								
GEOLOGIC STRUCTURES	[1, 11]Cleveland Hills Faults (Recent to 1.8 Ma)									
	[1]Foothills Fault System, Cohasset Ridge Fault, Magalia Fault (Recent? to 2.4 Ma)									
		[1, 7]Inks Creek Fold System, Hooker Dome, Sevenmile Dome, Tuscan Springs Dome and Salt Creek Dome (0.40 Ma to 0.45 Ma)								
		[9]Red Bluff Pediment Surface (0.45 Ma to 1.08 Ma)	[12, 13]Black Butte Fault (pre-3.3 Ma to post-Miocene (if present)							
		[1]Battle Creek Fault Zone (0.45 Ma to 1.09 Ma)	[12]Coast Range Fault (1.8 Ma to 65 Ma)							
		[1]Uplift of the Red Bluff Arch (0.45 Ma to 1.09 Ma?)	[1]Paskenta Fault Zone (3.3 Ma to 65 Ma)							
		[5]Formation of the Sutter Buttes and buried Colusa Dome (1.36 Ma to 1.56 Ma)	[1]Cold Fork and Elder Creek Fault Zones (3.4 Ma to 65 Ma)							
		[1, 6]Movement on the Red Bluff Fault (Pleistocene to Late Pliocene)		[1]Movement along the Willows Fault (4 Ma to 60 Ma)						
		[1]Corning Domes, Los Molinos Syncline, and Glenn Syncline, Greenwood Anticline and unnamed syncline (1.0 Ma to 2.5 Ma)		[12, 13]Stony Creek Fault, Green Valley Fault, Salt Lake Fault? (5 Ma to 65 Ma?)						
		[1]Movement on the Corning Fault (1.0 Ma to 2.5 Ma)								
		[1]Chico Monocline Flexure (1.1 Ma to 2.61 Ma)								
	[13]Great Valley Fault System (Recent to 65 Ma?)									
	[13]Sites Anticline and Fruto Syncline (Recent to 81 Ma)									
REGIONAL GEOLOGY	[10, 14]Cascade Volcanism / High Cascade Series (Recent to 5 Ma)			[10, 14]Cascade Volcanism / Western Cascade Series (5 Ma to 50 Ma)						?
	[4]Uplift of Sierra Nevada and northern Coast Ranges to present level					[14]Formation of the Klamath Mountains (50 Ma to 65 Ma)		[10]Emplacement of Sierra Nevada Plutons Nevada Orogeny (140 Ma to 150 Ma)		
	[10]Basin and Range Extension				[2]Subaerial exposure and erosion of surface topography		[2]Period of erosion and carving of submarine canyons, Lower Princeton Submarine Valley			
	Pacific shoreline Present day	[3,4]Pacific shoreline continuing to retreat further west to its present position	[4]Pacific shoreline west of the Sacramento Valley	?	[4]Pacific shoreline retreating west of the Sacramento Valley	[3]Pacific shoreline along eastern margin of (present day) Sacramento Valley (40 Ma to 65 Ma)		[3]Pacific Shoreline east of Sacramento (71-76 Ma); west of Sacramento (89-92 Ma)	[3]Formation and infilling of the oceanic forearc basin	
	[4]Marine Regression			[4]Marine Transgression/ Regression ocillations	[4]Marine Regression	[3, 4]Marine Transgression	[3, 4]Marine Regression			
	[1, 15]Lattitude and Northward Migration of Right-Lateral Transform Plate Boundary (Mendocino Triple Junction, San Andreas Fault Zone) between the North American Plate, the Pacific Plate, and the Juan de Fuca Plate (Present to 30 Ma)					[1,15]Convergent Plate Boundary between the North American Plate and the Pacific Plate (30 Ma to 200 Ma)				
	Present Lattitude at Cape Mendocino	[1,15]Approximate Latitude as North of Sutter Buttes	[1,15]Approximate Latitude as North of Sacramento	[1,15]Approximate Lattitude San Francisco/ Central California	[1,15]Approximate Lattitude Baja California					

*a: annum
**Ma: mega-annum (10^6 years)

References:
[1]Harwood and Helley 1987a&b; [2]Redwine 1972; [3]S.A. Graham 1981; [4]Olmsted and Davis 1961; [5]Hausback and Nilsen 1999; [6]Blake, et al 1999; [7]Harwood 1984; [8]Marchandt and Allwardt 1981; [9]Helley and Jaworowski 1985; [10]Norris and Webb 1990; [11]California Department of Water Resources 1979; [12]Earth Science Associates 1980; [13]William Lettis and Associates 2002; [14]Mack 1960; [15] Atwater 1970; [16]Williams and Curtis 1977; [17]Ingersoll and Dickinson 1981;

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4.2. Mesozoic Era — Triassic, Jurassic, and Cretaceous Periods

4.2.1. Geologic Setting

During the Mesozoic era, from the Late Jurassic to the mid-Cretaceous period, an oceanic fore-arc basin was forming, which created a moderately deep, marine environment for sediment deposition (Graham 1981). Between 92 mega-annum (Ma) (million years ago) and 89 Ma, the Pacific shoreline was approximately 25 miles west of the current position of Sacramento area and about 10 miles west of Redding, and then it migrated about 20 miles east of the Sacramento area from about 76 to 71 Ma (Graham 1981). The western boundary of the fore-arc basin was formed by the eastward-dipping convergent plate boundary zone causing subduction of the oceanic Pacific plate beneath the continental North American plate. Sediments from the Pacific plate were carried down the subduction zone and then the deformed and metamorphosed sediments were brought back to the surface, forming the Late Jurassic to Cretaceous age Franciscan Formation and Coast Range ophiolite, which make up much of the Coast Ranges.

The eastern boundary of the fore-arc basin was formed by the subsurface emplacement of the granitic component of the Sierran basement, which occurred during the mountain-building Nevadan orogeny in the Jurassic and Cretaceous periods. Folding, faulting, and subsequent uplift of the granitic intrusive rocks from depths of several thousand feet formed the ancestral Sierra Nevada (Olmsted and Davis 1961). Ensuing erosion of the ancestral Sierra Nevada provided sediment for the Late Jurassic to Late Cretaceous Great Valley sequence. As a result of this mountain-building phase and the convergence of the Pacific and North American tectonic plates, Pacific oceanic waters were in the process of being cut off by the slowly emerging Sierra Nevada mountain range, causing the shoreline to regress slowly westward during this time.

4.2.2. Geologic Formations

The following geologic formation descriptions focus on Mesozoic era sediments in the northern Sacramento Valley that are shown on the six geologic cross sections (Plates 2 and 3).

Sierran Basement (pKmi)

The Sierran basement rocks, of late Paleozoic to early Mesozoic age, are exposed throughout the Sierra Nevada and extend westward beneath the Sacramento Valley. Sierran basement rock consists of metamorphosed igneous and sedimentary rocks, and igneous plutonic rocks that were intruded during the Late Jurassic or Early Cretaceous Nevadan orogeny (Olmsted and Davis 1961). The metamorphic rocks are predominantly amphibolite, hornblende schist, and diabase, and the plutonic rocks are composed mainly of granodiorite. The ancestral Sierran basement rocks are overlain by the Great Valley sequence.

Great Valley Sequence (JKgvs)

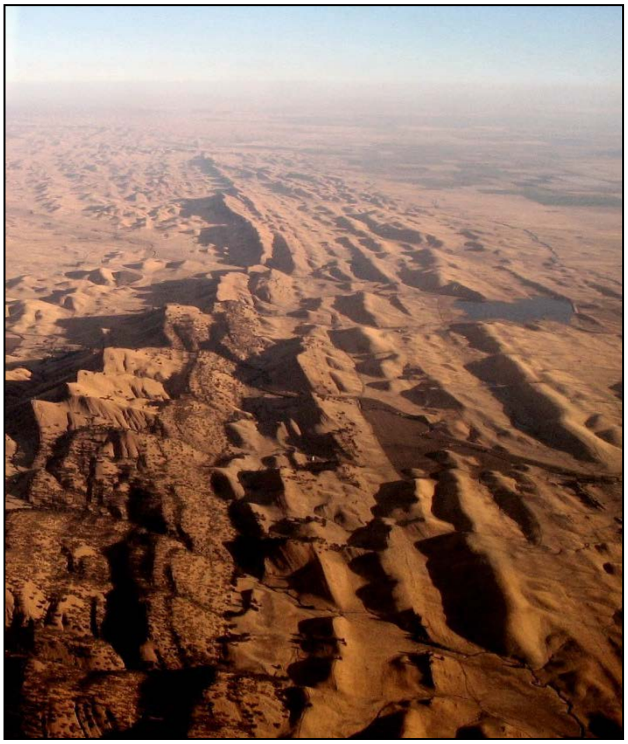
The Great Valley sequence overlies Sierran basement rocks on the east side of the northern Sacramento Valley and overlies undivided marine sedimentary rocks on the west side of the valley. The sequence formed throughout the Late Jurassic and Cretaceous periods. Outcrops of the Great Valley sequence can be seen throughout the northern Sacramento Valley. Exposures of sequence are seen in stream drainages on the east side of the Sacramento Valley and in outcrop around the Sutter Buttes. On the west side of the valley, the Great Valley sequence forms the extensive north-west trending strike ridges and valleys that roughly parallel the Coast Ranges as shown in Figure 4. The thickness of these massive sediments is about 45,000 feet (Ingersoll and Dickenson 1981).

The Great Valley sequence is characterized by deep-marine turbidites consisting of varying compositions of interbedded marine sandstone, siltstone, and conglomerate (Bailey et al. 1970; Bertucci 1983). The provenance for the Great Valley sequence sediments is the ancestral Sierran-Klamath terrane (Ojakangas 1968; Dickinson and Rich 1972; Mansfield 1979; Ingersoll and Dickinson 1981). Eroded sediments from these mountains were deposited into deep oceanic waters off the continental shelf as turbidity flows and submarine fans. Because of the marine nature of deposition, groundwater occurring in these sediments is primarily saline, except locally on the margins of the valley where the formational water has been flushed with newer fresh water. The Great Valley sequence is overlain by the lower Princeton Submarine Valley fill, upper Princeton Valley fill, Ione Formation, Tuscan Formation, or Tehama Formation.

4.2.3. Geologic Structure

There are no Mesozoic era geologic structures shown on the geologic map (Plate 1) or the geologic cross sections (Plates 2 and 3).

Figure 4. Great Valley Sequence North-West Trending Strike Ridges



(Photo credit: DWR)

4.3. Cenozoic Era — Paleogene Period

4.3.1. Geologic Setting

During the Paleogene period of the early Cenozoic era, convergence of the Pacific and North American plates was continuing to uplift the ancestral Sierra Nevada, forming a sea barrier. This caused the Pacific shoreline to regress west of the ancestral Sierra Nevada to the approximate location of the present-day eastern margin of the Sacramento Valley. A marine regression is a period that results in sea level lowering relative to the land surface, exposing former sea floor sediments or deposits and causing periods of erosion and carving of submarine canyons. A marine transgression is a period that results in sea level rising relative to the land surface initiating flooding over previously exposed inland regions and causing the deposition of sediments. Over the 42 million years of the Paleogene period, seas regressed, transgressed, and regressed again due to the tectonic stresses of the convergent plate boundaries.

During the westward marine regression that occurred during the Paleocene epoch, the lower Princeton Submarine Valley was carved and eroded. The Princeton Submarine Valley was up to 2,400 feet deep and extended in the subsurface more than 160 sinuous miles, from south of Redding to the Woodland area (Redwine 1972). In the subsequent Eocene epoch, subsidence lowered the land surface, causing the seas to transgress eastward. As the seas transgressed, the lower Princeton Submarine Valley was inundated with coarse sediments derived locally, forming the lower Princeton Submarine Valley fill. Following the inundation of the lower Princeton Submarine Valley, the Ione Formation was deposited by westward-coursing streams flowing off the partially submerged ancient Sierra Nevada and into the adjacent shallow sea as a shoreline deposit (Durrell 1987). Another period of marine regression occurred during the Oligocene epoch, causing the subaerial exposure of the ancestral Sierra Nevada and erosion of surface topography. It was also during this time that Sutter Formation sediments began accumulating (Williams and Curtis 1977).

During the continued uplift of the ancestral Sierra Nevada mountain range in the Paleocene epoch and early Eocene epoch, the Klamath mountains to the northwest were also being formed by subduction processes that were occurring between the Pacific plate and the North American plate (Mack 1960). From the early Eocene epoch and continuing on throughout the Miocene epoch, older Cascade volcanism of the Western Cascade series was forming the mountains northeast of the Sacramento Valley (Mack 1960).

During the late Paleogene period, the tectonic regime began changing from a subduction zone to a transform zone, which is thought to have begun near Baja California, Mexico (Atwater 1970). The transform plate boundary zone includes the Pacific, North American, and Juan de Fuca plates, which forms the Mendocino triple junction. As the triple junction progressed northward over time, the San Andreas fault zone was formed in its wake, becoming the transform plate boundary between the North American and Pacific plates. Throughout the Paleogene period, the transform and subduction processes associated with the plate motion initiated movement on older faults and folds in what is now the western part of the northern Sacramento Valley. These faults, fault systems, and folds include the Sites anticline, the Fruto syncline, the Great Valley fault system, the Stony Creek fault, the Green Valley fault, the Salt Lake fault, the Willows fault system, the Cold Fork and Elder Creek fault zones, the Paskenta fault zones, the Coast Range fault, and the Black Butte fault.

4.3.2. Geologic Formations

The following summary of geologic formation descriptions focus on Paleogene period deposits in the northern Sacramento Valley that are mapped on the geologic cross sections shown on Plates 2 and 3. A geologic map of the northern Sacramento Valley is shown on Plate 1, and a lithologic correlation of geologic map and cross section units is shown in Appendix C.

Lower Princeton Submarine Valley Fill (Tlpvf)

The lower Princeton Submarine Valley fill unconformably overlies the marine rocks of the Great Valley sequence and is Eocene in age. Although there are no surface exposures of the fill, the lower Princeton Submarine Valley fill has been identified in the subsurface from geophysical and lithologic logs of gas exploration wells drilled in the northern Sacramento Valley. The lower Princeton Valley fill is up to approximately 1,500 feet thick in the deepest part of the northern Sacramento Valley (Redwine 1972).

The lower Princeton Submarine Valley fill is composed of interlayered beds of shale and sandstone whose source area is the Sierran province to the east (Redwine 1972). Because sediments were deposited under marine conditions, interstitial water in this formation is saline. The lower Princeton Submarine Valley fill is considered to be the stratigraphic equivalent of the Capay Formation because it “probably shared the same depositional environment and has similar lithologic characteristics” (Redwine 1972).

The lower Princeton Submarine Valley fill was deposited into a submarine valley that was carved by drainage and erosion from the surrounding ancestral mountain ranges. Using gas well logs, Redwine (1972) identified the valley in the subsurface from Red Bluff to the Sutter Buttes along what is generally the present axis of the Sacramento Valley. The eastern and western limits of the lower Princeton Submarine Valley are the present borders of the Sacramento Valley (Redwine 1972). The sediments that filled the lower Princeton Valley are composed of fine grain clays (pelitic) and coarse grain sands that were deposited by turbidity currents during the Eocene, which formed the lower Princeton Submarine Valley fill. The fill is conformably overlain by the Ione Formation or, where the Ione has been removed by erosion, is overlain by upper Princeton Valley fill sediments.

Ione Formation (Ti)

The Eocene age Ione Formation lies conformably on the lower Princeton Submarine Valley fill and unconformably on the deeply weathered surface of the metamorphic and granitic rocks of the Sierra Nevada. The formation is discontinuously exposed on the east side of the Sacramento Valley from near Deer Creek north of Chico to around Friant in the San Joaquin Valley. The Ione Formation extends to the west in the subsurface toward the axis of the northern Sacramento Valley. The Ione Formation has a thickness of around 650 feet near Table Mountain in the Oroville area (Creely 1965).

The Ione Formation is composed of distinctive white to yellowish-white, highly quartzose friable sandstone with claystone and carbonaceous interbeds consisting of minor amounts of lignite and coal. Groundwater occurrence is saline to brackish except locally on the margins of the valley where the formational water has been flushed with newer fresh water. Sediments that were continentally derived contain fresh to brackish water and are poorly to moderately permeable (Olmsted and Davis 1961).

The Ione Formation was deposited by westward-flowing streams coursing off the ancient Sierra Nevada into the adjacent shallow sea as a shoreline deposit (Durrell 1987). Offshore currents sorted sediments of the formation as the ancestral sea became shallower due to an accumulation of lower Princeton Submarine Valley fill sediments. On the eastern side of the valley, nonmarine deltaic conditions characterized the depositional environment; in the south and central portions of the northern

Sacramento Valley, the Ione Formation was most likely deposited under marine deltaic conditions. The Ione Formation is regarded as a good marker bed, separating the lower Princeton Submarine Valley fill from upper Princeton Valley fill (Redwine 1972). Marker beds are characterized as thin, distinctive beds which were deposited over a wide area and over a relatively short depositional time period. The Ione Formation is overlain by the Lovejoy Basalt and the upper Princeton Valley fill.

4.3.3. Geologic Structures

This section describes the Paleogene period geologic structures that are shown on the geologic map (Plate 1) and on the geologic cross sections (Plates 2 and 3).

Sites Anticline and Fruto Syncline

The Sites anticline and Fruto syncline are a set of north-trending folds that are slightly asymmetric with their east-dipping limbs more steeply inclined than their west-dipping limbs suggesting an eastward vergence direction (Moxon 1990). They are a result of east-west compression of Great Valley sequence sediments occurring from 65 Ma to 5 Ma (Chuber 1961; Earth Sciences Associates 1980; William Lettis and Associates 2002). Studies of seismic reflection data by William Lettis and Associates (2002) suggest that the folds are related to activity on a system of segmented blind thrust faults, collectively referred to as the Cenozoic-aged Great Valley fault, that dips west beneath the eastern Coast Ranges. The anticline and syncline have been mapped from the town of Paskenta south to the town of Sites and are most prominently seen west of Wilson Creek and Stone Corral Creek (Earth Sciences Associates 1980).

Coast Range Fault

The Coast Range fault extends along the eastern margin of the Coast Ranges and is the structural contact between the Franciscan assemblage and the ultramafic rocks of the Coast Range ophiolite. The trend of the fault varies from west to north-west on the northern part of the fault, to north-south on the southern portion of the fault (CALFED Bay-Delta Program 1990). Analysis of seismic reflection studies done by William Lettis and Associates (2002) suggests that the Coast Range fault originally formed as an east-dipping fault or fault zone, and that the current trace of the fault has been uplifted, tilted, and folded by Late Cretaceous to Tertiary deformation along the western Sacramento Valley margin. Geomorphic investigations indicate that no movement has occurred on the fault zone since the late Pliocene (Earth Sciences Associates 1980).

Paskenta Fault Zone

The Paskenta fault zone is a northwest-striking fault that trends through the Black Butte Reservoir area (Orland Buttes) north to where it merges with the Stony Creek fault. Geologic mapping by William Lettis and Associates (2002) shows that the Paskenta fault dies out or becomes the Paskenta nose anticline in the Black Butte Reservoir area, and the researchers conclude that it is not connected, or directly related, to the Willows-Corning fault. However, studies and mapping by Harwood and Helley (1987a) link the Paskenta fault to the Willows-Corning fault system as a splay fault off of the Willows fault.

This fault was previously thought to be a left-lateral, strike-slip fault. However, later studies indicate that the Paskenta fault was originally an east-striking, north-dipping normal fault in the subsurface, with a total displacement of more than 5 miles (Jones et al. 1968, 1969; Moxon 1990). The fault was probably active during the Cretaceous and early Tertiary periods; movement ceased by the beginning of Tehama deposition, around 3.3 Ma (Jones et al. 1968, 1969; Moxon 1990). The fault was subsequently rotated to a northwest strike seen in outcrop by uplift and eastward tilting along the western margin of the Sacramento Valley (Moxon 1990; William Lettis and Associates 2002). Based on geomorphic profiles, Earth Sciences Associates (1980) and William Lettis and Associates (2002) concluded that there is no displacement on either the upper surface of the Tehama Formation or the late Pleistocene terraces and have determined that the Paskenta fault is not an active seismic source.

Cold Fork Fault Zone

The Cold Fork fault zone encompasses the region between the Willows fault and the Coast Range thrust as mapped by Harwood and Helley (1987a). The fault zone consists of a series of west-northwest-trending fault segments that were active during the Cretaceous period (Moxon 1990). These fault segments show left-lateral movement and have been determined to be anastomosing detachment (tear) faults. Movement on the faults ranges from about 6 to 60 miles, occurring during the Cretaceous period (Jones and Irwin 1971), with the latest estimate of movement at about 3.4 Ma (Harwood and Helley 1987a).

Elder Creek Fault Zone

The Elder Creek fault zone lies between the Cold Fork fault zone to the north and the Paskenta fault zone to the south (Harwood and Helley 1987a). The fault zone consists of several anastomosing, northwest-to-southeast-trending faults that converge with the Stony Creek fault at the top of the Coast Range ophiolite (Moxon 1990). The fault zone terminates against the Willows fault to the southeast and is believed to be surficially inactive (Harwood and Helley 1987a). The age of movement and tectonic regime is contemporaneous with the Cold Fork and Paskenta fault zones. Cretaceous-age displacement is similar to the Cold Fork fault zone and is also estimated to be between 6 and 60 miles (Jones and Irwin 1971); however, Harwood and Helley (1987a) estimated the latest movement on the fault to be about 3.4 Ma.

Willows Fault

The Willows fault is a steeply dipping, high-angle (greater than 74 degrees), reverse fault with east-side-up movement (Redwine 1972). Evidence of this fault comes from geophysical surveys performed on bore holes during the development of the Willows-Beehive Bend gas field in the 1950s (Redwine 1972). Offset in the Marathon Oil Co., Capital Company No. 1 Well (Township 20 North, Range 02 West, Section 30), shows that displacement on the fault ranges from about 1,600 feet on top of the Cretaceous rocks to about 1,565 feet on top of the Eocene Capay Formation, occurring between 60 and 53 Ma (Redwine 1972; Harwood and Helley 1987a). Evidence of the most recent movement on the fault is at the base of the Tehama Formation, where a small offset is inferred (Redwine 1972; Harwood and Helley 1987a). The estimated near-vertical slip rate on the Willows fault is 0.00055 inches per year (McPherson and Garven 1999).

The Willows fault progresses roughly north-northwest through the Sacramento Valley, trending from the south end of the valley at the Stockton fault near Stockton and terminating at the north end of the valley west of the Red Bluff fault. Traversing northwestward from the Stockton fault, the Willows fault progresses through the city of Sacramento and bends west-northwest around the Sutter Buttes where it displaces the Colusa dome. It then trends in a north-northwesterly direction through the Willows area where it again bends west-northwest. The Willows fault terminates at the north end of the Sacramento Valley in the Red Bank area west of Red Bluff. Notable splays off of the Willows fault include the Corning fault, the Paskenta fault zone, Black Butte Fault segment, the Elder Creek fault, and the Cold Fork fault (Jennings and Strand 1960; Harwood and Helley 1987a).

Great Valley Fault System

The Great Valley fault system is a regional system of structurally segmented, blind west-dipping thrust faults that are inferred to underlie the western boundary of the Central Valley (Working Group on California Earthquake Potential 1996). Based on seismic profiles, segmented portions of the Great Valley fault system underlie the region of the eastern Coast Ranges and valley floor boundary in the northwestern Sacramento Valley (William Lettis and Associates 2002).

In the northern Sacramento Valley, dip on the Great Valley fault segments steepens northward, ranging from shallow-dipping fault segments in the Sites area to steeper-dipping fault segments in the Orland area. These thrust-faulted segments along the western valley margin are inferred as the mechanisms for movement on the geologic structures encountered on the west side of the Sacramento Valley (William Lettis and Associates 2002). Examples of topographic expression of the movement along these fault segments are the Sites anticline, the Fruto syncline, and the prominent north-trending strike ridges of folded Cretaceous rocks on the western side of the valley, shown in Figure 4.

Stony Creek Fault

The Stony Creek fault is the structural contact between the Great Valley sequence and the Coast Range ophiolite (William Lettis and Associates 2002). The trace of the Stony Creek fault approximately follows the break in slope at the base of the Coast Ranges mountain front, extending from the Paskenta area to the vicinity southwest of Williams. The fault lies east of the Coast Range thrust fault, truncating it in several places (Earth Sciences Associates 1980). The Stony Creek fault is a high-angle fault showing evidence of both normal and reverse motion locally, with west-side-up movement (Earth Sciences Associates 1980). Movement on the fault is thought to have occurred between the Cretaceous period and the Pliocene epoch (Earth Sciences Associates 1980; William Lettis and Associates 2002). Based on these studies, it was concluded that the Stony Creek fault is not an active seismic source.

Green Valley Fault

The Green Valley fault is an east-dipping, primarily bedding-parallel thrust fault (William Lettis and Associates 2002). Air photo analysis and aerial and field reconnaissance conducted by William Lettis and Associates (2002) show that the fault has “no significant geomorphic expression and is locally overlain by undeformed late Quaternary geomorphic surfaces, colluvium, and fluvial deposits.” The study also reports that the Green Valley fault splays upward from the Stony Creek fault at depth, dying out in the lower Great Valley sequence deposits, and is not an “independent seismic source.”

Salt Lake Fault

The Salt Lake fault is a north-trending thrust fault extending about 12 miles from the South Fork of Willow Creek to around Stone Corral Creek, west of the town of Sites (William Lettis and Associates 2002). The Salt Lake fault has been mapped as paralleling the Sites anticline and the Fruto syncline to the west (Brown and Rich 1961; William Lettis and Associates 2002). In a study conducted by William Lettis and Associates (2002) for the DWR Sites-Colusa Reservoir dam site investigation titled “North-of-the-Delta Off-Stream Storage Investigation” (NODOS), data indicated that the Salt Lake fault is a right-lateral, east-dipping fault that is parallel to Great Valley sequence bedding. The Salt Lake fault is “visible on aerial photographs as a series of discontinuous topographic features, springs, and vegetation lineaments that coincide with truncated and locally folded strata of the Great Valley Group” (William Lettis and Associates 2002).

Results from trenching during the above-mentioned study reveal that the Salt Lake fault is a narrow zone about 1 to 2 feet wide and has an offset of about 500 feet. Trench logs from the study also indicate that offset occurred in late Pleistocene gravels around 30,000 to 70,000 years ago, and based on soil development profiles, the latest offset may have occurred during the early Holocene, 8,000 to 12,000 years ago. According to DWR’s Division of Safety of Dams (DSOD) guidelines (Fraser 2001), the Salt Lake fault is considered to be an active fault.

Black Butte Fault

The Black Butte fault has been mapped by Jennings and Strand (1960) as an unnamed northwest-trending fault passing on the west side of the Orland Buttes; it has been mapped by Helley and Harwood (1985) as part of the northwest-trending Willows fault. In both studies, the fault trends between Black Butte Reservoir and the upthrown block of the Orland Buttes, which is composed of the Lovejoy Basalt.

Russell (1931) identified the presence of a fault after a geologic investigation of the area revealed that rocks of the Cretaceous age Great Valley sequence, the Miocene age Lovejoy Basalt, and the Pliocene age Tehama Formation were exposed at the surface in and around the Orland Buttes (referred to as the Stony Creek Buttes in Russell's study). He measured the dip angle of the exposed Lovejoy Basalt (5 degrees east) and the Great Valley sequence (50 degrees to 55 degrees northeast) and projected the depth of the beds into the subsurface to intersect with core samples taken at depth from a bore hole drilled by the Orland Oil Syndicate. The well, known as the Johnson No. 1 Well, is located about 3 miles east of the northern part of the Orland Buttes. After analysis of the projected bed depths and a mineral analysis of surface and core samples of the Lovejoy Basalt, Russell concluded that sediments encountered at depth were brought to the surface by faulting.

However, studies of seismic reflection data and a review of previous work by William Lettis and Associates (2002) for the NODOS investigation suggest that there is not "compelling evidence for the presence of a fault along the base of the western Orland Buttes escarpment." The authors state that "the presence of the Orland Buttes can be entirely explained by eastward tilting in the hanging wall of a blind, west-dipping thrust fault." They concluded that, "if present, the Black Butte fault is a shallow, bedding-parallel fault, and thus is not an active, independent seismic source."

4.4. Cenozoic Era — Neogene Period

4.4.1. Geologic Setting

During the early Neogene period, the marine regression that started during the Oligocene epoch continued into the early Miocene epoch. Subaerial exposure and erosion of the surface topography enabled stream courses draining the adjacent mountain ranges to cut increasingly deep channels in the exposed Ione Formation. It was through these channels that the Lovejoy Basalt lava flowed across the valley floor from its volcanic source located in the northeastern mountains near the Honey Lake escarpment (Roberts 1985; Wagner and Saucedo 1990). The basalt flowed as far west as the Orland Buttes near Orland and as far south as Putnam Peak near Vacaville.

A minor eastward marine transgression occurred around the mid-Miocene with a corresponding depositional phase of mixed marine and continental sediments that compose the Sutter Formation and the upper Princeton Valley fill. A westward marine regression began in the Pliocene epoch and continental sediments were for the most part being deposited concurrently in the northern Sacramento Valley. These continental sediments compose the major fresh groundwater-bearing formations in the valley: the Tehama, Tuscan, and Laguna formations. The base of these continentally derived formations is considered to be significant as the generally accepted base of fresh water in the northern Sacramento

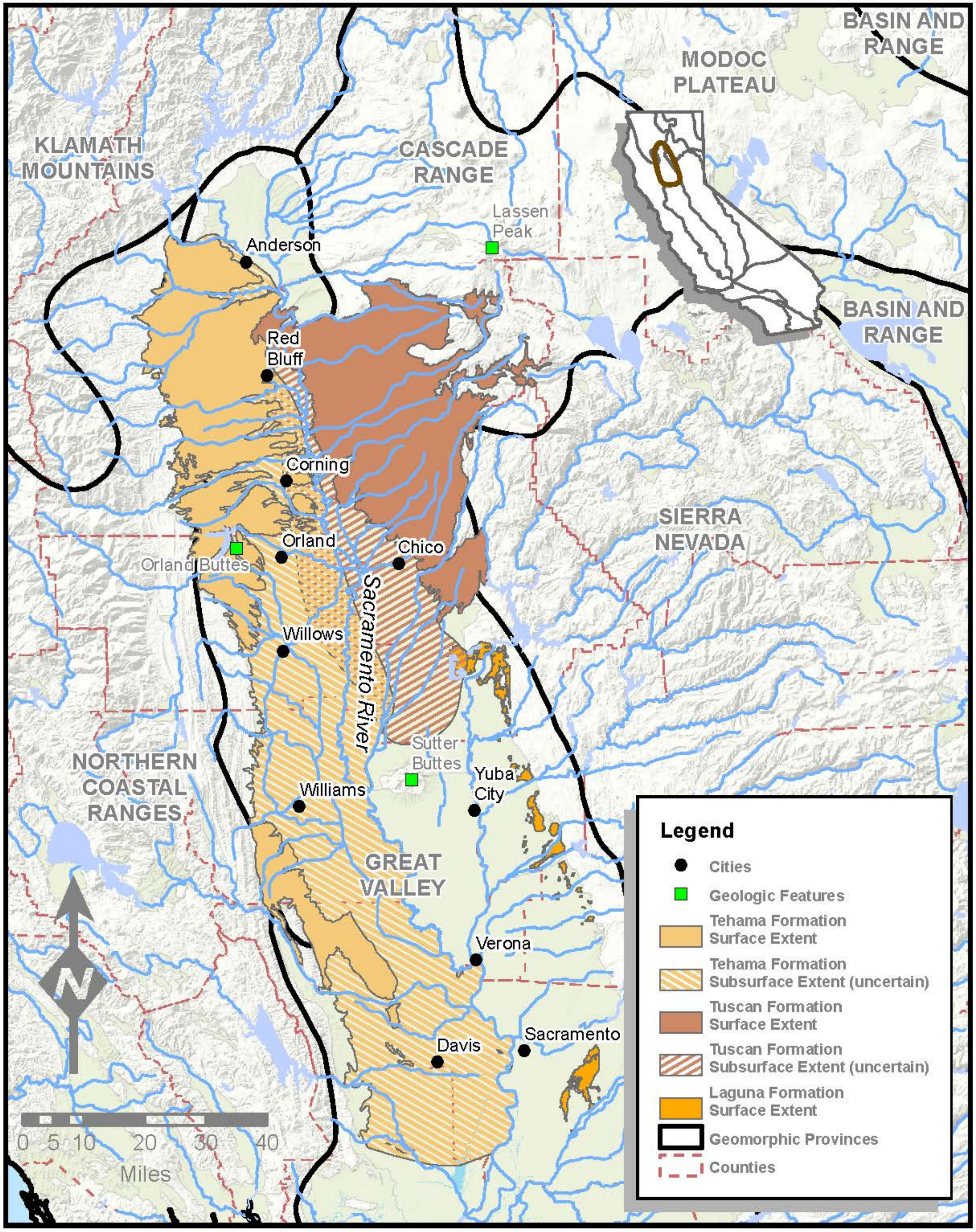
Valley (Berkstresser 1973). In addition, at or near the base of all three units lies the Nomlaki Tuff, which is a widespread, thin volcanic ash layer that provides an important stratigraphic marker, suggesting that the Tehama, Tuscan, and Laguna formations were deposited contemporaneously (Helley and Harwood 1985). Figure 5 shows the approximate surface and subsurface extent of the Pliocene Tehama and Tuscan formations, and the surface extent only of the Laguna Formation.

The tectonic regime between the Pacific and North American plates during the Neogene period was continuing to morph from a subduction zone to a transform plate boundary zone along the San Andreas fault system. The compressive stresses from the convergence between the two plates relaxed as the Mendocino triple junction migrated northward, causing extension between the plates. The movement of these plates, creating north-south compression and east-west extension, is the mechanism for the geologic structures seen regionally and in the northern Sacramento Valley today. Evidence from the resulting Basin and Range extension shows a general north-south trend of the mountains and valleys occurring regionally from eastern California to western Wyoming. It is also one of the mechanisms for the uplift of the current Sierra Nevada mountain range and Coast Ranges that began in the Pliocene epoch.

By the late Miocene epoch, the Mendocino triple junction had progressed as far north as the general latitude somewhere between central California and the San Francisco area (Harwood and Helley 1987a). In the early Pliocene epoch, the triple junction had migrated north to around the general latitude projecting westward from the area north of Sacramento, and by the late Pliocene epoch the Mendocino triple junction had progressed to about the same latitude as the Sutter Buttes.

Northward movement and the position of the Mendocino triple junction have been correlated with the emergence of geologic structures in the northern Sacramento Valley (Atwater 1970; Harwood and Helley 1987a). On the eastern side of the valley, movement of the triple junction initiated the formation of the Foothills fault system, the Cohasset Ridge fault, the Magalia fault, and the Chico monocline flexure. In the central part of the valley, the triple junction activated structural movement on the Corning fault and the Red Bluff fault, and initiated the formation of the Corning domes, the Los Molinos syncline, the Glenn syncline, the Greenwood anticline, and an associated unnamed syncline located west of the Greenwood anticline.

Figure 5. Approximate Surface and Subsurface Extent of the Tehama and Tuscan Formations, and Surface Extent Only of the Laguna Formation



(Figure source: California Department of Conservation, Division of Mines and Geology. 1960-1962. "Geologic Map of California." [Redding, Ukiah, Westwood, and Chico sheets].)

4.4.2. Geologic Formations

The following summary of geologic formation descriptions focuses on Neogene Period sediments in the northern Sacramento Valley that are mapped on the geologic cross sections shown on Plates 2 and 3. A geologic map of the northern Sacramento Valley is shown on Plate 1, and a lithologic correlation of geologic map and cross section units is shown in Appendix C.

Lovejoy Basalt (Tl)

The Miocene-age Lovejoy Basalt unconformably overlies the Ione Formation on the east side of the valley and the Great Valley sequence on the west side of the valley. The Lovejoy Basalt originated from the area around the Honey Lake escarpment in the Cascade Range near Susanville. During the Miocene epoch, basalt erupted from fissures in the Earth’s surface and flowed westward along ancient stream channels and areas of low relief, crossing the valley floor (Helley and Harwood 1985). The basalt is widespread but discontinuous in the subsurface of the northern Sacramento Valley. Notable outcrops of the Lovejoy Basalt are seen at Table Mountain near Oroville (Figure 6), at the Orland Buttes near Orland (Figure 7), at Putnam Peak near Vacaville (Figure 8), and in Little Chico Creek and Big Chico Creek near Chico.

The Lovejoy Basalt is composed of microcrystalline, porphyritic, highly fractured, dense olivine basalt that is important as a stratigraphic marker unit (Helley and Harwood 1985). Groundwater occurrence, if present, would be supplied through the secondary porosity of this dense but fractured basalt. The Lovejoy Basalt is unconformably overlain by the upper Princeton Valley fill, the Tehama Formation, and the Tuscan Formation.

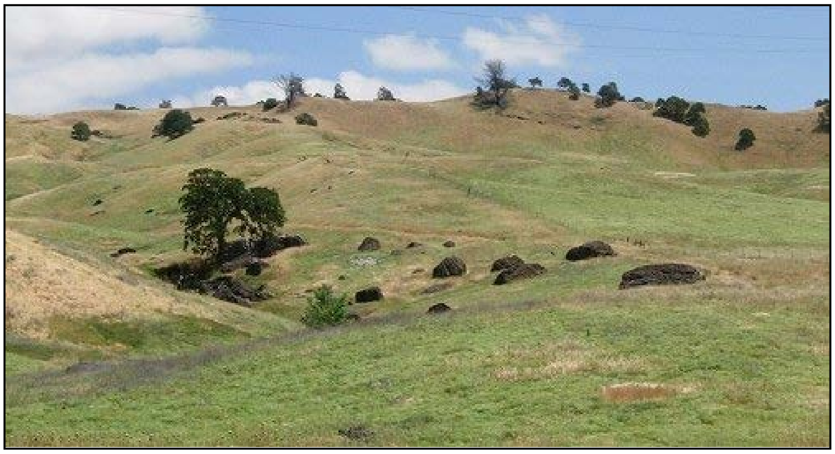
Figure 6. The Lovejoy Basalt Overlying the Ione Formation at Table Mountain near Oroville

(Photo credit: Jon Mulder)

Figure 7. The Lovejoy Basalt, Orland Buttes near Orland

(Photo credit: Kelly Staton)

Figure 8. The Lovejoy Basalt, Putnam Peak near Vacaville



(Photo credit: Andrew Alden, KQED Science)

Upper Princeton Valley Fill (Tupvf)

The Miocene-age upper Princeton Valley fill (Tlpvf) unconformably overlies the lower Princeton Submarine Valley fill, the Lovejoy Basalt, and the Ione Formation in various locations. Although there are no outcrops of the upper Princeton Valley fill, it extends in the subsurface throughout the northern Sacramento Valley from Red Bluff to around the Sutter Buttes (Redwine 1972); the upper Princeton Valley fill is up to 1,400 feet thick in places.

The upper Princeton Valley fill is composed mostly of sandstone but also includes frequent interbeds of pelite (mudstone) and occasional conglomerate and conglomeratic sandstone; the basal sandstone beds contain abundant basalt detritus (Redwine 1972). Volcaniclastic and lithic fragments are green, bluish-gray, buff, tan, and light to dark brown in color. The sediments are composed mostly of sandstone containing fresh to brackish interstitial water and were deposited by an ancient river whose laterally migrating and meandering course closely approximates that of the present-day Sacramento River (Redwine 1972). The fill is unconformably overlain by the Tehama, Tuscan, and Laguna formations.

Sutter Formation (Ts)

The Sutter Formation is late Miocene to early Pleistocene in age and unconformably overlies the lower Princeton Submarine Valley fill, the Ione Formation, or the Lovejoy Basalt. The Sutter Formation is exposed near the Sutter Buttes, where it has been deformed by igneous intrusion of the volcanic rocks. The deposits range in thickness from a few hundred feet near the Sierra Nevada foothills on the east side of the valley to a maximum thickness of up to 1,800 feet toward the center of the valley according to Garrison (1962), and up to 1,000 feet according to Williams and Curtis (1977).

The Sutter Formation consists of poorly consolidated to well-consolidated siltstone, sandstone, conglomerate, and shale that are composed of andesitic and rhyolitic sediments whose source area is the Sierra Nevada (Olmsted and Davis 1961; Williams and Curtis 1977). Although the Sutter Formation was considered, by Olmsted and Davis, to be contemporaneous with the Tuscan Formation to the north and the Mehrten Formation to the south, because of their similar volcanic compositions and source areas, recent analysis of tuff deposits within the Sutter Formation indicated that deposition of the Sutter Formation began prior to the deposition of the Tuscan Formation. Several outcrops believed to be representative of the Nomlaki Tuff have been identified within Sutter Formation around the Sutter Buttes. These Nomlaki Tuff deposits occur approximately 600 feet above the base of the Sutter Formation. Because the Nomlaki Tuff is present at or near the base of the Tuscan Formation, the location of the Nomlaki Tuff well above the base of Sutter Formation indicates that significant deposition of the Sutter Formation occurred prior to the beginning of Tuscan Formation deposition (Springhorn 2007). Groundwater in this formation ranges from brackish to fresh.

Prior to the development of the Sutter Buttes, the Sutter Formation was deposited in deltaic fans and on broad floodplains from the late Miocene epoch through the early Pleistocene epoch (Garrison 1962). Sediments were carried down by rivers from the Sierra Nevada and deposited in deltaic fans and on broad floodplains (Garrison 1962; Williams and Curtis 1977). The Sutter Formation is unconformably overlain by the Laguna Formation in the southeast portion of the northern Sacramento Valley and by the Pleistocene age Sutter Buttes ramparts.

Nomlaki Tuff (Ttn)

The Pliocene age Nomlaki Tuff lies discontinuously at or near the base of the Tehama, Tuscan, and Laguna formations. The occurrence of the tuff at the base of both the Tehama and Tuscan Formations was identified by Russell and VanderHoof (1931), suggesting these units must be in part contemporaneous. The age of the tuff has been identified by potassium-argon (K-Ar) dating as being around 3.4 Ma (Helley and Harwood 1985). It extends throughout the northern Sacramento Valley and is exposed at several locations such as at Tuscan Springs, Gas Point, Antelope Creek, and Richardson Springs; the maximum thickness of the tuff is about 80 feet at Tuscan Springs.

The Nomlaki Tuff is described by Anderson (1933) as “chiefly of white pumice fragments imbedded in a pink, gray, or white matrix of glass and crystal shards. The crystal shards consist of basic oligoclase, hypersthene, and green and brown hornblende.” Helley and Harwood (1985) described the tuff as a white, light gray to reddish-tan dacitic pumice tuff and pumice lapilli tuff. The source area of the tuff is most likely from ancestral volcanoes Mount Yana and Mount Maidu that were historically located northwest and south of Lassen Peak, in the Cascade Range (Lydon 1968). The Nomlaki Tuff is unconformably overlain by the Tehama, Tuscan, or Laguna formations.

Tehama Formation (Tte)

The Pliocene-age Tehama Formation unconformably overlies the Great Valley sequence, lower Princeton Submarine Valley fill, upper Princeton Valley fill, or Nomlaki Tuff. The Nomlaki Tuff occurs discontinuously at or near the base of the Tehama Formation, where it acts as a marker bed for the overlying Tehama, Tuscan, and Laguna formations. Exposures of the Tehama Formation are seen on the west side of the valley from Redding south to Vacaville. In the subsurface, the metamorphic and sedimentary deposits of the Tehama Formation intermix with the volcanic sediments of the Tuscan Formation (Helley and Harwood 1985). Previous studies inferred that the eastward extent of the intermixed sediments generally occurs in the subsurface west of the Sacramento River. Recent DWR efforts confirm the intermixing of Tehama and Tuscan formation sediments from analysis of lithologic cuttings and geophysical logs. Figure 9 shows photographs of a surface exposure and stream-cut exposure of the Tehama Formation.

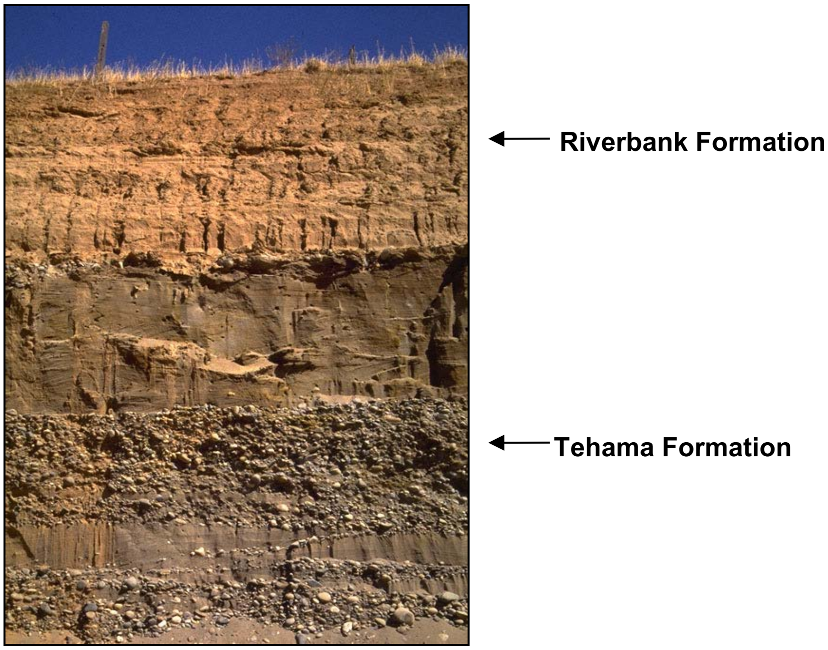
The Tehama Formation is composed of noncontiguous layers of metamorphic pale green, gray, and tan sandstone and siltstone, with lenses of pebble and cobble conglomerate (Helley and Harwood 1985). The source area of the Tehama Formation sediments is the Coast Ranges to the west and, to a lesser extent, the Klamath Mountains to the north. Sediments were deposited by streams flowing from the west under floodplain conditions. These fluvial deposits are characterized by a series of poorly sorted sediments, by channels of coarser sediments in the finer-textured strata, and by the lenticular character of the coarser beds (Russell 1931). The maximum thickness of the Tehama Formation is up to 2,000 feet (Olmsted and Davis 1961).

Groundwater occurs in the heterogeneous gravel and sand layers of the formation, and the base of the Tehama Formation is generally accepted as the base of fresh water (Olmsted and Davis 1961). DWR has corroborated the location of the base of fresh water through analysis of geophysical logs and water quality sampling results obtained from groundwater-level observation wells in the northern Sacramento Valley. In recent DWR work by Springfield and Hightower (2012), the base of fresh water was also found to intersect with the Tehama Formation in places.

The Tehama Formation is unconformably overlain intermittently by the Tuscan Formation toward the center of the valley; or by the Red Bluff, Modesto, or Riverbank formations; or by the Stony Creek fan alluvium in varying locations.

Figure 9. The Tehama Formation in Surface Exposure (above) and Road-Cut Exposure (below); the Riverbank Formation in Road-Cut Exposure (below)

(Photo credit: Larry Snell)



(Photo credit: Kelly Staton)

Tuscan Formation (Tt [undifferentiated], Tta, Ttb, Ttc, Ttd [Plate 1]; Tt [Plates 2 and 3])

The late Pliocene age Tuscan Formation unconformably overlies the upper Princeton Valley fill, Lovejoy Basalt, Late Cretaceous marine sedimentary rocks, or the Sierran basement complex with angular unconformity (Olmsted and Davis 1961). In addition, the Nomlaki Tuff also underlies the formation discontinuously at or near the base of the Tuscan Formation and acts as a marker bed for the overlying Tehama, Tuscan, and Laguna formations (Helley and Harwood 1985).

The formation extends from Redding south to near Oroville, where surface exposures of the Tuscan formation are seen on the east side of the Sacramento Valley. In the subsurface, the volcanic sediments of the Tuscan Formation intermix with the metamorphic sediments of the Tehama Formation (Garrison 1962; Lydon 1968). The westward extent of the intermixed sediments generally occurs in the subsurface west of the Sacramento River. DWR has confirmed the intermixing of Tuscan and Tehama formation sediments from analysis of lithologic cuttings and geophysical logs obtained from groundwater level observation wells that were drilled and installed over the last 15 years. The maximum thickness of the Tuscan Formation ranges from about 1,700 feet in the east to approximately 300 feet at the westward extent (Lydon 1968); however, in this study, the maximum thickness was about 1,500 feet. Figure 10 shows photographs of surface and stream-cut exposures of the Tuscan Formation.

Overall, the Tuscan Formation is composed of a series of volcanic lahars (mudflows) that includes volcanic conglomerate, sandstone, and siltstone, and pumiceous tuff layers that were deposited over a period of about 1 million years (Lydon 1968; Helley and Harwood 1985). The source areas of the lahars were the eroded ancestral volcanoes, Mount Yana and Mount Maidu, that were historically located northwest and south of Lassen Peak in the Cascade Range (Lydon 1968). As the lahars flowed westward off of the ancestral volcanoes and onto the valley floor, they fanned out, causing deposition to vary in thickness and in topographic elevation. Over time, ancient streams and rivers flowed downslope over the lahars, forming channels which were then infilled with reworked volcanic sand and gravel sediments whose pore spaces contain fresh groundwater. Subsequent lahars flowed over and covered the reworked sediments, creating a confining layer over the sand and gravel aquifers.

The Tuscan Formation has been divided into four units, Tta, Ttb, Ttc, and Ttd, by Helley and Harwood (1985). The oldest unit, Tta is composed of interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone that contain minor amounts of metamorphic rocks. Overlying the Tta unit in places is the Ttb unit, which is more widespread throughout the eastern part of the northern Sacramento Valley. It is composed of interbedded lahars, volcanic conglomerate, volcanic sand, volcanic sandstone, and siltstone, but no metamorphic rocks, and shows a more regularly layered sequence (Helley and Harwood 1985). Overlying the Ttb unit is the Ttc unit, which is composed of a series of lahars with some interbedded volcanic conglomerate and sandstone. Unit Ttd overlies Ttc and is composed of predominantly fragmental deposits characterized by large monolithic masses of gray andesite, black obsidian fragments, and pumice in a pumiceous mudstone matrix (Helley and Harwood 1985).

Groundwater occurs in the heterogeneous gravel and sand layers of the formation, and, as with the Tehama Formation, the base of the Tuscan Formation is generally accepted as the base of fresh water (Olmsted and Davis 1961). DWR has corroborated this assertion through analysis of geophysical logs and water quality sampling results obtained from groundwater level observation wells that were drilled, installed, and tested over the past 15 years or so in the northern Sacramento Valley.

The Tuscan Formation is unconformably and intermittently overlain by the youngest deposits of the Tehama Formation toward the center of the valley; or by the Red Bluff, Modesto, or Riverbank formations; or by stream channel and basin deposits in varying locations. In the south part of the valley, the tuff breccia of the Sutter Buttes overlies and possibly interfingers with the Tuscan Formation north of the Sutter Buttes.

Note: The Tuscan Formation is mapped as both an undifferentiated unit (Tt) and as individual units (Tta, Ttb, Ttc, and Ttd) on Plate 1. In the cross sections on Plates 2 and 3 and in the as-built well logs in Appendix A, the Tuscan Formation is mapped collectively as an undifferentiated unit (Tt).

Figure 10. The Tuscan Formation in Surface Exposure (above) and Stream-Cut Exposure (below)

(Photo credit: Debbie Spangler)

(Photo credit: Dan McManus)

Laguna Formation (Tla)

The Pliocene- to Pleistocene-age Laguna Formation unconformably overlies the upper Princeton Valley fill, Late Cretaceous rocks, and Sierran basement rocks in the southeastern part of the northern Sacramento Valley. In addition, the Nomlaki Tuff discontinuously underlies the Laguna

Formation and acts as a marker bed for the overlying Tehama, Tuscan, and Laguna formations (Helley and Harwood 1985). The Laguna Formation extends discontinuously from Oroville south into the San Joaquin Valley; exposures of the formation are of limited extent in the southeastern part of the northern Sacramento Valley. Estimates of formation thickness range from 180 feet (Helley and Harwood 1985) to 1,000 feet (Olmsted and Davis 1961) depending on the location.

The Laguna Formation is a heterogeneous mixture of interbedded alluvial gravel, fine sand, silt, and clay of granitic and metamorphic origin (Olmsted and Davis 1961). Near Oroville, the gravel deposits are of granitic or metamorphic composition and are contained within a silty to sandy matrix; clay is more predominant in the fine-grained sediments south of Oroville. The Laguna Formation was deposited by the ancestral Feather, Yuba, Bear, and American rivers (Helley and Harwood 1985). During the Pliocene and Pleistocene epochs, uplift of the Sierra Nevada increased the erosion of the plutonic and metamorphic rocks on the eastern side of the valley. Rivers and streams carried the eroded material westward to the valley floor, and as the water overtopped the banks, it spread out across the broad floodplains of the valley, depositing the sediments into broad alluvial fans.

As with the Tehama and Tuscan formations, groundwater occurs in the heterogeneous gravel and sand layers of the formation, and the base of the Laguna formation is generally accepted as the base of fresh water (Olmsted and Davis 1961). The Laguna Formation is overlain by the Riverbank Formation, the Modesto Formation, or surficial alluvium.

4.4.3. Geologic Structures

This section describes the Neogene period geologic structures that are shown on the geologic map on Plate 1. Structures that are in the vicinity of the cross-sections are also shown on Plates 2 and 3.

Chico Monocline

The Chico monocline is a northwest-trending, southwest-facing flexure that roughly follows the northeastern boundary of the Sacramento Valley, extending from Chico to Red Bluff. The monocline was formed under an east-west compressive stress regime that steeply thrust up the Sierra Mountains (Helley and Harwood 1985). This late Cenozoic tectonic feature was formed after deposition of the Ishi Tuff member of the Tuscan Formation, about 2.6 Ma, and prior to the Deer Creek olivine basalt eruption, which has been age-dated at 1.08 + 0.16 Ma (Helley and Harwood 1985). North of Chico, the Chico monocline deforms the Tuscan Formation and has a dip of up to 25 degrees where it becomes the eastward alluvial aquifer boundary (California Department of Water Resources 1978). South of Chico, beds have a gentler slope of approximately 2 degrees to 5 degrees, and evidence of the monocline disappears north of Oroville.

Corning Fault

The Corning fault is a north-trending, steeply dipping, east-side-up, reverse fault that has no surface expression; evidence of this fault comes from evaluation of seismic reflection data by Harwood (1984) and by Harwood and Helley (1987a). Seismic profiles indicate that the vertical displacement on the fault increases with depth, suggesting "progressive deformation through time" (Helley and Harwood 1985). The fault dips 74 degrees east, and offset on basement rock is at least 4,900 feet prior to the Late Cretaceous and about 1,000 feet post-Late Cretaceous (Helley and Harwood 1985). Analysis by William Lettis and Associates (2002) provided near-vertical, late Quaternary slip-rate estimates of between 0.0008 and 0.002 inches per year. B.J.O.L. McPherson and G. Garven (1999) estimated the slip rate at approximately 0.0007 inches per year.

The Corning fault began forming between about 1.0 and 2.5 Ma (Blake et al. 1999). Although the fault has no surface expression itself, older gravels of the Pleistocene Red Bluff Formation (0.45 to 1.09 Ma) show deformation by the Corning fault (Helley and Jaworowski 1985; Harwood and Helley 1987a). Based on data analysis, William Lettis and Associates (2002) have concluded that "the Corning fault is an active seismic source." The Corning fault splays northward off of the Willows fault near Willows, following the general trend of the Interstate 5 corridor to its terminus at the convergence of the Red Bluff fault and the Chico monocline, north of Red Bluff.

North and South Corning Domes

Upward and westward movement of the hanging wall of the Corning fault deformed the Tehama and Red Bluff formations (and older formations) into the north-trending Corning domes (Blake et al. 1999). Anticlinal folding produced the North and South Corning domes, whose surface expression can be seen in the Corning area. These domes trend parallel to the Corning fault and the Los Molinos syncline (described in the next section) and were formed under the same tectonic regime and during the same time period (1.0 to 2.5 Ma). Surface expression of the domes influences the flow patterns of Stony Creek and Thomes Creek. Stony Creek flows southeast of the domes, with regional flow, to the confluence of the Sacramento River, whereas Thomes Creek flows northeast of the domes, against regional flow, to the Sacramento River (Blake et al. 1999).

Los Molinos Syncline and Glenn Syncline

The Los Molinos syncline and the Glenn syncline were formed due to the same east-west compression regime that also formed the Corning fault, the Corning domes, and the Chico monocline; they have an age about of 1.0 to 2.5 Ma (Blake et al. 1999). The synclines lie between the Corning fault and the Chico monocline, forming "a north-northwest trending trough that locally controls the position of the Sacramento River" (Blake et al. 1999). The Sacramento River follows the axis of the Los Molinos syncline for about 8 miles, from south of Red Bluff to Los Molinos. The river then follows the Glenn syncline for about 18 miles, from north of Hamilton City to the town of Glenn, where the Glenn syncline dies out.

Greenwood Anticline and Unnamed Syncline

The Greenwood anticline and an unnamed syncline just west of the Greenwood anticline have been mapped near Artois, midway between Willows and Orland by Harwood and Helley (1987a). The axis of the Greenwood anticline is flexed along the change in strike near the Willows fault and Corning fault splay (William Lettis and Associates 2002). These two structures roughly trend in a northwesterly direction and were formed during the same time period, and under the same east-west tectonic stress regime, as the above-mentioned Corning fault-related structures.

Foothills Fault System

The Pliocene- to Holocene-age Foothills fault system is a group of northwest-trending, steeply east-dipping to vertical faults that trend along strike in the western foothills of the Sierra Nevada between Folsom and Cohasset. The Cohasset Ridge fault, the Magalia fault, and the Cleveland Hills fault are part of the Foothills fault system. The Cleveland Hills fault is a younger structure that branches off of the Foothills fault system and is described in the next section, 4.5, “Cenozoic Era — Quaternary Period.” The Foothills fault system is classified under the Alquist-Priolo Earthquake Fault Zoning Act of 1972 as seismically active. The Foothills faults are normal faults that have dip angles of about 75 degrees with an easterly dip direction and have slip rates of about 0.02+/-0.015 inches per year (California Department of Conservation, Division of Mines and Geology, 1996).

Cohasset Ridge Fault

The Cohasset Ridge fault is the northernmost extension of the Foothills fault system, which extends from Butte County northward into Tehama County, roughly paralleling the Chico monocline. The Cohasset Ridge fault can be traced north of Deer Creek and through an intensely fractured zone in the Tuscan Formation to the vicinity of Mill Creek, where it becomes obscured by a complex pattern of west- and northwest-trending arcuate faults (Harwood and Helley 1987a). This northwest-trending fault is a steeply east-dipping to vertical fault that has experienced up to 100 feet of movement in the past 2.4 Ma (Helley and Harwood 1985).

Magalia Fault

The Magalia fault trends north 20 degrees west and intersects the Cohasset Ridge fault about 6 miles north of Magalia (Helley and Harwood 1985). Helley and Harwood (1985) determined that the fault is “actually a complex fault zone consisting of numerous fault strands that have different orientations and amounts of displacement.” Evidence from mining records shows that the zone has experienced periodic movement with both normal east-side-down and reverse east-side-up displacement recorded (Helley and Harwood 1985). Helley and Harwood (1985) also determined that the latest movement appears to postdate movement on the Cohasset Ridge fault.

Red Bluff Fault

The Red Bluff fault strikes roughly north 60 degrees east, passes diagonally in the subsurface beneath the city of Red Bluff, and trends southwest for approximately 15 miles. Surface expression is absent southwest of Red Bluff; however, northeast of the city, the extended trend of the Red Bluff fault traverses into the Seven Mile, Tuscan Springs, and Salt Creek domes. The Red Bluff fault is a normal, south-dipping fault, which appears to have late Cenozoic displacement, which offsets the base of the Pliocene rocks by folding or faulting of about 500 feet (Blake et al. 1999). It has not been classified as an active seismic source by the California Department of Conservation, Division of Mines and Geology (1996).

4.5. Cenozoic Era — Quaternary Period

4.5.1. Geologic Setting

During the Quaternary period, the marine regression that began in the Pliocene epoch continued throughout the Pleistocene and Holocene epochs, with the Pacific shoreline retreating farther westward to its current location. Active processes of the High Cascade Series volcanism, Basin and Range extension, and uplift of Sierra Nevada and northern Coast Ranges to their present elevations continued throughout the Quaternary and are still active processes today.

Continuing erosion of the mountains surrounding the northern Sacramento Valley has provided Quaternary alluvial sediments for the fluvial deposition of the Red Bluff, Riverbank, and Modesto formations; the Stony Creek fan alluvium; basin and stream channel deposits; and surficial alluvium. These sediments were laid down as alluvial fans or as terrace and overbank deposits along streams and rivers draining the adjacent mountains.

Throughout the Quaternary period, the Mendocino triple junction has continued its northward migration to its present position off the Pacific coast at Cape Mendocino, causing geologic structural deformation in the northern Sacramento Valley. As the triple junction reached its current position at Cape Mendocino, approximately the same latitude as the city of Red Bluff, younger Pleistocene structures, such as the Inks Creek fold system and the Hooker, Seven Mile, Tuscan Springs, and Salt Creek domes, were emerging. In addition, formation of the Battle Creek fault zone, uplift of the Red Bluff arch, and development of the Red Bluff Formation’s pediment surface began taking place during this time (Helley and Harwood 1985). In the southern part of the valley, development of the Sutter Buttes and the buried Colusa dome was also occurring (Hausback and Nilsen 1999).

Movement on the Foothills fault system, Cohasset Ridge fault, and Magalia fault that began in the Pliocene epoch continued into the Pleistocene and initiated new movement along the Cleveland Hills faults. In addition, movement also continued on the Red Bluff and Corning faults, along with the continuing formation of the Corning domes, the Los Molinos syncline, the Glenn syncline, the Greenwood anticline and the unnamed syncline, and the Chico Monocline flexure.

4.5.2. Geologic Formations

The following summary of geologic formation descriptions focuses on Quaternary Period deposits in the northern Sacramento Valley that are mapped on the geologic cross sections shown on Plates 2 and 3. A geologic map of the northern Sacramento Valley is shown on Plate 1, and a lithologic correlation of geologic map and cross section units is shown in Appendix C.

Note: The Red Bluff Formation (Qrb), upper and lower Riverbank Formation (Qru and Qrl), upper and lower Modesto Formation (Qmu and Qml), Stony Creek fan alluvium (Qscf), basin deposits (Qb), and surficial alluvium (Qa) are mapped as individual units on the geologic map (Plate 1) and are mapped collectively as Quaternary alluvium (Qa) on the cross sections (Plates 2 and 3). It was necessary to map the younger geologic units together because of their relatively small thickness which made them unable to be clearly depicted individually at the scale used on the cross section diagrams.

Tuff Breccia of the Sutter Buttes (QTm [Plate 1]; included in Qa [Plates 2 and 3])

The tuff breccia of the Sutter Buttes is Pleistocene in age and overlies, and possibly interfingers with, the Tuscan Formation north of the buttes. Outcrops of the breccia are exposed locally, forming the gently sloping inclines surrounding the Sutter Buttes. The thickness of the breccia varies, averaging from about 250 feet to 500 feet, and it thins toward the margins of the buttes (Williams and Curtis 1977).

The tuff breccia is equivalent to the middle unit of the rampart beds of the Sutter Buttes as described by Williams and Curtis (1977). The rampart beds consist of three units: the lower, middle, and upper units. The lower unit, or basal member, consists of pale, fine-grained fluvial volcanic sediments derived from airfall deposits. The upper unit is composed of coarse andesitic debris laid down by lahars. The middle unit, or tuff breccia, is the major and most widespread of the three units. It consists of andesitic lithic debris derived from steam blast eruptions of the Sutter Buttes and includes lenses of coarse laharic material carrying blocks of andesite and rhyolite (Williams and Curtis 1977). The tuff breccia is overlain in places by the Riverbank or Modesto formations.

Red Bluff Formation (Qrb [Plate 1]; included in Qa [Plates 2 and 3])

The Pleistocene Red Bluff Formation unconformably overlies the Tehama and Tuscan formations and extends discontinuously from the Redding area southward to the vicinity of Cache Creek (Russell 1931; Olmsted and Davis 1961). The Red Bluff Formation is composed of highly weathered, bright-red, sandy gravels that lie on a mildly deformed pediment surface that formed from 0.45 to 1.08 Ma (Helley and Harwood 1985; Helley and Jaworowski 1985). Deposits of the formation were laid down under floodplain conditions and are relatively thin, with thickness ranging from 3 to 33 feet. Fresh groundwater occurs in the shallow gravel and sand deposits under perched conditions, which indicates an aquifer that occurs above the regional water table (Olmsted and Davis 1961).

The source areas for Red Bluff sediments on the west side of the valley are the metamorphic deposits of the Coast Ranges and Klamath Mountains. Sediments deposited on the east side of the valley were derived from the volcanic sediments of the Tuscan Formation and lava flows (Blake et al. 1999). The formation is overlain unconformably by alluvial fan deposits of late Pleistocene and Holocene age, such as the Riverbank and Modesto formations.

Riverbank Formation (Qrl and Qru [Plate 1]; included in Qa [Plates 2 and 3])

The Pleistocene-age Riverbank Formation unconformably overlies the Tehama Formation in the western portion of the northern Sacramento Valley and the Tuscan, Laguna, and Red Bluff formations in the eastern part of the valley. The Riverbank Formation consists of weathered gravel, sand, and silt that were deposited between 0.13 Ma and 0.45 Ma (Marchand and Allwardt 1981). The formation is exposed throughout the Sacramento Valley and the San Joaquin Valley, extending discontinuously from Redding south to Merced (Marchand and Allwardt 1981). The thickness of the Riverbank Formation ranges from less than 1 foot to more than 200 feet, depending on the location (Helley and Harwood 1985).

The Riverbank Formation is composed of a lower member and an upper member that are distinguished by their stratigraphic position. The lower member occupies the higher position in stream cut terraces and consists of red semi-consolidated gravel, sand, and silt (Helley and Harwood 1985). Conversely, the upper member forms the lower terrace deposits and consists of unconsolidated but compact, dark-brown to red alluvium containing gravel, sand, silt, and with minor clay (Helley and Harwood 1985). The terraces were formed by streams carrying eroded material from the surrounding mountain ranges to the base of the foothills, where they were deposited in wide alluvial fans and terrace deposits. Terrace deposits of the Riverbank Formation appear in stream cuts that are topographically above the younger Modesto Formation terrace deposits. Groundwater generally occurs under unconfined conditions. The Riverbank Formation is overlain by the Modesto Formation, basin deposits, or surficial alluvium.

Modesto Formation (Qml and Qmu [Plate 1]; included in Qa [Plates 2 and 3])

The Modesto Formation is Pleistocene in age and overlies the Riverbank Formation or the Tehama Formation in the western portion of the Sacramento Valley, and the Riverbank Formation or Tuscan Formation in the eastern part of the valley. The sediments were deposited in a manner similar to those of the Riverbank Formation but mark a more recent period of erosion and deposition, from 0.14 to 0.42 Ma (Marchand and Allwardt 1981). The Modesto Formation is widespread throughout the Sacramento Valley, occurring from Redding south into the San Joaquin Valley. The most notable occurrences are found along the Sacramento and Feather rivers and their tributaries. The Modesto Formation ranges in thickness from less than 10 feet in many of the stream terraces and along the margins of the valley to nearly 200 feet across the valley floor (Helley and Harwood 1985).

The Modesto Formation is composed of a lower member (older) and an upper member (younger). The lower member forms terraces that are topographically higher than the upper member (Helley and Harwood 1985). The lower member consists of unconsolidated, slightly weathered gravel, sand, silt, and clay. The upper member forms terraces that sit topographically lower and consists of unconsolidated, unweathered gravel, sand, silt, and clay. Together, both members of the Modesto Formation consist of tan and light-gray gravelly sand, silt, and clay except where they overlie the Tuscan Formation; in these areas the clasts within the formation are distinctly red, brown, or black (Helley and Harwood 1985). The Modesto sediments were deposited by streams that still exist today, and they are seen in the terrace and alluvial fan sediments that border present-day streams (Helley and Harwood 1985). The source area for the formation sediments are the surrounding Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada. Fresh groundwater occurs under unconfined conditions.

Stony Creek Fan Alluvium (Qscf, included in Qa [Plates 2 and 3])

The late Pleistocene- to Holocene-age Stony Creek Fan alluvium overlies the Tehama Formation and is exposed locally at the surface. The alluvial fan extends from around the Glenn-Tehama county line southward about 15 miles and from the Orland Buttes eastward to the Sacramento River. The alluvium's average thickness is around 50 to 80 feet, and it ranges up to around 120 feet in thickness.

The Stony Creek Fan alluvium is composed of rounded to sub-angular gravel and sand, with interbedded clay and silt layers and lenses of metamorphic and sedimentary origin. The Stony Creek Fan is a broad alluvial fan whose sediments were deposited by the floodwaters of Stony Creek, which flows westward from the Coast Ranges to its confluence with the Sacramento River (Olmsted and Davis 1961). The Stony Creek fan alluvium includes lenses of highly permeable gravel and sand that provide fresh groundwater to wells. Although the Stony Creek fan alluvium is specific to the area surrounding Stony Creek, these sediments have been mapped as the Riverbank Formation, the Modesto Formation, or alluvium on various regional geologic maps.

Basin Deposits (Qb [Plate 1]; included in Qa [Plates 2 and 3])

The Holocene-age basin deposits overlie the alluvial fans and terrace deposits of the Riverbank and Modesto formations. Large exposures of basin deposits are seen in Butte, Glenn, Colusa, and Sutter counties, where they form the highly productive agricultural soils characteristic of these areas. Thickness of the basin deposits varies throughout the Sacramento Valley from less than 10 feet along the valley margins to more than 200 feet in the center of the valley (Helley and Harwood 1985). The basin deposits are composed of fine silts and clays, which were deposited by sediment-laden floodwaters that rose above the natural levees of streams and rivers, overflowing and spreading out across vast low-lying areas. These deposits provide limited quantities of groundwater to shallow wells because of the fine-grained nature of the sediments (Olmsted and Davis 1961).

Surficial Alluvium (Qa [Plate 1]; included in Qa [Plates 2 and 3])

Holocene-age surficial alluvium is the youngest of the geologic units present in the northern Sacramento Valley. The surficial alluvium overlies the Riverbank and Modesto formations and can be up to 30 feet thick (Helley and Harwood 1985). These alluvial deposits occur throughout the northern Sacramento Valley, forming natural levees primarily along rivers and streams. Surficial alluvium consists of unweathered gravel, sand, and silt that has been transported and deposited by present-day streams and rivers that drain the Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada (Helley and Harwood 1985). Because of the limited extent and thickness of the alluvium, it is not considered a significant water-bearing unit.

4.5.3. Geologic Structures

This section describes the Quaternary period geologic structures that are shown in the geologic map on Plate 1. Structures that are in the vicinity of the cross sections are also shown on Plates 2 and 3.

Cleveland Hills Faults

The Cleveland Hills faults are a branch of the Foothills fault system and are located southeast of Oroville. They are a series of en echelon ground cracks that occurred during the 6.1-magnitude Oroville earthquake and subsequent aftershocks in 1975. The north- and northwest-trending surface ruptures and faults are discernible for about 3.4 miles at the ground surface (Helley and Harwood 1985; Jennings and Saucedo 1999). Trenching done in 1975 revealed that in most cases, there was faulting in the bedrock below the surface ruptures (California Department of Water Resources 1979).

Sutter Buttes

The Sutter Buttes are the eroded remnants of a single volcano that erupted during the early Pleistocene, less than 2 million years ago (Hausback and Nilsen 1999). The buttes are located about 9 miles east of Colusa in the southernmost portion of the northern Sacramento Valley. They are a small-scale volcanic mountain range formed by piercement intrusions and extrusions of rhyolite and andesite that disrupted and buckled older valley sediments upward. Harwood and Helley (1987a) suggest that deformation occurred in an east-west compressive stress field due to the orientation of faults and fractures found throughout the Sutter Buttes area.

According to Williams and Curtis (1977), volcanism and deformation occurred in two phases. During the early phase of magma injection, Late Cretaceous, and Paleogene and Neogene rocks were arched into a dome about 8 miles across, fractured by normal and high-angle reverse faults, and then quickly eroded before the explosive phase of volcanism occurred (Harwood and Helley 1987a). Later, beds of tuff and tuff breccia forming the outer deposits of the Sutter Buttes were produced by the explosive volcanism phase (Harwood and Helley 1987a).

Areas of the Sutter Buttes corresponding to sedimentary and structural features were given the names "Rampart," "Moat," "Castellated Core," and "Central Lake Beds" by Williams and Curtis (1977). The outer ring of deposits, called the Ramparts, consists of fluvial volcanic sediments that form the gently sloping inclines surrounding the Sutter Buttes. The inner ring, called the Moat, forms a periphery surrounding the volcanic core, consisting of previously deposited Upper Cretaceous, Eocene, and Miocene to Pliocene strata that were upwarped, folded, and faulted by rhyolitic and andesitic intrusions (Hausback and Nilsen 1999). The Castellated Core is a cluster of Pelean, or spiny, domes, the most notable of which are the North Butte at an elevation of 1,863 feet above mean sea level (amsl) and the South Butte at 2,132 feet amsl (Williams and Curtis 1977). The Central Lake Beds are a small, oval-shaped deposit of lacustrine beds that were deposited in a deep crater lake during an explosive phase of volcanism and have since been intruded and deformed by the surrounding andesite domes (Hausback and Nilsen 1999).

Previous reports of potassium-argon (K-Ar) dating of volcanic activity range from 2.4 to 1.4 Ma (Williams and Curtis 1977). However, later reports of argon 40/argon 39 (Ar40/Ar39) dating indicate that volcanism began about 1.59 Ma (Hausback and Nilsen 1999). Preliminary Ar40/Ar39 dating from the core of the Sutter Buttes reveals the youngest age of magmatic activity to be from 1.56 Ma to 1.36 Ma, indicating that magmatism most likely occurred over a period of between 30,000 and 230,000 years during the early Pleistocene epoch (Hausback and Nilsen 1999).

The origin of the Sutter Buttes remains unanswered; the age and composition of eruptions correspond to eruptions of the Clear Lake volcanoes in the Coast Ranges 50 miles to the west. However, they also correspond to eruptions of the southernmost volcanoes of the Cascade Range 90 miles to the east and north (Hausback and Nilsen 1999). Hausback and Nilsen (1999) also state that the Sutter Buttes magmatism coincides with a time of tectonic transition, which suggests that the Sutter Buttes may have formed in response to newer tectonic conditions, such as the northward movement of the Mendocino triple junction.

Colusa Dome

The Colusa dome is a subsurface feature that has been identified on geophysical logs of wells that were drilled for the natural gas industry. The dome is found at depth about 4 miles west of the Sutter Buttes and is a large, oval-shaped uplift measuring about 12 miles north to south and about 3 to 4 miles east to west (Williams and Curtis 1977). The vertical axis or arch of the dome is more than 1,500 feet (Williams and Curtis 1977). Williams and Curtis (1977) state that uplift of the Cretaceous sedimentary beds was caused by viscous bodies of magma rising and was similar to the cause of uplift of the Sutter Buttes.

However, Harwood and Helley (1987a) analyzed electric logs from oil and gas wells drilled in the area and concluded that the buried Colusa dome was formed partly by east-side-up drag on a high-angle reverse fault, most likely caused by the Willows fault, or a splay off of the Willows fault, and partly by magmatic intrusion that was localized by movement on that fault. In addition, they concluded that the orientation and movement patterns of geologic structures near the Sutter Buttes and the buried Colusa dome suggest that deformation occurred in a regional east-west compressive stress field. The age of the Colusa dome is contemporaneous with the age of the Sutter Buttes, about 1.36 to 1.56 Ma (Hausback and Nilsen 1999).

Battle Creek Fault Zone

The eastward-trending Battle Creek fault zone lies along the boundary between Tehama and Shasta counties. East of the Sacramento River, the fault zone is seen as a prominent south-facing escarpment with normal displacement. West of the river, the Battle Creek fault zone is on strike with the course of Cottonwood Creek and in part structurally controls its direction (Helley and Harwood 1985; Blake et al. 1999). Offset on sediments east of the Sacramento River dates movement on the Battle Creek fault zone as younger than 1.09 Ma, yet channeling of the Rockland ash bed along the fault zone suggests that faulting occurred prior to 0.45 Ma (Harwood and Helley 1987a).

This fault zone has been classified under the Alquist-Priolo Earthquake Fault Zoning Act of 1972, by the California Geological Survey (California Department of Conservation, Division of Mines and Geology 1996). The California Geological Survey states that the Battle Creek fault is a normal fault with a length of about 20 miles, with a dip angle of 75 degrees, a southerly dip direction, and a slip rate of 0.02+/-0.015 inches per year (California Department of Conservation, Division of Mines and Geology 1996).

Inks Creek Fold System and Hooker Dome

The Inks Creek fold system consists of a dome and a southwest-plunging anticline and syncline that structurally control the major bends in the Sacramento River near Jelly’s Ferry and Table Mountain, in Tehama County (Harwood and Helley (1987a). The alignment of the foremost syncline in the fold set passes through Table Mountain and extends northeastward, creating a structural low along which Inks Creek flows. Upper strata of the Tuscan Formation are exposed along the anticlinal fold that parallels Inks Creek to the north (Helley and Harwood 1985). The axial trace of the anticline merges with the trend of the Battle Creek fault zone and dies out along the fault zone to the northeast.

West of the Sacramento River, the Inks Creek fold system is expressed as a broad area of uplift known as the Hooker dome. The Hooker dome is located north of the Red Bluff fault and has a major influence on drainage patterns, especially along Hooker and Blue Tent creeks. The age of deformation of the Inks Creek fold system and the Hooker dome has been correlated by Helley and Harwood (1985) using the age of the Rockland ash bed and deformation of the Riverbank Formation, which provides an age date of 0.45 to 0.4 Ma. The northeast- to southwest-trending anticlinal structure of the Inks Creek fold system is part of the hydrogeologic divide between the Redding and the northern Sacramento Valley groundwater basins.

Seven Mile Dome, Tuscan Springs Dome, and Salt Creek Dome

The Seven Mile, Tuscan Springs, and Salt Creek domes are located southeast of the Inks Creek fold system and north of the Chico monocline. The extended trend of the Red Bluff fault traverses to the northeast folding the Pliocene volcanic rocks of the Tuscan Formation into the Seven Mile, Tuscan Springs, and Salt Creek domes. The deformation creating the domes is thought to have occurred during the same period that produced the Inks Creek fold system and the Battle Creek fault zone, about 0.4 to 0.45 Ma (Harwood and Helley 1987a).

Red Bluff Arch

The Red Bluff Arch is an area of late Cenozoic regional tectonic compression, which generally encompasses the Red Bluff fault; the Inks Creek fold system; and the Seven Mile, Tuscan Springs, Salt Creek, and Hooker Creek domes. These combined east-northeast-trending structures create a barrier to groundwater flow between the northern Sacramento Valley and Redding groundwater basins. Groundwater north of the divide flows into the Redding groundwater basin, while groundwater south of the divide recharges the Sacramento Valley groundwater basin (California Department of Water Resources 1978). Influence of the Red Bluff Arch on surface water drainage patterns is markedly seen as the topographic high of Hooker dome, between Hooker, Pine, Blue Tent, and Cottonwood creeks. In this region, Hooker Creek and Pine Creek flow northward into Cottonwood Creek, whereas Blue Tent Creek and Dibble Creek flow in a southeasterly direction, draining into the Sacramento River.

Section 5. Discussion of Geologic Cross Sections

Six geologic cross sections were constructed to illustrate the subsurface geology of the northern Sacramento Valley. The cross sections are based on stratigraphy and are not an indication of the aquifer system distribution. This section provides general information about the cross sections as well as describes the stratigraphy and the sand provenance petrographic analyses in relation to the geologic formations. Plate 2 shows three cross sections that are oriented in a generally east-west direction (labeled A-A', B-B', and C-C') and one cross section that is oriented in an approximately northeast-southwest direction (D-D'). Plate 3 shows two cross sections that are oriented in a generally north-south direction (E-E' and F-F'). Because cross section F-F' traverses a great distance, it is shown on the plate in two parts, with the southernmost part of the cross section illustrated below the northern part of the cross section. The groundwater observation wells are identified according to the State's well numbering system referred to in Section 2.3.3, which includes the township, range, and section where each well is located.

5.1. Cross Section A-A'

Cross section A-A' is the northernmost east-west cross section and is shown on Plate 2. The western end point of the cross section starts in Township 23 North, Range 04 West, Section 15, near the south fork of Hall Creek; and the eastern end point is in Township 25 North, Range 01 East, Section 30, near the middle fork of Brush Creek. The stratigraphy depicted in this cross section indicates sequential layering of sedimentary geologic formations ranging from the marine Great Valley sequence and lower Princeton Submarine Valley fill to the continental upper Princeton Valley fill and the Tuscan and Tehama formations.

5.1.1. Stratigraphy

The Great Valley sequence is the deepest formation mapped in the subsurface along cross section A-A' and is not exposed at the surface. Both the eastern and western edges of the Great Valley sequence are folded upward, forming a trough. The surface of the Great Valley sequence is further deformed by offset on the Corning and Chico monocline faults, folding that formed the Corning domes, and erosion that formed the lower Princeton Submarine Valley.

Unconformably above the Great Valley sequence lies the lower Princeton Submarine Valley fill. It extends across nearly the entire cross section and is deformed by the same structural features as the Great Valley sequence. The lower Princeton Submarine Valley fill is up to approximately 1,000 feet thick along this section. It is thickest along an approximately 3-mile-wide low area in the surface of the Great Valley sequence that can be seen just to the east of the center of the section. Stratigraphic data from a natural gas exploration well in Township 23 North, Range 04 West, indicates that Lovejoy Basalt is locally present above the lower Princeton Submarine Valley fill, but the total extent of the basalt is unknown.

The upper Princeton Valley fill lies unconformably above the lower Princeton Submarine Valley fill. It extends nearly across the cross section and is deformed by the same structural features as the Great Valley sequence and the lower Princeton Submarine Valley fill. The upper Princeton Valley fill is up to approximately 1,000 feet thick and is thickest in the same area as the thickest portion of the lower Princeton Submarine Valley fill, just east of the center of the section.

The upper Princeton Valley fill is overlain by the Tehama Formation on the west side of the cross section and the Tuscan Formation on the east side. Both the Tehama and Tuscan formations are deformed at their base by the same structural features as the Great Valley sequence, the lower Princeton Submarine Valley fill, and the upper Princeton Valley fill. The Tehama Formation is up to 1,500 feet thick, with the thickest area toward the western end of the cross section. The Tuscan Formation is up to approximately 1,200 feet thick and is thickest east of the center of the cross section. Intermixing and interlayering of the sediments occur near the center of the valley where the two formations intersect.

The Tehama and Tuscan formations are unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.1.2. Sand Provenance Analysis

Lithologic samples from three groundwater observation wells on cross section A-A’ were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 24N03W29Q001M, 24N02W29N003M, and 24N01W04M001M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 4 and presented graphically as pie charts on the cross section at each sample location.

Well 24N03W29Q001M is located on the western portion of the cross section. Results from the sand provenance analysis show that the samples from 260 to 270 feet below ground surface (ft-bgs), 660 to 680 ft-bgs, and 980 to 1,000 ft-bgs are composed primarily of lithic metamorphic and lithic sedimentary constituents that make up the Tehama Formation, which is commonly seen on the west side of the northern Sacramento Valley.

Well 24N02W29N003M is located toward the center of the cross section and is also shown on cross section F-F’. Sand provenance results are mixed at this location; samples from 200 to 220 ft-bgs and 270 to 280 ft-bgs show an almost equal distribution of lithic metamorphic, lithic volcanic, and lithic sedimentary constituents indicating an area of reworked or intermixed sediments (or both) of the

Tehama and Tuscan formations. The sample from 380 to 400 ft-bgs shows a predominance of lithic metamorphic constituents, indicating the west side source area of the Tehama Formation. However, three samples, from 640 to 660 ft-bgs, 740 to 760 ft-bgs, and 890 to 900 ft-bgs, show a predominance of lithic volcanic constituents, indicating the east side source area of the Tuscan Formation. The deepest sample, from 920 to 930 ft-bgs, is a mixture of about two-thirds lithic metamorphic constituents and about one-third lithic volcanic and sedimentary constituents. The metamorphic constituents are characteristic of the Tehama Formation, and the volcanic and sedimentary constituents may indicate mixing with the deeper upper Princeton Valley fill sediments.

Well 24N01W04M001M is located on the eastern portion of the cross section, and results from all samples throughout the interval show that almost 100 percent of the sediments are composed of volcanic constituents, indicating the east side source area of the Tuscan Formation.

Table 4. Sand Provenance Analysis for Cross Section A-A’

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
24N03W29Q001M	260-270	95	3	2	Tehama
	660-680	58	20	22	Tehama
	980-1,000	85	3	12	Tehama
24N02W29N003M	200-220	29	37	34	Tehama/Tuscan/intermixing
	270-280	46	34	20	Tehama/Tuscan/intermixing
	380-400	76	1	23	Tehama
	640-660	1	97	2	Tuscan
	740-760	0	100	0	Tuscan
	890-900	1	99	0	Tuscan
	920-930	70	15	15	Tehama/upper Princeton Valley fill
24N01W04M001M	340-350	4	96	0	Tuscan
	730-740	0	100	0	Tuscan
	920-930	0	100	0	Tuscan

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

5.2. Cross Section B-B’

Cross section B-B’ is located approximately 12 to 18 miles south of cross section A-A’ and is shown on Plate 2. The western end point of the cross section is located in Township 23 North, Range 04 West, Section 15, west of Orland; and the eastern end point is located in Township 25 North, Range 01 East, Section 30, east of Chico. The stratigraphy shown in this cross section indicates sequential layering of sedimentary geologic formations ranging from the marine Great Valley sequence and lower

Princeton Submarine Valley fill to the transitional deltaic Ione Formation and finally to the continental upper Princeton Valley fill and the Tuscan and Tehama formations.

5.2.1. Stratigraphy

The Great Valley sequence is the deepest formation mapped in the subsurface along cross section B-B’ and is not exposed at the surface. Both the eastern and western edges of the Great Valley sequence are folded upward, forming a widely spread trough. The surface of the Great Valley sequence is further deformed by offset on the Corning and Chico monocline faults, folding that formed the Corning domes, and erosion that formed the lower Princeton Submarine Valley.

The Great Valley sequence is overlain unconformably by the lower Princeton Submarine Valley fill. The fill extends eastward from the Corning fault to approximately Highway 99 East and is deformed by the same structural features as the Great Valley sequence. The lower Princeton Submarine Valley is up to 700 feet along this section and is thickest under the Sacramento River.

The Ione Formation unconformably overlies the lower Princeton Submarine Valley fill on the east side of the cross section. It is seen in outcrop east of the cross section and extends westward into the subsurface of the valley. The Ione Formation is deformed by offset on the Chico monocline fault and the Glenn syncline and is up to 400 feet thick in this location.

The Lovejoy Basalt lies unconformably on the Ione formation; evidence of this is seen in stratigraphic and geophysical data from a natural gas exploration well in Township 22 North, Range 01 East. The thickness of the Lovejoy Basalt is approximately 200 feet in the subsurface, and the basalt is presumed to be contiguous with surface outcrops east of the cross section. The Lovejoy is deformed by offset on the Chico monocline fault.

The upper Princeton Valley fill lies unconformably above the lower Princeton Submarine Valley fill, the Ione Formation, and the Lovejoy Basalt on the east side of the cross section. It extends from approximately the center of the cross section east to the Chico monocline and is presumed to be deformed by the Glenn syncline, although geophysical logs along this portion of the section do not clearly indicate folding. The upper Princeton Valley fill is up to 800 feet thick along this section and is thickest through Township 22 North, Range 01 West.

The Tehama Formation lies unconformably above the Great Valley sequence and lower Princeton Submarine Valley fill on the west side of the cross section. It extends from the west end of the section eastward toward the Sacramento River and is deformed, primarily on the bottom surface, by the Corning fault and the Greenwood anticline. The Tehama Formation is up to 1,500 thick feet along this section, with the thickest portion from near the Corning fault east to the Greenwood anticline. Intermixing and interlayering of the sediments occur near the center of the valley, where the Tehama and Tuscan formations intersect.

The Tuscan Formation lies unconformably above the upper Princeton Valley fill on the eastern side of the cross section. It extends from the east end of the cross section westward to approximately the Greenwood anticline and is deformed by the Chico monocline. It is also presumed to be deformed by the Glenn syncline, although geophysical logs along this portion of the section do not clearly indicate folding. The Tuscan Formation is up to 1,300 feet thick along this section and is thickest east of the Sacramento River. Intermixing and interlayering of the sediments occur near the center of the valley, where the Tuscan and Tehama formations intersect.

The Tehama and Tuscan formations are unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.2.2. Sand Provenance Analysis

Lithologic samples from three groundwater observation wells on cross section B-B’ were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 21N04W12A001M, 21N03W01R002M, and 22N02E30C002M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 5 and presented graphically as pie charts on the cross section at each sample location.

Well 21N04W12A001M is located on the western portion of the cross section. Results from the sand provenance analysis show that the samples taken from 240 to 250 ft-bgs and 600 to 610 ft-bgs, are composed primarily of lithic metamorphic constituents that make up the Tehama Formation, indicating a west side source area.

Well 21N03W01R002M is located toward the center of this cross section and is also shown on cross section F-F’. Sand provenance results are mixed at this location; results from analysis show that the sample from 240 to 260 ft-bgs is composed primarily of metamorphic lithic sediments that characterize the Tehama Formation. Evidence of intermixing of Tehama and Tuscan sediments is seen in the sample from 800 to 820 ft-bgs, which is composed mainly of lithic metamorphic and constituents as well as some lithic volcanic and lithic sedimentary constituents. The sample from 1,020 to 1,040 ft-bgs, is composed primarily of sedimentary lithic deposits, indicating a reworking and lithification of sediments. Results from the two deepest samples suggest that there is intermixing of Tehama and upper Princeton Valley fill sediments. The sample taken from 1,300 to 1,320 ft-bgs is composed primarily of lithic metamorphic constituents and also contains some lithic sedimentary and volcanic constituents. The sample from 1,480 to 1,500 ft-bgs is similar to the previous sample and is composed primarily of lithic metamorphic constituents, with an intermixing of lithic volcanic and sedimentary material.

Well 22N02E30C002M is located on the eastern portion of this cross section and is also shown on cross section E-E'. Results from two samples that were taken from 40 to 50 ft-bgs and 160 to 170 ft-bgs show that they are composed of almost 100 percent volcanic constituents of the Tuscan Formation, indicating an east side source area.

Table 5. Sand Provenance Analysis for Cross Section B-B'

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
21N04W12A001M	240-250	92	0	8	Tehama
	600-610	96	0	4	Tehama
21N03W01R002M	240-260	96	4	0	Tehama
	800-820	60	21	19	Tehama/Tuscan
	1,020-1,040	18	3	79	Tehama
	1,300-1,320	71	13	16	Tehama/upper Princeton Valley fill
	1,480-1,500	81	9	10	Tehama/upper Princeton Valley fill
22N02E30C002M	40-50	0	97	3	Tuscan
	160-170	0	100	0	Tuscan

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

5.3. Cross Section C-C'

Cross section C-C' is located approximately 13 to 17 miles south of cross section B-B' and is shown on Plate 2. The western end point of the section is located in Township 19 North, Range 05 West, Section 13, near the northern extent of the Salt Lake fault; the eastern end point is located in Township 19 North, Range 04 East, Section 29, southeast of Oroville. The stratigraphy depicted on this cross section indicates sequential layering of sedimentary geologic formations ranging from the marine Great Valley sequence and lower Princeton Submarine Valley fill to the transitional deltaic Ione Formation and finally to the continental upper Princeton Valley fill and the Tuscan and Tehama formations.

5.3.1. Stratigraphy

The Great Valley sequence underlies nearly the entire span of this cross section. The only exception is on the eastern end of the section, where the Sierran basement is present. The Great Valley sequence outcrops in surface exposure on the west end of the cross section. Both the eastern and western edges of the Great Valley sequence are folded upward, forming a widely spread trough. The surface of the Great Valley sequence is further deformed by offset on the Willows fault and by erosion that formed the lower Princeton Submarine Valley.

Unconformably overlying the Great Valley sequence is the lower Princeton Submarine Valley fill. The fill extends from east of the Sacramento River to west of Interstate 5 and is deformed by displacement on the Willows fault. The lower Princeton Submarine Valley fill is up to 1,500 feet thick along this section and is thickest near Highway 45.

Along the eastern portion of the cross section, the lower Princeton Submarine Valley fill and Great Valley sequence are overlain by the deltaic Ione Formation. It is seen in outcrop east of the cross section and extends westward into the subsurface of the valley. The Ione Formation is estimated to be up to 300 feet thick in this location.

Stratigraphic and geophysical data from two natural gas exploration wells along this section indicate that the Lovejoy Basalt is present in the subsurface. The extent of the Lovejoy Basalt in this location is unknown; however, the absence of geophysical data in surrounding wells indicates a limited extent. The Lovejoy Basalt is approximately 300 feet thick in these locations.

The upper Princeton Valley fill unconformably overlies the Ione Formation and the Lovejoy Basalt, and the lower Princeton Submarine Valley fill along the western portion of the cross section. It extends nearly the entire span of the cross section. It is presumed that the upper Princeton Valley fill is deformed by offset on the Willows fault. The upper Princeton Valley fill is up to 800 feet thick along this section and is thickest near the area where Little Dry Creek crosses the C-C’ cross section line near Township 19 North, Ranges 01 East and 02 East.

The Tehama Formation unconformably overlies the upper Princeton Valley fill on the western portion of the cross section. It extends from the surface outcrops of the Great Valley sequence in the west to just east of the Butte-Glenn county line and is deformed primarily on the bottom surface by the Willows fault. The Tehama Formation is up to 1,300 feet thick along this section and is thickest near the Willows fault.

The Tuscan Formation lies unconformably above the upper Princeton Valley fill on the eastern portion of the cross section. It extends from Highway 45 east to the Thermalito Afterbay. The Tuscan Formation is up to 1,000 feet thick along this section and is thickest near the Butte-Glenn county line. The Laguna Formation unconformably overlies the upper Princeton Valley fill east of the Tuscan Formation and extends eastward from the Thermalito Afterbay area. The Laguna Formation is up to 800 feet thick along this section and is thickest where it underlies the Thermalito Afterbay.

The Tehama, Tuscan, and Laguna formations are unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.3.2. Sand Provenance Analysis

Lithologic samples from four groundwater observation wells on cross section C-C’ were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 19N04W14M002M, 19N01E35B002M, 19N02E07K002M, and 19N02E13Q002M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 6 and presented graphically as pie charts on the cross section at each sample location.

Well 19N04W14M002M is located on the western portion of the cross section. Results from the sand provenance analysis show that the sample taken from 40 to 60 feet ft-bgs is composed primarily of lithic sedimentary and metamorphic constituents of the Tehama Formation, indicating a west side source area.

Well 19N01E35B002M is located east of the Sacramento River on cross section C-C’ and is also shown on cross sections D-D’ and E-E’. Sand provenance results from all four sand samples suggest an east side source area for these sediments. The sample taken from 426 to 436 ft-bgs is composed mostly of lithic volcanic constituents with some lithic metamorphic sediment. The samples from 826 to 846 ft-bgs and 946 to 966 ft-bgs are composed almost totally of lithic volcanic constituents. The deepest sample, from 1,016 to 1,026 ft-bgs, is composed of about two-thirds lithic volcanic constituents and about one-third lithic metamorphic and sedimentary constituents, which indicate intermixing of sediments at depth, possibly with upper Princeton Valley fill sediments and Tuscan Formation.

Well 19N02E07K002M is about 2 miles east of well 19N01E35B002M and is also shown on cross sections D-D’ and E-E’. Sediments samples from 340 to 350 ft-bgs and 560 to 570 ft-bgs are composed of predominantly lithic volcanic constituents with some lithic metamorphic material. Results of the deepest sample from 940 to 950 ft-bgs indicate that sediments from this depth are mostly of volcanic origin with some metamorphic and sedimentary sediments, also indicating possible intermixing with upper Princeton Valley fill and Tuscan sediments.

Well 19N02E13Q002M is on the eastern portion of cross section C-C’. Results from the sand provenance analysis show that the sample from 70 to 80 feet ft-bgs is composed predominantly of lithic metamorphic constituents with some lithic volcanic and sedimentary constituents which are characteristic of the Laguna Formation and Quaternary alluvium. The sample from 220 to 230 ft-bgs is composed primarily of volcanic sediments that are characteristic of the Tuscan Formation. Intermixing of the Tuscan Formation and possibly the upper Princeton Valley fill is suggested by test results from 650 to 660 ft-bgs. These results show that over half of the sample material is composed of lithic volcanic constituents, and the remainder is a mix of lithic metamorphic and sedimentary constituents. All samples from this well location indicate a primarily east side source area.

Table 6. Sand Provenance Analysis for Cross Section C-C'

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
19N04W14M002M	40-60	6	16	78	Tehama Formation
19N01E35B002M	426-436	25	75	0	Tuscan
	826-846	8	92	0	Tuscan
	946-966	7	93	0	Tuscan
	1,016-1,026	30	64	6	Tuscan/upper Princeton Valley fill
19N02E07K002M	340-350	17	78	5	Tuscan
	560-570	6	93	1	Tuscan
	940-950	24	68	8	Tuscan/upper Princeton Valley fill
19N02E13Q002M	70-80	83	14	3	Laguna/Quaternary alluvium
	220-230	5	95	0	Tuscan
	650-660	21	64	15	Tuscan/upper Princeton Valley fill

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

5.4. Cross Section D-D'

Cross section D-D,' shown on Plate 2, traverses southwest to northeast from Township 15 North, Range 03 West, Section 19, southwest of Williams, to Township 20 North, Range 03 East, Section 18, southeast of Durham. The stratigraphy depicted on this cross section indicates sequential layering of sedimentary geologic formations ranging from the marine Great Valley sequence and lower Princeton Submarine Valley fill to the transitional deltaic Ione Formation and finally to the continental upper Princeton Valley fill, Tehama Formation, and Tuscan Formation.

5.4.1. Stratigraphy

The Great Valley sequence underlies the entire span of cross section D-D' (with the exception of the Sierran basement on the east end) and is not exposed at the surface. Both the eastern and western edges of the Great Valley sequence are folded upward, forming a widely spread trough. The surface of the Great Valley sequence is further deformed by offset on the Willows fault. The surface trace of an unnamed fault intersects the cross section just east of the Willows fault; however, there is no subsurface data available to indicate the offset.

The lower Princeton Submarine Valley fill unconformably overlies the Great Valley sequence. The extent of the lower Princeton Submarine Valley fill is limited to several miles on the east and west side of the Willows fault. The lower Princeton Submarine Valley fill is deformed by offset on the Willows fault and is up to 700 feet thick along this section; it is thickest just west of the Willows fault.

The Ione Formation unconformably overlies the Great Valley sequence and lower Princeton Submarine Valley fill on the east side of the cross section. It is seen in outcrop east of the cross section and extends westward into the valley subsurface. The Ione Formation is up to 300 feet thick along this area of the cross section.

Stratigraphic and geophysical data from several natural gas exploration wells along the east side of the cross section indicate that Lovejoy Basalt is present in the subsurface. A significant exposure of Lovejoy Basalt is present east of the cross section at Table Mountain. The thickness of the Lovejoy Basalt is up to 300 feet in the subsurface in this area.

The upper Princeton Valley fill lies unconformably above the Lovejoy Basalt, Ione Formation, lower Princeton Submarine Valley fill, and Great Valley sequence lies the upper Princeton Valley fill. It extends westward from the east side of the cross section to near Interstate 5 and is deformed by offset on the Willows fault. The upper Princeton Valley fill is up to 900 feet thick along this section and is thickest through Township 19 North, Range 01 East.

The Tehama Formation unconformably overlies the upper Princeton Valley fill and Great Valley sequence on the west side of the cross section. It extends from the west side of the cross section eastward to the Butte-Glenn county line and is deformed, primarily on the bottom surface, by offset on the Willows fault. The Tehama Formation is up to 1,500 feet thick along this section and is thickest near the Sacramento River.

Unconformably above the upper Princeton Valley fill and the Lovejoy Basalt on the east side of the cross section lies the Tuscan Formation. From east of the cross section, it extends westward to around the Butte-Glenn county line. The Tuscan Formation is up to 1,000 feet thick along this section and is thickest just east of the Butte-Glenn county line.

The Tehama and Tuscan formations are unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.4.2. Sand Provenance Analysis

Lithologic samples from three groundwater observation wells on cross section D-D' were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 16N02W04J001M, 19N01E35B002M, and 19N02E07K002M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 7 and presented graphically as pie charts on the cross section at each sample location.

Well 16N02W04J001M is located on the western portion of this cross section and is also shown on cross section F-F'. An asterisk (✳) is shown on the cross-sections above the sand provenance pie chart for this well to reference this text for further explanation of the geology in this area. Results from the sand provenance analysis show that the sample from 260 to 270 feet ft-bgs is composed primarily of lithic metamorphic constituents that are characteristic of the Tehama Formation, indicating a west side source area. Test results for samples from 670 to 680 ft-bgs and 890 to 900 ft-bgs are somewhat anomalous; both samples are composed of about two-thirds lithic volcanic constituents and about one-third lithic metamorphic and sedimentary constituents, which may indicate an area of reworking or intermixing sediments. Their composition matches most closely with other samples that have been identified as either the upper Princeton Valley fill or the Tuscan Formation. However, when plotted on the cross sections, a designation of upper Princeton Valley fill or Tuscan Formation for these samples was inconsistent with other sources of information. Sand provenance results are consistent with the field geologist’s classification of the original samples and are considered to be high-quality data. At this point, there is not sufficient evidence to justify changing the depiction of the subsurface geology in this area to be consistent with these two samples; future study in the area may clarify this issue. For these reasons, the geologic formation name for these two samples is listed as “Unknown” in Tables 7 and 9 and on the observation well log shown in Appendix A.

Well 19N01E35B002M is located east of the Sacramento River on cross section D-D', and is also shown on cross sections C-C’ and E-E’. The sample from 426 to 436 ft-bgs is composed mainly of lithic volcanic constituents with some lithic metamorphic constituents, suggesting an east side source area. Samples from 826 to 846 ft-bgs and 946 to 966 ft-bgs are composed of predominantly lithic volcanic constituents, also suggesting an east side source area. The deepest sample, from 1,016 to 1,026 ft-bgs, is composed of about two-thirds lithic volcanic constituents and about one-third lithic metamorphic and sedimentary constituents. This suggests possible intermixing of upper Princeton Valley fill and Tuscan Formation sediments at depth, and a primarily east side source area.

Well 19N02E07K002M, also shown on cross sections C-C’ and E-E’, is about 2 miles east of well 19N01E35B002M and is of similar composition. Sediment samples from 340 to 350 ft-bgs and 560 to 570 ft-bgs are composed of predominantly lithic volcanic constituents, with some lithic metamorphic constituents. Test results from 940 to 950 ft-bgs indicate that sediments from this depth are composed mostly of lithic volcanic constituents, with some lithic metamorphic and sedimentary constituents, also suggesting a possible intermixing of upper Princeton Valley fill and Tuscan Formation sediments.

Table 7. Sand Provenance Analysis for Cross Section D-D’

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
16N02W04J001M	260-270	78	14	8	Tehama
✳	670-680	28	66	7	Unknown
	890-900	33	60	7	Unknown
19N01E35B002M	426-436	25	75	0	Tuscan
	826-846	8	92	0	Tuscan
	946-966	7	93	0	Tuscan
	1,016-1,026	30	64	6	Tuscan/upper Princeton Valley fill
19N02E07K002M	340-350	17	78	5	Tuscan
	560-570	6	93	1	Tuscan
	940-950	24	68	8	Tuscan/upper Princeton Valley fill

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

5.5. Cross Section E-E’

Cross section E-E’ extends approximately north to south for 42 miles on the east side of the valley and is shown on Plate 3. The northern end point of the cross section is located in Township 23 North, Range 01 East, Section 12, north of Chico; and the southern end point is located in Township 16 North, Range 01 East, Section 12, near the Sutter Buttes. The stratigraphy depicted on this cross section indicates sequential layering of sedimentary geologic formations, ranging from the marine Great Valley sequence and lower Princeton Submarine Valley fill to the transitional deltaic Ione Formation and finally to the continental upper Princeton Valley fill, Tehama Formation, and Tuscan Formation.

5.5.1. Stratigraphy

The Great Valley sequence underlies the entire span of cross section E-E’ and is not exposed at the surface. The Great Valley sequence is uplifted on both ends of the section. Uplift toward the north end of the cross section was caused by the Chico monocline fault, and uplift toward the south end was caused by intrusion of the Sutter Buttes, which deformed the valley sediments.

The Ione Formation unconformably overlies the Great Valley sequence and is shown in the subsurface, although few subsurface data are available to confirm that presumption. The Ione Formation is likely deformed by offset on the Chico monocline fault and is presumed to be as much as 500 feet thick along this cross section.

The Lovejoy Basalt lies unconformably above the Ione Formation. Stratigraphic and geophysical data from several natural gas exploration wells indicate that the Lovejoy Basalt is encountered in the subsurface in several locations along this cross section. Surface exposures of the

Lovejoy Basalt are seen in canyons east of Chico. The Lovejoy Basalt is likely deformed by offset on the Chico monocline fault and is up to 300 feet thick along the cross section.

The upper Princeton Valley fill unconformably overlies the Lovejoy Basalt and the Ione Formation along most of this cross section. The fill extends from north of Chico near Rock Creek to beyond the southern end of the cross section, where it is deformed by intrusion of the Sutter Buttes. The upper Princeton Valley fill is up to 800 feet thick along this section, maintaining a relatively consistent thickness.

The Tuscan Formation unconformably overlies the upper Princeton Valley fill and Lovejoy Basalt along the entire span of this cross section. Surface exposures of the formation are seen on the north end of the cross section. The formation is deformed by offset on the Chico monocline fault and by the intrusion of the Sutter Buttes and is up to 1,100 feet thick along this section.

The tuff breccia of the Sutter Buttes lies unconformably above the Tuscan Formation along the southern portion of the cross section. It extends from the southern end of the cross section northward to just beyond the Cherokee Canal. The tuff breccia of the Sutter Buttes is up to 600 feet thick along this section and is thickest through Township 17 North, Range 01 East.

The Tuscan Formation and the tuff breccia of the Sutter Buttes are unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.5.2. Sand Provenance Analysis

Lithologic samples from four groundwater observation wells on cross section E-E’ were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 22N02E30C002M, 19N02E07K002M, 19N01E35B002M, and 17N01E24A002M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 8 and presented graphically as pie charts on the cross section at each sample location.

Well 22N02E30C002M is located on the northern portion of this cross section and is also shown on cross section B-B’. Results from the sand provenance analysis show that the samples taken from 40 to 50 ft-bgs and 160 to 170 ft-bgs are composed predominantly of volcanic sediments that characterize the Tuscan Formation, indicating an east side source area.

Well 19N02E07K002M is located northeast of the intersection of cross section lines C-C’, D-D’, and E-E’ and is shown on all three cross sections. Sediments samples taken from 340 to 350 ft-bgs and 560 to 570 ft-bgs are composed of predominantly lithic volcanic constituents, with some lithic metamorphic constituents. Test results from the deepest sample, 940 to 950 ft-bgs, suggest that sediments from this depth are mostly of volcanic origin, with some lithic metamorphic and sedimentary constituents, also indicating possible intermixing with upper Princeton Valley fill and Tuscan Formation sediments.

Well 19N01E35B002M is located southwest of the intersection of cross section lines C-C’, D-D’, and E-E’ and is shown on all three cross sections. The sample from 426 to 436 ft-bgs is composed mostly of lithic volcanic constituents, with some lithic metamorphic constituents, indicating a primarily east side source area. The samples taken from 826 to 846 ft-bgs and 946 to 966 ft-bgs are composed of almost all volcanic sediment, also indicating an east side source area. The deepest sample, from 1,016 to 1,026 ft-bgs, is composed of about two-thirds lithic volcanic constituents and about one-third lithic metamorphic and sedimentary constituents. This suggests some intermixing of sediments at depth, possibly with upper Princeton Valley fill and Tuscan Formation sediments, and a primarily east side source area.

Well 17N01E24A002M is located on the southernmost end of the cross section, just north of the Sutter Buttes. Results from the sand provenance analysis show that the samples from 220 to 230 ft-bgs and 430 to 440 ft-bgs are composed primarily of lithic volcanic constituents, with minor amounts of lithic metamorphic and sedimentary constituents whose composition and placement on the cross section suggest the Tuff breccia of the Sutter Buttes. Sample results from 950 to 960 ft-bgs show that the sediments are composed of almost equal parts of lithic volcanic and metamorphic constituents that may indicate intermixing of Tuscan Formation sediments and the underlying upper Princeton Valley fill sediments. Sediments from 1,060 to 1,070 ft-bgs are composed of primarily lithic volcanic constituents, whose composition and placement on the cross section suggest the Tuscan Formation. Sample results from 1,360 to 1,370 ft-bgs and 1,390 to 1,400 ft-bgs show that sediments are composed of more than half lithic metamorphic constituents with the remainder composed of lithic volcanic and sedimentary constituents, suggesting intervals of intermixing before becoming primarily upper Princeton Valley fill sediments.

Table 8. Sand Provenance Analysis for Cross Section E-E’

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
22N02E30C002M	40-50	0	97	3	Tuscan
	160-170	0	100	0	Tuscan
19N02E07K002M	340-350	17	78	5	Tuscan
	560-570	6	93	1	Tuscan
	940-950	24	68	8	Tuscan/upper Princeton Valley fill
19N01E35B002M	426-436	25	75	0	Tuscan
	826-846	8	92	0	Tuscan
	946-966	7	93	0	Tuscan
	1,016-1,026	30	64	6	Tuscan/upper Princeton Valley fill
17N01E24A002M	220-230	7	91	2	Tuff breccia of the Sutter Buttes
	430-440	7	78	14	Tuff breccia of the Sutter Buttes
	950-960	43	55	2	Tuscan/upper Princeton Valley fill
	1,060-1,070	4	83	13	Tuscan
	1,360-1,370	58	30	2	Upper Princeton Valley fill
	1,390-1,400	52	24	24	Upper Princeton Valley fill

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

5.6. Cross Section F-F’

Cross section F-F’ extends approximately north to south for 60 miles on the west side of the valley and is shown on Plate 3. The northern end point of the cross section is located in Township 26 North, Range 03 West, Section 26, near Gerber; and the southern end point is located in Township 16 North, Range 02 West, Section 27, west of Colusa. The stratigraphy depicted in this cross section indicates sequential layering of sedimentary geologic formations, ranging from the marine Great Valley sequence and lower Princeton Submarine Valley fill to the transitional deltaic Ione Formation and finally to the continental upper Princeton Valley fill, Tehama Formation, and Tuscan Formation.

5.6.1. Stratigraphy

The Great Valley sequence underlies the entire span of this cross section, and there are no outcrops or surface exposures along this section. The Great Valley sequence is deformed by uplift near the north end of the cross section, by uplift of the Corning domes, and by offset on the Willows-Corning fault.

The lower Princeton Submarine Valley fill unconformably overlies the Great Valley sequence and extends from north of the cross section south to the vicinity of the Glenn-Colusa county line. The fill is deformed by uplift of the Corning domes and offset on the Willows-Corning fault. The lower

Princeton Submarine Valley fill is up to 1,000 feet thick along this cross section and is thickest on the south side of the Willows-Corning fault.

Unconformably overlying the lower Princeton Submarine Valley fill and Great Valley sequence is the upper Princeton Valley fill. It extends beyond both ends of the cross section and is deformed by offset on the Willows-Corning fault and by uplift at the Corning domes. The upper Princeton Valley fill ranges in thickness from 200 feet to 900 feet along this cross section and is thickest north of the Corning domes.

Unconformably overlying the upper Princeton Valley fill is the Tehama Formation. It spans the entire length of the cross section but is only seen in surface exposure in a small, localized area near the Corning domes. The Tehama Formation is deformed by offset on the Willows fault and by uplift associated with the Corning domes. The Tehama Formation ranges in thickness from 200 feet to 1,800 feet along this section and is thickest through the southern half of the cross section.

The Tuscan Formation intermixes with the Tehama Formation in the subsurface in the north part of the cross section. The thickness of the formation is up to 1,500 feet in the north, and it gradually pinches out in the south.

The Tehama formation is unconformably overlain by younger sediment, which may include the Red Bluff Formation, the Riverbank Formation, or the Modesto Formation; basin deposits; or surficial alluvium. These younger geologic units have been mapped collectively as Quaternary alluvium on the cross section due to their relatively small thickness compared with the underlying geologic formations.

5.6.2. Sand Provenance Analysis

Lithologic samples from five groundwater observation wells on cross section F-F’ were petrographically analyzed for sand provenance. The wells are identified according to the State well numbering system as 24N02W29N003M, 22N02W18C001M, 21N03W01R002M, 21N02W33M001M, and 16N02W04J001M. Results from the petrographic analyses are reported as the percentages of the three types of lithic sand grains: lithic metamorphic, lithic volcanic, and lithic sedimentary. The results are shown in Table 9 and presented graphically as pie charts on the cross section at each sample location.

Well 24N02W29N003M is located on the north end of this cross section and is also shown on cross section A-A’. Sand provenance results are mixed at this location; samples from 200 to 220 ft-bgs and 270 to 280 ft-bgs show an almost equal distribution of lithic metamorphic, lithic volcanic, and lithic sedimentary constituents indicating an area of reworked or intermixed sediments (or both) of the Tehama and Tuscan formations. The sample from 380-400 ft-bgs shows a predominance of lithic metamorphic constituents, indicating the west side source area of the Tehama Formation. However, three samples, from 640 to 660 ft-bgs, 740 to 760 ft-bgs, and 890 to 900 ft-bgs, show a predominance of lithic volcanic constituents, indicating the east side source area of the Tuscan Formation. The deepest sample, from 920 to 930 ft-bgs, is a mixture of about two-thirds lithic metamorphic constituents and about one third lithic volcanic and sedimentary constituents. The metamorphic constituents are characteristic of the Tehama Formation, and the volcanic and sedimentary constituents may indicate mixing with the deeper upper Princeton Valley fill sediments.

Well 22N02W18C001M is located west of the Orland area on cross section F-F'. Sand provenance test results show that the sample from 540 to 560 ft-bgs is composed of predominantly lithic metamorphic constituents characteristic of the Tehama Formation and a west side source area. The interval sampled from 810 to 820 ft-bgs is a composite mixture of lithic volcanic, metamorphic, and sedimentary material, indicating intermixing of sediments with multiple source areas. The deepest interval sampled is from 980 to 990 ft-bgs; results show that it is composed of primarily lithic volcanic constituents, with some metamorphic and sedimentary material, suggesting an east side source area.

Well 21N03W01R002M is located toward the center of this cross section and is also shown on cross section F-F'. Sand provenance results are mixed at this location; results from analysis show that the sample from 240 to 260 ft-bgs is composed primarily of metamorphic lithic sediments that characterize the Tehama Formation. Evidence of intermixing of Tehama and Tuscan sediments is seen in the sample from 800 to 820 ft-bgs, which is composed mainly of lithic metamorphic and constituents as well as some lithic volcanic and lithic sedimentary constituents. The sample from 1,020 to 1,040 ft-bgs is composed primarily of sedimentary lithic deposits, indicating a reworking and lithification of sediments. Results from the two deepest samples suggest that there is intermixing of Tehama Formation sediments and upper Princeton Valley fill sediments. The sample taken from 1,300 to 1,320 ft-bgs is composed primarily of lithic metamorphic constituents and also contains some lithic sedimentary and volcanic constituents; the sample from 1,480 to 1,500 ft-bgs is similar to the previous sample and is composed primarily of lithic metamorphic constituents with an intermixing of lithic volcanic and sedimentary material.

Well 21N02W33M001M is located toward the center of the cross section and test results show that this area is primarily metamorphic in nature. Results from 860 to 900 ft-bgs and 1,000 to 1,020 ft-bgs show that the sediments are composed primarily of lithic metamorphic constituents characteristic of the Tehama Formation, with some intermixing of lithic volcanic and sedimentary constituents.

Well 16N02W04J001M is located on the western portion of this cross section and is also shown on cross section D-D'. An asterisk (✳) is shown on the cross-sections above the sand provenance pie chart for this well to reference this text for further explanation of the geology in this area. Results from the sand provenance analysis show that the sample from 260 to 270 feet ft-bgs is composed primarily of lithic metamorphic constituents that are characteristic of the Tehama Formation, indicating a west side source area. Test results for samples from 670 to 680 ft-bgs and 890 to 900 ft-bgs are somewhat anomalous; both samples are composed of about two-thirds lithic volcanic constituents and about one-third lithic metamorphic and sedimentary constituents, which may indicate an area of reworking or intermixing sediments. Their composition matches most closely with other samples that have been identified as either the upper Princeton Valley fill or the Tuscan Formation. However, when plotted on the cross sections, a designation of upper Princeton Valley fill or Tuscan Formation for these samples was inconsistent with other sources of information. Sand provenance results are consistent with the field geologist's classification of the original samples and are considered to be high-quality data. At this point, there is not sufficient evidence to justify changing the depiction of the subsurface geology in this area to be consistent with these two samples; future study in the area may clarify this issue. For these reasons, the geologic formation name for these two samples is listed as "Unknown" in Tables 7 and 9 and on the observation well log shown in Appendix A.

Table 9. Sand-Provenance Analysis for Cross Section F-F'

Well	Sample depth range (feet below ground surface)	Percent composition [a]			Predominant source formation
		Lm	Lv	Ls	
24N02W29N003M	200-220	29	37	34	Unknown
	270-280	46	34	20	Tehama
	380-400	76	1	23	Tehama
	640-660	1	97	2	Tuscan
	740-760	0	100	0	Tuscan
	890-900	1	99	0	Tuscan
	920-930	70	15	15	Tehama/upper Princeton Valley fill
22N02W18C001M	540-560	91	4	5	Tehama
	810-820	44	32	24	Tehama/Tuscan Intermixing
	980-990	16	71	13	Tuscan
21N03W01R002M	240-260	96	4	0	Tehama
	800-820	60	21	19	Tehama
	1020-1040	18	3	79	Tehama
	1300-1320	71	13	16	Tehama
	1480-1500	81	9	10	Tehama/upper Princeton Valley fill
21N02W33M001M	860-900	57	28	15	Tehama
	1000-1020	70	21	9	Tehama
16N02W04J001M	260-270	78	14	8	Tehama
✳	670-680	28	66	7	Unknown
	890-900	33	60	7	Unknown

Notes:

[a] Lm = lithic metamorphic; Lv = lithic volcanic; Lm = lithic sedimentary.

Section 6. Conclusions

Over the last 5 million years or so, the Northern Sacramento Valley has been in a westward marine regression, characterized by the erosion and deposition of continental sediments that compose the majority of fresh, groundwater-bearing formations in the valley. Geologic sediments are transported and deposited by creeks, streams, and rivers flowing from the surrounding source-area mountains toward the center of the valley during episodic precipitation and storm events. Deposition of these sediments results in geologic formations that are composed of a heterogeneous and diverse mix of sediments, which subsequently results in discontinuous deposits and intermittent groundwater aquifer zones.

Results from the lithologic logging and petrographic analyses confirm that the heterogeneous sediments of the Tehama and Tuscan formations intermix in the subsurface in various areas near the center of the valley. The results also show that toward the westward and eastward extents of the valley, formational sediments become more unified in composition due to shorter travel times from their respective sediment source areas. On the west side of the valley, the Coast Ranges are the major source of the metamorphic sediments of the Tehama Formation, and on the east side of the valley, the Cascade Range is the major source area for the volcanic sediments of the Tuscan Formation.

Additional data are needed to further define the geology and hydrogeology of the northern Sacramento Valley. A textural analysis of formational sediments using driller’s well logs is needed to better identify aquifer production zones. Drilling and installing groundwater observation wells in areas of little or no data can provide the information needed to determine the extent and variability of the valley’s groundwater aquifers. In addition, groundwater-level data supplied by the observation wells can provide valuable information for monitoring aquifer conditions, for determining the change in groundwater levels over time, and for assessing the ability of groundwater to move through the geologic aquifer sediments.

In summary, the geologic and tectonic forces that formed the northern Sacramento Valley have created the valley and mountains’ notable geologic surface features, as well as formed the subsurface sediments of the valley’s groundwater-bearing geologic formations. The information related in this report provides a history and setting for the geology of the northern Sacramento Valley and will provide valuable information for additional studies in the future.

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Appendix A. Observation Well As-Built Drawings

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Figure A-1. Observation Well As-Built Location Map

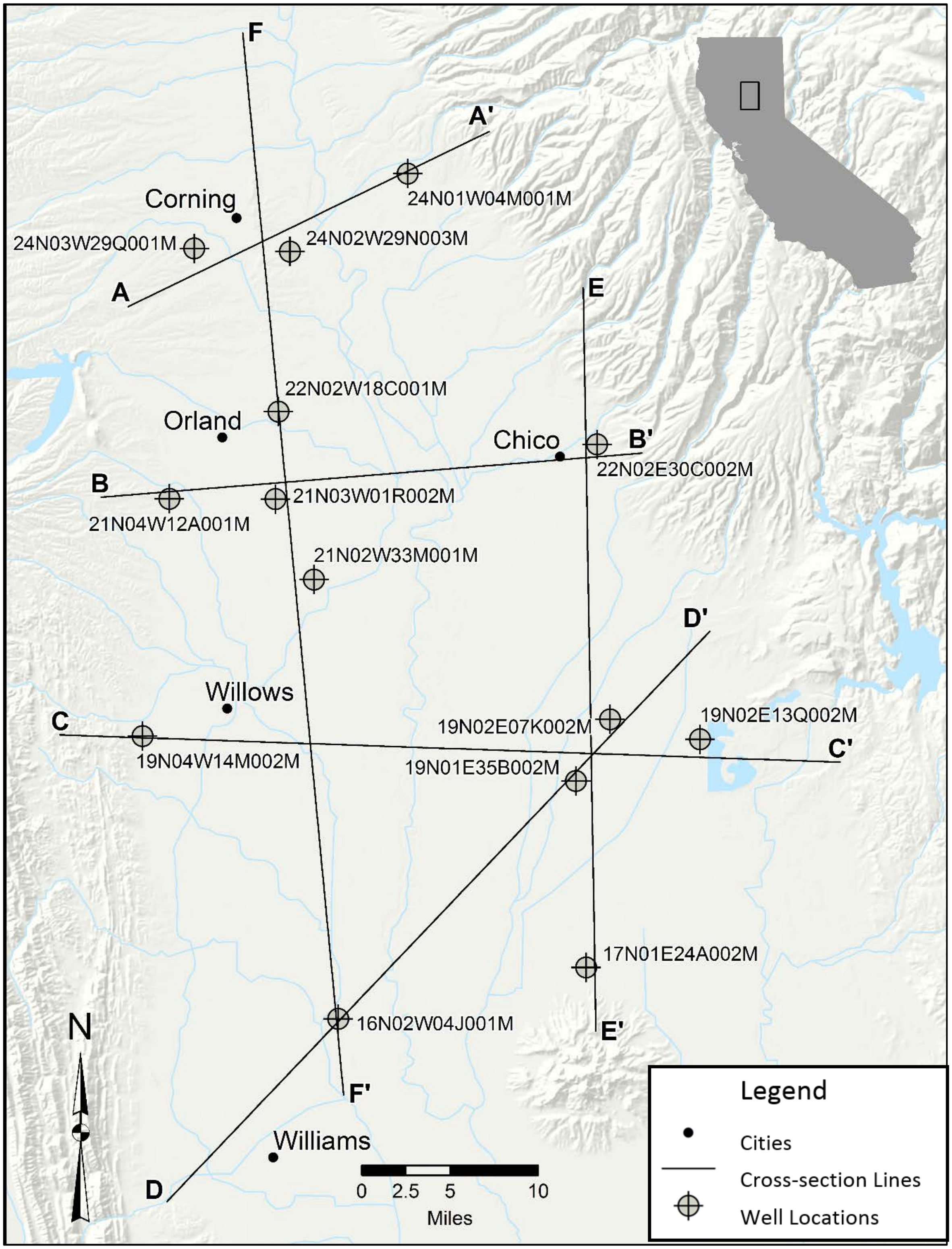


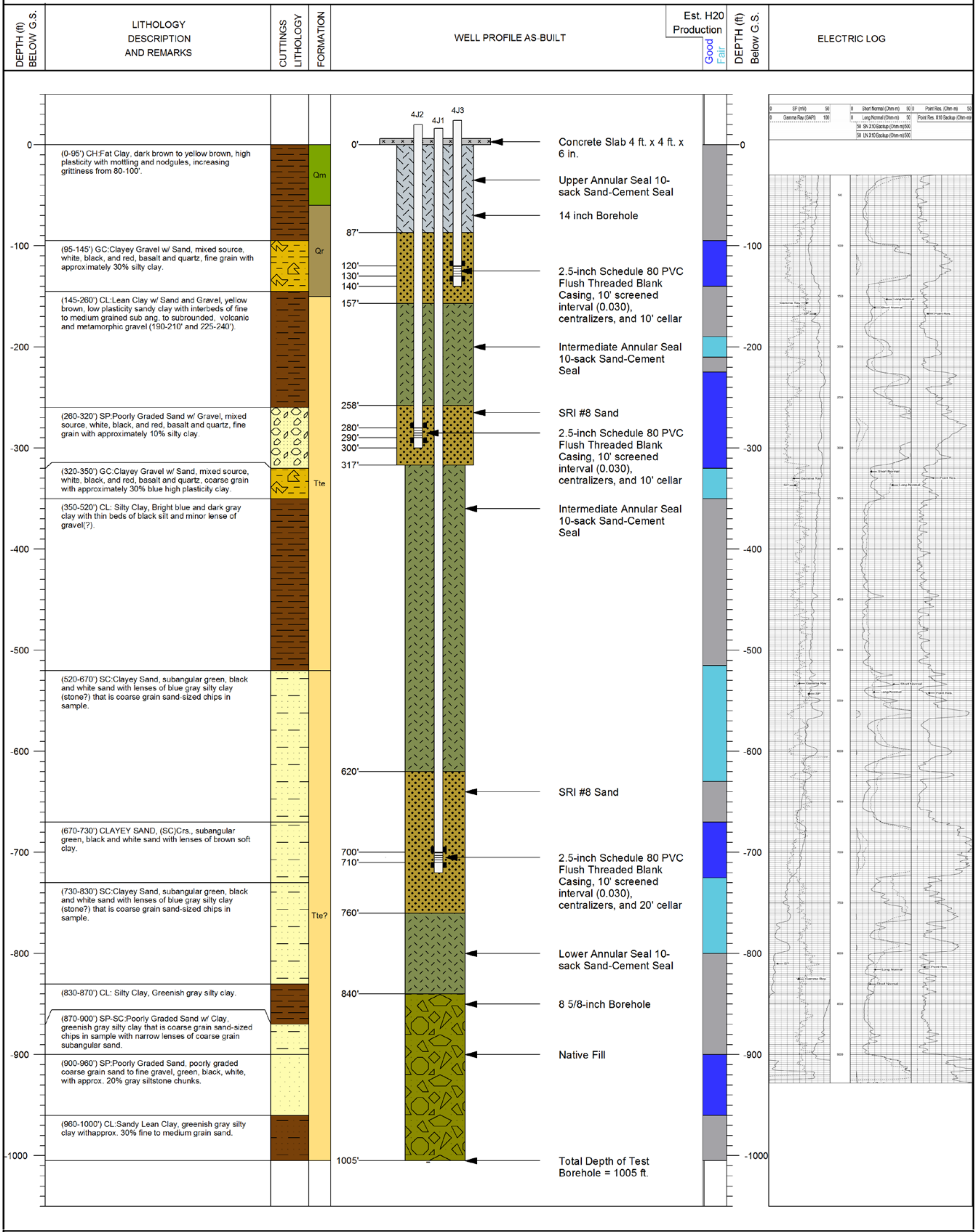
Figure A-2. As-built for triple-completion observation well; state well numbers: 16N02W04J001M, 16N02W04J002M, and 16N02W04J003M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Colusa Rancheria MW Drilling	STATE WELL NUMBER	16N02W04J001M	16N02W04J002M	16N02W04J003M
FEATURE / USE	Multicompletion Monitoring Well	LOCAL IDENTIFICATION	4J1 - Deep	4J2 - Intermediate	4J3 - Shallow
LOCATION	Near Halloway Rd. and Maxwell Rd.	WELL DEPTH (ft-bgs)	760	317	157
COORDINATES	NAD 83, Zone 10, Meters	TEST HOLE DEPTH (ft-bgs)	1005	1005	1005
EASTING	579449	TOP OF SCREEN (ft-bgs)	700	280	120
NORTHING	4346952	BOTTOM OF SCREEN (ft-bgs)	710	290	130
GSE (ft-msl)	57.16	SANITARY SEAL (ft-bgs)	(0-87') Cement Slurry	(0-87') Cement Slurry	(0-87') Cement Slurry
DRILL DATE	02/09/06 - 02/13/06	REFERENCE POINT (ft-msl)	58.69	58.94	59.19
DRILLING METHOD	Mud Rotary	SITE GEOLOGIST	Ehorn/Spangler	COMMENTS	
DRILLING CONTRACTOR	Eaton Drilling (Job #7919)				
WCR	E044003				

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-95') CH:Fat Clay, dark brown to yellow brown, high plasticity with mottling and nodgules, increasing grittiness from 80-100'.

(95-145') GC:Clayey Gravel w/ Sand, mixed source, white, black, and red, basalt and quartz, fine grain with approximately 30% silty clay.

(145-260') CL:Lean Clay w/ Sand and Gravel, yellow brown, low plasticity sandy clay with interbeds of fine to medium grained sub ang. to subrounded, volcanic and metamorphic gravel (190-210' and 225-240').

(260-320') SP:Poorly Graded Sand w/ Gravel, mixed source, white, black, and red, basalt and quartz, fine grain with approximately 10% silty clay.

(320-350') GC:Clayey Gravel w/ Sand, mixed source, white, black, and red, basalt and quartz, coarse grain with approximately 30% blue high plasticity clay.

(350-520') CL: Silty Clay, Bright blue and dark gray clay with thin beds of black silt and minor lense of gravel(?).

(520-670') SC:Clayey Sand, subangular green, black and white sand with lenses of blue gray silty clay (stone?) that is coarse grain sand-sized chips in sample.

(670-730') CLAYEY SAND, (SC)Crs., subangular green, black and white sand with lenses of brown soft clay.

(730-830') SC:Clayey Sand, subangular green, black and white sand with lenses of blue gray silty clay (stone?) that is coarse grain sand-sized chips in sample.

(830-870') CL: Silty Clay, Greenish gray silty clay.

(870-900') SP-SC:Poorly Graded Sand w/ Clay, greenish gray silty clay that is coarse grain sand-sized chips in sample with narrow lenses of coarse grain subangular sand.

(900-960') SP:Poorly Graded Sand, poorly graded coarse grain sand to fine gravel, green, black, white, with approx. 20% gray siltstone chunks.

(960-1000') CL:Sandy Lean Clay, greenish gray silty clay withapprox. 30% fine to medium grain sand.

Geologic Legend:
Qm - Modesto Formation
Qr - Riverbank Formation
Tte- Tehama Formation

Prepared By: R. Hull Date: 2/21/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

Figure A-3. As-built for quadruple-completion observation well; state well numbers: 17N01E24A002M, 17N01E24A003M, 17N01E24A004M, and 17N01E24A005M

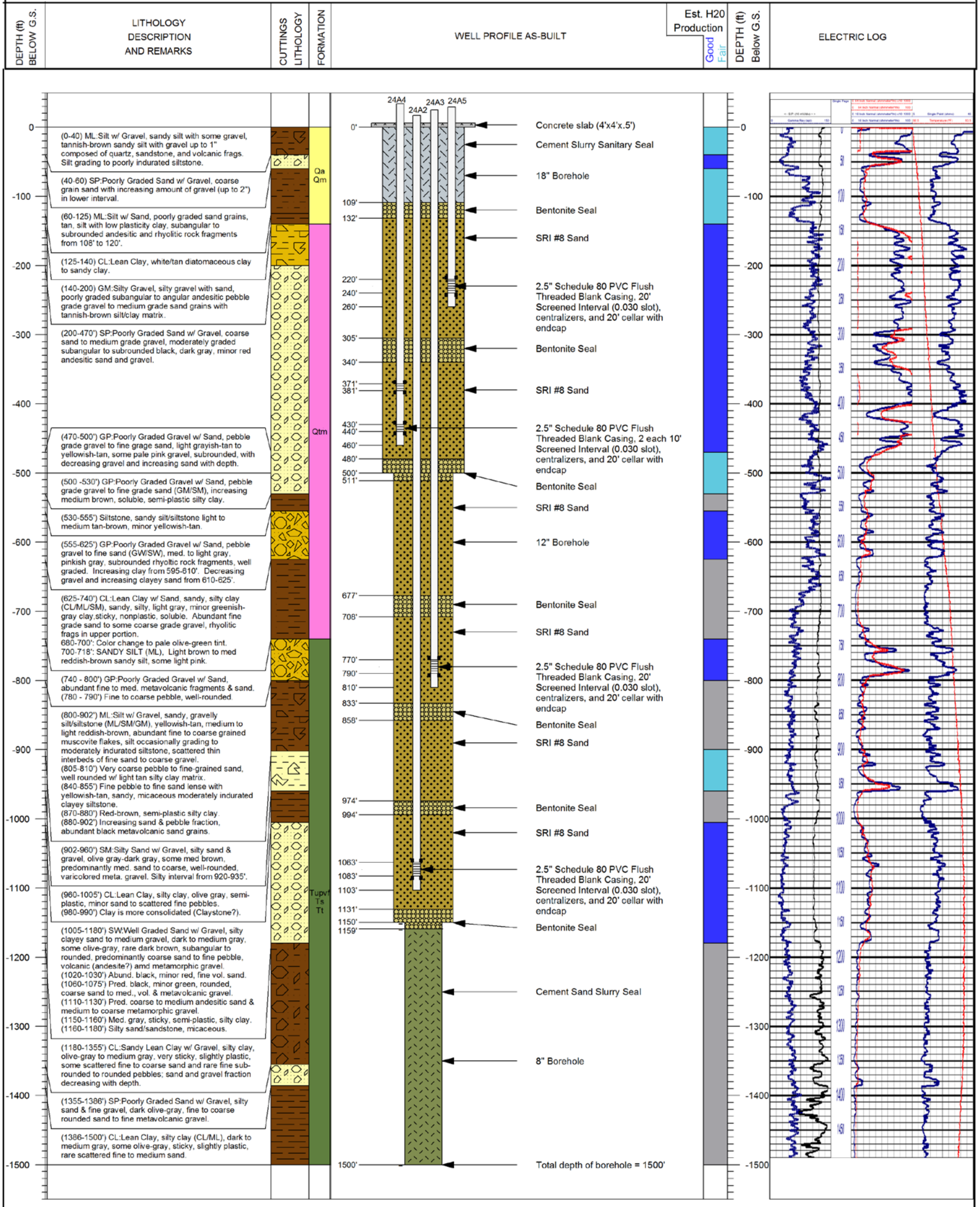
STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT: DPLA Drilling Contract
FEATURE / USE: Multi-Completion Monitoring Well
LOCATION: Butte Co., Gray Lodge Wildlife Area
COORDINATES: NAD83, Zone 10, Meters
EASTING: 603411.618
NORTHING: 4352633.461
GSE (ft-msl): 72.8 (DWR Elevation Survey)
DRILL DATE: March 2007
DRILLING METHOD: Mud Rotary
DRILLER: Eaton Drilling
WCR: E054678

STATE WELL NUMBER	17N01E24A002M	17N01E24A003M	17N01E24A004M	17N01E24A005M
LOCAL IDENTIFICATION	24A2 - Deep	24A3 - Inter Deep	24A4 - Inter Shallow	24A5 - Shallow
WELL DEPTH (ft-bgs)	1131	833	480	305
TEST HOLE DEPTH (ft-bgs)	1500	1500	1500	1500
TOP OF SCREEN (ft-bgs)	1063	770	371	220
BOTTOM OF SCREEN(ft-bgs)	1083	790	440	240
SANITARY SEAL (ft-bgs)	(0-132') Cement/Bent	(0-132') Cement/Bent	(0-132') Cement/Bent	(0-132') Cement/Bent
REFERENCE POINT (ft-msl)	74.576 (El. Survey)	75.55 (El. Survey)	75.83 (El. Survey)	75.798 (El. Survey)

SITE GEOLOGIST: Staton/Mulder
COMMENTS: Pennington & Rutherford Rd, 10' N of single completion well

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



LITHOLOGY DESCRIPTION AND REMARKS

(0-40) ML:Silt w/ Gravel, sandy silt with some gravel, tannish-brown sandy silt with gravel up to 1" composed of quartz, sandstone, and volcanic frags. Silt grading to poorly indurated siltstone.

(40-60) SP:Poorly Graded Sand w/ Gravel, coarse grain sand with increasing amount of gravel (up to 2") in lower interval.

(60-125) ML:Silt w/ Sand, poorly graded sand grains, tan, silt with low plasticity clay, subangular to subrounded andesitic and rhyolitic rock fragments from 108' to 120'.

(125-140) CL:Lean Clay, white/tan diatomaceous clay to sandy clay.

(140-200) GM:Silty Gravel, silty gravel with sand, poorly graded subangular to angular andesitic pebble grade gravel to medium grade sand grains with tannish-brown silt/clay matrix.

(200-470') SP:Poorly Graded Sand w/ Gravel, coarse sand to medium grade gravel, moderately graded subangular to subrounded black, dark gray, minor red andesitic sand and gravel.

(470-500') GP:Poorly Graded Gravel w/ Sand, pebble grade gravel to fine grage sand, light grayish-tan to yellowish-tan, some pale pink gravel, subrounded, with decreasing gravel and increasing sand with depth.

(500 -530') GP:Poorly Graded Gravel w/ Sand, pebble grade gravel to fine grade sand (GM/SM), increasing medium brown, soluble, semi-plastic silty clay.

(530-555') Siltstone, sandy silt/siltstone light to medium tan-brown, minor yellowish-tan.

(555-625') GP:Poorly Graded Gravel w/ Sand, pebble gravel to fine sand (GW/SW), med. to light gray, pinkish gray, subrounded rhyoltic rock fragments, well graded. Increasing clay from 595-610'. Decreasing gravel and increasing clayey sand from 610-625'.

(625-740') CL:Lean Clay w/ Sand, sandy, silty clay (CL/ML/SM), sandy, silty, light gray, minor greenish-gray clay,sticky, nonplastic, soluble. Abundant fine grade sand to some coarse grade gravel, rhyolitic frags in upper portion.
680-700': Color change to pale olive-green tint.
700-718': SANDY SILT (ML), Light brown to med reddish-brown sandy silt, some light pink.

(740 - 800') GP:Poorly Graded Gravel w/ Sand, abundant fine to med. metavolcanic fragments & sand.
(780 - 790') Fine to coarse pebble, well-rounded.

(800-902') ML:Silt w/ Gravel, sandy, gravelly silt/siltstone (ML/SM/GM), yellowish-tan, medium to light reddish-brown, abundant fine to coarse grained muscovite flakes, silt occasionally grading to moderately indurated siltstone, scattered thin interbeds of fine sand to coarse gravel.
(805-810') Very coarse pebble to fine-grained sand, well rounded w/ light tan silty clay matrix.
(840-855') Fine pebble to fine sand lense with yellowish-tan, sandy, micaceous moderately indurated clayey siltstone.
(870-880') Red-brown, semi-plastic silty clay.
(880-902') Increasing sand & pebble fraction, abundant black metavolcanic sand grains.

(902-960') SM:Silty Sand w/ Gravel, silty sand & gravel, olive gray-dark gray, some med brown, predominantly med. sand to coarse, well-rounded, varicolored meta. gravel. Silty interval from 920-935'.

(960-1005') CL:Lean Clay, silty clay, olive gray, semi-plastic, minor sand to scattered fine pebbles.
(980-990') Clay is more consolidated (Claystone?).

(1005-1180') SW:Well Graded Sand w/ Gravel, silty clayey sand to medium gravel, dark to medium gray, some olive-gray, rare dark brown, subangular to rounded, predominantly coarse sand to fine pebble, volcanic (andesite?) amd metamorphic gravel.
(1020-1030') Abund. black, minor red, fine vol. sand.
(1060-1075') Pred. black, minor green, rounded, coarse sand to med., vol. & metavolcanic gravel.
(1110-1130') Pred. coarse to medium andesitic sand & medium to coarse metamorphic gravel.
(1150-1160') Med. gray, sticky, semi-plastic, silty clay.
(1160-1180') Silty sand/sandstone, micaceous.

(1180-1355') CL:Sandy Lean Clay w/ Gravel, silty clay, olive-gray to medium gray, very sticky, slightly plastic, some scattered fine to coarse sand and rare fine sub-rounded to rounded pebbles; sand and gravel fraction decreasing with depth.

(1355-1386') SP:Poorly Graded Sand w/ Gravel, silty sand & fine gravel, dark olive-gray, fine to coarse rounded sand to fine metavolcanic gravel.

(1386-1500') CL:Lean Clay, silty clay (CL/ML), dark to medium gray, some olive-gray, sticky, slightly plastic, rare scattered fine to medium sand.

Geologic Legend:
Qa: Alluvium
Qm: Modesto Formation
QTm: Tuff Breccia
Ts: Sutter Formation
Tt: Tuscan Formation
Tupvf: Upper Princeton Valley Fill

Prepared By: R. Hull Date: 2/22/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

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Figure A-4. As-built for double-completion observation well; state well numbers: 19N01E35B002M and 19N01E35B003M

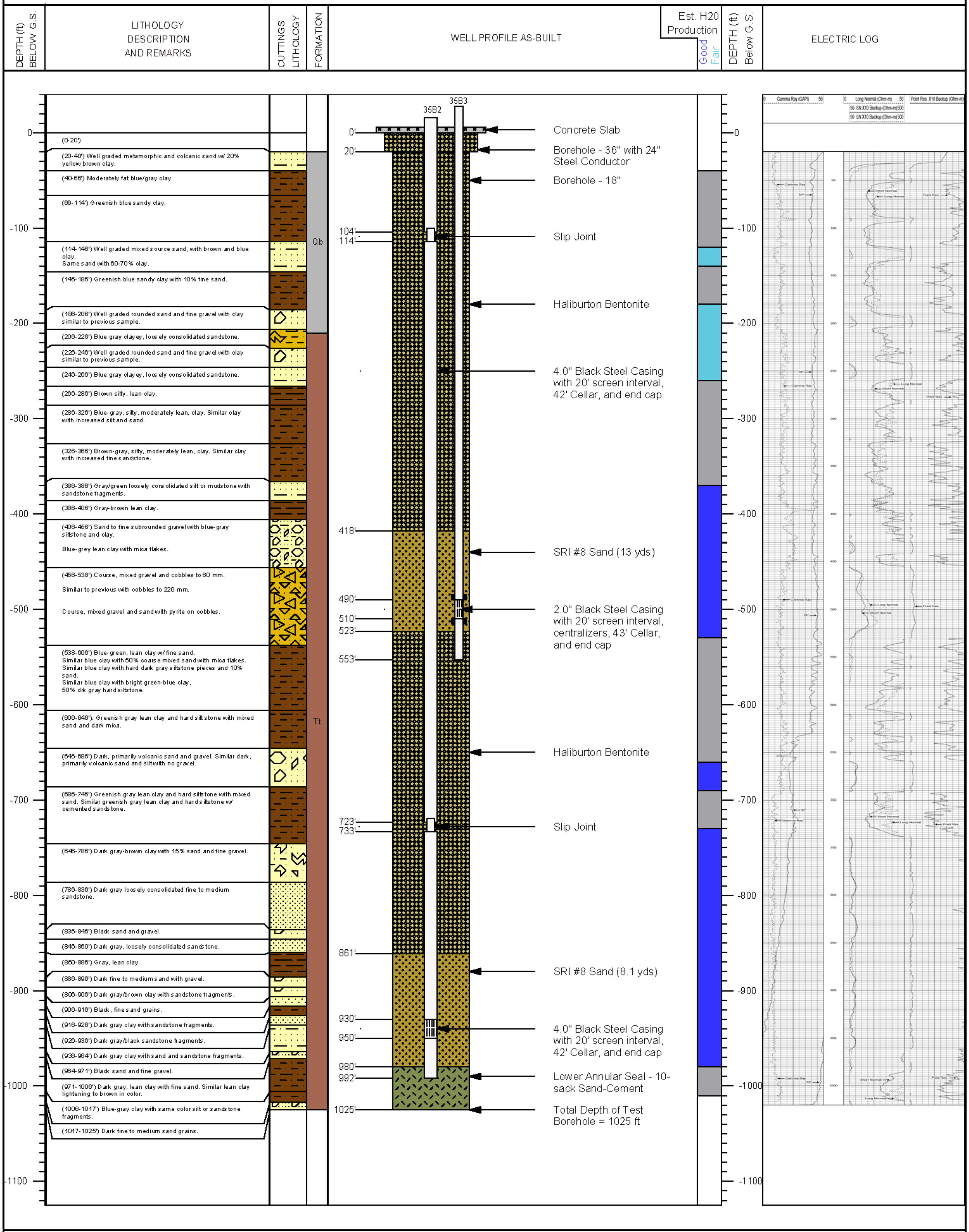
STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Butte County Extensometer Drilling Project 2003
FEATURE / USE	Double Completion Extensometer/Obs Well
LOCATION	1.5 miles east of Aquas Frias Rd. on Hwy 162
COORDINATES	NAD83, UTM Zone 10
EASTING	600841.961
NORTHING	4368862.438
GSE (ft-msl)	86.5
DRILL DATE	06/18/2003
DRILLING METHOD	Reverse Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	726836

STATE WELL NUMBER		19N01E35B002M	19N01E35B003M	Blank
LOCAL IDENTIFICATION		35B2 - Deep/Ext	35B3 - Intermediate	
WELL DEPTH	(ft-bgs)	980	418	
TEST HOLE DEPTH	(ft-bgs)	1025	1025	
TOP OF SCREEN	(ft-bgs)	930	490	
BOTTOM OF SCREEN	(ft-bgs)	950	510	
SANITARY SEAL	(ft-bgs)	(0-418') Bentonite	(0-418') Bentonite	
REFERENCE POINT	(ft-msl)	92.435 (El. Survey)	89.59 (El Survey)	
SITE GEOLOGIST		Spangler/Lawrence	COMMENTS	

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-20')

(20-40') Well graded metamorphic and volcanic sand w/ 20% yellow brown clay.

(40-66') Moderately fat blue/gray clay.

(66-114') Greenish blue sandy clay.

(114-146') Well graded mixed source sand, with brown and blue clay.
Same sand with 60-70% clay.

(146-186') Greenish blue sandy clay with 10% fine sand.

(186-206') Well graded rounded sand and fine gravel with clay similar to previous sample.

(206-226') Blue gray clayey, loosely consolidated sandstone.

(226-246') Well graded rounded sand and fine gravel with clay similar to previous sample.

(246-266') Blue gray clayey, loosely consolidated sandstone.

(266-286') Brown silty, lean clay.

(286-326') Blue-gray, silty, moderately lean, clay. Similar clay with increased silt and sand.

(326-366') Brown-gray, silty, moderately lean, clay. Similar clay with increased fine sandstone.

(366-386') Gray/green loosely consolidated silt or mudstone with sandstone fragments.

(386-406') Gray-brown lean clay.

(406-456') Sand to fine subrounded gravel with blue-gray siltstone and clay.

Blue-grey lean clay with mica flakes.

(456-538') Course, mixed gravel and cobbles to 60 mm.

Similar to previous with cobbles to 220 mm.

Course, mixed gravel and sand with pyrite on cobbles.

(538-606') Blue-green, lean clay w/ fine sand.
Similar blue clay with 50% coarse mixed sand with mica flakes.
Similar blue clay with hard dark gray siltstone pieces and 10% sand.
Similar blue clay with bright green-blue clay,
50% drk gray hard siltstone.

(606-646'): Greenish gray lean clay and hard silt stone with mixed sand and dark mica.

(646-686') Dark, primarily volcanic sand and gravel. Similar dark, primarily volcanic sand and silt with no gravel.

(686-746') Greenish gray lean clay and hard siltstone with mixed sand. Similar greenish gray lean clay and hard siltstone w/ cemented sandstone.

(646-786') Dark gray-brown clay with 15% sand and fine gravel.

(786-836') Dark gray loosely consolidated fine to medium sandstone.

(836-846') Black sand and gravel.

(846-860') Dark gray, loosely consolidated sandstone.

(860-886') Gray, lean clay.

(886-896') Dark fine to medium sand with gravel.

(896-906') Dark gray/brown clay with sandstone fragments.

(906-916') Black, fine sand grains.

(916-926') Dark gray clay with sandstone fragments.

(926-936') Dark gray/black sandstone fragments.

(936-964') Dark gray clay with sand and sandstone fragments.

(964-971') Black sand and fine gravel.

(971-1006') Dark gray, lean clay with fine sand. Similar lean clay lightening to brown in color.

(1006-1017') Blue-gray clay with same color silt or sandstone fragments.

(1017-1025') Dark fine to medium sand grains.

Geologic Legend:
Qb - Basin Deposits
Tt - Tuscan Formation

Prepared By: R. Hull Date: 3/29/2011 File Name & Location:

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Figure A-5. As-built for triple-completion observation well; state well numbers: 19N02E07K002M, 19N02E07K003M, and 19N02E07K004M

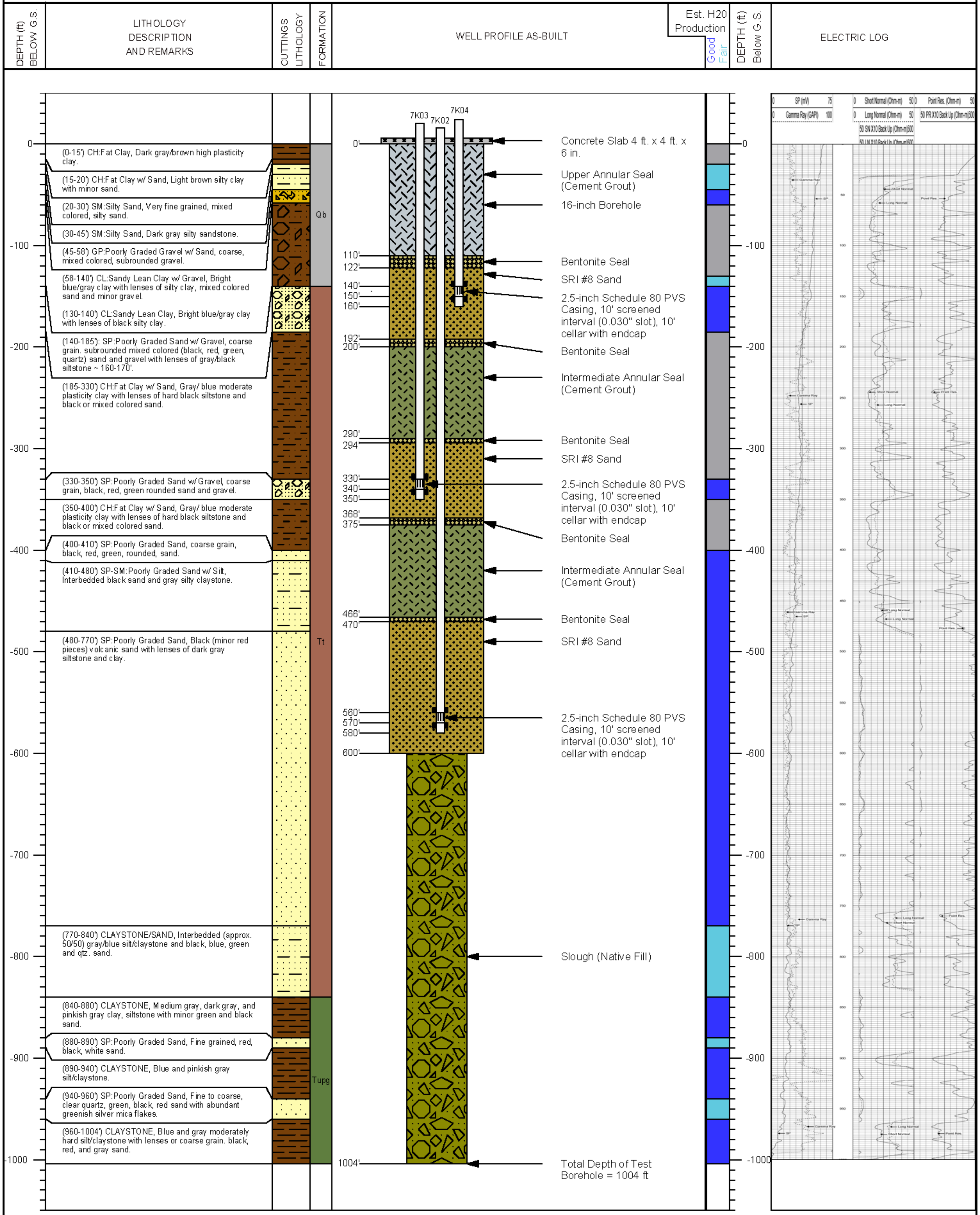
STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Western Canal AB303 2005 MW Drilling
FEATURE / USE	Multicompletion Observation Well
LOCATION	0.28mi. west of Harris Rd., NW of Richvale, CA
COORDINATES	NAD83, Zone 10, Meters
EASTING	604192.159
NORTHING	4374274.025
GSE (ft-msl)	102.286 (DWR Elevation Survey)
DRILL DATE	09/12/2006
DRILLING METHOD	Mud Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	816273

STATE WELL NUMBER		19N02E07K002M	19N02E07K003M	19N02E07K004M
LOCAL IDENTIFICATION		07K2 - Deep	07K3 - Intermediate	07K4 - Shallow
WELL DEPTH	(ft-bgs)	600	368	192
TEST HOLE DEPTH	(ft-bgs)	1004	1004	1004
TOP OF SCREEN	(ft-bgs)	560	330	140
BOTTOM OF SCREEN	(ft-bgs)	570	340	150
SANITARY SEAL	(ft-bgs)	(0-122') Cement/Bentonite	(0-122') Cement/Bentonite	(0-122') Cement/Bentonite
REFERENCE POINT	(ft-msl)	106.05 (El. Survey)	106.116 (El. Survey)	106.211 (El. Survey)
SITE GEOLOGIST		Spangler	COMMENTS	Butte County - Boeger

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-15') CH:Fat Clay, Dark gray/brown high plasticity clay.

(15-20') CH:Fat Clay w/ Sand, Light brown silty clay with minor sand.

(20-30') SM:Silty Sand, Very fine grained, mixed colored, silty sand.

(30-45') SM:Silty Sand, Dark gray silty sandstone.

(45-58') GP:Poorly Graded Gravel w/ Sand, coarse, mixed colored, subrounded gravel.

(58-140') CL:Sandy Lean Clay w/ Gravel, Bright blue/gray clay with lenses of silty clay, mixed colored sand and minor gravel.

(130-140') CL:Sandy Lean Clay, Bright blue/gray clay with lenses of black silty clay.

(140-185'): SP:Poorly Graded Sand w/ Gravel, coarse grain. subrounded mixed colored (black, red, green, quartz) sand and gravel with lenses of gray/black siltstone ~ 160-170'.

(185-330') CH:Fat Clay w/ Sand, Gray/ blue moderate plasticity clay with lenses of hard black siltstone and black or mixed colored sand.

(330-350') SP:Poorly Graded Sand w/ Gravel, coarse grain, black, red, green rounded sand and gravel.

(350-400') CH:Fat Clay w/ Sand, Gray/ blue moderate plasticity clay with lenses of hard black siltstone and black or mixed colored sand.

(400-410') SP:Poorly Graded Sand, coarse grain, black, red, green, rounded, sand.

(410-480') SP-SM:Poorly Graded Sand w/ Silt, Interbedded black sand and gray silty claystone.

(480-770') SP:Poorly Graded Sand, Black (minor red pieces) volcanic sand with lenses of dark gray siltstone and clay.

(770-840') CLAYSTONE/SAND, Interbedded (approx. 50/50) gray/blue silt/claystone and black, blue, green and qtz. sand.

(840-880') CLAYSTONE, Medium gray, dark gray, and pinkish gray clay, siltstone with minor green and black sand.

(880-890') SP:Poorly Graded Sand, Fine grained, red, black, white sand.

(890-940') CLAYSTONE, Blue and pinkish gray silt/claystone.

(940-960') SP:Poorly Graded Sand, Fine to coarse, clear quartz, green, black, red sand with abundant greenish silver mica flakes.

(960-1004') CLAYSTONE, Blue and gray moderately hard silt/claystone with lenses or coarse grain. black, red, and gray sand.

Geologic Legend:
Qb: Basin Deposits
Tt: Tuscan Formation
Tupg: Upper Princeton Valley Fill

Prepared By: R. Hull Date: 3/18/2011 File Name & Location:

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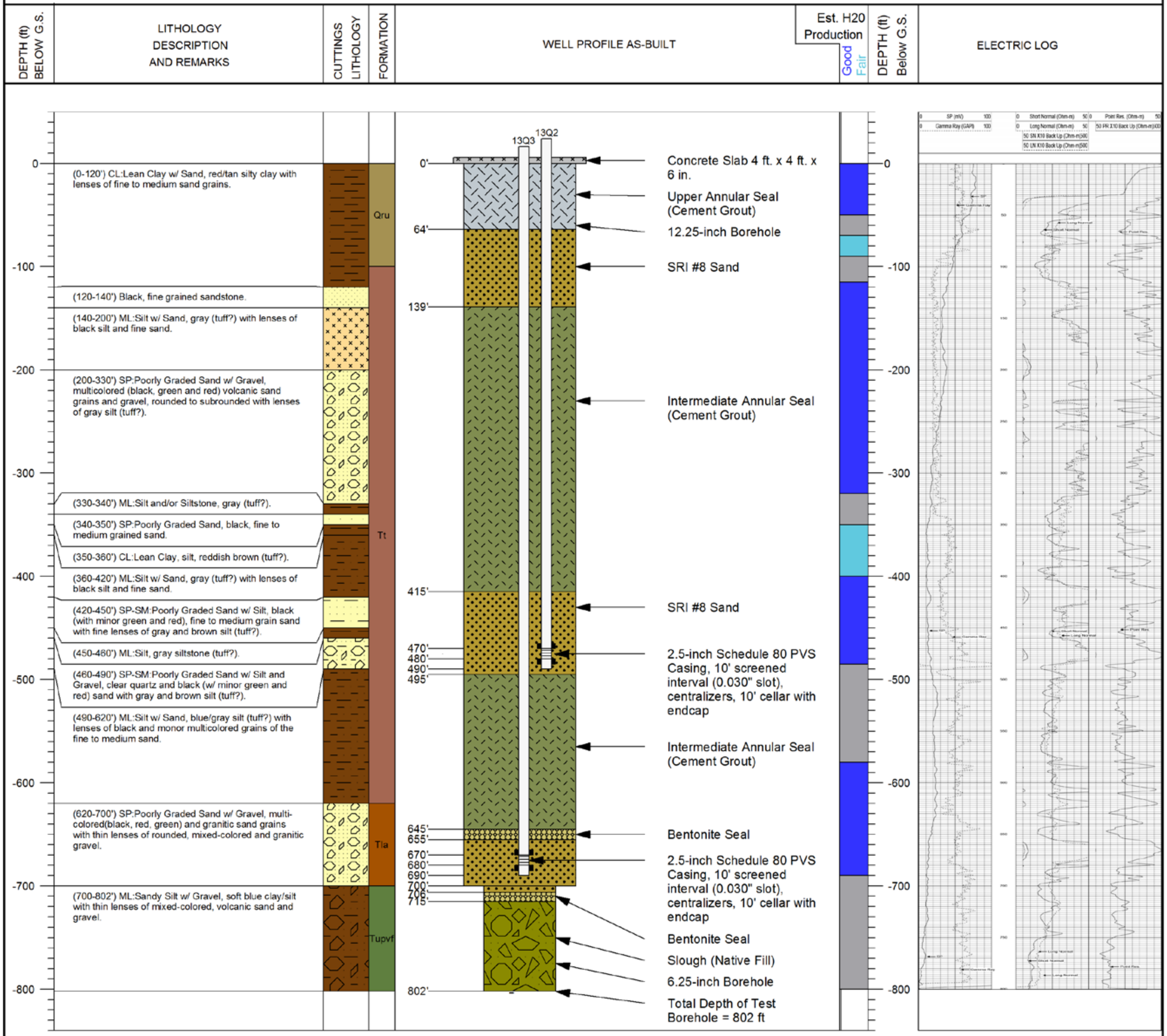
Figure A-6. As-built for double-completion observation well; state well numbers: 19N02E13Q002M and 19N02E13Q003M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Butte Co. - AB303 Drilling Contract
FEATURE / USE	Multicompletion Monitoring Well
LOCATION	0.2 mi. west of Hwy 99E on Richvale Hwy
COORDINATES	NAD83, UTM, Zone 10
EASTING	612378
NORTHING	4372467
GSE (ft-msl)	117.6' (informal survey)
DRILL DATE	08/02/05 - 08/11/2005
DRILLING METHOD	Direct Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	816262

STATE WELL NUMBER		19N02E13Q002M	19N02E13Q003M	Blank
LOCAL IDENTIFICATION		13Q2 - Intermediate	13Q3 - Deep	
WELL DEPTH	(ft-bgs)	495	706	
TEST HOLE DEPTH	(ft-bgs)	802	802	
TOP OF SCREEN	(ft-bgs)	470	670	
BOTTOM OF SCREEN	(ft-bgs)	480	680	
SANITARY SEAL	(ft-bgs)	(0-64') Cement Slurry	(0-64') Cement Slurry	
REFERENCE POINT	(ft-msl)	120.4	120.25	
SITE GEOLOGIST		Spangler	COMMENTS LaMalfa Farms	

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-120') CL:Lean Clay w/ Sand, red/tan silty clay with lenses of fine to medium sand grains.

(120-140') Black, fine grained sandstone.

(140-200') ML:Silt w/ Sand, gray (tuff?) with lenses of black silt and fine sand.

(200-330') SP:Poorly Graded Sand w/ Gravel, multicolored (black, green and red) volcanic sand grains and gravel, rounded to subrounded with lenses of gray silt (tuff?).

(330-340') ML:Silt and/or Siltstone, gray (tuff?).

(340-350') SP:Poorly Graded Sand, black, fine to medium grained sand.

(350-360') CL:Lean Clay, silt, reddish brown (tuff?).

(360-420') ML:Silt w/ Sand, gray (tuff?) with lenses of black silt and fine sand.

(420-450') SP-SM:Poorly Graded Sand w/ Silt, black (with minor green and red), fine to medium grain sand with fine lenses of gray and brown silt (tuff?).

(450-460') ML:Silt, gray siltstone (tuff?).

(460-490') SP-SM:Poorly Graded Sand w/ Silt and Gravel, clear quartz and black (w/ minor green and red) sand with gray and brown silt (tuff?).

(490-620') ML:Silt w/ Sand, blue/gray silt (tuff?) with lenses of black and monor multicolored grains of the fine to medium sand.

(620-700') SP:Poorly Graded Sand w/ Gravel, multi-colored(black, red, green) and granitic sand grains with thin lenses of rounded, mixed-colored and granitic gravel.

(700-802') ML:Sandy Silt w/ Gravel, soft blue clay/silt with thin lenses of mixed-colored, volcanic sand and gravel.

Geologic Legend:
Qru - Riverbank Formation (upper)
Tt - Tuscan Formation
Tla - Laguna Formation
Tupvf - Upper Princeton Valley Fill Group

Prepared By: R. Hull Date: 2/21/13 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

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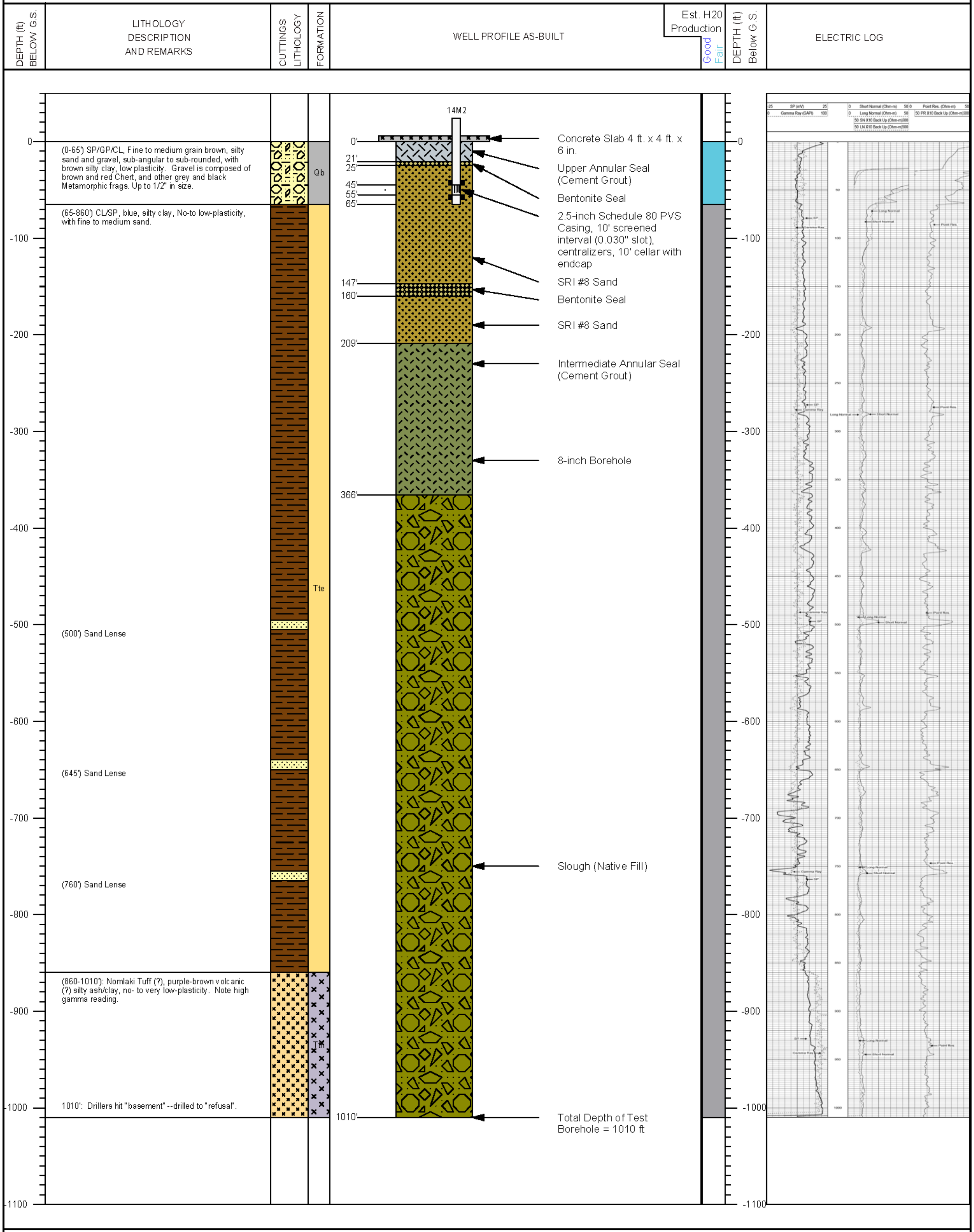
Figure A-7. As-built for single-completion observation well; state well number: 19N04W14M002M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Glenn County AB303 Drilling Project	STATE WELL NUMBER	19N04W14M002M	Blank	Blank
FEATURE / USE	Single Completion Monitoring Well	LOCAL IDENTIFICATION	14M2 - Shallow		
LOCATION	Glenn Co., Road BB, ~1.5 mil S of Hwy 162	WELL DEPTH (ft-bgs)	147		
COORDINATES	NAD83, UTM, Zone 10	TEST HOLE DEPTH (ft-bgs)	1010		
EASTING	561582.077	TOP OF SCREEN (ft-bgs)	45		
NORTHING	4372764.018	BOTTOM OF SCREEN (ft-bgs)	55		
GSE (ft-msl)	185.994 (DWR Elevation Survey)	SANITARY SEAL (ft-bgs)	(0-25') Cement/Bentonite		
DRILL DATE	02/24/2005 - 03/17/2005	REFERENCE POINT (ft-msl)	187.825 (El. Survey)		
DRILLING METHOD	Mud Rotary	SITE GEOLOGIST	Staton, Lawrence	COMMENTS	Hansen Ranch
DRILLING CONTRACTOR	Eaton Drilling				
WCR	816220				

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-65') SP/GP/CL, Fine to medium grain brown, silty sand and gravel, sub-angular to sub-rounded, with brown silty clay, low plasticity. Gravel is composed of brown and red Chert, and other grey and black Metamorphic frags. Up to 1/2" in size.

(65-860') CL/SP, blue, silty clay, No-to low-plasticity, with fine to medium sand.

(500') Sand Lense

(645') Sand Lense

(760') Sand Lense

(860-1010'): Nomlaki Tuff (?), purple-brown volcanic (?) silty ash/clay, no- to very low-plasticity. Note high gamma reading.

1010': Drillers hit "basement" --drilled to "refusal".

Geologic Legend:
Qb - Basin Deposits
Tte - Tehama Formation
Ttn - Nomlaki Tuff (?)

Prepared By: R. Hull Date: 3/18/2011 File Name & Location:

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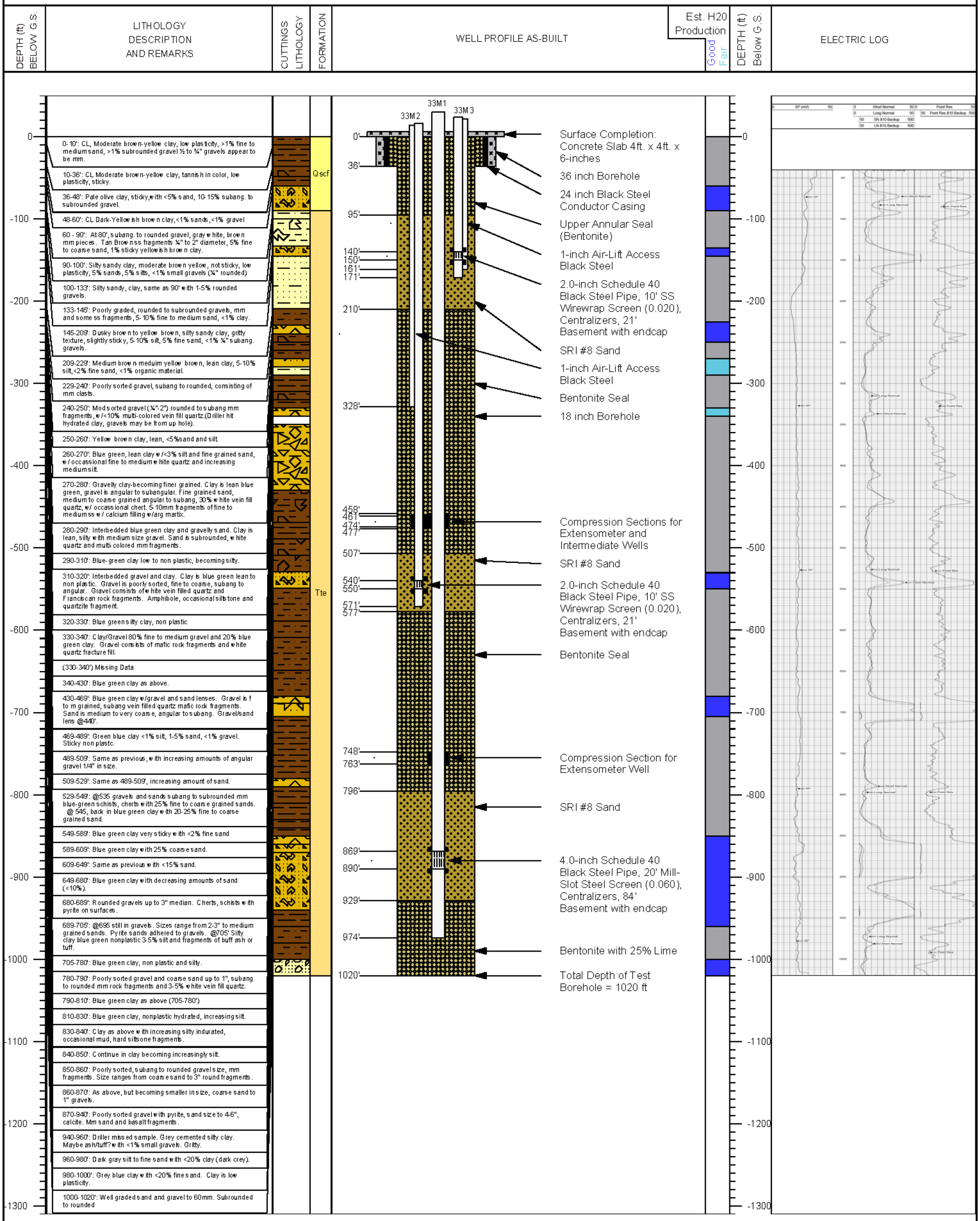
Figure A-8. As-built for triple-completion observation well; state well numbers: 21N02W33M001M, 21N02W33M002M, and 21N02W33M003M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Glenn Co, AB303-1 2001 Drilling Contract
FEATURE / USE	Extensometer/Multicompletion MW
LOCATION	Glenn Co. County Rd S and County Rd 30
COORDINATES	NAD83, UTM, Zone 10
EASTING	577179.782
NORTHING	4387068.250
GSE (ft-msl)	148.9 (from Surveyed Ref Pt)
DRILL DATE	7/12/2002 - 7/24/2002
DRILLING METHOD	Reverse Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	726724

STATE WELL NUMBER	21N02W33M001M	21N02W33M002M	21N02W33M003M
LOCAL IDENTIFICATION	33M1 - Ext	33M2 - Deep	33M3 - Shallow
WELL DEPTH (ft-bgs)	929	577	210
TEST HOLE DEPTH (ft-bgs)	1020	1020	1020
TOP OF SCREEN (ft-bgs)	869	540	140
BOTTOM OF SCREEN (ft-bgs)	890	550	150
SANITARY SEAL (ft-bgs)	(0-95') Cement/Bentonite	(0-95') Cement/Bentonite	(0-95') Cement/Bentonite
REFERENCE POINT (ft-msl)	151.601	151.261	151.493
SITE GEOLOGIST	Staton, McManus, Lawrence	COMMENTS R&D Farms	

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



0-10': CL, Moderate brown-yellow clay, low plasticity, >1% fine to medium sand, >1% subrounded gravel ½ to ¾" gravels appear to be mm.

10-36': CL Moderate brown-yellow clay, tannish in color, low plasticity, sticky.

36-48': Pale olive clay, sticky,with <5% sand, 10-15% subang. to subrounded gravel.

48-60': CL Dark-Yellowish brown clay,<1% sands,<1% gravel

60 - 90': At 80', subang. to rounded gravel, gray white, brown mm pieces. Tan Brown ss fragments ¼" to 2" diameter, 5% fine to coarse sand, 1% sticky yellowish brown clay.

90-100': Silty sandy clay, moderate brown yellow, not sticky, low plasticity, 5% sands, 5% silts, <1% small gravels (¼" rounded)

100-133': Silty sandy, clay, same as 90' with 1-5% rounded gravels.

133-145': Poorly graded, rounded to subrounded gravels, mm and some ss fragments, 5-10% fine to medium sand, <1% clay.

145-209': Dusky brown to yellow brown, silty sandy clay, gritty texture, slightly sticky, 5-10% silt, 5% fine sand, <1% ¼" subang. gravels.

209-229': Medium brown-meduim yellow brown, lean clay, 5-10% silt,<2% fine sand, <1% organic material.

229-240': Poorly sorted gravel, subang to rounded, consisting of mm clasts.

240-250': Mod sorted gravel (¼"-2") rounded to subang mm fragments, w/<10% multi-colored vein fill quartz.(Driller hit hydrated clay, gravels may be from up hole).

250-260': Yellow brown clay, lean, <5%sand and silt.

260-270': Blue green, lean clay w/<3% silt and fine grained sand, w/occassional fine to medium white quartz and increasing medium silt.

270-280': Gravelly clay-becoming finer grained. Clay is lean blue green, gravel is angular to subangular. Fine grained sand, medium to coarse grained angular to subang, 30% white vein fill quartz, w/ occassional chert. 5-10mm fragments of fine to medium ss w/ calcium filling w/arg martix.

280-290': Interbedded blue green clay and gravelly sand. Clay is lean, silty with medium size gravel. Sand is subrounded, white quartz and multi-colored mm fragments.

290-310': Blue-green clay low to non plastic, becoming silty.

310-320': Interbedded gravel and clay. Clay is blue green lean to non plastic. Gravel is poorly sorted, fine to coarse, subang to angular. Gravel consists of white vein filled quartz and Franciscan rock fragments. Amphibole, occasional siltstone and quartzite fragment.

320-330': Blue green silty clay, non plastic

330-340': Clay/Gravel 80% fine to medium gravel and 20% blue green clay. Gravel consists of mafic rock fragments and white quartz fracture fill.

(330-340') Missing Data

340-430': Blue green clay as above.

430-469': Blue green clay w/gravel and sand lenses. Gravel is f to m grained, subang vein filled quartz mafic rock fragments. Sand is medium to very coarse, angular to subang. Gravel/sand lens @440'.

469-489': Green blue clay <1% silt, 1-5% sand, <1% gravel. Sticky non plastc.

489-509': Same as previous, with increasing amounts of angular gravel 1/4" in size.

509-529': Same as 489-509', increasing amount of sand.

529-549': @535 gravels and sands subang to subrounded mm blue-green schists, cherts with 25% fine to coarse grained sands. @ 545, back in blue green clay with 20-25% fine to coarse grained sand.

549-589': Blue green clay very sticky with <2% fine sand

589-609': Blue green clay with 25% coarse sand.

609-649': Same as previous with <15% sand.

649-680': Blue green clay with decreasing amounts of sand (<10%).

680-689': Rounded gravels up to 3" median. Cherts, schists with pyrite on surfaces.

689-705': @695 still in gravels. Sizes range from 2-3" to medium grained sands. Pyrite sands adhered to gravels. @705' Silty clay blue green nonplastic 3-5% silt and fragments of buff ash or tuff.

705-780': Blue green clay, non plastic and silty.

780-790': Poorly sorted gravel and coarse sand up to 1", subang to rounded mm rock fragments and 3-5% white vein fill quartz.

790-810': Blue green clay as above (705-780')

810-830': Blue green clay, nonplastic hydrated, increasing silt.

830-840': Clay as above with increasing silty indurated, occasional mud, hard siltsone fragments.

840-850': Continue in clay becoming increasingly silt.

850-860': Poorly sorted, subang to rounded gravel size, mm fragments. Size ranges from coarse sand to 3" round fragments.

860-870': As above, but becoming smaller in size, coarse sand to 1" gravels.

870-940': Poorly sorted gravel with pyrite, sand size to 4-6", calcite. Mm sand and basalt fragments.

940-960': Driller missed sample. Grey cemented silty clay. Maybe ash/tuff? with <1% small gravels. Gritty.

960-980': Dark gray silt to fine sand with <20% clay (dark crey).

980-1000': Grey blue clay with <20% fine sand. Clay is low plasticity.

1000-1020': Well graded sand and gravel to 60mm. Subrounded to rounded

Geologic Legend:
Qscf - Stoney Creek Fan Alluvium
Tte - Tehama Formation

Prepared By: R. Hull Date: 3/18/2011 File Name & Location:

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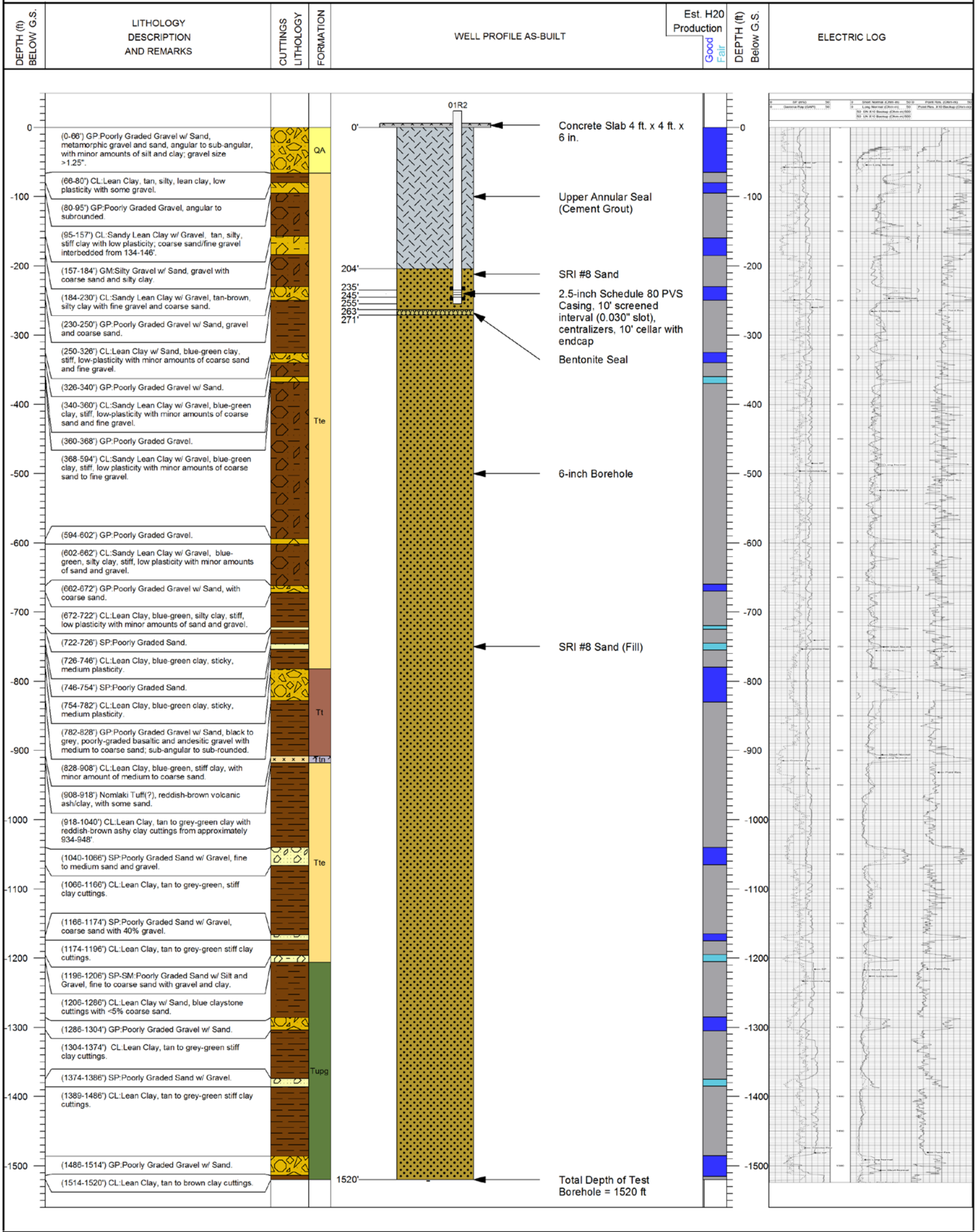
Figure A-9. **As-built for single-completion observation well; state well number: 21N03W01R002M**

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Orland-Artois Water District	STATE WELL NUMBER	21N03W01R002M	Blank	Blank
FEATURE / USE	Single Completion Monitoring Well	LOCAL IDENTIFICATION	01R2 - Shallow Single		
LOCATION	Glenn County: NW Corner RD 25 and P, Orland	WELL DEPTH (ft-bgs)	263		
COORDINATES	NAD83, UTM, Zone 10	TEST HOLE DEPTH (ft-bgs)	1520		
EASTING	573681.897	TOP OF SCREEN (ft-bgs)	235		
NORTHING	4394402.728	BOTTOM OF SCREEN (ft-bgs)	245		
GSE (ft-msl)	203.279 (DWR Elevation Survey)	SANITARY SEAL (ft-bgs)	(0-204') Sand Slurry		
DRILL DATE	12/4/2003 - 12/12/2003	REFERENCE POINT (ft-msl)	206.769 (El. Survey)		
DRILLING METHOD	Reverse Rotary	SITE GEOLOGIST	Staton	COMMENTS	
DRILLING CONTRACTOR	Eaton Drilling				
WCR	726894				

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-66') GP:Poorly Graded Gravel w/ Sand, metamorphic gravel and sand, angular to sub-angular, with minor amounts of silt and clay; gravel size >1.25".

(66-80') CL:Lean Clay, tan, silty, lean clay, low plasticity with some gravel.

(80-95') GP:Poorly Graded Gravel, angular to subrounded.

(95-157') CL:Sandy Lean Clay w/ Gravel, tan, silty, stiff clay with low plasticity; coarse sand/fine gravel interbedded from 134-146'.

(157-184') GM:Silty Gravel w/ Sand, gravel with coarse sand and silty clay.

(184-230') CL:Sandy Lean Clay w/ Gravel, tan-brown, silty clay with fine gravel and coarse sand.

(230-250') GP:Poorly Graded Gravel w/ Sand, gravel and coarse sand.

(250-326') CL:Lean Clay w/ Sand, blue-green clay, stiff, low-plasticity with minor amounts of coarse sand and fine gravel.

(326-340') GP:Poorly Graded Gravel w/ Sand.

(340-360') CL:Sandy Lean Clay w/ Gravel, blue-green clay, stiff, low-plasticity with minor amounts of coarse sand and fine gravel.

(360-368') GP:Poorly Graded Gravel.

(368-594') CL:Sandy Lean Clay w/ Gravel, blue-green clay, stiff, low plasticity with minor amounts of coarse sand to fine gravel.

(594-602') GP:Poorly Graded Gravel.

(602-662') CL:Sandy Lean Clay w/ Gravel, blue-green, silty clay, stiff, low plasticity with minor amounts of sand and gravel.

(662-672') GP:Poorly Graded Gravel w/ Sand, with coarse sand.

(672-722') CL:Lean Clay, blue-green, silty clay, stiff, low plasticity with minor amounts of sand and gravel.

(722-726') SP:Poorly Graded Sand.

(726-746') CL:Lean Clay, blue-green clay, sticky, medium plasticity.

(746-754') SP:Poorly Graded Sand.

(754-782') CL:Lean Clay, blue-green clay, sticky, medium plasticity.

(782-828') GP:Poorly Graded Gravel w/ Sand, black to grey, poorly-graded basaltic and andesitic gravel with medium to coarse sand; sub-angular to sub-rounded.

(828-908') CL:Lean Clay, blue-green, stiff clay, with minor amount of medium to coarse sand.

(908-918') Nomlaki Tuff(?), reddish-brown volcanic ash/clay, with some sand.

(918-1040') CL:Lean Clay, tan to grey-green clay with reddish-brown ashy clay cuttings from approximately 934-948'.

(1040-1066') SP:Poorly Graded Sand w/ Gravel, fine to medium sand and gravel.

(1066-1166') CL:Lean Clay, tan to grey-green, stiff clay cuttings.

(1166-1174') SP:Poorly Graded Sand w/ Gravel, coarse sand with 40% gravel.

(1174-1196') CL:Lean Clay, tan to grey-green stiff clay cuttings.

(1196-1206') SP-SM:Poorly Graded Sand w/ Silt and Gravel, fine to coarse sand with gravel and clay.

(1206-1286') CL:Lean Clay w/ Sand, blue claystone cuttings with <5% coarse sand.

(1286-1304') GP:Poorly Graded Gravel w/ Sand.

(1304-1374') CL:Lean Clay, tan to grey-green stiff clay cuttings.

(1374-1386') SP:Poorly Graded Sand w/ Gravel.

(1389-1486') CL:Lean Clay, tan to grey-green stiff clay cuttings.

(1486-1514') GP:Poorly Graded Gravel w/ Sand.

(1514-1520') CL:Lean Clay, tan to brown clay cuttings.

Geologic Legend:
Qa - Alluvium
Tte - Tehama Formation
Tt - Tuscan Formation
Ttn - Nomlaki Tuff
Tupg - Upper Princeton Valley Fill Group

Prepared By: R. Hull Date: 2/21/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

Figure A-10. As-built for double-completion observation well; state well numbers: 21N04W12A001M and 21N04W12A002M

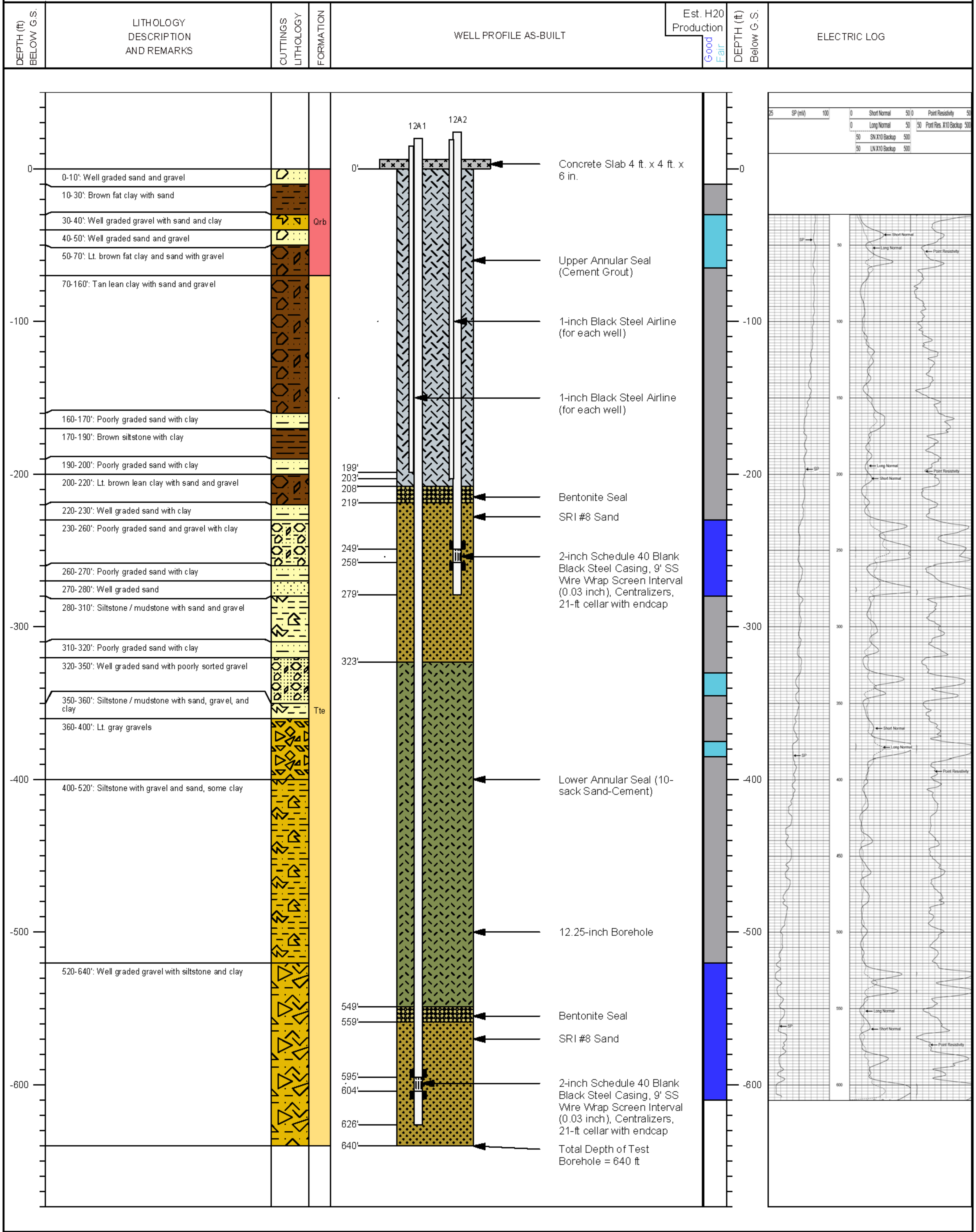
STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Glenn County AB303 2001 Drilling Project
FEATURE / USE	Double Completion Monitoring Well
LOCATION	Glenn County: Rd 25 and D, Big W Farm
COORDINATES	NAD83, UTM, Zone 10
EASTING	564017.603
NORTHING	4394404.887
GSE (ft-msl)	247.5 (DWR Elevation Survey)
DRILL DATE	08/19/2002 - 08/27/2002
DRILLING METHOD	Direct Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	726739

STATE WELL NUMBER	21N04W12A001M	21N04W12A002M	Blank
LOCAL IDENTIFICATION	12A1 - Deep (abandoned)	12A2 - Shallow	
WELL DEPTH (ft-bgs)	640	323	
TEST HOLE DEPTH (ft-bgs)	640	640	
TOP OF SCREEN (ft-bgs)	595	249	
BOTTOM OF SCREEN (ft-bgs)	604	258	
SANITARY SEAL (ft-bgs)	(0-208') Cement/Bentonite	(0-208') Cement/Bentonite	
REFERENCE POINT (ft-msl)	249.33 (El. Survey)	249.88 (El. Survey)	
SITE GEOLOGIST	Staton, Spangler	COMMENTS	

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



0-10': Well graded sand and gravel
10-30': Brown fat clay with sand
30-40': Well graded gravel with sand and clay
40-50': Well graded sand and gravel
50-70': Lt. brown fat clay and sand with gravel
70-160': Tan lean clay with sand and gravel
160-170': Poorly graded sand with clay
170-190': Brown siltstone with clay
190-200': Poorly graded sand with clay
200-220': Lt. brown lean clay with sand and gravel
220-230': Well graded sand with clay
230-260': Poorly graded sand and gravel with clay
260-270': Poorly graded sand with clay
270-280': Well graded sand
280-310': Siltstone / mudstone with sand and gravel
310-320': Poorly graded sand with clay
320-350': Well graded sand with poorly sorted gravel
350-360': Siltstone / mudstone with sand, gravel, and clay
360-400': Lt. gray gravels
400-520': Siltstone with gravel and sand, some clay
520-640': Well graded gravel with siltstone and clay

Concrete Slab 4 ft. x 4 ft. x 6 in.

Upper Annular Seal (Cement Grout)

1-inch Black Steel Airline (for each well)

1-inch Black Steel Airline (for each well)

Bentonite Seal

SRI #8 Sand

2-inch Schedule 40 Blank Black Steel Casing, 9' SS Wire Wrap Screen Interval (0.03 inch), Centralizers, 21-ft cellar with endcap

Lower Annular Seal (10-sack Sand-Cement)

12.25-inch Borehole

Bentonite Seal

SRI #8 Sand

2-inch Schedule 40 Blank Black Steel Casing, 9' SS Wire Wrap Screen Interval (0.03 inch), Centralizers, 21-ft cellar with endcap

Total Depth of Test Borehole = 640 ft

Geologic Legend:
Qrb - Red Bluff Formation
Tte - Tehama Formation

Prepared By: R. Hull Date: 3/18/2011 File Name & Location:

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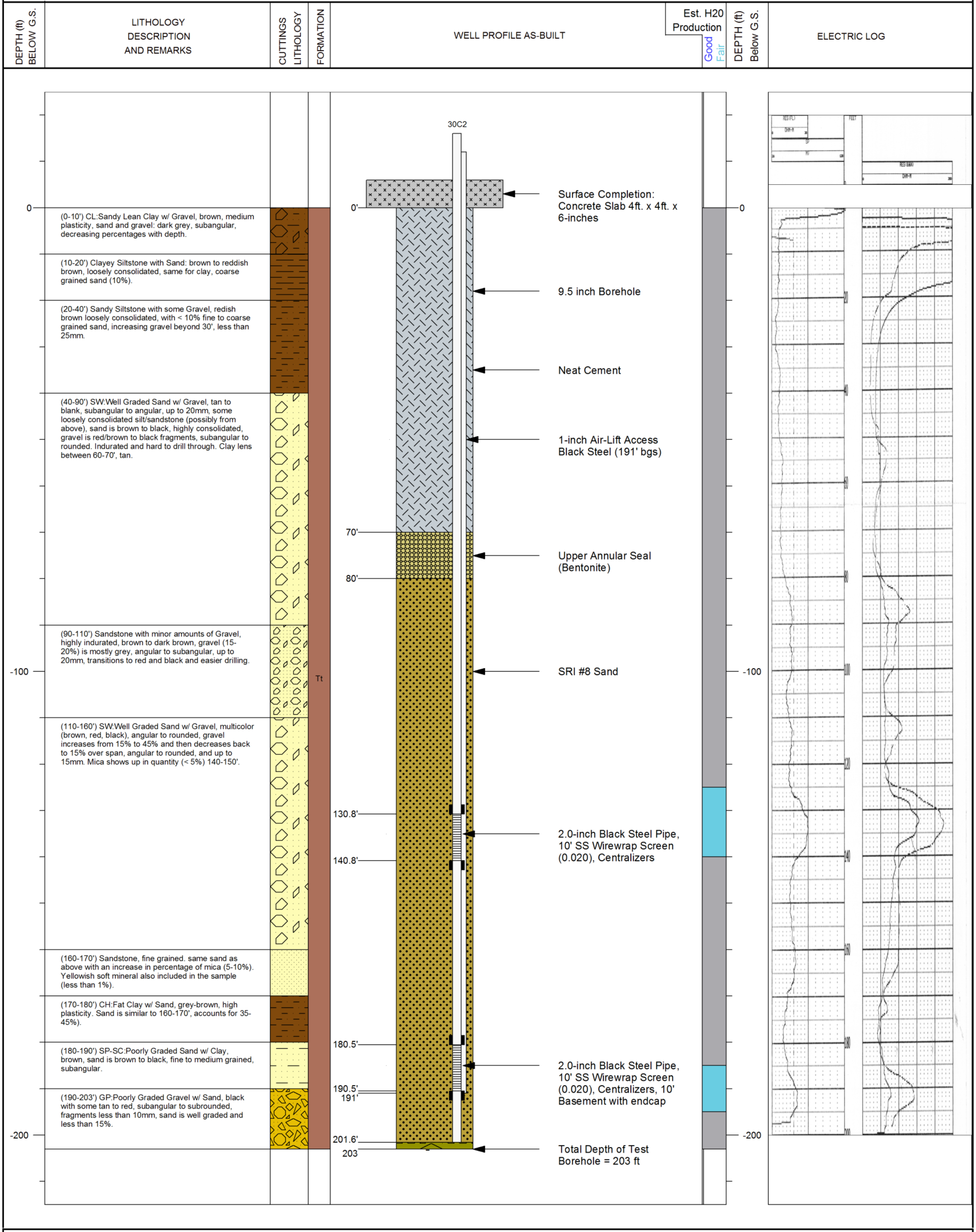
Figure A-11. **As-built for quadruple-completion observation well; state well number: 22N02E30C002M**

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Pending	STATE WELL NUMBER	22N02E30C002M	Blank	Blank
FEATURE / USE	Single Monitoring Well	LOCAL IDENTIFICATION	30C2 - Shallow		
LOCATION	Butte Co., Humboldt and El Monte Rd, Chico	WELL DEPTH (ft-bgs)	201.6		
COORDINATES	NAD83, UTM, Zone 10	TEST HOLE DEPTH (ft-bgs)	203		
EASTING	602978.745	TOP OF SCREEN (ft-bgs)	130.8		
NORTHING	4399399.013	BOTTOM OF SCREEN (ft-bgs)	190.5		
GSE (ft-msl)	241.3	SANITARY SEAL (ft-bgs)	(0-70') Neat Cement		
DRILL DATE	11/21/2001	REFERENCE POINT (ft-msl)	242.8		
DRILLING METHOD	Mud Rotary	SITE GEOLOGIST	Lawrence	COMMENTS	
DRILLING CONTRACTOR	Spectrum Exploration				
WCR	782044				

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-10') CL:Sandy Lean Clay w/ Gravel, brown, medium plasticity, sand and gravel: dark grey, subangular, decreasing percentages with depth.

(10-20') Clayey Siltstone with Sand: brown to reddish brown, loosely consolidated, same for clay, coarse grained sand (10%).

(20-40') Sandy Siltstone with some Gravel, redish brown loosely consolidated, with < 10% fine to coarse grained sand, increasing gravel beyond 30', less than 25mm.

(40-90') SW:Well Graded Sand w/ Gravel, tan to blank, subangular to angular, up to 20mm, some loosely consolidated silt/sandstone (possibly from above), sand is brown to black, highly consolidated, gravel is red/brown to black fragments, subangular to rounded. Indurated and hard to drill through. Clay lens between 60-70', tan.

(90-110') Sandstone with minor amounts of Gravel, highly indurated, brown to dark brown, gravel (15-20%) is mostly grey, angular to subangular, up to 20mm, transitions to red and black and easier drilling.

(110-160') SW:Well Graded Sand w/ Gravel, multicolor (brown, red, black), angular to rounded, gravel increases from 15% to 45% and then decreases back to 15% over span, angular to rounded, and up to 15mm. Mica shows up in quantity (< 5%) 140-150'.

(160-170') Sandstone, fine grained. same sand as above with an increase in percentage of mica (5-10%). Yellowish soft mineral also included in the sample (less than 1%).

(170-180') CH:Fat Clay w/ Sand, grey-brown, high plasticity. Sand is similar to 160-170', accounts for 35-45%).

(180-190') SP-SC:Poorly Graded Sand w/ Clay, brown, sand is brown to black, fine to medium grained, subangular.

(190-203') GP:Poorly Graded Gravel w/ Sand, black with some tan to red, subangular to subrounded, fragments less than 10mm, sand is well graded and less than 15%.

Geologic Legend: Tt - Tuscan Formation

Prepared By: R. Hull Date: 2/21/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

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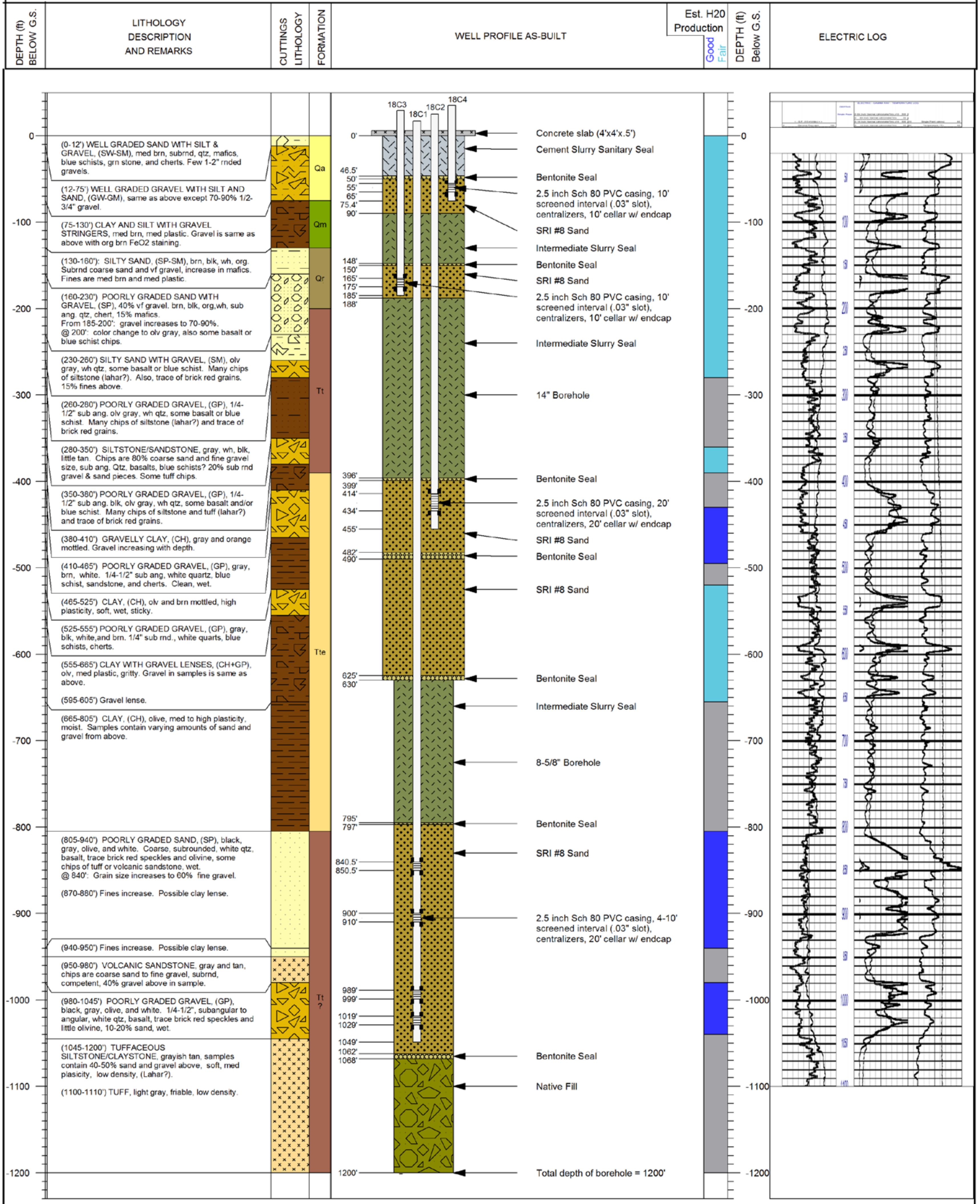
Figure A-12. As-built for quadruple-completion observation well; state well numbers: 22N02W18C001M, 22N02W18C002M, 22N02W18C003M, and 22N02W18C004M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Stony Creek Fan Partners - 3 Districts
FEATURE / USE	Multicompletion Monitoring Well
LOCATION	Glenn Co. - Road 9 (0.2 miles east of Rd P)
COORDINATES	NAD83, UTM, Zone 10
EASTING	573963.238
NORTHING	4402387.601
GSE (ft-msl)	221 (USGS Topographic map)
DRILL DATE	7/31/2006 - 8/11/2006
DRILLING METHOD	Mud Rotary
DRILLER	Eaton Drilling
WCR	E044014

STATE WELL NUMBER	22N02W18C001M	22N02W18C002M	22N02W18C003M	22N02W18C004M
LOCAL IDENTIFICATION	18C1 - Deep	18C2 - Deep Inter	18C3 - Shall Inter	18C4 - Shallow
WELL DEPTH (ft-bgs)	1062	482	188	90
TEST HOLE DEPTH (ft-bgs)	1200	1200	1200	1200
TOP OF SCREEN (ft-bgs)	840.5	414	165	55
BOTTOM OF SCREEN (ft-bgs)	1029	434	175	65
SANITARY SEAL (ft-bgs)	0-50 Cement Slurry	0-50 Cement Slurry	0-50 Cement Slurry	0-50 Cement Slurry
REFERENCE POINT (ft-msl)	222.2	222.4	223.1	223.5
SITE GEOLOGIST	Ehorn	COMMENTS		

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-12') WELL GRADED SAND WITH SILT & GRAVEL, (SW-SM), med brn, subrnd, qtz, mafics, blue schists, grn stone, and cherts. Few 1-2" rnded gravels.

(12-75') WELL GRADED GRAVEL WITH SILT AND SAND, (GW-GM), same as above except 70-90% 1/2-3/4" gravel.

(75-130') CLAY AND SILT WITH GRAVEL STRINGERS, med brn, med plastic. Gravel is same as above with org brn FeO2 staining.

(130-160'): SILTY SAND, (SP-SM), brn, blk, wh, org. Subrnd coarse sand and vf gravel, increase in mafics. Fines are med brn and med plastic.

(160-230') POORLY GRADED SAND WITH GRAVEL, (SP), 40% vf gravel. brn, blk, org,wh, sub ang. qtz, chert, 15% mafics.
From 185-200': gravel increases to 70-90%.
@ 200': color change to olv gray, also some basalt or blue schist chips.

(230-260') SILTY SAND WITH GRAVEL, (SM), olv gray, wh qtz, some basalt or blue schist. Many chips of siltstone (lahar?). Also, trace of brick red grains. 15% fines above.

(260-280') POORLY GRADED GRAVEL, (GP), 1/4-1/2" sub ang. olv gray, wh qtz, some basalt or blue schist. Many chips of siltstone (lahar?) and trace of brick red grains.

(280-350') SILTSTONE/SANDSTONE, gray, wh, blk, little tan. Chips are 80% coarse sand and fine gravel size, sub ang. Qtz, basalts, blue schists? 20% sub rnd gravel & sand pieces. Some tuff chips.

(350-380') POORLY GRADED GRAVEL, (GP), 1/4-1/2" sub ang. blk, olv gray, wh qtz, some basalt and/or blue schist. Many chips of siltstone and tuff (lahar?) and trace of brick red grains.

(380-410') GRAVELLY CLAY, (CH), gray and orange mottled. Gravel increasing with depth.

(410-465') POORLY GRADED GRAVEL, (GP), gray, brn, white. 1/4-1/2" sub ang, white quartz, blue schist, sandstone, and cherts. Clean, wet.

(465-525') CLAY, (CH), olv and brn mottled, high plasticity, soft, wet, sticky.

(525-555') POORLY GRADED GRAVEL, (GP), gray, blk, white,and brn. 1/4" sub rnd., white quarts, blue schists, cherts.

(555-665') CLAY WITH GRAVEL LENSES, (CH+GP), olv, med plastic, gritty. Gravel in samples is same as above.

(595-605') Gravel lense.

(665-805') CLAY, (CH), olive, med to high plasticity, moist. Samples contain varying amounts of sand and gravel from above.

(805-940') POORLY GRADED SAND, (SP), black, gray, olive, and white. Coarse, subrounded, white qtz, basalt, trace brick red speckles and olivine, some chips of tuff or volcanic sandstone, wet.
@ 840': Grain size increases to 60% fine gravel.

(870-880') Fines increase. Possible clay lense.

(940-950') Fines increase. Possible clay lense.

(950-980') VOLCANIC SANDSTONE, gray and tan, chips are coarse sand to fine gravel, subrnd, competent, 40% gravel above in sample.

(980-1045') POORLY GRADED GRAVEL, (GP), black, gray, olive, and white. 1/4-1/2", subangular to angular, white qtz, basalt, trace brick red speckles and little olivine, 10-20% sand, wet.

(1045-1200') TUFFACEOUS SILTSTONE/CLAYSTONE, grayish tan, samples contain 40-50% sand and gravel above, soft, med plasicity, low density, (Lahar?).

(1100-1110') TUFF, light gray, friable, low density.

Geologic Legend:
Qa - Alluvium
Qm - Modesto Formation
Qr - Riverbank Formation
Tt - Tuscan Formation
Tte- Tehama Formation

Prepared By: R. Hull Date: 2/21/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

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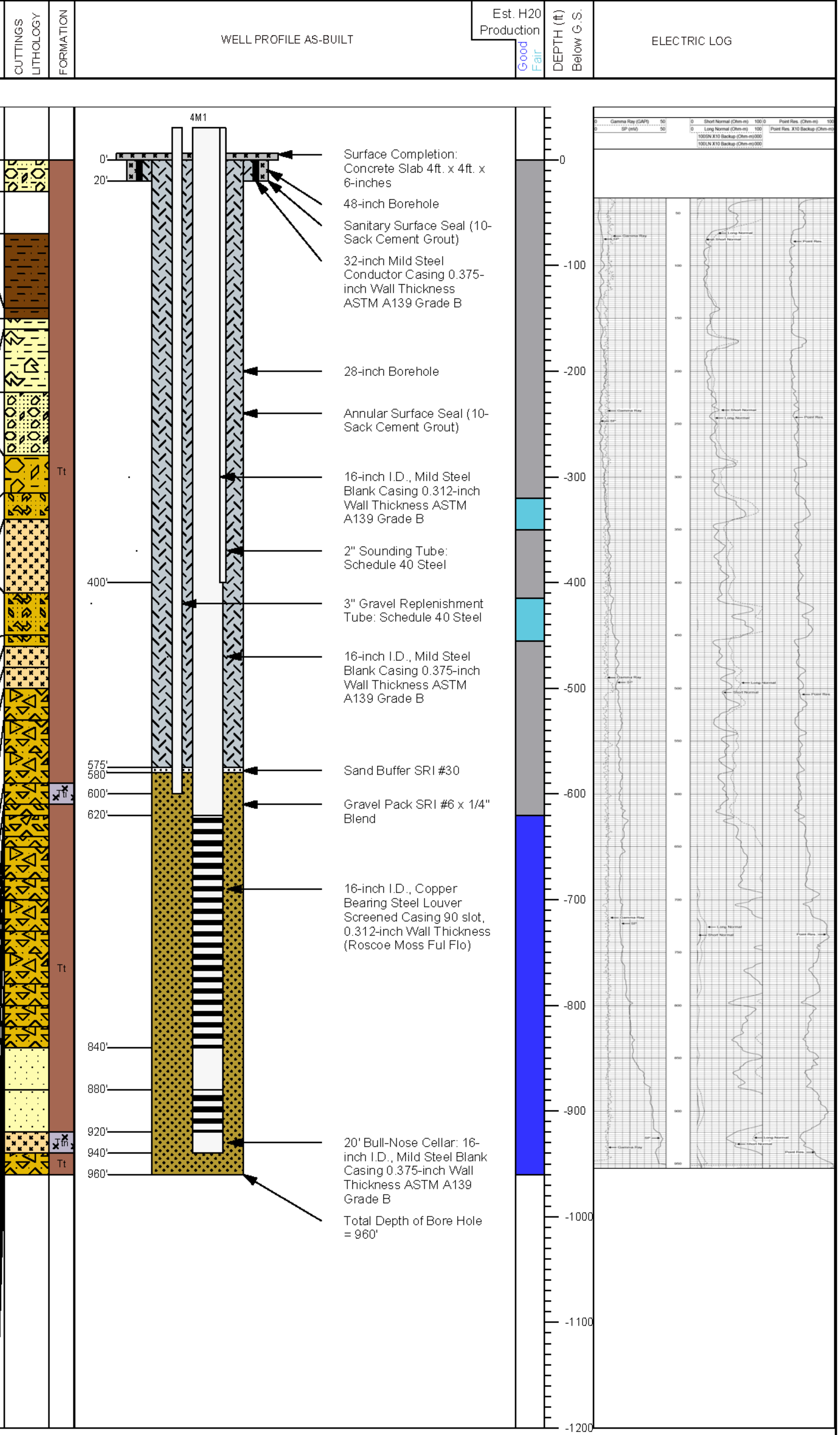
Figure A-13. As-built for pilot test-production well; state well number: 24N01W04M001M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Pilot Test Production Well	STATE WELL NUMBER	24N01W04M001M
FEATURE / USE	Deer Creek Water Exchange Pilot Program	LOCAL IDENTIFICATION	4M1 - Production
LOCATION	Tehama Co, Reed Orchard Rd, Vina, Ca	WELL DEPTH (ft-bgs)	960
COORDINATES	NAD83, UTM, Zone 10	TEST HOLE DEPTH (ft-bgs)	960
EASTING	585864.564	TOP OF SCREEN (ft-bgs)	620
NORTHING	4424073.174	BOTTOM OF SCREEN (ft-bgs)	920
GSE (ft-msl)	310' (USGS Topographic Map)	SANITARY SEAL (ft-bgs)	(0-575') Cement Slurry
DRILL DATE	11/21/2002-01/21/2003	REFERENCE POINT (ft-msl)	310.5
DRILLING METHOD	Mud Rotary	SITE GEOLOGIST	McManus
DRILLING CONTRACTOR	Eaton Drilling	COMMENTS	
WCR	726808		

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation
GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface

DEPTH (ft) BELOW G.S.	LITHOLOGY DESCRIPTION AND REMARKS
0	0-30' Weathered Tuscan "C", andesite and basalt cobbles and tuff
	30-70' Not Logged
	70-140' 20-30% Lt Brn Clay with ~70% tuffaceous sandstone. Potential poor water zone
-100	140-150' Lt Brn, tuffaceous sandstone, very fine-med sand size grains. Potential poor water zone
	150-160' 30-40% Gry-Blk, rnd-sbrnd, basalt frags, 30-40% Tuffaceous ss, 10-20% Clay. Potential poor-fair water zone
-200	160-220' 60-70% Tuffaceous ss, f-vf grain size,15% rnd-sbang blk basalt frags. Potential poor water zone
	220-280' 40-60% Dk Gr-Gr/Blk, Andesite & Andesitic Basalt, rnd-sbrnd, 20-40% tan-med brn, Tuffaceous ss, vf-c grain size, w/occ hornblend inclusions. Potential fair-good water zone
-300	280-315 60-70% Lt Brn, 5-12mm Tuffaceous ss frags, rnd-sbrnd, vf-m sd gr size, 20-30% med gy-rdsh brn- dk gn, 1-10mm Andesite/Basalt frags, sbang-rnd, CA plag phenocryst. Potential fair-good water zone
	315-340 70-90% Andesite/Basalt frags, multi col, 1-4mm, ang-sbrnd, mod-abnt vesicles. 5-10% Lt Brn Tuff (as above). Potential fair-good water zone
	340-410 70-80% Lt brn Tuff (as above), 15-20% Andesite/Basalt frags (as above). Potential poor-fair water zone
-400	410-450 70-80% Andesite/Basalt frags, 3-12mm ang-sbang frags, Basalt is gy-gn col, Andesite has CA incls, 10-20% Lt Brn Tuff (as above). Potential good water zone. Hard drilling
	450-460 70-80% Andesite/Basalt frags as above, with <1% rdsh-brn Chert. Hard drilling
	460-480 60% Tuff, 40% Andesite/Basalt, as above.
-500	480-500 60-70% Tuff, 10-20% Andesite/Basalt Frags.
	500-530 Increase in Andesite/Basalt and frag size. 50% #8 sieve, 50% #30 sieve. Basalt is gr-blk (5GY6) w/5% olivine, Tuff is gry-brn 5YR3, Andesite is dk rdsh brn 10R3
-600	530-590 Increase in Tuffaceous ss (70-80%), decrease in frag size, 10-20% #8 sieve, 65-80% #30 sieve, voc frags are multi col, Tuff consist of f-m sd size gr.
	590-610 As above w/poss Ishi Tuff, 3-5% wht tuff. soft, Bio incl (white tuff from 590-600')
	610-620 Increasing Andesite/Basalt with Color change from brnsh-blk (5YR2) to Olive-blk (SY2). 3-10mm frags, ang-sbang. Plag phenocryst in Andestie, 10-25% olivine/pyroxene incl in basalt. Becming harder
-700	620-640 As above, but very hard drilling ROP=.29'/min
	640-650 70-80% Basalt/Andesite frags, Andesite frags=5-10mm, ang-sbang, <5% Tuff, Hard
-800	650-680 As above w/ 20-30% 5-10mm Andesite frags and 50-60% Basalt frags, Basalt=dk rdsh-brn (10R3) com small vesicles
	680-700 Incr in fines. ~10-15% dk brn cly, 30% blk, f gr, vol sand. Hard spot at 700'
	700-730 Decr fines. 40-50% smpl >#8 sieve. 60-70% Ang-sbrnd olive-blk basalt,10-20% rdsh-bren andesite. Possible good water zone.
-900	730-780 Interbdd hard Basalt/Andesite and f-vf blk Vol Sands. 40% Basalt/Andesite frags <#8 sieve, 45%= #8-30 sieve, 5-10% = #100-200 sieve
	780-800 As above, sl incr rdsh-brn vesicular basalt at 790'
-1000	800-820 As above, incr in larger frags ~25% >#4 sieve, 3-5% lt brn Tuff, welded in part w/v smooth texture and occ micro-lam, 3-5% brick red-rdsh brn 2-10 mm vol frags.
	820-840 As above, vol frags becmng more rndd, sbang-sbrndd, 1-3% wh vein-fill qtz
	840-880 Black Vol Sands. Pred fine grained, uniform
-1100	880-920 Drop in blk sand, incr in 1-3 mm, rnd-sbrnd vol frags. With lt brn fine textured tuff. Pot good water zone
	920-940 Nomlaki tuff ?, Lt tan-lt yellow tuff frags. Soft, occ hydrated, very large 10-50mm samples over shakers. occ blk hornblende incls, occ bcmng sdy, pred sbrnd-rnd frags, occ yellow harder frags w/conch frac, occ micro-lam on surf, occ dk br-blk surf staini
-1200	940-960 Tuff dropping out. 25% fuff, 50% andesite, 15% basalt frags, w/occ wh qts frac filling.



Surface Completion: Concrete Slab 4ft. x 4ft. x 6-inches

48-inch Borehole

Sanitary Surface Seal (10-Sack Cement Grout)

32-inch Mild Steel Conductor Casing 0.375-inch Wall Thickness ASTM A139 Grade B

28-inch Borehole

Annular Surface Seal (10-Sack Cement Grout)

16-inch I.D., Mild Steel Blank Casing 0.312-inch Wall Thickness ASTM A139 Grade B

2" Sounding Tube: Schedule 40 Steel

3" Gravel Replenishment Tube: Schedule 40 Steel

16-inch I.D., Mild Steel Blank Casing 0.375-inch Wall Thickness ASTM A139 Grade B

Sand Buffer SRI #30

Gravel Pack SRI #6 x 1/4" Blend

16-inch I.D., Copper Bearing Steel Louver Screened Casing 90 slot, 0.312-inch Wall Thickness (Roscoe Moss Ful Flo)

20' Bull-Nose Cellar: 16-inch I.D., Mild Steel Blank Casing 0.375-inch Wall Thickness ASTM A139 Grade B

Total Depth of Bore Hole = 960'

Geologic Legend: Tt - Tuscan Formation
Tti: Ishi Tuff
Ttn: Nomlaki Tuff

Prepared By: R. Hull Date: 3/17/2011 File Name & Location:

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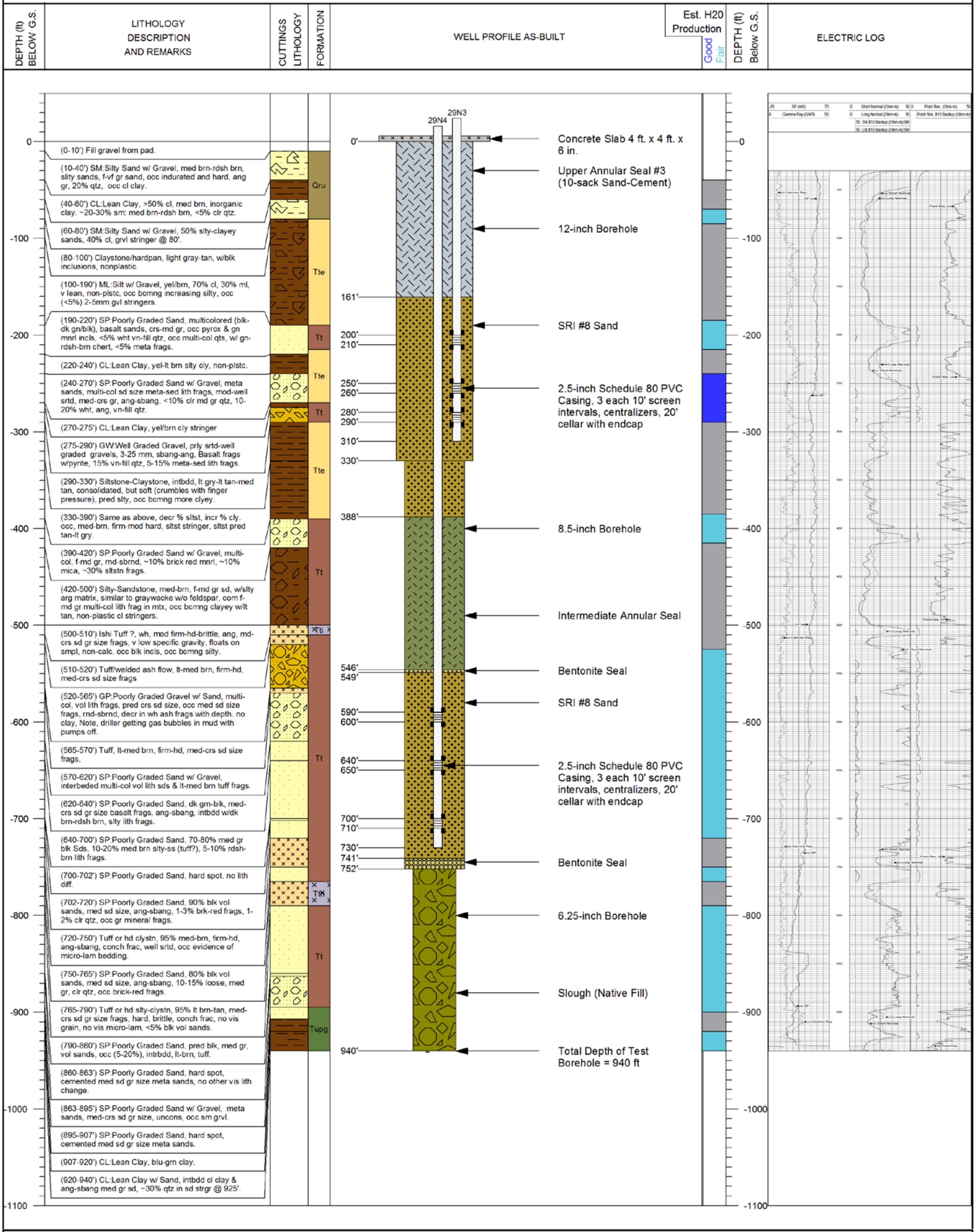
Figure A-14. As-built for double-completion observation well; state well numbers: 24N02W29N003M and 24N02W29N004M

STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Tehama County 2004, AB303 MW Drilling	STATE WELL NUMBER		24N02W29N003M	24N02W29N004M
FEATURE / USE	Multicompletion Monitoring Well	LOCAL IDENTIFICATION		29N3 - Shallow	29N4 - Deep
LOCATION	Tehama County, Hall Rd, East of Corning	WELL DEPTH	(ft-bgs)	388	741
COORDINATES	NAD83, UTM, Zone 10	TEST HOLE DEPTH	(ft-bgs)	940	940
EASTING	574992.886	TOP OF SCREEN	(ft-bgs)	200	590
NORTHING	4416983.795	BOTTOM OF SCREEN	(ft-bgs)	290	710
GSE (ft-msl)	212.4' (from Surveyed Ref Pt)	SANITARY SEAL	(ft-bgs)	(0-161') Cement Slurry	(0-161') Cement Slurry
DRILL DATE	3/10/2004 - 3/19/2004	REFERENCE POINT	(ft-msl)	213.764 (El. Survey)	213.448 (El. Survey)
DRILLING METHOD	Mud Rotary	SITE GEOLOGIST		McManus	COMMENTS
DRILLING CONTRACTOR	Eaton Drilling				
WCR	726917				

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-10') Fill gravel from pad.

(10-40') SM:Silty Sand w/ Gravel, med brn-rdsh brn, slity sands, f-vf gr sand, occ indurated and hard, ang gr, 20% qtz, occ cl clay.

(40-60') CL:Lean Clay, >50% cl, med brn, inorganic clay. ~20-30% sm: med brn-rdsh brn, <5% clr qtz.

(60-80') SM:Silty Sand w/ Gravel, 50% slty-clayey sands, 40% cl, grvl stringer @ 80'.

(80-100') Claystone/hardpan, light gray-tan, w/blk inclusions, nonplastic.

(100-190') ML:Silt w/ Gravel, yel/brn, 70% cl, 30% ml, v lean, non-plstc, occ bcmng increasing silty, occ (<5%) 2-5mm gvl stringers.

(190-220') SP:Poorly Graded Sand, multicolored (blk-dk gn/blk), basalt sands, crs-md gr, occ pyrox & gn mnrl incls, <5% wht vn-fill qtz, occ multi-col qts, w/ gn-rdsh-brn chert, <5% meta frags.

(220-240') CL:Lean Clay, yel-lt brn slty cly, non-plstc.

(240-270') SP:Poorly Graded Sand w/ Gravel, meta sands, multi-col sd size meta-sed lith frags, mod-well srtd, med-crs gr, ang-sbang, <10% clr md gr qtz, 10-20% wht, ang, vn-fill qtz.

(270-275') CL:Lean Clay, yel/brn cly stringer

(275-290') GW:Well Graded Gravel, prly srtd-well graded gravels, 3-25 mm, sbang-ang, Basalt frags w/pyrite, 15% vn-fill qtz, 5-15% meta-sed lith frags.

(290-330') Siltstone-Claystone, intbdd, lt gry-lt tan-med tan, consolidated, but soft (crumbles with finger pressure), pred slty, occ bcmng more clyey.

(330-390') Same as above, decr % sltst, incr % cly. occ, med-brn, firm-mod hard, sltst stringer, sltst pred tan-lt gry.

(390-420') SP:Poorly Graded Sand w/ Gravel, multi-col, f-md gr, rnd-sbrnd, ~10% brick red mnrl, ~10% mica, ~30% sltstn frags.

(420-500') Silty-Sandstone, med-brn, f-md gr sd, w/slty arg matrix, similar to graywacke w/o feldspar, com f-md gr multi-col lith frag in mtx, occ bcmng clayey w/lt tan, non-plastic cl stringers.

(500-510') Ishi Tuff ?, wh, mod firm-hd-brittle, ang, md-crs sd gr size frags, v low specific gravity, floats on smpl, non-calc. occ blk incls, occ bcmng silty.

(510-520') Tuff/welded ash flow, lt-med brn, firm-hd, med-crs sd size frags

(520-565') GP:Poorly Graded Gravel w/ Sand, multi-col, vol lith frags, pred crs sd size, occ med sd size frags, rnd-sbrnd, decr in wh ash frags with depth. no clay, Note, driller getting gas bubbles in mud with pumps off.

(565-570') Tuff, lt-med brn, firm-hd, med-crs sd size frags,

(570-620') SP:Poorly Graded Sand w/ Gravel, interbeded multi-col vol lith sds & lt-med brn tuff frags.

(620-640') SP:Poorly Graded Sand, dk grn-blk, med-crs sd gr size basalt frags, ang-sbang, intbdd w/dk brn-rdsh brn, slty lith frags.

(640-700') SP:Poorly Graded Sand, 70-80% med gr blk Sds, 10-20% med brn slty-ss (tuff?), 5-10% rdsh-brn lith frags.

(700-702') SP:Poorly Graded Sand, hard spot. no lith diff.

(702-720') SP:Poorly Graded Sand, 90% blk vol sands, med sd size, ang-sbang, 1-3% brk-red frags, 1-2% clr qtz, occ gr mineral frags.

(720-750') Tuff or hd clystn, 95% med-brn, firm-hd, ang-sbang, conch frac, well srtd, occ evidence of micro-lam bedding.

(750-765') SP:Poorly Graded Sand, 80% blk vol sands, med sd size, ang-sbang, 10-15% loose, med gr, clr qtz, occ brick-red frags.

(765-790') Tuff or hd slty-clystn, 95% lt brn-tan, med-crs sd gr size frags, hard, brittle, conch frac, no vis grain, no vis micro-lam, <5% blk vol sands.

(790-860') SP:Poorly Graded Sand, pred blk, med gr, vol sands, occ (5-20%), intrbdd, lt-brn, tuff.

(860-863') SP:Poorly Graded Sand, hard spot, cemented med sd gr size meta sands, no other vis lith change.

(863-895') SP:Poorly Graded Sand w/ Gravel, meta sands, med-crs sd gr size, uncons, occ sm grvl.

(895-907') SP:Poorly Graded Sand, hard spot, cemented med sd gr size meta sands.

(907-920') CL:Lean Clay, blu-grn clay.

(920-940') CL:Lean Clay w/ Sand, intbdd cl clay & ang-sbang med gr sd, ~30% qtz in sd strgr @ 925'.

Geologic Legend:
- Qru - Upper Riverbank Formation
- Tte - Tehama Formation
- Tt - Tuscan Formation
- Tupg - Upper Princeton Valley Fill
- Ttn - Nomlaki Tuff (?)
- Tti - Ishi Tuff (?)

Prepared By: R. Hull Date: 2/21/2013 File Name & Location:

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Figure A-15. As-built for triple-completion observation well; state well numbers: 24N03W29Q001M, 24N03W29Q002M, and 24N03W29Q003M

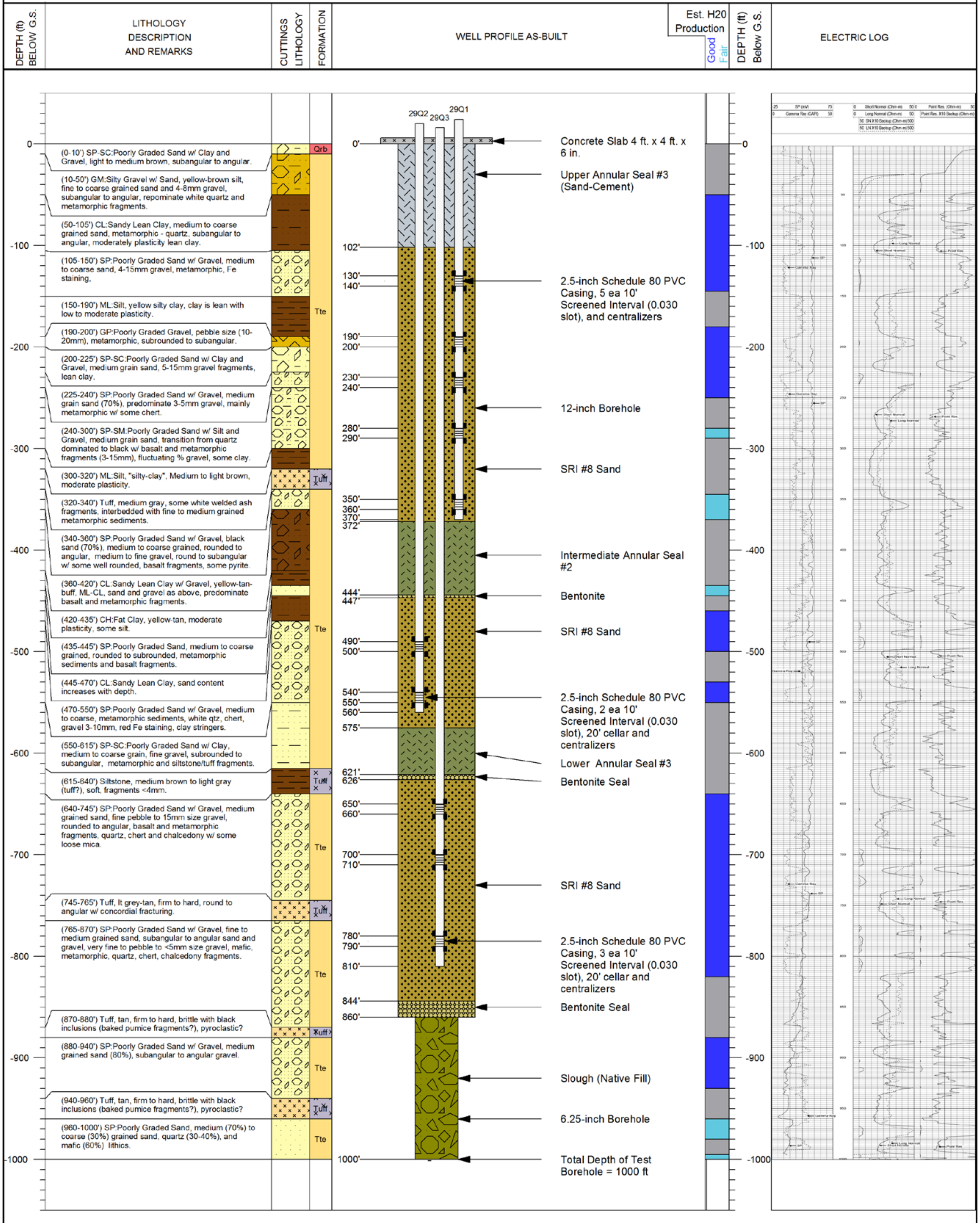
STATE OF CALIFORNIA - RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

PROJECT	Tehama Co AB303 MW Drilling Project
FEATURE / USE	Multicompletion Monitoring Well
LOCATION	Tehama Co, Maywood Farms, Mt Shasta Ave
COORDINATES	NAD83, UTM, Zone 10
EASTING	566285.490
NORTHING	4417284.031
GSE (ft-msl)	314.1 (Based on DWR Elevation Survey)
DRILL DATE	3/22/2004 - 4/2/2004
DRILLING METHOD	Mud Rotary
DRILLING CONTRACTOR	Eaton Drilling
WCR	726918

STATE WELL NUMBER	24N03W29Q001M	24N03W29Q002M	24N03W29Q003M
LOCAL IDENTIFICATION	29Q1 - Shallow	29Q2 - Intermediate	29Q3 - Deep
WELL DEPTH (ft-bgs)	372	575	844
TEST HOLE DEPTH (ft-bgs)	1000	1000	1000
TOP OF SCREEN (ft-bgs)	130	490	650
BOTTOM OF SCREEN (ft-bgs)	360	550	790
SANITARY SEAL (ft-bgs)	(0-102') Cement Slurry	(0-102') Cement Slurry	(0-102') Cement Slurry
REFERENCE POINT (ft-msl)	316.176 (El. Survey)	315.763 (El. Survey)	315.403 (El. Survey)
SITE GEOLOGIST	McManus	COMMENTS	

Note: Estimated water production is a qualitative assessment based on lithology and elog evaluation

GSE: Ground Surface Elevation **ft-msl:** feet-mean sea level **ft-bgs:** feet-below ground surface



(0-10') SP-SC:Poorly Graded Sand w/ Clay and Gravel, light to medium brown, subangular to angular.

(10-50') GM:Silty Gravel w/ Sand, yellow-brown silt, fine to coarse grained sand and 4-8mm gravel, subangular to angular, repominate white quartz and metamorphic fragments.

(50-105') CL:Sandy Lean Clay, medium to coarse grained sand, metamorphic - quartz, subangular to angular, moderately plasticity lean clay.

(105-150') SP:Poorly Graded Sand w/ Gravel, medium to coarse sand, 4-15mm gravel, metamorphic, Fe staining.

(150-190') ML:Silt, yellow silty clay, clay is lean with low to moderate plasticity.

(190-200') GP:Poorly Graded Gravel, pebble size (10-20mm), metamorphic, subrounded to subangular.

(200-225') SP-SC:Poorly Graded Sand w/ Clay and Gravel, medium grain sand, 5-15mm gravel fragments, lean clay.

(225-240') SP:Poorly Graded Sand w/ Gravel, medium grain sand (70%), predominate 3-5mm gravel, mainly metamorphic w/ some chert.

(240-300') SP-SM:Poorly Graded Sand w/ Silt and Gravel, medium grain sand, transition from quartz dominated to black w/ basalt and metamorphic fragments (3-15mm), fluctuating % gravel, some clay.

(300-320') ML:Silt, "silty-clay", Medium to light brown, moderate plasticity.

(320-340') Tuff, medium gray, some white welded ash fragments, interbedded with fine to medium grained metamorphic sediments.

(340-360') SP:Poorly Graded Sand w/ Gravel, black sand (70%), medium to coarse grained, rounded to angular, medium to fine gravel, round to subangular w/ some well rounded, basalt fragments, some pyrite.

(360-420') CL:Sandy Lean Clay w/ Gravel, yellow-tan-buff, ML-CL, sand and gravel as above, predominate basalt and metamorphic fragments.

(420-435') CH:Fat Clay, yellow-tan, moderate plasticity, some silt.

(435-445') SP:Poorly Graded Sand, medium to coarse grained, rounded to subrounded, metamorphic sediments and basalt fragments.

(445-470') CL:Sandy Lean Clay, sand content increases with depth.

(470-550') SP:Poorly Graded Sand w/ Gravel, medium to coarse, metamorphic sediments, white qtz, chert, gravel 3-10mm, red Fe staining, clay stringers.

(550-615') SP-SC:Poorly Graded Sand w/ Clay, medium to coarse grain, fine gravel, subrounded to subangular, metamorphic and siltstone/tuff fragments.

(615-640') Siltstone, medium brown to light gray (tuff?), soft, fragments <4mm.

(640-745') SP:Poorly Graded Sand w/ Gravel, medium grained sand, fine pebble to 15mm size gravel, rounded to angular, basalt and metamorphic fragments, quartz, chert and chalcedony w/ some loose mica.

(745-765') Tuff, lt grey-tan, firm to hard, round to angular w/ concordial fracturing.

(765-870') SP:Poorly Graded Sand w/ Gravel, fine to medium grained sand, subangular to angular sand and gravel, very fine to pebble to <5mm size gravel, mafic, metamorphic, quartz, chert, chalcedony fragments.

(870-880') Tuff, tan, firm to hard, brittle with black inclusions (baked pumice fragments?), pyroclastic?

(880-940') SP:Poorly Graded Sand w/ Gravel, medium grained sand (80%), subangular to angular gravel.

(940-960') Tuff, tan, firm to hard, brittle with black inclusions (baked pumice fragments?), pyroclastic?

(960-1000') SP:Poorly Graded Sand, medium (70%) to coarse (30%) grained sand, quartz (30-40%), and mafic (60%) lithics.

Geologic Legend:
Qrb - Red Bluff Formation
Tte - Tehama Formation

Tuff: Undifferentiated Tuff/Ash Deposits

Prepared By: R. Hull Date: 2/21/2013 File Name & Location: R:\Sections\GGI\DRILLING\2_ LogPlots\Geology_NSacValley

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Appendix B. Northern Sacramento Valley Sand Provenance Study Final Memorandum Report

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www.brownandcaldwell.com

October 12, 2007

BROWN AND
CALDWELL

Mr. Dan McManus
Senior Engineering Geologist
Department of Water Resources—Northern District
2440 Main Street
Red Bluff, California 96080

132332.001/1011

Subject: Northern Sacramento Valley Sand Provenance Study
Final Memorandum Report

Dear Mr. McManus:

Brown and Caldwell, in conjunction with Water Resources Information Management Engineering (WRIME), is pleased to provide the California Department of Water Resources—Northern District (DWR-ND) with the attached final memorandum report summarizing the preliminary results of the Northern Sacramento Valley Sand Provenance Study. Brown and Caldwell has worked closely with our subconsultant, Raymond V. Ingersoll of the University of California, Los Angeles to develop the data and preliminary results.

As detailed in the report, the preliminary results appear very encouraging; with lithic volcanic (Lv) sand grains predominating in the northeast valley (Tuscan Formation), lithic metamorphic sand grains in the west valley (Tehama Formation) and interfingering in the central and southern areas.

The study has also tentatively identified four distinct petrographic trends and compositional suites (petrofacies) using discriminate analysis. These petrofacies are primarily defined by the percentages of the three types of lithic sand grains (Lv, lithic metamorphic (Lm), and lithic sedimentary (Ls), referred to as LmLvLs%, although locations, depths, and other petrographic parameters were also factors. The four tentative petrofacies and potential provenances (source areas) are as follows:

Table 1. Tentative Petrofacies

Petrofacies	Description	Potential Provenance(s)
M	Metamorphic	Coast Ranges Franciscan and/or Klamath terranes
V	Volcanic	Cascades and/or Modoc Plateau
VM	Mixed Volcanic and Metamorphic	Cascades, Modoc Plateau and/or Sierra Nevada
VMS	Mixed Volcanic, Metamorphic, and Sedimentary	Mixed terranes

The results are similar to Brown and Caldwell's Davis area sand provenance studies in that lithic grains predominate, but there is much greater variability in sand compositions and multiple provenances in the North Sacramento Valley compared to the Davis area.

As per the scope of work, the attached Summary of Petrographic Results, by Dr. Ingersoll, includes a discussion of the study methods, materials, references, tables, images and text. Photomicrographs of representative grain types with reference to sample sources were provided electronically prior to the BC/DWR-ND workshop to interpret the results on August 22, 2007 in Red Bluff, California.

Subsequent to the workshop, we reviewed selected thin sections and identified high potassium volcanics in samples 4JI #2, 4JI #3, and 13Q1 #1. These results confirm the workshop's tentative interpretation that some samples in the southern portion of the study area contain non-Tuscan volcanics. We also reviewed the "uncountable" samples and high lithic sedimentary (Ls) samples, and confirmed that there is uncertainty in distinguishing Ls grains from intrabasinal agglomerations. We do not believe either of these factors invalidates DWR's hydrostratigraphic correlations and interpretations, and we recommend that additional samples be selected for petrographic analysis in critical areas, as is currently being contemplated.

We appreciate the opportunity to perform the Sand Provenance Study for DWR, and hope that the results prove useful in aiding DWR's water resources management efforts in the Sacramento Valley. We look forward to continuing to assist you as desired.

Very Truly Yours,

BROWN AND CALDWELL

MARTIN G. STEINPRESS
No. 29
CERTIFIED
HYDROGEOLOGIST

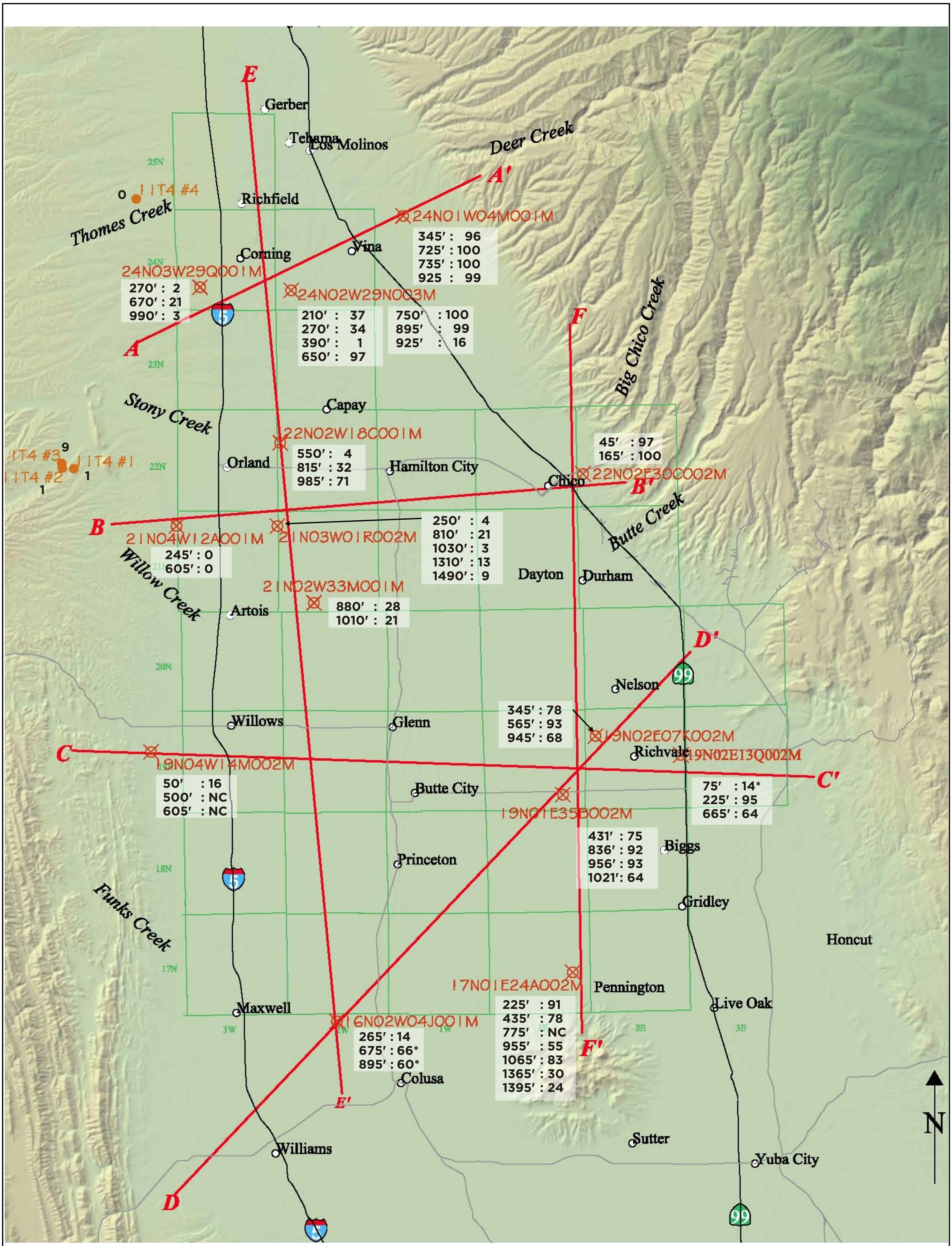
Martin Steinpress
Chief Hydrogeologist

California Professional Geologist #5090
California Certified Hydrogeologist #29

Reviewed by: Robert Vince, P.G., CHg., Brown and Caldwell
Rob Beggs, Ph.D., P.E., Brown and Caldwell

MS:jle

Attachments (3):
Figure 1. Lithic Volcanic (Lv) Percent
Figure 2. Sand Petrofacies
North Sacramento Valley Sand Provenance Study—Summary of Petrographic Results



Legend

- ☒ State Well Number with Sample Depth and Lm Lv Ls % Lv
- ● Surface Sample Showing Lm Lv Ls % Lv
- NC Not Counted
- * High Potassium Lv

SITE
North Sacramento Valley Sand Provenance Study

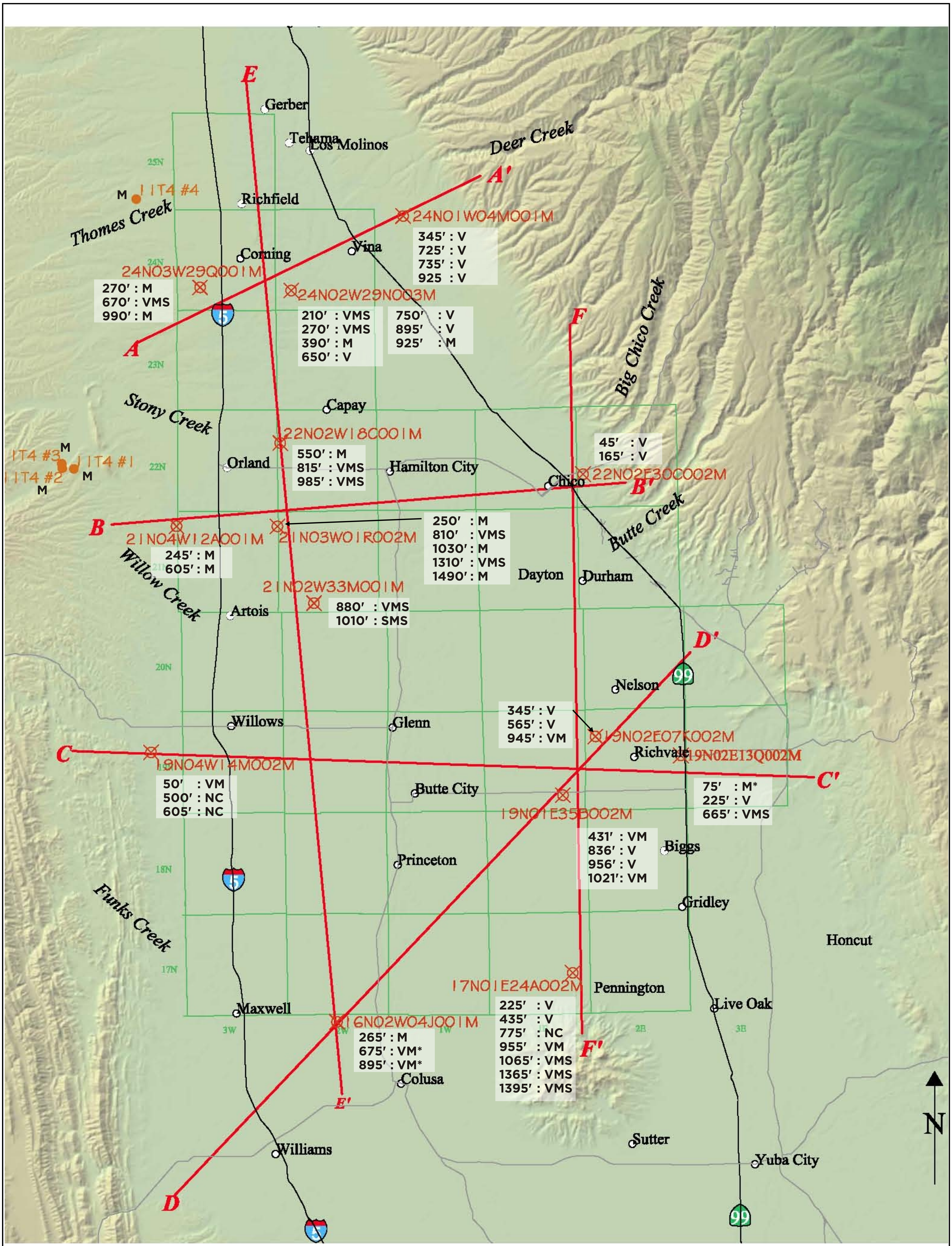
TITLE
Lithic Volcanic (Lv) Percent

BROWN AND CALDWELL

DATE
October 2007

PROJECT
133332.002

Figure
1



Legend

☒ State Well Number with Sample Depth and Petrofacies

● Surface Sample Showing Petrofacies

NC Not Counted

* High Potassium Lv

SITE
North Sacramento Valley Sand Provenance Study

TITLE
Sand Petrofacies

BROWN AND CALDWELL

DATE
October 2007

PROJECT
133332.002

Figure 2

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Northern Sacramento Valley Sand Provenance Study

Summary of Petrographic Results

Raymond V. Ingersoll, PhD
Department of Earth and Space Sciences
University of California
Los Angeles, CA 90095-1567

In Association with Brown and Caldwell

October 12, 2007

INTRODUCTION

The purpose of this study is the petrographic characterization of sand recovered from multiple wells, outcrops, and modern sands from the Sacramento Valley of northern California. The study was conducted under subcontract to Brown and Caldwell for the California Department of Water Resources—Northern District (DWR-ND). The location and depth of recovery for the samples were unknown to the petrographers (R.V.Ingersoll and M.G.Steinpress) at the time of the study, to prevent operator bias. Composition of the sand (as determined petrographically, using a transmitted-light microscope) is primarily a function of the composition of rocks in the drainage areas of the streams or rivers that transported the sand to the depositional sites penetrated by the wells. Thus, knowledge of sand composition allows inferences to be drawn regarding the source (provenance) of the sand. This knowledge, in turn, improves our understanding of dispersal directions of the sand, and therefore, possible architecture and correlations of subsurface sand bodies that are the aquifers that might provide economic water resources. This study defines four distinct compositional suites (petrofacies), reflecting four distinct sources, respectively: M: metamorphic, V: volcanic, VM: mixed volcanic and metamorphic, and VMS: mixed volcanic, metamorphic and sedimentary. These petrofacies reflect the following potential source areas, respectively: M: Coast Ranges Franciscan and/or Klamath terranes; V: Modoc Plateau and/or Cascades; VM: Modoc Plateau, Cascades, and/or Sierra Nevada; VMS: mixed. These conclusions are, however, tentative, as details of the wells and locations were unknown to the author.

METHODS

Fifty-six sand samples were selected by DWR-ND staff, who dried, disaggregated and sieved the samples with 0.0625 mm and 2mm screens. The sample locations are shown in Figure 1. The size fraction remaining between the two screens was the sand from each sample (defined as all particles with diameters between 0.0625 and 2mm; e.g., Pettijohn et al., 1987). Sand represents the best grain size for provenance analysis because it is a grain size that is very common in detrital sediment, and because the individual grains and crystals are conducive to petrographic (microscopic) analysis. These samples were labeled and shipped to UCLA.

A fraction of each sample was given to a technician, who created artificial rocks by mixing the samples with epoxy. These artificial rocks, were then sliced and polished on one side, and mounted on glass slides. The opposite side of each sample was ground and polished until each sample was 0.03mm thick, the standard thickness of “thin sections.” By utilizing standard thicknesses, all petrographers can make use of universally adopted criteria for the identification of minerals and textures (e.g., Kerr, 1959; Deer et al., 1966; Williams et al., 1982; Pettijohn et al., 1987).

The thin sections were etched in concentrated hydrofluoric acid, then stained in a saturated solution of sodium cobaltinitrite (method described by Ingersoll and Cavazza, 1991). This method results in etching of all feldspars (to distinguish them from quartz) and the yellow staining of all grains containing potassium (especially potassium feldspar (Fk) and potassium-rich volcanic lithic fragments (Lv). This staining method has proven to be the most useful in studies of actualistic sand(stone) petrofacies (e.g., Ingersoll, 1990; Ingersoll et al., 1993). Stained thin sections were then cover-slipped, and examined using a petrographic microscope.

Four of the 56 thin sections were determined to be unusable because the sand consisted primarily of intrabasinal material. In other words, rather than consisting of original sand grains transported from source rocks in the stream drainages (extrabasinal grains, the target in any provenance study), most of the sand grains consisted of mudstone created by the agglomeration of fine material within the basin or during transport (intrabasinal). These agglomeration grains, thus, signify little regarding provenance. If these grains were included in the petrographic study, they would be counted as sedimentary lithic fragments (Ls), leading to the erroneous conclusion that the sand was derived from sedimentary rocks. Recognition and exclusion of intrabasinal grains are essential for accurate provenance studies (Zuffa, 1985).

The remaining fifty-two samples were determined to be suitable for point-counting, following methods described by Dickinson (1970, 1985), Ingersoll (1983, 1990), Zuffa (1985), Ingersoll and Cavazza (1991) and Ingersoll et al. (1993). Three-hundred extrabasinal sand grains were counted within each thin section, using an automatic mechanical stage attached to the petrographic microscope. The author (Ingersoll) counted 39 sections; co-worker Steinpress counted 13 sections, in consultation with the author to assure standardization of grain identification. Table 1 defines counted and recalculated point-count parameters. All point-count data and recalculated parameters are summarized in Table 2.

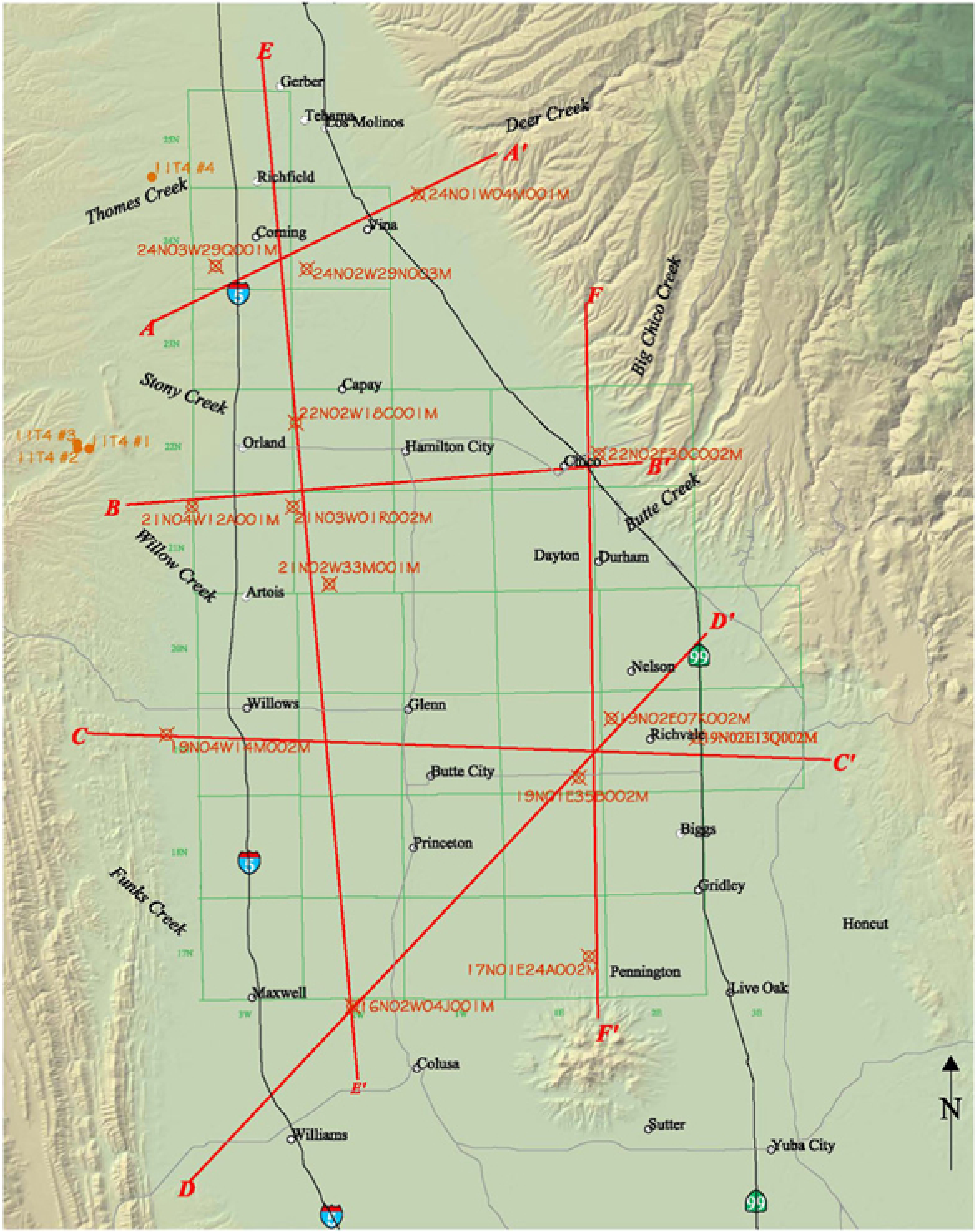

Figure 1. Sample Location Map (DWR-ND)

Table 1. Definition of Point-Count Categories

COUNTED PARAMETERS	
Qm	Monocrystalline quartz
Qp	Polycrystalline quartz
Fp	Plagioclase feldspar
Fk	Potassium feldspar
Lmv	Metavolcanic lithic
Lms	Metasedimentary lithic
Ls	Sedimentary lithic
Lv	Volcanic-hypabyssal lithic
M	Phyllosilicate (mica) minerals
D	Dense (accessory) minerals
S	Serpentinite
Misc.	Miscellaneous and Unidentified
OTHER ABBREVIATIONS	
Q = Qm + Qp	Total quartzose grains
F = Fp + Fk	Total feldspar grains
L = Lm + Lv + Ls	Unstable (nonquartzose) lithic grains
Lm = Lmv + Lms	Metamorphic lithic grains
Lvm = Lv + Lmv	Volcanic-hypabyssal and metavolcanic lithic grains
Lsm = Ls + Lms	Sedimentary and metasedimentary lithic grains
RECALCULATED PARAMETERS AND RATIOS	
QFL%Q = 100 x Q/(Q + F + L)	LmLvLs%Lm = 100 x (Lm/L)
QFL%F = 100 x F/(Q + F + L)	LmLvLs%Lv = 100 x (Lv/L)
QFL%L = 100 x L/(Q + F + L)	LmLvLs%Ls = 100 x (Ls/L)
QmFkFp%Qm = 100 x Qm/(Qm + Fk + Fp)	QpLvmLsm%Qp = 100 x Qp/(L + Qp)
QmFkFp%Fk = 100 x Fk/(Qm + Fk + Fp)	QpLvmLsm%Lvm = 100 x Lvm/(L + Qp)
QmFkFp%Fp = 100 x Fp/(Qm + Fk + Fp)	QpLvmLsm%Lsm = 100 x Lsm/(L + Qp)
%D = 100 x D/300	Fp/F = Fp/(Fp + Fk)
%M = 100 x M/300	Qp/Q = Qp/(Qp + Qm)
%S = 100 x S/300	

Table 2. Original Point-Count Data and Recalculated Parameters

Sample Number	Raw Counts												Recalculated Parameters																
	Qm	Qp	Fk	Fp	Lms	Lmv	Lv	Ls	M	D	S	Misc.	Qp/Q	Fp/F	%M	%D	%S	QFL%			QmFkFp%			LmLvLs%			QpLvmLsm%		
																		Q	F	L	Qm	Fk	Fp	Lm	Lv	Ls	Qp	Lvm	Lsm
1R2#1	120	45	0	0	124	0	5	0	1	2	0	3	0.27	0.00	0.33	0.67	0.00	56.12	0.00	43.88	100.00	0.00	0.00	96.12	3.88	0.00	25.86	2.87	71.26
1R2#2	46	9	0	29	95	30	43	40	0	2	6	0	0.16	1.00	0.00	0.67	2.00	18.84	9.93	71.23	61.33	0.00	38.67	60.10	20.67	19.23	4.15	33.64	62.21
1R2#3	10	0	1	7	48	2	9	220	3	0	0	0	0.00	0.88	1.00	0.00	0.00	3.37	2.69	93.94	55.56	5.56	38.89	17.92	3.23	78.85	0.00	3.94	96.06
1R2#4	30	11	1	16	116	54	30	38	1	3	0	0	0.27	0.94	0.33	1.00	0.00	13.85	5.74	80.41	63.83	2.13	34.04	71.43	12.61	15.97	4.42	33.73	61.85
1R2#5	57	20	5	6	145	24	18	22	0	2	0	0	0.26	0.55	0.00	0.67	0.00	25.93	3.70	70.37	83.82	7.35	8.82	80.86	8.61	10.53	8.73	18.34	72.93
4J1#1	80	45	0	11	86	37	22	13	0	2	0	4	0.36	1.00	0.00	0.67	0.00	42.52	3.74	53.74	87.91	0.00	12.09	77.85	13.92	8.23	22.17	29.06	48.77
4J1#2	70	31	6	14	46	0	110	11	3	3	0	6	0.31	0.70	1.00	1.00	0.00	35.07	6.94	57.99	77.78	6.67	15.56	27.54	65.87	6.59	15.66	55.56	28.79
4J1#3	46	15	28	25	45	13	103	12	0	13	0	0	0.25	0.47	0.00	4.33	0.00	21.25	18.47	60.28	46.46	28.28	25.25	33.53	59.54	6.94	7.98	61.70	30.32
4M1#1	0	0	0	78	0	8	180	0	0	34	0	0	0.00	1.00	0.00	11.33	0.00	0.00	29.32	70.68	0.00	0.00	100.00	4.26	95.74	0.00	0.00	100.00	0.00
4M1#2	0	0	0	84	0	0	188	0	0	28	0	0	0.00	1.00	0.00	9.33	0.00	0.00	30.88	69.12	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
4M1#3	0	0	0	71	0	0	202	0	0	27	0	0	0.00	1.00	0.00	9.00	0.00	0.00	26.01	73.99	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
4M1#4	0	0	0	74	1	1	194	0	0	30	0	0	0.00	1.00	0.00	10.00	0.00	0.00	27.41	72.59	0.00	0.00	100.00	1.02	98.98	0.00	0.00	99.49	0.51
7K2#1	7	2	0	61	14	20	154	9	0	33	0	0	0.22	1.00	0.00	11.00	0.00	3.37	22.85	73.78	10.29	0.00	89.71	17.26	78.17	4.57	1.01	87.44	11.56
7K2#2	2	0	0	53	4	8	210	3	0	15	5	0	0.00	1.00	0.00	5.00	1.67	0.71	18.93	80.36	3.64	0.00	96.36	5.33	93.33	1.33	0.00	96.89	3.11
7K2#3	25	0	12	26	33	17	145	17	6	19	0	0	0.00	0.68	2.00	6.33	0.00	9.09	13.82	77.09	39.68	19.05	41.27	23.58	68.40	8.02	0.00	76.42	23.58
11T4#1	49	13	0	3	180	32	3	10	6	1	3	0	0.21	1.00	2.00	0.33	1.00	21.38	1.03	77.59	94.23	0.00	5.77	94.22	1.33	4.44	5.46	14.71	79.83
11T4#2	53	15	0	4	188	22	2	11	1	1	3	0	0.22	1.00	0.33	0.33	1.00	23.05	1.36	75.59	92.98	0.00	7.02	94.17	0.90	4.93	6.30	10.08	83.61
11T4#3	56	15	0	5	151	9	20	44	0	0	0	0	0.21	1.00	0.00	0.00	0.00	23.67	1.67	74.67	91.80	0.00	8.20	71.43	8.93	19.64	6.28	12.13	81.59
11T4#4	50	12	0	1	205	14	0	17	0	1	0	0	0.19	1.00	0.00	0.33	0.00	20.74	0.33	78.93	98.04	0.00	1.96	92.80	0.00	7.20	4.84	5.65	89.52
11T4#5	NOT COUNTABLE																												
12A1#1	65	85	0	2	131	0	0	11	2	4	0	0	0.57	1.00	0.67	1.33	0.00	51.02	0.68	48.30	97.01	0.00	2.99	92.25	0.00	7.75	37.44	0.00	62.56
12A1#2	70	9	0	0	181	26	0	9	0	4	1	0	0.11	0.00	0.00	1.33	0.33	26.78	0.00	73.22	100.00	0.00	0.00	95.83	0.00	4.17	4.00	11.56	84.44
13Q1#1	57	11	6	29	123	18	23	6	12	15	0	0	0.16	0.83	4.00	5.00	0.00	24.91	12.82	62.27	61.96	6.52	31.52	82.94	13.53	3.53	6.08	22.65	71.27
13Q2#2	10	1	0	54	8	1	169	0	3	53	0	1	0.09	1.00	1.00	17.67	0.00	4.53	22.22	73.25	15.63	0.00	84.38	5.06	94.94	0.00	0.56	94.97	4.47
13Q2#3	15	9	0	43	32	9	127	31	4	30	0	0	0.38	1.00	1.33	10.00	0.00	9.02	16.17	74.81	25.86	0.00	74.14	20.60	63.82	15.58	4.33	65.38	30.29
14M2#1	14	7	5	10	6	9	42	198	3	0	0	6	0.33	0.67	1.00	0.00	0.00	7.22	5.15	87.63	48.28	17.24	34.48	5.88	16.47	77.65	2.67	19.47	77.86
14M2#2	NOT COUNTABLE																												
14M2#3	NOT COUNTABLE																												
18C1#2	49	11	0	0	192	15	10	11	0	2	10	0	0.18	0.00	0.00	0.67	3.33	20.83	0.00	79.17	100.00	0.00	0.00	90.79	4.39	4.82	4.60	10.46	84.94
18C1#3	34	7	1	10	79	25	76	58	2	0	8	0	0.17	0.91	0.67	0.00	2.67	14.14	3.79	82.07	75.56	2.22	22.22	43.70	31.93	24.37	2.86	41.22	55.92
18C1#4	6	3	1	33	35	5	175	32	0	7	1	2	0.33	0.97	0.00	2.33	0.33	3.10	11.72	85.17	15.00	2.50	82.50	16.19	70.85	12.96	1.20	72.00	26.80
24A2#1	4	0	1	43	1	13	192	5	5	36	0	0	0.00	0.98	1.67	12.00	0.00	1.54	16.99	81.47	8.33	2.08	89.58	6.64	91.00	2.37	0.00	97.16	2.84
24A2#2	1	0	0	57	11	4	157	29	1	40	0	0	0.00	1.00	0.33	13.33	0.00	0.39	22.01	77.61	1.72	0.00	98.28	7.46	78.11	14.43	0.00	80.10	19.90
24A2#3	NOT COUNTABLE																												
24A2#4	56	9	4	22	28	54	105	3	9	9	0	1	0.14	0.85	3.00	3.00	0.00	23.13	9.25	67.62	68.29	4.88	26.83	43.16	55.26	1.58	4.52	79.90	15.58
24A2#5	5	0	0	23	12	0	223	35	1	1	0	0	0.00	1.00	0.33	0.33	0.00	1.68	7.72	90.60	17.86	0.00	82.14	4.44	82.59	12.96	0.00	82.59	17.41
24A2#6	46	8	6	25	77	42	63	25	1	4	3	0	0.15	0.81	0.33	1.33	1.00	18.49	10.62	70.89	59.74	7.79	32.47	57.49	30.43	12.08	3.72	48.84	47.44
24A2#7	25	3	6	20	77	48	59	57	0	5	0	0	0.11	0.77	0.00	1.67	0.00	9.49	8.81	81.69	49.02	11.76	39.22	51.87	24.48	23.65	1.23	43.85	54.92
29N3#1	11	4	3	16	48	25	92	84	0	16	1	0	0.27	0.84	0.00	5.33	0.33	5.30	6.71	87.99	36.67	10.00	53.33	29.32	36.95	33.73	1.58	46.25	52.17
29N3#2	49	6	5	18	79	21	74	43	0	3	2	0	0.11	0.78	0.00	1.00	0.67	18.64	7.80	73.56	68.06	6.94	25.00	46.08	34.10	19.82	2.69	42.60	54.71
29N3#3	96	53	0	4	106	2	1	33	0	1	3	1	0.36	1.00	0.00	0.33	1.00	50.51	1.36	48.14	96.00	0.00	4.00	76.06	0.70	23.24	27.18	1.54	71.28
29N3#4	1	0	0	50	2	0	209	4	0	34	0	0	0.00	1.00	0.00	11.33	0.00	0.38	18.80	80.83	1.96	0.00	98.04	0.93	97.21	1.86	0.00	97.21	2.79
29N3#5	0	0	0	75	0	0	194	0	0	31	0	0	0.00	1.00	0.00	10.33	0.00	0.00	27.88	72.12	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
29N3#6	2	2	0	94	1	0	187	0	0	14	0	0	0.50	1.00	0.00	4.67	0.00	1.40	32.87	65.73	2.08	0.00	97.92	0.53	99.47	0.00	1.05	98.42	0.53
29N3#7	101	64	0	0	82	3	19	18	0	2	6	5	0.39	0.00	0.00	0.67	2.00	57.49	0.00	42.51	100.00	0.00	0.00	69.67	15.57	14.75	34.41	11.83	53.76
29Q1#1	119	56	0	0	113	4	3	3	0	1	0	1	0.32	0.00	0.00	0.33	0.00	58.72	0.00	41.28	100.00	0.00	0.00	95.12	2.44	2.44	31.28	3.91	64.80
29Q1#2	38	11	2	4	114	26	50	53	0	0	2	0	0.22	0.67	0.00	0.00	0.67	16.44	2.01	81.54	86.36	4.55	9.09	57.61	20.58	21.81	4.33	29.92	65.75
29Q1#3	82	28	0	0	148	10	6	23	1	0	1	0	0.25	0.00	0.33	0.00	0.33	37.04	0.00	62.96	100.00	0.00	0.00	84.49	3.21	12.30	13.02	7.44	79.53
30C2#1	0	0	0	28	0	0	227	7	0	38	0	0	0.00	1.00	0.00	12.67	0.00	0.00	10.69	89.31	0.00	0.00	100.00	0.00	97.01	2.99	0.00	97.01	2.99
30C2#2	0	0	0	90	0	0	186	0	0	24	0	0	0.00	1.00	0.00	8.00	0.00	0.00	32.61	67.39	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
33M1#1	21	9	0	6	101	42	71	38	0	3	9	0	0.30	1.00	0.00	1.00	3.00	10.42	2.08	87.50	77.78	0.00	22.22	56.75	28.17	15.08	3.45	43.30	53.26
33M1#2	40	14	1	15	116	34	46	20	0	6	8	0	0.26	0.94	0.00	2.00	2.67	18.88	5.59	75.52	71.43	1.79	26.79	69.44	21.30	9.26	6.09	34.78	59.13
35B2#1	25	1	1	25	27	33	180	0	0	8	0	0	0.04	0.96	0.00	2.67	0.00	8.90	8.90	82.19	49.02	1.96	49.02	25.00	75.00	0.00	0.41	88.38	11.20
35B2#2	12	1	0	43	10	8	195	0	1	30	0	0	0.08	1.00	0.33	10.00	0.00	4.83	15.99	79.18	21.82	0.00	78.18	8.45	91.55	0.00	0.47	94.86	4.67
35B2#3	6	0	0	46	8	6	200	0	0	34	0	0	0.00	1.00	0.00	11.33	0.00	2.26	17.29	80.45	11.54	0.00	88.46	6.54	93.46	0.00	0.00	96.26	3.74
35B2#4	37	1	3	61	38	18	120	12	1	9	0	0	0.03	0.95	0.33	3.00	0.00	13.10	22.07	64.83	36.63	2.97	60.40	29.79	63.83	6.38	0.53	73.02	26.46

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RESULTS

Because locations, depths and geological context were not available during point-counting of the 52 samples, the results are based solely on sand composition. Preliminary examination of the thin sections clearly indicated two end-member compositional groups: volcanic (primarily basaltic) and metamorphic (primarily quartz-mica tectonites). Most other samples were mixtures of these two end members; some samples included significant sedimentary lithic grains (only extrabasinal grains were counted).

A trilinear diagram was generated to illustrate the relative percentages of quarts-feldspar-lithic grains (QFL%). The QFL% diagram (Figure 2) shows that all the samples have a high percentage of lithic grains, indicating relatively immature source terrains. The lithic metamorphic-volcanic-sedimentary percentages ($L_mL_vL_s$%) (Figure 3) show that (except for two samples) the lithic grains range from volcanic dominated to metamorphic dominated (with mixtures in between).

Following completion of the point counting, depths and locations were provided by DWR-ND and entered into a SYSTAT spreadsheet, along with all recalculated data to conduct a discriminant analysis (Table 3). This spreadsheet shows the 52 samples, with sample numbers provided by DWR-ND. The discriminant analysis utilizes the sample numbers 1-52, corresponding to the DWR-ND sample numbers. Petrofacies designations were the defining parameters in the discriminant analysis; only the final four petrofacies are included in Table 3 (see discussion in Appendix A for details of the procedure and output). The purpose of discriminant analysis is to classify multivariate observations into mathematically defined groups (e.g., Koch and Link 1971). The most stable configuration of groups resulted in the following 4 petrofacies: V (volcanic), M (metamorphic), VM (mixed volcanic and metamorphic) and VMS (mixed volcanic, metamorphic and sedimentary) (as indicated in Table 3).

For illustrative purposes, the mean percentages of the four petrofacies are plotted on a QFL% diagram (Figure 4) and $L_mL_vL_s$% diagram (Figure 5). Additional parameters such as dense minerals (D), micas (M), serpentinite (S) and other parameter rations have secondary value and may be further analyzed in the future. The primary petrofacies have been plotted on cross sections by DWR-ND for analysis and have been plotted in map view by Brown and Caldwell.

CONCLUSIONS AND FUTURE WORK

The results presented herein should be analyzed in the context of the individual wells and aquifers to test for consanguinity of petrofacies. Many of the wells contain only one petrofacies (e.g., 4M1#1-4M1#4), whereas other wells contain several petrofacies (e.g., 24A2#1-24A2#7). This contrast in homogeneity versus heterogeneity probably is a function of the actual complexity of erosional, dispersal and depositional sedimentary systems: where only volcanics occur in the source area, V results, whereas mixed sources result in mixed petrofacies. On the other hand, including 4-dimensional geological constraints in the analysis might result in modifications to the petrofacies that would provide additional insights regarding the interconnectivity (or lack thereof) of aquifers. Mapping of the petrofacies could provide important insights regarding the aquifers.

Table 3. Discriminant Analysis Results

Sample Number	Petrofacies	East West	South North	Depth (ft)	Qp/Q	Fp/F	Percent			QFL%			QmFkFp%			LmLvLs%			QpLvmLsm%		
							M	D	S	Q	F	L	Qm	Fk	Fp	Lm	Lv	Ls	Qp	Lvm	Lsm
1R2#1	M	17	460	250	0.27	0.00	0.33	0.67	0.00	56.12	0.00	43.88	100.00	0.00	0.00	96.12	3.88	0.00	25.86	2.87	71.26
1R2#2	VMS	17	460	810	0.16	1.00	0.00	0.67	2.00	18.84	9.93	71.23	61.33	0.00	38.67	60.10	20.67	19.23	4.15	33.64	62.21
1R2#3	M	17	460	1030	0.00	0.88	1.00	0.00	0.00	3.37	2.69	93.94	55.56	5.56	38.89	17.92	3.23	78.85	0.00	3.94	96.06
1R2#4	VMS	17	460	1310	0.27	0.94	0.33	1.00	0.00	13.85	5.74	80.41	63.83	2.13	34.04	71.43	12.61	15.97	4.42	33.73	61.85
1R2#5	M	17	460	1490	0.26	0.55	0.00	0.67	0.00	25.93	3.70	70.37	83.82	7.35	8.82	80.86	8.61	10.53	8.73	18.34	72.93
4J1#1	M	81	1011	265	0.36	1.00	0.00	0.67	0.00	42.52	3.74	53.74	87.91	0.00	12.09	77.85	13.92	8.23	22.17	29.06	48.77
4J1#2	VM	81	1011	675	0.31	0.70	1.00	1.00	0.00	35.07	6.94	57.99	77.78	6.67	15.56	27.54	65.87	6.59	15.66	55.56	28.79
4J1#3	VM	81	1011	895	0.25	0.47	0.00	4.33	0.00	21.25	18.47	60.28	46.46	28.28	25.25	33.53	59.54	6.94	7.98	61.70	30.32
4M1#1	V	153	119	345	0.00	1.00	0.00	11.33	0.00	0.00	29.32	70.68	0.00	0.00	100.00	4.26	95.74	0.00	0.00	100.00	0.00
4M1#2	V	153	119	735	0.00	1.00	0.00	9.33	0.00	0.00	30.88	69.12	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
4M1#3	V	153	119	925	0.00	1.00	0.00	9.00	0.00	0.00	26.01	73.99	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
4M1#4	V	153	119	735	0.00	1.00	0.00	10.00	0.00	0.00	27.41	72.59	0.00	0.00	100.00	1.02	98.98	0.00	0.00	99.49	0.51
7K2#1	V	367	695	345	0.22	1.00	0.00	11.00	0.00	3.37	22.85	73.78	10.29	0.00	89.71	17.26	78.17	4.57	1.01	87.44	11.56
7K2#2	V	367	695	565	0.00	1.00	0.00	5.00	1.67	0.71	18.93	80.36	3.64	0.00	96.36	5.33	93.33	1.33	0.00	96.89	3.11
7K2#3	VM	367	695	945	0.00	0.68	2.00	6.33	0.00	9.09	13.82	77.09	39.68	19.05	41.27	23.58	68.40	8.02	0.00	76.42	23.58
11T4#1	M	-209	399	0	0.21	1.00	2.00	0.33	1.00	21.38	1.03	77.59	94.23	0.00	5.77	94.22	1.33	4.44	5.46	14.71	79.83
11T4#2	M	-223	399	0	0.22	1.00	0.33	0.33	1.00	23.05	1.36	75.59	92.98	0.00	7.02	94.17	0.90	4.93	6.30	10.08	83.61
11T4#3	M	-224	392	0	0.21	1.00	0.00	0.00	0.00	23.67	1.67	74.67	91.80	0.00	8.20	71.43	8.93	19.64	6.28	12.13	81.59
11T4#4	M	-144	99	0	0.19	1.00	0.00	0.33	0.00	20.74	0.33	78.93	98.04	0.00	1.96	92.80	0.00	7.20	4.84	5.65	89.52
12A1#1	M	-97	462	245	0.57	1.00	0.67	1.33	0.00	51.02	0.68	48.30	97.01	0.00	2.99	92.25	0.00	7.75	37.44	0.00	62.56
12A1#2	M	-97	462	605	0.11	0.00	0.00	1.33	0.33	26.78	0.00	73.22	100.00	0.00	0.00	95.83	0.00	4.17	4.00	11.56	84.44
13Q1#1	M	462	716	75	0.16	0.83	4.00	5.00	0.00	24.91	12.82	62.27	61.96	6.52	31.52	82.94	13.53	3.53	6.08	22.65	71.27
13Q2#2	V	462	716	225	0.09	1.00	1.00	17.67	0.00	4.53	22.22	73.25	15.63	0.00	84.38	5.06	94.94	0.00	0.56	94.97	4.47
13Q2#3	VMS	462	716	655	0.38	1.00	1.33	10.00	0.00	9.02	16.17	74.81	25.86	0.00	74.14	20.60	63.82	15.58	4.33	65.38	30.29
14M2#1	VM	-126	712	50	0.33	0.67	1.00	0.00	0.00	7.22	5.15	87.63	48.28	17.24	34.48	5.88	16.47	77.65	46.67	64.20	77.86
18C1#2	M	17	372	550	0.18	0.00	0.00	0.67	3.33	20.83	0.00	79.17	100.00	0.00	0.00	90.79	4.39	4.82	7.25	3.76	84.94
18C1#3	VMS	17	372	815	0.17	0.91	0.67	0.00	2.67	14.14	3.79	82.07	75.56	2.22	22.22	43.70	31.93	24.37	22.61	38.39	55.92
18C1#4	VMS	17	372	985	0.33	0.97	0.00	2.33	0.33	3.10	11.72	85.17	15.00	2.50	82.50	16.19	70.85	12.96	8.11	81.89	26.80
24A2#1	V	342	957	225	0.00	0.98	1.67	12.00	0.00	1.54	16.99	81.47	8.33	2.08	89.58	6.64	91.00	2.37	24.14	92.89	2.84
24A2#2	V	342	957	435	0.00	1.00	0.33	13.33	0.00	0.39	22.01	77.61	1.72	0.00	98.28	7.46	78.11	14.43	5.56	93.04	19.90
24A2#4	VM	342	957	955	0.14	0.85	3.00	3.00	0.00	23.13	9.25	67.62	68.29	4.88	26.83	43.16	55.26	1.58	53.70	47.92	15.58
24A2#5	VM	342	957	1065	0.00	1.00	0.33	0.33	0.00	1.68	7.72	90.60	17.86	0.00	82.14	4.44	82.59	12.96	0.00	93.54	17.41
24A2#6	VMS	342	957	1365	0.15	0.81	0.33	1.33	1.00	18.49	10.62	70.89	59.74	7.79	32.47	57.49	30.43	12.08	32.00	34.78	47.44
24A2#7	VMS	342	957	1395	0.11	0.77	0.00	1.67	0.00	9.49	8.81	81.69	49.02	11.76	39.22	51.87	24.48	23.65	35.76	34.50	54.92
29N3#1	VMS	27	201	210	0.27	0.84	0.00	5.33	0.33	5.30	6.71	87.99	36.67	10.00	53.33	29.32	36.95	33.73	30.43	56.25	52.17
29N3#2	VMS	27	201	270	0.11	0.78	0.00	1.00	0.67	18.64	7.80	73.56	68.06	6.94	25.00	46.08	34.10	19.82	21.14	38.17	54.71
29N3#3	M	27	201	390	0.36	1.00	0.00	0.33	1.00	50.51	1.36	48.14	96.00	0.00	4.00	76.06	0.70	23.24	1.79	2.39	71.28
29N3#4	V	27	201	650	0.00	1.00	0.00	11.33	0.00	0.38	18.80	80.83	1.96	0.00	98.04	0.93	97.21	1.86	0.00	98.85	2.79
29N3#5	V	27	201	750	0.00	1.00	0.00	10.33	0.00	0.00	27.88	72.12	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
29N3#6	V	27	201	895	0.50	1.00	0.00	4.67	0.00	1.40	32.87	65.73	2.08	0.00	97.92	0.53	99.47	0.00	0.00	98.94	0.53
29N3#7	M	27	201	925	0.39	0.00	0.00	0.67	2.00	57.49	0.00	42.51	100.00	0.00	0.00	69.67	15.57	14.75	3.53	9.27	53.76
29Q1#1	M	-72	197	270	0.32	0.00	0.00	0.33	0.00	58.72	0.00	41.28	100.00	0.00	0.00	95.12	2.44	2.44	3.42	1.26	64.80
29Q1#2	VMS	-72	197	670	0.22	0.67	0.00	0.00	0.67	16.44	2.01	81.54	86.36	4.55	9.09	57.61	20.58	21.81	19.18	23.28	65.75
29Q1#3	M	-72	197	990	0.25	0.00	0.33	0.00	0.33	37.04	0.00	62.96	100.00	0.00	0.00	84.49	3.21	12.30	6.33	2.44	79.53
30C2#1	V	352	405	45	0.00	1.00	0.00	12.67	0.00	0.00	10.69	89.31	0.00	0.00	100.00	0.00	97.01	2.99	0.00	100.00	2.99
30C2#2	V	352	405	165	0.00	1.00	0.00	8.00	0.00	0.00	32.61	67.39	0.00	0.00	100.00	0.00	100.00	0.00	0.00	100.00	0.00
33M1#1	VMS	55	547	880	0.30	1.00	0.00	1.00	3.00	10.42	2.08	87.50	77.78	0.00	22.22	56.75	28.17	15.08	28.19	31.95	53.26
33M1#2	VMS	55	547	1010	0.26	0.94	0.00	2.00	2.67	18.88	5.59	75.52	71.43	1.79	26.79	69.44	21.30	9.26	21.08	24.30	59.13
35B2#1	VM	331	762	431	0.04	0.96	0.00	2.67	0.00	8.90	8.90	82.19	49.02	1.96	49.02	25.00	75.00	0.00	39.53	70.69	11.20
35B2#2	V	331	762	836	0.08	1.00	0.33	10.00	0.00	4.83	15.99	79.18	21.82	0.00	78.18	8.45	91.55	0.00	13.11	88.81	4.67
35B2#3	V	331	762	956	0.00	1.00	0.00	11.33	0.00	2.26	17.29	80.45	11.54	0.00	88.46	6.54	93.46	0.00	10.00	92.48	3.74
35B2#4	VM	331	762	1021	0.03	0.95	0.33	3.00	0.00	13.10	22.07	64.83	36.63	2.97	60.40	29.79	63.83	6.38	7.06	3.23	6.92

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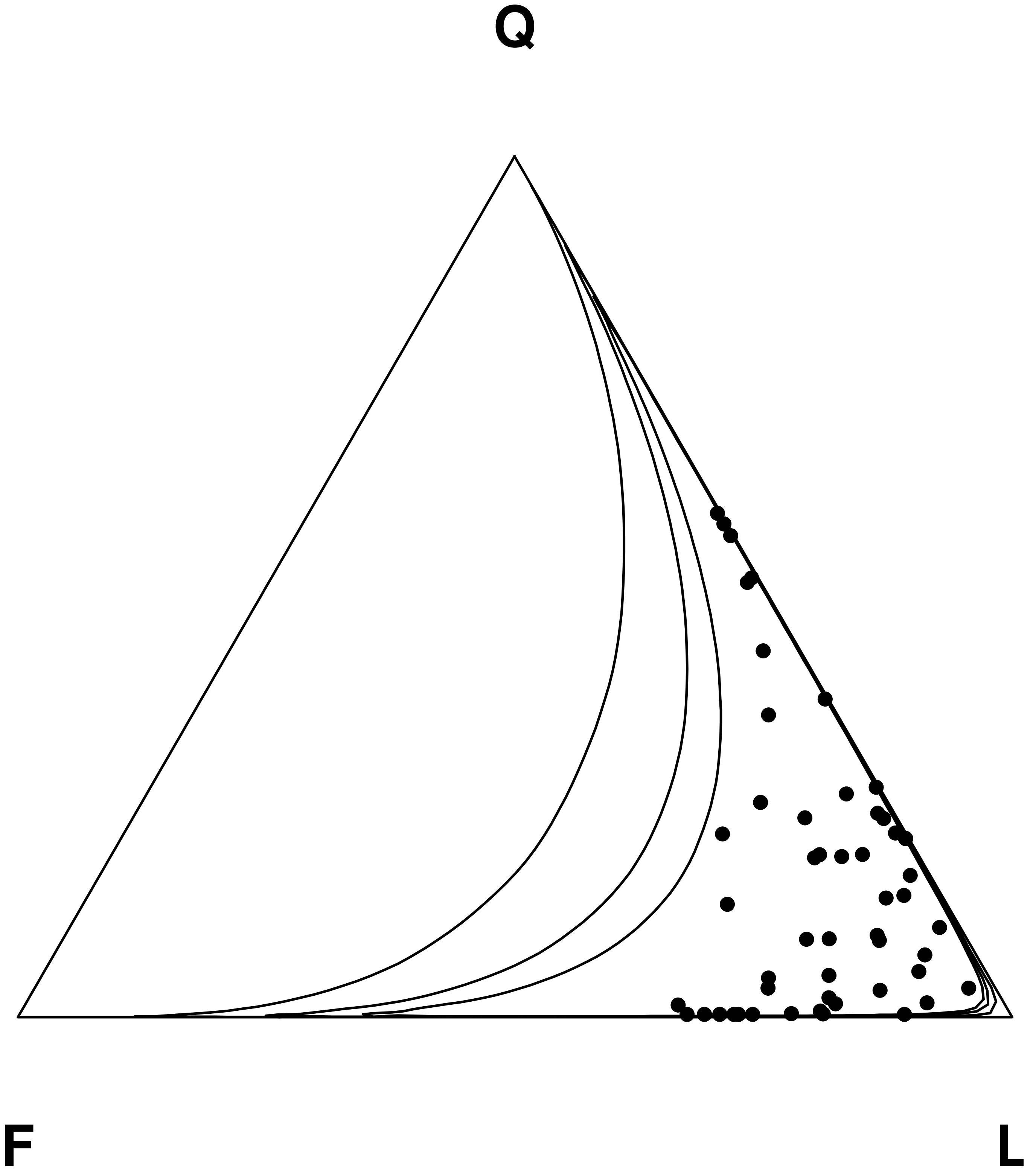

Figure 2. QFL% Diagram

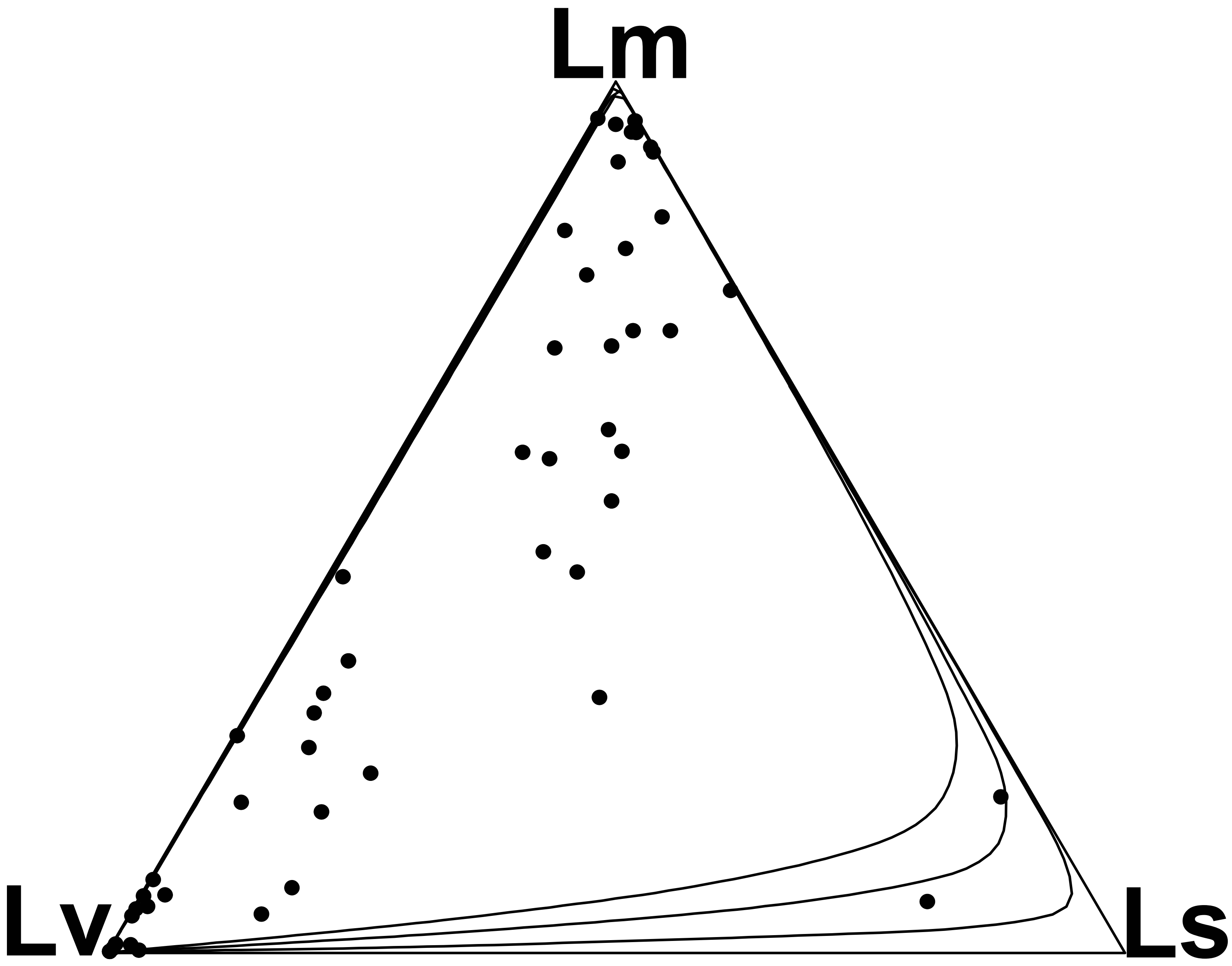

Figure 3. $L_mL_vL_s$% Diagram

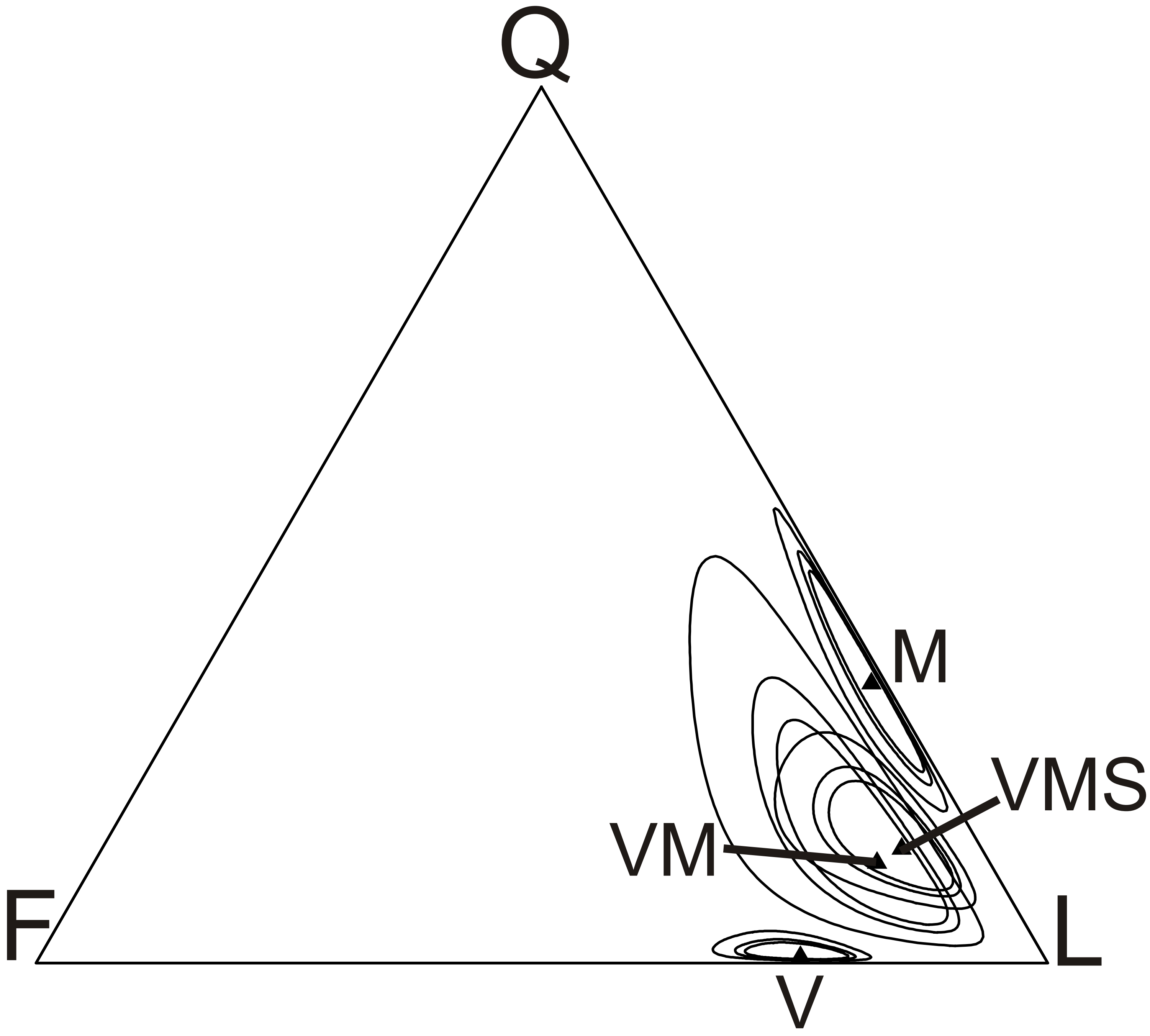

Figure 4. QFL Petrofacies Plot of Mean Value Showing 90, 95, and 99% Confidence Regions

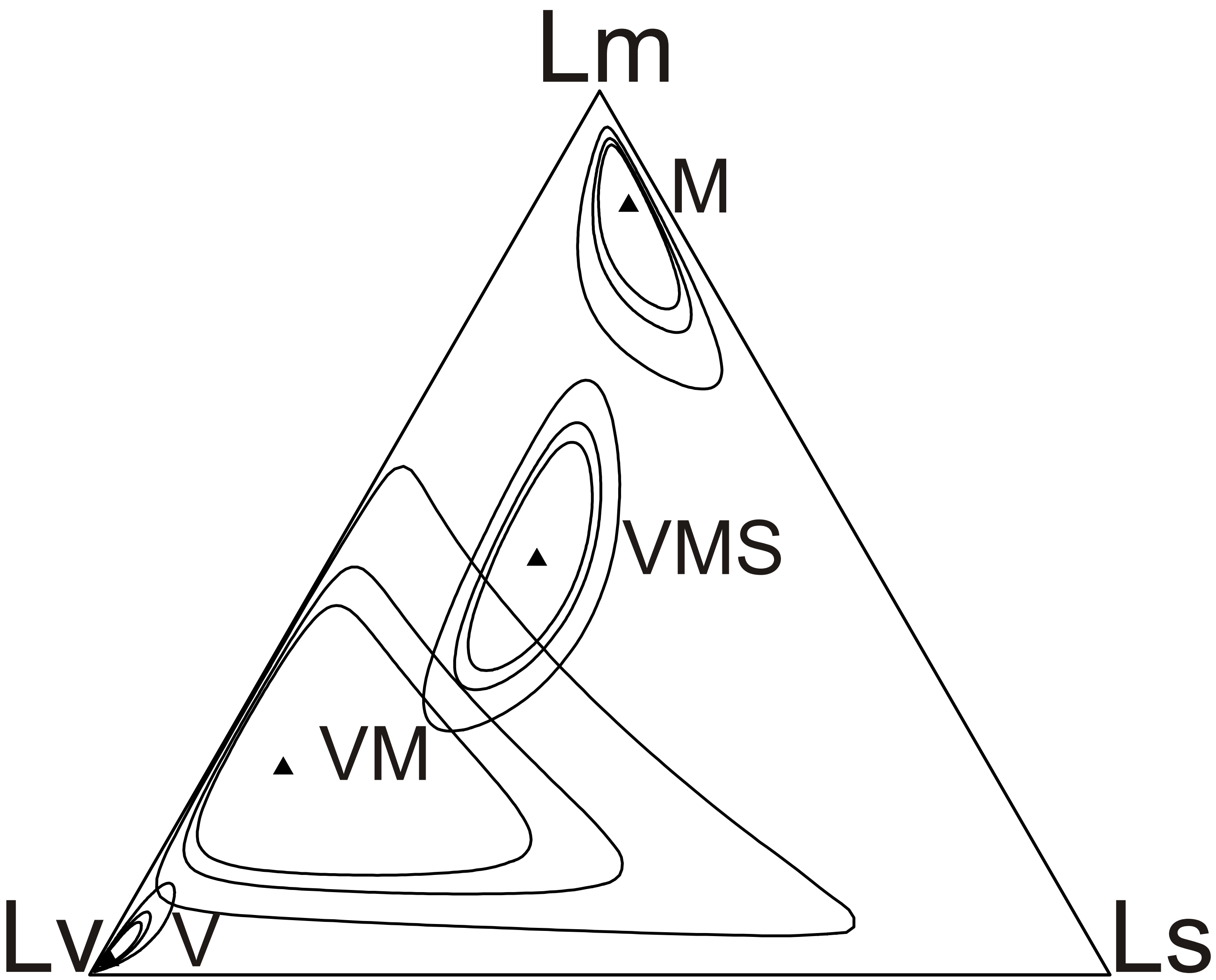

Figure 5. LmLvLs Petrofacies Plot of Mean Value Showing 90, 95, and 99% Confidence Regions

There is a high probability that petrofacies V represents derivation from the young volcanics of the Modoc Plateau and/or Cascades, whereas petrofacies M represents derivation from either the Coast Ranges Franciscan and/or the Klamath metamorphic terranes. The VM petrofacies may represent mixing of Modoc/Cascades and Sierra Nevada sources. These are very tentative conclusions, however, based solely on the general east/west and south/north trends in petrofacies. Definitive determination of sources for the petrofacies (and therefore, the aquifers) awaits additional petrofacies analysis in conjunction with mapping them in the subsurface. Additional sampling of modern streams and/or outcrops in potential source areas would provide additional insights into petrofacies compositions of both modern and ancient systems.

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APPENDIX A

Discriminant Analysis

Appendix A

Discriminant Analysis

Following completion of the point counting, depths and locations were provided and entered into a SYSTAT spreadsheet, along with all recalculated point count data. This spreadsheet shows 52 samples, with sample numbers provided by CDWR. The discriminant analysis utilizes the sample numbers 1-52, corresponding to the CDWR sample numbers. Petrofacies designations were the defining parameters in the discriminant analysis; only the final four petrofacies are included in Table 3 (see following discussion). Distances East/West and South/North of Gerber, CA were measured by Brown and Caldwell staff using the attached sample location map from DWR-N, and provided in arbitrary units (relative distances are all that matter in the present analysis). East/West is positive in the East direction and negative in the West direction (relative to Gerber); South/North increases in value to the south, with zero value at Gerber latitude. Depth is average depth of each sample in each well in feet, as supplied by CDWR.

The purpose of discriminant analysis is to classify multivariate observations into mathematically defined groups (e.g., Koch and Link 1971). This procedure optimally clusters the data as ellipsoidal clouds in multidimensional space, such that the directions and lengths of the distances connecting ellipsoid centers maximize the spatial distinction (or separation, or discrimination) among the groups (Koch and Link 1971). The SYSTAT application combines these principles of discriminant analysis and canonical correlation to generate a grid that represents ellipsoidal clouds of optimally separated points in two-dimensional space (e.g., figure at end of final discriminant analysis output). Three variates ("factors" in this figure) are represented as axes. Pairings of variates are shown in individual cells of the grid, and each pairing reveals the elliptical cross section of the ellipsoidal cloud in the corresponding plane. Confidence ellipses are defined by the resulting scatter of points determined by the pair of equations that comprise the variates. Each of the cells that form the main diagonal of the grid represents one of the variates (e.g., Factor[1] in the upper left), with point frequency as the vertical axis (analogous to univariate frequency curves).

The initial discriminant analysis utilized three petrofacies: V (volcanic), M (metamorphic) and S (sedimentary), as determined by dominant LmLvLs percentages. This resulted in excellent discrimination, as expected. On the other hand, some of the samples were misclassified according to the discriminant analysis because they consisted of mixed composition, rather than end-member composition. There were only two samples in the S petrofacies, which represents a statistically insignificant group. Next, the mixed samples were put into a VM petrofacies, making 4 groups. Close to 100% discrimination was achieved, but the small number (2) in the S petrofacies distorted the results. Next, discriminant analysis with six petrofacies was run: V, M, S, VM, VS and MS (the latter three representing mixing of the two dominant LmLvLs components). Several discriminant analyses were completed, after each of which ambiguous or borderline samples were moved from group to group, based on calculated multivariate distances from centroid means of each group. Groups were combined and separated based on these distances. The most stable configuration of groups (all of comparable size) resulted in the following 4 petrofacies: V (volcanic), M (metamorphic), VM (mixed volcanic and metamorphic) and VMS (mixed volcanic, metamorphic and sedimentary) (as indicated in Table 3).

Appendix A

The SYSTAT output (final discriminant analysis with four groups) produced 100% correct classification (meaning that the four groups are each internally consistent and statistically distinct from the other groups). Even though some overlap of points and ellipsoids is indicated in parts of the figure at the end of the output, this is only true in two-dimensional representations of the data and ellipses. In three dimensions (the three factors), there is no overlap. Various enlargements of plots of Factor 1 versus Factor 2 for each group and the 4 combined groups are included as an additional file.

The SYSTAT output also shows the following:

A. Group frequencies (number of samples in each petrofacies: 16, 16, 8 and 12).

B. Group means (notice that M is mostly to the west (negative), V is mostly to the east (positive), and VM is most common to the south (higher values).

C. The table in the middle of the second page of the output indicates that the most important discriminating variables are (in order of decreasing importance): LmLvLs%Lv, LmLvLs%Ls, LmLvLs%Lm, QFL%Q and QpLvmLsm%Qp. This is not surprising given that the original petrofacies designations were based on LmLvLs percentages. It is, however, important to keep in mind that: 1. Following the initial petrofacies designations, samples were moved freely between groups, after each discriminant analysis. 2. All of the variables were included in calculations of the three Canonical Variables (Factors), with the exception of QFL%L and QmFkFp%Fp (right side of table). 3. Most of the recalculated variables covary, either positively or negatively, and several are additive inverses, so variance in one parameter may be included in the variance of another parameter. Thus, the program will deselect variables whose variation is accounted for by a previously chosen variable.

D. The classification matrix indicates 100% correct classification.

E. The Canonical scores of group means (p. 4) show the magnitude and sign of each factor for each petrofacies. Thus, M is highly positive in Factor 1, whereas V is highly negative. This shows up in the plots of Factor 1 (horizontal) versus Factor 2 (vertical) in the Canonical Scores Plot (left-center box, which is enlarged on the supplemental plots of Score 1 versus Score 2). ("Factor" and "Score" are used interchangeably herein.)

F. Canonical scores are shown for each sample in each petrofacies, so that distances from group means can be assessed. In earlier discriminant analyses, these distances were the bases for reassigning samples to neighboring petrofacies.

North Sacramento Valley
Sand Sample Identification

SAMPLE CODES	SWN	AKA	Cross-Section Line	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)	Sample ID	Sample Interval (ft bgs)
29Q1	24N03W29Q001M	[redacted]	A-A'	**29Q1 #1**	**260-280**	**29Q1 #2**	**660-680**	**29Q1 #3**	**980-1000**								
29N3	24N02W29N003M	[redacted]	A-A', E-E'	**29N3 #1**	**200-220**	**29N3 #2**	**260-280**	**29N3 #3**	**380-400**	**29N3 #4**	**640-660**	**29N3 #5**	**740-760**	**29N3 #6**	**890-900**	**29N3 #7**	**920-930**
4M1	24N01W04M001M	[redacted]	A-A'	**4M1 #1**	**340-350**	**4M1 #2**	**730-740**	**4M1 #3**	**920-930**	**4M1 #4**	**730-740 duplicate**						
18C1	22N02W18C001M	[redacted]	E-E'	**ns**	**ns**	**18C1 #2**	**540-560**	**18C1 #3**	**810-820**	**18C1 #4**	**980-990**						
30C2	22N02E30C002M	[redacted]	B-B'; F-F'	**30C2 #1**	**40-50**	**30C2 #2**	**160-170**										
12A1	21N04W12A001M	[redacted]	B-B'	**12A1 #1**	**240-250**	**12A1 #2**	**600-610**										
1R2	21N03W01R002M	[redacted]	B-B'; E-E'	**1R2 #1**	**240-260**	**1R2 #2**	**800-820**	**1R2 #3**	**1020-1040**	**1R2 #4**	**1300-1320**	**1R2 #5**	**1480-1500**				
33M1	21N02W33M001M	[redacted]	E-E'	**33M1 #1**	**860-900**	**33M1 #2**	**1000-1020**										
14M2	19N04W14M002M	[redacted]	C-C'	**14M2 #1**	**40-60**	**14M2 #2**	**490-510**	**14M2 #3**	**700-730**								
13Q1	19N02E13Q002M	[redacted]	C-C'	**13Q1 #1**	**70-80**	**13Q2 #2**	**220-230**	**13Q2 #3**	**650-660**								
7K2	19N02E07K002M	[redacted]	D-D', F-F'	**7K2 #1**	**340-350**	**7K2 #2**	**560-570**	**7K2 #3**	**940-950**								
4J1	16N02W04J001M	[redacted]	D-D; E-E'	**4J1 #1**	**260-270**	**4J1 #2**	**670-680**	**4J1 #3**	**890-900**								
24A2	17N01E24A002M	[redacted]	F-F'	**24A2 #1**	**220-230**	**24A2 #2**	**430-440**	**24A2 #3**	**770-780**	**24A2 #4**	**950-960**	**24A2 #5**	**1060-1070**	**24A2 #6**	**1360-1370**	**24A2 #7**	**1390-1400**
35B2	19N01E35B002M	[redacted]	C-C';D-D'	**35B2 #1**	**426-436**	**35B2 #2**	**826-846**	**35B2 #3**	**946-966**	**35B2 #4**	**1016-1026**						
	Formation Samples	Tehama	outcrop	**11T4 #1**	Road cut along Rd 200A - 2.1 miles west of 200A/206 intersection												
	Formation Samples	Tehama	alluvium	**11T4 #2**	Stony Crk west of Black Butte Res. - Rd. 200A .5 miles beyond bridge												
	Formation Samples	Tehama	alluvium	**11T4 #3**	Small Trib feeding Stony Crk - Rd. 200A .5 miles beyond bridge												
	Formation Samples	Tehama	alluvium	**11T4 #4**	Thomes Creek - at Simpson Rd. Bridge												
	Formation Samples	Red Bluff ?	outcrop	**11T4 #5**	Red Bluff - Paskenta Rd. road cut												

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```
SYSTAT Rectangular file C:\Program Files\SYSTAT 10.2\Data\SacValWaterWells6PetrofaciesData.SYD,
created Tue Jul 03, 2007 at 14:56:04, contains variables:

          WELL$     PETROFACIES$        EASTWEST     SOUTHNORTH          DEPTH
         FPDIVF         MPERCENT        DPERCENT       SPERCENT           QFLQ
           QFLL        QMFKFPQM        QMFKFPFK        QMFKFPFP      LMLVLSLM
       LMLVLSLS      QPLVMLSMQP     QPLVMLSMLVM     QPLVMLSMLSM

 52 cases and 22 variables processed and saved.


SYSTAT Rectangular file C:\Program Files\SYSTAT 10.2\SacValWaterWells4PetrofaciesData.SYD,
created Tue Jul 03, 2007 at 15:31:11, contains variables:

          WELL$     PETROFACIES$        EASTWEST     SOUTHNORTH          DEPTH
         FPDIVF         MPERCENT        DPERCENT       SPERCENT           QFLQ
           QFLL        QMFKFPQM        QMFKFPFK        QMFKFPFP      LMLVLSLM
       LMLVLSLS      QPLVMLSMQP     QPLVMLSMLVM     QPLVMLSMLSM


Group frequencies

         M           V          VM         VMS

        16          16           8          12

Group means

                        M          V          VM         VMS
                        -        246.18     218.62     108.83
     EASTWEST      29.562      8          5          3
                    405.50     464.56     858.37     498.91
   SOUTHNORTH      0          2          5          7
                    442.81     552.00     754.62     864.58
        DEPTH      2          0          5          3
       QPDIVQ       0.254      0.056      0.136      0.227
       FPDIVF       0.578      0.999      0.785      0.885
     MPERCENT       0.542      0.208      0.958      0.222
     DPERCENT       0.792     10.437      2.583      2.194
     SPERCENT       0.562      0.104      0.000      1.111
         QFLQ      34.004      1.213     14.931     13.052
         QFLF       1.837     23.296     11.541      7.582
         QFLL      64.159     75.491     73.528     79.366
     QMFKFPQM      91.207      4.813     48.000     57.553
     QMFKFPFK       1.214      0.130     10.131      4.140
     QMFKFPFP       7.578     95.056     41.869     38.307
     LMLVLSLM      82.033      3.967     25.143     48.382
     LMLVLSLV       5.040     94.311     56.705     32.991
     LMLVLSLS      12.927      1.722     21.754     18.627
   QPLVMLSMQP       9.342      3.398     21.325     19.283
  QPLVMLSMLVM       9.382     96.488     59.156     41.356
  QPLVMLSMLSM      74.760      3.570     26.458     52.037

Between groups F-matrix  --  df =    18     31
```

	M	V	VM	VMS
M	0.000			
V	33.518	0.000		
VM	15.632	11.039	0.000	
VMS	6.397	13.453	6.594	0.000

Wilks' lambda
Lambda = 0.0031 df = 18 3 48
Approx. F= 10.2093 df = 54 93 prob = 0.0000

Classification functions

	M	V	VM	VMS
CONSTANT	-6446.495	-6537.003	-6749.563	-6535.505

EASTWEST	0.404	0.378	0.399	0.410
SOUTHNORTH	-0.160	-0.152	-0.151	-0.164
DEPTH	0.213	0.215	0.214	0.218
QPDIVQ	-64.109	-93.872	-82.180	-63.976
FPDIVF	280.706	278.892	279.631	285.112
MPERCENT	2.541	-0.720	3.639	0.610
DPERCENT	0.746	3.069	0.221	1.267
SPERCENT	14.343	18.280	15.069	17.228
QFLQ	16.327	16.103	16.078	16.121
QFLF	-1.360	-0.162	-1.024	-1.139
QFLL	0.000	0.000	0.000	0.000
QMFKFPQM	4.768	5.149	5.566	4.978
QMFKFPFK	5.062	4.909	6.120	5.412
QMFKFPFP	0.000	0.000	0.000	0.000
LMLVLSLM	92.547	92.839	94.681	93.181
LMLVLSLV	109.084	109.425	111.464	109.704
LMLVLSLS	87.751	88.415	90.314	88.503
QPLVMLSMQP	7.549	7.882	7.755	7.805
QPLVMLSMLVM	15.996	16.687	16.911	16.403
QPLVMLSMLSM	29.783	29.254	29.322	29.620

```
Variable    F-to-remove  Tolerance |   Variable     F-to-enter  Tolerance
 3 EASTWEST        2.72   0.256472 |   13 QFLL            0.00   0.000000
 4 SOUTHNORTH      2.08   0.401533 |   16 QMFKFPFP        0.00   0.000000
 5 DEPTH           4.73   0.489826 |
 6 QPDIVQ          1.84   0.541339 |
 7 FPDIVF          4.31   0.454008 |
 8 MPERCENT        2.06   0.595662 |
 9 DPERCENT        6.33   0.510698 |
10 SPERCENT        2.49   0.687635 |
11 QFLQ           13.39   0.165157 |
12 QFLF            2.42   0.428394 |
14 QMFKFPQM        3.53   0.126799 |
15 QMFKFPFK        5.65   0.544097 |
17 LMLVLSLM       32.37   0.006426 |
18 LMLVLSLV       64.66   0.006156 |
19 LMLVLSLS       32.65   0.006380 |
20 QPLVMLSMQP     10.42   0.417301 |
21 QPLVMLSMLVM     3.90   0.097154 |
22 QPLVMLSMLSM   -10.33   0.058963 |
```

Classification matrix (cases in row categories classified into columns)

	M	V	VM	VMS	%correct
M	16	0	0	0	100
V	0	16	0	0	100
VM	0	0	8	0	100
VMS	0	0	0	12	100
Total	16	16	8	12	100

Jackknifed classification matrix

	M	V	VM	VMS	%correct
M	12	0	0	4	75
V	0	15	0	1	94
VM	0	0	7	1	88
VMS	1	1	0	10	83
Total	13	16	7	16	85

Eigenvalues

20.180	5.181	1.442

Canonical correlations

0.976	0.916	0.768

Cumulative proportion of total dispersion

0.753	0.946	1.000

Wilks' lambda= 0.003
Approx.F= 10.230 df= 54, 93 p-tail= 0.0000

Pillai's trace= 2.381
Approx.F= 7.058 df= 54, 99 p-tail= 0.0000

Lawley-Hotelling trace= 26.803
Approx.F= 14.725 df= 54, 89 p-tail= 0.0000

Canonical discriminant functions

	1	2	3
Constant	10.412	-39.558	-5.162

EASTWEST	0.003	0.002	0.005
SOUTHNORTH	-0.001	0.001	-0.003
DEPTH	-0.000	0.000	0.002
QPDIVQ	2.928	0.228	3.977
FPDIVF	0.248	0.050	1.824
MPERCENT	0.250	0.496	-0.504
DPERCENT	-0.195	-0.319	0.031
SPERCENT	-0.320	-0.272	0.648
QFLQ	0.020	-0.018	-0.036
QFLF	-0.109	-0.069	-0.048
QFLL	.	.	.
QMFKFPQM	-0.042	0.088	-0.019
QMFKFPFK	0.006	0.185	0.057
QMFKFPFP	.	.	.
LMLVLSLM	-0.044	0.311	0.038
LMLVLSLV	-0.052	0.345	0.010
LMLVLSLS	-0.081	0.341	0.016
QPLVMLSMQP	-0.029	-0.000	0.048
QPLVMLSMLVM	-0.068	0.076	0.017
QPLVMLSMLSM	0.051	-0.019	0.022

Canonical discriminant functions -- standardized by within variances

	1	2	3
EASTWEST	0.411	0.319	0.764
SOUTHNORTH	-0.226	0.149	-0.690
DEPTH	-0.056	0.007	0.586
QPDIVQ	0.363	0.028	0.492
FPDIVF	0.070	0.014	0.512
MPERCENT	0.198	0.393	-0.399
DPERCENT	-0.475	-0.777	0.076
SPERCENT	-0.254	-0.216	0.516
QFLQ	0.214	-0.187	-0.378
QFLF	-0.556	-0.353	-0.246
QFLL	.	.	.
QMFKFPQM	-0.632	1.340	-0.285
QMFKFPFK	0.026	0.850	0.261
QMFKFPFP	.	.	.
LMLVLSLM	-0.664	4.677	0.568
LMLVLSLV	-0.674	4.470	0.124
LMLVLSLS	-1.296	5.423	0.249
QPLVMLSMQP	-0.348	-0.000	0.581
QPLVMLSMLVM	-0.963	1.072	0.239
QPLVMLSMLSM	0.659	-0.247	0.285

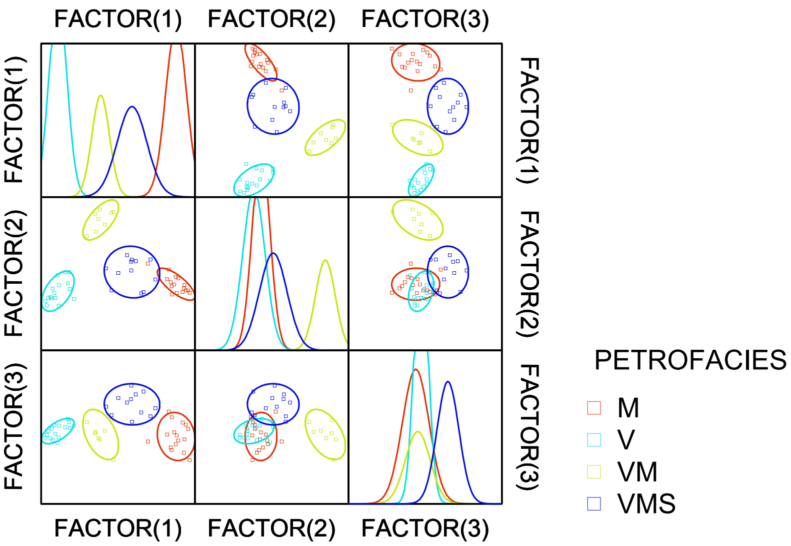
Canonical scores of group means

	1	2	3
M	5.302	-0.958	-0.855
V	-5.474	-1.607	-0.367
VM	-1.575	4.904	-0.671
VMS	1.280	0.151	2.077

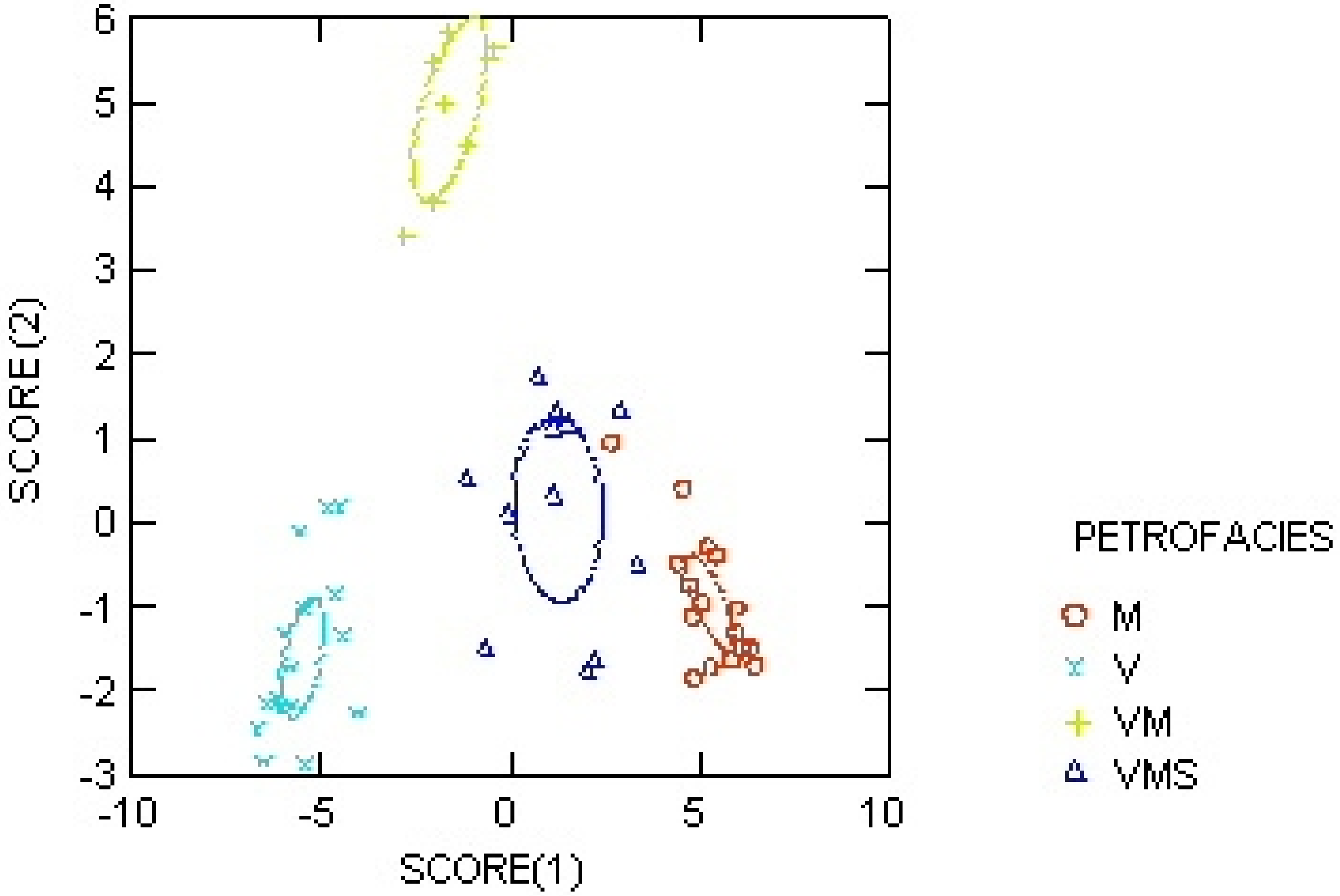
```
M            Canonical scores
------------  -------- -------- --------
      1        6.020  -1.343  -2.336
      3        5.133   -.983   -.475
      5        4.642    .371   1.420
      6        2.720    .925  -1.316
     16        5.262   -.316  -1.566
     17        5.361  -1.753   -.754
     18        4.811   -.777  -1.846
     19        6.405  -1.526   -.168
     20        5.896  -1.664    .418
     21        4.886  -1.147  -2.102
```

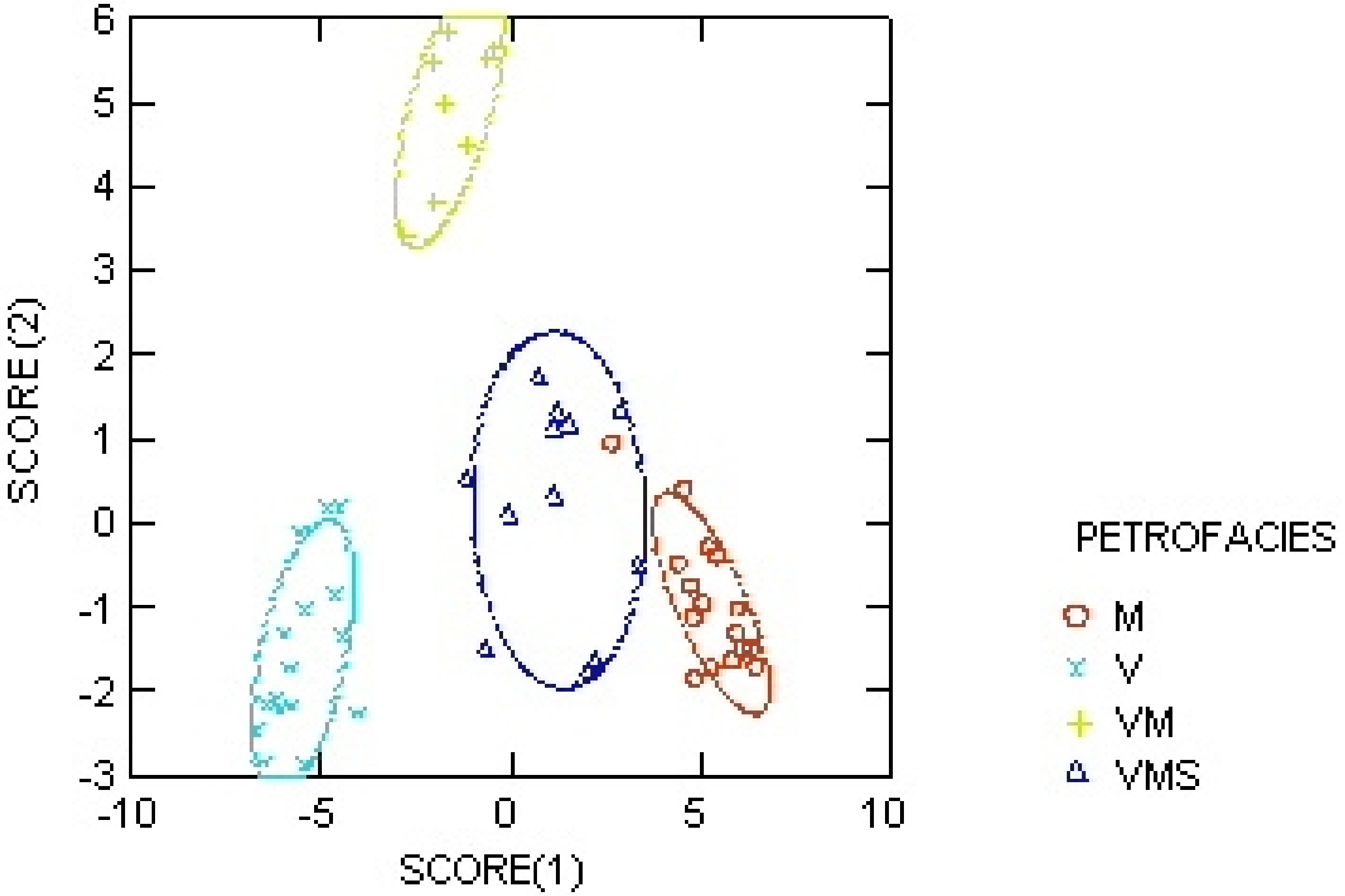
```
     22          5.500   -.418   -1.224
     26          4.919  -1.890     .901
     37          6.191  -1.522     .204
     41          4.481   -.508    -.687
     42          6.539  -1.737   -3.027
     44          6.060  -1.045   -1.118

V            Canonical scores
------------  -------- -------- --------
      9        -6.487  -2.881    -.703
     10        -6.359  -2.200    -.359
     11        -5.789  -1.752     .160
     12        -6.040  -2.255    -.138
     13        -4.001  -2.301     .120
     14        -4.442    .137     .447
     23        -6.150  -2.141   -1.025
     29        -5.516   -.150   -1.418
     30        -5.395  -2.912    -.951
     38        -5.707  -2.216    -.626
     39        -6.619  -2.511    -.972
     40        -4.571   -.880     .741
     45        -4.382  -1.390    -.088
     46        -5.950  -1.348   -1.193
     50        -4.799    .139    -.009
     51        -5.377  -1.057     .140

VM             Canonical scores
------------  -------- -------- --------
      7         -.413   5.637   -2.990
      8        -1.779   4.987   -1.009
     15        -2.078   5.478    -.569
     25         -.633   5.537     .660
     31        -1.185   4.499    -.327
     32        -2.019   3.828    -.450
     49        -2.840   3.417     .454
     52        -1.653   5.851   -1.136

VMS             Canonical scores
------------  -------- -------- --------
      2         2.126  -1.800    1.337
      4         3.419   -.531    1.725
     24         -.587  -1.529    1.087
     27          .825   1.694    2.239
     28        -1.071    .481    1.866
     33         1.193   1.093    2.546
     34         1.622   1.142    2.979
     35          .033    .069    2.650
     36         1.287   1.278     .492
     43         2.965   1.299     .985
     47         1.216    .289    3.772
     48         2.331  -1.668    3.242
```

Canonical Scores Plot

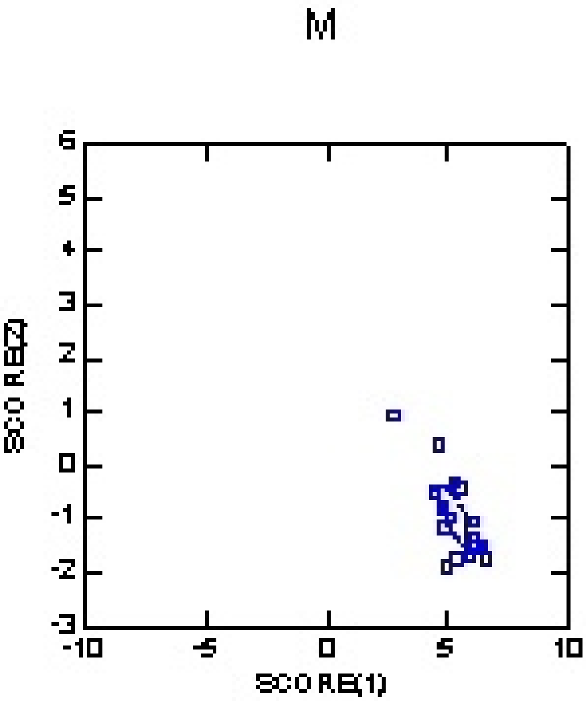


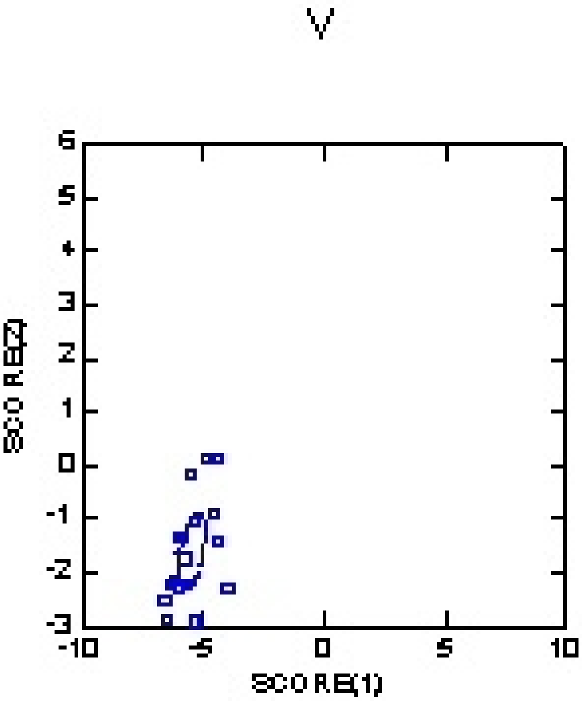
Predicted group indicator and canonical discriminant scores are saved.
52 cases have been saved.

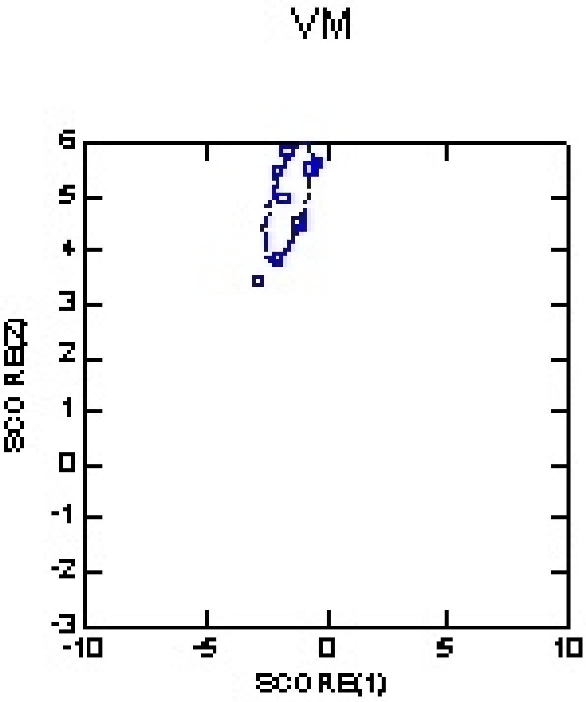

6
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10
SCORE (2)
SCORE(1)
PETROFACIES
M
V
VM
VMS



6
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10
SCORE(1)
SCORE(2)
PETROFACIES
M
V
VM
VMS


M
SCORE(2)
SCORE(1)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10


V
SCORE(2)
SCORE(1)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10


VM
SCORE(2)
SCORE(1)
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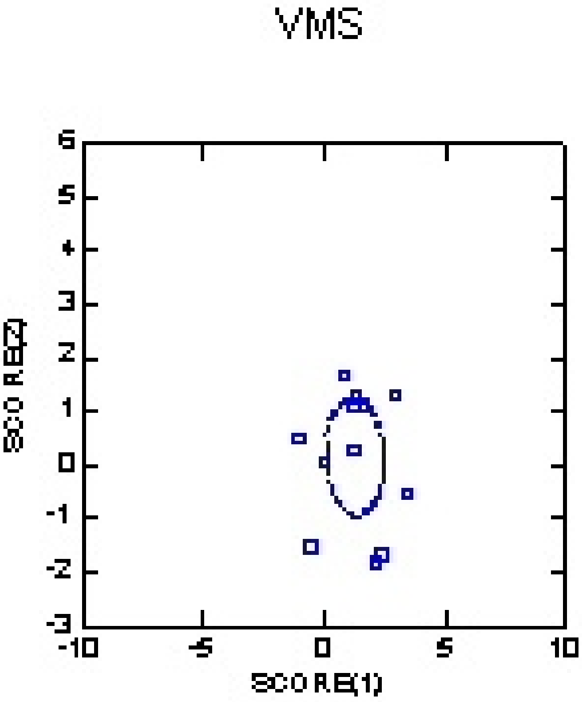
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10


VMS
SCORE(2)
SCORE(1)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
0
5
10

Sample Point Locations Relative to Gerber (inches)

Location ID	South	West/East
IIT4#4	0.99	1.44 W
IIT4#1	3.99	2.09 W
IIT4#2	3.99	2.23 W
IIT4#3	3.92	2.24 W
24N01W04M001M	1.19	1.53 E
24N03W29Q001M	1.97	0.72 W
24N02W29N003M	2.01	0.27 E
22N02W18C001M	3.72	0.17 E
22N02E30C002M	4.05	3.52 E
21N04W12A001M	4.62	0.97 W
21N03W01R002M	4.6	0.17 E
21N02W33M001M	5.47	0.55 E
19N02E07K002	6.95	3.67 E
19N02E13Q002M	7.16	4.62 E
19N04W14M002M	7.12	1.26 W
19N01E35B002M	7.62	3.31 E
17N01E24A002M	9.57	3.42 E
16N02W04J001M	10.11	0.81 E

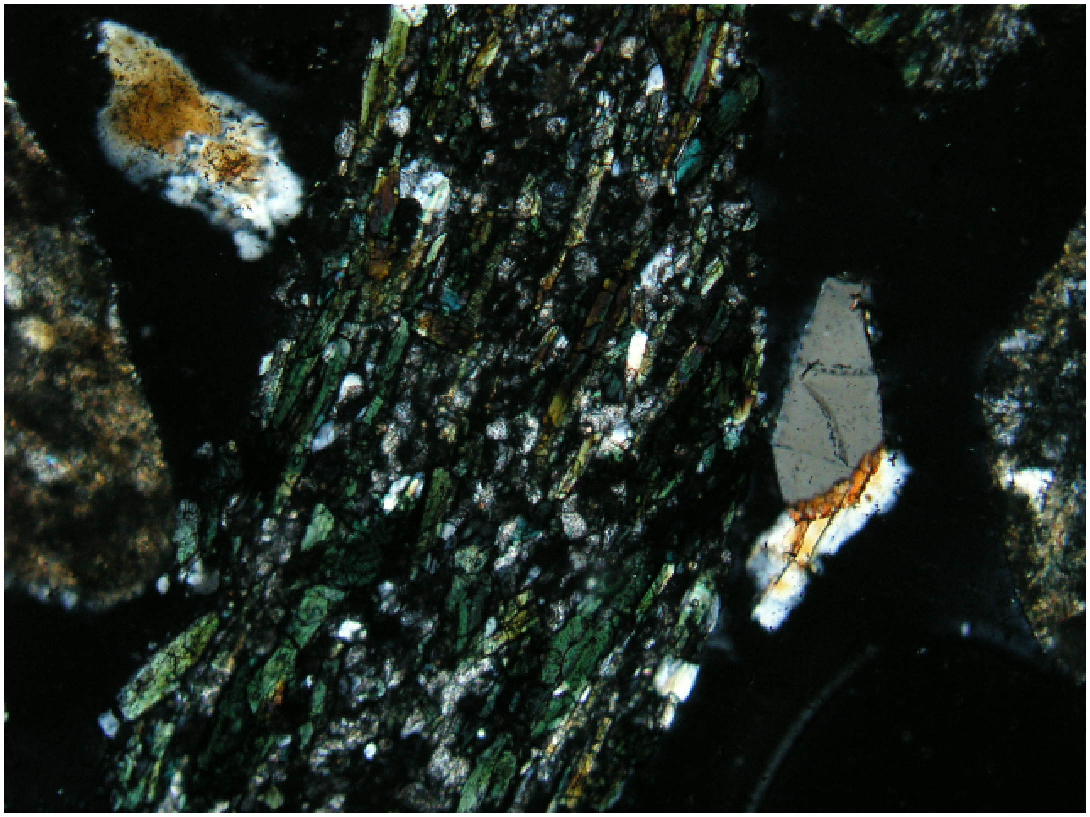
APPENDIX B

Photomicrographs

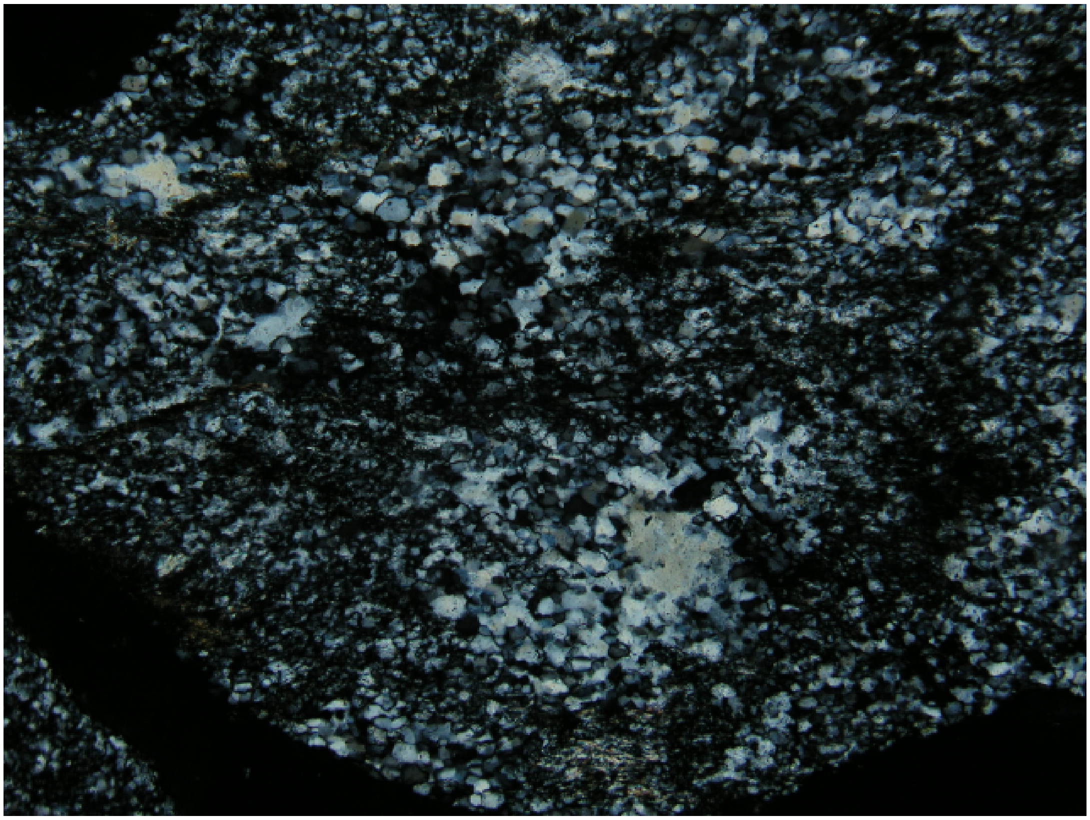
Appendix B

Photomicrographs of North Sacramento Valley Sand Samples

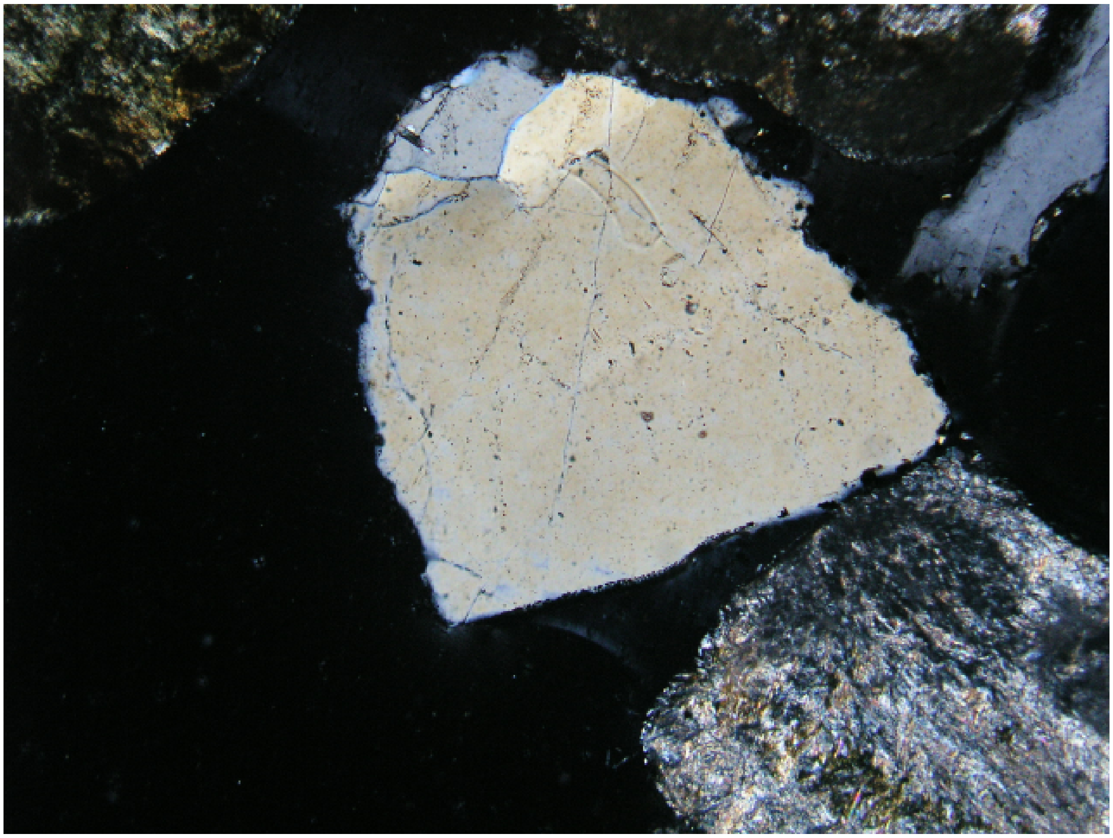
Image	Sample	Petrofacies	Magnification (Horizontal Dimension)	Crossed Polars (X) or Plane Polarized (P)	Common Grains
P7241302.jpg	13Q#1	M	1.7mm	X	Lm, Qm
P7241304.jpg	13Q#1	M	1.7mm	X	Lm, Qp, M
P7241305.jpg	13Q#1	M	1.7mm	X	Qm, Lm
P7241306.jpg	1R2#1	M	3.4mm	X	Lm
P7241307.jpg	1R2#1	M	1.7mm	X	Lm
P7241308.jpg	1R2#1	M	3.4mm	X	Lm, Qm, Qp
P7241309.jpg	1R2#1	M	3.4mm	X	Lm, Qm, Qp
P7241310.jpg	24A2#5	VM	3.4mm	X	Lv, Fp
P7241311.jpg	24A2#5	VM	3.4mm	P	Lv, Fp
P7241312.jpg	24A2#5	VM	1.7mm	X	Lv, Fp
P7241313.jpg	24A2#5	VM	1.7mm	X	Lv, Fp, D
P7241314.jpg	4M1#2	V	3.4mm	X	Lv, Fp, D
P7241315.jpg	4M1#2	V	3.4mm	X	Lv, Fp, D
P7241316.jpg	4M1#2	V	3.4mm	X	Lv, Fp, D
P7241317.jpg	4M1#2	V	3.4mm	X	Lv, Fp, D
P7241318.jpg	13Q2#3	VMS	3.4mm	X	Lv, Fp, Qp, Qm, Lm
P7241319.jpg	13Q2#3	VMS	3.4mm	P	Lv, Fp, Qp, Qm, Lm
P7241320.jpg	13Q2#3	VMS	1.7mm	X	Lv, Lm, Fp, Qm
P7241321.jpg	13Q2#3	VMS	3.4mm	X	D,Lv, Fp, Qm, Lm,Ls
P7241322.jpg	1R2#3	M	3.4mm	X	Lm, Lv, Ls
P7241323.jpg	1R2#3	M	3.4mm	P	Lm, Lv, Ls



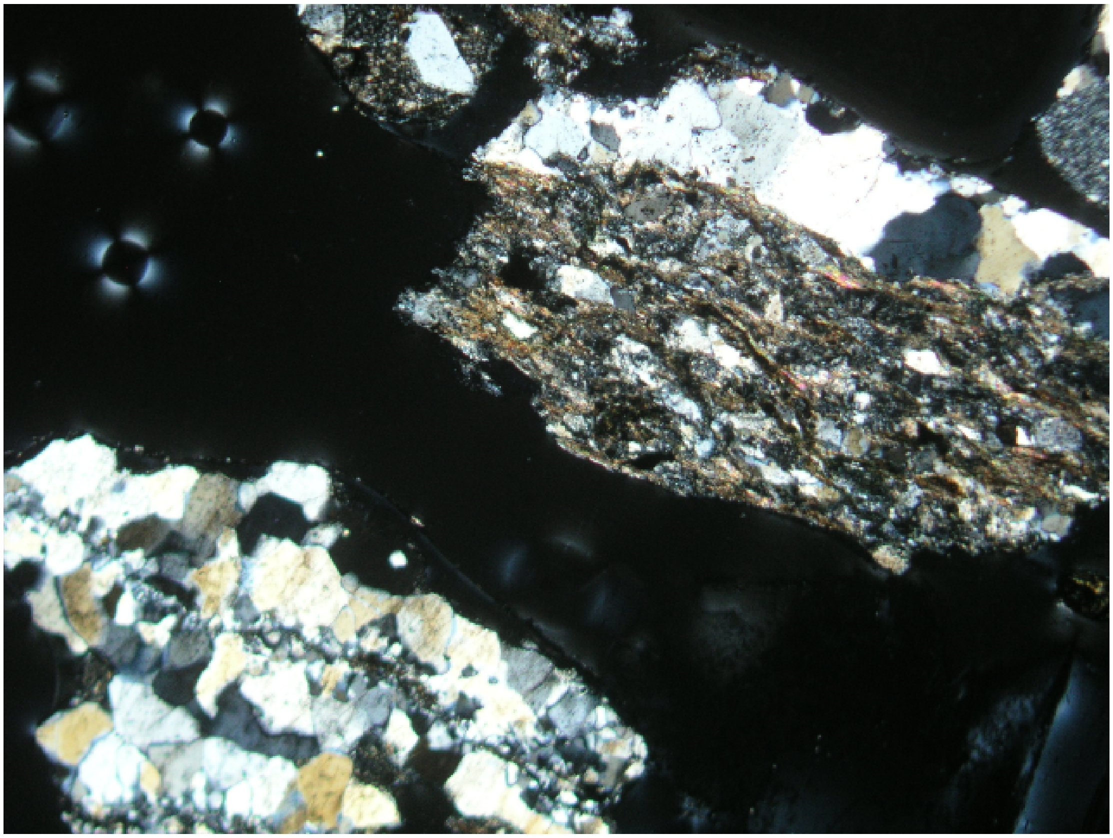
P7241302-13Q#1



P7241304-13Q#1



P7241305-13Q#1



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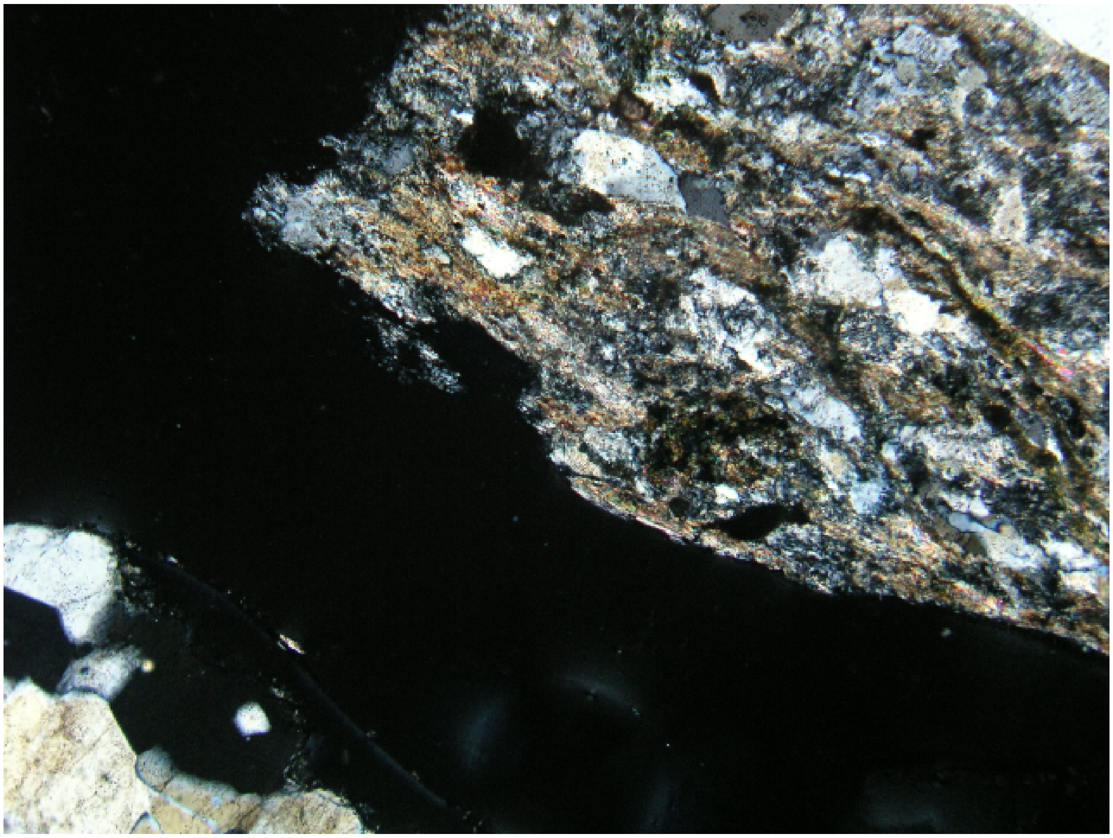

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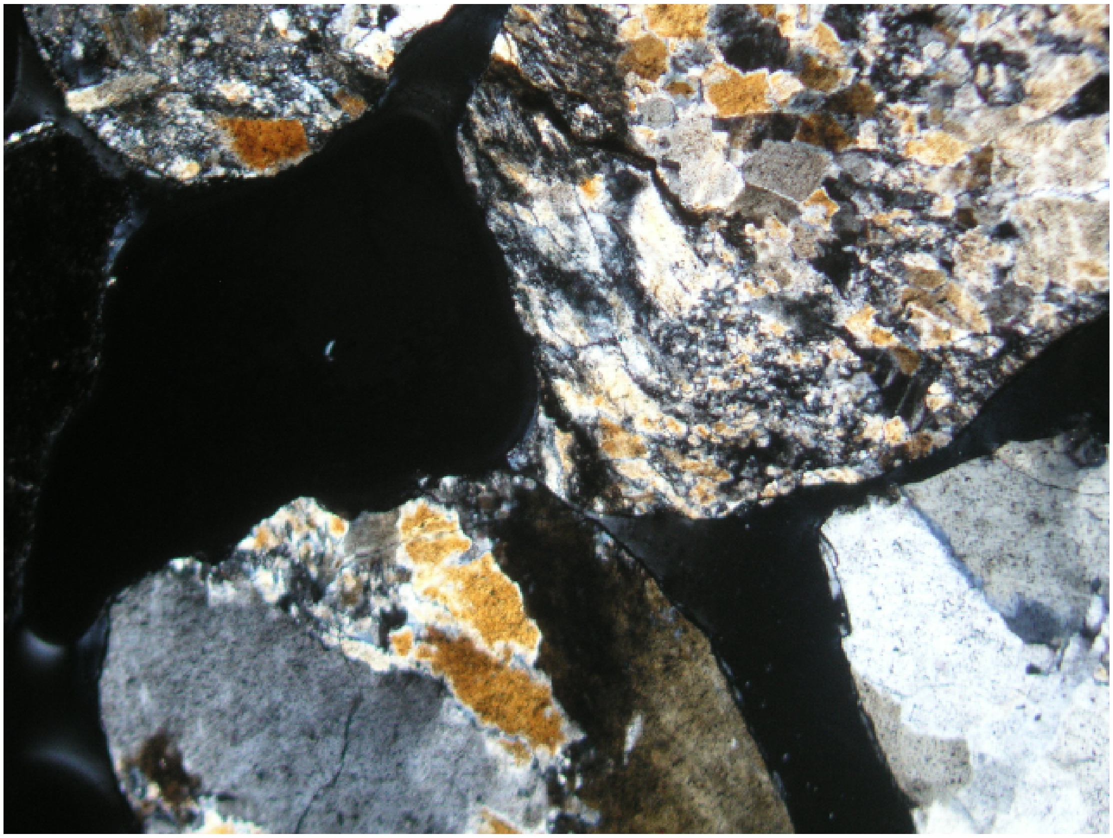

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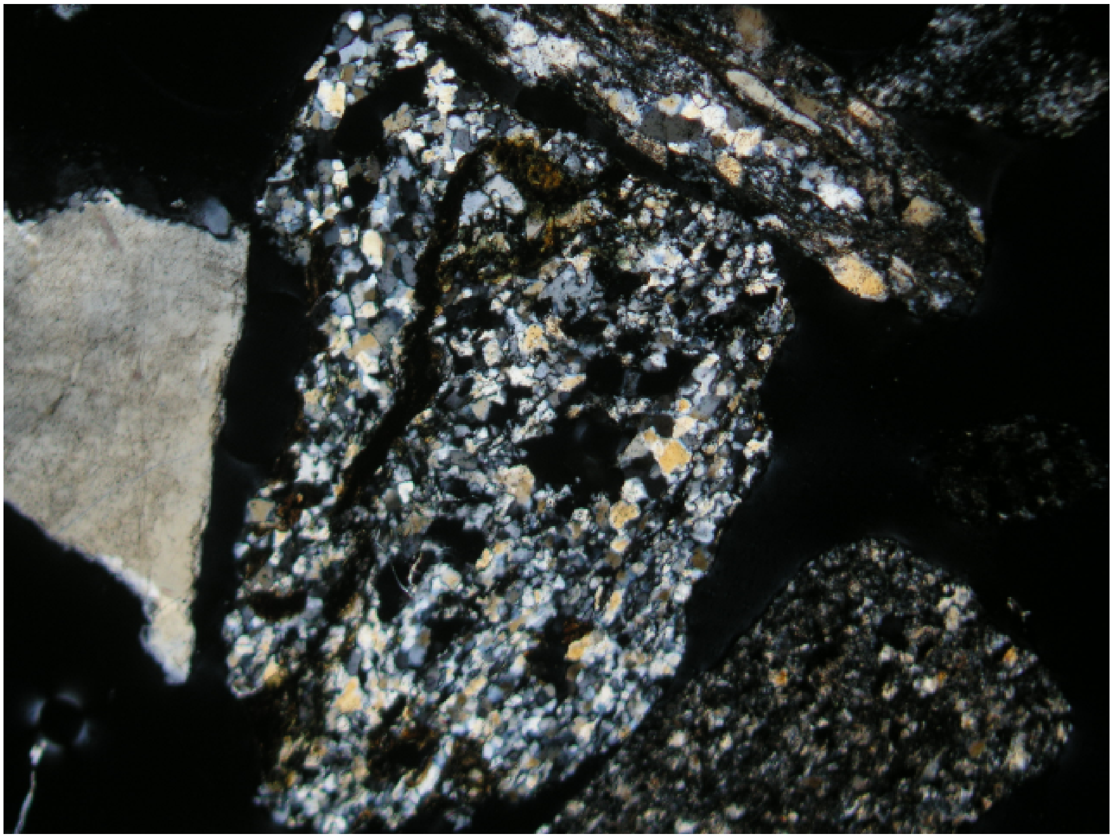
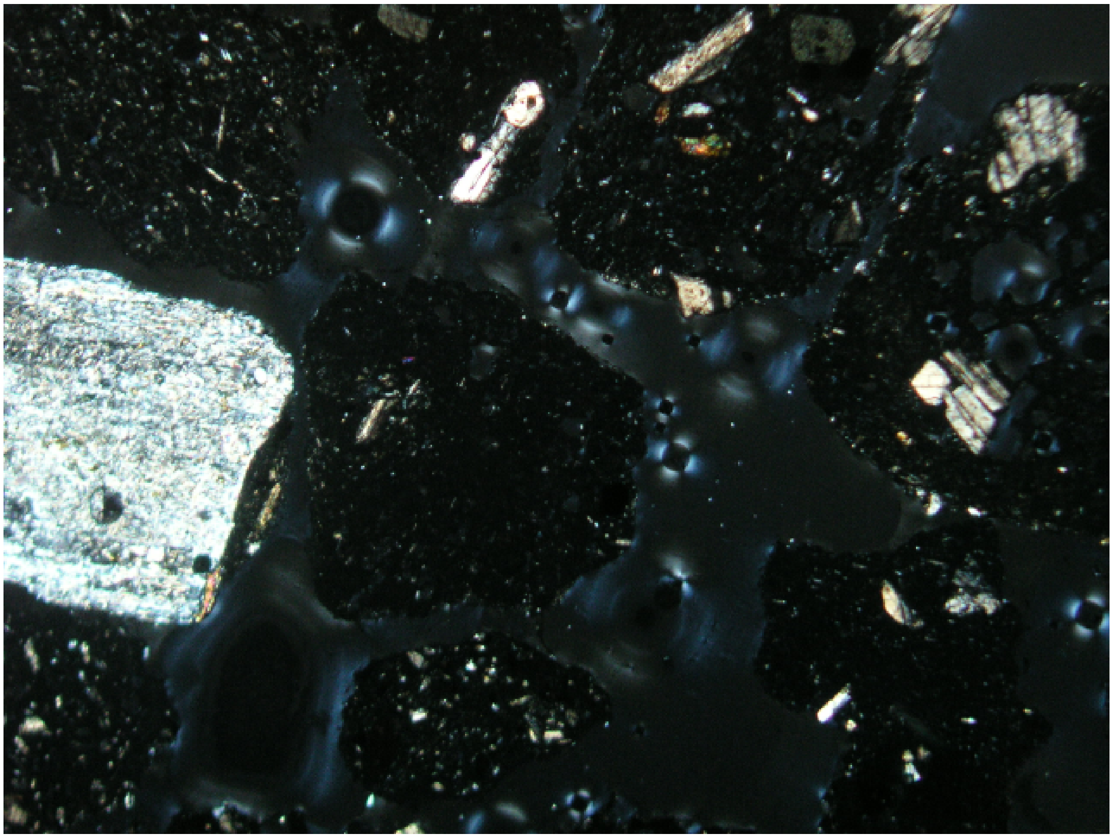
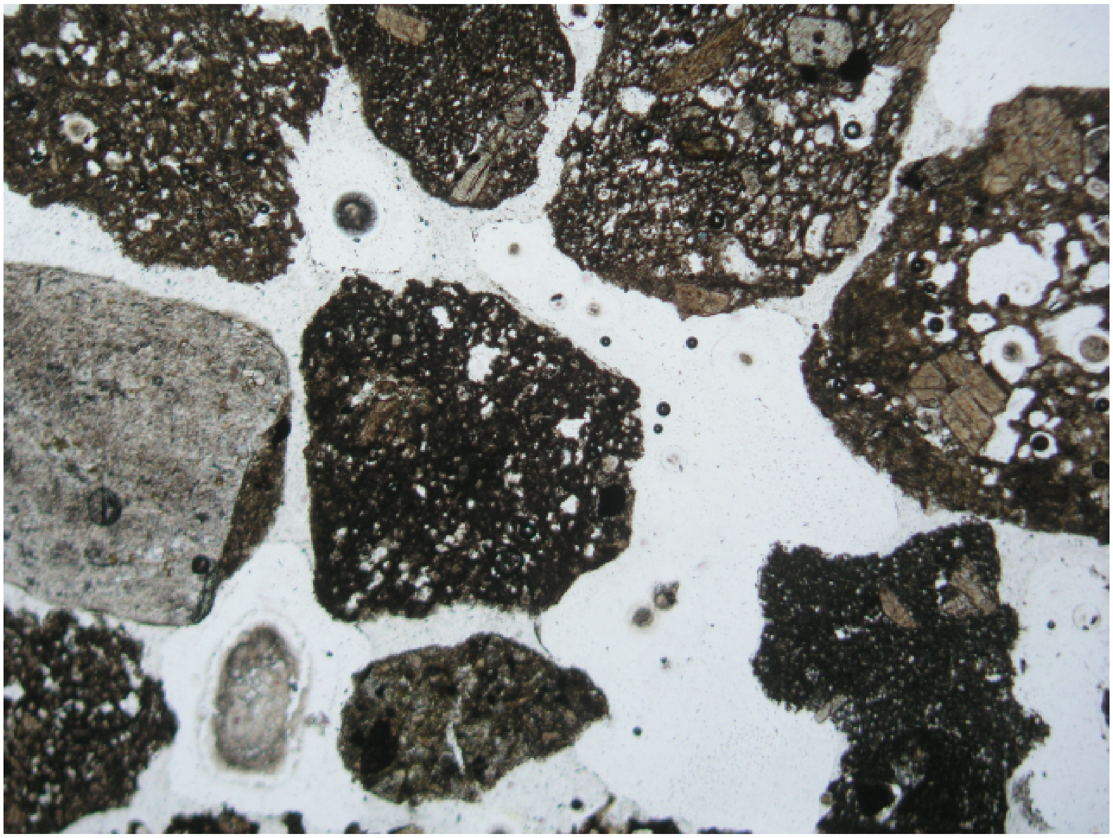


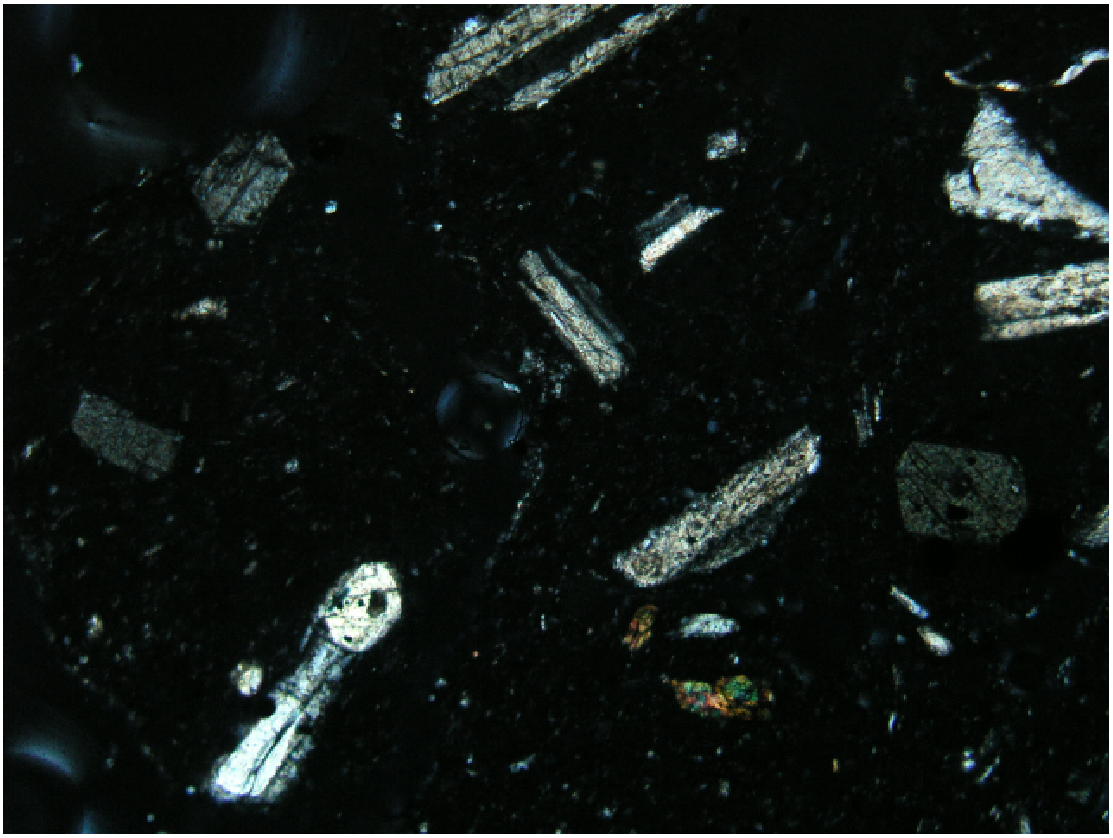
P7241309-1R2#1



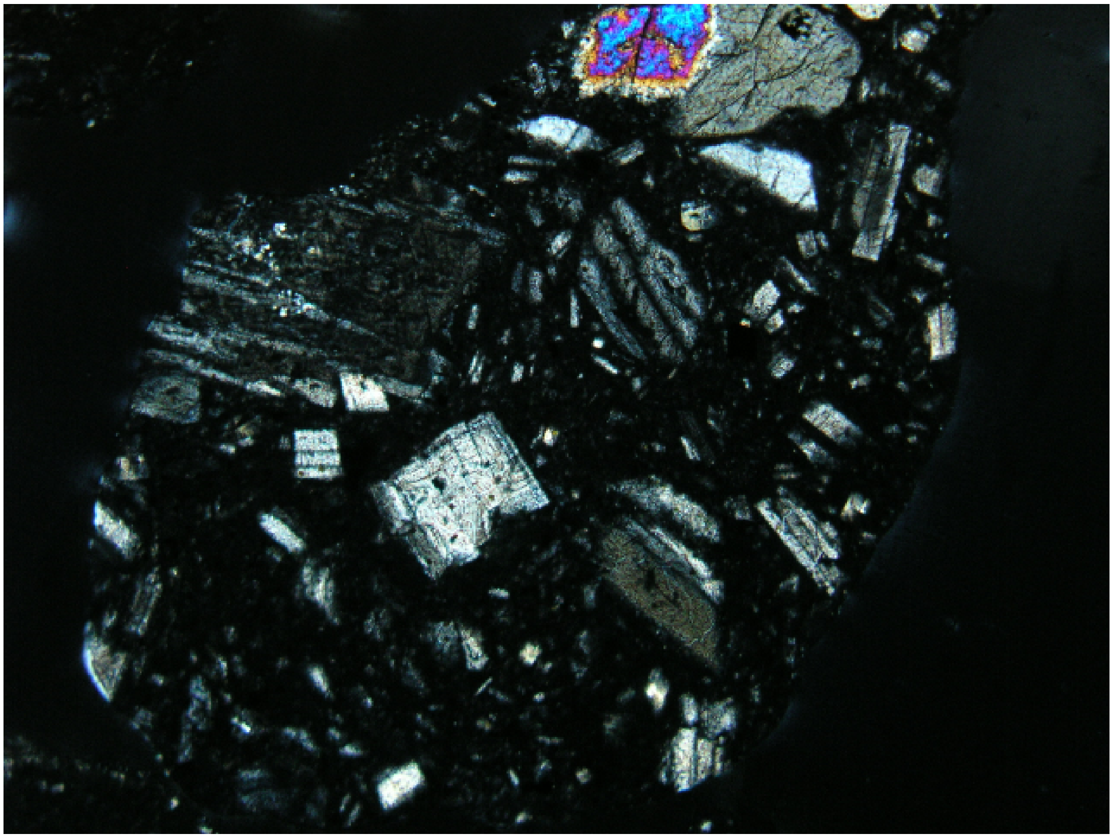
P7241310-24A2#5



P7241311-24A2#5



P7241312-24A2#5



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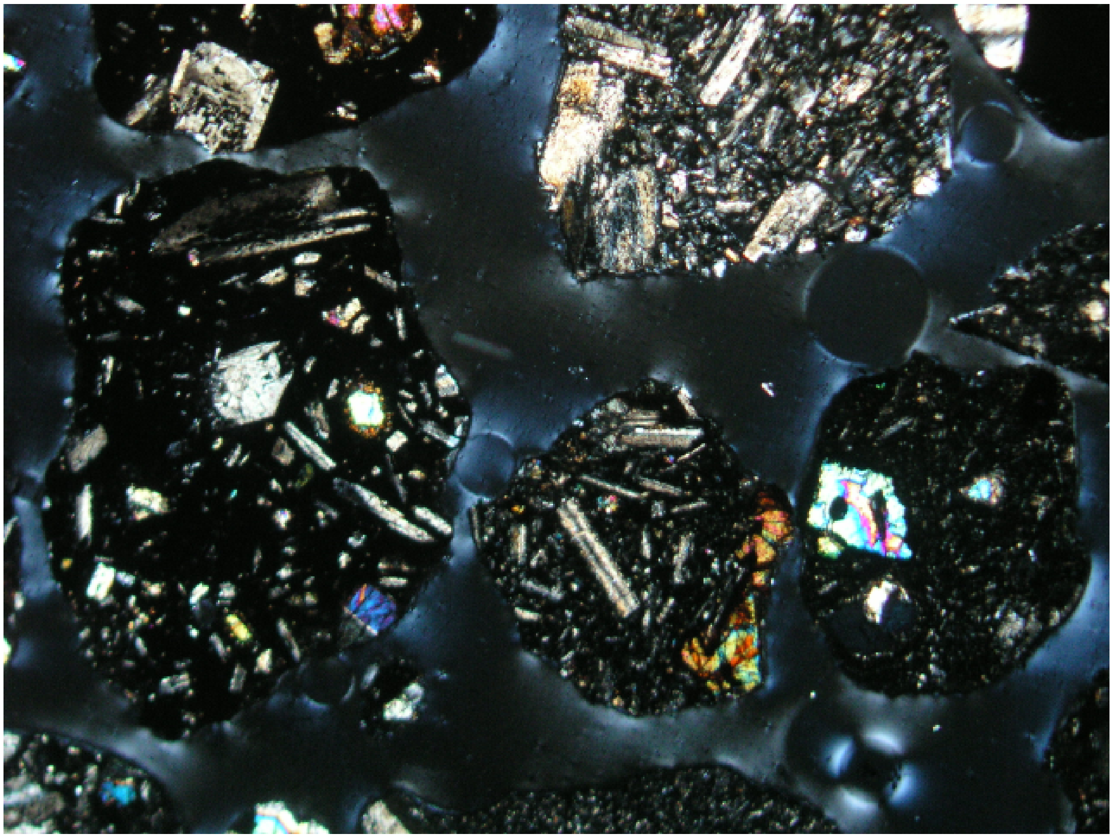

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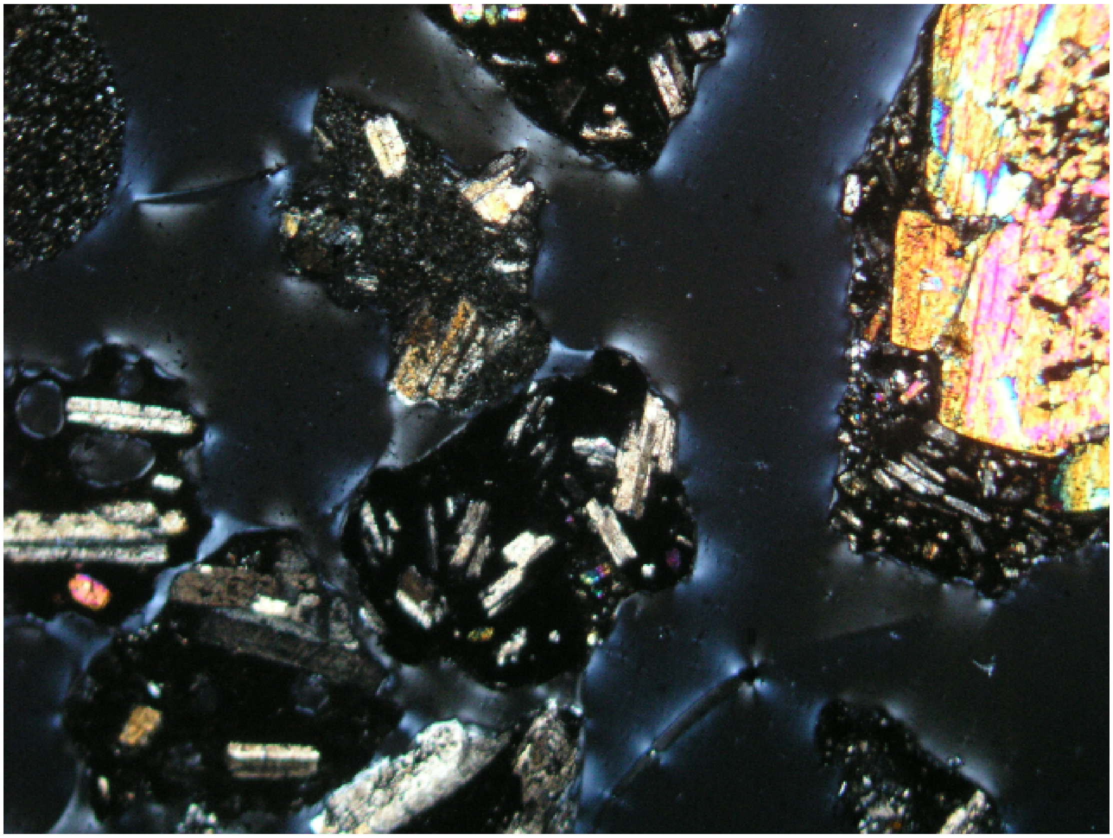
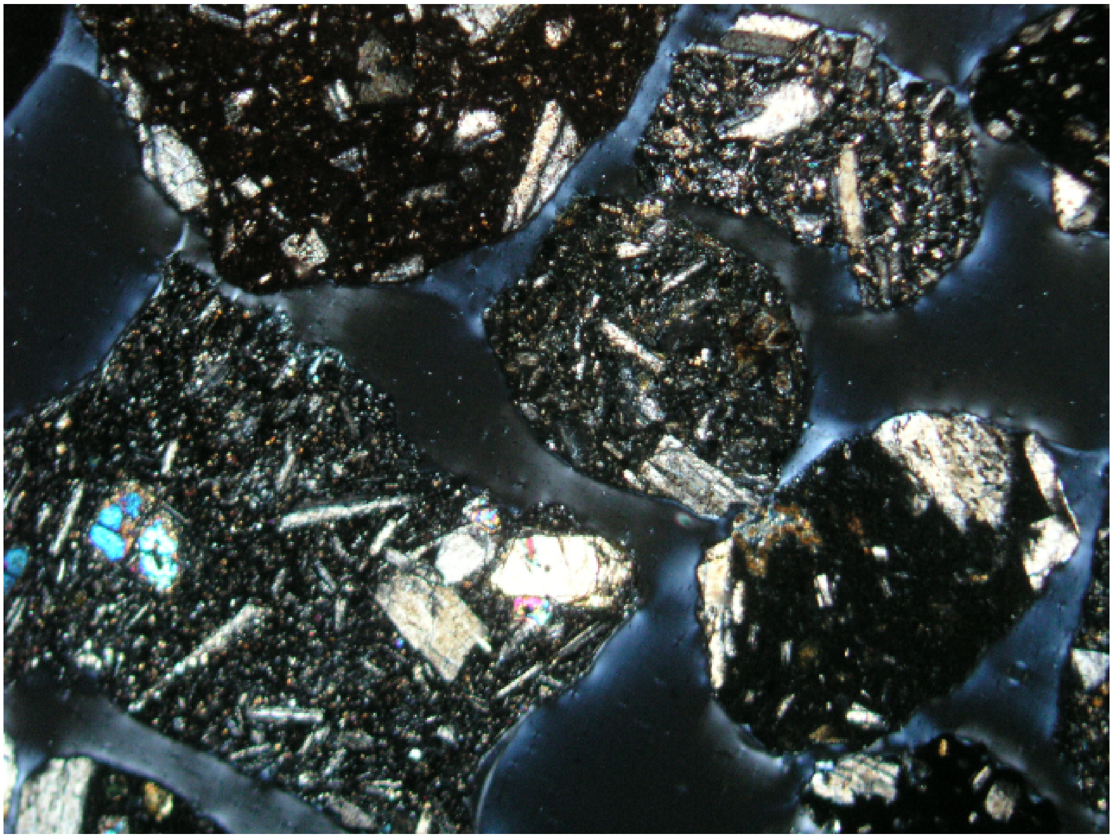


P7241315-4M1#2



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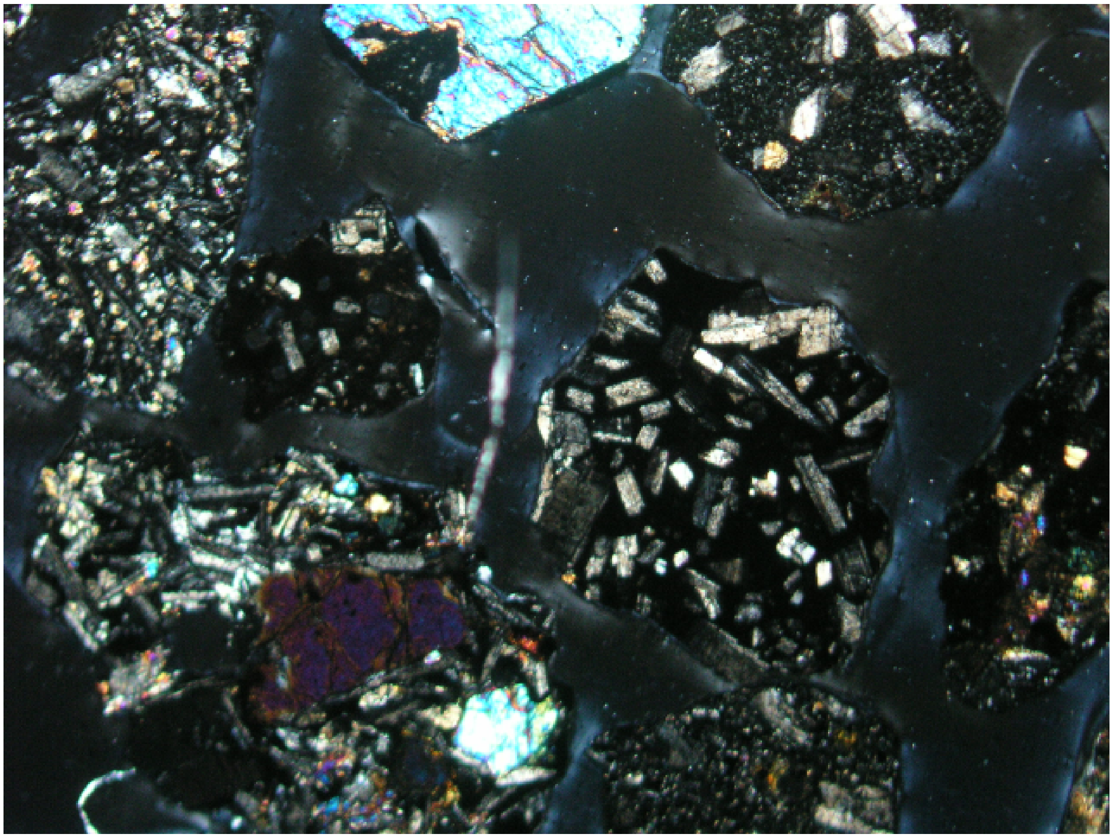

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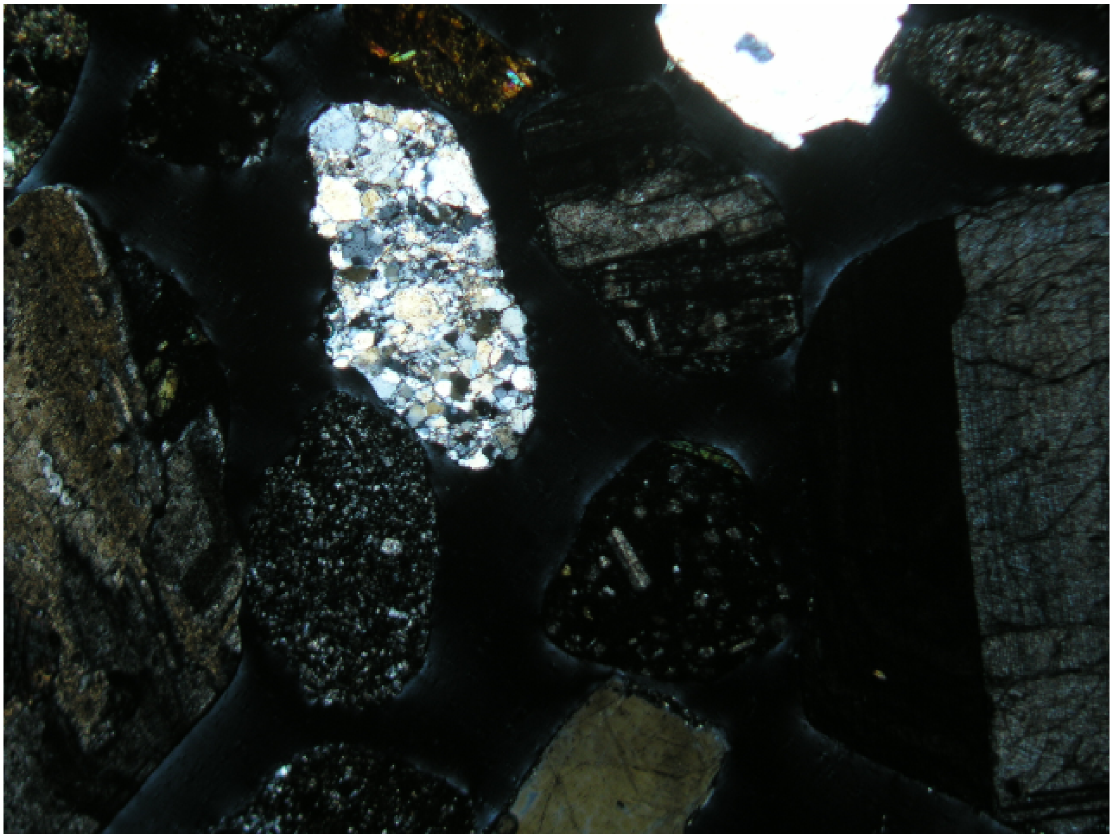

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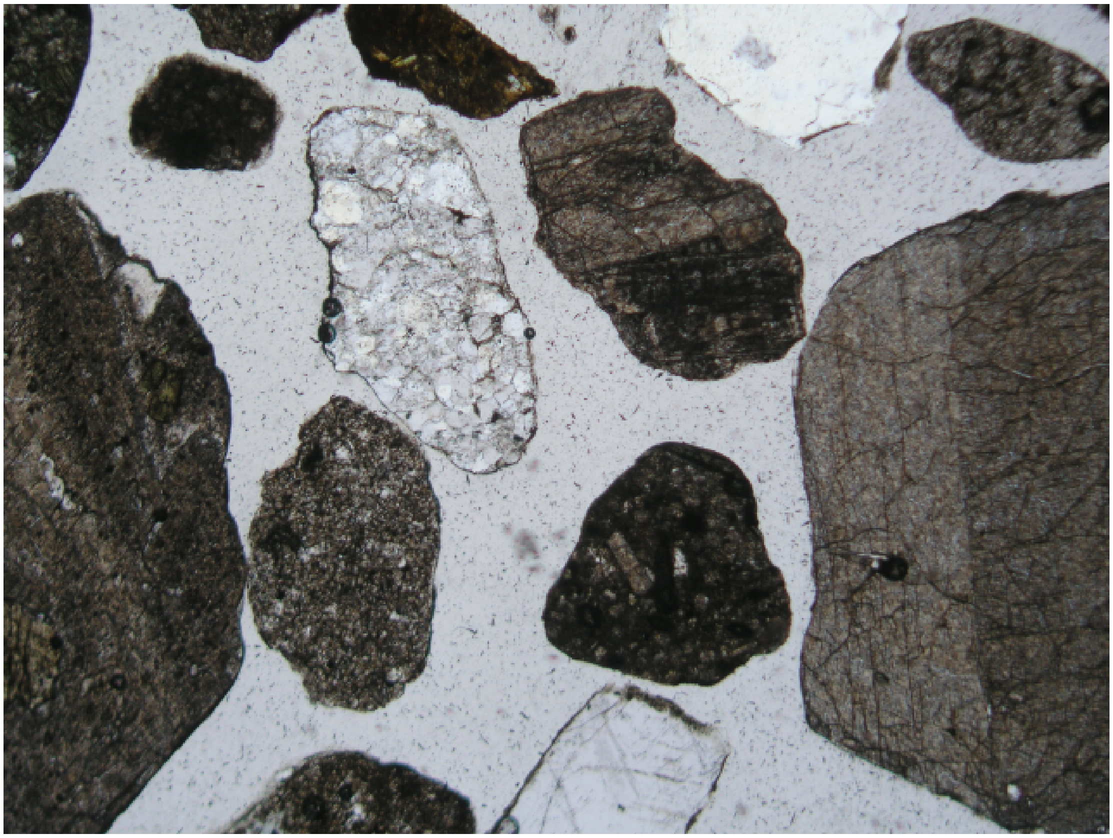
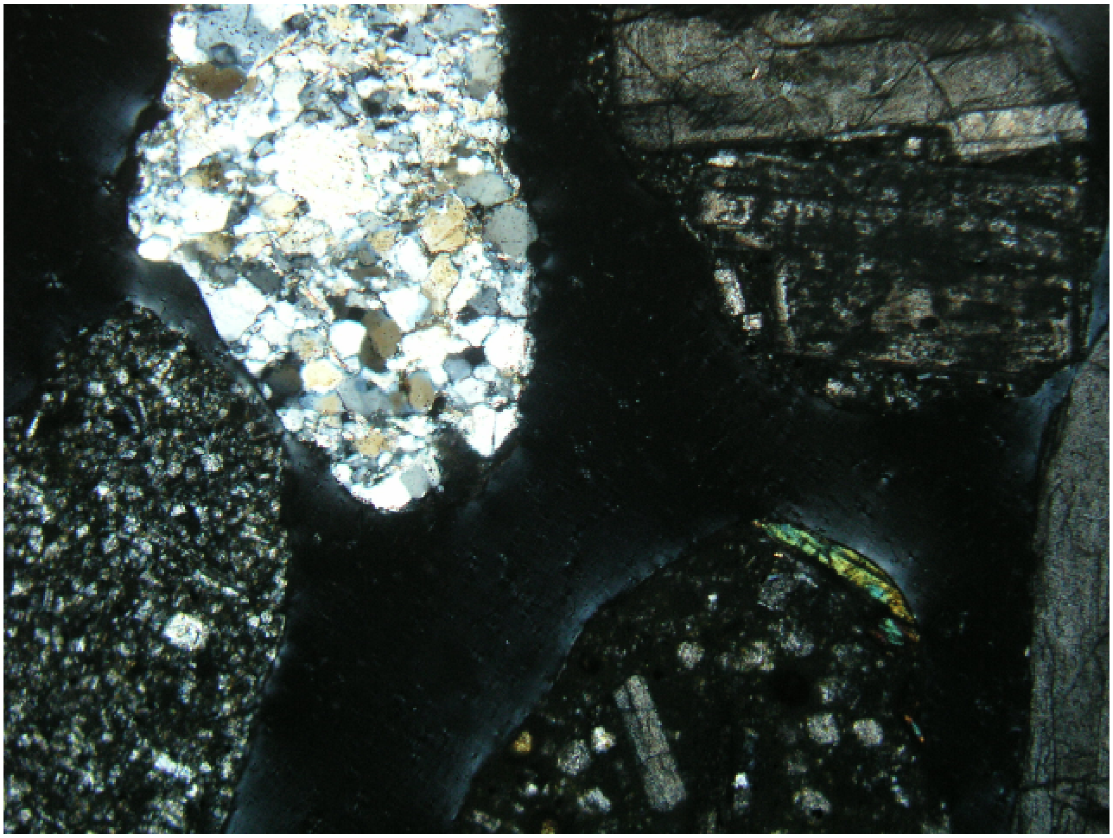
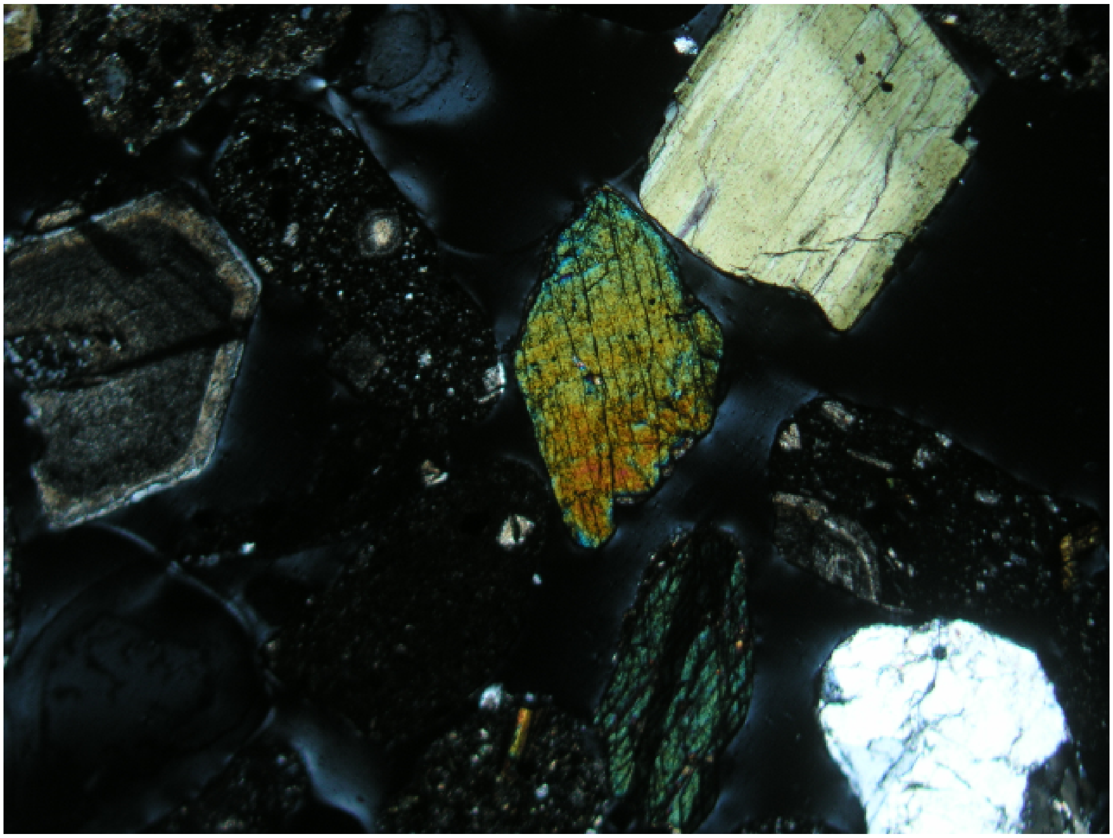


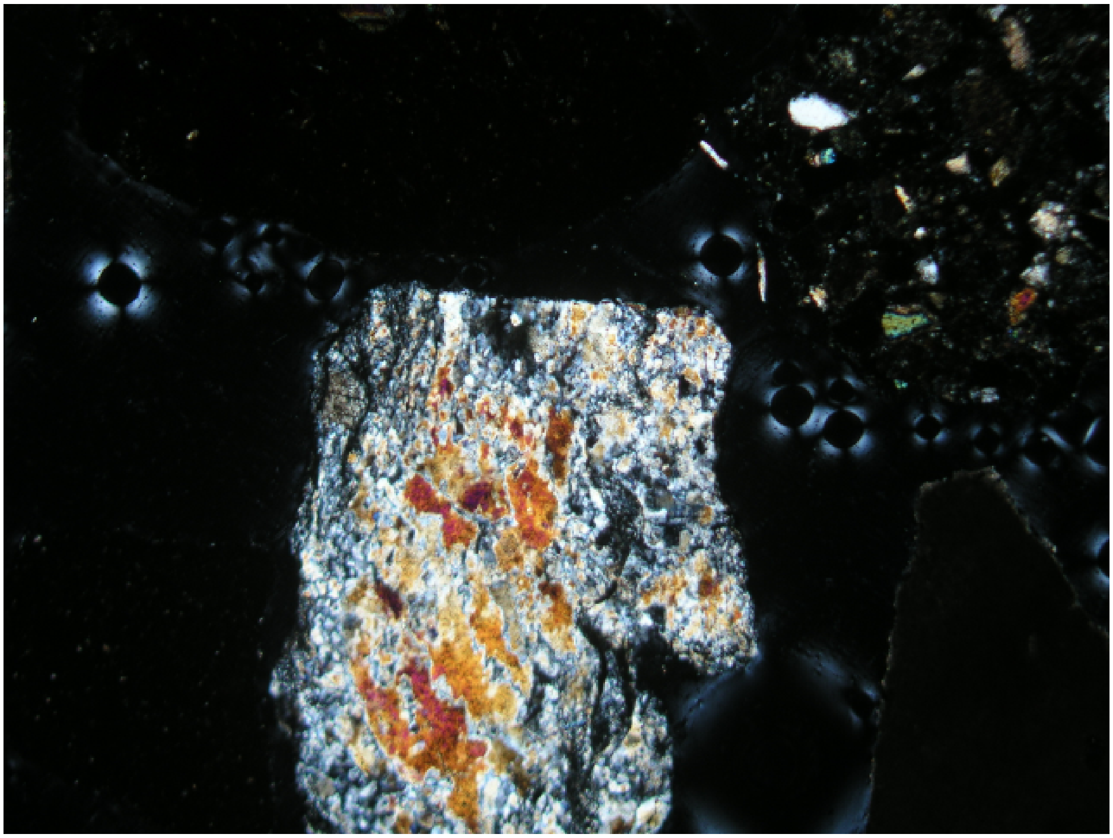
P7241319-13Q2#3



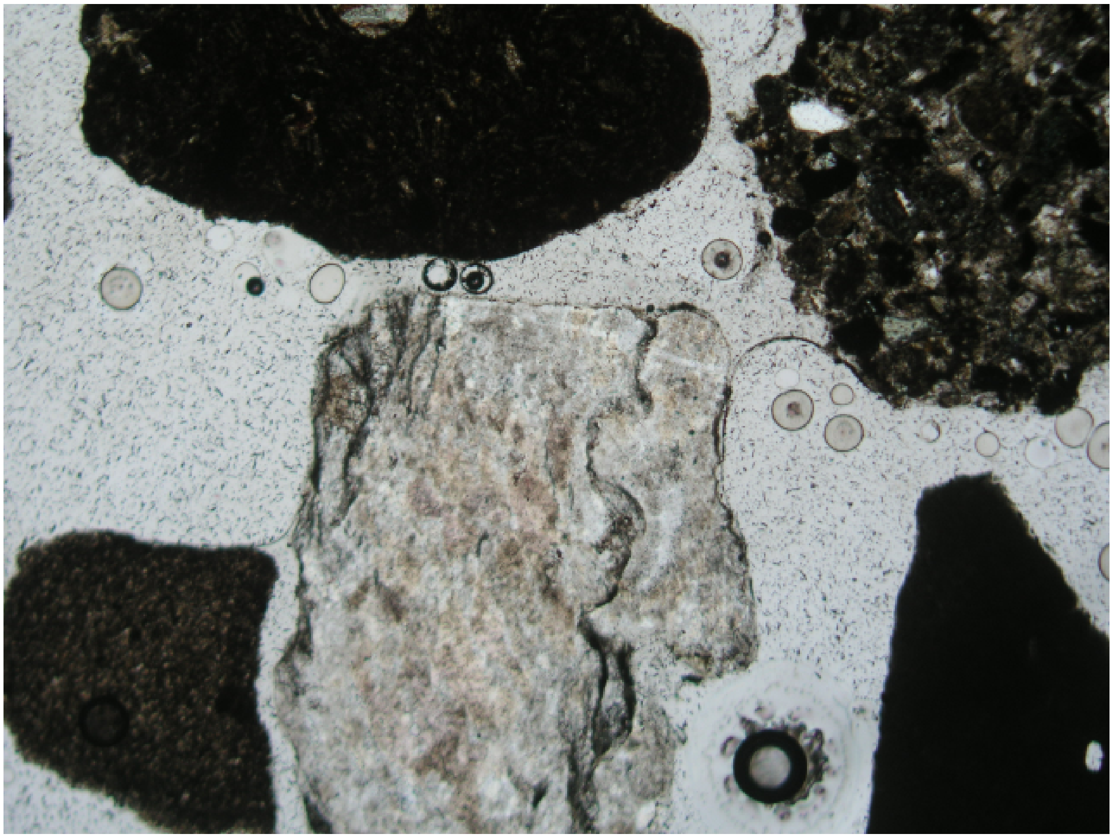
P7241320-13Q2#3



P7241321-13Q2#3



P7241322-1R2#3



P7241323-1R2#3

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Appendix C. Description of Geologic Units Depicted on Geologic Map (Plate 1) and Cross Sections (Plates 2 and 3)

Description of Geologic Units Shown on Geologic Map (Plate 1)

Many of the following descriptions were adapted from “Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California” by Helley and Harwood (1985). Citations within the original text remain and are italicized, but they were not reviewed by the authors and are not included in the Selected References section of this document. Please refer to the original document for complete citation information.

Surficial Deposits

Qsc — Stream Channel Deposits (Holocene) — Deposits of open, active stream channels without permanent vegetation. These deposits are being transported under modern hydrologic conditions; consequently they are light tan and gray, unweathered, and usually in contact with modern surface waters. The mapping merely limits the right and left bank boundaries of the active stream channel. Morphology within the deposits is constantly changing. Thickness may reach 25 m on the Sacramento River or be less than a few centimeters in bedrock canyons (Helley and Harwood 1985).

Qa — Alluvium (Holocene) — Unweathered gravel, sand, and silt deposited by present-day stream and river systems that drain the Coast Ranges, Klamath Mountains, and Sierra Nevada. Differentiated from older stream-channel deposits (Qao and Qal) by position in modern channels. These units lie outboard of unit Qsc but inside the first low terraces flanking modern stream channels. The deposits form levees along the main course of the Sacramento River, and broad alluvial fans of low surface relief along the western and southwestern side of the valley. Because of high organic content, the levee deposits are darker gray than the alluvium flanking the channels on smaller streams. Thickness varies from a few centimeters to 10 m (Helley and Harwood 1985).

Qo — Overbank Deposits (Holocene) — Sand, silt, and minor lenses of gravel deposited by floods and during high water stages; form low terraces adjacent to present-day alluvial stream channels; coincident with tan and gray organic-rich sediments (Qm) which generally mark high-water trim lines of historical floodwaters. The deposits probably do not exceed 3 meters in maximum thickness (Helley and Harwood 1985).

Qal — Alluvial Deposits, Undivided (Holocene) — Undivided Gravel, sand, and silt; these contacts are generally taken from previous mapping (Helley and Harwood 1985).

Qb — Basin Deposits, Undivided (Holocene) — Fine-grained silt and clay derived from the same sources as modern alluvium. The dark-gray to black deposits are the distal facies of unit Qa. The undivided basin deposits provide rich and valuable farmland especially for rice production in the Sacramento Valley. This unit covers much of the valley in the southern half of map area. Thickness varies from 1 or 2 m along the valley perimeter to as much as 60 m in the center of the valley (Helley and Harwood 1985).

Qm — Marsh Deposits (Holocene) — Fine-grained, very organic rich marsh deposits; differentiated from the undivided basin deposits (Qb) by generally being under water (Helley and Harwood 1985).

Qls — Landslides (Holocene and Pleistocene) — Slumped, rotated chaotic mixtures of underlying bedrock units and colluvium; particularly abundant and extensive in the Montgomery Creek and Chico Formations (Helley and Harwood 1985).

Qmu — Upper Member, Modesto Formation (Pleistocene) — Unconsolidated, unweathered gravel, sand, silt, and clay. The upper member forms terraces that are topographically the lowest of the two Modesto terraces. It also forms alluvial fans along the east side of the Sacramento Valley from Red Bluff to Oroville. Soils at the top of the upper member have A/C horizon profiles, but unlike the lower member they lack argillic B horizons. Deposits belonging to the upper member of the Modesto are only a few meters thick and generally form a thin veneer deposited on older alluvial deposits. Original surficial fluvial morphology is usually preserved and gives relief of 1 or 2 m. C-14 age determination on plant remains from the upper member at Tulare Lake suggest that the unit is between 12,000 and 26,000 years old *(Brian Atwater, oral commun., 1982).* Thus the deposition of the upper member of the Modesto Formation appears to correspond with the Tioga glaciation in the Sierra Nevada *(Birkland and others, 1976)* (Helley and Harwood 1985).

Qml — Lower Member, Modesto Formation (Pleistocene) — Unconsolidated, slightly weathered gravel, sand, silt, and clay. The lower member forms terraces that are topographically a few meters higher than those of the upper member. It forms alluvial fans along the main channel of the Sacramento River and Feather River and large levees bordering the Sacramento River from Stony Creek to Sutter Buttes. Upstream from Stony Creek, the lower member of the Modesto is preserved as scattered terrace remnants. Alluvium of the lower member of the Modesto surrounds the Dunnigan Hills and borders Cache Creek near Esparto. Soils developed on the lower member contain an argillic B horizon, which is marked by a noticeable increase in clay content and a distinct red color. Its surface fluvial morphology is remarkably smooth and displays little relief. The unit is much more extensive than the upper member and probably represents a longer period of deposition. The lower member of the Modesto unit is the youngest deposit from which we have evidence for possible fault displacement. Conspicuous linear-edged terraces composed of the lower member deposited along the northeast fan of the Dunnigan Hills may also reflect fault displacement.

Marchand and Allwardt (1981) gave an age for the lower member as probably Altonean (early and middle Wisconsinan) based on an open-system uranium series minimum age of 29,407 +/- 2,027 yr on bone from basin deposits of the lower member of the Modesto. A radiocarbon age on wood from a depth of 15-16 m in basin deposits of the lower member was 42,000 +/- 1,000 yr B.P. *(Marchand and Allwardt, 1981, p. 57).* Marchand and Allwardt speculate that this may be the older age limit of the lower member. Since the dates were from flood-plain deposits where deposition may have continued long after terrace deposition ceased, the ages may be too young (Helley and Harwood 1985).

Qru — Upper Member, Riverbank Formation (Pleistocene) — Unconsolidated but compact, dark-brown to red alluvium composed of gravel, sand, silt and with minor clay. Topographically forms the lower of the two Riverbank terraces; forms dissected alluvial fans on the northwest and southeast sides of the Sacramento Valley with distinct and now abandoned distributary channels cut into the lower member and older deposits. The Riverbank members generally are separated vertically by about 3 m, but the lower member of the Modesto may be more than 5 m lower in elevation. The upper member, while smoother than the more dissected lower member, displays more relief than the lower member of the Modesto (Helley and Harwood 1985).

Qrl — Lower Member, Riverbank Formation (Pleistocene) — Red semiconsolidated gravel, sand, and silt. Comprises the higher of the two Riverbank terraces and remnants of dissected alluvial fans. This terrace is cut and backfilled into the Red Bluff and older alluvial deposits. Its surface is much more dissected than the upper member with several meters of local relief. Where eroded it also displays much stronger, almost maximal soil profiles with hues approaching a maximum 2.5 YR. Like the upper member, the lower member is best preserved in the northwestern and southeastern parts of the valley; the most extensive exposures are in and around the city of Sacramento. Most of the alluvium of the lower member near Sacramento is very arkosic, and it was probably derived from the western slopes of the Sierra Nevada and deposited by the American River. The modern Sacramento River impinges on the alluvial fan comprising the lower member of the Riverbank and appears to be cannibalizing it.

Northwest of the confluence of the Sacramento and American Rivers, numerous small discontinuous outcrops of the lower member are buried partially by Holocene alluvial and basin deposits. The deposits of the lower member in that area probably mark the ancient distal edge of the Riverbank fan. It also appears that the lower member was cut by a south-flowing ancient channel of the Feather River or Bear River, or both. Today, the Feather River departs from its due-south course below its confluence with the Bear and abruptly strikes southwesterly around the numerous outcrops of the lower member of the Riverbank (Helley and Harwood 1985).

Qrb — Red Bluff Formation (Pleistocene) — A thin veneer of distinctive, highly weathered bright-red gravels beveling and overlying the Tehama, Tuscan, and Laguna Formations. In this study Helley and Harwood interpret the Red Bluff Formation as a sedimentary cover on a pediment surface and therefore suggest that it formed in response to a fixed base level caused by impeded or closed drainages of the Sacramento Valley. The Red Bluff pediment is overlain by the Rockland ash bed (0.45 m.y. old) *(Meyer and others, 1980)* and in turn overlies the basalt of *Deer Creek (1.08+-0.16 m.y.)*. Therefore, the pediment must have formed sometime within that 630,000-year interval.

The Red Bluff is best preserved in the northern part of the valley from Redding to south of the Orland Buttes on the west and south to Chico on the east; it also occurs along the southwest side of the valley where its pediment character is less clear. The scattered capping of the Arroyo Seco Gravel of *Piper and others (1939) and Schlemon (1967)* in the Sacramento area and also the half dozen or so scattered gravel remnants south of woodland between Cache and Putah Creeks may actually be Red Bluff. The Red Bluff is deformed by the Dunigan Hills anticline, a doubly plunging fold west of Arbuckle, and it unconformably overlies the Tehama on a structural high south of Woodland that may be a continuation of that fold. The Red Bluff also unconformably overlies the Tehama in intermittent patches along the western valley between Winters and the mouth of Cache Creek (Helley and Harwood 1985).

Qtl — Turlock Lake Formation (Pleistocene) — Deeply weathered and dissected arkosic gravels with minor resistant metamorphic rock fragments and quartz pebbles; sand and silt present along the south and east sides of the Sacramento Valley. The Turlock Lake is more widespread in the San Joaquin Valley where *Arkley (1954)* first recognized this unit, but it was named by *Davis and Hall (1959)* for arkosic alluvium overlying the Mehrten Formation and underlying the Riverbank Formation in eastern Stanislaus and northern Merced Counties. The Turlock Lake is easily recognized in both valleys by its characteristic arkosic lithology, geomorphic form, and relation to underlying and overlying units. The Turlock Lake stands topographically above the younger fans and terraces and commonly displays as much as 30 m of erosional relief. The unit represents eroded alluvial fans derived primarily from the plutonic rocks of the Sierra Nevada to the east.

In the San Joaquin Valley, *Arkley (1954)* recognized that the Turlock Lake consists of two distinct units separated by a very strongly developed soil on the lower part, while the upper part contains two distinct members, the Corcoran Clay Member and the Friant Pumice Member. *Janda (1965)* reported a K-Ar age of 0.62 +/- 0.02 m.y. for the pumice member. The paleomagnetic data of Verosub *(in Marchand and Allwardt, 1981)* support this age by showing the upper part of the Turlock Lake has normal polarity and the lower part has reversed polarity, and thus is greater than 0.7 m.y. old. The upper part of the Turlock Lake is probably correlative with the Red Bluff pediment because there is overlap in the age range of the units. The upper part of the Turlock Lake and the Red Bluff pediment also may be physically related through the Corcoran Clay Member of the Turlock Lake, which represents lacustrine conditions that may have impeded through-flowing drainage from the Sacramento Valley thus favoring the Red Bluff pediment-forming process. The Turlock Lake mapped in the Sacramento Valley probably correlates with the lower part of the Turlock Lake of the San Joaquin Valley since it overlies the Laguna Formation and is truncated by the Red Bluff Formation pediment. The Red Bluff pediment may have developed in the time interval between the deposition of the Corcoran Clay Member about 600,000 year ago and the deposition of the Rockland ash bed approximately 450,000 year ago (Helley and Harwood 1985).

QTog — Older Gravel Deposits (Pleistocene and (or) Pliocene) — Moderately well indurated, coarse to very coarse gravel with minor coarse sand resting unconformably on a truncated soil profile developed on the Tuscan Formation that is well-exposed along Hogback Road and in Salt Creek east of Red Bluff. These coarse gravels, derived from the Tuscan Formation, are bright reddish tan (2.5 YR) to yellowish tan, well rounded, and locally deeply weathered. The deposits are expressed geomorphically as very steep-sloping, symmetrical alluvial fans that probably developed during or soon after formation of the Chico monocline (Helley and Harwood 1985).

Sedimentary Rocks Including Some Volcanic Rocks

Tte — Tehama Formation (Pliocene) — Pale-green, gray, and tan sandstone and siltstone with lenses of crossbedded pebble and cobble conglomerate derived from the Coast Ranges and Klamath Mountains; named by *Diller (1984)* for typical exposures in Tehama County in northwestern Sacramento Valley.

The Tehama rests with marked unconformity on Cretaceous rocks of the Great Valley sequence along the west side of the valley and on plutonic and metamorphic rocks of the Klamath Mountains west of Redding where the Mesozoic sedimentary rocks are missing. The Tehama is unconformably overlain by gravels of the Red Bluff pediment; excellent exposures of this stratigraphic relationship are visible a few kilometers south of Red Bluff along Interstate 5 and along the river bluffs at Redding.

North of Red Bluff the Tehama Formation interfingers with the Tuscan Formation in a broad zone extending approximately from Interstate 5 east to the Sacramento River. The clastic debris becomes progressively more andesitic in composition and Tuscan-like in appearance eastward in this area of sediment interfingering. The contact with the Tuscan Formation is gradational and Helley and Harwood have arbitrarily chosen the Sacramento River channel as the map contact. Since both the Tehama and Tuscan contain the Nomlaki Tuff Member at or near their stratigraphic bases they are considered coeval. In the southwestern part of the Sacramento Valley, the Tehama also contains the Putah Tuff Member near its base; the Putah is the same age as, but stratigraphically below, the Nomlaki *(Sarna-Wojcicki), 1976, p.18; oral commun., 1982).*

Maximum thickness of the Tehama is about 600m *(Olmsted and Davis, 1961).* The Tehama is significant because the base of the unit is also the base of fresh groundwater in the entire Sacramento Valley (Helley and Harwood 1985).

Tt — Tuscan Formation (Pliocene) — Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff. Divided into:

- Ttd — Unit D, Tuscan Formation (Pliocene) — Predominantly fragmental deposits characterized by large monolithologic masses of gray hornblende andesite, augite-olivine basaltic andesite, black pumice, and smaller fragments of black obsidian and white and gray hornblende-bearing pumice in a grayish-tan pumiceous mudstone matrix. Locally in Battle Creek and elsewhere this unit contains an unlayered basal deposit of dark-gray andesite tuff with abundant black scoria and less abundant black glass fragments. Size of monolithologic fragments increases to the east toward Mineral, California; highly fractured monolithological masses 8 to 10 m in diameter are exposed in new road cuts on California Highway 36 on the south slope of Inskip Hill. Unit D probably originated from a major explosive event at its source volcano and consists of directed blast or avalanche deposits, or both, juvenile pyroclastic deposits of andesitic tuff, and lahars derived from the blast deposits. Samples from two monolithologic masses of andesite in the avalanche (?) deposit at Inskip Hill gave K-Ar ages of 2.49 +/- 0.08 and 2.43 +/- 0.07 m.y. *(J. von Essen, written commun., 1982);* slightly older than the basalt of Cohasset Ridge. Locally separated from unit C by the tuff of Hogback Road; where tuff is absent, lahars of unit D are distinguished from those of unit C by the presence of monolithologic rock masses, black obsidian fragments, and white and dove-gray dacitic pumice fragments. Unit D lies gradationally above the tuff of Hogback Road and unconformably above unit C where the tuff is missing. The unit ranges in thickness from about 10 to 50 m (Helley and Harwood 1985).
- Tth — Tuff of Hogback Road (Pliocene) — Discontinuous thin lapilli tuff, pumiceous sandstone, and conglomerate composed of rounded white hornblende-bearing dacitic pumice fragments as much as 3 cm in diameter and smaller gray and black pumice fragments admixed with varying amounts of andesitic detritus. Unit is commonly thin bedded, locally cross-bedded water-worked dacitic ash deposit that rests unconformably on unit C. Excellent exposures are found on the southwestern slope of Tuscan Buttes and in the broad topographic depression between Tuscan Buttes and Tuscan Springs where the unit is about 15 m thick. The tuff is about 2.5 m thick at the hogback on Hogback Road (Helley and Harwood 1985).

- Ttc — Unit C, Tuscan Formation (Pliocene) — Lahars with some interbedded volcanic conglomerate and sandstone locally, north of Antelope Creek, separated from overlying units by partially stripped soil horizon. Along the Chico monocline southeast of Richardson Springs, unit C consists of several lahars 3 to 12 m thick separated from each other by thin layers of volcanic sediments; lahars contain abundant casts of wood fragments and prominent cooling fractures. Along Dye Creek Canyon, unit C consists of interfingering and overlapping discontinuous lahars without significant interbeds of volcanic sediments. At Tuscan Springs and around Tuscan Buttes, unit C consists of indistinctly layered to chaotic lahars with minor scattered volcanic conglomerate and crossbedded sandstone occupying distinct and restricted channels in the volcanic deposits. Unit C is about 50 m thick in Mud Creek Canyon west of Richardson Spring and about 80 m thick near Tuscan Springs (Helley and Harwood 1985).
- Tti — Ishi Tuff Member (Pliocene) — White to light-gray, fine grained, pumiceous air-fall tuff commonly reworked and contaminated with variable amounts of volcanic sandstone and silt. Distinguished by abundant black to bronze biotite flakes about 1 mm in diameter. The Ishi was originally identified along the Chico monocline where it occurs as a 0.03 m thick ash layer deposited on volcanic conglomerate and silt at the top of unit B. Subsequent mapping identified a white, biotite-bearing tuff near Millville that correlates chemically with the Ishi *(A. M. Sarna-Wojcicki, oral commun., 1982).* East of Millville the Ishi contains pumice clasts as much as 8 cm in diameter and rests directly on a welded ash-flow tuff identical to that at Bear Creek Falls dated by *Evernden and others (1964)* at 3.4 m.y. and correlated by *Anderson and Russell (1939)* with the type Nomlaki Tuff Member (of the Tehama Formation). Biotite, plagioclase, and hornblende, which are separated from the large pumice clasts in the Ishi near Millville, give discordant K-Ar ages; a fission-track age of 2.7 m.y. obtained from zircons separated from the pumice clasts is the best current estimate of the age of the Ishi Tuff Member (Helley and Harwood 1985).
- Ttb — Unit B, Tuscan Formation (Pliocene) — Defined along the Chico monocline as interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone similar to unit C, but underlying the Ishi Tuff Member. Lahars and volcanoclastic rocks interbedded in approximately equal proportions give a more regularly layered sequence than in the lahar rich unit C. Maximum thickness of conglomerate layers is about 15 m. Coarse cobble to boulder conglomerate predominant in the eastern and northern parts of

mapped unit; crossbedded and channeled volcanic sandstone increases in abundance to the west and south. Unit B is about 130 m thick (Helley and Harwood 1985).

- Tta — Unit A, Tuscan Formation (Pliocene) — Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone all containing scattered fragments of metamorphic rocks. Metamorphic rock fragments, as much as 20 cm in diameter, include white vein quartz, green, gray, black chert, greenstone, greenish-gray slate, and serpentinite. Metamorphic clasts usually make up less than 1 percent of the rock; the remainder is basaltic and basaltic andesite volcanic fragments. The top of the member is defined by the highest lahar or volcanic conglomerate layer that contains metamorphic fragments. Unit A is about 65 m thick along the Chico monocline where it is defined (Helley and Harwood 1985).
- Ttn — Nomlaki Tuff Member (Pliocene) — White, light-gray, locally reddish-tan to salmon dacitic tuff and pumice lapilli tuff exposed in widely separated areas at or very near the bases of the Tuscan and Tehama Formations. Pumice fragments as much as 20 cm in diameter are generally white in the lower part of the member and a mixture of white light gray, and dark gray in the upper part. Member varies from massive nonlayered ash flow at Tuscan Springs, Gas Point, and Antelope Creek to distinctly bedded, reworked pumiceous sediment west of Richardson Springs. Maximum thickness is 25 m at Tuscan Springs, about 20 m at Antelope Creek, 1 m at Richardson Springs, and 30 m at Gas Point on the west side of the valley in the Cottonwood Creek drainage. Lahars containing metamorphic rock fragments typical of unit A of the Tuscan occur below the Nomlaki Tuff Member in Rock Creek and at the west end of the exposures of the Lovejoy Basalt in Bidwell Park east of Chico. *Everden and others (1964)* obtained a K-Ar age of 3.4 m.y. for a welded ash-flow tuff at Bear Creek Falls, which *Anderson and Russell (1939)* correlated with the type Nomlaki.

  The Nomlaki Tuff Member has been identified from trace-element content of the glass by Sarna-Wojcicki, *(written commun., 1982)* at eight localities near the base of gravel and sand deposits, mapped as the Laguna Formation *(Olmsted and Davis, 1961: Busacca, 1982),* around Oroville and points south to the Yuba River and Beale Air Force Base. The presence of the Nomlaki Tuff near the base of the Laguna Formation suggests that the Laguna is coeval with the Tuscan and Tehama (Helley and Harwood 1985).

Tla — Laguna Formation (Pliocene) — Interbedded alluvial gravel, sand, and silt. Pebbles and cobbles of quartz and metamorphic rock fragments generally dominate the gravels, but the matrix of the gravelly units and finer sediments are invariably arkosic. In the vicinity of Oroville, volcanic rocks may comprise as much as 20 percent of the gravels, but again the finer sediments are dominantly arkosic. The Laguna is lithologically indistinguishable from the Turlock Lake Formation, but the Turlock Lake is more compact at the surface due to a preserved B2t soil horizon. The Laguna, on the other hand, has had its former soil profiles stripped by erosion. The Turlock Lake and the Laguna can be distinguished by their stratigraphic positions relative to pediment gravels, by the presence or absence of some soil profiles, and by their topographic settings. In the Oroville area the Laguna is easier to distinguish because it contains the Nomlaki Tuff Member near its base *(Busacca, 1982, p. 103).* Helley and Harwood did not find the Nomlaki in the Laguna in the Sacramento area nor anywhere south of Beale Air Force Base.

The Laguna Formation was named by *Piper and others (1939)* for arkosic deposits in the vicinity of Laguna Creek, San Joaquin County. These Sierran-derived deposits overlie the Mehrten Formation and are unconformably overlain by gravel of the Northern Merced pediment. Although the Laguna gravels are not exposed continuously from the type area northward into the Sacramento Valley, similar arkosic sediments overlying the Mehrten and truncated by the Red Bluff pediment occur in the Sacramento Valley and have been correlated with the Laguna *(Olmsted and Davis, 1961 and Busacca, 1982).* Helley and Harwood agree with this correlation. The Laguna displays highly dissected rolling topography with tens of meters of relief. The only exposures are between Oroville and Sacramento on the Southeast side of the valley. The Laguna was deposited by the ancestral west-flowing Feather, Yuba, Bear, and American Rivers.

The thickness of the Laguna is difficult to estimate because its base is rarely exposed and its surface has been highly eroded except where preserved beneath the Red Bluff Formation. The Laguna is probably about 60 m thick in the Oroville and thins to about 20 m or so south of Sacramento (Helley and Harwood 1985).

Ts — Sutter Formation of *Williams and Curtis (1977)* (Pliocene, Miocene, and Oligocene) — *Williams and Curtis (1977)* described these beds in the Sutter Buttes as consisting “almost exclusively of volcanic sediments transported by rivers from the Sierra Nevada to be deposited in deltaic fans and on broad flood plains that occupied most of the Sacramento Valley during the Oligocene, Miocene, and Pliocene times” *(Williams and Curtis, 1977, p. 13).* Unit thickness ranges from 180 m to as much as 300 m (Helley and Harwood 1985).

Tc — Channel Deposits (Pliocene and Miocene) — Sandstone, laminated siltstone, conglomerate, and tuff breccias composed almost entirely of andesitic material exposed in some of the deeper canyons below the Tuscan Formation; includes the New Era Formation of *Creely (1965).* Unit is exposed near the New Era Mine in the northeast central part of the map, in Butte Creek, in Mud Creek below the Nomlaki Tuff Member of the Tuscan Formation and west of the Lovejoy Basalt, in the West Fork of

Rock Creek below the Nomlaki, and at Tuscan Springs below the Nomlaki. Cobble to pebble conglomerate has rounded, commonly disk-shaped clasts showing variable degrees of imbrications. Clasts include greenstone, gray quartzite, red, green, and black chert, white vein quartz, and lesser amounts of green and gray phyllite. Variable amounts of basalt identical to that in the Tuscan Formation are intermixed with the polycycle metamorphic fragments. Maximum thickness is about 20 m (Helley and Harwood 1985).

Tm — Mehrten Formation (Pliocene and Miocene) — Sandstone, laminated siltstone, conglomerate, and tuff breccia composed almost entirely of andesitic material with only small amounts of igneous and metamorphic rock fragments. The fragments of andesite are almost always dark-gray porphyritic andesite with phenocrysts of hornblende and plagioclase in a microcrystalline to glassy groundmass. The only outcrop of the Mehrten in the map area occur in a few square kilometers of the southeast side of the valley northeast of Roseville along Interstate Highway 80 where the unit rests unconformably on granitic basement. In the San Joaquin Valley the strata that underlie the Laguna Formation and overlie the Valley Springs Formation have been mapped as the Mehrten Formation by *Piper and others (1939) (Helley and Harwood 1985).*

Te — Sedimentary Rocks in Sutter Buttes Area (Eocene) — Consist of what *Allen (1925)* and *Williams and Curtis (1977)* variously referred to as their "Capay Shales", "Ione Sands", and "Butte Gravels". At Sutter Buttes the Capay consists of "buff sands locally rich in ferruginous concretions and glauconitic shales rich in foraminifera. Carbonaceous mudstones are occasionally present as are thin seams of low-grade coal especially on the north and east sides of the Buttes" *(Williams and Curtis, 1977, p. 12).* Maximum thickness is about 1,200 m on the western side of the buttes. The Ione consists of white well-sorted quartz sand with irregular pink, purple, or brown streaks of oxidation with minor amounts of bleached anauxite. Thickness ranges from 30 to 50 m. The Butte Gravels consist of poorly consolidated interbedded gravel and sand with thin lenses of limestone and sandstone. The clasts on the gravel are primarily colorless and milky vein quartz with other minor clasts of quartz porphyry, varigated chert, schist, and hornfels. The Butte Gravels is as much as 400 m thick (Helley and Harwood 1985).

Tmc — Montgomery Creek Formation (Eocene) — Gray, yellowish-orange-weathering, arkosic sandstone with conglomerate and shale; crops out on the Battle Creek escarpment along the road between Manton and Shingletown in the upper part of Lack Creek and Ash Creek, and occurs much more extensively in major southwest trending drainages of the Millville and Whitmore quadrangles. The rock is commonly massive to thick-bedded nonmarine sandstone with scattered lenses of pebble conglomerate and shale. Detrital muscovite and feldspar are common in the sandstone; red, green, and gray chert are the most common clasts in the conglomerate lenses. The unit is about 80 m thick at its south limit and apparently thickens to the north where *Anderson and Russell (1939)* reported 200 m of the formation exposed in Montgomery Creek. *Anderson and Russell (1939)* collected fossil leaves form the Montgomery Creek, which Chaney identified as definitely Eocene in age (Helley and Harwood 1985).

Ti — Ione Formation (Eocene) — Light-colored, commonly white conglomerate, sandstone, and claystone. Argillaceous sandstone and claystone comprise about 75 percent of the Ione along the southeast side of Sacramento Valley; northward the rest of the unit consists of interbedded siltstone, conglomerate, and shale. It should be noted that the map area is far north of the type locality at Ione in Amador County. The Ione is generally soft, deeply eroded, and marked by numerous landslides. Ione sandstones are characterized by fine grains of angular quartz and thin stringers of weathered anauxite. *Allen (1929)* interpreted the Ione sediments to be similar to modern deltaic deposits. He also correlated the Ione sediments with Sierran auriferous gravels based on a comparison of mineralogy and stratigraphic position. The Ione underlies the Lovejoy Basalt at Oroville Table Mountain and it is present in the Lincoln Area. The maximum thickness of the Ione near Table Mountain is 200 m *(Creely, 1965)* (Helley and Harwood 1985).

Kc — Chico Formation (Cretaceous) — Tan, yellowish-brown to light-gray, fossiliferous marine sandstone with lenticular beds of pebble to fine cobble conglomerate and minor siltstone. Clasts in the conglomerate include rounded to well-rounded, red, green, and black chert, white vein quartz, quartzite, granite, and greenstone. Calcite-cemented concretions and layers of fossil fragments are common. The sandstone is composed of fine to medium, angular to subrounded grains of quartz, plagioclase, alkali feldspar, lithic fragments, and detrital chert. At the type section on Big Chico Creek the unit is about 650 m thick *(Taff and others, 1940, p. 1317)* (Helley and Harwood 1985).

Volcanic Deposits Including Minor Sedimentary Deposits

Qif1-3 — Flank Fissure Flows, Inskip Hill (Pleistocene) — Several small, blocky basalt flows originating from vents along two parallel, northeast-trending fissures on the north slope of Little Inskip Hill located 29 km northeast of Red Bluff. These flows extend 1 to 2.5 km northward toward Battle Creek. Although the flows appear to be contemporaneous, three separate pulses of lava, which are inferred from their superposition, are labeled from oldest to youngest, Qif1, Qif2, Qif3. Flows erupted first from the northern fissure and their proximal parts were overlapped by subunit Qif3 from the northeast end of the upper fissure. Individual thickness of the flows is unknown due to their blocky nature and brushy cover; they probably are less than 5 m in individual thickness (Helley and Harwood 1985).

Qic — Cinder Cone Deposits, Inskip Hill (Pleistocene) — Red and black basaltic cinders forming the prominent cones of Inskip Hill and Little Inskip Hill; four small cinder cones with essentially uneroded morphology are superposed on the larger older cone of Inskip Hill. These smaller cones are crudely aligned in a north-south direction across the main mass of Inskip Hill and, thus reflect the north-trending fracture system prominent in the underlying Tuscan Formation. Two satellitic eruptive centers marked by small basaltic lava flows and cinder cones lie southeast of Inskip Hill near the settlement of Paynes Creek and in the upper reaches of Oak Creek near McKenzie Place (southwest corner of the Manton 15' quadrangle) (Helley and Harwood 1985).

Qip — Basalt Flows of Paynes Creek, Inskipp Hill (Pleistocene) — Thin, black to dark-gray basalt flows that were erupted at Inskip Hill and flowed primarily westward into the drainage of Paynes Creek and reached the Sacramento River at Chinese Rapids near Bend (southwest corner Tuscan Buttes 15' quadrangle). On the flanks of Inskip Hill, the flows are characterized by small lava tubes, pahoehoe texture, and thin scoria layers. Farther from the eruptive center the Paynes Creek flows display scattered yellowish-brown phenocrysts of olivine and glassy-green phenocrysts of clinopyroxene, set in a matrix of fine-grained plagioclase, clinopyroxene, and glass. Northeast of Dales in the Tuscan Buttes 15' quadrangle, the Paynes Creek lava is about 8 m thick; where it crosses the Manton Road northeast of Dales Lake, it is about 2 m thick. The age of the Paynes Creek flows is unknown, but it must be less than 26,000 yr and possibly less than 12,000 yr because the flows overlie the upper member of the Modesto Formation in a tributary of Inks Creek (Helley and Harwood 1985).

Qiu — Undifferentiated Basalt Flows of Inskip Hill (Pliestocene) — Divided into:

Qbbb — Cinder Blanket Deposits, Black Butte (Pleistocene) — Black, well-bedded basaltic cinder deposits forming a dissected ejecta blanket that ranges in thickness from about 10 m just north of Black Butte to about 1.5 m in the south rim of Ash Creek. Beds ranging from 1 to 20 cm thick show normal grading. No major unconformities or buried soil horizons were found in the cinder deposits suggesting rapid accumulation. Total remaining volume of cinder blanket and cone deposits is 6 x 10^6 m^3 (Helley and Harwood 1985).

Qbbf — Basalt Flow of Black Butte (Pleistocene) — Dark-gray to black basalt similar in texture and mineralogy to the Paynes Creek flows from Inskip Hill. Olivine and clinopyroxene phenocrysts are scattered in a diktytaxitic matrix of clinopyroxene and plagioclase. Volcanic activity at Black Butte began with the eruption of a small flow of olivine basalt and progressed to the formation of a cinder cone. The flow formed two branches, one part moved about 1 km west of the vent into the upper reaches of Rancherio Creek; the other part cascaded over the Battle Creek fault scarp and formed a bulbous puddle of blocky lava just north of the Darrah Spring Fish Hatchery. The basalt flow of Black Butte, like that of Paynes creek, is high in aluminum (17.41 percent) and remarkably low in potassium (0.19

percent). The basalt flow of Black Butte is probably no older than the basalt flow of Paynes Creek (Helley and Harwood 1985).

Qbbc — Cinder Cone Deposits, Black Butte (Pleistocene) — Thinly layered and loosely aggregated, brick-red and black basaltic cinder deposits containing scattered red and black scoriaceous to glassy bombs of basalt as much as 2 m in length. The vent is marked be a conical depression 15 to 20 m deep and offset slightly to the south of center. The north rim of the cone is a spatter rampart that rises about 25 m above the south rim of the cone (Helley and Harwood 1985).

Qbdc — Cinder Cone Deposits, Digger Butte (Pleistocene) — Black and red basaltic cinders forming two small cones atop the east end of the basalt flows of Digger Buttes (Helley and Harwood 1985).

Qdb — Basalt Flows of Digger Buttes (Pleistocene) — A series of thin, dark-gray to black, high alumina olivine basalt flows that originated from a vent or vents at Digger Buttes and flowed westward about 4.5 km. Unconformably overlies the Rockland ash bed (0.45 m.y.) and volcanic units as old as the Tuscan Formation. The rock is a fine-grained olivine basalt with trachytic texture that contains scattered olivine phenocrysts in a matrix of clinopyroxene and plagioclase. Total thickness of the flows is unknown but is probably only a few tens of meters (Helley and Harwood 1985).

Qbw — Basalt of Whitmore Quad (Pleistocene) — Two broad flows of olivine basalt as mapped by Macdonald and Lydon (1972). *Helley and Harwood (1982)* identified these rocks as Qvu (Volcanic rocks of the Whitmore, Millville, and Manton Quadrangles) (Helley and Harwood 1985).

Qbs3 — Basalt of Shingletown Ridge (Pleistocene) — Composed of three subunits of dark-gray, fine-grained, diktytaxitic, and locally porphyritic basalt with rounded phenocrysts of brownish-green olivine scattered in an openwork mesh matrix of plagioclase and clinopyroxene. They are high-alumina basalts containing about 47.6 percent SiO2, 18.09 percent Al2O3, and 0.19 percent K2O. Chemically, mineralogically, and texturally the rocks are very similar to the underlying basalt of Coleman Forebay, and both units may have originated from the same source area at separate, but perhaps not widely spaced, times. The flows of olivine basalt cap Shingletown Ridge north of Manton and extend westward north of Ash Creek and Bear Creek. The flows extend westward from the southern part of the Whitmore quadrangle *(Macdonald and Lydon, 1972) and Macdonald (1963)* traced them eastward into the Red Mountain Lake area in the Manzanita Lake quadrangle where they may have originated from a series of vents distributed along a fissure system trending north-northwest form the vicinity of Lassen Peak. The basalt flows overlie the Tuscan formation and have a total thickness of about 30 m north of Manton, but they are only about 5 m thick near Bear Creek (Helley and Harwood 1985).

Qab — Andesite of Brokeoff Mountain (Pleistocene) — At least two distinct flows of porphyritic hypersthene andesite that contain abundant white plagioclase phenocrysts, minor amounts of hypersthene, and sparse augite phenocrysts set in a fine-grained matrix of plagioclase microlites and brown glass. The lower part of the andesite sequence contains light-gray cumulate knots of plagioclase and clinopyroxene. These flows spill over the Battle Creek escarpment north of Digger Buttes and follow the Battle Creek fault zone to the southwest for about 35 km. The flows apparently are continuous with the andesite of Brokeoff Mountain mapped by *Macdonald and Lydon (1972)* in the adjacent Whitmore quadrangle. On the Battle Creek escarpment, the hypersthene andesite flows rest unconformably on rocks as old as Eocene (Montgomery Creek Formation), and on the footwall of the fault zone they rest on the Rockland ash bed, which is dated at 0.45 m.y. old *(Meyer and others, 1980).* North of Manton the total thickness of the andesite flows is about 20 m (Helley and Harwood 1985).

Qar — Rockland Ash Bed (Pleistocene) — Unit is equivalent to the ash of Mount Maidu of *Harwood and others (1981) and Helley and others (1981).* Helley and Harwood use the name Rockland ash bed for this unit for reasons given by *Sarna-Wojcicki and others (written commun., 1982).* White loosely aggregated pumice lapilli ash with scattered coarse pumice fragments as large as 20 cm in diameter form a major dacitic to rhyolitic ash-flow tuff deposit between Digger Buttes and the Battle Creek escarpment. One arm of the deposit filled the lowland southeast of Digger Buttes and extends to the north rim of the canyon of the South Fork of Battle Creek. Scattered erosional remnants of the ash bed represent channel deposits north and northwest of Long Ranch. Round Mountain west of Table Mountain in the Bend section of the Sacramento River is made up of this ash deposit. Farther south the ash bed underlies a dozen or so low hills, locally known as the Sand Hills, that rise above alluvial fan deposits derived from the Tuscan Formation. The ash deposit has been dated by fission-track method at 0.45 m.y. (Meyer and others, 1980). The ash bed is also recognized in core samples from a test well near Zamora (T.12 N., R.1 E. SW 1/4 SE 1/4 sec 34) at a depth of 137 m *(Page and Bertoldi, 1983),* where it was deposited by the ancestral Sacramento River or a major tributary presumably at or near sea level. The position of the ash bed in the well at Zamora gives a local rate of subsidence of 0.3 m/10^3 yr. The ash is predominantly fine grained glass, locally distinctly bedded in the distal exposures and generally massive with scattered large pumiceous fragments in the proximal areas. The pumiceous fragments are composed primarily of silky white, wispy, vesicular glass that contains scattered crystals of clear to white plagioclase and sanidine, green hornblende, hypersthene, and minor magnetite. *Wilson (1961)* determined the refractive index of the glass to be 1.500 +/- 0.001, indicative of a silica content of about 67 percent, and an overall dacitic composition. The ash flow is at least 60 m thick north of Digger Buttes, but it is generally less than 5 m thick in the scattered patches to the west (Helley and Harwood 1985).

Qeb — Basalt of Eagle Canyon (Pleistocene) — Dark-gray, vesicular, diktytaxitic olivine basalt underlying the broad plain carved by the North Fork of Battle Creek from the vicinity of Ponderosa

Way on the east along the toe of Battle Creek escarpment nearly to the Coleman Powerhouse (northeast quarter of the Tuscan Buttes 15' quadrangle). This basalt, along with the underlying conglomerate here mapped as the Red Bluff Formation, and the basalt below the conglomerate were compositely grouped by *Wilson (1961, p. 11)* in his Long Ranch (basalt) unit. The upper unit of basalt is here designated the (olivine) basalt of Eagle Canyon; the lower basalt, which underlies the Red Bluff Formation, is herein termed the basalt of Coleman Forebay (Helley and Harwood 1985).

Qcb — Basalt of Coleman Forebay (Pleistocene) — Light-rusty-gray-weathering, dark-gray olivine basalt with pronounced diktytaxitic texture and scattered large vesicles and voids that form large rounded pits on the weathered surfaces. This basalt underlies the Red Bluff Formation in several isolated areas extending from Coleman Forebay on the Battle Creek fault escarpment southward to the vicinity of Hog Lake, 17 km northeast of Red Bluff on California Highway 36. The unit is undated but is older than the Red Bluff Formation and has a maximum thickness of about 10 m (Helley and Harwood 1985).

Qbd — Olivine Basalt of Devils Half Acre (Pleistocene) — Gray glomeroporphyritic vesicular basalt showing well-developed columnar jointing on the north rim of Antelope Creek. Aggregates of strongly zoned plagioclase as much as 10 mm is diameter and euhedral to anhedral olivine as much as 5 mm in diameter are set in an ophitic matrix of nearly equal amounts of plagioclase microlites and clinopyroxene. Magnetite is scattered throughout the matrix and rutile (?) and is included within the plagioclase. Clear to white opal lines some vesicles and also occurs as fracture fillings in some plagioclase phenocrysts. Maximum thickness is 15 m (Helley and Harwood 1985).

Qbdc — Olivine Basalt of Deer Creek (Pleistocene) — Dark-gray to greenish-black, sparsely vesicular olivine basalt flows locally exposed on the north and south rims of the canyon of Deer Creek (northeast quarter of the Corning 15' quadrangle). Euhedral to subhedral olivine phenocrysts as much as 3 mm in diameter set in a fine-grained matrix of plagioclase and clinopyroxene. The clinopyroxene is intergranular to plagioclase microlites and which are strongly aligned giving a trachitic texture. Olivine and clinopyroxene are slightly altered to iddingsite. Magnetite and ilmenite are present in the intergranular spaces. Plagioclase microlites contain small amounts of black dust-like opaque inclusions of magnetite (?) and light colored fluid inclusions. The contact between the olivine basalt of Deer Creek and the underlying older gravel deposits is exposed in the older, western part of the quarry at the head of Juniper Gulch. The base of the basalt exposed in the quarry is a scoriaceous layer 0.3 m thick showing westward overturned flow folds outlined by deformed vesicles. A K-Ar age of 1.24 +/- 0.11 m.y. *(J. Von Essen, written commun., 1978)* was obtained on basalt from the quarry; the maximum thickness is 20 m weathers to a bright-brick-red (5-2.5 TR) soil (Helley and Harwood 1985).

Qbr — Blue Ridge Rhyolite of *Coe (1977)* (Pleistocene) — Mottled and flow banded, light- and dark-gray, pink, and lavender glassy rhyolite, variably devitrified; minor perlite, pumice, and pitchstone near base. Contains andesine, oxyhornblende, hypersthene, and rare biotite phenocrysts; potassium-rich glassy matrix devitrified to feldspar and silica-rich spherulites. Wilson (1961, p. 68) gives one complete and four partial chemical analyses for the rhyolite; Gilbert (1968, p. 27) gives K-Ar ages of 1.15 +/- 0.07 m.y. on glass and 1.24 +/- 0.11 m.y. on plagioclase from the rhyolite (Helley and Harwood 1985).

QTvl — Volcanic Lake Bed (Pleistocene and Pliocene) — Well-bedded volcanogenic sediments of mainly lacustrine but partly fluviatile, origin occupying an area measuring 1.6 by 2.7 km in the center of the buttes; *(Williams and Curtis, 1977, p.35)* (Helley and Harwood 1985).

QTa — Andesites in Sutter Buttes Area (Pleistocene and Pliocene) — Gray and brown, porphyritic, biotite-hornblende andesite that contains variable amounts of biotite, hornblende, and plagioclase phenocrysts set in a dense nonvesicular pilotaxitic matrix; generally located in the central part of Sutter Buttes where the andesite forms a coalescing group of intrusive and extrusive domes *(Williams and Curtis, 1977, p. 21-22, 44-45*) (Helley and Harwood 1985).

QTr — Rhyolite Domes in Sutter Buttes Area (Pleistocene and Pliocene) — Conspicuous white topographic domes composed of light-gray to white porphyritic rhyolite and dacite that contrast sharply with exposures of the darker andesites. Both rhyolite and dacite contain variable amounts of biotite, quartz, plagioclase, and subordinate sanidine phenocrysts in a dense, micro- to crypto-felsitic matrix *(Williams and Curtis, 1977, p. 23-27, 46-47)* (Helley and Harwood 1985).

QTm — Tuff Breccia in Sutter Buttes Area (Pleistocene and Pliocene) — Tuff breccia primarily comprising the peripheral topographic ring surrounding Sutter Buttes; equivalent to the middle unit of the Rampart Beds of *William and Curtis (1977, p. 26)* (Helley and Harwood 1985).

QTmb — Tuff Breccia of Mineral Area (Pleistocene and Pliocene) — These rocks were mapped and described originally by *Wilson (1961, p. 14-16)* and an abbreviated description based on his report and Helley and Harwood's reconnaissance is used here. The tuff breccia consists of layers of angular blocks of basaltic andesite and andesite interbedded locally with andesitic tuff, scoria, and minor andesite flows. The unit is about 240 m thick at the head of Mill Creek Canyon (Helley and Harwood 1985).

Tpa — Platy Andesite (Pliocene) — Light to dark-gray, bluish-gray, and brick red, fine-grained, sparsely porphyritic, slab-weathering to massive, locally streaked and flow-banded platy andesite exposed on the Battle Creek escarpment near Bailey Creek and at the top of Tuscan Buttes. Andesite at these widely separated areas was never part of the same flow and it represents chemically and mineralogically different flows that originated at different, unknown sources. The rocks share only a common platy structure and a similar stratigraphic position unconformably above the Tuscan Formation. The andesite is about 70 m thick at Tuscan Buttes and about 55 m thick at Bailey Creek.

At Tuscan Buttes the unit consists of several flows that are gray through most of their thickness and brick red at their tops. The rock is fine grained, sparsely porphyritic and composed of a matrix of oriented plagioclase microlites rimmed by devitrified glass. Glass contains scattered phenocrysts and reddish-brown basaltic hornblende as much as 3 mm long altered to varying degrees to dust like opaque magnetite particles. Sparse hornblende phenocrysts define a subtle, subhorizontal lineation oriented roughly east-west throughout the flows; the phenocrysts lie parallel to distinct flow banding in the rocks exposed in cliffs on the southwest face of the east butte. Layers in the flow-banded andesite range in thickness from 3 to 10 mm and locally contain angular fragments of porphyritic andesite. The andesite at Tuscan Buttes probably represents the remnants of a channelized flow or flows *(Anderson, 1933)* that may have originated from a vent or vents now marked by andesite plugs located in and near Antelope Creek to the east.

At Bailey Creek the platy andesite is bluish-gray, locally flow banded, and composed predominantly of devitrified glass; phenocrysts of plagioclase, hypersthene, and green hornblende combine to make up generally less than 15 percent of the rock (Helley and Harwood 1985).

Tbp — Olivine Basalts of Paradise (Pliocene) — Gray, slightly vesicular, glomeroporphyritic olive basalt with aggregates of plagioclase as much as 15 mm in length that form abundant white knots. Aggregates of olivine as large as 10 mm in diameter form glassy yellowish-green phenocrysts in a gray matrix of plagioclase microlites and intergranular clinopyroxene. Plagioclase phenocrysts have well-developed oscillatory zoning and pronounced sieve texture with abundant inclusions of clinopyroxene in the middle zones. The edges of the plagioclase crystals are resorbed and crowded with black dust like opaque inclusions and clear fluid inclusions. Magnetite occurs with intergranular clinopyroxene. Maximum thickness in the map area is about 25 m. The most extensive exposures are in and around the village of Paradise just east of Chico with two less extensive exposures on Mill Ridge due north of Paradise (Helley and Harwood 1985).

Tba — Basaltic Andesite of Antelope Creek (Pliocene) — Dark-gray to greenish-gray, massive to highly fractured, fine-grained, sparsely vesicular basaltic andesite exposed in Antelope Creek and to a lesser extent in Salt Creek; locally altered to brick red and reddish-gray. Red and reddish-gray scoria layers about 1 m thick alternate with layers of more massive gray basaltic andesite of about equal thickness in the western exposures in Antelope and Salt Creeks, which suggests that these exposures are near the distal end of the flow. Plagioclase laths as much as 2 mm long are strongly aligned and locally swirled around equidimensional to elongate masses of iddingsite (?) and fine-grained magnetite, probably pseudomorphous after olivine. No fresh olivine was seen in this rock type, which was originally described as a basalt (olivine basalt of Antelope Creek) *(Harwood and others, 1981),* but which is now known to contain 54.7 percent SiO2 and thus is located on the generally accepted basalt-andesite boundary of 54 percent SiO2. A K-Ar age of 3.99 +/- 0.12 m.y. was obtained on the basaltic andesite of Antelope Creek *(J. Von Essen, oral commun., 1979)* (Helley and Harwood 1985).

Tbc — Olivine Basalt of Cohasset Ridge (Pliocene) — Gray vesicular porphyritic basalt flows with olivine phenocrysts as much as 6 mm in diameter set in a diktytaxitic matrix of plagioclase and clinopyroxene. Clinopyroxene as much as 2 mm in length is intergranular to plagioclase microlites. Magnetite and ilmenite occur with clinopyroxene. High-relief, knee-shaped twinned crystals, possibly rutile, occur in the plagioclase. Drusy clear quartz and clear to white opal line many vesicles. A sample taken from the road cut on the east side of Cohasset Highway at the intersection of Keefer Road gives a K-Ar age of 2.41+/- 0.12 m.y. *(J. von Essen, written commun., 1978).* Maximum thickness is about 25 m (Helley and Harwood 1985).

Tl — Lovejoy Basalt (Miocene) — Black, dense, hard, microcrystalline to extremely grained, equigranular to sparsely porphyritic basalt. Where porphyritic, it contains scattered phenocrysts of plagioclase and lesser amounts of clinopyroxene in an hypocrystalline groundmass of felted plagioclase microlites, intergranular clinopyroxene, olivine and magnetite, and intersertal grayish-green to black, opaque basaltic glass. It is everywhere highly fractured with distinctive conchoidal fracture surfaces.

The Lovejoy comprises the prominent Orland Buttes on the west side of the valley as well as the conspicuous Table Mountain at Oroville on the east side of the valley. The Lovejoy Basalt is also exposed in deep canyons cut through the Tuscan Formation that narrow markedly where the Lovejoy exposed. In Big and Little Chico Creeks, the Lovejoy is incised in very narrow channels only a few meters wide but as much as 60 m deep. The basalt at Putnam Peak at the south end of the English Hills near Vacaville is also composed of the Lovejoy Basalt *(S. Gromme, oral comm., 1981).* It is also exposed in the foothills northwest of Winters. The Lovejoy is penetrated by numerous wells in the valley *(van den Berge, 1968)* where a narrow linear subsurface distribution pattern strongly suggests that the Lovejoy flowed in a channel or channels across the present site of the Sacramento Valley. The outcrop and subcrop pattern *(van der Berge, 1968)* definitely suggests the Lovejoy flowed down more than one channel. The maximum thickness in the mapped area is about 20 m.

Dalrymple (1964) obtained a K-Ar age of 23.8 m.y. on a thin dacite ash just beneath the Lovejoy at Oroville Table Mountain. The date seems reasonable since the Lovejoy and the dacite ash overlie both the Eocene Ione and the auriferous gravels at Oroville. *The Delleker Formation (not mapped in this report), which overlies the Lovejoy elsewhere, has been dated by Evernden and others (1964)* at 22.2 m.y. near the type locality of the Lovejoy. Therefore the Lovejoy Basalt is bracketed within the early Miocene (Helley and Harwood 1985).

Bedrock

pTms — Metamorphic, Intrusive, and Sedimentary (Pre-Tertiary) — Undivided metamorphosed Paleozoic and Mesozoic volcanic and sedimentary rocks intruded by Mesozoic and older granitic rocks in the Klamath Mountains; the Franciscan Complex and the Coast Range ophiolite *(discussed in detail by Irwin, 1966, Murphy and others, 1969, and Irwin and others, 1978);* and the overlying unmetamorphosed sedimentary rocks of the Great Valley sequence (*see Bailey and Jones, 1973)* (Helley and Harwood 1985).

pKmi — Metamorphic and Igneous Rocks (Pre-Cretaceous) — Undivided slate, quartzite, metaconglomerate, marble, metavolcanic rocks, serpentinite, metagabbro, diorite, and monzonite *(see Creely; Hiettanen, 1973, 1976)* (Helley and Harwood 1985).

Description of Geologic Units Shown on Cross Sections (Plates 2 and 3)

Many of the following descriptions were adapted from "Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California" by Helley and Harwood (1985). Citations within the original text remain and are italicized, but they were not reviewed by the authors and are not included in the Selected Bibliography section of this document. Please refer to the original document for complete citation information.

Surficial Deposits

Q — Undifferentiated Surficial Deposits — includes Qsc Stream Channel, Qa Alluvium, Qo Overbank Deposits, Qal undivided Alluvial Deposits, Qb Basin Deposits, Qm Marsh Deposits, Qls Landslides, Qmu Modesto Formation Upper Member, Qml Modesto Formation Lower Member, Qru Riverbank Formation Upper Member, Qrl Riverbank Formation Lower Member, Qrb Red Bluff Formation, Qtog Older Gravel Deposits — *see description of geologic map units for detailed descriptions of these units*.

Sedimentary Rocks Including Some Volcanic Rocks

Tte — Tehama Formation (Pliocene) — Pale-green, gray, and tan sandstone and siltstone with lenses of crossbedded pebble and cobble conglomerate derived from the Coast Ranges and Klamath Mountains; named by *Diller (1984)* for typical exposures in Tehama County in the northwestern Sacramento Valley.

The Tehama rests with marked unconformity on Cretaceous rocks of the Great Valley sequence along the west side of the valley and on plutonic and metamorphic rocks of the Klamath Mountains west of Redding where the Mesozoic sedimentary rocks are missing. The Tehama is unconformably overlain by gravels of the Red Bluff pediment; excellent exposures of this stratigraphic relation are visible a few kilometers south of Red Bluff along Interstate 5 and along the river bluffs at Redding.

North of Red Bluff the Tehama Formation interfingers with the Tuscan Formation in a broad zone extending approximately from Interstate 5 east to the Sacramento River. The clastic debris becomes progressively more andesitic in composition and Tuscan-like in appearance eastward in this area of sediment interfingering. The contact with the Tuscan Formation is gradational and Helley and Harwood have arbitrarily chosen the Sacramento River channel as the map contact. Since both the Tehama and Tuscan contain the Nomlaki Tuff Member at or near their stratigraphic bases they are considered coeval. In the southwestern part of the Sacramento Valley, the Tehama also contains the Putah Tuff Member near its base; the Putah is the same age as, but stratigraphically below, the Nomlaki *(Sarna-Wojcicki), 1976, p.18; oral commun., 1982).*

Maximum thickness of the Tehama is about 600m *(Olmsted and Davis, 1961).* The Tehama is significant because the base of the unit is also the base of fresh groundwater in the entire Sacramento Valley (Helley and Harwood 1985).

Tt — Tuscan Formation (Pliocene) — Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff. Divided into Unit D, Tuff of Hogback, Unit C, Ishi Tuff, Unit B, Unit A, and Nomlaki Tuff on the geologic map, but grouped together on the cross sections for lack of data to differentiate particular members in the subsurface. *See description of geologic map units for detailed descriptions of these units* (Helley and Harwood 1985).

Tla — Laguna Formation (Pliocene) — Interbedded alluvial gravel, sand, and silt. Pebbles and cobbles of quartz and metamorphic rock fragments generally dominate the gravels, but the matrix of the gravelly units and finer sediments are invariably arkosic. In the vicinity of Oroville, volcanic rocks may comprise as much as 20 percent of the gravels, but again the finer sediments are dominantly arkosic. The Laguna is lithologically indistinguishable from the Turlock Lake Formation, but the Turlock Lake is more compact at the surface due to a preserved B2t soil horizon. The Laguna, on the other hand, has had its former soil profiles stripped by erosion. The Turlock Lake and the Laguna can be distinguished by their stratigraphic positions relative to pediment gravels, by the presence or absence of some soil profiles, and by their topographic settings. In the Oroville area the Laguna is easier to distinguish because it contains the Nomlaki Tuff Member near its base *(Busacca, 1982, p. 103).* We have not found the Nomlaki in the Laguna in the Sacramento area nor anywhere south of Beale Air Force Base.

The Laguna Formation was named by *Piper and others (1939)* for arkosic deposits in the vicinity of Laguna Creek, San Joaquin County. These Sierran-derived deposits overlie the Mehrten Formation and are unconformably overlain by gravel of the Northern Merced pediment. Although the Laguna gravels are not exposed continuously from the type area northward into the Sacramento Valley, similar arkosic sediments overlying the Mehrten and truncated by the Red Bluff pediment occur in the Sacramento Valley and have been correlated with the Laguna *(Olmsted and Davis, 1961 and Busacca, 1982).* Helley and Harwood agree with this correlation. The Laguna displays highly dissected rolling topography with tens of meters of relief. The only exposures are between Oroville and Sacramento on the Southeast side of the valley. The Laguna was deposited by the ancestral west-flowing Feather, Yuba, Bear, and American Rivers.

The thickness of the Laguna is difficult to estimate because its base is rarely exposed and its surface has been highly eroded except where preserved beneath the Red Bluff Formation. The Laguna is probably about 60 m thick in the Oroville and thins to about 20 m or so south of Sacramento (Helley and Harwood 1985).

Tupvf — Upper Princeton Valley Fill (Miocene) — Non-marine sediments composed of sandstone with interbeds of mudstone, occasional conglomerate, and conglomerate sandstone. Consists of fluvial sediments deposited by an ancient river whose laterally migrating and meandering course most likely approximates that of the present Sacramento River. Sandstone and conglomerate beds consist primarily of varicolored volcaniclastic minerals and lithic fragments, commonly described as greenish gray and gray and sometimes locally dark gray to black. Included pelite beds are described as green, bluish green, bluish gray, buff, tan, and light to dark brown. Thickness of the Upper Princeton Valley fill is variable because of the meandering nature of the ancient river course with a maximum of approximately 1,400 feet (Redwine 1972**{** TC "Redwine 1972" \f C \l "1" **}**).

Ti — Ione Formation (Eocene) — Light-colored, commonly white conglomerate, sandstone, and claystone. Argillaceous sandstone and claystone comprise about 75 percent of the Ione along the southeast side of Sacramento Valley; northward the rest of the unit consists of interbedded siltstone, conglomerate, and shale. It should be noted that the map area is far north of the type locality at Ione in Amador County. The Ione is generally soft, deeply eroded, and marked by numerous landslides. Ione sandstones are characterized by fine grains of angular quartz and thin stringers of weathered anauxite. *Allen (1929)* interpreted the Ione sediments to be similar to modern deltaic deposits. He also correlated the Ione sediments with Sierran auriferous gravels based on a comparison of mineralogy and stratigraphic position. The Ione underlies the Lovejoy Basalt at Oroville Table Mountain and it is present in the Lincoln Area. The maximum thickness of the Ione near Table Mountain is 200 m *(Creely, 1965)* (Helley and Harwood 1985).

Tlpvf — Lower Princeton valley Fill (Eocene) — Includes Capay Formation. Marine sandstone, conglomerate, and interbedded silty shale. The Lower Princeton Submarine Valley fill is composed of interlayered beds of shale and sandstone whose source area is the Sierran province to the east (Redwine 1972**{** TC "Redwine 1972" \f C \l "1" **}**). The Lower Princeton Submarine Valley was carved by erosion during the Paleocene and later filled by pelitic and coarse-grained turbidity currents during the Eocene. The submarine valley extends geographically from Red Bluff to the Sutter Buttes and is up to approximately 1,500 feet thick.

The fill lies unconformably on Cretaceous to Upper Cretaceous marine rocks and is conformably overlain by the Ione Formation or, where the Ione has been erosionally removed, the Upper Princeton Valley fill sediments. The Lower Princeton Submarine Valley fill is considered to be the stratigraphic equivalent of the Capay Formation because it “probably shared the same depositional environment and has similar lithologic characteristics.” Maximum thickness is approximately 2,200 feet (Redwine 1972**{** TC "Redwine 1972" \f C \l "1" **}**).

JKgvs — Great Valley Sequence (Late Jurassic-Upper Cretaceous) — Marine clastic sedimentary rock consisting of siltstone, shale, sandstone, and conglomerate. The Great Valley sequence consists of north-trending, interbedded sandstone, mudstone, and conglomerate that range from Late Jurassic to Cretaceous in age (Bailey et al. 1970**{** TC "Bailey et al. 1970" \f C \l "1" **}**). It is exposed in outcrop along the west side of the northern Sacramento Valley and extends southward throughout the Central Valley. Ingersoll and Dickenson (1981)**{** TC "Ingersoll and Dickenson (1981)" \f C \l "1" **}** subdivided the Great Valley sequence into five different petrologic intervals, which he named the Stony Creek, Lodoga, Boxer, Cortina, and Rumsey formations. These formations generally represent shoaling or filling of the deep marine forearc basin during the Mesozoic. The thickness of these massive deposits totals about 45,000 feet of sediments (Ingersoll and Dickenson 1981**{** TC "Ingersoll and Dickenson 1981" \f C \l "1" **}**).

The provenance for the Great Valley sequence sediments is the ancestral Sierran-Klamath terrane (Ingersoll and Dickinson 1981**{** TC "Ingersoll and Dickinson 1981" \f C \l "1" **}**). Eroded sediments from these mountains were deposited as turbidity flows and submarine fans into the deep oceanic waters off the continental shelf. Because of the marine nature of the deposition, groundwater occurring in these sediments is saline except locally on the margins of the valley where the formational water has been flushed with newer fresh water.

The Great Valley sequence is underlain by the Coast Range ophiolite and the Franciscan Formation in the west. It overlies the Nevadan and older basement terranes of the Klamath Mountains and Sierra Nevada in the north and along the east side of the Sacramento Valley. The Great Valley sequence is overlain in the valley by the Lower Princeton Submarine Valley fill, Upper Princeton Valley fill, Ione Formation, Tuscan Formation, or Tehama Formation.

Maximum thickness 15,000 feet (Redwine 1972).

Volcanic Deposits Including Minor Sedimentary Deposits

Qtm — Tuff Breccia in Sutter Buttes Area (Pleistocene and Pliocene) — Tuff breccia primarily comprising the peripheral topographic ring surrounding Sutter Buttes; equivalent to the middle unit of the Rampart Beds of *William and Curtis (1977, p. 26)* (Helley and Harwood 1985).

Qta — Andesites in Sutter Buttes Area (Pleistocene and Pliocene) — Gray and brown, porphyritic, biotite-hornblende andesite that contains variable amounts of biotite, hornblende, and plagioclase phenocrysts set in a dense nonvesicular pilotaxitic matrix; generally located in the central part of Sutter Buttes where the andesite forms a coalescing group of intrusive and extrusive domes *(Williams and Curtis, 1977, p. 21-22, 44-45*) (Helley and Harwood 1985).

Tl — Lovejoy Basalt (Miocene) — Black, dense, hard, microcrystalline to extremely grained, equigranular to sparsely porphyritic basalt. Where porphyritic, it contains scattered phenocrysts of plagioclase and lesser amounts of clinopyroxene in an hypocrystalline groundmass of felted plagioclase microlites, intergranular clinopyroxene, olivine and magnetite, and interstitial grayish-green to black, opaque basaltic glass. It is everywhere highly fractured with distinctive conchoidal fracture surfaces.

The Lovejoy comprises the prominent Orland Buttes on the west side of the valley as well as the conspicuous Table Mountain at Oroville on the east side of the valley. The Lovejoy Basalt is also exposed in deep canyons cut through the Tuscan Formation that narrow markedly where the Lovejoy exposed. In Big and Little Chico Creeks, the Lovejoy is incised in very narrow channels only a few meters wide but as much as 60 m deep. The basalt at Putnam Peak at the south end of the English Hills near Vacaville is also composed of the Lovejoy Basalt *(S. Gromme, oral comm., 1981).* It is also exposed in the foothills northwest of Winters. The Lovejoy is penetrated by numerous wells in the valley *(van den Berge, 1968)* where a narrow linear subsurface distribution pattern strongly suggests that the Lovejoy flowed in a channel or channels across the present site of the Sacramento Valley. The outcrop and subcrop pattern *(van denBerge, 1968)* definitely suggests the Lovejoy flowed down more than one channel. The maximum thickness in the mapped area is about 20 m.

Dalrymple (1964) obtained a K-Ar age of 23.8 m.y. on a thin dacite ash just beneath the Lovejoy at Oroville Table Mountain. The date seems reasonable since the Lovejoy and the dacite ash overlie both the Eocene Ione and the auriferous gravels at Oroville. The Delleker Formation (not mapped in this report), which overlies the Lovejoy elsewhere, has been dated by *Evernden and others (1964)* at 22.2 m.y. near the type locality of the Lovejoy. Therefore the Lovejoy Basalt is bracketed within the early Miocene (Helley and Harwood 1985).

Bedrock

pKmi — Metamorphic and Igneous Rocks (Pre-Cretaceous) — Undivided slate, quartzite, metaconglomerate, marble, metavolcanic rocks, serpentinite, metagabbro, diorite, and monzonite *(see Creely; Hiettanen, 1973, 1976)* (Helley and Harwood 1985).

References

Bailey EH, MC Blake, and DL Jones. 1970. "On-land Mesozoic oceanic crust in California coast ranges." U.S. Geological Survey Professional Paper 700-C:C70-C81.

Helley EJ and DS Harwood. 1985. "Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California." U.S. Geological Survey Miscellaneous Field Studies Map MF-1790: 24 pp., 5 sheets, scale 1:62,500.

Ingersoll RV and WR Dickinson. 1981. "Great Valley Group (Sequence), Sacramento Valley, California," in V Frizzell, ed., *Upper Mesozoic Franciscan rocks and Great Valley Sequence, Central Coast ranges, California*. Society of Economic Paleontologists and Minerologists, Pacific Section, Los Angeles, CA: p. 1-33.

Redwine, L.E. 1972. The Tertiary Princeton submarine valley system beneath the Sacramento Valley, California: Univ. of California, Los Angeles, unpubl. thesis (Ph.D): 480 p.

Plates

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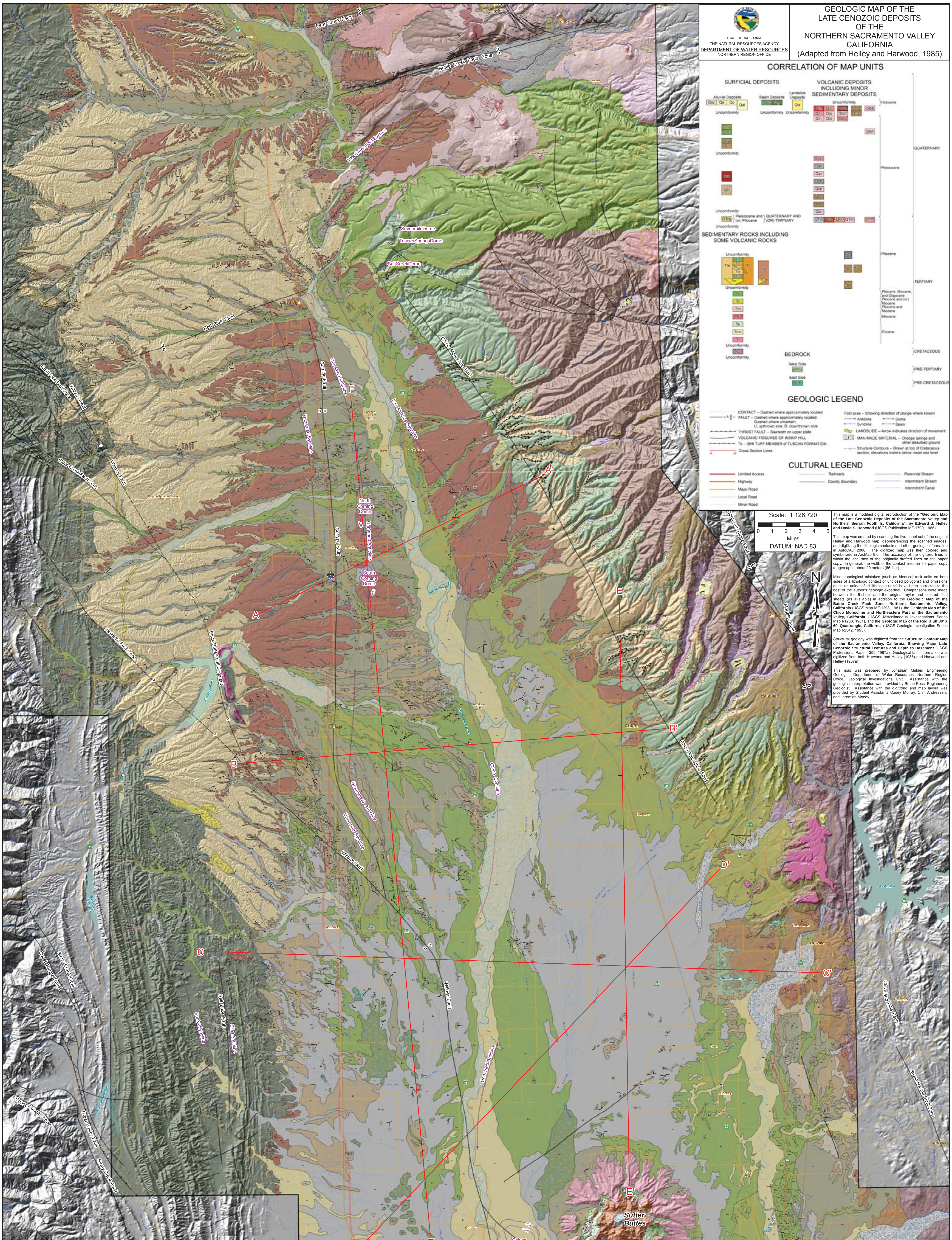
PLATE 1

STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN REGION OFFICE

GEOLOGIC MAP OF THE LATE CENOZOIC DEPOSITS OF THE NORTHERN SACRAMENTO VALLEY CALIFORNIA

(Adapted from Helley and Harwood, 1985)



This map is a modified digital reproduction of the **"Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California", by Edward J. Helley and David S. Harwood** (USGS Publication MF-1790, 1985).

This map was created by scanning the five-sheet set of the original Helley and Harwood map, georeferencing the scanned images, and digitizing the lithologic contacts and other geologic information in AutoCAD 2006. The digitized map was then colored and symbolized in ArcMap 9.0. The accuracy of the digitized lines is within the accuracy of the originally drafted lines on the paper copy. In general, the width of the contact lines on the paper copy ranges up to about 20 meters (66 feet).

Minor topological mistakes (such as identical rock units on both sides of a lithologic contact or unclosed polygons) and omissions (such as unidentified lithologic units) have been corrected to the best of the author's geologic expertise. Comparisons were made between the 5-sheet and the original mylar and colored field sheets (as available) in addition to the **Geologic Map of the Battle Creek Fault Zone, Northern Sacramento Valley, California** (USGS Map MF-1298, 1981), the **Geologic Map of the Chico Monocline and Northeastern Part of the Sacramento Valley, California** (USGS Miscellaneous Investigations Series Map I-1238, 1981), and the **Geologic Map of the Red Bluff 30' X 60' Quadrangle, California** (USGS Geologic Investigation Series Map I-2542, 1995).

Structural geology was digitized from the **Structure Contour Map of the Sacramento Valley, California, Showing Major Late Cenozoic Structural Features and Depth to Basement** (USGS Professional Paper 1359, 1987a). Geological fault information was digitized from both Harwood and Helley (1985) and Harwood and Helley (1987a).

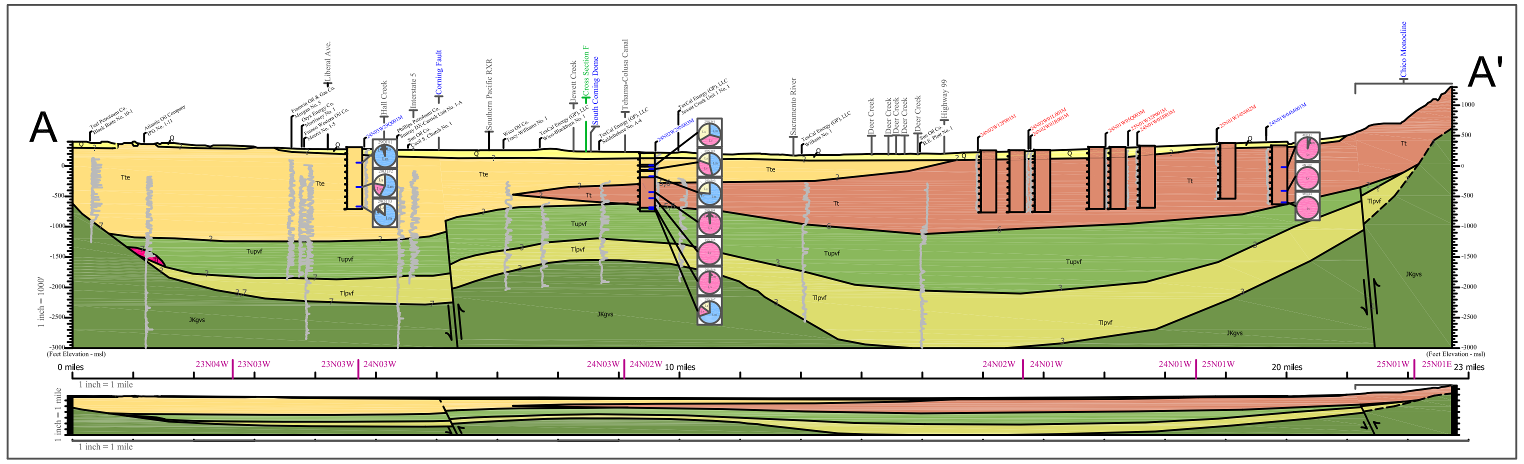
This map was prepared by Jonathan Mulder, Engineering Geologist, Department of Water Resources, Northern Region Office, Geological Investigations Unit. Assistance with the geological interpretation was provided by Bruce Ross, Engineering Geologist. Assistance with the digitizing and map layout was provided by Student Assistants Casey Murray, Clint Andreasen, and Jeremiah Moody.

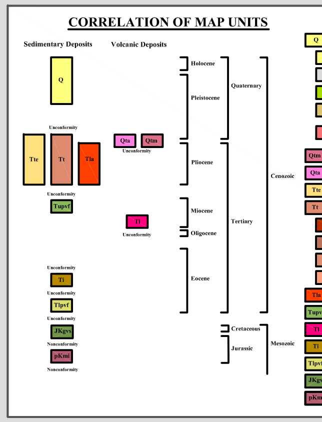
PLATE 2

STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN REGION OFFICE

GEOLOGIC CROSS SECTIONS A - D

GEOLOGY OF THE NORTHERN SACRAMENTO VALLEY, CALIFORNIA

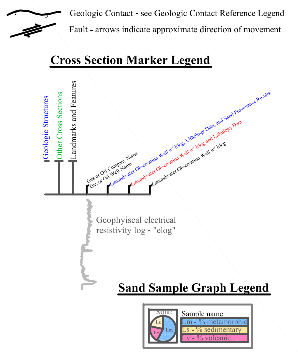



CORRELATION OF MAP UNITS

DESCRIPTION OF MAP UNITS

Q	**Includes the following formations:**
Qa	**Alluvium** (Holocene)-Includes surficial alluvium and stream channel deposits of unweathered gravel, sand and silt; maximum thickness 80 ft. *(adapted from Helley & Harwood, 1985).*
Qb	**Basin deposits** (Holocene)-Fine-grained silt and clay derived from adjacent mountain ranges; maximum thickness up to 200 ft. *(adapted from Helley & Harwood, 1985).*
Qm	**Modesto Formation** (Pleistocene)-Includes upper and lower formation members. Alluvial fan and terrace deposits consisting of unconsolidated weathered and unweathered gravel, sand, silt and clay; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood, 1985).*
Qr	**Riverbank Formation** (Pleistocene)-Includes upper and lower formation members. Alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand, and silt; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood, 1985).*
Qrb	**Red Bluff Formation** (Pleistocene)-Consists of a thin veneer of distinctive, highly weathered, bright red gravels overlying the Tehama, Tuscan, and Laguna Formations. *(adapted from Helley & Harwood, 1985).*
Qtm	**Tuff Breccia** (Plio-Pleistocene)-Tuff breccia forming outer ring surrounding the Sutter Buttes *(adapted from Helley & Harwood, 1985).*
Qta	**Volcanic Andesites**, Undifferentiated (Plio-Pleistocene)-Younger andesites forming the center of the Sutter Buttes *(adapted from Helley & Harwood, 1985).*
Tte	**Tehama Formation** (Plio-Pleistocene)-Includes Red Bluff Formation. Pale green, gray and tan sandstone and siltstone with lenses of pebble and cobble conglomerate; maximum thickness 2,000 ft. *(adapted from Helley & Harwood, 1985).*
Tt	**Tuscan Formation** (Plio-Pleistocene)-Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff *(adapted from Helley & Harwood, 1985).* Includes the following unit divisions:
Ttd	**Tuscan Unit D** (Plio-Pleistocene)-Fragmental flow deposits characterized by monolithic masses containing gray hornblende and basaltic andesites and black pumice; maximum thickness 160 ft. *(adapted from Helley & Harwood, 1985).*
Ttc	**Tuscan Unit C** (Plio-Pleistocene)-Includes Red Bluff Formation. Volcanic lahars with some interbedded volcanic conglomerate and sandstone, and reworked sediments; maximum thickness 600 ft. *(adapted from Helley & Harwood, 1985).*
Ttb	**Tuscan Unit B** (Pliocene)-Layered, interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone; maximum thickness 600 ft. *(adapted from Helley and Harwood, 1985).*
Tta	**Tuscan Unit A** (Pliocene)-Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone containing metamorphic rock fragments; maximum thickness 400 ft. *(adapted from Helley & Harwood, 1985).*
Tla	**Laguna Formation** (Pliocene)-Interbedded alluvial gravel, sand, and silt; maximum thickness 450 feet. *(adapted from Helley & Harwood, 1985; Olmsted and Davis, 1961; DWR Bulletin 118-6, 1978).*
Tupvf	**Upper Princeton Valley Fill** (Miocene)-Non-marine sediments composed of sandstone with interbeds of mudstone, occasional conglomerate, and conglomerate sandstone; maximum thickness 1,400 ft. *(adapted from Redwine, 1972).*
Tl	**Lovejoy Basalt** (early Miocene)-Black, dense, hard microcrystalline basalt; maximum thickness 65 ft. *(adapted from Helley & Harwood, 1985).*
Ti	**Ione Formation** (Eocene)-Marine to non-marine deltaic sediments, light colored, commonly white conglomerate, sandstone and siltstone, soft and easily eroded; maximum thickness 650 ft. *(adapted from DWR Bulletin 118-6, 1978; Creely, 1965).*
Tlpvf	**Lower Princeton Valley Fill** (Eocene)-Includes Capay Formation. Marine sandstone, conglomerate, and interbedded silty shale; maximum thickness 2,400 ft. (*adapted from Redwine, 1972*)
JKgvs	**Great Valley Sequence** (Late Jurassic to Upper Cretaceous)-Marine clastic sedimentary rock consisting of siltstone, shale, sandstone, and conglomerate; maximum thickness 15,000 ft.
pKmi	**Metamorphic and Igneous Rocks** (pre-Cretaceous)-Undivided. Slate, quartzite, metaconglomerate, marble, metamorphic rocks, serpentinite, metagabbro, diorite, and monzonite; maximum thickness unknown. *(adapted from Helley & Harwood, 1985).*

LEGEND AND NOTES


Geologic Legend

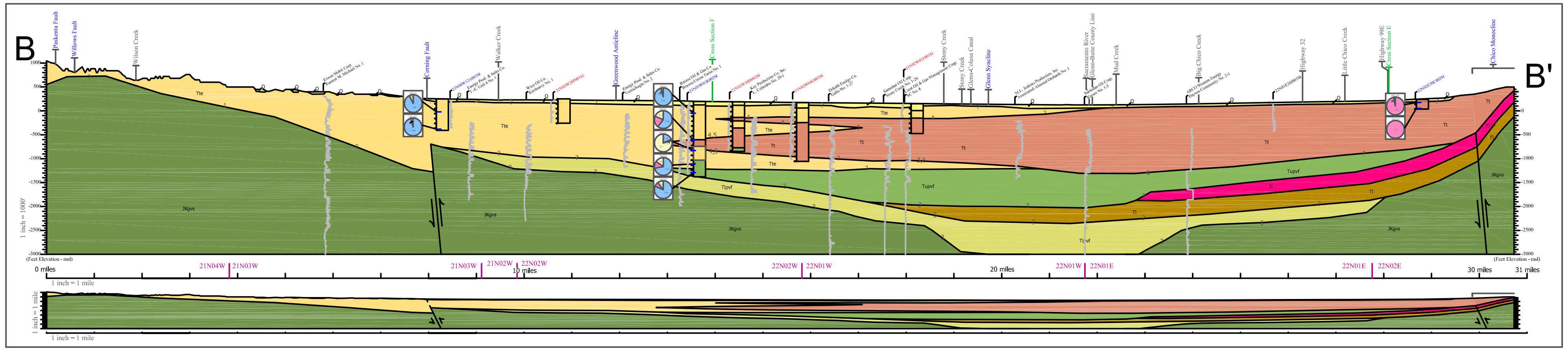
Geologic Contact - see Geologic Contact Reference Legend

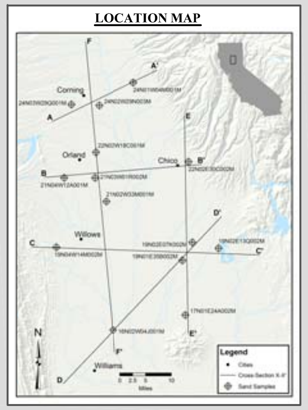
Fault - arrows indicate approximate direction of movement

Cross Section Marker Legend

Sand Sample Graph Legend

Sample name
Lm - % metamorphic
Ls - % sedimentary
Lv - % volcanic




LOCATION MAP

GEOLOGIC CONTACT REFERENCE LEGEND

1 - Harwood, D.S., Helley E.J. 1987 Late Cenozoic tectonism of the Sacramento Valley, California: U.S. Geological Survey, Professional Paper 1359, scale 1:250000.

2 - Helley, E.J., and Harwood, D.S. 1985. Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California. Department of the Interior - U.S. Geological Survey. Miscellaneous Field Studies Map MF-1790, 1-24 p., 5 sheets, Scale 1:62500.

3 - Redwine, L.E., 1972, The Tertiary Princeton Submarine Valley System Beneath the Sacramento Valley, California: Univ. of California, Los Angeles, unpubl. thesis (Ph.D), 480 p., 12 plates.

4 - Drill cutting lithology derived from drilling of dedicated observation wells in the northern Sacramento Valley.

5 - Ingersoll, R.V., and Steinpress, M. 2007. Northern Sacramento Valley Sand Provenance Study, unpubl.

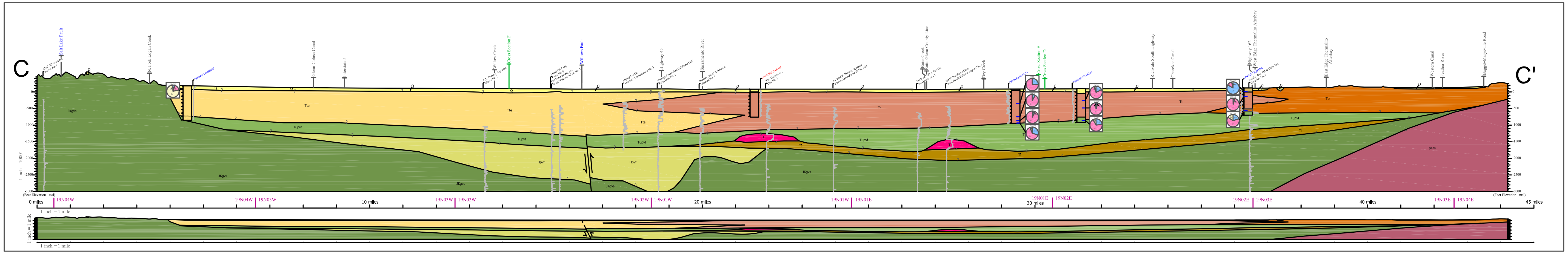
6 - Geophysical resistivity log signature

7 - Lithologic data provided from Division of Oil and Gas

? - Geologic contact unknown or inferred

Notes:
Geologic contact lines depicted here may not exactly match the data that is also displayed because many of the wells are projected onto the cross section line and lateral variation occurs within the geologic formations.

* The source of the volcanic grains in the deeper samples is undetermined.



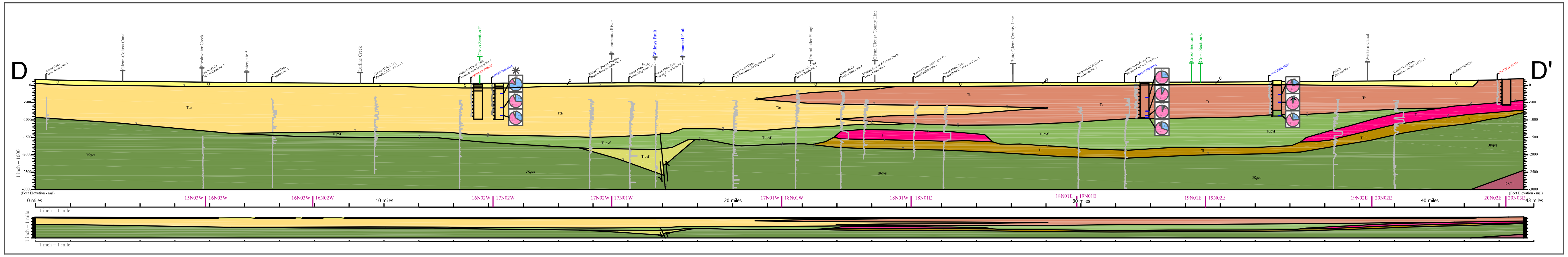
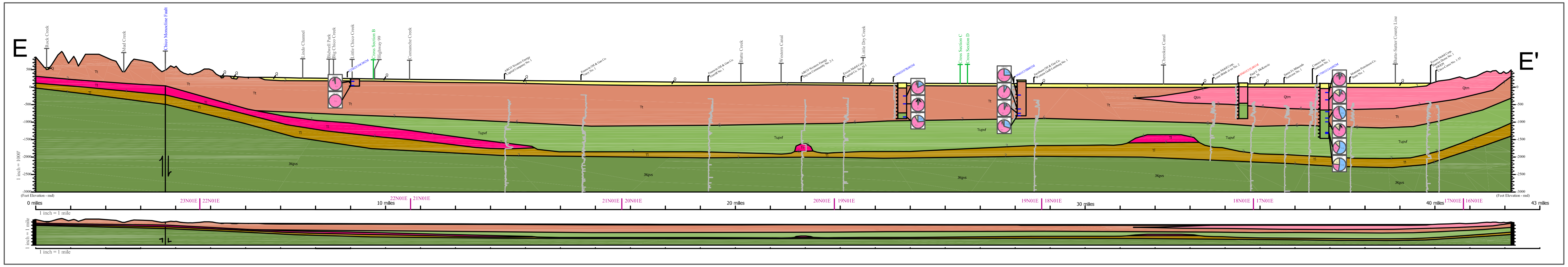


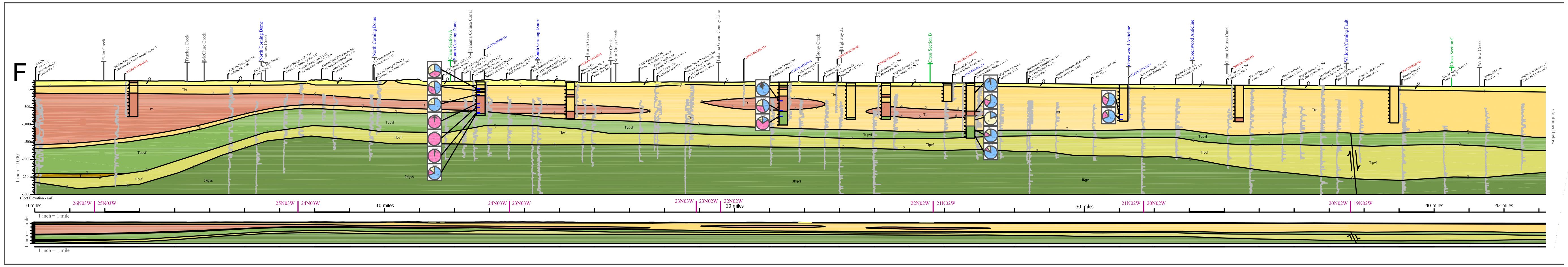
PLATE 3

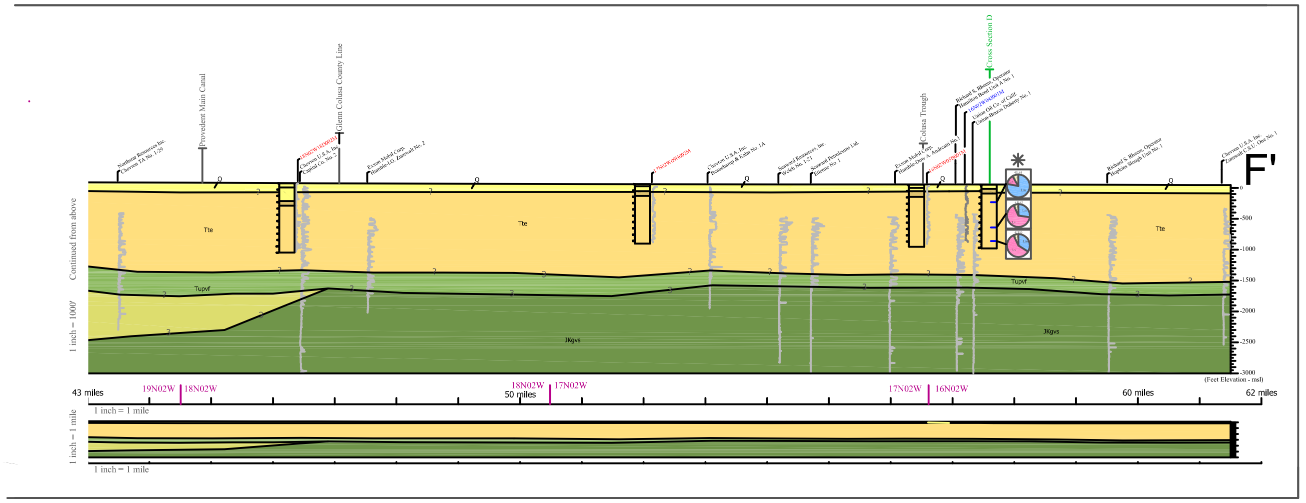
STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN REGION OFFICE

GEOLOGIC CROSS SECTIONS E - F

GEOLOGY OF THE NORTHERN SACRAMENTO VALLEY, CALIFORNIA







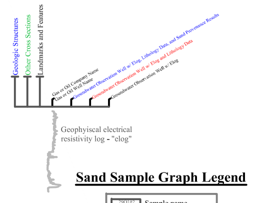
LEGEND AND NOTES

Geologic Legend

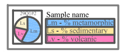
Geologic Contact - see Geologic Contact Reference Legend

Fault - arrows indicate approximate direction of movement

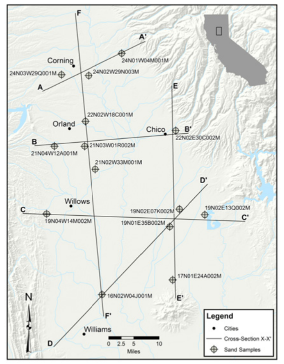
Cross Section Marker Legend



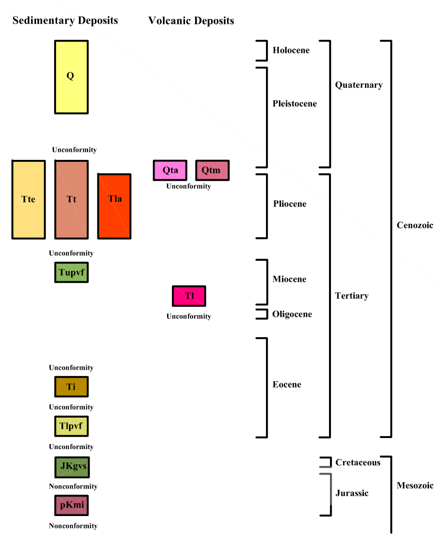
Sand Sample Graph Legend



LOCATION MAP



CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Cenozoic

Q Includes the following formations:

Qa **Alluvium** (Holocene)-Includes surficial alluvium and stream channel deposits of unweathered gravel, sand and silt, maximum thickness 80 ft. *(adapted from Helley & Harwood, 1985)*.

Qb **Basin deposits** (Holocene)-Fine-grained silt and clay derived from adjacent mountain ranges, maximum thickness up to 200 ft. *(adapted from Helley & Harwood, 1985)*.

Qm **Modesto Formation**, undifferentiated (Pleistocene)-alluvial fan and terrace deposits consisting of unconsolidated weathered and unweathered gravel, sand, silt and clay, maximum thickness approximately 200 ft. *(adapted from Helley & Harwood , 1985).*

Qr **Riverbank Formation**, undifferentiated (Pleistocene)-alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand and silt, maximum thickness approximately 200 ft. *(adapted from Helley & Harwood, 1985).*

Qtm **Tuff Breccia** (Plio-Pleistocene)-tuff breccia forming outer ring surrounding the Sutter Buttes *(adapted from Helley & Harwood, 1985)*.

Qta **Volcanic Andesites**, undifferentiated (Plio-Pleistocene)-younger andesites forming the center of the Sutter Buttes *(adapted from Helley & Harwood, 1985).*

Tte **Tehama Formation** (Plio-Pleistocene)-includes Red Bluff Formation on west side. Pale green, gray and tan sandstone and siltstone with lenses of pebble and cobble conglomerate, maximum thickness 2,000 ft. *(adapted from Helley & Harwood, 1985).*

Tt **Tuscan Formation** (Plio-Pleistocene)-Interbedded lahars, colcanic conglomerate, volcanic sandstaone, siltstone, and pumiceous tuff. Includes the following unit dividsions. *(adapted from Helley & Harwood, 1985).*

Ttd **Tuscan Unit D** (Plio-Pleistocene)-Fragmental flow deposits characterized by monolithic masses containing gray hornblende and basaltic andesites and black pumice, maximum thickness 160 ft. *(adapted from Helley & Harwood, 1985).*

Ttc **Tuscan Unit C** (Plio-Pleistocene)-includes Red Bluff Formation on east side. Volcanic lahars with some interbedded volcanic conglomerate and sandstone, and reworked sediments, maximum thickness 600 ft. *(adapted from Helley & Harwood, 1985, DWR Bulletin 118-7 (in progress), 2001).*

Ttb **Tuscan Unit B** (Pliocene)-Layered, interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone, maximum thickness 600 ft. *(adapted from Helley and Harwood, 1985; DWR Bulletin 118-7 (in progress), 2001).*

Tta **Tuscan Unit A** (Pliocene)-Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone containing metamorphic rock fragments, maximum thickness 400 ft. *(adapted from Helley & Harwood, 1985; DWR Bulletin 118-7 (in progress), 2001).*

Tla **Laguna Formation** (Pliocene)-Interbedded alluvial gravel, sand and silt, maximum thickness 450 feet. *(adapted from Helley & Harwood, 1985; Olmsted and Davis, 1961; DWR Bulletin 118-6, 1978).*

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Tl **Lovejoy Basalt** (early Miocene)-Black, dense, hard microcrystalline basalt, maximum thickness 65 ft. *(adapted from Helley & Harwood, 1985).*

Ti **Ione Formation** (Eocene)-Marine to non-marine deltaic sediments, light colored, commonly white conglomerate, sandstone and siltstone, which is soft and easily eroded, max. thickness 650 ft. *(adapted from DWR Bulletin 118-6, 1978; Creely, 1965).*

Mesozoic

Tlpvf **Lower Princeton Valley Fill** (Eocene)-includes Capay Formation. Marine sandstone, conglomerate and interbedded silty shale, maximum thickness 2,400 ft. (*adapted from Redwine, 1972*)

JKgvs **Great Valley Sequence** (Late Jurassic to Upper Cretaceous)-Marine clastic sedimentary rock consisting of siltstone, shale, sandstone and conglomerate, maximum thickness 15,000 ft.

pKmi **Metamorphic and Igneous** Rocks (pre-Cretaceous)-Undivided slate, quartzite, metaconglomerate, marble, metamorphic rocks, serpentinite, metagabbro, diorite, and monzonite. *(adapted from Helley & Harwood, 1985).*

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Notes:
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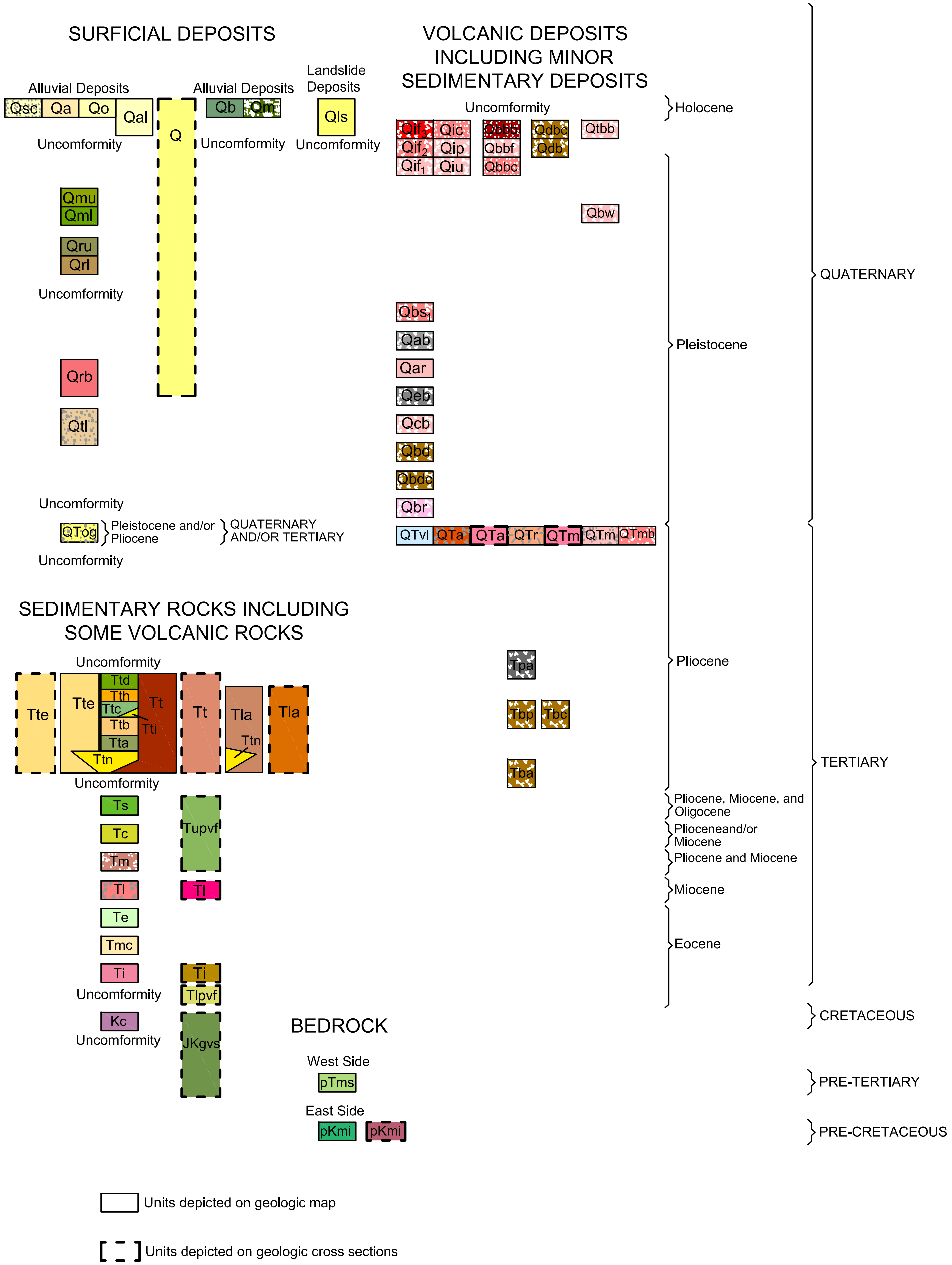
* The source of the volcanic grains in the deeper samples is undetermined.

CORRELATION OF MAP AND CROSS SECTION UNITS



LIST OF MAP AND CROSS SECTION UNITS

PLATE 4

SURFICIAL DEPOSITS

Qsc	Stream Channel
Qa	Alluvium
Qo	Overbank Deposits
Qal	Alluvial Deposits, Undivided
Q	Undifferentiated Surficial Deposits (cross section diagrams)
Qb	Basin Deposits, Undivided
Qm	Marsh Deposits
Qls	Landslides
Qmu	Modesto Formation - Upper Member
Qml	Modesto Formation - Lower Member
Qru	Riverbank Formation - Upper Member
Qrl	Riverbank Formation - Lower Member
Qrb	Red Bluff Formation
Qtl	Turlock Lake Formation
Qtog	Older Gravel Deposites

SEDIMENTARY ROCKS INCLUDING SOME VOLCANIC ROCKS

Tte	Tehama Formation
Tte	Tehama Formation (cross section diagrams)
Tt	Tuscan Formation
Tt	Tuscan Formation (cross section diagrams)
Ttd	Tuscan Formation - Unit D
Tth	Tuff of Hogback Road
Ttc	Tuscan Formation - Unit C
Tti	Ishi Tuff Member
Ttb	Tuscan Formation - Unit B
Tta	Tuscan Formation - Unit A
Ttn	Nomlaki Tuff Member
Tla	Laguna Formation
Tla	Laguna Formation (cross section diagrams)
Ts	Sutter Formation of Williams and Curtis (1977)
Tc	Channel Deposits
Tm	Mehrten Formation
Tupvf	Upper Princeton Valley Fill
Tl	Lovejoy Basalt
Tl	Lovejoy Basalt (cross section diagrams)
Te	Sedimentary Rocks in Sutter Buttes Area
Tmc	Montgomery Creek Formation
Ti	Ione Formation
Ti	Ione Formation (cross section diagrams)
Tlpvf	Lower Princeton Valley Fill (cross section diagrams)

VOLCANIC DEPOSITS INCLUDING MINOR SEDIMENTARY DEPOSITS

Qif$_3$	Flank Fissure Flows - Inskip Hill
Qif$_2$	Flank Fissure Flows - Inskip Hill
Qif$_1$	Flank Fissure Flows - Inskip Hill
Qic	Cinder Cone Deposits - Inskip Hill
Qip	Basalt Flows of Paynes Creek - Inskip Hill
Qiu	Undifferentiated Basalt Flows - Inskip Hill
Qbcb	Cinder Blanket Deposits - Black Butte
Qbbf	Basalt Flow - Black Butte
Qbbc	Cinder Cone Deposits - Black Butte
Qdbc	Cinder Cone Deposits - Digger Butte
Qdb	Basalt Flows - Digger Butte
Qtbb	Basalt of Tuscan Buttes
Qbw	Basalt of Whitmore Quad
Qbs$_1$	Basalt of Shingletown Ridge
Qab	Andesite of Brokeoff Mountain
Qar	Rockland Ash Bed
Qeb	Basalt of Eagle Canyon
Qcb	Basalt of Coleman Forebay
Qbd	Olivine Basalt of Devils Half Acre
Qbdc	Olivine Basalt of Deer Creek
Qbr	Blue Ridge Rhyolite of Coe (1977)
QTvl	Volcanic Lake Bed
QTa	Andesites in Sutter Buttes Area
QTa	Volcanic Andesites - Sutter Buttes (cross section diagrams)
QTr	Rhyolite Domes - Sutter Buttes
QTm	Tuff Breccia - Sutter Buttes (cross section diagrams)
QTm	Tuff Breccia - Sutter Buttes
QTmb	Tuff Breccia of Mineral Area
Tpa	Platy Andesite
Tbp	Olivine Basalt of Paradise
Tba	Basaltic Andesite of Antelope Creek
Tbc	Olivine Basalt of Cohasset Ridge

Bedrock

pTms	Metamorphic, Intrusive, and Sedimentary Rocks
pKmi	Metamorphic and Igneous Rocks
pKmi	Metamorphic and Igneous Rocks (cross section diagrams)

☐ Units depicted on geologic map

[ ] Units depicted on geologic cross sections