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J. Wagoner

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Wagoner, Jeffrey L.
Lawrence Livermore National Laboratory
Atmospheric, Earth and Energy Division
P.O. Box 808, Livermore, CA 94551

ABSTRACT

The objective of the Westcarb Kimberlina pilot project is to safely inject 250,000 t CO_2/yr for four years into the deep subsurface at the Clean Energy Systems (CES) Kimberlina power plant in southern San Joaquin Valley, California. In support of this effort, we have constructed a regional 3D geologic model of the southern San Joaquin basin. The model is centered on the Kimberlina power plant and spans the UTM range E 260000-343829 m and N 3887700-4000309 m; the depth of the model ranges from the topographic surface to >9000 m below sea level. The mapped geologic units are Quaternary basin fill, Tertiary marine and continental deposits, and pre-Tertiary basement rocks. Detailed geologic data, including surface maps, borehole data, and geophysical surveys, were used to define the geologic framework. Fifteen time-stratigraphic formations were mapped, as well as >140 faults. The free surface is based on a 10 m lateral resolution DEM. We use Earthvision (Dynamic Graphics, Inc.) to integrate the geologic and geophysical information into a 3D model of x,y,z,p nodes, where p is a unique integer index value representing the geologic unit. This grid represents a realistic model of the subsurface geology and provides input into subsequent flow simulations.

INTRODUCTION

The Westcarb Partnership, led by the California Energy Commission (CEC), will conduct a geologic CO_2 storage demonstration project in the southern San Joaquin basin in central California. The project will inject 1 million tons of CO_2 over 4 years into a deep geologic formation below a zero-emission power plant near Kimberlina, CA. The Clean Energy Systems (CES) plant uses natural or synthesis gas in an oxyfuel system and produces a relatively pure stream of CO_2. This CO_2 will be compressed and injected into one of a number of potential storage formations below the plant. In order to predict the fate of the CO_2, we need to understand the subsurface geology below and surrounding the plant.

Fundamental to subsurface geologic characterization is the compilation of spatial distributions of lithology and physical properties. Being able to easily manipulate a large, complex data set provides the geoscientist with the opportunity to detect and visually analyze spatial correlations between different types of data, and this leads to an increased understanding of the subsurface geology. Three-dimensional models can be very well constrained in areas where seismic and borehole data are available. The process is to revise the 3D model as new data are progressively added or as our interpretative understanding of the geology evolves. New data are often slowly acquired over time during which this "living" model evolves.

Software is available for interpolating and projecting geologic data into the subsurface. Map-derived data, along with geophysical, borehole and seismic data, can be assembled into a realistic 3D model as a set of surfaces, with the volumes defined by those surfaces. Earthvision, developed by Dynamic Graphics Inc., is a 3D model-building and visualization software package, with which precise 3D models can be created and updated.

DATA and METHODS

A regional 3D geologic model of the southern San Joaquin basin (Figure 1) was constructed. The model is centered on the Kimberlina power plant and spans the UTM range E 260000-343829 m and N 3887700-4000309 m; the depth ranges from the topographic surface to >9000 m below sea level. The projection of the model is UTM zone 11 Clarke 1866/NAD27. The mapped geologic units are Quaternary basin fill, Tertiary marine and continental deposits, and pre-Teritary basement rocks. Detailed geologic data, including surface maps, borehole data, and geophysical surveys, were used to define the geology. Fifteen time-stratigraphic formations were mapped, as well as >140 faults. The free surface is based on a 10 m lateral resolution DEM, downloaded from the Web.

The first step in building this model was to define the node structure to create a topographic surface. The free surface is based on a 10 m lateral resolution DEM, which we converted to a 2D grid within Earthvision. Stratigraphic tops for all of the major stratigraphic units were collected and digitized. The data were converted to elevation and 2D grids were generated for the top of each unit. The fault traces were digitized. Having no other information available, we assumed a 80 degree dip for all of the faults (the dips will be altered on a fault to fault basis as the model is better defined). Using the assumed dip and the digitized trace, a 2D grid was generated for each fault.

Figure 2 shows the full range of the regional model, centered on the Kimberlina power plant. This map shows the surface geology, oil and gas fields, faults (as projected to the surface), and roads. The large red polygon is the estimated areal extent of the Oligocene Vedder Formation, which is the current target for the injection of the CO_2. This regional model was also developed to improve our understanding of the location and character of other potential sequestration targets in this part of the San Joaquin basin. This model provides a framework for constructing smaller models of the injection site. This regional framework model is about 84 km x 112 km in size. Once the larger model is constructed, smaller models of any size can be easily extracted within this range, using the same basic data sets.

Most of the geologic information integrated into this model is defined by borehole contacts from the oil & gas industry, available from the California Division of Oil and Gas and Geothermal Resources (DOGGR) (Figure 3). Geologic information is available primarily for the oil and gas fields. The only publicly-available data for areas outside of the fields are from wildcat exploration wells that were drilled prior to 1980. Many of these wells provide stratigraphic tops, but the data are sporadic. EOG Resources, Inc. generously provided stratigraphic information for areas near the Kimberlina power plant; these data also included seismic reflection interpretations, which were independent of the wildcat well locations.

The fault data are taken from DOGGR documents on specific oil and gas fields in the basin. Our current understanding of the faulting between the oil and gas fields is poor and this is an area for which more work is required. There are plans to either acquire or field 3D seismic surveys in the future.

GEOLOGIC SETTING

The San Joaquin Valley is the southern extension of the Great Valley, an elongate basin located between the Sierra Nevada and the California Coast Ranges. The southern part of the San Joaquin basin is filled by more than 7000 m of Tertiary marine and nonmarine sediments, which bury the downwarped western margin of the Sierra Nevada metamorphic-plutonic terrane. The stratigraphic section is generally thin and predominately continental on the east side of the basin, but it thickens into largely deep-water marine facies to the west. The structure is basically a monocline dipping toward the west, characterized by block faulting and broad, open folds. A major feature of the basin is the Bakersfield Arch, a westward-plunging structural bowing on the east side of the basin. This structure plunges south-southwest into the basin for approximately 25 km, separating the basin into 2 subbasins. The structural feature is the site of several major oil fields.

The stratigraphic relationships of the major formations are shown in Figure 4. Structural surfaces were constructed for the following formations:

Kern River Formation (Plio-Pleistocene)
Mainly nonmarine sediments. These are the youngest oil-producing sediments in the basin. This unit extends close to the surface and consists of interbedded claystone, shale, sandstone, and conglomerate.

Etchegoin Formation (Pliocene)
Unconformably overlies the Chanac Formation in the model area. Mostly fine- to coarse-grained marine sandstone and micaceous shale. The Etchegoin consists of 3 members: the basal sandstone, the Macoma Clay, and the upper sandstone.

Macoma Clay (Pliocene)
Mostly marine claystone and siltstone. This is a member of the Etchegoin Formation. Basal Etchegoin sandstone occurs stratigraphically below this fine-grained unit. This unit is mapped because it provides a useful time-stratigraphic marker.

Chanac Formation (Pliocene)
Mostly fine- to coarse-grained nonmarine sandstone, with interbedded siltstone and claystone. This deposit grades basinward into siliceous marine shale. Confined to a narrow zone in the subsurface of the southeastern part of the basin. The Chanac is the nonmarine equivalent to the Santa Margarita Formation.

Santa Margarita Formation (upper Miocene)
Rests unconformably on the Fruitvale Formation. Mostly coarse-grained sandstone, with sandy shale increasing toward the base of the unit. This unit rests on progressively older sediments toward the eastern edge of the basin. This unit is time equivalent to the Stevens Sand in the central part of the basin. The formation contains both marine and nonmarine facies.

McLure Formation (upper Miocene)
Fractured marine shale. Dominant shale member of the Monterey Formation in the central part of the basin.

Stevens Sand (upper Miocene)
Fine- to coarse-grained turbidite sandstone, with interbedded hard siltstone. The sandstone is highly variable in thickness and lateral extent. In the central part of the basin, thick siliceous shales overlie the Stevens.

Fruitvale Shale (upper Miocene)
Mainly marine deep water shale. Rests unconformably on top of the Round Mountain Formation. Massive marine siltstone and shale, with streaks of sandtone. Thickens toward the center of the basin. Dominant shale member of the Monterey Formation in the southeastern part of the basin.

Round Mountain Formation (middle Miocene)
The unit is mostly hard marine siltstone and shale.

Olcese Formation (lower Miocene)
Medium- to coarse-grained sandstone. Gradational contact with the underlying Freeman-Jewett Formation. The upper and lower parts of this unit are marine, while the middle portion of the Olcese is nonmarine in origin.

Freeman-Jewett Formation (lower Miocene)
Rests conformably on the Vedder Formation. Mostly hard marine shale and siltstone with thin streaks of sandstone. Grades vertically into the overlying Olcese Formation and represents the beginning of a regressive phase of the Miocene marine deposition.

Vedder Formation (lower Miocene)
Fine- to coarse-grained massive marine sandstone, with subordinate siltstone and shale. The younger Rio Bravo and Pyramid Hill sands (basal member of the overlying Freeman-Jewett Formation) have been included in this unit. This is the oldest of the significant oil-producing deposits on the eastern side of the basin. The sands included in the Vedder range from a few feet to several hundred feet thick.

Walker Formation (lower Miocene)
The Walker Formation rests on basement rocks on the east side of the basin, is continental in origin, and consists mainly of sandstone and claystone. Toward the center of the basin, the Walker interfingers with the time-equivalent Vedder Formation.

Temblor Formation (lower to middle Miocene)
This formation has a widespread distribution in the subsurface of the southern and central San Joaquin basin. The formation has several different members, with different lithologies. It represents the basinward time equivalent of the Vedder, Freeman-Jewett, and Olcese Formations.

Undifferentiated deposits (Eocene)
There are a number of Eocene formations in this part of the San Joaquin basin, but the Tumey Formation is probably the most common, and it occurs directly below the Vedder in the model area. The Tumey is a marine shale.

Basement (pre-Tertiary)
The basement in this part of the basin is mainly quartz diorite intrusive rocks.

THE REGIONAL GEOLOGIC MODEL

The regional geologic model shows the spatial distribution of the stratigraphic layers in the subsurface, including faults, and represents a realistic interpretation of the subsurface. Figure 5 shows the full regional model in a cut-away view at the location of the power plant. The legend on the left identifies the colors of the individual stratigraphic units. Note that the stratigraphic control decreases toward the center of the basin, thus the tops of the units are much less well constrained, especially deeper in the section. The general structural dip to the west is supported by the well picks as well as the seismic picks.

Figure 6 is a smaller submodel centered on the Kimberlina power plant (50 km on each side) and shows the borehole data (and total depths of the wells) that were used to constrain the surfaces of the stratigraphic units. Also shown are the locations of most of the oil and gas reservoirs in the area. The main pools are shown for each field and the pools are color-coded according to depth. Pools that are <800m deep are colored pink, while those deeper than 800m are colored green. CO_2 is supercritical at a depth of 800m, so those pools >800m deep would be considered potential targets for sequestration.

THE SITE-SPECIFIC GEOLOGIC MODEL

Smaller site-specific models were also constructed for the site. Additional models are easily extracted from the regional model, using the same primary data sets. Figure 7 shows a 10 km x 10 km geologic model of the power plant site. The tops of the stratigraphic units are generally well constrained in this area, due to the proximity of several oil and gas wildcat exploratory wells. There are also seismic data available within the range of this smaller model. The stratigraphic section dips about 7 degrees to the southwest. The top of the Vedder Formation (Figure 8) is defined by both well picks and seismic picks, provided by EOG Resources, Inc. The northwest-striking Pond fault north of the power plant displaces the top of the Vedder and was identified in the seismic data. There are other minor faults that penetrate this surface, but we don't currently have access to these data. Further work on the fault characterization is planned for the future.

Geophysical logs are available for many of the wells in this area and these data were used to generate detailed 2D cross sections through the smaller model. These data are also used to confirm the stratigraphic picks that are publicly available and determine that the picks are consistent with the geophysical logs. SP logs are the most common log type available and these were used to construct the cross sections. Figure 9 shows the locations of the sections, as well as the location of the reflection seismic data used in this report. Cross section 2 (Figure 10) trends SW-NE and is located ~7km north of the power plant. Cross section 3 (Figure 11) is the closest section to the power plant; Bender West 1 is located <1 km south of the site. Both sections reflect the shallow structural dip toward the southwest.

The southwesterly-dipping fault shown on both sections is called the Pond fault. The location of this structure is inferred from the seismic reflection interpretations provided by EOG Resources, Inc. The location and attitude of this fault are also supported by earlier geotechnical studies (LADWP, 1974; Holzer, 1980; Smith, 1983). The Pond fault apparently propagates to the land surface and is expressed as a 3.4 km long scarp, with up to 1.5 m displacement (Holzer, 1980). The Los Angeles Department of Water and Power originally investigated this feature as part of a potential siting of a nuclear power plant in the 1970's. They drilled boreholes, ran geophysical logs, collected vibroseis data, and constructed trenches across surface lineaments. They concluded that the Pond fault is a kilometer-wide zone of northwesterly-striking normal faults, dipping to the southwest at 50-70 degrees. LADWP also concluded that the Pond fault was an extension of the Poso Creek fault, which is located on the west edge of the Poso Creek Field (Figure 8). Further investigation by Holzer (1980) suggests that the surface displacements of the faults are the result of differential surface subsidence due to groundwater withdrawal. Smith (1983) provided additional field observations of the Pond fault surface displacements.

Figure 9 shows the location of the fault where it cuts through the top of the Vedder Formation, in relation to the lines of section and boreholes. The 2 cross sections (Figures 10 and 11) reflect this location and show the fault projected to the surface, lined up to where the surface displacements occur. Section 2 shows the fault between boreholes KCL A83-35 and Tenneco-Sun 11x. As interpreted here, the fault cuts through Tenneco Sun 11x and displaces a section of the Etchegoin Formation at a depth of about 1100 m. This interpretation is based on a detailed correlation of the SP logs. Section 3 shows the fault intersecting borehole Gow 1-161. The evidence is more convincing in this section, as it appears that sections of the lower Fruitvale/Round Mountain and upper Olcese Formations are missing. Based on the local stratigraphic framework, the predicted stratigraphic section that may be encountered at the Kimberlina power plant site is shown in Figure 12.

STATUS OF WELLS NEAR THE POTENTIAL SEQUESTRATION SITE

The geologic model of the Kimberlina site provides a framework for analyzing the potential risk that the injected CO_2 will not remain sequestered in the injected zone. One of the main concerns is the potential of leakage from boreholes that have been drilled in the area around the injected site. Important issues are distance from the site, depth of penetration, potential intersection of the seal and reservoir, and condition of the borehole and annulus. Table 1 provides the latest information on wells within a 6 km radius of the power plant at Kimberlina. Figure 9 shows the locations of these wells in relationship to the Kimberlina power plant. The boreholes are all abandoned oil and gas wildcat wells drilled between 1928-1983. The available completion reports detail the method of abandonment and how and where the holes were plugged. There is uncertainty on the plugging of some of the wells, partly because the wells are old and some of the completion and abandonment reports are incomplete. As noted in Table 1, most of the wells intersected the Freeman-Jewett and Vedder Formations. Figure 13 shows the location and downhole status of wells. The yellow areas indicate where the boreholes were plugged; the red areas indicate portions of the hole that are either open or filled in with drilling mud upon well abandonment. Figures 13 and 14 show where the boreholes intersect the Vedder Formation. The location of the power plant is identified by the pink symbol.

Table 1. List of oil and gas wells plotted in figures 9, 13, and 14.

easting	northing	well name	Distance from power plant (m)	Elevation (m)	TD (m)	Spud date
300591	3937093	Bender West 1	1007	135	2129	12/12/48
301837	3936957	Woodward-Sheedy 1	1868	136	1390	?
301267	3940312	KCL-A 58-8	2431	135	2831	10/8/38
303406	3940068	Gow 1	3666	148	2506	2/15/61
304178	3938830	Coberly West Co. 15-1	3918	150	2437	11/25/83
296994	3935532	Kimberlina 1-25	4194	121	3956	8/29/83
305004	3937209	C.W.O.D. 87	4747	144	1597	12/26/54
304168	3935237	Union-Mattei 1-34	4764	150	2437	8/12/74
303327	3941905	Steele Pet CO 4-1	4867	153	2281	12/1/56
305090	3940092	Kuhn 81	5168	169	2356	6/8/47
304795	3935419	MobilFlorida 1-27	5187	153	2239	2/21/75
304134	3934438	Mattei 1	5254	147	1289	7/25/28
305845	3936789	McCulloch/IDS-Vignoloetal 1-26	5656	146	1288	9/19/72

easting	northing	well name	Abandonment date	Cement plugs	Junk left in hole	Measured depth to Vedder (m)
300591	3937093	Bender West 1	12/30/48	yes	yes	n/a
301837	3936957	Woodward-Sheedy 1	?	no?	?	n/a
301267	3940312	KCL-A 58-8	12/9/38	yes	none	2177
303406	3940068	Gow 1	?	yes	none	1978
304178	3938830	Coberly West Co. 15-1	12/19/83	yes	none	2012
296994	3935532	Kimberlina 1-25	12/10/83	yes	none	2869
305004	3937209	C.W.O.D. 87	1/11/55	yes	none	n/a
304168	3935237	Union-Mattei 1-34	8/27/84	yes	none	2168
303327	3941905	Steele Pet CO 4-1	12/18/56	yes	none	1868
305090	3940092	Kuhn 81	7/10/47	yes	none	1787
304795	3935419	MobilFlorida 1-27	3/2/75	yes	none	2107
304134	3934438	Mattei 1	9/21/28	no	none	n/a
305845	3936789	McCulloch/IDS-Vignoloetal 1-26	10/3/72	yes	none	n/a

Although less of a concern, groundwater wells must also be considered, and these types of wells are very common in the Kimberlina area. Groundwater wells in California are generally much shallower than oil and gas wells, and thus should not approach the injection zone and will not penetrate the seal above the reservoir (this might not be the case in other areas of the country). Figure 15 shows the number of California Department of Water Resources groundwater well records per section in the area of the Kimberlina power plant (the green symbol near the center of the figure). In theory, this number represents the maximum number of groundwater wells ever drilled in each section. The locations of groundwater wells are very poorly constrained at this point, so we used this methodology to characterize the groundwater well risk. Additional work is required to document the locations and total depths of the wells.

SUMMARY

We have constructed a regional 3D geologic model of the southern San Joaquin basin in support of the Westcarb Kimberlina CO_2 sequestration demonstration project. This model includes the entire Tertiary section from the surface to the pre-Tertiary basement complex. Over 140 faults are included in the model. These faults are generally restricted to the oil and gas fields, but additional faults will be modeled when the data become available. This is considered a "living model" and will be continually updated and refined with the acquisition of new geologic and geophysical data. We use Earthvision to integrate the geologic and geophysical information into a 3D model of x,y,z,p nodes, where p is a unique integer index value representing the geologic unit. This grid represents a realistic model of the subsurface geology and will provide input into future flow simulations.

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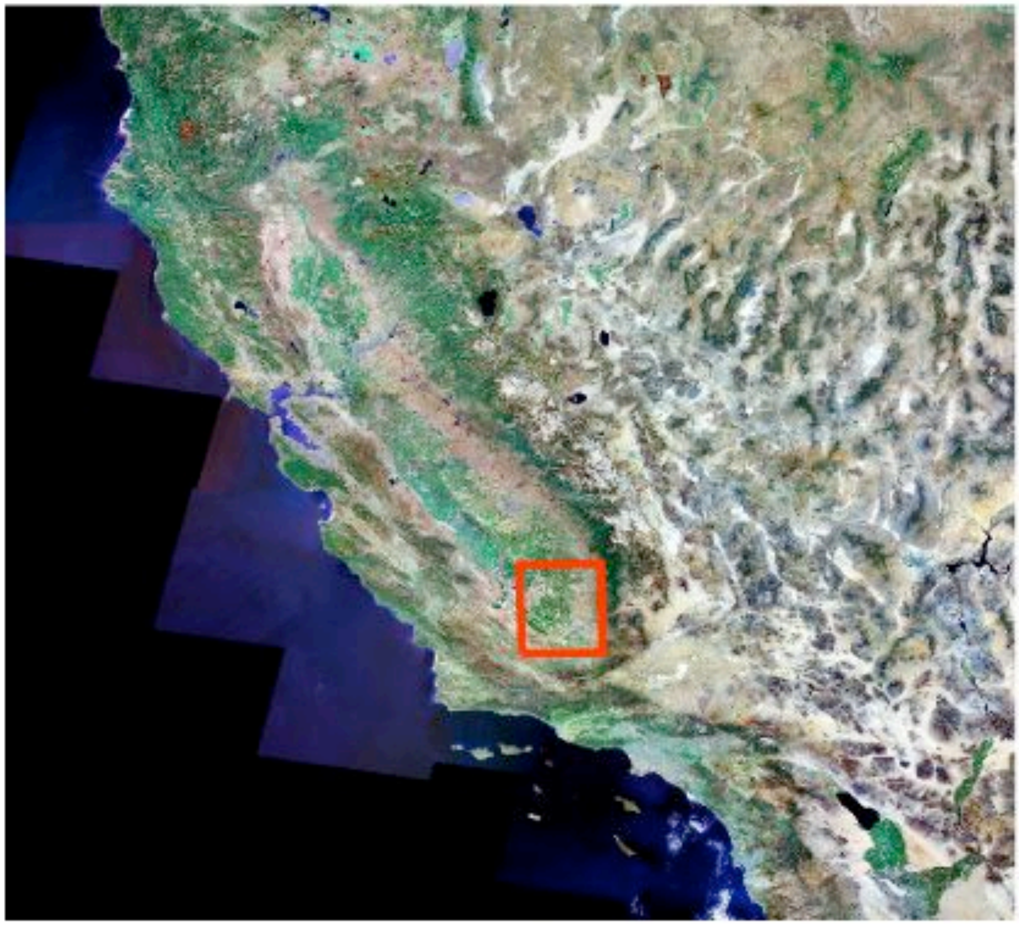

Figure 1. Satellite photo showing the location and range of the southern San Joaquin basin regional geologic model.

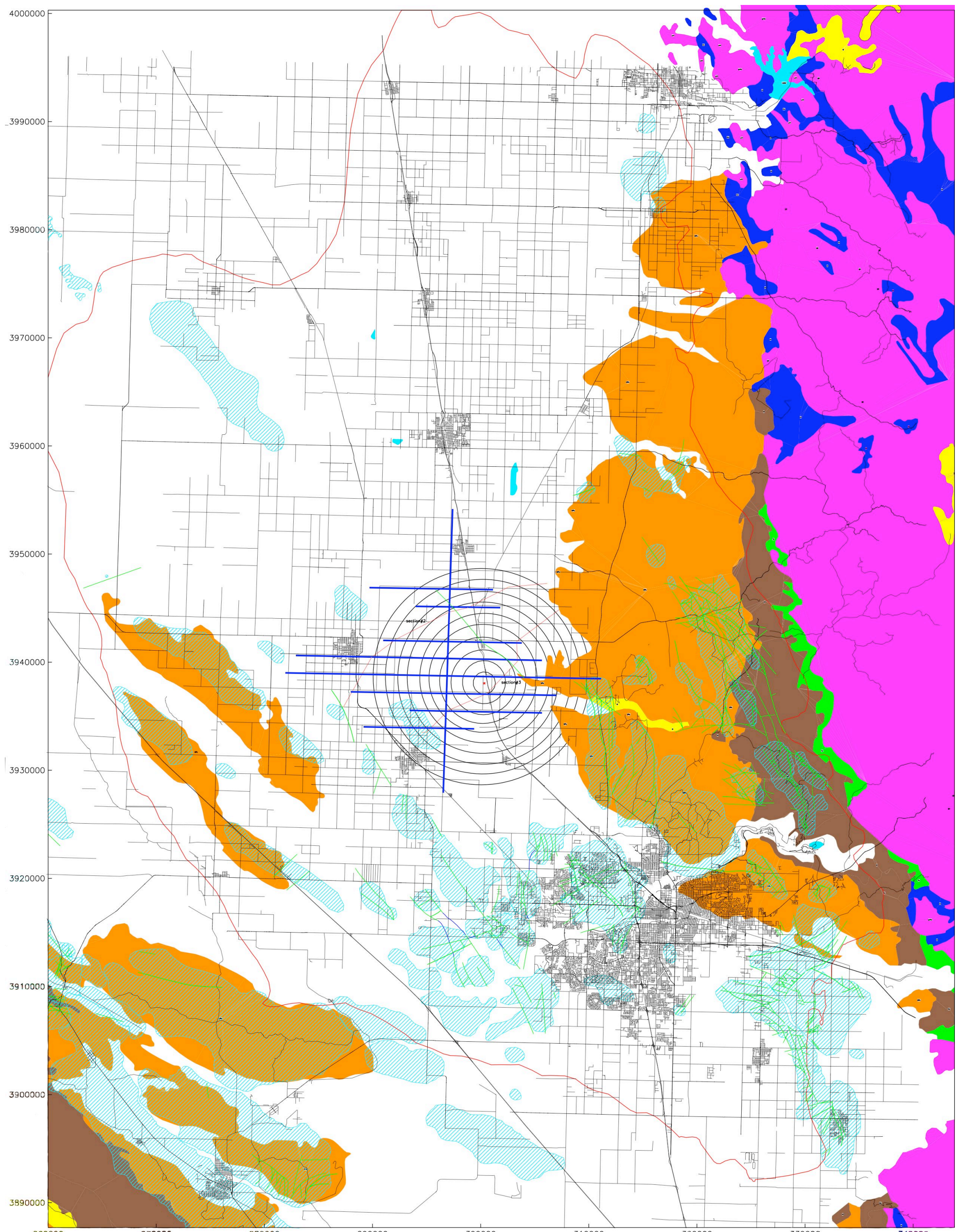

Figure 2. Plan map of the southern San Joaquin basin, showing the full range of the regional model. This map shows the Kimberlina power plant (red star), 1 km radius circles from the power plant, oil and gas fields (light blue polygons), faults (green lines), roads (gray lines), and the areal extent of the Vedder Formation (large red polygon). The surface geology is also shown: white=Quaternary alluvium, pink and dark blue=pre-Tertiary basement rocks, all other colors=Tertiary sedimentary rocks.

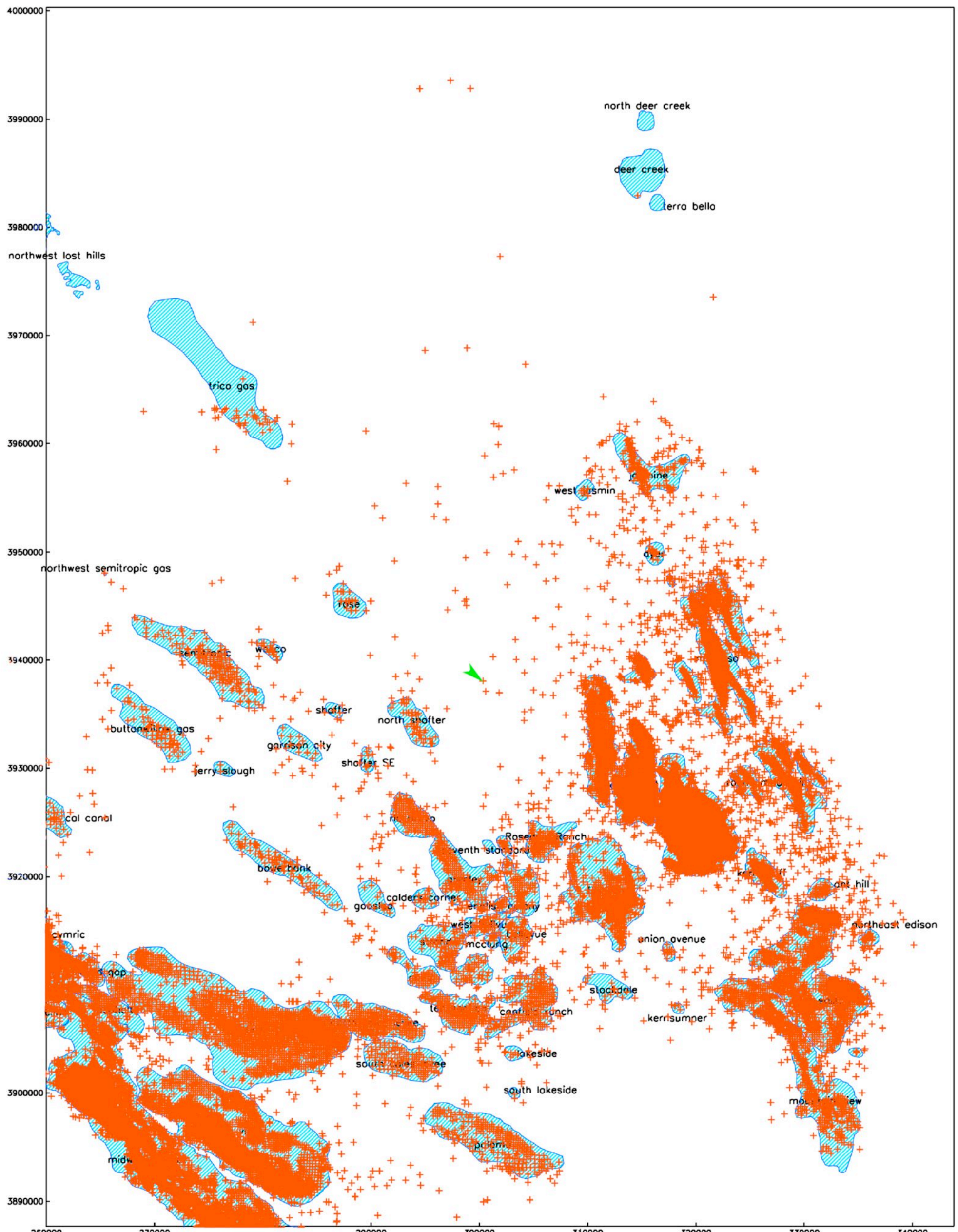

Figure 3. Plan map of the southern San Joaquin basin showing the locations of wells, many of which provided stratigraphic data for the model construction. The blue polygons are the oil and gas fields. The green arrow indicates the power plant.

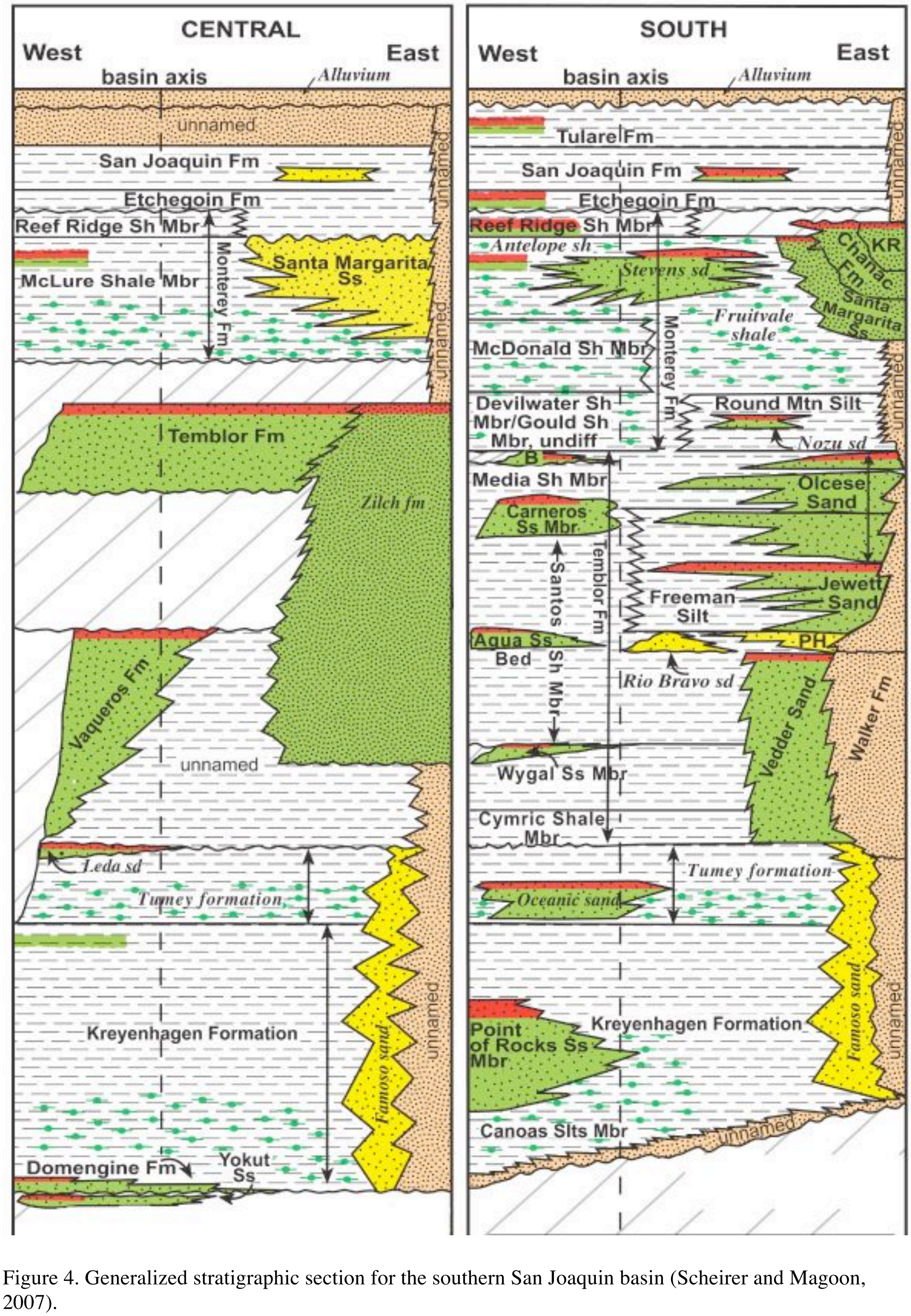

Figure 4. Generalized stratigraphic section for the southern San Joaquin basin (Scheirer and Magoon, 2007).

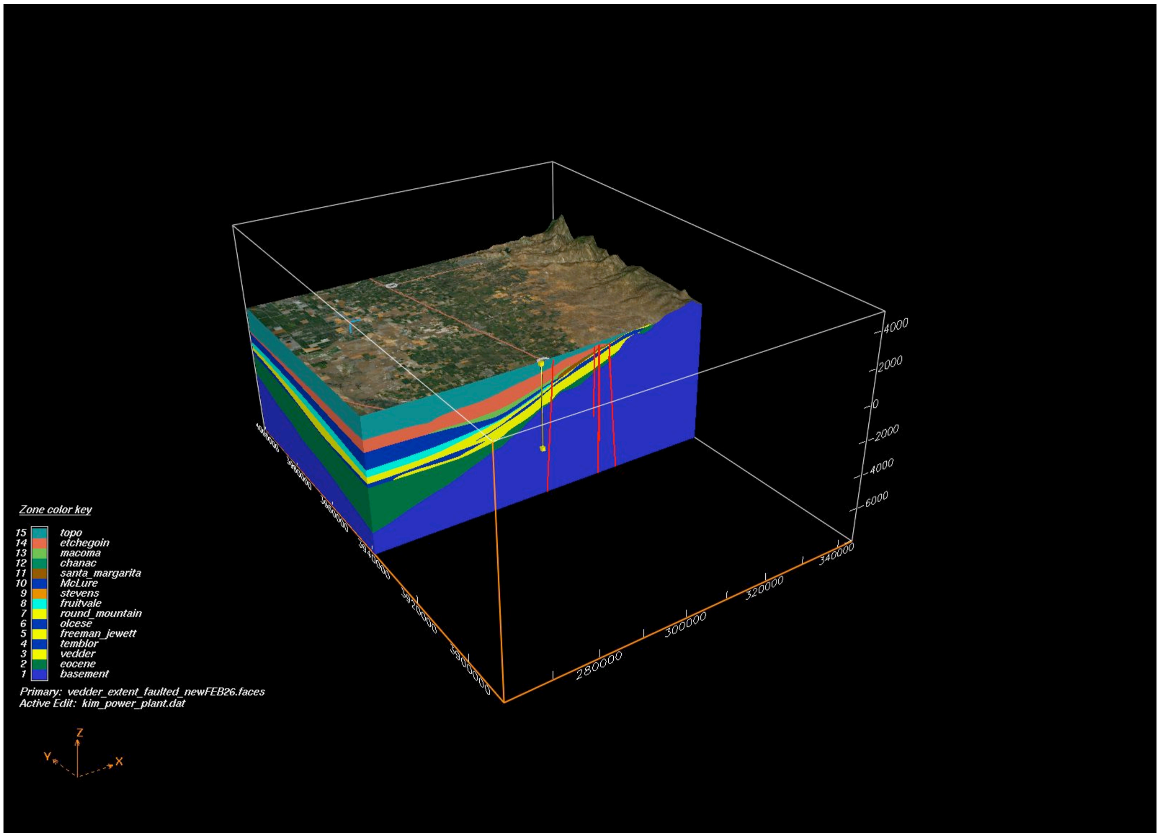

Figure 5. This is a cut-away view of the regional model at the location of the power plant (vertical yellow line). The faults are shown as subvertical red lines. (4x vertical exaggeration).

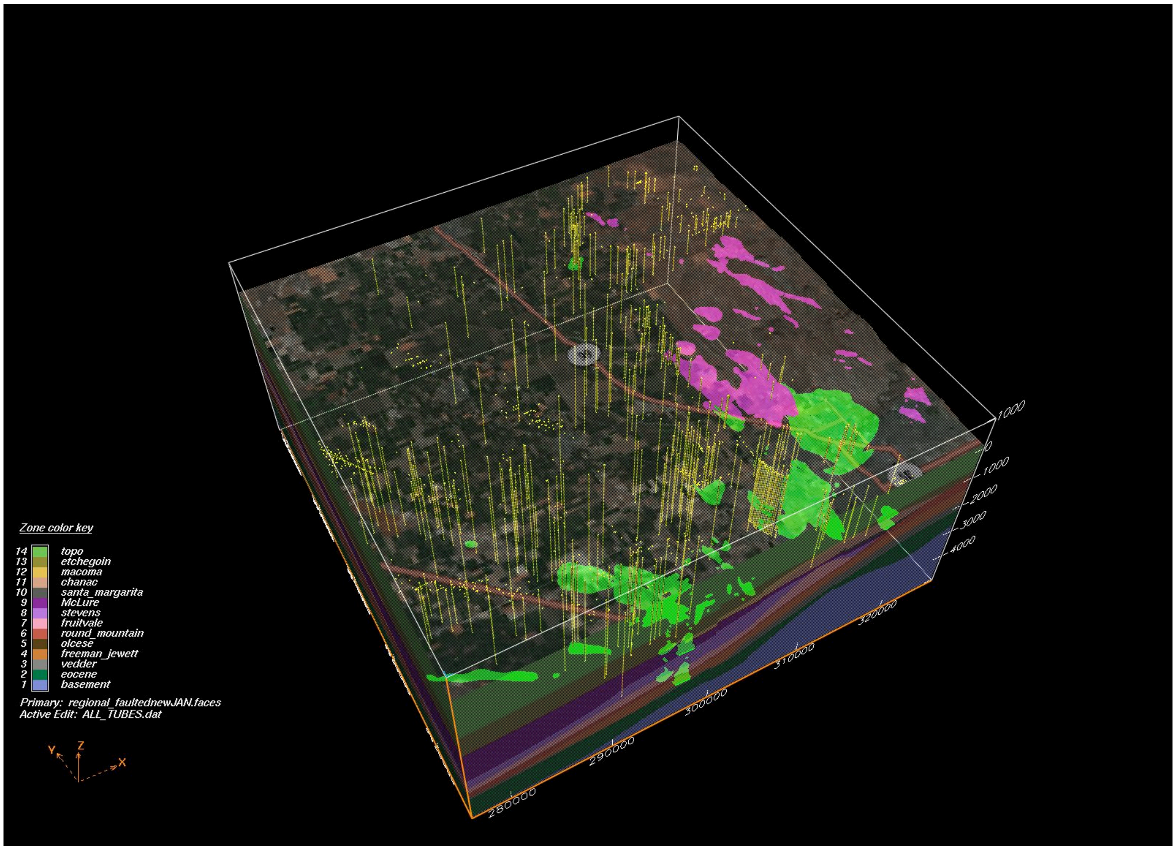

Figure 6. View of a 50 km x 50 km model showing the location of boreholes. Most of these boreholes provided stratigraphic data used to create the geologic relationships in the model. Also note the locations of pools within the oil and gas fields. The pink pools are <800 m deep, while the green pools are >800 m deep. (4x vertical exaggeration).

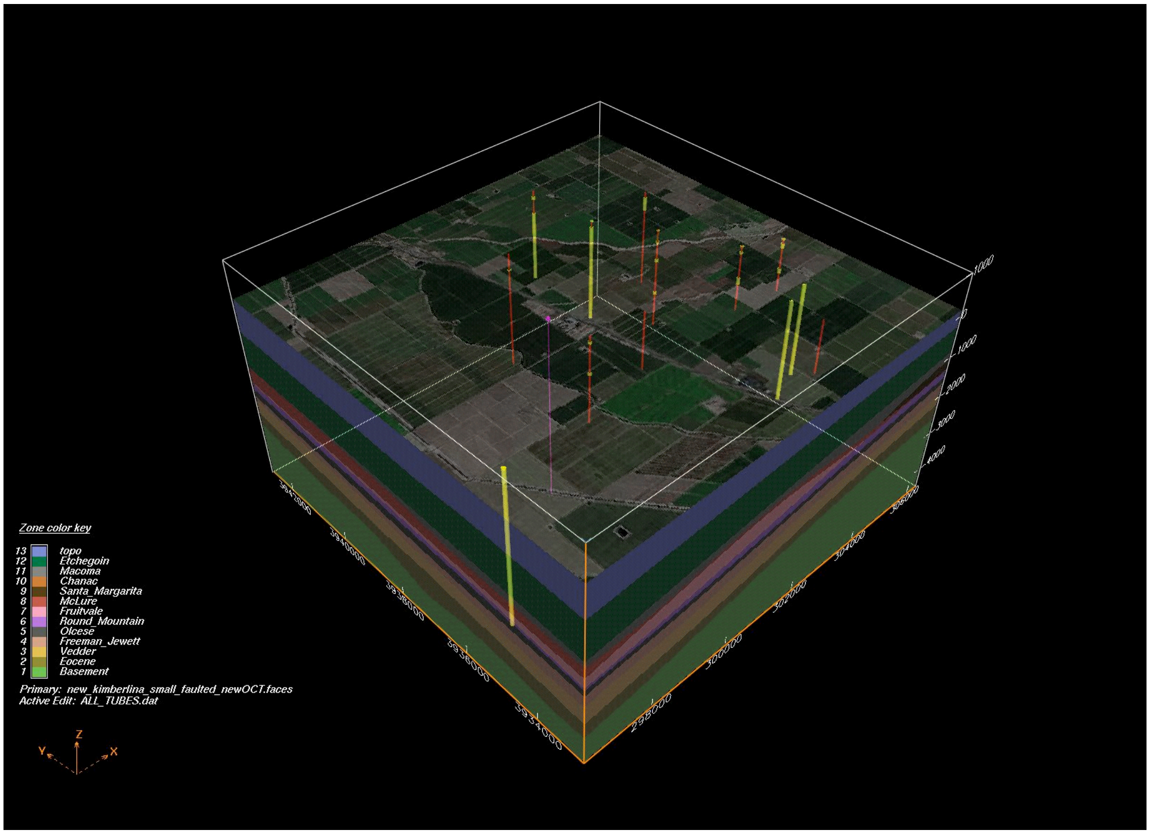

Figure 7. This is a 10 km x 10 km submodel showing the locations of oil and gas wells near the Kimberlina power plant. The power plant is located at the purple symbol. All of these wells were wildcat exploratory wells and all have been abandoned. The yellow columns are areas where the hole has been plugged with cement. The red areas of the well are either open or filled in with drilling mud. These data are based on records from the California Division or Oil and Gas and Geothermal Resources (Bakersfield office). (no vertical exaggeration).

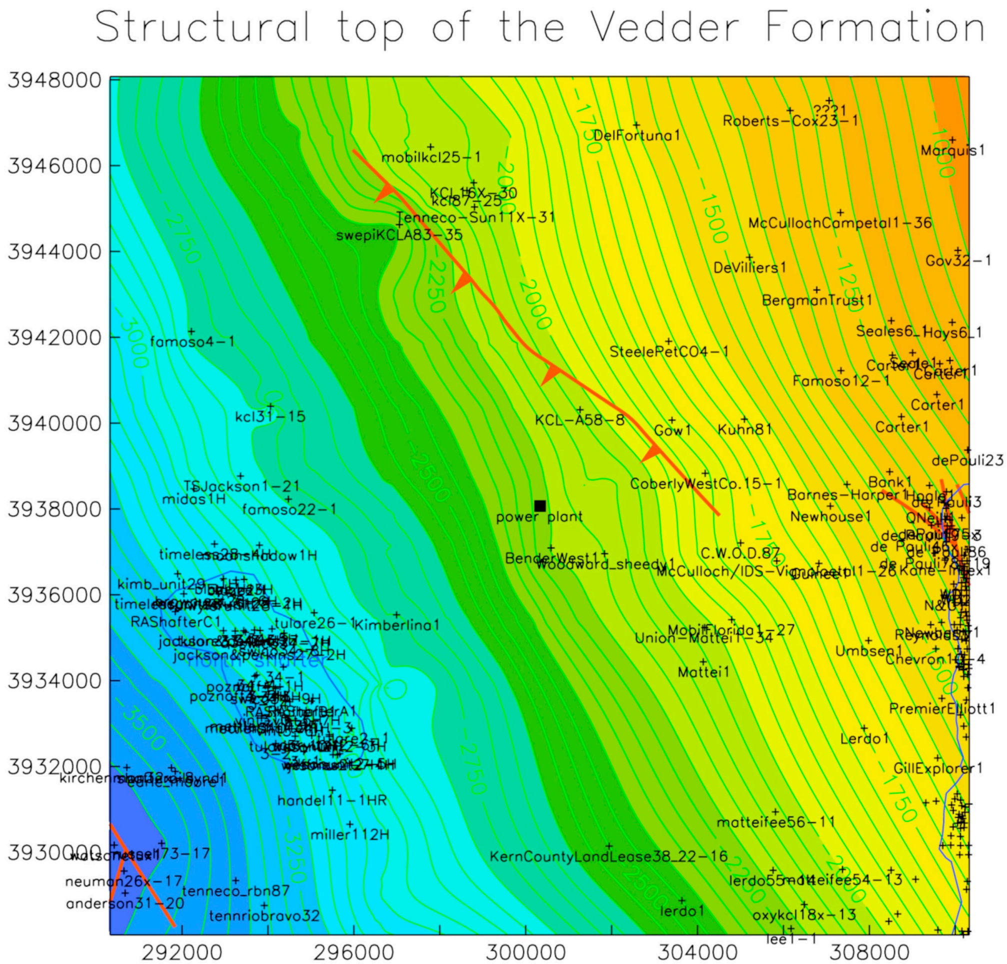

Figure 8. Structural contour map of the top of the Vedder Formation. The oil and gas wells are shown on this map, as well as the faults. The northwest-striking fault north of the power plant displaces the top of the Vedder and was identified in the seismic data. There are other minor faults that penetrate this surface, but we don’t currently have access to these data. Further work on the fault characterization is planned for the future.

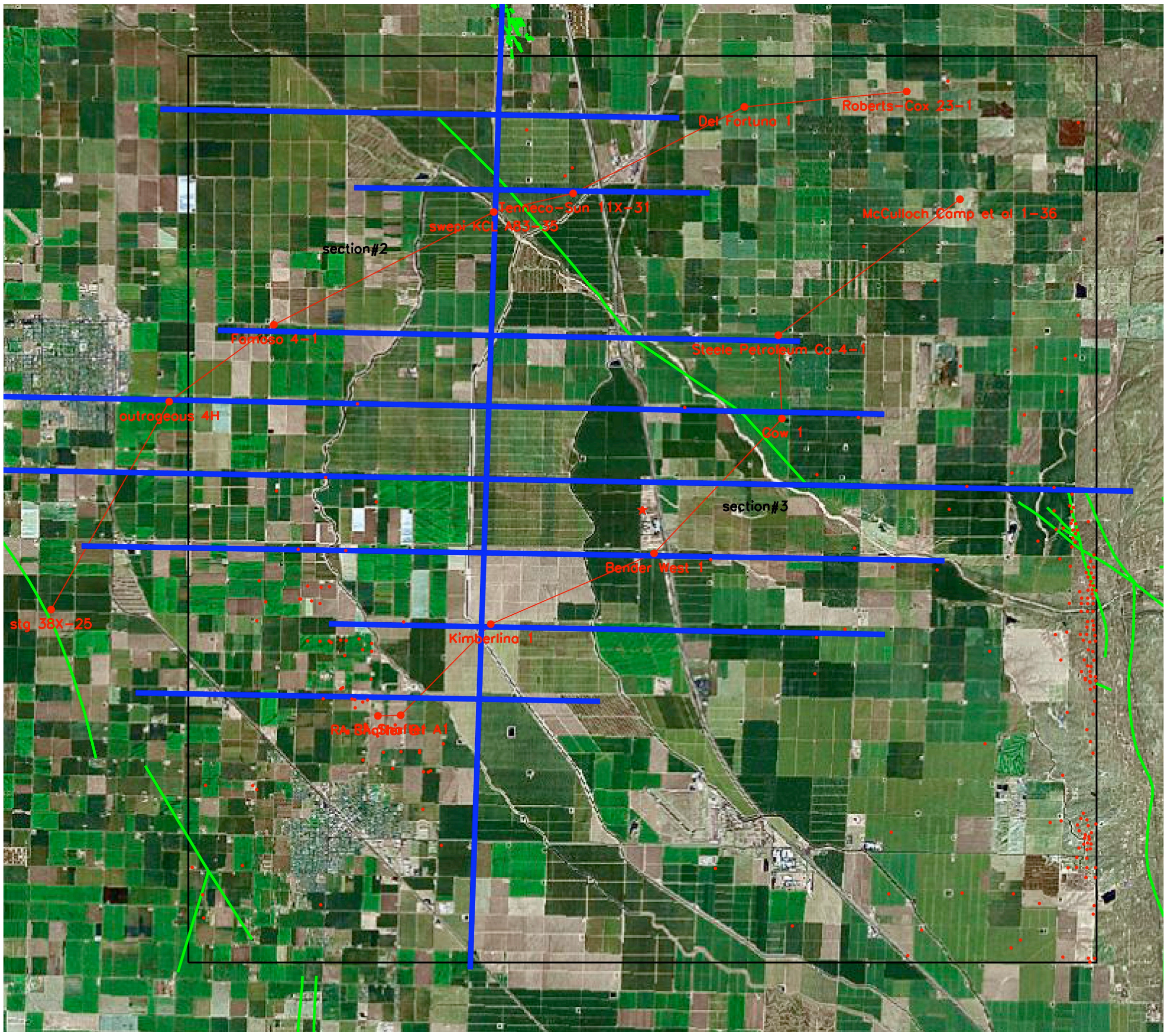

Figure 9. This figure shows the locations of oil and gas wells near the Kimberlina power plant. The power plant is located at the red star near the center of the map. The 2 cross section lines are plotted in red. The pink lines are the seismic lines from which stratigraphic tops were interpreted by EOG Resources, Inc. Well locations are the red dots on the map. The black square denotes the range of the 20 km x 20 km model. The green lines indicate approximate fault locations.

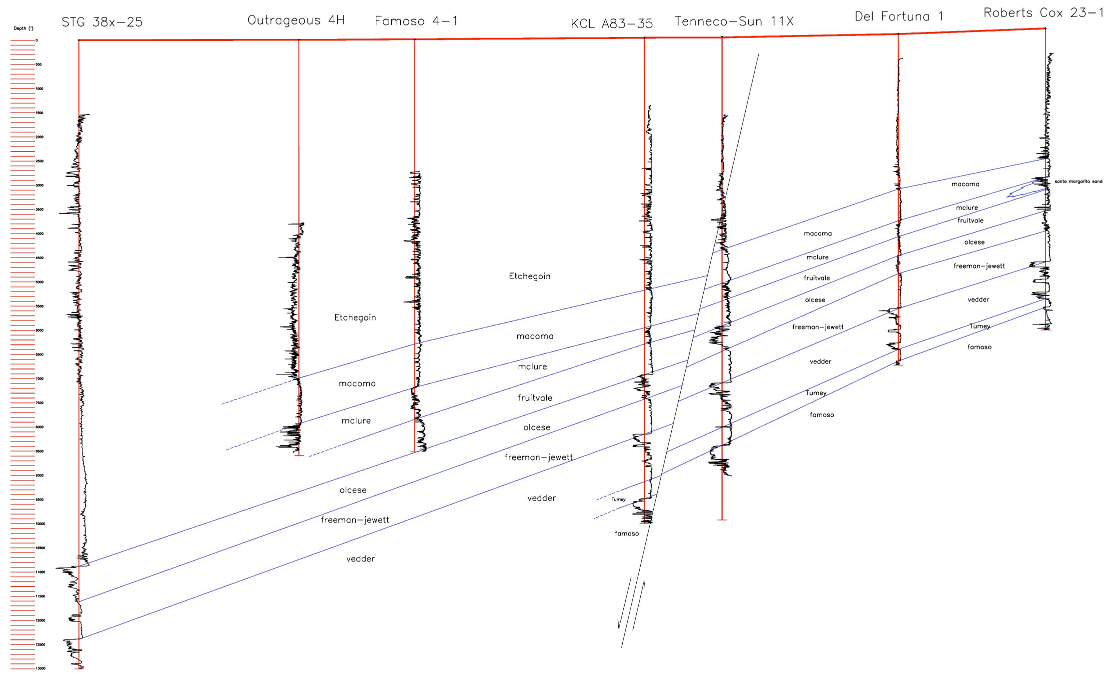

Figure 10. Cross section #2 trends SW-NE, ~7 km north of the power plant (see location in figures 2 and 9). The correlated geophysical logs are SP logs.

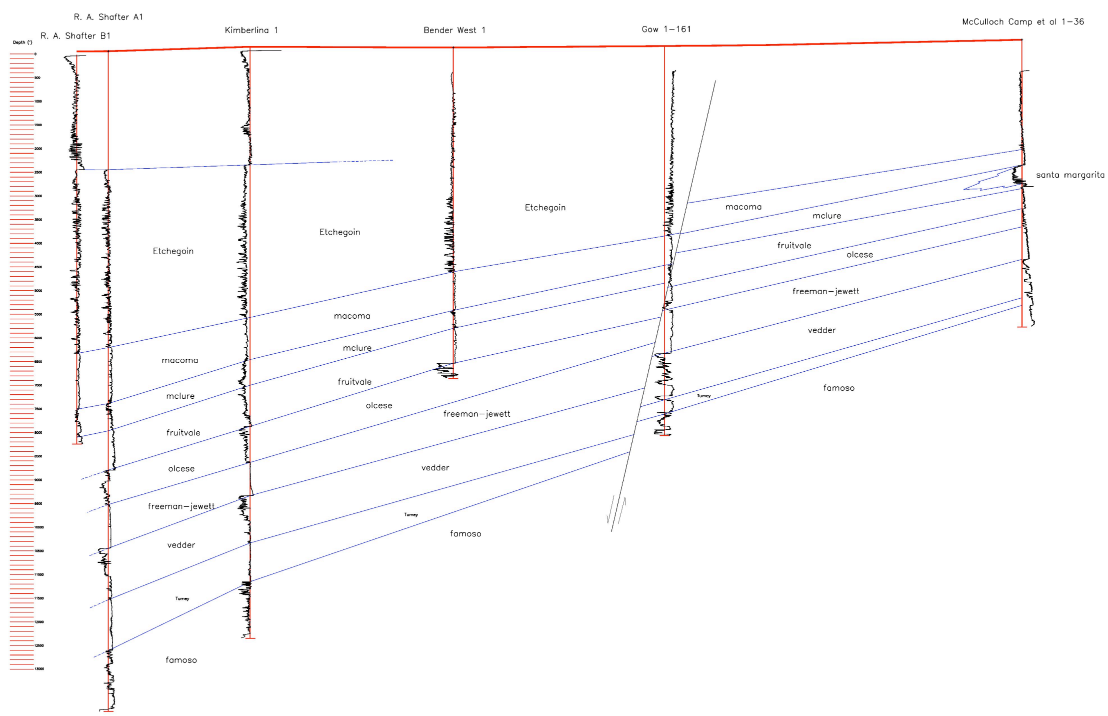

Figure 11. Cross section #3 trends SW-NE and is located south of the power plant (see location in figures 2 and 9). The power plant is located ~1 km north of well Bender West 1.

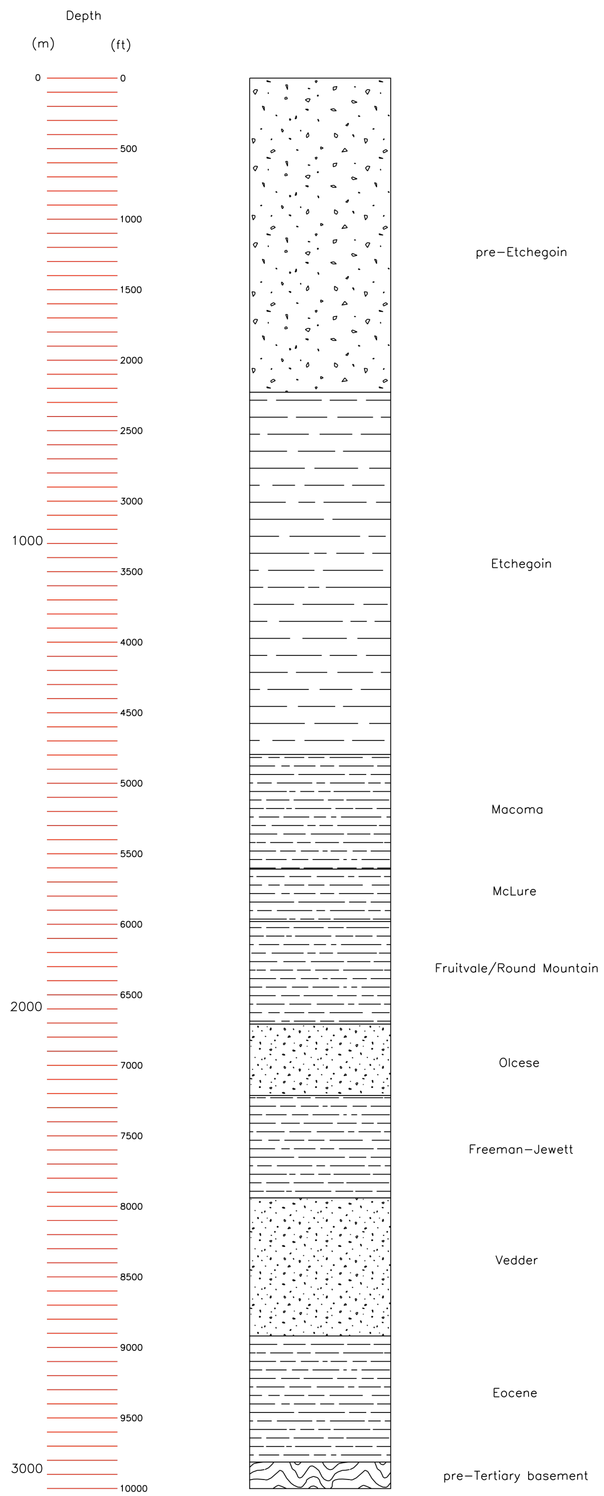

Figure 12. The projected stratigraphic section at the Kimberlina power plant site has been estimated from the 3D geologic model, as well as correlation of nearby well logs.

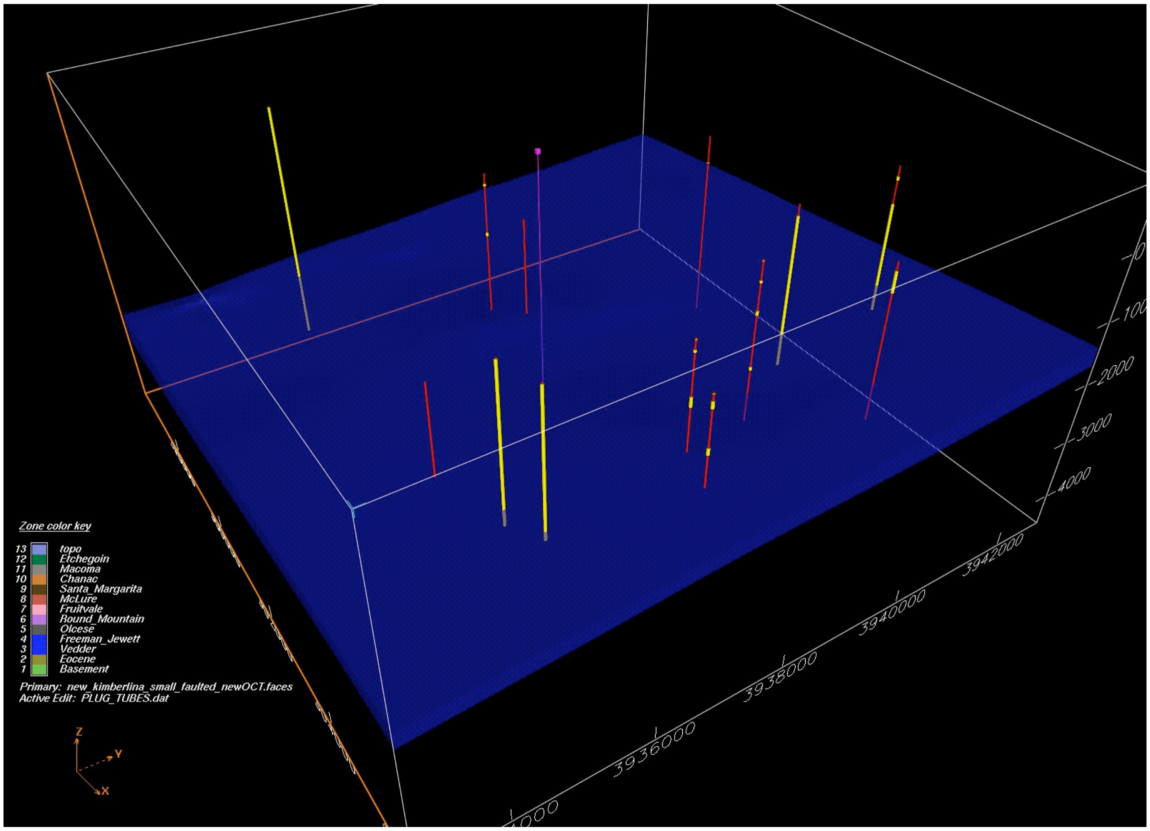

Figure 13. This figure shows the same wells as in figure 9, and shows the boreholes in relation to the Vedder Formation. The Kimberlina power plant is represented by the purple symbol. The yellow areas of the boreholes are plugged by cement. (no vertical exaggeration).

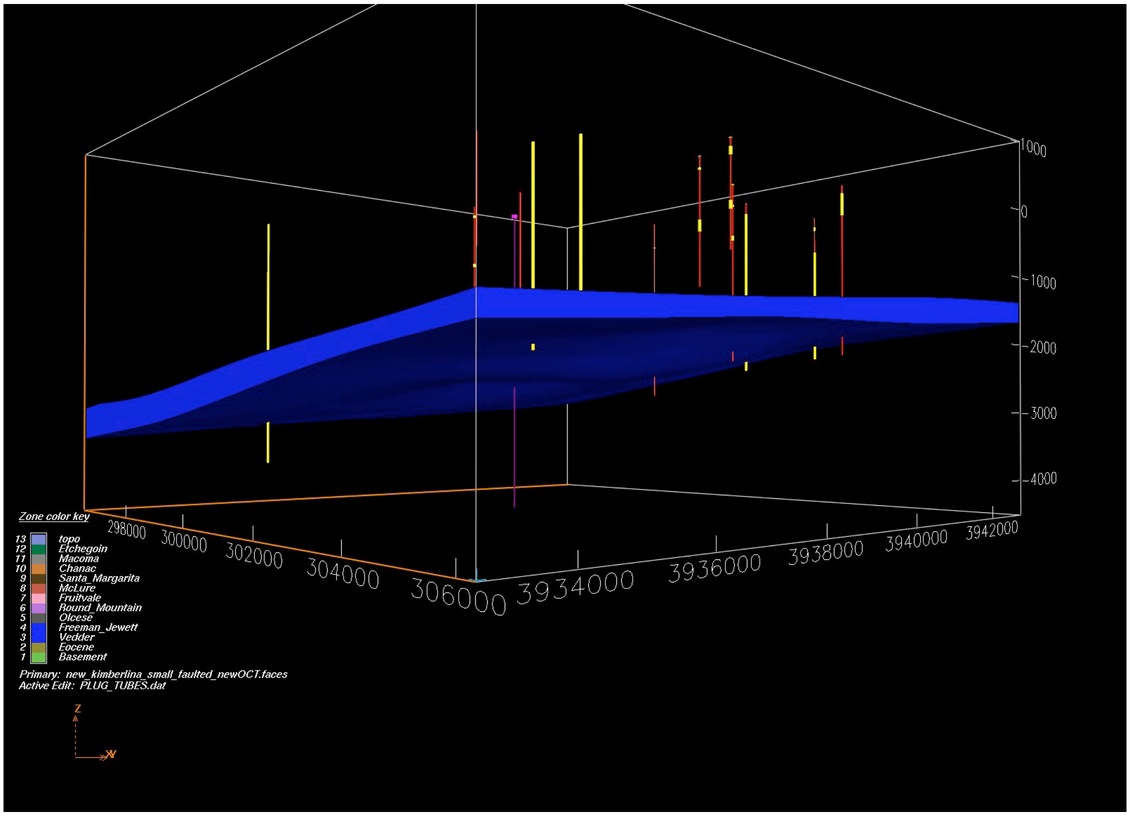

Figure 14. This figure shows the boreholes intersecting the Vedder Formation as in figure 13, but from a different perspective. (no vertical exaggeration).

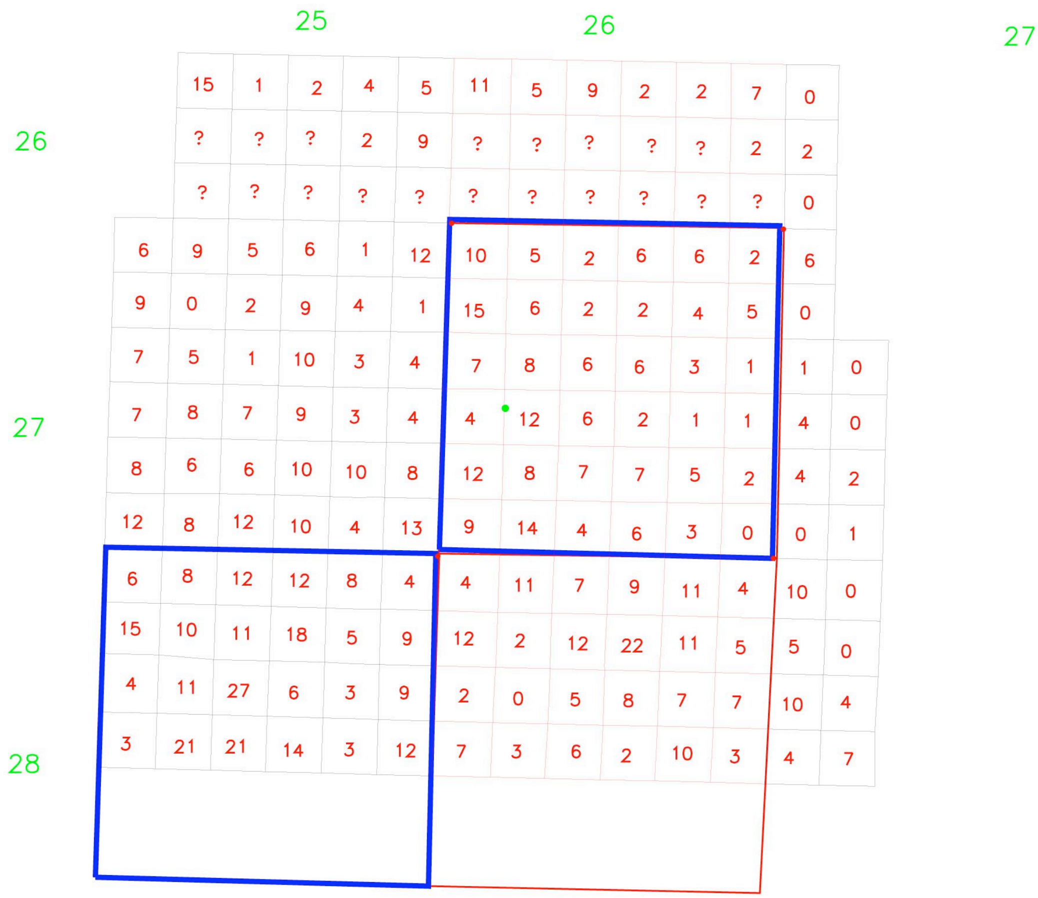

Figure 15. This figure shows the number of DWR water well records in each section near the Kimberlina power plant (green dot in T27-R26). DWR indicates that there may be duplicates, so this number represents the maximum number of water wells ever drilled in each section. Water wells that once existed may be now abandoned.