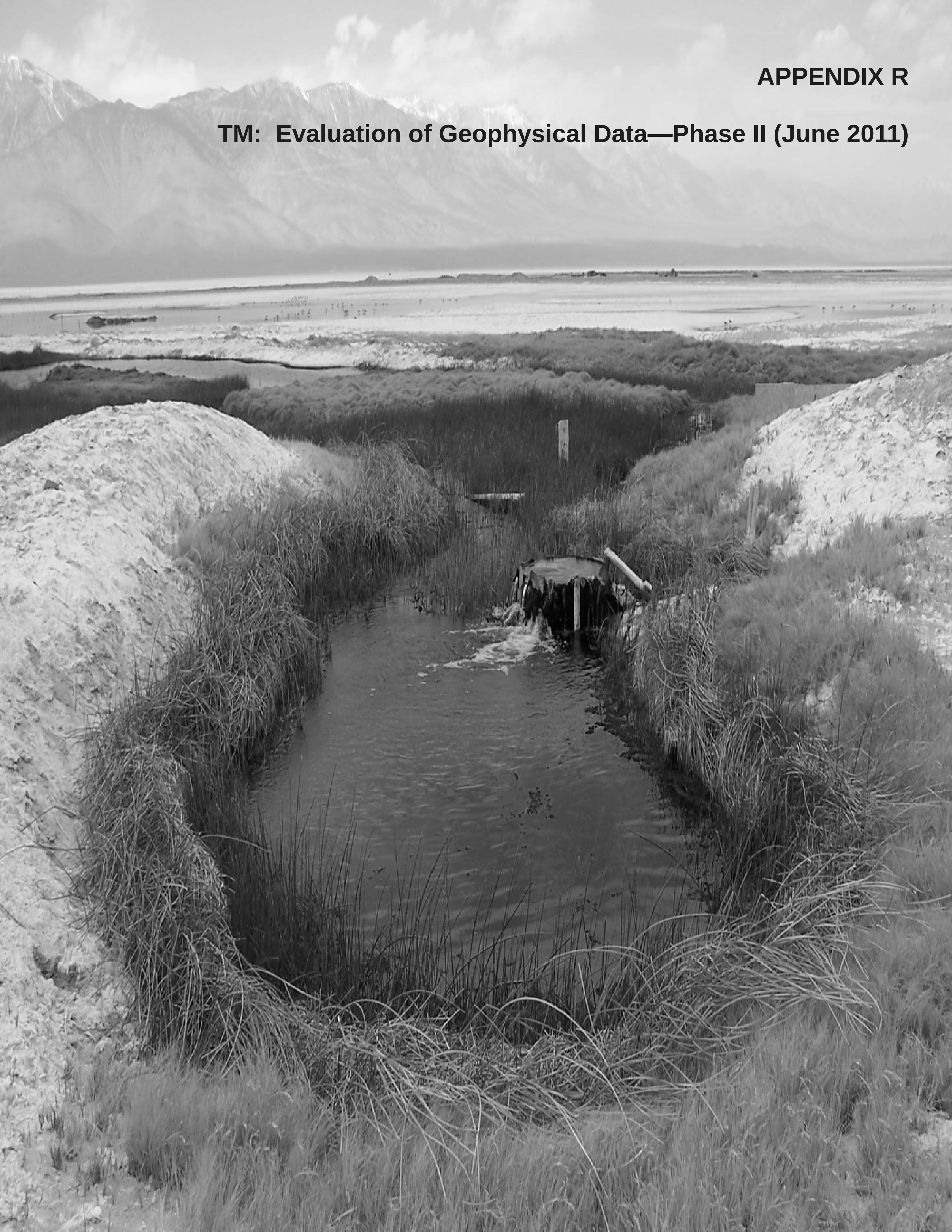
APPENDIX R

TM: Evaluation of Geophysical Data—Phase II (June 2011)



MWH
BUILDING A BETTER WORLD

Technical Memorandum

TO:	*LADWP*	DATE:	*June 2011*
FROM:	*MWH Team*	REFERENCE:	*Task 401.1.9 (II)*
SUBJECT:	*Evaluation of Geophysical Data for Incorporation into the OLGEP*		

EXECUTIVE SUMMARY

The purpose of this Technical Memorandum (TM) is to present the results of the combined Phase I and Phase II evaluation of geophysical data for incorporation into the Owens Lake Groundwater Evaluation Project (OLGEP), which were developed in September 2010 and June 2011, respectively. The location for this investigation is the Owens Lake area from Lone Pine south to Haiwee Reservoir, where ten (10) new deep monitoring wells have been constructed recently as part of the OLGEP project. Eight hydrostratigraphic cross sections were developed to illustrate the structure and hydrostratigraphy of the study area.

This work demonstrated that the combination of seismic data interpretation, borehole lithologic and geophysical data, and surface geologic mapping is a powerful tool for interpretation of the structural geology, depositional history, and hydrostratigrapy of the OLGEP study area. In turn, this data will feed directly into the layering strategy and estimation of hydraulic parameters for the numerical groundwater model. Interpretation of the data leads to the following important conclusions regarding the hydrogeologic conceptual model of the OLGEP study area:

- Employing well-established methods of seismic sequence stratigraphy in combination with borehole information, five (5) discrete aquifers in the delta area of the lake have been identified that are separated in various degrees by aquitards. Correlating units to these five aquifers have been interpreted over the entirety of the lake. The lowermost aquifer is interpreted to be braided stream or floodplain deposits that predate Owens Lake and are greater than 1,500 feet deep in the central portion of the basin. These sequences will be extremely useful in determining model layering surfaces.

- It is important to note that the sequences identified are heterogeneous, with generally increasing grain size or coarseness in a radial direction away from the center of the lake. Aquifers and aquitards identified in the delta area using the seismic sequence boundaries are not expected to have the same hydraulic properties or lithology laterally across the study area. This is because a seismic sequence is essentially a time-stratigraphic unit: a set of facies deposited at the same time and genetically linked by the depositional processes active during that time. Thus, they do not necessarily represent the same hydraulic properties from point to point. Even though the seismic reflections are relatively consistent, the hydraulic properties and lithology are not. Nevertheless, the correlation of sequence boundaries to lithologic and borehole geophysical data shows a strong *relative* correlation of expected hydraulic conductivity.

- The seismic data shows the western portion of the study area to consist of a double plunging, asymmetric syncline with the north-south trending axis near the western shore of the lakebed. The syncline is bounded by faults on the west and east. Faults on the southeast margin appear to be splays of the larger faults terminating against the Coso Mountains.

- While the bedrock interface on the west side of the lake dips steeply (near vertical), more gently shallowing bedrock is observed on the east side of the lake. The synclinal features seen in the sequence boundaries along the west side of the study area are assumed to reflect the underlying form of the bedrock; however, because of its great depth, bedrock cannot be detected by seismic methods in the majority of the western side of the basin. The slope of the bedrock surface on the eastern edge of the basin is displaced in several locations by the Inyo Mountain Front Fault.

- A number of fault zones were mapped in the survey area based on the seismic data. The faults are generally high angle with displacement spread across multiple fault strands rather than a single fault plane. The three largest fault zones are the Owens Valley Fault, Owens River Fault, and the Inyo Mountain Front Fault. They are roughly parallel and trend north-northwest to south-southeast. Other faults intersect the three large fault zones.

- The displacement of aquifers and juxtaposition with relatively impermeable aquitard units allows for qualitative evaluation of the extent to which the faults act as barriers to horizontal groundwater flow. Such an evaluation would not be possible using borehole data alone. This is expected to result in a very significant improvement of previous modeling efforts, which did not incorporate the effect of faulting in any way.

- Interpretation of the depositional history of the basin illustrates sediments deposited before the formation of Owens Lake, followed by at least four transgressive/regressive sequences that record rising and falling water levels in the ancestral Owens Lake. Understanding of the depositional history is a key element for development of representative conceptual and numerical models.

Using the seismic data and structural features, the basin geometry can be mapped with greater precision than would be possible using borehole information alone and the seismic data provides valuable insight in areas where wells do not exist. The relationship between sequence boundaries to subsurface structure presents an obvious method to develop numerical model layering. The results of the geophysics interpretation allow for the correlation of stratigraphic sequences throughout the study area. These improvements directly translate to a greatly improved understanding of the basin and commensurate accuracy and credibility of subsequent numerical modeling.

INTRODUCTION

Under Agreement 47830 between MWH and the Los Angeles Department of Water & Power (LADWP), MWH is conducting the Owens Lake Groundwater Evaluation Project (OLGEP) for the LADWP. The location for this investigation is the Owens Lake area from Lone Pine south to Haiwee Reservoir, where ten (10) new deep monitoring wells have been constructed recently as part of the OLGEP project (**Figure 1a**). The purpose of the OLGEP is to evaluate the feasibility of using groundwater for a portion of the dust mitigation activities on Owens Lake. The project involves compilation of existing hydrogeologic and related data, development of a preliminary conceptual model, identification of data gaps, drilling of monitoring wells and collection of additional field data to fill data gaps, revision of the conceptual model, as well as development and application of a numerical groundwater model.

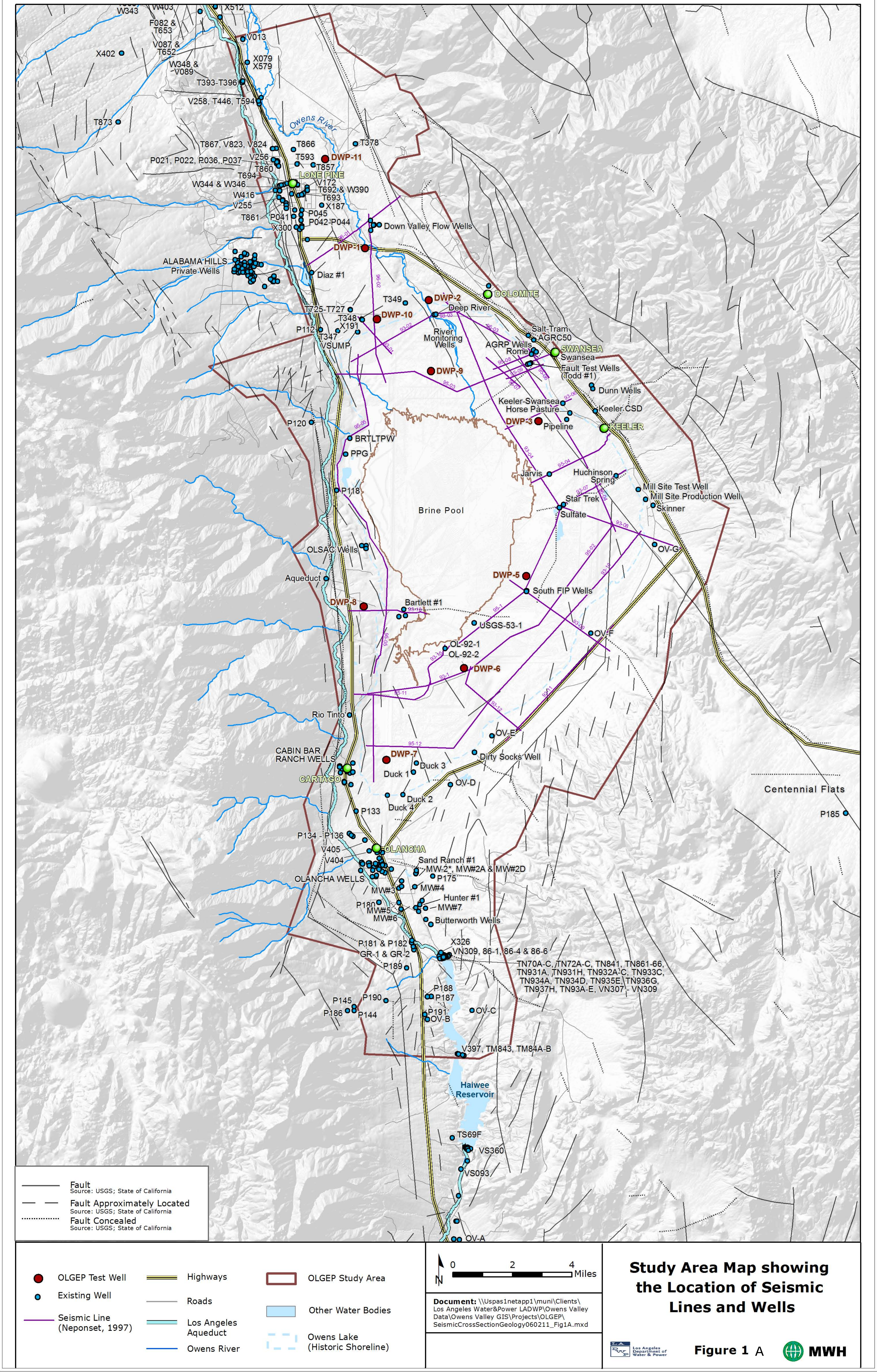
Task 401.1.9 is a subtask of OLGEP, entitled *"Evaluation of Geophysical Data for Incorporation into the OLGEP"* that is divided into two phases. Results of the Phase I pilot study work (MWH, 2010) demonstrated the utility of using seismic data as part of a hydrogeologic investigation and how the data can be used effectively for OLGEP. The Phase I work included two hydrostratigraphic sections that are included as **Attachment A**. The purpose of the Phase II work (documented in this TM) is to utilize the proven methods from the pilot study to analyze all available seismic reflection data in conjunction with drilling information from new wells on the lakebed to provide critical information to improve the understanding of the hydrostratigraphy and geologic structure of the study area.

The purpose of this TM is to describe the incorporation of new data from recently-drilled monitoring wells and re-interpreted geophysical data with existing geophysical, geologic, and hydrogeologic data to provide a detailed interpretation of the hydrostratigraphy. Based on this data, six (6) representative cross sections using Groundwater Modeling System (GMS) software are presented. In addition, three-dimensional surfaces of key geologic horizons over the entire study area were generated. This TM summarizes the results and analysis from Phase II work and also builds upon the results of the Phase I TM (MWH, 2010) by presenting the compiled findings and conclusions of the geophysical study.

BACKGROUND AND STUDY AREA

During the initial compilation of existing data for the OLGEP, seismic reflection data was identified that has the potential to greatly enhance the understanding of the hydrostratigraphy of the study area. The data were acquired for Great Basin Unified Air Pollution Control District (GBUAPCD). Seismic geophysical methods involve the measurement of the reflection of energy (sound) waves artificially introduced at the earth's surface. Typically, this data is collected along a linear deployment of motion sensors (geophones) that record the reflections of a seismic wave originating from a controlled energy source. The result is a two-dimensional image, or profile, in which the reflection patterns result from stratigraphic and structural features.

The study area is the Owens Lake area and underlying groundwater basin. The Phase I pilot study selected a smaller area located at the northern boundary of Owens Lake for initial evaluation of geophysical data. In the larger-scale Phase II study, geophysical and lithologic data from new OLGEP monitoring wells was combined with data from existing wells and geophysical data throughout the study area as shown in **Figure 1a** and **1b** to create six (6) cross sections. The location of the Phase II cross sections are shown on **Figure 1b** (C - C' through H - H'). Note that Phase I cross sections A - A' and B - B' (**Attachment A**) are also shown on **Figure 1b**. Phase I and Phase II cross sections differ in that Phase I cross sections are a direct export from the seismic workstation software, whereas Phase II cross sections were created by transferring the sequence boundaries (elevations) into Groundwater Modeling System (GMS) software to create a solids model.



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Study Area Map showing the Location of Seismic Lines and Wells

Los Angeles Department of Water & Power

Figure 1 A

MWH

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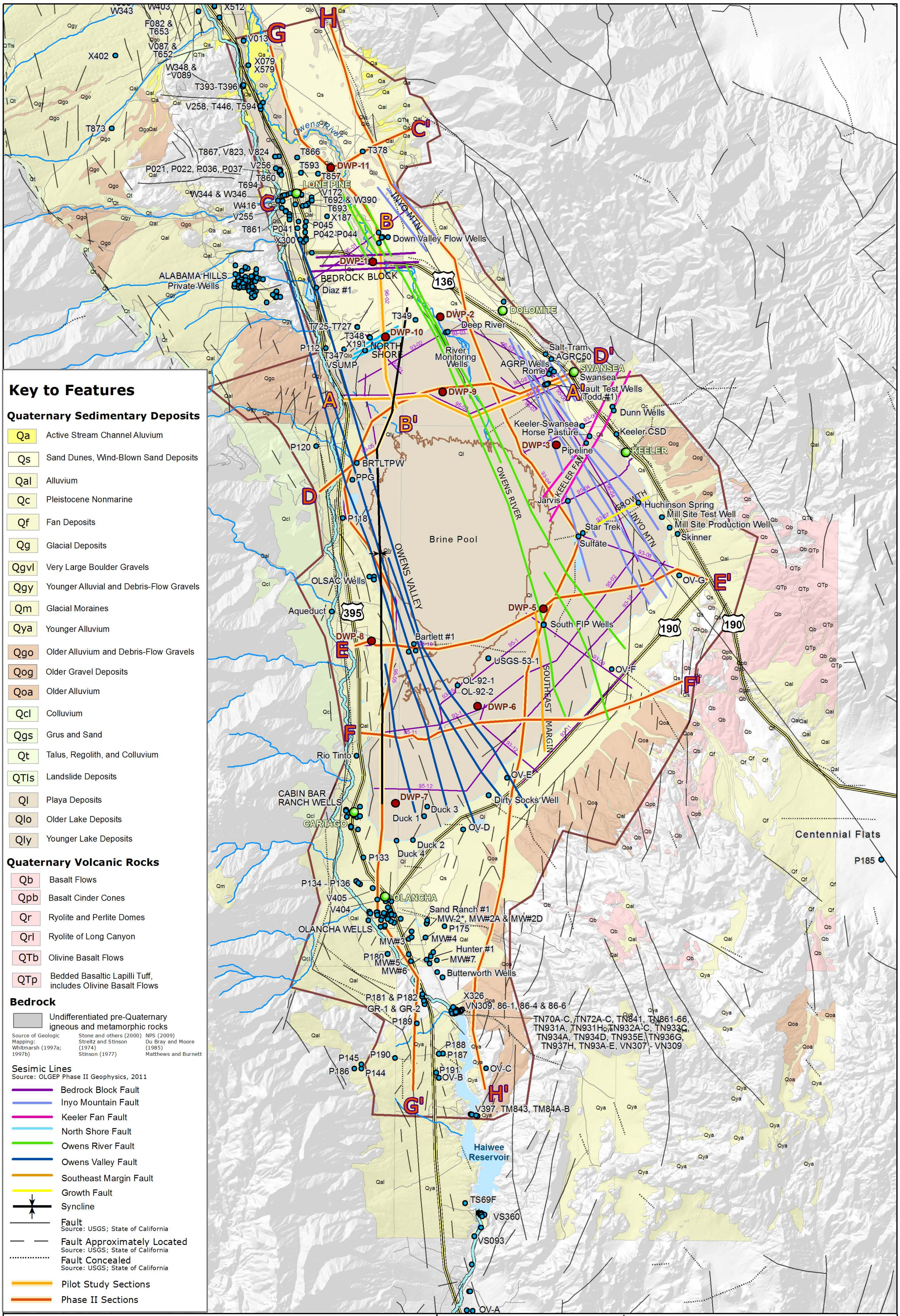

● OLGEP Test Well

● Existing Well

Seismic Line (Neponset, 1997)

Highways

Roads

Los Angeles Aqueduct

Owens River

OLGEP Study Area

Other Water Bodies

Owens Lake (Historic Shoreline)

N

0 2 4 Miles

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Geologic Map Showing Phase I and Phase II Cross Section Locations

Los Angeles Department of Water & Power

Figure 1B

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This map has been designed to print size 11'' by 17''.

SUMMARY OF KEY TERMS

This TM makes extensive use of terminology that may not be familiar to some readers; therefore, a glossary of terms and associated definitions is included as **Table 1**. The seismic line nomenclature and locations are described in more detail in Neponset and Aquila (1995; 1997).

Table 1
Glossary of Terms and Definitions

Term	Definition
Accumulation Space	The amount of vertical space available for accumulation of sediments between the water surface and the bottom of the water body.
Anticline	An anticline is inverted U-shaped or concave downward fold, with sediments that dip away from the center (or axis) of the structure. A plunging anticline is an anticline in which the axis of the anticline dips (is not horizontal).
Common Depth Point (CDP)	Indexing scheme for processed seismic data. Consists of adding the shot point station and the receiver station. For example, CDP station 100 is the sum of all shot/receiver pairings that add up to 100 (e.g.--50/50, 49/51, 48/52, 47/53, etc....). For processed data, the CDP station is equal to 2-times the station location.
CDP Section	A time-domain profile of the seismic data. CDP sections are the most basic data profile that can be interpreted. CDP sections can serve as input into subsequent enhancement processes.
Clinoform	The sloping depositional strata that is commonly associated with sediments prograding into deep water.
Depth Domain	Indicates the vertical scale is in a depth unit, typically feet or meters.
Diffraction	A hyperbolic signature that results from the seismic wave encountering a feature that is smaller than the wavelength of the seismic pulse. In this study diffractions occur at the termination of a reflection horizon, such as the termination of a horizon at a fault.
Facies	Bodies of sediment recognizably different from adjacent sediment deposited in a different depositional environment. Generally, facies are distinguished by what aspect of the rock or sediment is being studied. Thus, facies based on petrological characters such as grain size and mineralogy are called lithofacies, whereas facies based on fossil content are called biofacies.
Field Data, Field Records	Raw field data records of geophone traces from a single shot source. Generally not useful until processed into CDP sections.
Geophone	Sensitive motion detectors that record the ground motion. Sensors provide a voltage output that is related to the velocity of ground movement (not the vertical displacement).
Growth Fault	A growth fault is a type of fault on which there were displacements at the same time as the sediments on either side of the fault were accumulating. Most growth faults are normal faults because such faults cause the basins in which sediments are deposited to subside. A growth fault is characterized by preserving greater vertical thicknesses of sedimentary horizons on the side of the fault that has been thrown down.
Horizon	A laterally extensive geologic feature that is identified in the interpretation as a significant reflection. Generally of stratigraphic origin.
Lacustrine	Refers to “of a lake” or relating to a lake. For example, lacustrine sediments were deposited at the bottom of a lake.
Migrated Section	Time-domain data in which migration has been performed. Input is the CDP section.

Table 1 (cont'd)
Glossary of Terms and Definitions

Term	Definition
Migration	A data enhancement process that corrects the spatial relationship of reflectors in a time-domain section. The process collapses diffraction energy to the originating point. The process repositions, or migrates, structure to the correct spatial position, which is always in the updip direction. Migrated data should be used, whenever possible, for structural mapping and depth conversion.
Oolite	An oolite (or an oolith) is a sphere consisting of several concentric layers of calcite (a form of calcium carbonate) that was created by precipitation in the supersaturated warm tidal waters of shallow water bodies.
Receiver Station, Receiver Location	Station location of the geophones.
Seismogram	A recording or display of a trace or traces.
Seismic Section, Stack Section	Synonymous terms for processed data that is usually presented in 2-way travel time. Sections are generally considered in the time-domain unless specifically referred to as depth-sections.
Stratigraphic Sequence	A stratigraphic sequence is a stratigraphic package of sediments that are depositionally interrelated and bounded above and below be an unconformity or a correlative conformity.
Sequence Boundary	Top or base of a stratigraphic sequence.
Station	A field location that refers to the shotpoint and receiver locations.
Strike and Dip	Strike and dip refer to the orientation or attitude of a geologic feature, such as a fault. The strike line of a bed, fault, or other planar feature is a line representing the intersection of that feature with a horizontal plane. Dip refers to the angle that the geologic feature tilts into the earth's surface.
Shot Point, Source Location	Seismic energy source location.
Synthetic Seismogram	A computed trace generally derived from sonic and/or density well logs. Best used to correlate the seismic waveform of the seismic sections with the lithologic characteristics evident in the well logs. Can also be used to develop a time-to-depth conversion, but not as robust a VSP.
Syncline	A syncline is U-shaped or concave upward fold, with sediments that dip toward the center (or axis) of the structure. A plunging syncline is a syncline in which the axis of the syncline dips (is not horizontal).
Time Domain	Indicates the vertical scale of the data is in 2-way reflection time. Typical units given in milliseconds.
Trace	A time series of seismic amplitudes that are either recorded from a geophone, processed field records, computed from synthetic seismograms or computed seismic models.
Travel Time	The elapsed time between two events, usually the time from the impact of the seismic source and the arrival of the corresponding reflection.
Unconformity	A surface of erosion or non-deposition separating younger strata from older rocks, along which there is evidence of erosion or a significant hiatus of deposition. A correlative conformity is a similar stratigraphic horizon as the unconformity but without evidence of erosion or hiatus.

Table 1 (cont'd)
Glossary of Terms and Definitions

Term	Definition
Velocity Function	The compressional wave, or p-wave, velocity defines the distance a reflected wave travels per unit of time. P-wave velocities generally increase with depth. A velocity function can be used to convert between time domain to depth domain.
Vertical Seismic Profiles (VSP)	A well survey used to obtain seismic transmit times and develop a velocity function. Typically uses geophones placed at known depths and a surface seismic source. Transmit times to each depth is a one-way time measurement, and is doubled to determine the two-way travel time used in time sections. Data allows computation of a time-to-depth conversion of seismic sections. Results in the bulk, or average, velocity from surface to a specified depth; in contrast, a sonic log measures velocity across a specific depth interval in the well. VSP's do not provide specific correlation with subsurface bedding, aquifers, or other features unless the geophone is specifically placed at that depth.
Wiggle Trace	A display presentation method in which the data are plotted as positive and negative amplitudes from a central zero line.
Wiggle Trace Variable Area (WTVA)	A display presentation method in which either the peak (positive excursion) or the trough (negative excursion) are shaded to enhance visual perception of lateral continuity.
Wiggle Trace Variable Density (WTVD)	A display presentation style where trace peaks and troughs are shaded. Similar to WTVA (above) except shading can be a variety of colors, and color shade or intensity can relate to the amplitude of the peak or trough.

HISTORY OF THE SEISMIC REFLECTION PROJECT AT OWENS LAKE

The seismic reflection data at Owens Lake were acquired by Neponset Geophysical Corporation and Aquila Geosciences, Inc. (Aquila) at Owens Lake, Inyo County, California, for GBUAPCD. A total of about 120 line-miles of data were collected in the period of 1992 through 1997 as part of the Deep Aquifer Characterization Project conducted by GBUAPCD. The objective of the seismic reflection program was to develop an understanding of the geologic history of the Owens Lake sedimentary basin. The seismic work was conducted in four (4) phases, each complementing the previous phases.

- **Phase 1** tested the viability of the seismic reflection method for characterizing the subsurface beneath the dry lake bed.

- **Phase 2** (Neponset and Aquila, 1995) acquired a loose network consisting of about 50 line-miles of seismic data covering the area around the north, northeast, and southeast portions of the dry lake bed. Vertical Seismic Profiles (VSP) were acquired in five (5) wells, resulting in direct time-to-depth measurements that facilitates the integration of the well and seismic data. The interpretation of this data demonstrated that the sedimentary basin underlying the dry lake bed has had a complex structural history. However, data coverage was not dense enough to definitively map the structure of the basin or to develop a good stratigraphic interpretation of the sedimentary sequence underlying the dry lake bed.

- **Phase 3** was designed based on the results of the Phase 2 work. An additional 48 line-miles of seismic data extended coverage around the entire circumference of the dry lake bed. In addition, several closed loops were constructed in the southeastern and northern part of the dry lake bed. Closed loops are required to make an internally consistent interpretation of seismic reflection data in a manner that is conceptually similar to land surveyors using closed loops to determine the quality of a survey. In addition to the seismic reflection data acquired during this phase, VSP's were acquired in new wells on the lake bed. Synthetic seismograms were constructed using digital sonic logs run in the new wells, whereby synthetic seismograms provided correlation between the lithologic logs and the reflection character evident in the seismic sections.

- **Phase 4** was designed based on previous work. A total of 20 line-miles of seismic data were acquired. Seismic coverage was extended north toward Lone Pine, and a number of closed loops were constructed on the northeast side of the dry lake bed.

Despite the extensive nature of previous geophysical work conducted, there still remained some unresolved issues that need to be addressed prior to the use of the geophysical data for the OLGEP project. These issues include:

- The focus of the original interpretations was determined by the goals and objectives of the GBUAPCD's Deep Aquifer Characterization Project. The OLGEP goals and objectives are substantively different, and many geologic issues were not adequately evaluated in previous work. Examples of geologic features not previously interpreted (but evaluated for OLGEP) include mapping of aquitard thicknesses, identification of faults that juxtapose aquifers and aquitards, and identifying structural zones that may act as barriers or potential preferential pathways of groundwater flow.

- The Phase 3 and 4 interpretation was understood to be incomplete because the relative paucity of well information did not allow a full interpretation. Geologic features, such as smaller fault networks and stratigraphic detail were not identified because the confidence in those interpretations could not be quantified without additional wells. The recently-drilled OLGEP wells provide the data needed to more fully develop the interpretation.

- Technological improvements allow a more in-depth evaluation. The workstation tools currently available are significant improvements over previous tools. The improved technical rigor and efficiency allows for a more in-depth analysis of specific features.

- Current tools facilitate integration with other disciplines and software used in the OLGEP. The visualization capabilities of modern software allow the seismic and well data to be tightly integrated and displayed so the three-dimensional configuration of the basin as well as the interrelationship of the geologic structure, and stratigraphy can be easily displayed. The results can also be readily exported to industry-standard GIS and gridding/contouring packages to efficiently facilitate integration of the data into the numerical groundwater model.

APPROACH

The Phase II evaluation of geophysical data for incorporation into the OLGEP consisted of six (6) generally sequential subtasks as described below:

- **Subtask 1 - Retrieve and Load Data**. This subtask was completed using the Seisware Seismic Interpretation Workstation from Seisware International, Inc. Survey locations for the stations were reviewed and merged with the seismic data using the Seisware software. Well locations, logs, and interpreted aquifer tops and bottoms were also input into the system. The location of geophysical data used in this study is shown in **Figure 1**.

- **Subtask 2 – Interpret Well Logs and Generate Synthetic Seismograms**. Well logs were interpreted by project hydrogeologists and geophysicists, and these interpretations were correlated across the study area using the seismic data. The well log interpretations were revisited throughout the task as additional information was derived from the seismic data. The iterative nature of the review and interpretation ensured that the well information and seismic interpretation coalesced to form an internally consistent interpretation.

  A synthetic seismogram (or synthetic) is a computed seismic trace that is calculated from either a sonic log, density log, or (ideally) both. A synthetic is compared with the seismic data in order to tie the seismic data to the well information. The strength of this analysis is the correlation between reflection character and lithologic character, which is necessary to allow projection of well data and interpretations along the seismic profiles. The analysis also permits a time-to-depth conversion at the well location. At Owens Lake, sonic logs are available in five of the GBUAPCD wells and all of the deepest OLGEP wells. **Table 2** shows the wells used in this interpretation, total depth, and the data used to correlate with the seismic data.

  Figure 2 shows an example of a correlation between seismic data and the computed synthetic seismogram at the Todd #1 Well. The Todd #1 well is the deepest of the wells at an area that is referred to as the “Fault Test Site” (Sierra GeoSciences, 2002). A vertical seismic profile (VSP) is available at the Todd #1 well and was used, in conjunction with the synthetic, to determine the time-to-depth conversion at the Todd #1 Well.

  As shown on **Table 2**, the recently-completed OLGEP wells significantly increased the number of monitoring wells with digital logs that could be tied to the seismic reflection data. In addition, OLGEP wells are much deeper than most existing data (typically 1,500 to 1,600 feet), allowing for more correlations with depth than previously available. MWH also digitized the Bartlett #1 paper log for use in interpretation. The result is an increase of 5 to 15 well locations with digital logs, and combined total depth of wells with digital logs increased from 4,246 linear feet to 24,897 linear feet. This increase in available correlations is the fundamental basis for the significant improvement in the interpretation of the existing seismic data.

- **Subtask 3 - Develop Seismic Interpretation in Time Domain**. Seismic data is collected by measuring the amount of time it takes for sound waves to reach a particular geophone. Therefore, the data is originally analyzed in what is called “time domain”. The seismic interpretation focused on:

  - <u>Boundaries of Stratigraphic Sequences</u>. A stratigraphic sequence represents a set of facies deposited contemporaneously and whose deposition is genetically linked by the processes active at that time. Seismic reflections, therefore, are the products of sedimentation processes, and the three-dimensional pattern of seismic reflections is principally of geologic origin. In practical terms, a sequence boundary is a reflection horizon that is areally extensive and forms a boundary between successive depositional episodes. Reflections within the sequence can show depositional patterns that provide insight into the facies, and correlations at wells allow borehole data to be extrapolated laterally, taking depositional processes into account.

Table 2
Summary of Well Data Used in Seismic Interpretation

Well Name	Drilled by	Total Depth	Seismic Horizon Reached[1]	Logs	How used in Seismic Interpretation
River Site	GBUAPCD	595	Lt Blu Base	Paper	VSP[2] data and well tops from log interpretation used for correlation
Keeler Swansea	GBUAPCD	390	Brn	Paper	VSP data and well tops from log interpretation used for correlation
OL92-2	USGS and GBUAPCD	1,059	Dk Grn	Paper	Well tops from log interpretation used for correlation[3]
South FIP	GBUAPCD	902	Org Base	Digital	Correlation of synthetic seismogram[4]
Star Trek	GBUAPCD	800	Brn	Digital	Correlation of synthetic seismogram
Fault Test-Todd #1	GBUAPCD	734	Brn	Digital	Correlation of synthetic seismogram
Down Valley Flow Test – South Pad	GBUAPCD	752	Org	Digital	Correlation of synthetic seismogram
Down Valley Flow Test – North Pad	GBUAPCD	1,058	Dk Grn Base	Digital	Correlation of synthetic seismogram
Bartlett #1		6,929	Brn	Paper-Digitized[5]	Correlation of synthetic seismogram
W416	LADWP	562	Brn	Digital	Correlation of synthetic seismogram
DWP-1	LADWP-OLGEP	1,504	Brn	Digital	Correlation of synthetic seismogram
DWP-2	LADWP-OLGEP	1,534	Brn	Digital	Correlation of synthetic seismogram
DWP-3	LADWP-OLGEP	1,005	Brn	Digital	Correlation of synthetic seismogram
DWP-5	LADWP-OLGEP	1,503	Brn	Digital	Correlation of synthetic seismogram
DWP-6	LADWP-OLGEP	1,506	Brn	Digital	Correlation of synthetic seismogram
DWP-7	LADWP-OLGEP	1,500	Brn	Digital	Correlation of synthetic seismogram
DWP-8	LADWP-OLGEP	1,500	Org	Digital	Correlation of synthetic seismogram
DWP-9	LADWP-OLGEP	1,604	Brn	Digital	Correlation of synthetic seismogram
DWP-10	LADWP-OLGEP	1,504	Brn	Digital	Correlation of synthetic seismogram

Note*:* DWP-11 was also utilize in the subsurface interpretation, but was not directly correlated to the seismic data because it is several miles away from the nearest seismic line.

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[1] In this geophysics study, seismic horizons are identified by color (see **Table 3** presented in "Seismic Interpretation" section). Reflection horizons are the result of geologic features, such as lithologic contrasts, unconformities, conformal conformities, structural features, and so forth. Reflections may not represent the same lithology across the study area; therefore, reflections are referenced by color as opposed to the correlative geologic name as a means of distinguishing from the actual geologic unit and the apparent correlative seismic response.

[2] VSP-Vertical Seismic Profile.

[3] A VSP was acquired at OL92-2 and the South FIP wells; however, anomalously low seismic velocities were identified in clayey zones and are attributed to methane coming out of solution due to the release of pressure in the immediate vicinity of the well bore.

[4] A Synthetic Seismogram (or Synthetic) is generated by computing the expected seismic response from a sonic log.

[5] Paper Log was digitized as part of the OLGEP project.

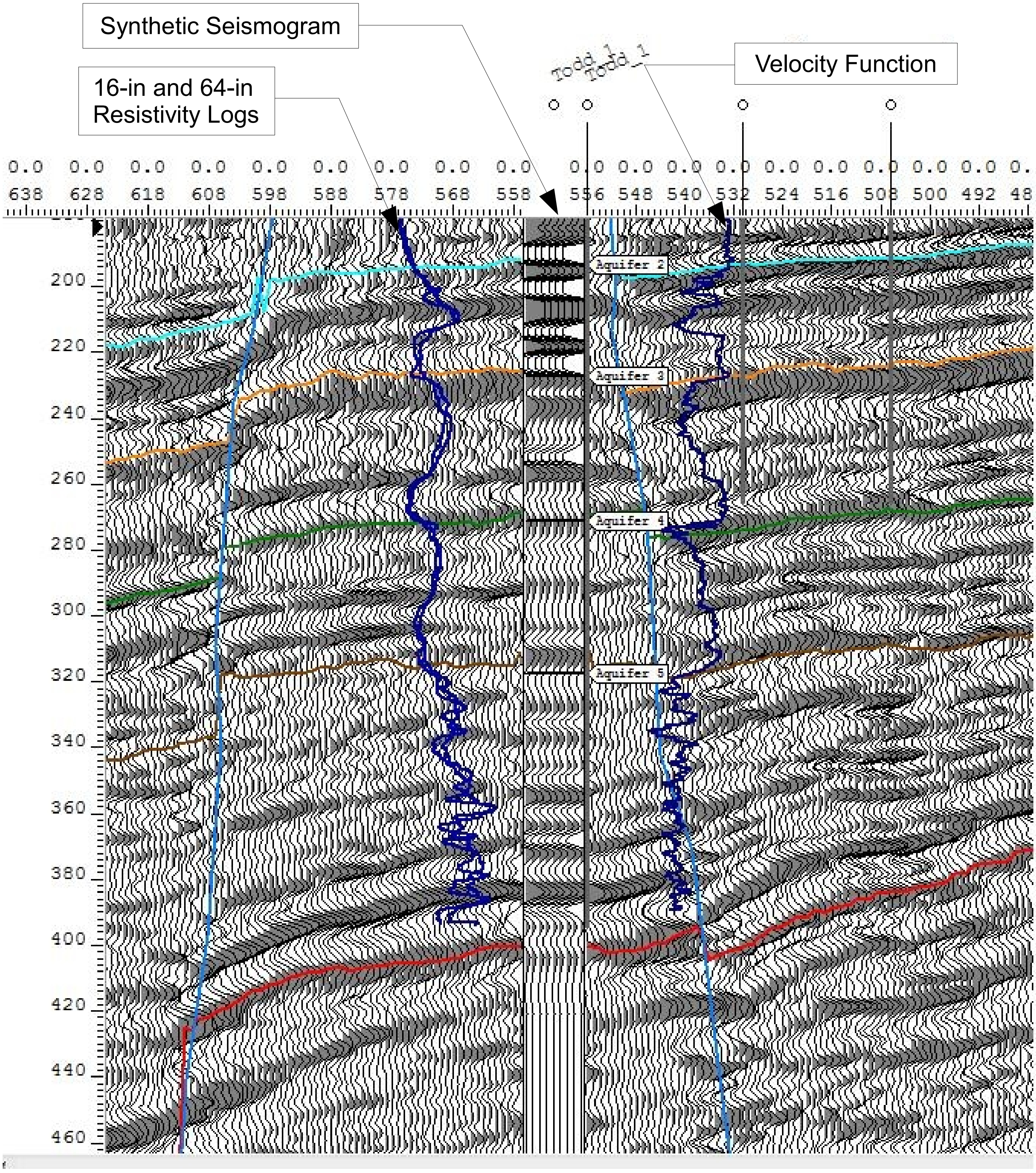


Figure 2: Synthetic seismogram generated at the Todd #1 well. Synthetic is computed from the sonic log (not shown). A wavelet extracted from 170 to 325 ms was used to compute the reflection response for the synthetic seismogram (shown center). The primary zone of focus at the time of this screenshot was 180 to 320 ms. 16-in and 64-in resistivity logs are included to the left for lithologic correlation. The resulting velocity function is shown to the right of well. Display format is Wiggle Trace Variable Area (WTVA).

- Structural Deformation Consisting of Folding and Faulting. Owens Lake is located in a strike-slip pull-apart basin, and the faulting tends to be high angle (Johnson et al., 1999). Vertical displacement along these faults was estimated from the depth sections. However, in a strike-slip basin, faults may be hydraulically significant but may not have significant vertical offset. Seismic reflection data can be used to map faults and fractures that have little or non-existent vertical offset. These faults and fractures can play a significant role in groundwater modeling. Common depth point (CDP) sections were used to identify diffraction patterns that occur at faults, and then the location of the faults were transferred to the migrated sections.

Figure 3 presents an example of a seismic section from the eastern margin of the study area, showing the interpreted layers and fault structures. **Figure 3** also contains a well with digital logs (DWP-3) and without digital logs (Keeler-Swansea). Annotated versions of all seismic sections were generated in digital format and uploaded to the project SharePoint site.

The quality of an interpretation is determined by its internal consistency. Internal consistency is characterized by three evaluations:

- Tying to direct data. The seismic data should tie with all wells such that specific geologic horizons contiguous between wells, such as aquifers or bedrock, project correctly and tie at all wells.

- Tying the seismic data along loops. Wherever the seismic data forms a closed polygon, or loop, the interpreted horizons must track around the loop and terminate at the same horizon. All available loops must be honored in the interpretation in order for the interpretation to be considered internally consistent.

- Consistency with structural and stratigraphic styles. The geologic structure and stratigraphy shown in the interpretation should be consistent with the known geologic setting. For example, an interpretation becomes problematic when the mapped faulting is typical of structural compression but the area is known to be in structural tension.

An interpretation becomes robust when all wells are tied to the seismic lines, and all of the seismic lines are tied together in a manner that is consistent with the structural and stratigraphic styles of the study area. In this study, all loops were tied for all mapped horizons. As a result, the confidence in the well log interpretations is very high, and the confidence in the well-to-well correlations between wells is also considered to be very high.

- **Subtask 4 - Generate Grids and Conceptualize Geology**. The interpreted seismic data measure the vertical dimension (depth) in terms of two-way reflection time. Wells measure depth in feet. The velocity profiles, determined at the wells by either synthetic seismograms or VSP's, create a time-to-depth relationship at the wells. Wells in which data are available are identified in **Table 2**.

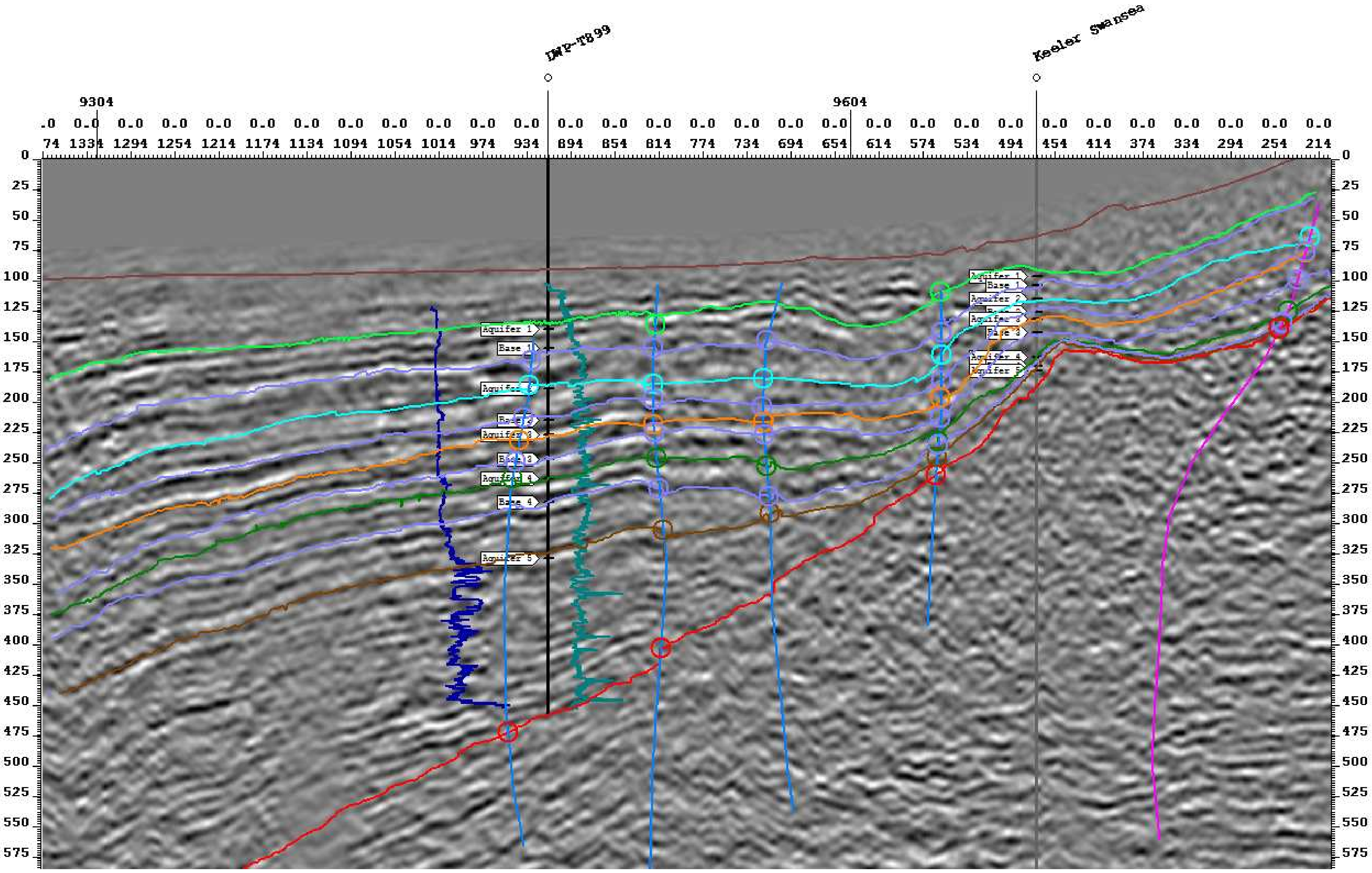


Figure 3: Interpreted Line 93-06 with DWP-3 and Keeler-Swansea wells. DWP-3 reached bedrock, allowing interpretation of the bedrock surface. Guard log (blue) and Natural Gamma log (light blue) are shown next to the well location.

Abrupt or erratic changes in layer thickness can cause instability in a groundwater model. Therefore, the project team focused on a gridding/contouring approach designed to minimize the occurrence of erratic changes in thickness while maintaining accuracy with the known geologic information. The project team determined to allow gridding/contouring surfaces to continue through vertical fault offsets, effectively smoothing the structural effects of faulting. The geologic rationale is that, while faults were found that juxtaposed aquifers and aquitards, the lateral extent of that offset appears to be limited. This concept is discussed more fully in the section on structural geology. Minimum curvature gridding was selected by the project team to generate the smoothest possible surface while maintaining accuracy of the input control points.

The time-depth data from the seismic sections was used to develop a three-dimensional grid surface for each mapped horizon. The grids used a 50-meter node spacing, and depth is measured in milliseconds two-way travel time. Following gridding, the surface was then projected back onto the seismic section to evaluate the degree of smoothing caused by the minimum curvature algorithim (**Figure 4**). **Figure 4** (left side) shows the Org horizons (shown in orange) intersecting a high-angle fault, whereas the right side of **Figure 4** shows the same data, but with the projected horizon from the gridded data overlain (shown in red). Note the red horizon accurately tracks the Org input, smoothing the input data, particularly across the fault. The gridding parameters selected effectively smooth the data while maintaining accuracy at the level of resolution anticipated for the numerical groundwater model.

Gridding seismic data provides unique challenges. Data are densely spaced along the seismic line (in this case, every 12.5 feet or 3.8 meters), but the lines can be miles apart. So the data is a combination of sparsely distributed datasets, yet each dataset contains spatially dense data points. As stated previously, the minimum curvature algorithim creates a surface that honors the input data as closely as possible while creating a surface that has the minimum amount of curvature. The potential exists in the “blank areas” between seismic lines that successive layers may have slightly different flexure in the computed surfaces. This will cause anomalous thinning or thickening of the layers when, in fact, there is no data supporting the variability. In other words, layer thickness anomalies could be an artifact of the gridding algorithim and the spatial distribution of the data.

Any gridding algorithim attempts to approximate values across grid nodes that do not have data points. The method to interpolate values is what differentiates each gridding algorithim. The goal here is to minimize the impact of gridding artifacts on the data. Using a simplified scenario to illustrate this point,

- Assume that a gridding algorithim creates a fixed error, say ±5 percent, due to interpolation across a no-data area, such as the center of a loop of seismic lines.
- If the depth of the horizon is 600 feet, then the depth error is approximately ± 30 feet.
- If the next deeper horizon is 700 feet, then the depth error is ±35 feet.
- The layer thickness in this hypothetical example should be 100 feet thick; however the error caused by the gridding algorithim causes the thickness to vary from 35 feet to 170 feet.

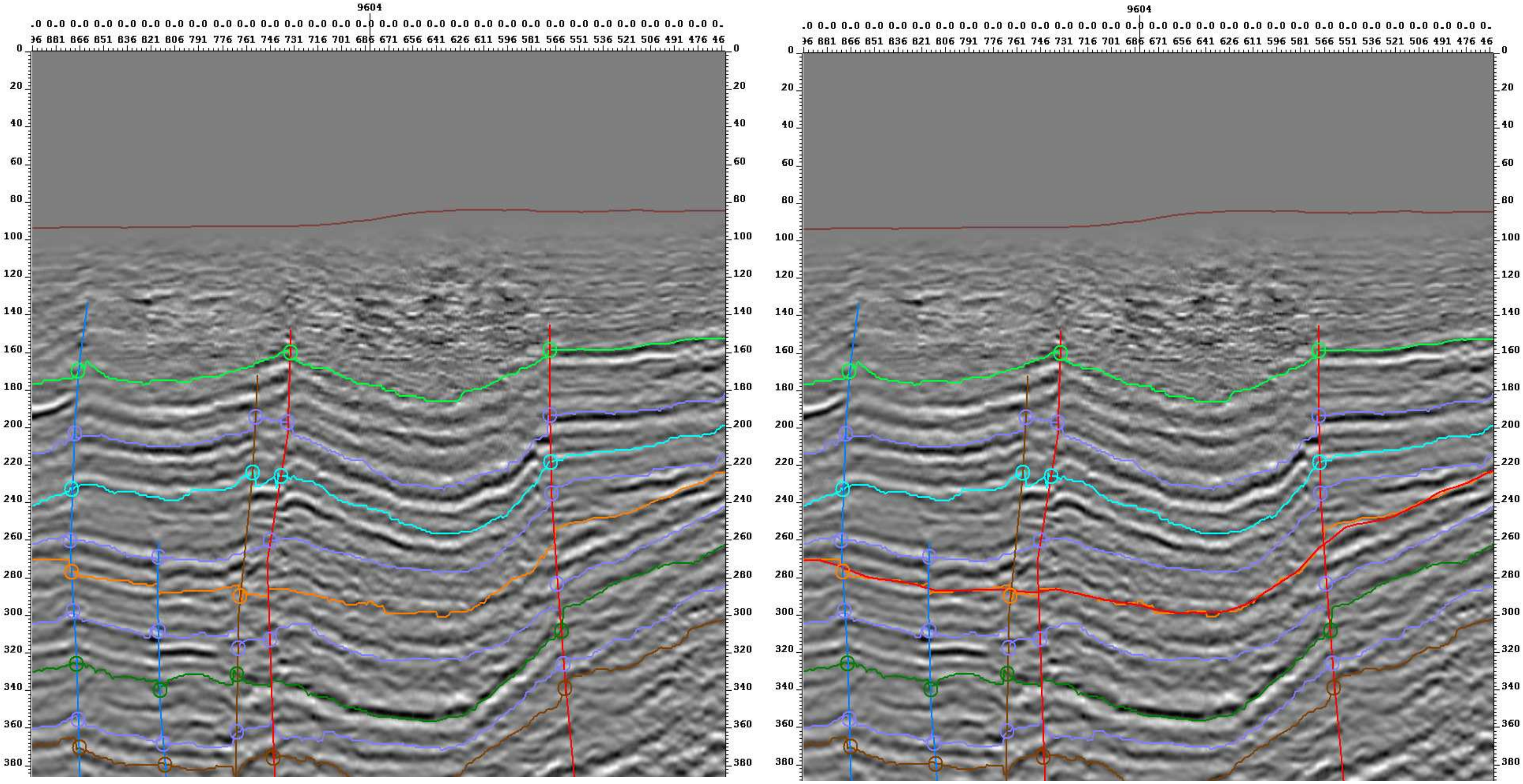


Figure 4: Analysis of smoothing caused by gridding operation. Data input for the ORG horizon Was used in the gridding process as shown on left. Data were gridded using 50-meter nodes, and the resulting surface projejct onto the section (shown right). Note the gridded surface closely approximates the input data

The solution is to develop grid maps of the layer thicknesses directly. Using a parallel example, if the layer is 100-feet thick and the error range is 5 percent, then the range computed by the gridding algorithm would be 95 to 105 feet. Grid models for each layer were generated by:

- Generating a velocity function grid for each surface based on the velocity functions developed at each well.
- Converting time-depths to depths in feet along each of the seismic lines. The velocity grid was used to compute the depth (in feet) of each layer on each seismic profile.
- Determining the thickness of each layer by the difference between depths of successive layers. For example, the Lt Grn layer thickness is determined by subtracting the depth of the Lt Grn from the Lt Grn Base depth. This provided a layer thickness for each layer at each station along the seismic line.
- Gridding the thickness values for each layer, and contouring to create isopach maps. **Figure 5** provides the isopach map of the Lt Blu layer.
- Computing the elevation grid of the Lt Grn horizon, which is the shallowest horizon mapped. The elevation of the top horizon (Lt Grn) was computed directly from the seismic sections and velocity function.
- Computing the elevation of each successively deeper layer. The thickness of each layer was subtracted from the corresponding horizon to determine the elevation grid of the top of the next boundary. **Figure 6** shows the elevation contour map of the Brown horizon, which is the deepest mapped horizon.

All gridding was completed using minimum curvature algorithims. The benefit is that errors in layer thickness due to the gridding algorithim and spatial geometry of the data are minimized. The downside is that thickness errors could cumulatively add to create depth error, and that errors in shallow layers could then be projected onto successively deeper layers. The project team determined that this trade-off resulted in the best overall approach to support future construction of the numerical groundwater model.

- **Subtask 5 - Create Depth Sections**. In this subtask, the time-domain cross sections produced in Subtask 3 were used to conceptualize folding, faulting, and stratigraphic interactions such as thickening or thining of the aquifers. In the meantime, x, y, and z files generated in Subtask 4 tie each of the selected horizons to an elevation. Six (6) cross sections were constructed using GMS software in which the elevation of each top and bottom of each aquifer depicted to illustrate key hydrogeologic features (**Figures 7 - 12**). Cross section locations are shown on **Figure 1b**.

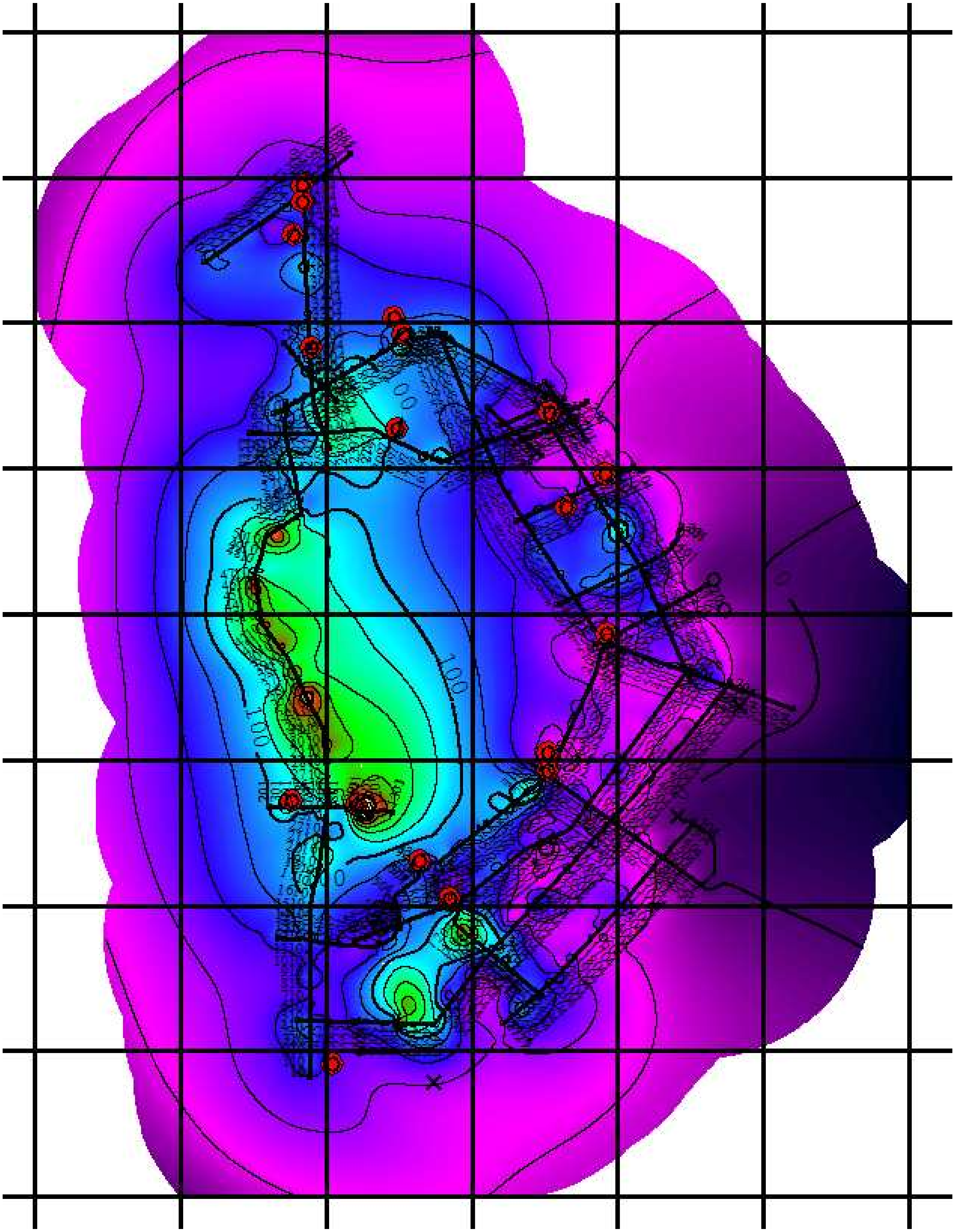


Figure 5: Example isopach map for the Lt Blu sequence. Contour interval is 20 feet.

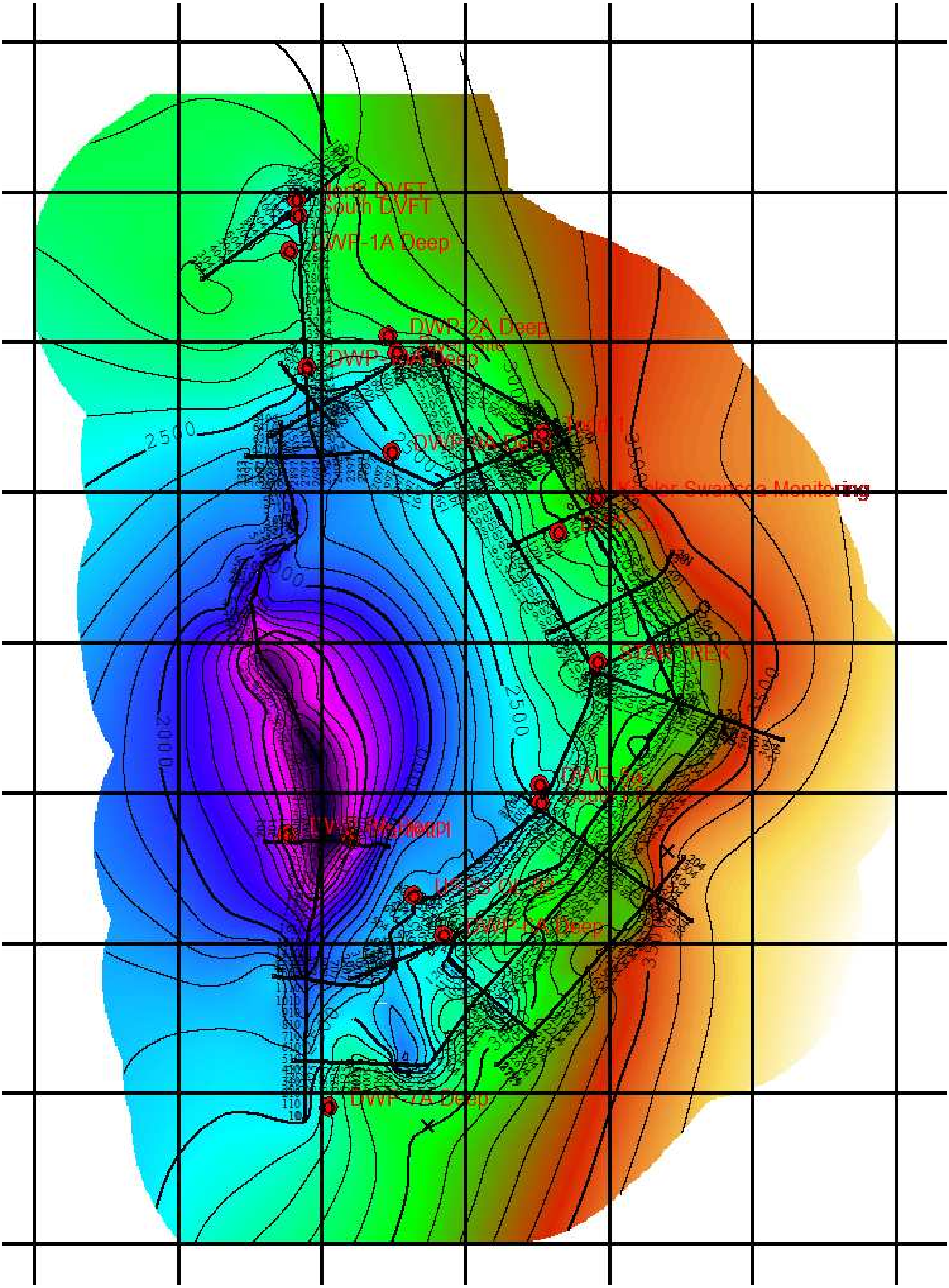


Figure 6: Example depth grid for the Brn horizon. Contours are elevation in feet AMSL. Contour interval is 100 feet.

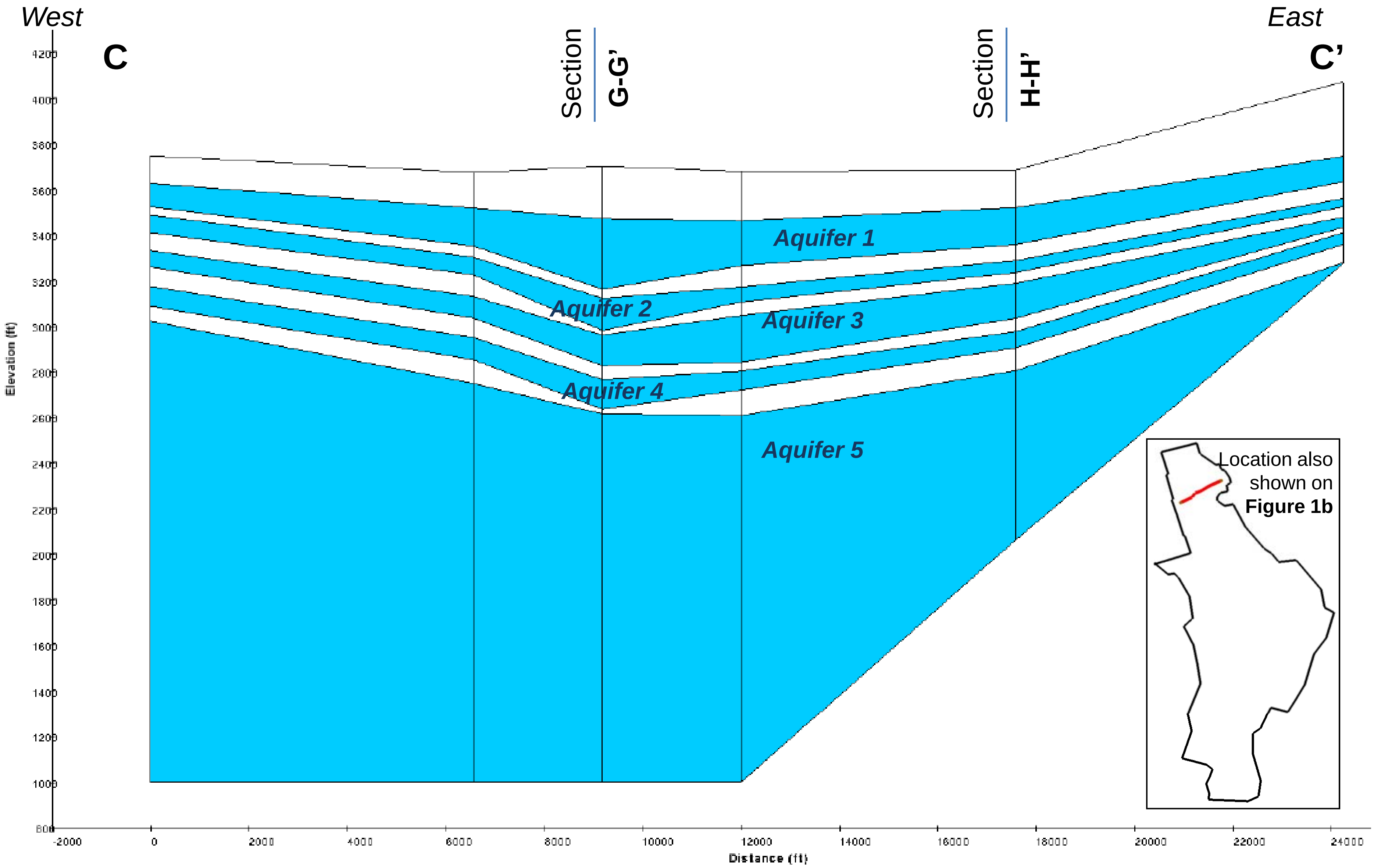


Figure 7
Cross Section C-C'

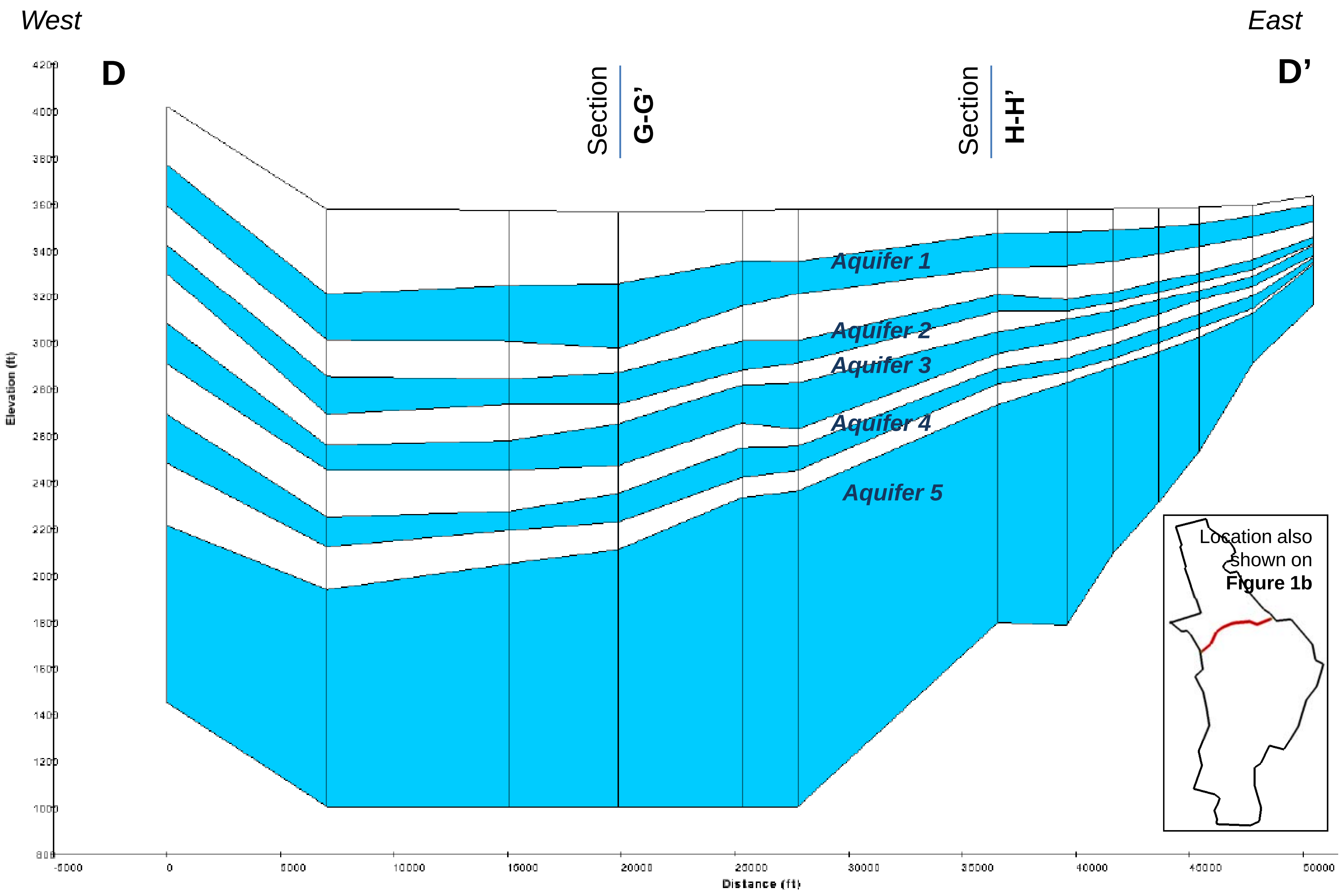


Figure 8
Cross Section D - D’

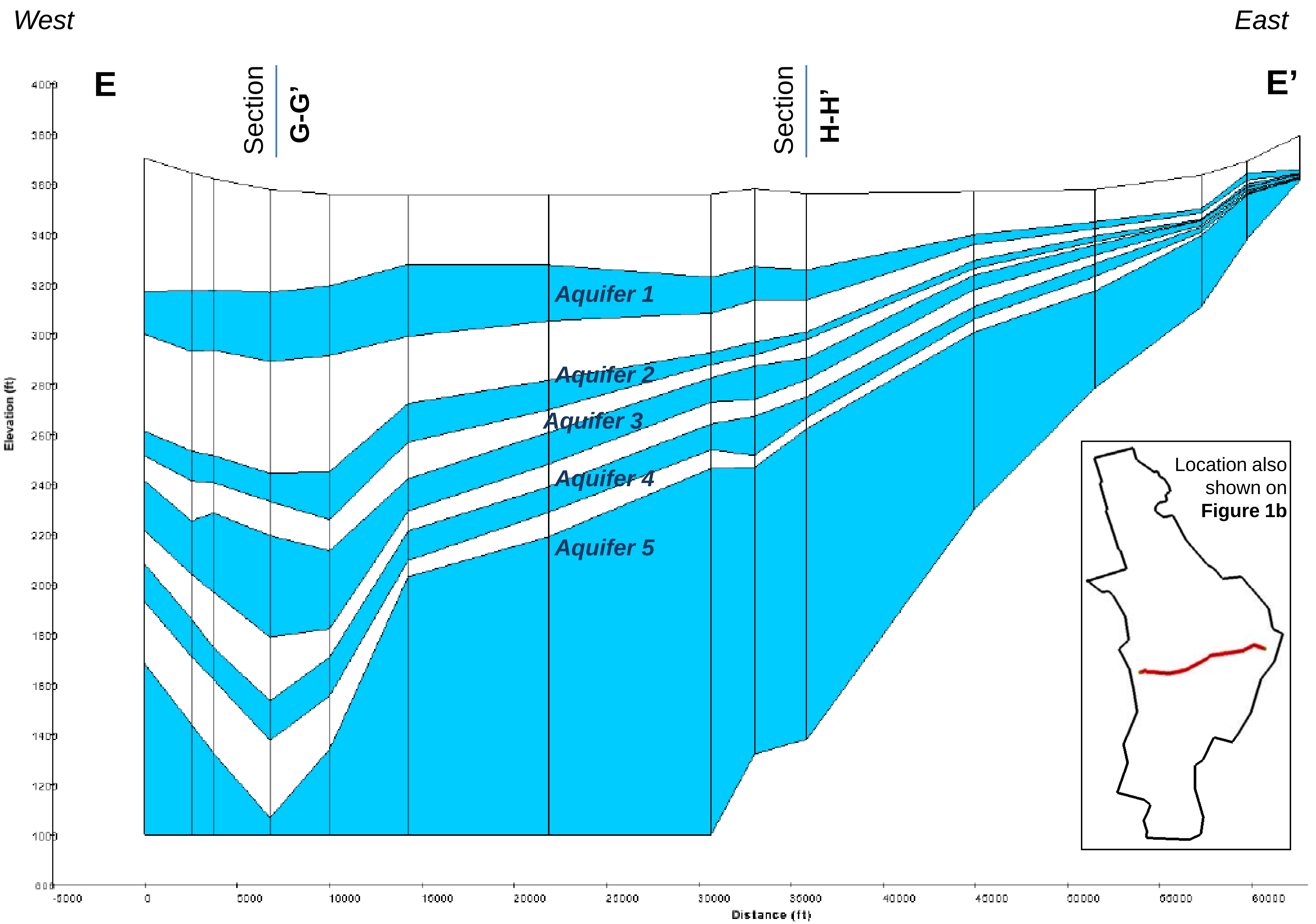


Figure 9
Cross Section E - E'

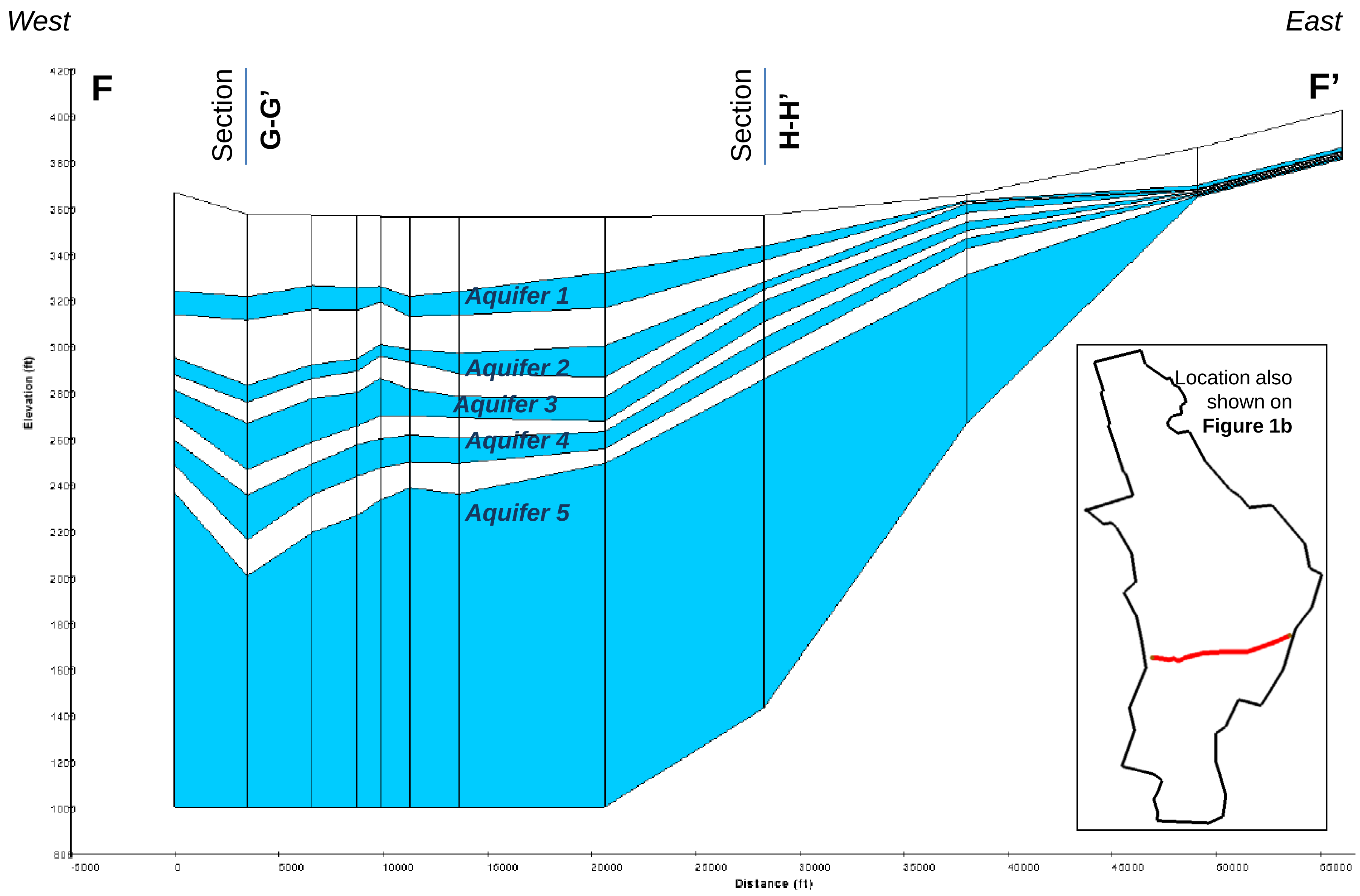


Figure 10
Cross Section F - F'

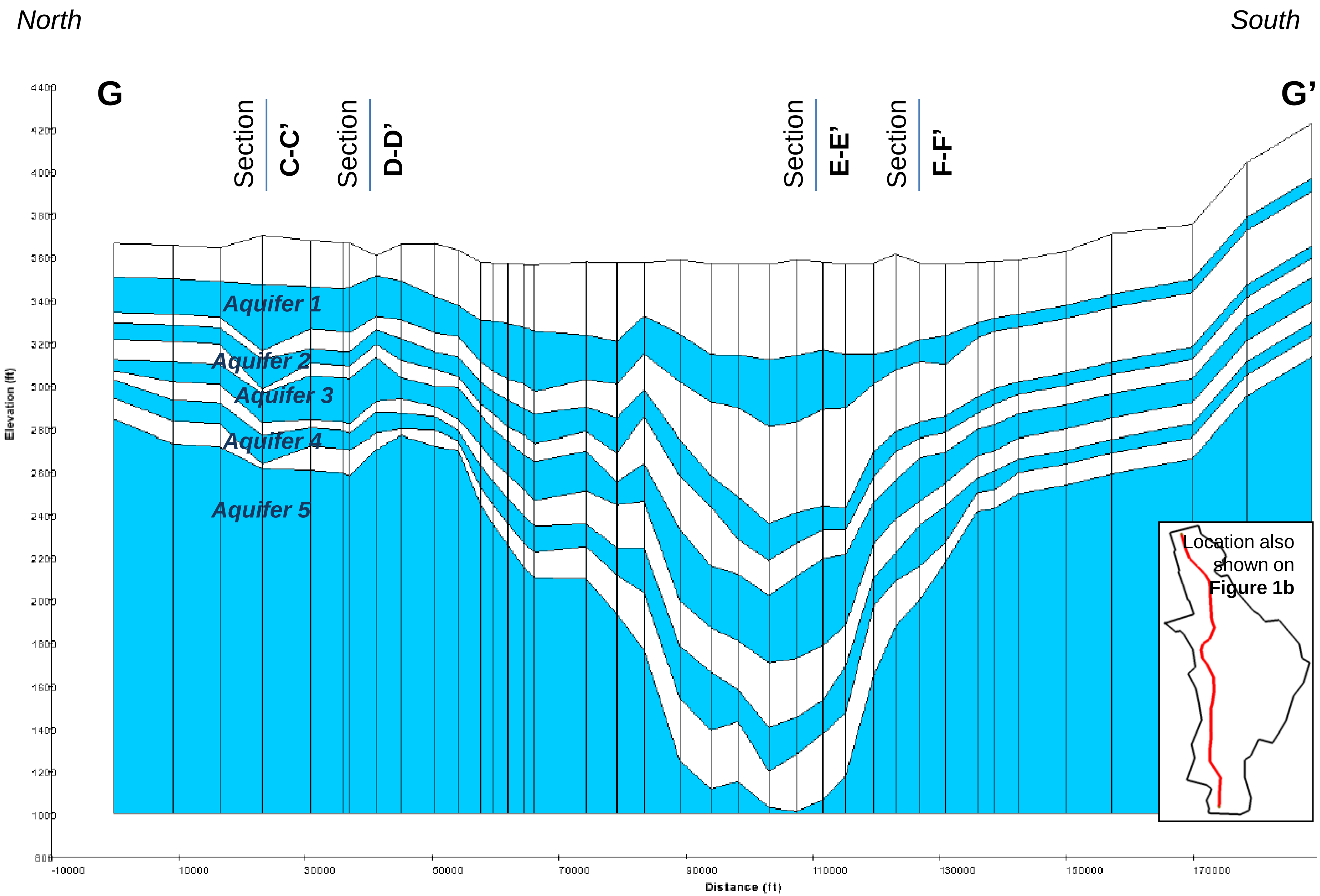
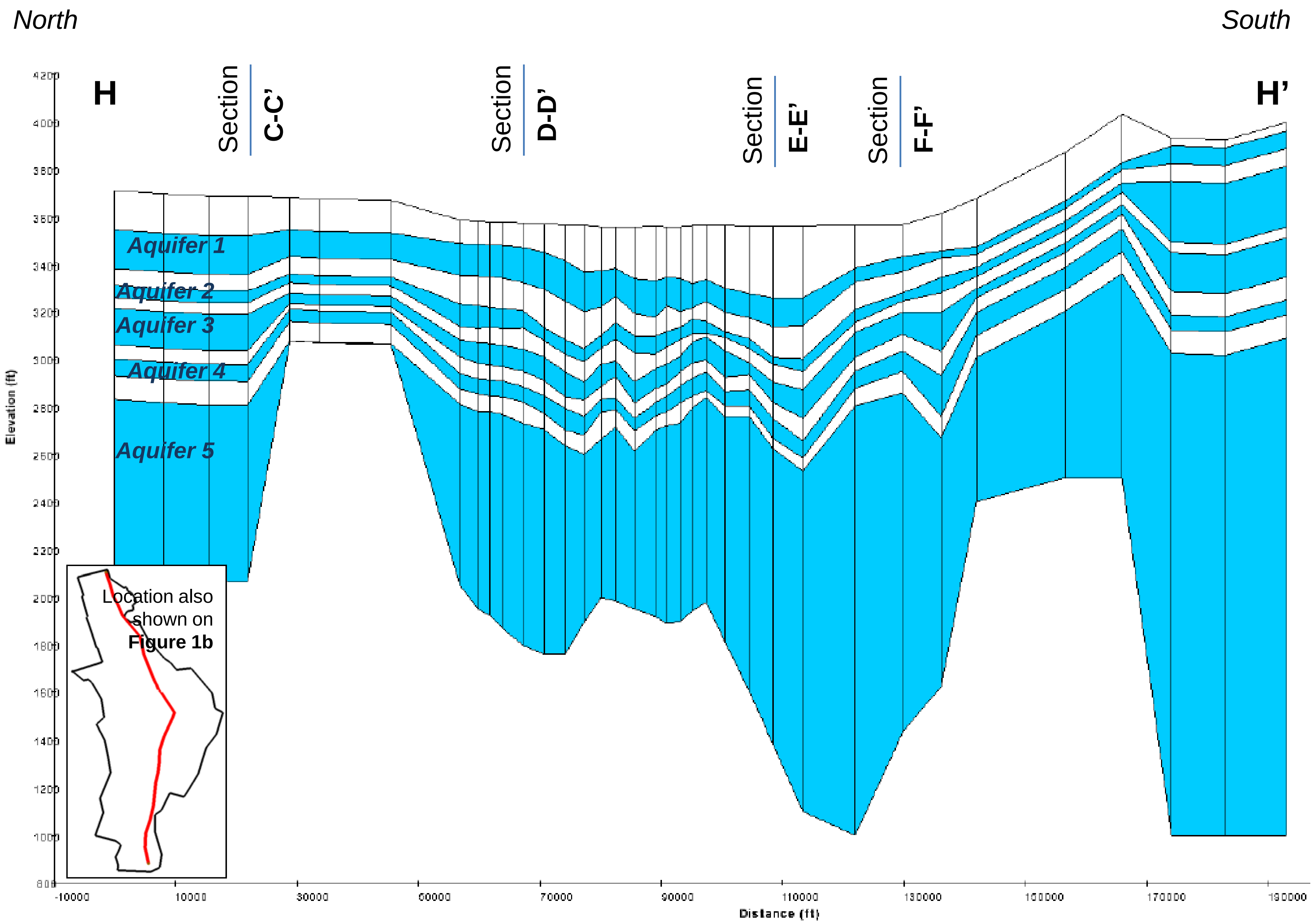


Figure 11
Cross Section G – G'



Location also shown on **Figure 1b**

Figure 12
Cross Section H - H’

- **Subtask 6 – Generate Data Archive** Results of the seismic interpretation were exported to the following formats:
    - Time-Depths for all layers and all lines in csv format
    - Velocity and Depth data for each line in csv format
    - Location of all faults in tab-delimited format
    - Grid files of horizons and thicknesses in Surfer™ format
    - Shape files of contours for horizon elevation and layer thickness
    - Image of interpreted seismic time-domain sections with nearby wells superimposed.
    - Images of annotated interpreted seismic time domain sections--as above but with interpreted annotations.

  The data were also archived on the project SharePoint site. In addition, the data are archived so that the project can be revisited using the Seisware software package. Seisware uses industry standard formats, and it is anticipated that other software will also be able to use the data and interpretation.

SEISMIC INTERPRETATION

The first step in the seismic interpretation was to identify stratigraphic units at new and existing wells. The project team reviewed well logs and identified significant horizons that also correlated to seismic reflections. Specific lithologic and geophysical log indicators (such as ash beds, resistivity, or gamma log patterns) provided a very useful correlative tool even in areas with variable lithologies. The well interpretations were correlated to the seismic data using synthetic seismograms and VSP’s.

The seismic reflection data were then analyzed to map area-wide reflection horizons that mark stratigraphic sequence boundaries. These boundaries act as marker horizons that permit analysis of the stratigraphy and structure as well as the interrelationship between the two.

In a traditional definition, sequence stratigraphy is the branch of geology that attempts to subdivide and link sedimentary deposits into unconformity-bounded units and to explain the stratigraphic units in terms of sea-level changes and variation in sediment supply. Owens Lake, which is at the terminus of a closed drainage basin, shows lacustrine deposition that is dependent on lake level and sediment supply, and is therefore analogous to coastal processes. The application of sequence stratigraphic approach and analysis has proven effective in the past to explain the geologic framework observed at the Owens Lake sedimentary basin (Johnson et al., 1999).

Previous interpretation of the seismic data (Neponset and Aquila, 1997) focused on mapping five sequence boundaries identified on the seismic lines. Correlation with drilling data showed that the sequence boundaries frequently identified the top of aquifers, when those aquifers were present. This name and color convention has been retained from past work in order to maintain continuity. Regionally extensive reflection horizons have also been identified between the sequence boundaries that correlate to changes in lithologic and well log character, generally correlating with the tops of finer-grained silts and clays. These horizons are referred to as “base” boundaries. They are characterized by weak reflections and were not mapped in previous work. The color designation and the generalized hydrostratigraphic correlation for each of these horizons is provided in **Table 3**. **Figure 3** is an example profiles showing all of the horizons.

Table 3
Seismic Horizons and Correlative Hydrologic Units

Seismic Horizon	Color Used	Hydrostratigraphic Unit
Lt Grn	Light Green	Top of Aquifer 1
Lt Grn Base	Purple-gray	Base of Aquifer 1
Lt Blu	Light Blue	Top of Aquifer 2
Lt Blu Base	Purple-gray	Base of Aquifer 2
Org	Orange	Top of Aquifer 3
Org Base	Purple-gray	Base of Aquifer 3
Dk Grn	Dark Green	Top of Aquifer 4
Dk Grn Base	Purple-gray	Base of Aquifer 4
Brn	Brown	Top of Aquifer 5
Bedrock	Red	Top of Bedrock

INTERPRETED STRUCTURAL GEOLOGY

Sequence boundaries are either an unconformity or correlative conformity that occurs at a change in the depositional regime. Therefore, a sequence boundary marks a horizon of uniform time. The five horizons that correlate to the top of aquifers are considered to be sequence boundaries. The sequence boundaries and base horizons provide a series of marker horizons that allow mapping of the basin geometry and structure.

The displacement observed across faults indicates faulting was syn-depositional (e.g., deposition occurred contemporaneously with structural displacement). **Figure 13** shows a seismic section where different interval thicknesses occur on either side of the high-angle fault (shown in red). In the upper intervals, such as the Lt Grn-Lt Grn Base interval, the layer thickness is approximately equal on either side of the fault. The Lt Grn through Lt Blu horizons show little displacement, indicating that recent movement has been minimal. However, deeper horizons show increasing thickness on the right side of the fault, indicating displacement during deposition.

The deepest part of the basin is located near the Bartlett #1 Well on the west margin of the basin. Johnson, et al (1999) identified the Owens Lake as a right-lateral strike-slip pull-apart basin with the greatest accommodation space forming on the west margin (**Figure 6**). The seismic lines show a double plunging, asymmetric syncline with the north-south trending axis near the western shore of the lakebed (**Figure 14**). The syncline is bounded by faults on the west and east. Faults on the southeast margin appear to be splays of the larger faults terminating against the Coso Mountains.

Relatively shallow bedrock was noted underlying the east side of the basin. The synclinal features seen in the sequence boundaries are assumed to reflect the form of the underlying bedrock; however, bedrock in the western portion of the basin is deeper than can be resolved using the seismic data. A localized anticline was identified north of the lakebed (**Figure 14**). The feature is identified only on Seismic Line 96-02 (**Figure 15**), and the axis is assumed to be approximately east-west. An uncorrelated horizon is highlighted in red, and shows the sediment pile appears to be thickening in both directions. The anticline appears to act as a divide, potentially separating two sub-basins: sequences dipping down to the north and down to the south towards Owens Dry Lake.

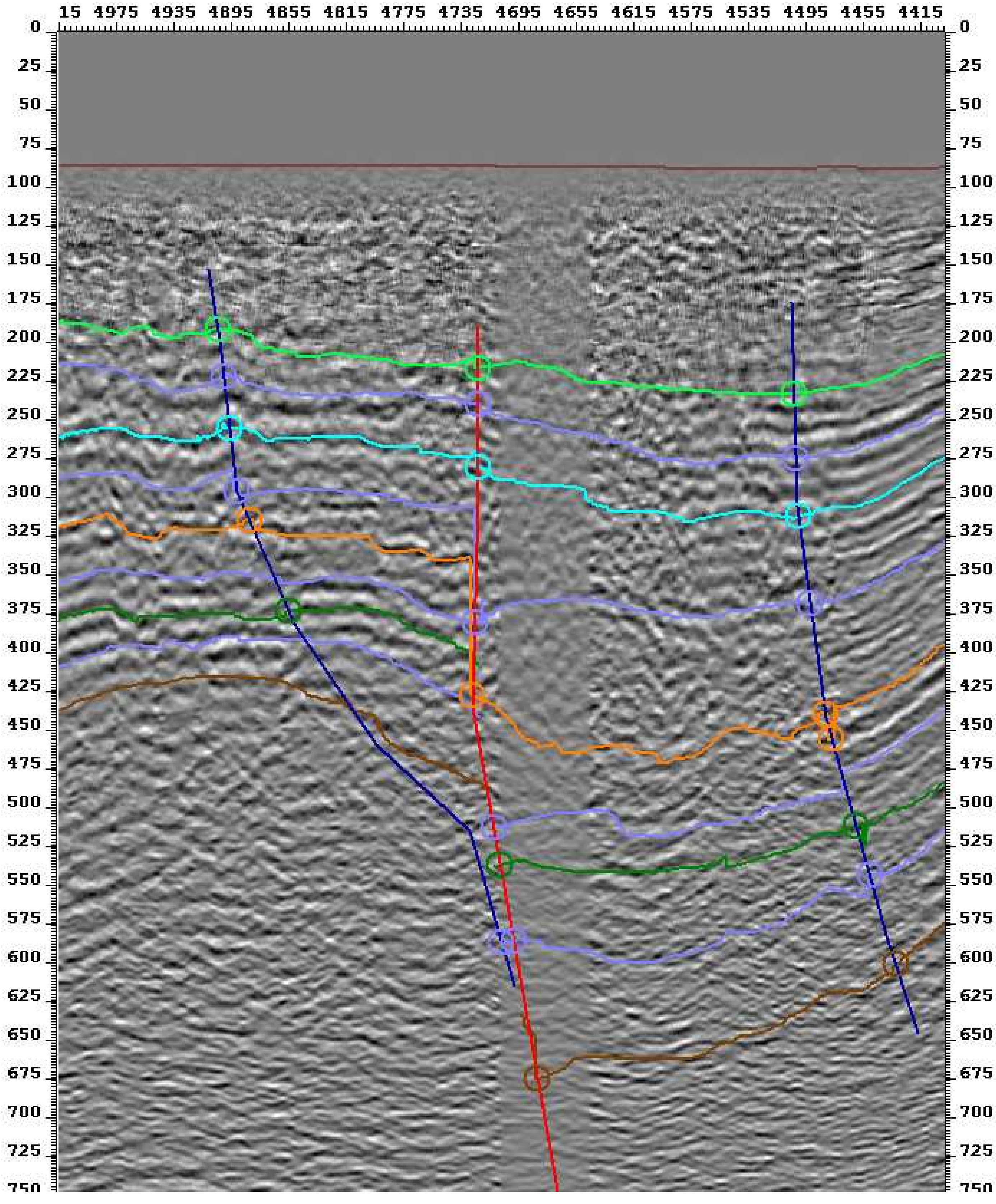


Figure 13: Line 93-10 CDP4700 shows differential deposition across a high-angle fault in the Owens Valley Fault Zone (individual fault strand shown in red). Fault is downthrown to the right on all hoizons below Lt Blu. The differential of layer thicknesses across the fault for these layers indicates fault movement during deposition. Lt Grn, Lt Grn Base, and Lt Blu sequence boundaries are nearly continuous across the fault, indicating displacement on this fault has ceased.

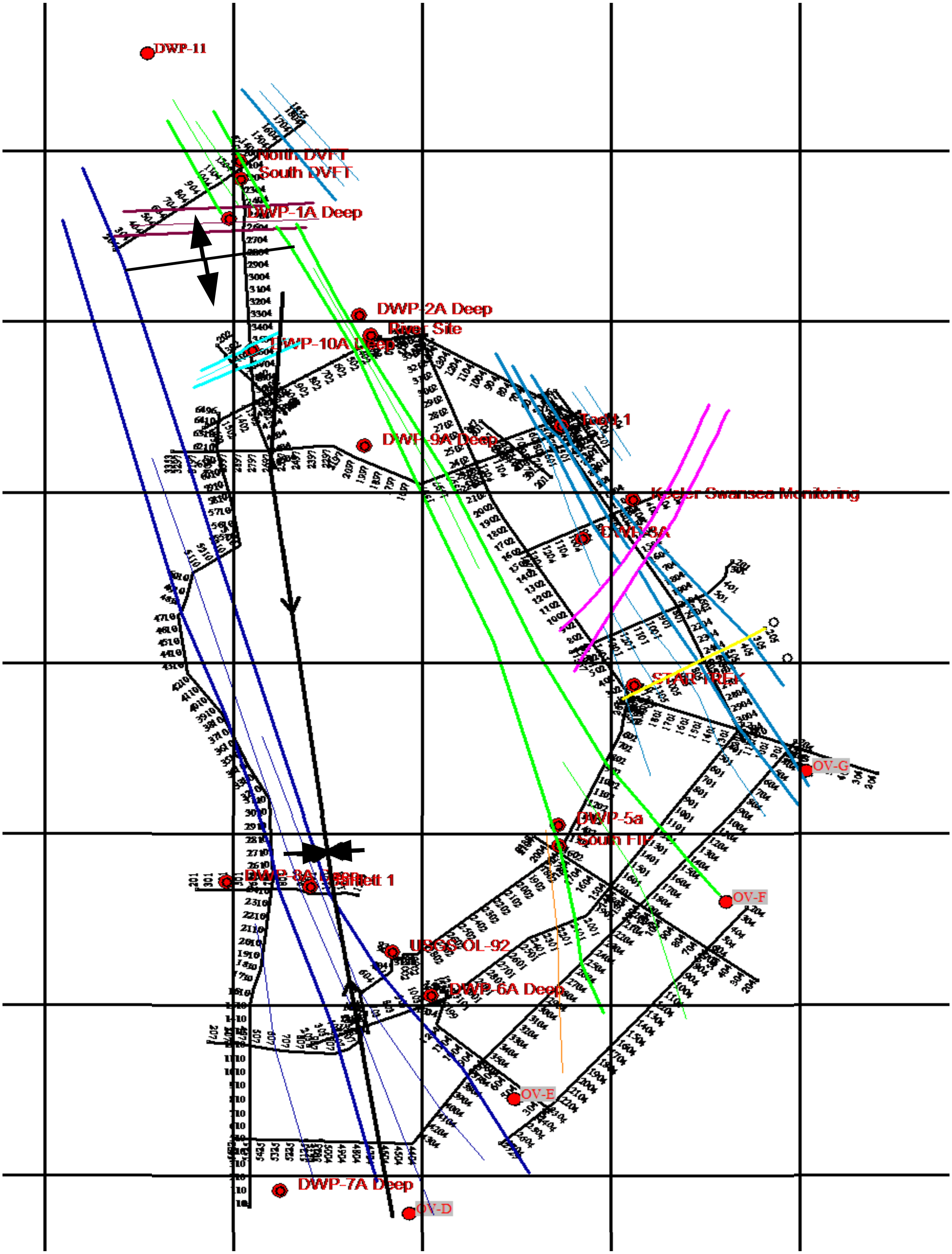


Figure 14: Structure map derived from the interpretation of the seismic data. Faults are grouped into zones, and differentiated by color (See Table 4).

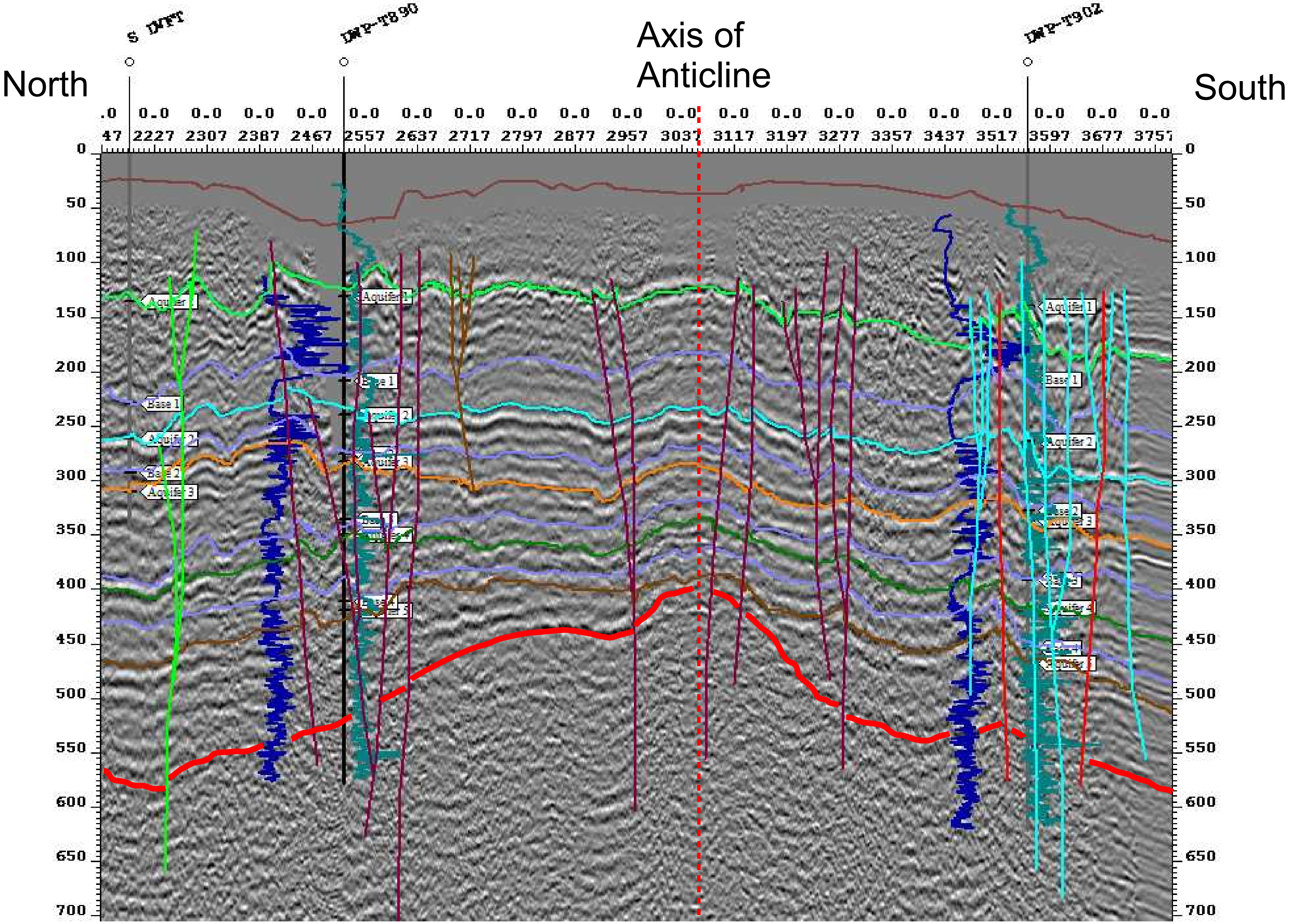


Figure 15: Segment of Line 96-02 showing anticline centered at CDP 3050, and sediments draped over the high point. An uncorrelated horizon is highlighted in red. Note the increasing thickness of the sediments toward both the north and the south.

Bedrock was mapped on the on the east side of the basin, along the Inyo Mountains. Bedrock exhibited reflections typical of sedimentary layering, consistent with the meta-sediments that comprise the Inyo Mountains (**Figure 3**). Bedrock was encountered in LADWP's recently-drilled Sulfate Facility well, although DWP-3 was the only well to encounter bedrock within the network of seismic lines. No wells have been identified that penetrate significantly into the bedrock to provide logs, cuttings, or other bedrock characterization. Reflections that show bedrock layering (such as **Figure 3**) suggest lithologic contrasts exist in the bedrock that could be interpreted as variable depths of bedrock weathering, or the original layering of the now-metamorphosed sediments.

Bedrock appears on the seismic sections on the northeast and east margins of the seismic coverage. Bedrock is locally irregular, and tends to show more relief than the overlying sediments. As bedrock shallows, the mapped sequences drape over bedrock and thin, pinch-out, or truncate against the bedrock (**Figure 3**).

Bedrock was not identified on the southwestern and western margin. Bedrock may be evident on the seismic data; however, reflections are neither continuous with interpreted bedrock, diagnostically unique to bedrock, nor do any wells other than DWP-3 contact bedrock. As a result, the bedrock surface cannot be confidently mapped on the southeastern or western margin with the existing data set.

FAULT ZONES

A number of fault zones were mapped in the study area. The faults are generally high angle with displacement spread across multiple fault strands rather than a single fault plane. This is typical of faulting in strike-slip structural styles. Faults are listed in **Table 4** and shown in **Figure 14**. The color key in **Table 4** is used on the structure map (**Figure 14**) as well as on the seismic sections.

Table 4
Summary of Fault Zones

Fault	Color	Description
Owens Valley	Dark blue	Located along the western shoreline of the lakebed.
Owens River	Light green	Located along the Owens River, interpreted to transect the lakebed to the southeast shore.
Inyo Mtn Front	Blue-gray	Series of faults that roughly parallel the northeastern shore of the lakebed.
Keeler Fan	Magenta	A northeast/southwest trending fault that appears to originate on the Keeler Fan.
Bedrock Block	Plum	East-west oriented faults that appear to originate from bedrock. Interpreted to cause the Owens River Fault to be right-lateral offset (toward the east).
North Shore	Light blue	East-west oriented fault zone that roughly parallels the northern shore.
Southeast Margin	Orange	Faults identified on the seismic lines in the southeast seismic lines. Orientation is unknown because correlation between lines is difficult to establish.
Growth	Brown	Growth faults appear to be caused by differential compaction of the underlying sediment pile. Do not appear to originate from bedrock.

The three largest fault zones are the Owens Valley Fault, Owens River Fault, and the Inyo Mountain Front Fault. They are roughly parallel and trend north-northwest to south-southeast. Other faults have strikes intersecting with the three large fault zones. **Figure 16** shows two close-up examples of faults with sufficient vertical offset to juxtapose aquifers and aquitards.

- **Figure 16a** shows a fault at Seismic Line 96-02, CDP 2265 where the aquifer in the Lt Blu sequence (identified in nearby South DVFT and DWP-1 wells) is offset on the north against the clays at the base of the Lt Grn sequence (on the south side of the fault). In addition, the Lt Blu sequence on the down-thrown side of the fault terminates against the base of the Lt Blu. The Org sequence also shows offset that is approximately 30% of the aquifer thickness, which may result in restriction of groundwater flow.

- **Figure 16b** shows a fault at Line 93-05, CDP 685 where aquifers juxtapose aquitards on the Lt Blu and Dk Grn horizons. The Org sequence shows offset of approximately 40% of thickness. The sequences correlate to either productive aquifers or a cemented sand in the nearby Todd #1 well, and the base horizons correlate to clay units. Offsets of comparable magnitude exist on the fault strand at CDP 600.

Faults that juxtapose sediments of low and high hydraulic conductivity are potential barriers to groundwater flow. Crushed material and clay gouge along the fault zones may further restrict groundwater flow. Conversely, fracturing and cracking of consolidated sediments may actually act as conduits or preferential pathways to groundwater flow. Although seismic data does not allow for direct interpretation of the hydraulic impact of faults, it does allow for quantification of displacement that is not possible using borehole data alone. It is expected that the degree to which faults act as barriers is related to the degree to which fault displacement places relatively impermeable material adjacent to permeable aquifers.

While juxtaposed aquifers are evident, the degree of juxtaposition generally does not extend laterally along the faults to adjacent seismic lines to the same degree. **Figure 17** shows seismic lines 95-08, 93-05, and 95-09 (**Figures 17a**, **17b**, and **17c**, respectively) that are in close proximity and show the same fault system. Lines 95-08 and 95-09 are parallel and offset by approximately ¼ mile to the north and south of 93-05, and all three lines intersect 96-04 orthogonally (inset map, **Figure 17**). Note that **Figure 17b** is the same section as shown in **Figure 16b**.

Three faults are identified and mapped across the three seismic lines (identified as A, B, and C). On Line 93-05 (**Figure 17b**), Fault A is has sufficient offset to juxtapose aquifers and aquitard horizons. The same fault is evident on Line 95-08, CDP 490 (**Figure 17a**) and Line 95-09 CDP 508 (**Figure 17c**). In both instances, Fault A is not apparent on the upper three sequences, and does not offset the remaining sequences sufficiently to inhibit lateral flow. Also note that offset is similarly variable across the lines for Faults B and C.

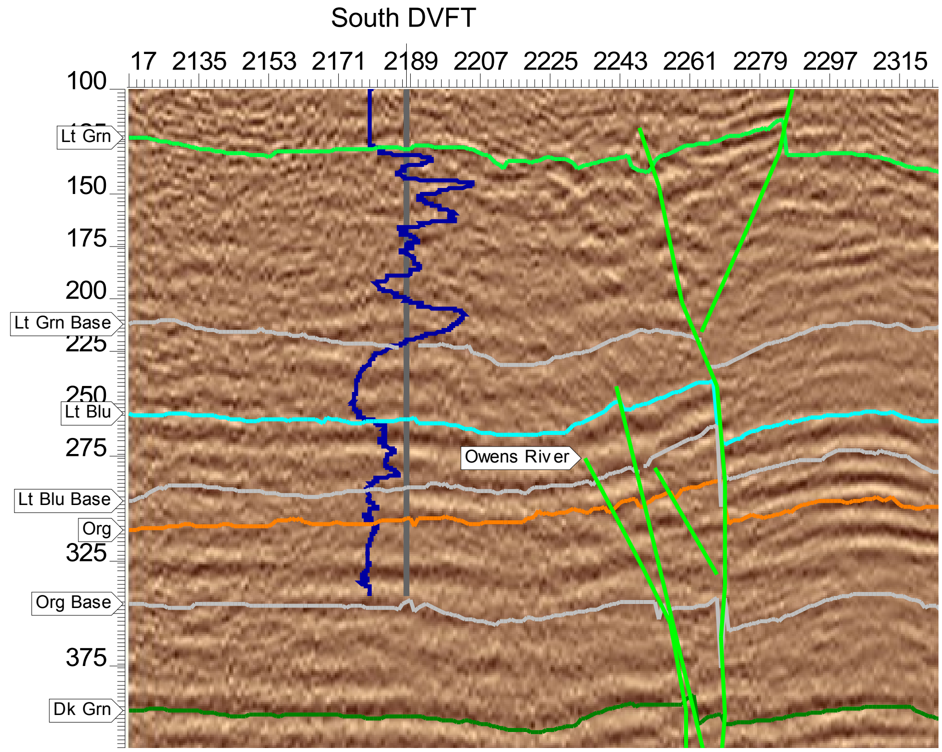


Figure 16a: Line 9602 (Transect B-B'). High angle fault strand intersects the Lt Blu horizon at CDP 2265. Fault is down-thrown to the south. Lt Blu sequence on the upthrown block (left side) is juxtaposed downthrown Lt Grn Base. Lt Blu sequence on the downthrown (right) block is juxtaposed the Lt Blu Base.

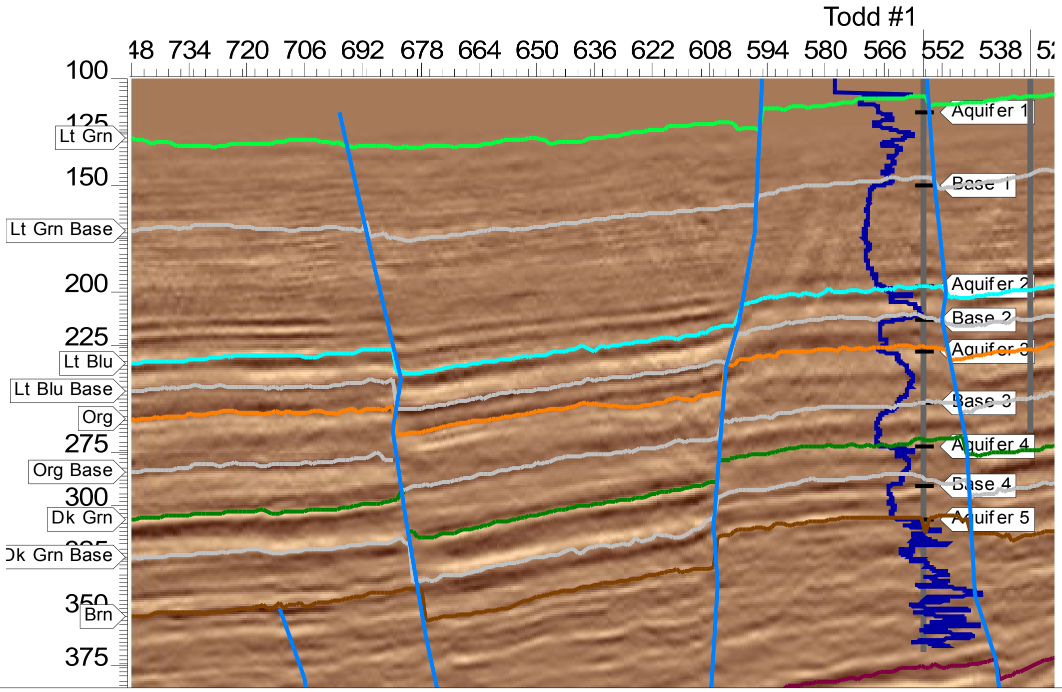


Figure 16b: Line 9305 (Transect A-A'). Fault strand intersects the Lt Blu horizon at CDP 685, downthrown to the east. Lt Blu and Dk Grn are juxtaposed clay sequences on both sides of the fault. Org has an approximate 40% offset. Offsets comparable to sequence thicknesses are also evident on the fault strand at CDP 600.

Figure 16: Seismic sections showing vertical fault offsets that are likely to be hydrologically significant. Correlation at nearby wells shows Lt Blu correlates with Aquifer 2, Org correlates with Aquifer 3. Dk Grn corresponds with Aquifer 4 at South DVFT and a correlative cemented sand at Todd #1. The Lt Blu Base, Org Base, and Dk Grn Base correspond with clays at Base 2, 3, and 4, respectively. See Figure 1 for locations.

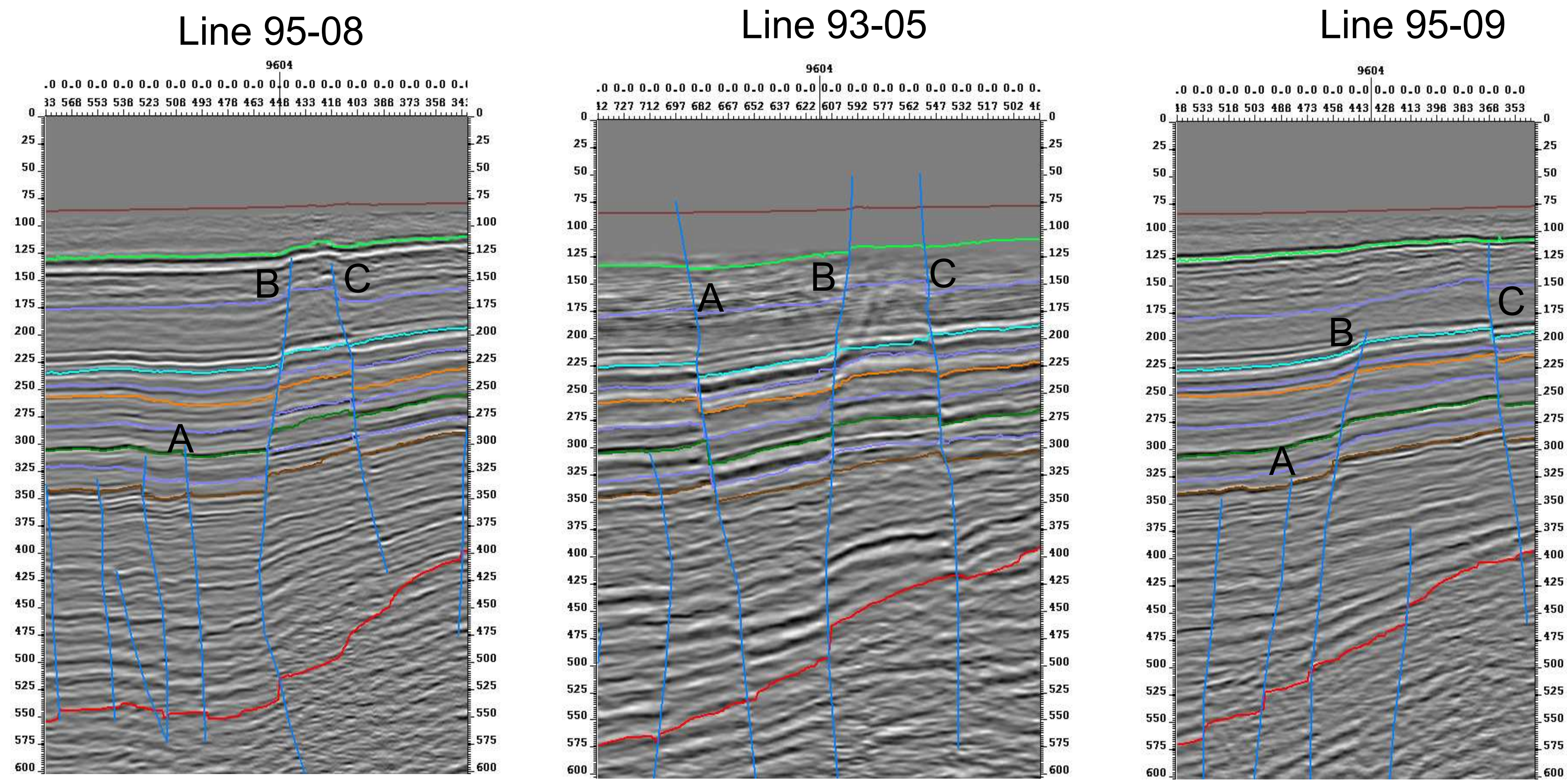


Figure 17a

Figure 17b

Figure 17c

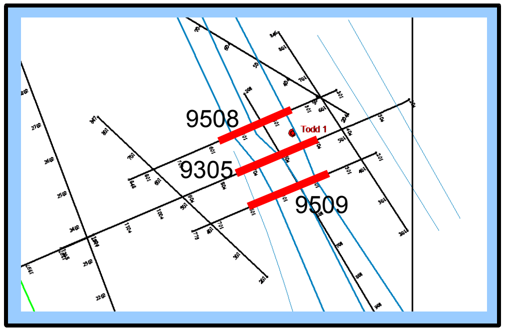


Figure 17: Faults correlated across three parallel seismic lines. Fault A is identified in Figure 16b as having aquifers juxtaposed against aquitard zones. The offsets evident in Fault A do not carry through to parallel lines to the north or to the south. See inset map for location; displayed sections shown in red.

One fault was found where offsets with juxtaposed sequences extended across multiple seismic lines. The fault is associated with the SE Margin faults and trends north-south, crossing four seismic lines (**Figure 18**):

- Line 93-09, CDP 2000 (**Figure 18a**)
- Line 95-01, CDP 1700 (**Figure 18b**)
- Line 95-02, CDP2200 (**Figure 18c**)
- Line 93-10 CDP 3000 (**Figure 18d**)

The fault is downthrown to the southeast. This fault is currently mapped as part of the SE margin faults. However, the fault could be associated with the Owens River Fault.

Regardless of the hydraulic significance of faults in the Owens Lake area, knowledge of the exact location and approximate displacement will allow for more accurate modeling of groundwater flow as well as accounting for fault-related impacts in the calibration process. This is expected to result in a very significant improvement of previous modeling efforts, which did not incorporate the effect of faulting. The following sections provide a description of each fault zone shown in **Figure 14**.

Owens Valley Fault

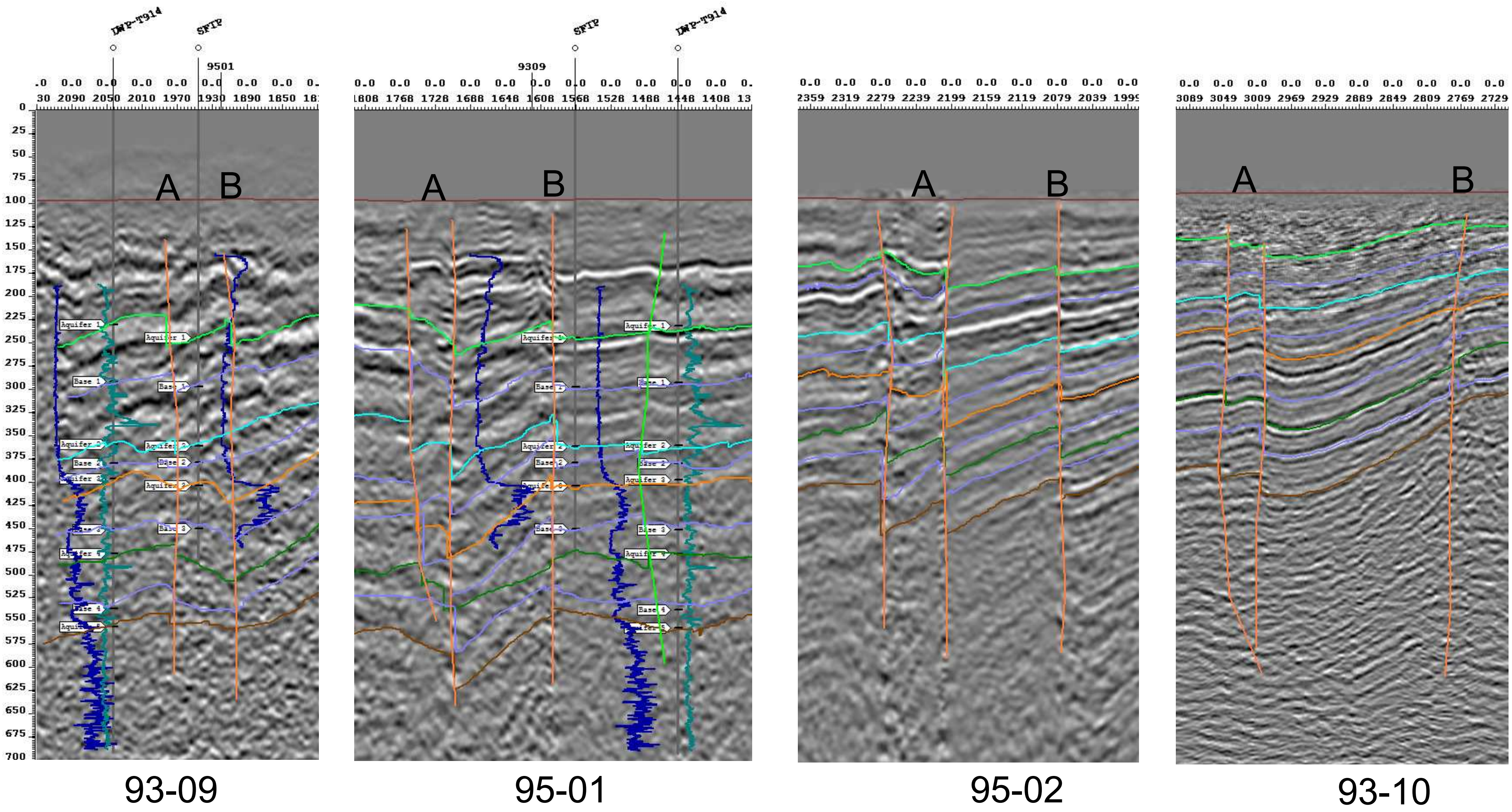
The Owens Valley Fault is a major fault zone along the western margin of the lakebed (**Figure 14**). Horizons are not continuous within the fault zone, implying extensive deformation. The fault is high angle with extensive deformation within the fault zone as seen at the west end of Seismic Line 95-03 and east end of Line 95-10. The fault is also evident on the west end of Line 96-01, although not enough seismic data is available over the zone to assess the extent of deformation. Some layering and internal structure are evident on Line 95-05, which is sub-parallel to the fault. At the south end of the lakebed the fault appears to splay, becoming a group of individual fault strands with stratigraphic definition still clearly evident within the fault zone.

Owens River Fault

This fault is located along the channel of the Owens River in the north and extending across the lakebed toward the southeast shore. On line 96-01, deformation within the fault zone disrupts stratigraphic layering on the seismic sections. At the northern part of the seismic coverage, the fault appears to be offset in a right-lateral sense by bedrock block faults (**Figure 14**). The Owens River Fault is interpreted to cross the lakebed and for the fault strands to splay at the southern end of the zone. Continuity of stratigraphic layering within the fault zone is clearly evident on all seismic data south of Line 96-01.

Inyo Mountain Front Fault

Located parallel to the northeast shore, the fault zone consists of network of high-angle faults that appear to originate from bedrock. The bedrock faults propagate upwards into the overlying sediments. The general trend is the individual faults are downthrown to the west. The bedrock rise and faulting creates a complex interaction of structural displacement with stratigraphic sequences thinning toward the east. Horizons may pinch out or may truncate against bedrock or faults.



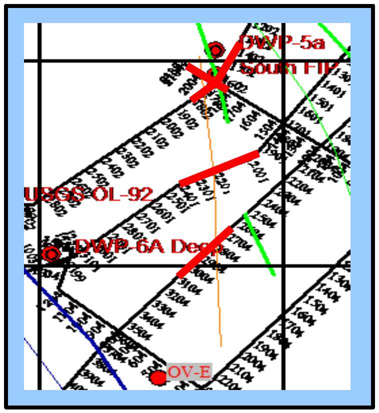


Figure 18: Faults A and B have aquifer sequences juxtaposed to aquitards across multpile seismic lines. Fault A is a two-strand fault on most of the sections, and appears as a single strand on 93-09. Location of seismic data shown in red on map (inset).

North Shore Fault Zone

A fault zone was identified along the northern shore of the lakebed, termed the North Shore Fault. The fault is located near the intersection of seismic lines 93-01 and 96-02, and appears to strike east-northeast. The sediments are disrupted by faulting (**Figure 15**), but the reflections are sufficiently continuous to allow mapping sequence boundaries across the fault zone. The fault is not identified on any other seismic lines.

Bedrock Block Faults

Located north of the North Shore Fault Zone, the bedrock block faults appear to strike east-west, sub parallel to the North Shore Fault (**Figure 14**). The fault zone appears to cause a right-lateral displacement in the Owens River Fault, which is reflected in the channel of the Owens River. The Bedrock Block faults may cause a similar right-lateral offset for the Inyo Mountain Front fault zone. The nature of the intersection of this fault with the Owens Valley fault is not evident in the seismic data due to lack of coverage.

Keeler Fan Fault

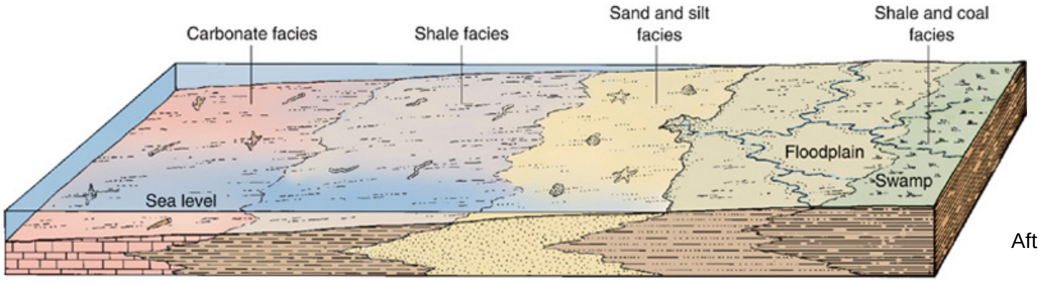
The Keeler Fan Fault appears to originate on the Keeler Fan with a northeast-southwest strike (**Figure 14**). The fault appears to be associated with a local bedrock depression, or perhaps a paleo-channel, as shown on 96-04 and 93-04. The fault appears to splay, getting wider toward the southwest. The seismic data does not cover the area where the Keeler Fan and Owens River Fault zones are interpreted to intersect. As a result, the nature of that fault intersection is not known.

Southeast Margin Faults

In general, this group of faults describes a series of faults that do not appear to have consistent strike or displacement sense. The exception is the example of juxtaposed aquifers discussed above (**Figure 18**). The faults may actually be related to the termination of the Owens Valley and/or Owens River faults; however, the line-to-line correlation is not clear. As a result, this group of faults is better described as a category of unassigned faults rather than an identified fault system.

INTERPRETED DEPOSITIONAL HISTORY

The combination of interpretation of seismic reflection data, borehole geophysical data, lithologic logs, and geologic maps results in a relatively vivid picture of the depositional history of the basin. To interpret the history of deposition, it is helpful to evaluate sedimentary facies that are currently present at the lake. Understanding the depositional history of the OLGEP study area is expected to greatly improve numerical model parameterization model calibration. **Figure 19** is a schematic representation of typical facies present in along an ocean shoreline. Facies present at Owens Lake are similar to those shown in **Figure 19**, except that muds, silts, and organic deposits are found in place of carbonates, shale, or coal, respectively.

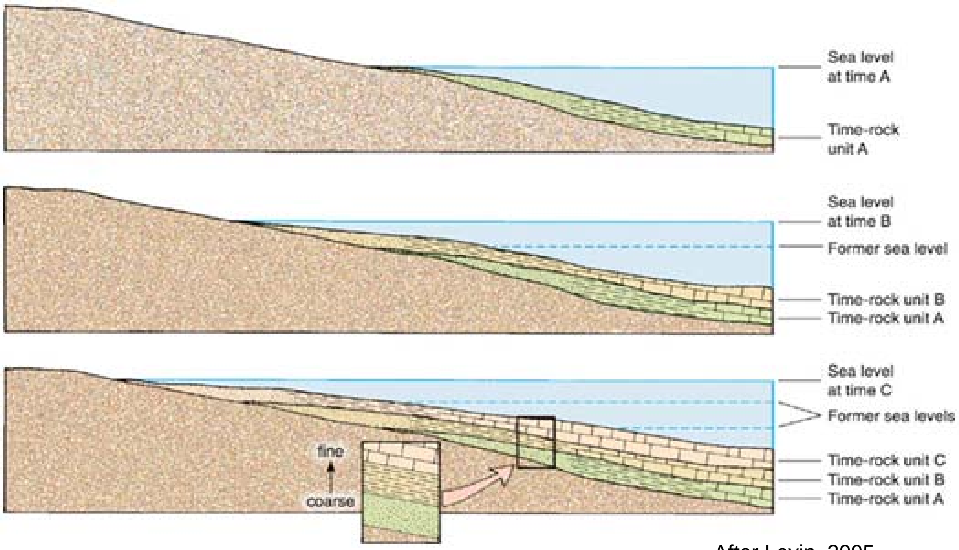


After Levin, 2005

Figure 19
Schematic Representation of Typical Facies Present along an Ocean Shoreline

Note that at any particular time period, sediments become finer toward the depositional center, which is generally assumed to be the center of the lake. In the nearshore submerged environment, benthic organisms such as gastropods may be found. In the beach environments, sediments are well sorted and may contain oolites due to wave and wind action. In the floodplain or delta subaerial environment, extensive organic material may be present due to shallow fresh groundwater and sunlight. Further landward, fluvial deposits and bajadas may exist that interfinger with the lacustrine deposits.

As the lake level changes through time, the deposition of sediments is altered as the shoreline moves laterally. **Figure 20** depicts the deposition of sediments as the lake level rises, or “transgresses”. As the water level rises and deposition is continuous, sediments are deposited in a fining-upward sequence, and a sequence that represents a successively deeper depositional environment. If the lake level drops (or regresses), the reverse is true, whereby a coarsening upward sequence is found. Deposition follows the receding waters, creating progradational deposits, i.e.- the delta is extending progressively further into the lake because water level is either static or retreating.



After Levin, 2005

Figure 20
Schematic showing the Deposition of Sediments as Lake Level Transgresses

Accommodation space is the volume available for sediment deposition. To a first approximation, the volume of Owens Lake at any given water level would be the accommodation space. The accommodation space will vary due to changes in lake level due to runoff and/or tectonic activity which affects the lake level relative to the existing sediments. Changes in accommodation space can be a complex interaction of infilling sediments, climactic changes, and tectonic movement. The depositional patterns reflect this interaction.

Figure 21 shows examples of depositional patterns caused by net decreases in accommodation space. On Line 96-02 (location shown on **Figure 14**), a prograding delta is highlighted in dark purple in the Lt Grn sequence. The uniformity in the top of the clinoform indicates water levels were likely unchanged during the time of deposition. In the Lt Blu and Dk Grn horizons, dominantly prograding deposits are evident and shown in dark purple. However, aggradation is also evident (shown in red), implying minor or shorter-term intervals of increasing water levels. The interpretation for these two sequences is that the depositional regime was dominantly progradational with interspersed cyclic water level changes.

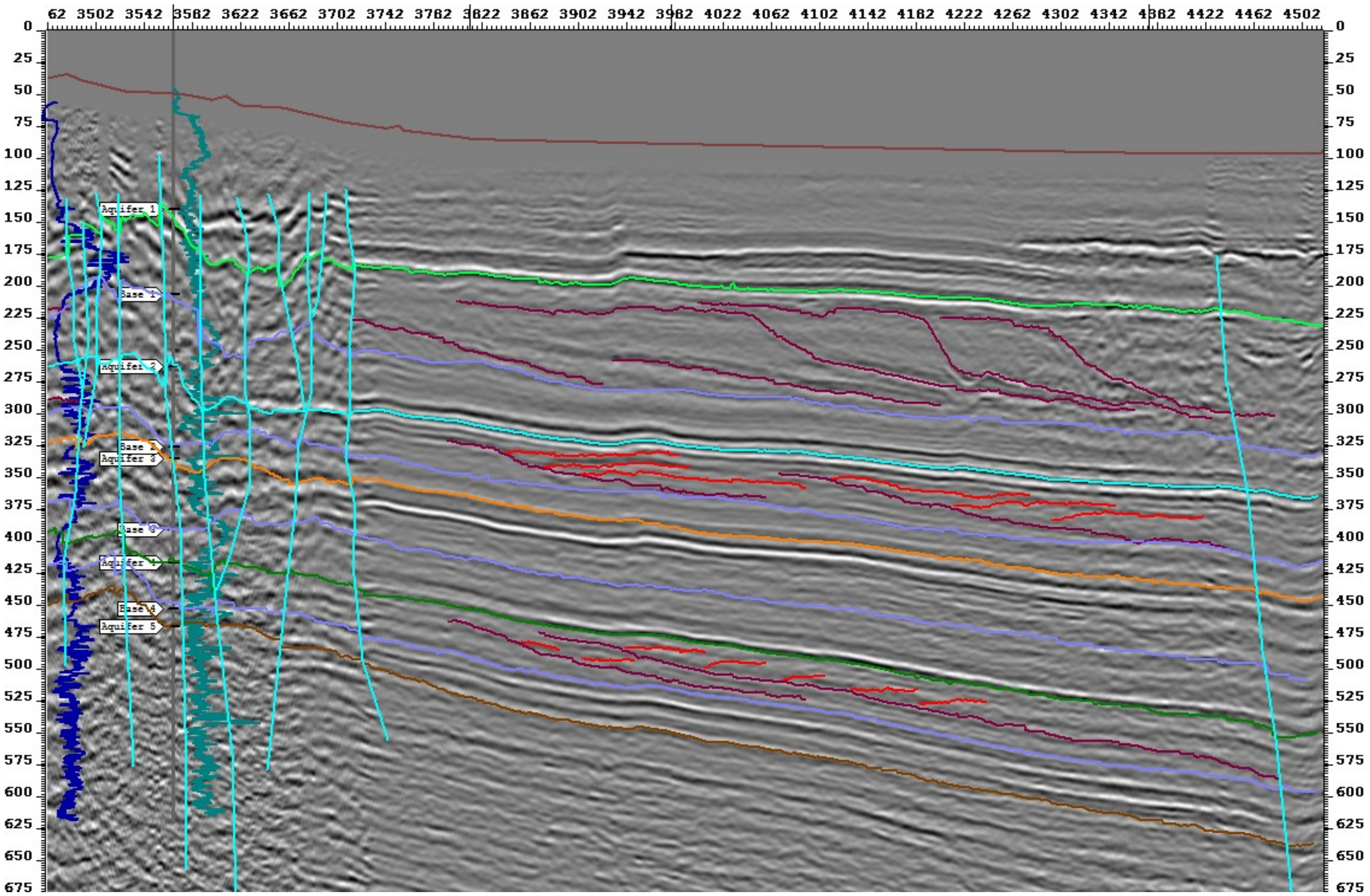
Figure 21 also shows Line 95-10, located along the western margin of the lakebed and near DWP-8 (**Figure 14**). The section shows lacustrine deposits with overlying alluvium deposits (shown in red) prograding into the lake above the Lt Grn sequence boundary. Also shown are aggradational deposits in the Lt Grn base interval (shown in dark purple) that are interpreted to be beach ridge deposits at the west margin of finer grained lacustrine deposits. At DWP-8, projected onto the left end of the section, cutting samples showed largely sand deposits and virtually no low-energy lacustrine deposits as found in the majority of the other wells on or near the lakebed.

On the northeast and southeast margins, the basin is terminated structurally by bedrock highs causing thinning or pinching-out of the mapped sequences. On the west, the sequences coarsen and lacustrine deposits are absent. Bedrock depth cannot be resolved based the seismic data nor have any boreholes encountered in wells on the west side of the basin.

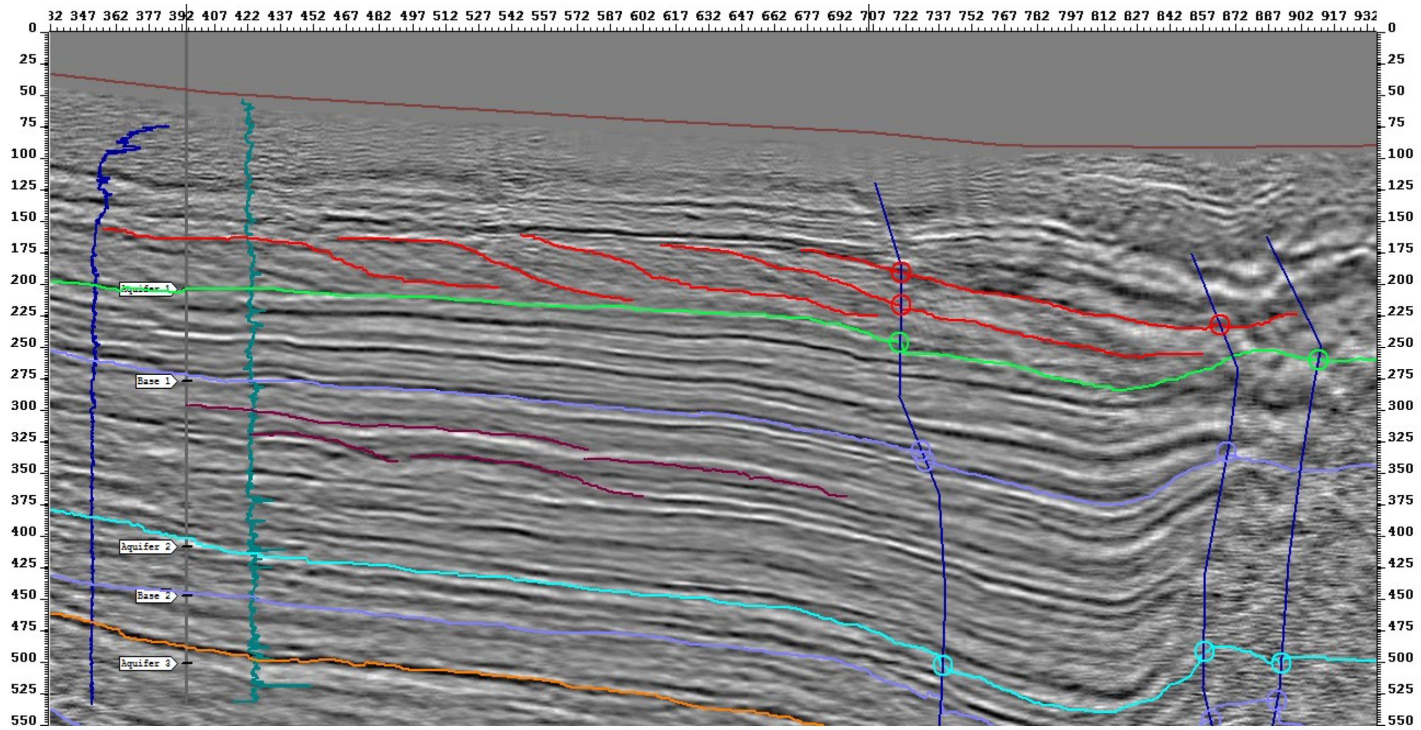
Combining the well data and seismic data, it was found the sequence boundaries tend to correlate with the top or near the top of aquifers, in locations where aquifers were found to exist. In addition, surfaces were also identified that tend to correlate with the base of the aquifers, where aquifers exist. These are referred to as the ”Base” horizons. By combining the seismic and well data, we can draw insights into the depositional character of the aquifers.

The geophysical and lithologic data in the delta area provides evidence of a pre-lake period of deposition of flood plain or braided stream deposits, then the first evidence of the lake being formed, followed by at least four regressive events where lake levels dropped (separated by transgressive events). **Figure 22** illustrates the sequence of deposition at DWP-9, showing the correlation between lithologic observations, resistivity, and the interpreted depositional environment. This pattern is remarkably recognizable in many of the boreholes in the study area.

While seismic data does provide evidence of depositional environment and patterns, the seismic data does not directly provide meaningful information on grading of the sediment source or distribution within the sequence, and therefore does not provide useful insight into whether a stratigraphic sequence has graded laterally to a geologic material of differing hydraulic properties. This information comes primarily from borehole geophysical logs and lithologic logs based on drilling cuttings. The seismic data provided the means to correlate the various sequences from well to well and to provide information in three dimensions.



Line 96-02

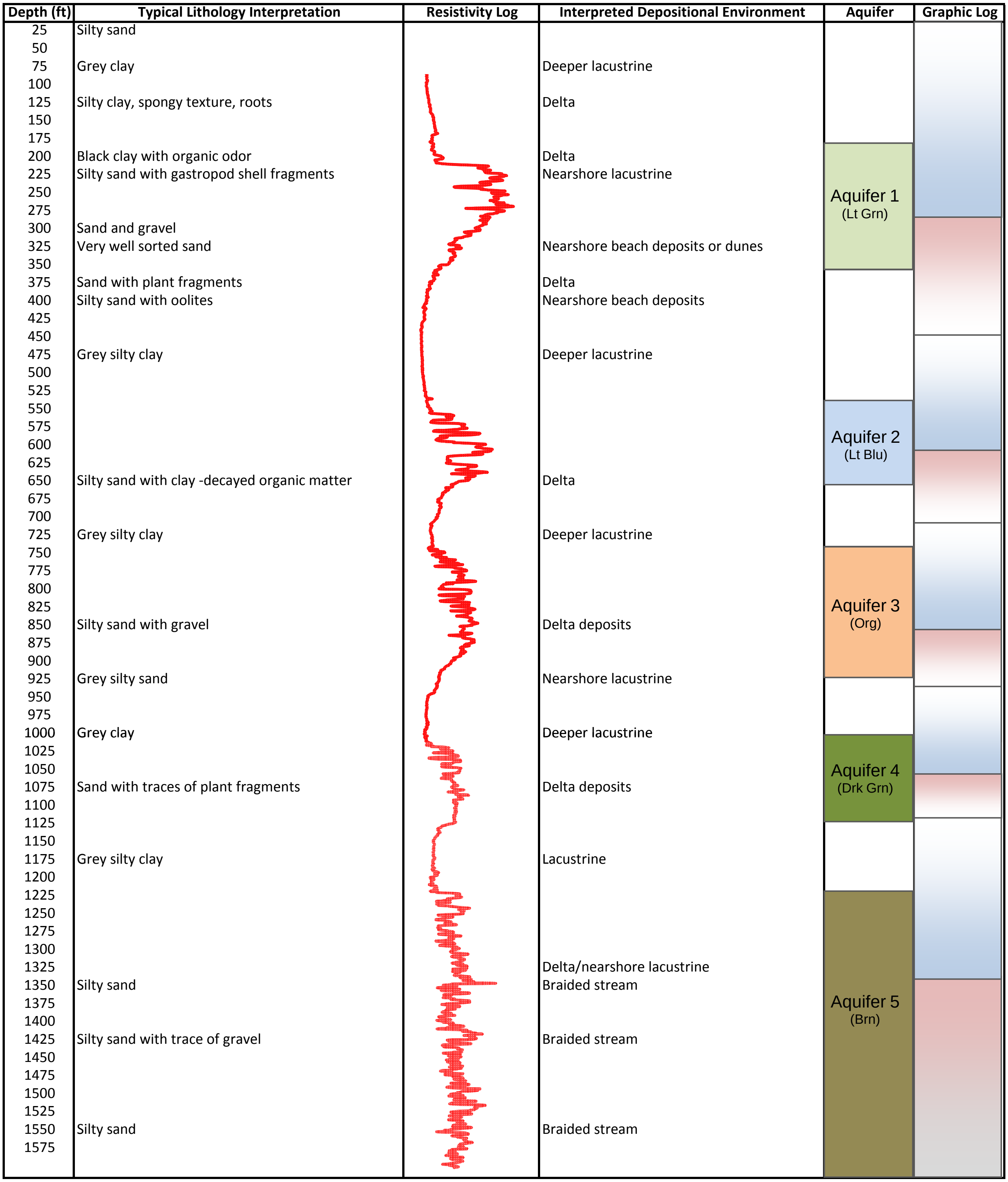


Line 95-10

Figure 21: Examples of progradational and aggradational deposition on Lines 96-02 and 95-10. Line 96-02 shows a progradational sequence in the Lt Grn, Lt Blu, and Dk Grn sequences. On Line 95-10, a progradational sequence, shown red, is interpreted to be alluvium deposited from the Cottonwood drainage basin. Aggradational deposits, shown in dark purple, are interpreted to be beach ridges.

Figure 22

Lithology, Resistivity and Interpreted Depositional Environment for DWP-9 (T896)



Depth (ft)	Typical Lithology Interpretation	Resistivity Log	Interpreted Depositional Environment	Aquifer	Graphic Log
25	Silty sand				
50					
75	Grey clay		Deeper lacustrine		
100					
125	Silty clay, spongy texture, roots		Delta		
150					
175					
200	Black clay with organic odor		Delta	Aquifer 1 (Lt Grn)	
225	Silty sand with gastropod shell fragments		Nearshore lacustrine		
250					
275					
300	Sand and gravel				
325	Very well sorted sand		Nearshore beach deposits or dunes		
350					
375	Sand with plant fragments		Delta		
400	Silty sand with oolites		Nearshore beach deposits		
425					
450					
475	Grey silty clay		Deeper lacustrine		
500					
525					
550				Aquifer 2 (Lt Blu)	
575					
600					
625					
650	Silty sand with clay -decayed organic matter		Delta		
675					
700					
725	Grey silty clay		Deeper lacustrine		
750				Aquifer 3 (Org)	
775					
800					
825					
850	Silty sand with gravel		Delta deposits		
875					
900					
925	Grey silty sand		Nearshore lacustrine		
950					
975					
1000	Grey clay		Deeper lacustrine		
1025				Aquifer 4 (Drk Grn)	
1050					
1075	Sand with traces of plant fragments		Delta deposits		
1100					
1125					
1150					
1175	Grey silty clay		Lacustrine		
1200					
1225				Aquifer 5 (Brn)	
1250					
1275					
1300					
1325			Delta/nearshore lacustrine		
1350	Silty sand		Braided stream		
1375					
1400					
1425	Silty sand with trace of gravel		Braided stream		
1450					
1475					
1500					
1525					
1550	Silty sand		Braided stream		
1575					

▨	No lake – prior to lake development
▨	Transgressive sequence – lake levels rising, sediments fining upwards
▨	Regressive sequence – lake levels dropping – sediments coarsening upwards

INTERPRETED HYDROSTRATIGRAPHY

Whereas sedimentary facies are a result of the depositional environment in which the sediment was deposited, hydrostratigraphy refers primarily to the hydraulic properties of the sediments, such as hydraulic conductivity and storage coefficient. It is the hydrostratigraphy that is of most interest in groundwater modeling because it is the hydraulic characteristics of the sediments that will control groundwater flow. However, because in many cases the depositional environment has a strong influence on hydraulic characteristics, the various sedimentary facies discussed previously translate well into hydraulic properties. For example, deeper lacustrine deposits of clay have very low hydraulic conductivity resulting in an aquitard, whereas beach deposits or delta deposits may have relatively high hydraulic conductivity, resulting in a potentially productive aquifer.

It is important to note that stratigraphic sequences are not universally synonymous with aquifers or aquitards. A stratigraphic sequence is a depositional episode in which all source material (ranging from coarse to fine material) is deposited depending on the depositional facies. Assuming water supply is not limited, material is laterally distributed based on the energy, or velocity of the water or wind. A stratigraphic sequence will contain the full range of sediment size from coarse to fine. The lateral and vertical distribution of the layers will be genetically linked by the depositional processes in place at the time of deposition, and the lithology at any specific location cannot be determined from the seismic data alone. Borehole lithologic or geophysical data are required to identify lithology and lithologic trends within each sequence.

An example of this concept can be seen in **Figures 7 - 12** (cross sections C - C' through H – H'). To be consistent with previous work, five (5) aquifers have been named (from shallowest to deepest) as Aquifers 1 though 5. The designation as aquifers is somewhat misleading, because although the stratigraphic sequences correspond to aquifers and aquitards in the delta area (as shown in **Figure 22**), the shallower stratigraphic sequences transition from permeable materials to clay near the center of the lake, and are thus inappropriate to refer to as “aquifers”. However, keeping the aquifer nomenclature for the time being, the following observations can be made:

- Aquifer 1 is the shallowest aquifer, characterized by a lithology of relatively well-sorted coarse sands and gravels in the delta area. Overall, the resistivity observed in this aquifer is characteristically very high, suggesting an absence of clay or silt material and a subaerial depositional environment. However, beneath the lake, this stratigraphic sequence transitions to lacustrine clays.

- Aquifer 2 consists of relatively coarse material in the delta, but tends to have declining resistivity (higher percentage of fine material) with depth of the aquifer. The tops of this aquifer correlates with the Light Blue (Lt Blu), Orange (Org), and Dark Green (Dk Grn) sequence boundaries on Sections A-A’ and B-B’. The sequence transitions to lacustrine clays in the southern part of the lake in a pattern similar to Aquifer 1.

- Aquifers 3 and 4 also consist of relatively coarse material in the delta, but tend to have declining resistivity (higher percentage of fine material) with depth of the aquifer. The tops of these aquifers correlate with the Light Blue (Lt Blu), Orange (Org), and Dark Green (Dk Grn) sequence boundaries on Sections A-A’ and B-B’. Again, beneath the lake, these stratigraphic sequences contain increasing amounts of fine material.

- The top of Aquifer 5 corresponds to the Brown (Brn) sequence boundary. This stratigraphic sequence has a characteristic geophysical and lithologic signature. It is composed of silty sand with interbedded sands and occasional clay. The resistivity of this aquifer is relatively uniform. As noted above, this aquifer is interpreted to be the result of a flood plain or braided stream depositional environment, deposited before the formation of Owens Lake. The bottom of Aquifer 5 is deeper than 1,500 feet over most of the area, except in the eastern portion of the basin, where it is underlain by bedrock at relatively shallow depths.

Again, the seismic sequences are not expected to have the same hydraulic properties or lithology laterally across the study area. Thus, they do not necessarily represent the same hydraulic properties from point to point. Even though the seismic reflections are relatively consistent, the hydraulic properties and lithology are not. Nevertheless, the correlation of sequence boundaries to lithologic and borehole geophysical data shows a strong *relative* correlation of expected hydraulic conductivity.

Because the stratigraphic sequences reflect the structure of the basin very well, they represent an obvious method to develop numerical model layering. Results of this work will directly contribute to the layering strategy to be used by the numerical model. This strategy is under development as part of Task 401.1.5 of OLGEP.

CONCLUSIONS AND RECOMMENDATIONS

The OLGEP geophysics work has demonstrated that the seismic reflection data is a powerful tool to support development of a revised hydrogeologic conceptual model and numerical model layering strategy. The combination of seismic reflection interpretation with geologic data from surface geologic maps and borehole information allows for development of detailed information on structural geology, depositional history, and hydrostratigraphy. Structural features and the basin geometry have been mapped with greater precision than would be possible using borehole information alone, and the seismic data provides valuable insight in areas where wells do not exist. The key is the combination of seismic, drilling data, and surface data that allows for a much more detailed understanding than could be possible with any on data source alone.

Modern seismic interpretation software has greatly improved the ability to image and analyze features, such as the hydyrostratigraphic and structural complexities that cannot be mapped using borehole data. The seismic interpretation allows for contouring of seismic sequences that have been directly transferred to groundwater modeling software.

The results of the geophysics study has allowed for a comprehensive hydrogeologic conceptualization for numerical model development. This approach involved the incorporation of the seismic, well log interpretation, geologic maps, and other information to create a conceptual model that represents the full body of geologic knowledge currently available. This work has resulted in the determination of mapped horizons to be used in the model, depth grids, fault significance, and other characteristics that are significant or related to the framework of the numerical model. Elevation grid files (xyz) of aquifer tops and bottoms of stratigraphic sequences were used to create conceptual cross sections of the study area.

The following steps are recommended to utilize the information generated in this work in groundwater model development:

1. Utilize the seismic sequence boundaries identified in this work as the starting point for numerical model layering. Consider abandoning the designation of “aquifers”, with the more general nomenclature of “layers”.

2. Subdivide the shallowest and deepest layers as necessary to most practically represent shallow surface features such as springs, and very deep sediments below the investigation depth of drilling and surface geophysics.

3. Utilize lithologic information from drilling, aquifer testing data, and depositional environment information from seismic interpretation to develop aquifer property zonation and anisotropy properties within each model layer.

4. Add faults to the model based on structural interpretations documented by this study. A practical, generalize multiple splays of faults as one fault. During initial calibration efforts, base the extent to which faults acts on barriers on the relative amount of vertical displacement noted in the interpretations.

REFERENCES

Johnson, K., Eliason, J., Maddox, G., and Brooks, T., 1999. Summary Report, Characterization of the Owens Lake Basin Hydrology System, Inyo County, California.

Levin, Harold. 2005. The Earth Through Time. Eighth Edition, Wiley, Hoboken, New Jersey.

MWH, 2010. Evaluation of Geophysical Data for Incorporation into the OLGEP (Phase I), 29 pages. September.

Neponset Geophysical Corporation (Neponset) and Aquila Geosciences, Inc. 1995. Final Report, Phase 2 Seismic Program, Owens Lake, Inyo County, California, 54 pp.

Neponset Geophysical Corporation (Neponset) and Aquila Geosciences, Inc. 1997. Final Report, Phase 3 and 4 Seismic Program. For Great Basin Unified Air Pollution Control District . Owens Lake, Inyo County. California.

Seisware International. 2010. http://www.seisware.com/index.htm.

Sierra Geosciences LLC and Geologic Analysis and Consulting Services, 2001. Final Report, 1999 River Site, Regional Pumping Test and Analysis, Owens Lake, California.

Sierra Geosciences LLC, 2002. Summary of Construction, Analyses, and Long Term Monitoring – Fault Test Site, Owens Lake, California. Report for Great Basin Unified Air Pollution Control District. November.

ATTACHMENT A

Phase I Cross Sections A - A' and B - B'

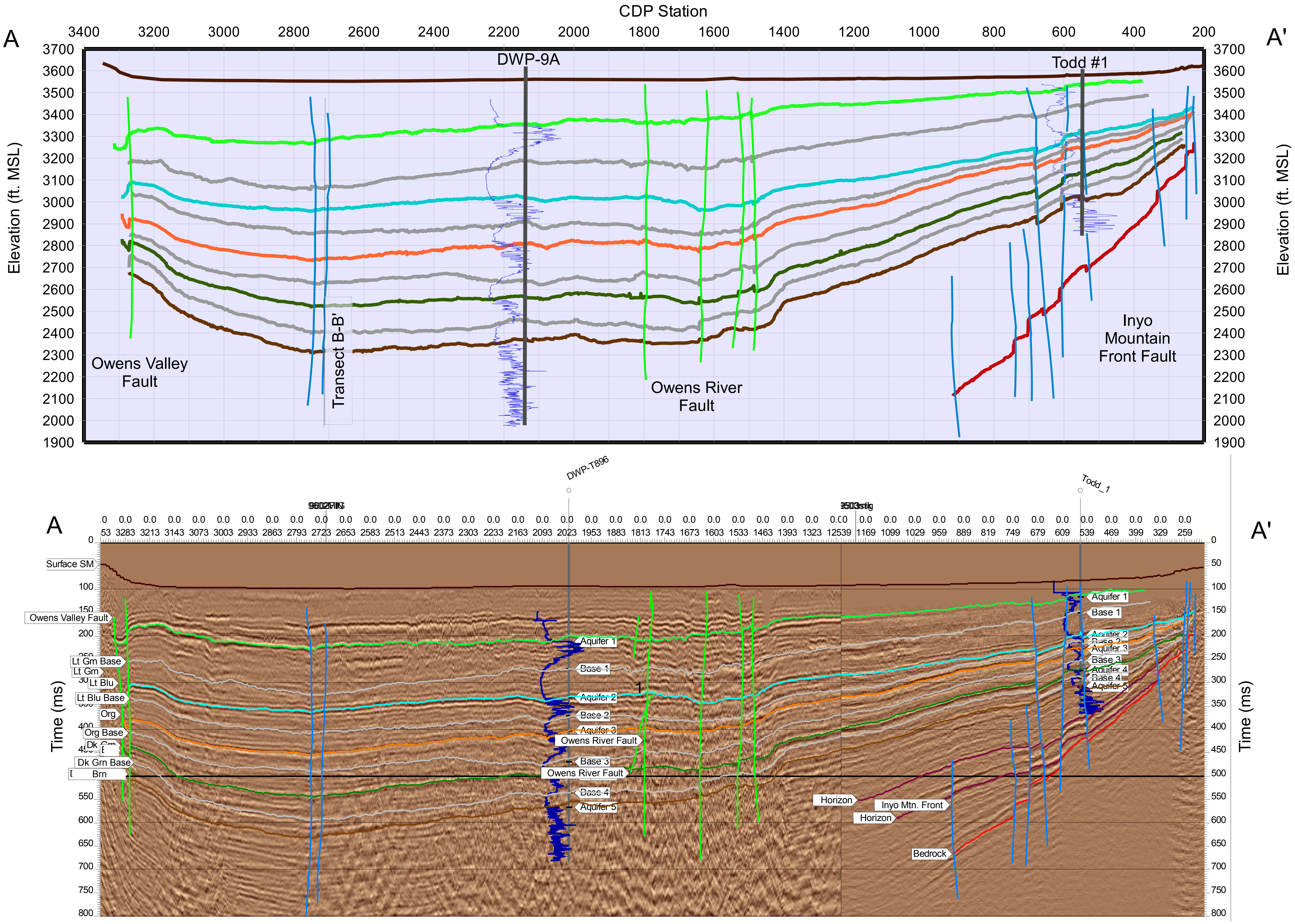


Figure 3: Transect A-A' interpreted depth section (top) and migrated time section (bottom). Sequence boundaries are shown in colors, and clays are shown in gray. Bedrock is shown in red. Wells are shown with guard logs overlaid in blue. Note that DWP-9A is projected slightly differently on the two profiles. The well is projected due south on the time section and closest distance on the depth section. See Figure 1 for location.

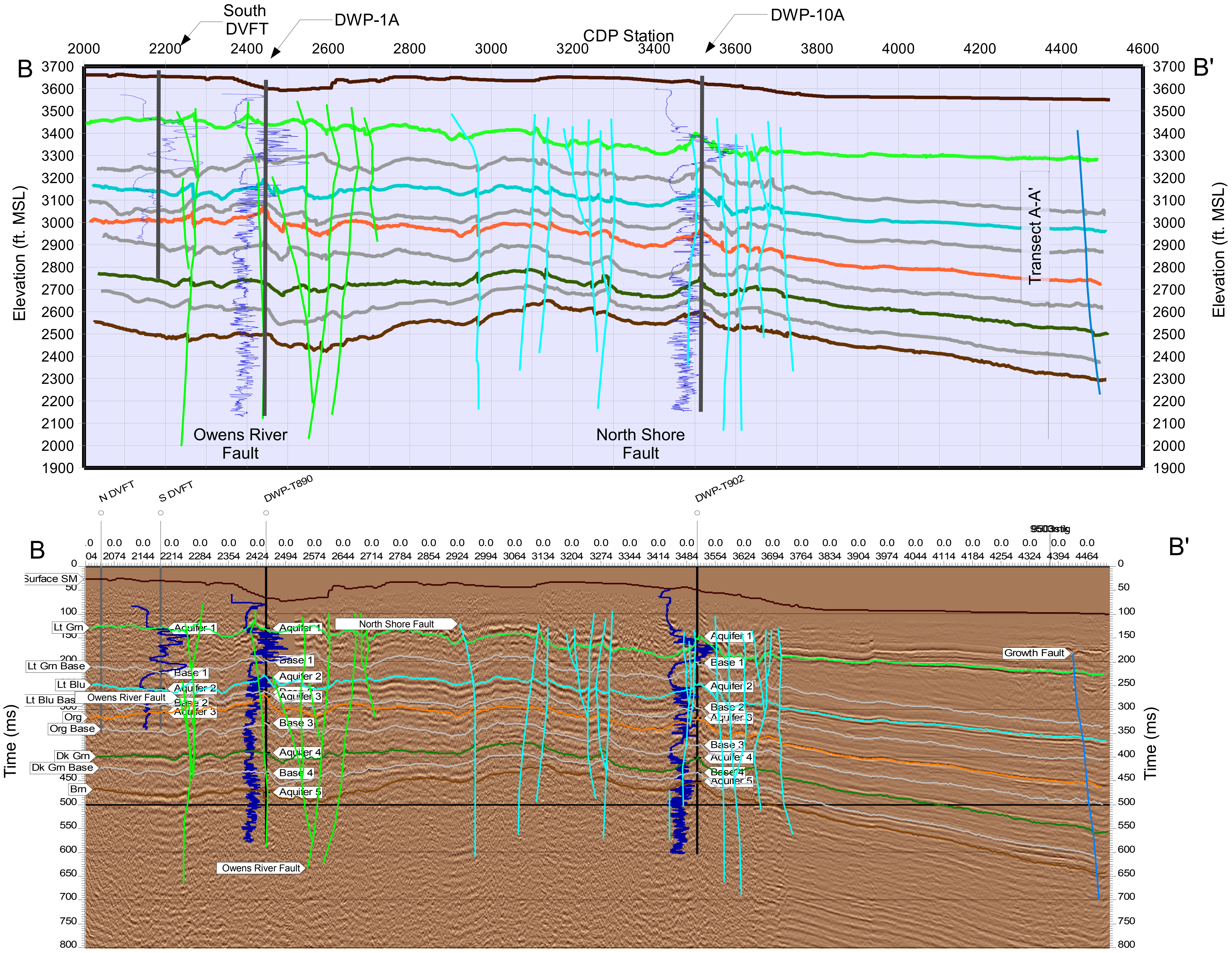


Figure 4: Transect B-B' interpreted depth section (top) and migrated time section (bottom). Sequence boundaries are shown in colors, and clays are shown in gray. Wells are shown with electric logs overlaid in blue. Guard logs are displayed at DWP-1A and DWP-10A. South DVFT is a 64-in electric log. See Figure 1 for location.