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Defining Aquifer Architecture Using Seismic and Sequence Stratigraphy in the Los Angeles Basin, California: a Foundation for Future Assessment and Management of Groundwater Resources*

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Abstract

Sequence stratigraphic models for the Pleistocene to Holocene sediments of the Los Angeles (LA) Basin will provide better understanding of regional groundwater flow and have helped identify seawater intrusion pathways into important groundwater aquifers. Because groundwater provides more than one-third of the municipal water supply for the coastal LA Basin, the aquifer architecture of this system is a high priority for groundwater managers. Seismic and sequence stratigraphy are now incorporated into groundwater resource assessments and environmental investigations. By evaluating subsurface data using sequence stratigraphy, the geometry and distribution of aquifer and aquitard sediments are defined, thus groundwater contaminant plumes and sea water intrusion pathways are better understood. The U. S. Geological Survey (USGS), in cooperation with Los Angeles County Department of Public Works and the Water Replenishment District of Southern California undertook an investigation of the groundwater stratigraphy of the Wilmington – Long Beach area of the LA Basin. Sequence stratigraphic methods were used to integrate preexisting groundwater well data with: (1) new borehole observations, (2) structural and physical properties data derived from geophysical measurements, (3) hi-resolution seismic reflection data obtained offshore of the present shoreline, and (4) vintage oil company exploration seismic reflection data from both onshore and offshore of the shoreline. These data were used to construct a series of Pleistocene to Holocene environment of deposition maps that show the overall progradation of sequences seaward over time. In addition, seawater intrusion pathways into coastal groundwater aquifers were identified and mapped. On a more regional scale, a vintage Texaco seismic reflection data set from the greater LA Basin was interpreted and integrated with a regional network of multi-level ground-water monitoring wells. The sequence stratigraphic correlation shows that many of the defined groundwater aquifers are not correlative. For example, one of the major groundwater supply aquifers, the Silverado Aquifer, when tied to the seismic reflection data has different ages depending on location. This new understanding demonstrates the need for a re-evaluation of the Pleistocene to Holocene stratigraphy using existing seismic reflection data integrated with well data from the LA Basin in order to understand the regional distribution of groundwater aquifers.

Seismic Data Sets

Over 2,000 trackline-kilometers of intermediate and high-resolution seismic-reflection data were collected in the Los Angeles – Long Beach harbor areas as well as the San Pedro shelf and interpreted as part of this investigation. Four primary seismic-reflection data sets collected during the two USGS cruises were interpreted to develop the stratigraphic model (see Figure 1).

The seismic reflection data sets include:

- Intermediate Resolution (interpretable data up to 800 - 1000 msec TWTT)
    - Multichannel 14 cubic-inch sleeve gun (USGS Cruise E-1-01-SC)
    - Multichannel 1.5 kilojoule minisparker (USGS Cruise A-1-00-SC)
- High Resolution (interpretable data up to 200 msec TWTT)
    - Single channel geopulse (USGS Cruises A-1-00-SC and E-1-01-SC)
    - Single channel minisparker (USGS Cruise A-1-00-SC)

The USGS data are available from the NAMSS website:
http://walrus.wr.usgs.gov/NAMSS/

- Oil Company Seismic Data
    - Texaco regional exploration seismic reflection data set from the Central Basin (1980's)
    - Chevron regional exploration seismic reflection data from the West Coast Basin (1970's)

The Texaco data set was collected in the mid-1980's and covers a large area of the Central Basin (Figure 1). Major seismic transects used railroad right-of-ways and the Los Angeles and San Gabriel Rivers, Compton Creek, and Rio Hondo to collect relatively continuous regional lines.

Well Data Sets

Several different well and borehole data sets were integrated into the seismic stratigraphic analysis of the region as shown on Figure 1.

- Dominguez Gap Barrier Project (DGBP)
- Historic groundwater production wells
- Environmental groundwater monitoring wells
- Oil wells (both exploration and production)
- U. S. Geological Survey stratigraphic wells drilled as part of this investigation
    - LBPC: Long Beach Pier C well
    - LBPF: Long Beach Pier F well

    - LBCH: Long Beach Cabrillo High School well
    - LWEB: Long Beach Webster well
- USGS – WRDSC monitoring wells
    - Pico-1
    - Rio Hondo-1
    - South Gate-1
    - Compton-1
    - Long Beach-2

Overview of Sequence Stratigraphy

Using techniques of seismic and sequence stratigraphy outlined in Mitchum and others (1977) and Van Wagoner and others (1990), ten defined sequences were defined and correlated in the Long Beach - Wilmington area of the LA Basin. These ten sequences that overlie undifferentiated Tertiary strata as shown on the Cross Sections A' - A", B - B' - B", and C - C' are presented on Figure 2, Figure 3, and Figure 4. Each sequence boundary is defined by a seismic reflector/surface that shows evidence of truncation below and/or onlap above, and are discussed at length in Ehman and Edwards (2014).

The older sequences are best delineated with the medium-resolution multichannel sleeve gun data collected inside the harbor (Figure 2a). The upper sequences, particularly the Dominguez (Light Blue), Mesa (Orange), and Pacific (Pink) are best delineated on the high-resolution, single-channel data collected inside Los Angeles harbor complex (Figure 2b).

In the area of seismic coverage in the Los Angeles - Long Beach Harbor complex and adjacent San Pedro shelf, the aquifer architecture offshore was not delineated until the work of Edwards and others (2009) and Ehman and Edwards (2014). The coastal aquifers as discussed by California Department of Water Resources (1961) and Zielbauer and others (1962) has been only identified onshore. However, because of the generally high quality of marine seismic reflection data, the sequence stratigraphy of the region can be better defined offshore, particularly when tied to detailed stratigraphic data derived from USGS boreholes LBPC and LBPF (Figure 5). Once defined, the sequences can be correlated onshore, and the aquifers can be better understood within a sequence stratigraphic framework (Ponti and others, 2007; Edwards and others, 2009; Ehman and Edwards, 2014). Ponti (1989) initiated the new chronostratigraphic names (although not linked to the sequences at that time). Ponti and others (2007) assigned each of the sequences a new chronostratigraphic name to avoid confusion with the aquifer names used in reports such as California Department of Water Resources (1961) and Zielbauer and others, (1962).

North to south cross section A - A' - A" (Figure 2 and Figure 6) shows the distribution of Upper Pliocene to Holocene sequences in the Wilmington – Long Beach harbor complex. The cross section extends from Interstate 405 south to Pier F in Long Beach Harbor. The axis of the oil-producing Wilmington anticline is located near USGS LBPC. To the north of the axis of the Wilmington anticline, the Pacific Coast Highway fault (PCH fault) was first described by Ponti and others (2007) and appears to have been active during the late Pleistocene, but does not offset the Holocene-age Dominguez sequence (Gaspur aquifer).

In addition to the distribution of sequences, cross section A'' - A' illustrates problems with the aquifer designations in this area (Figure 6). For example, the main bulk of the Silverado aquifer north of the PCH fault is within the Upper Wilmington sequence, and extends into the overlying lower Bent Spring sequence and underlying upper Lower Wilmington sequence. The USGS LWEB well is located approximately 2,000 feet (610 m) from the type Silverado well, *4/13-23G2*, identified by Poland and others (1956). In the LWEB well, the Silverado aquifer of the upper Wilmington sequence reflects a progradational, gradually upward-coarsening package of shallow marine, deltaic, and locally capping distributary delta or fluvial channel deposits (Ponti and others, 2007). This Silverado unit is truncated by the PCH fault and the unconformity at the base of the Harbor sequence has removed the coarse-grained Silverado aquifer material on the south side of the fault (Figure 6). South of the fault, the sequence is generally fine-grained with a few thin sandy units that have been classified as "400-foot gravel" or Lynwood aquifer by Zielbauer and others (1962). In the harbor area, based on the USGS LBPC and LBPF core holes, the sequence is composed principally of muds that gradually thin offshore into San Pedro Bay.

Similarly, the Lynwood aquifer observed in the LWEB area is restricted to the Harbor sequence. However, south of the PCH fault, the Lynwood is within the Upper Wilmington sequence (Figure 6). The Bent Spring sequence on the south end of cross section A'' - A' contains a series of south-dipping clinoform reflectors and is probably the classic San Pedro Sand described by Woodring and others (1946) on the Palos Verdes Peninsula (Ponti and others, 2007), but not the type Silverado section observed in LWEB.

Cross section A – A' (Figure 6) when compared to California Department of Water Resources (1961) cross sections (Figure 7) illustrates the fundamental problem with the aquifer designations in this area. The aquifer units are not chronostratigraphic sequences, thus correlating aquifers without understanding the sequence stratigraphic architecture is not possible. In this example, both the structure of the region and the subtle angular discordances between sequences play a critical role in defining the aquifer architecture in the Long Beach - Wilmington area. Edwards and others (2009) further discuss this issue in regards to salt water intruding into freshwater aquifers in this area. A seismic facies map from the Dominguez sequence is presented on Figure 8, and is an example of one of the series of maps generated in this investigation.

Problems with aquifer correlation in the Central Basin are illustrated on Figure 9, Figure 10, and Figure 11. Figure 9 shows the correlation of the "Silverado Aquifer" in the USGS - WRDSC monitoring wells from the northern West Coast Basin near LWEB across to the Central Basin to the north (section D - D' in Figure 1). Examination of the correlation from the LWEB well to the wells Rio Hondo-1 and South Gate-1 on Figure 9 and integrating it with the seismic reflection data (Figure 10), demonstrates the problems arising from the correlation of aquifers in the lithostratigraphic style of California Department of Water Resources (1961) (for example, Figure 7) where the seismic interpretation shows the reflections crossing correlation lines. Figure 10 shows seismic lines AA-2 and AA-3 that are sub parallel to the well log cross section shown on Figure 9. Although the upper part of the seismic line (0.15 seconds) is muted, stratigraphy below approximately 0.20 seconds (~250 feet below the surface) is well defined. The aquifers on Figure 11 are from Reichard and others (2003) and represent the previous understanding of the aquifer distribution. Based on the seismic stratigraphic correlation, aquifers identified in the wells, are not chronostratigraphic units as shown by the seismic reflections crossing the aquifer correlation (Figure 11).

Conclusions

By constructing a series of cross sections and seismic facies maps interpreted from the integration of seismic reflection lines and well logs, this investigation further defined ten sequences of Late Pliocene to Holocene age in the Wilmington - Long Beach area of the Los Angeles Basin first described by Ponti and others (2007). The stratigraphic framework established in the Wilmington - Long Beach area is extended into the Central Basin of the greater Los Angeles area by utilizing 1980s and older vintage petroleum exploration land seismic reflection data integrated with borehole data from groundwater monitoring wells and petroleum exploration and production wells. These sequences are characterized by a series of deltaic stratigraphic packages (clinoform intervals) that are oldest in the Central Basin and progressively prograde to the south where the youngest clinoform intervals are observed in the subsurface of San Pedro Bay.

Implications of a sequence stratigraphic framework on sea water intrusion were discussed by Edwards and others (2009) and expanded in Ehman and Edwards (2014) by presenting a series of regional maps of seismic facies and environments of deposition for the five youngest sequences: the Dominquez Sequence, the Mesa Sequence, the Pacific Sequence, the Harbor Sequence, and the Bent Spring Sequence.

Tying the seismic data to the available network of well logs from the groundwater monitoring wells in the Central and West Coast Basins reveals problems in historical aquifer correlation, and provides new insights into a more robust groundwater model for the greater Los Angeles Basin area in the future.

The sequence stratigraphic framework established in this study has major implications in redefining and correlating major aquifers in the greater Los Angeles Basin area. Such aquifers include the Gage (“200 Foot Sand”), the Lynwood (“400 Foot Gravel”), and Silverado aquifers and are each shown to be regionally diachronous. If groundwater flow paths are better understood in light of sequence stratigraphic rather than lithostratigraphic models, then the groundwater model developed for the basin (Reichard and others, 2003), has an opportunity to be reassessed in light of this new understanding of the aquifer architecture.

By incorporating the sequence stratigraphic framework established in this report to address specific groundwater issues, groundwater managers have new tools/insights to explain many of the problems and anomalies associated with current groundwater production and recharge.

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Finally, this paper is dedicated to the memory of hydrogeologist Wayne Jackson, formally of the Los Angeles County Department of Public Works, for supporting this project and advocating sequence stratigraphy as a means of solving problems associated with salt water intrusion of coastal aquifers in the Los Angeles Basin.

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Figure 1. Study area base map.

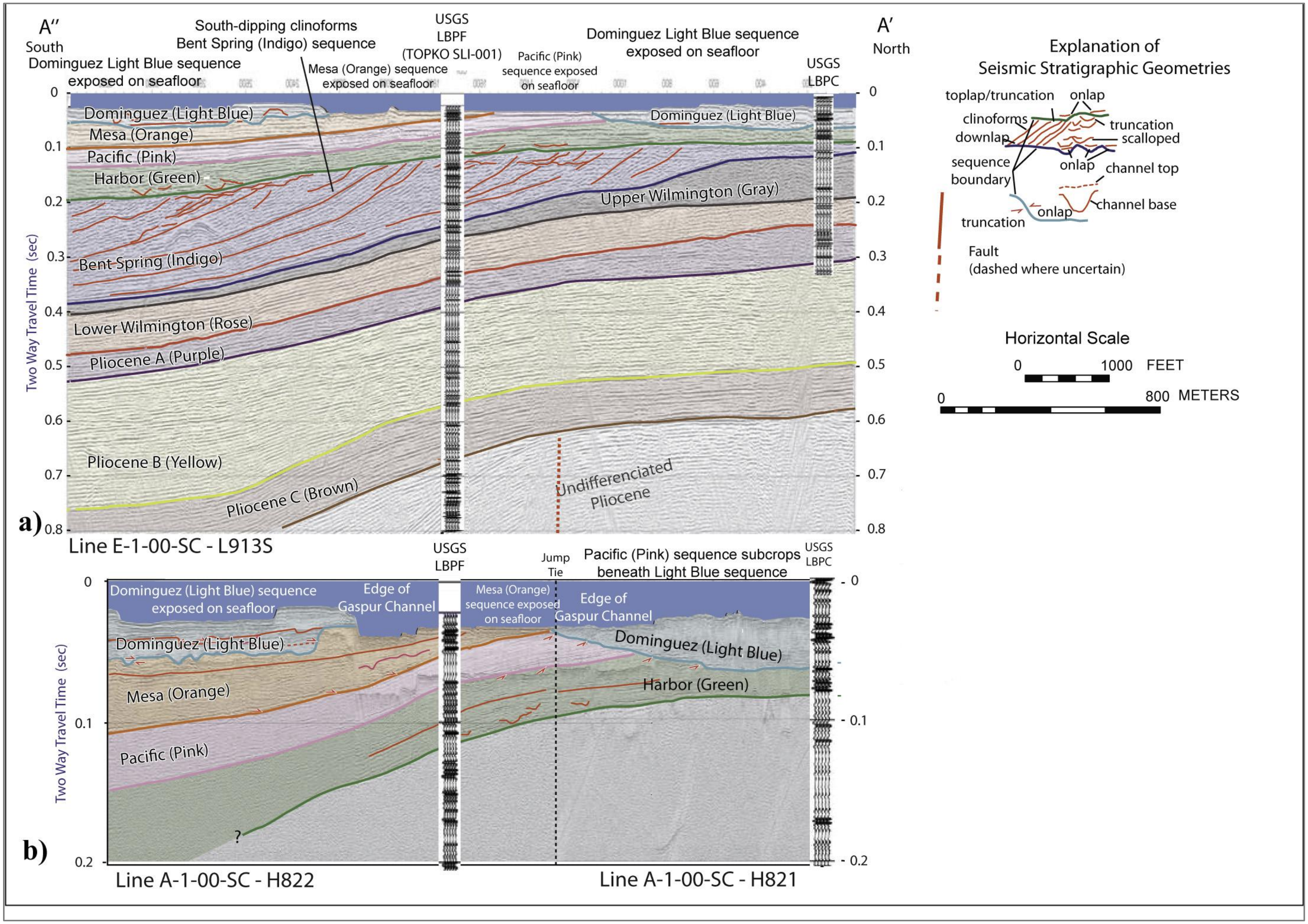

Figure 2. Interpreted seismic profiles along the southern part of cross section A'' - A'. a) Multi channel seismic reflection line E-1-00-SC-L913S. Synthetic well ties from USGS LBPF (combined with TOPKO SLI-001) and USGS LBPC projected on to line (see Figure 1 for location). b) Single channel seismic reflection line A-1-00-SC-H822 and A-1-00-SC-H821. Synthetic ties from USGS LBPF and USGS LBPC projected on to line. Modified from Ehman and Edwards (2014) Figure 11.

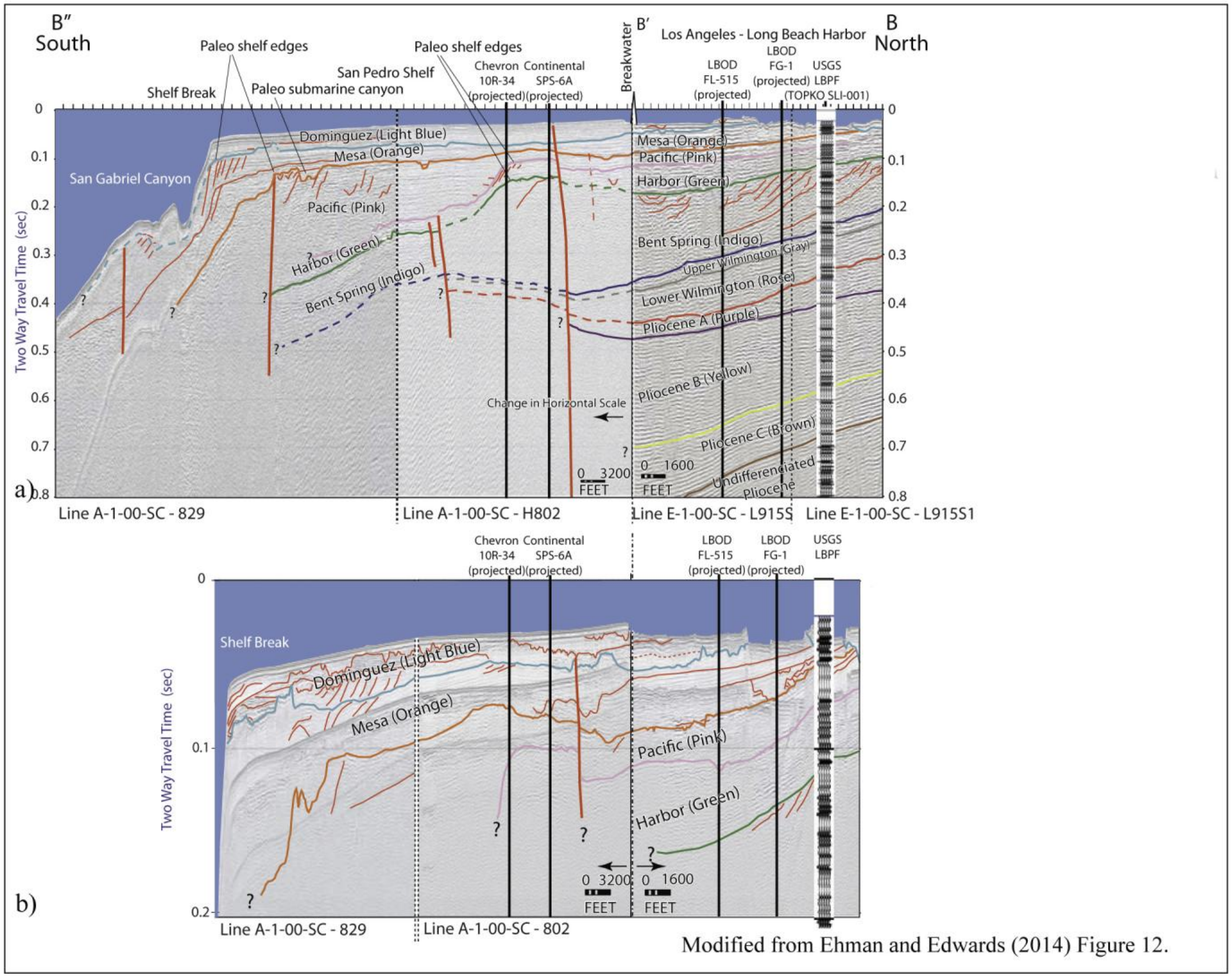

Figure 3a. Cross section B - B'- B" constructed from multi-channel seismic reflection lines E-1-00-SC-L915S1, E-1-00-SC-915S, A-1-00-SCH802, and A-1-00-SC-829 (see Figure 1 for location). Synthetic well ties from USGS LBPF combined with TOPKO SLI-001 are projected on to line.

Figure 3b. Cross section B - B'- B" constructed from single-channel seismic reflection lines A-1-00- SC-829 and A-1-00-SC-802 (see Figure 1). Synthetic well ties from USGS LBPF combined with TOPKO SLI-001 are projected on to line.

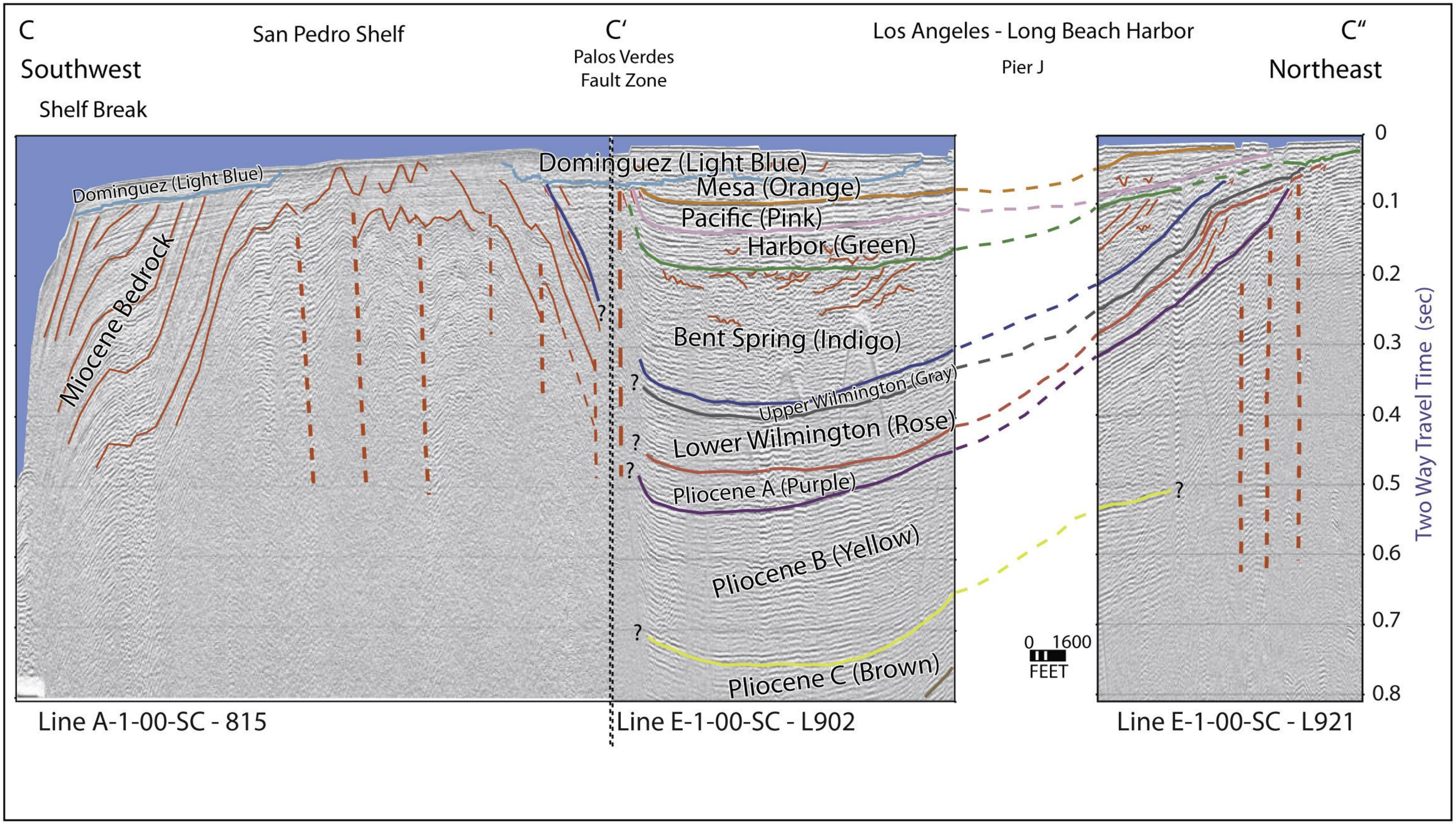

Figure 4. Cross section C - C' constructed from multi-channel seismic reflection lines A-1-00-SC-815, E-1-00-SC-L902, and E-1-00-SC-L921 (see Figure 1 for location). Modified from Ehman and Edwards (2014) Figure 13.

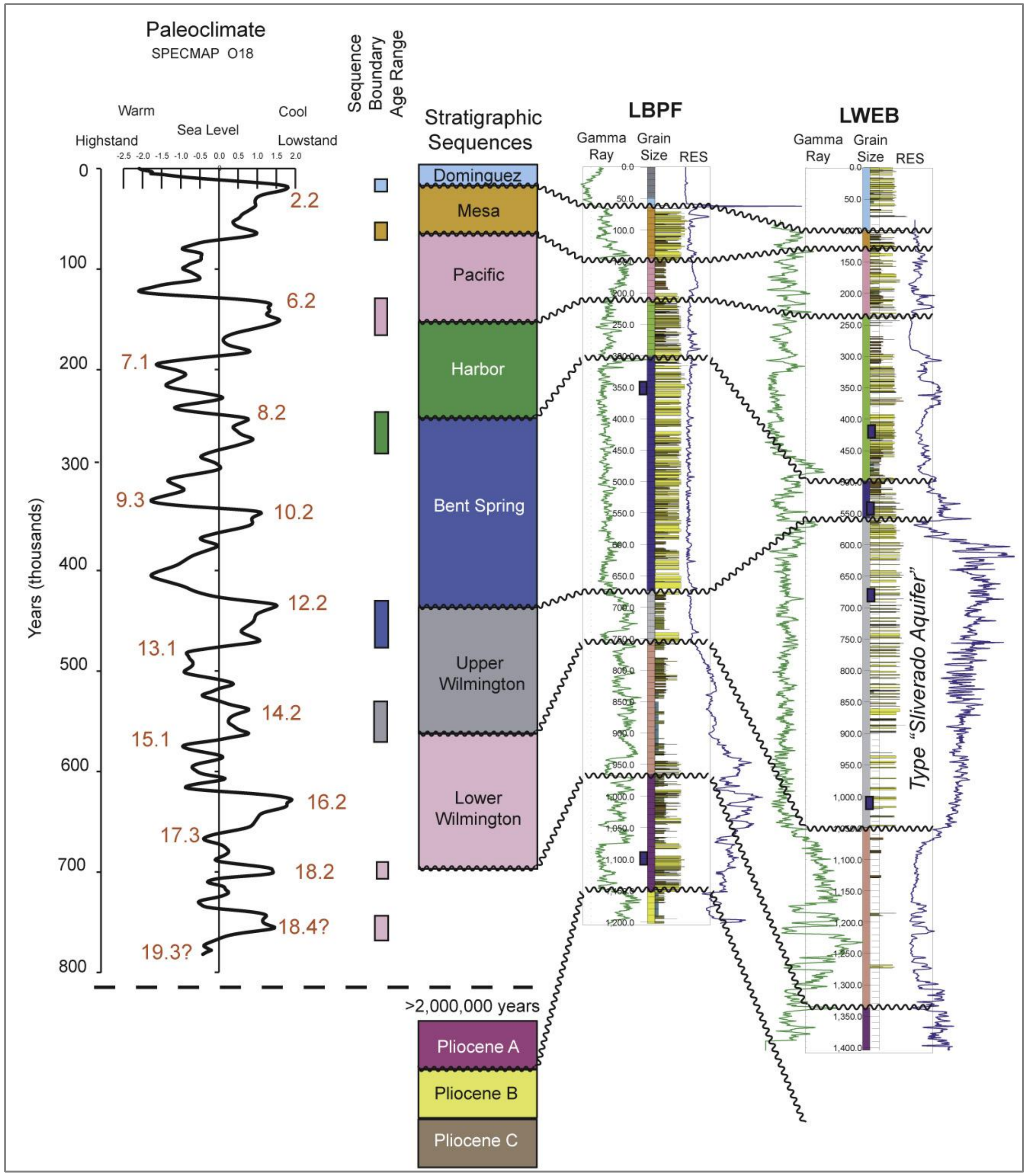

Figure 5. Age model based on sequence stratigraphy. Paleoclimate, stages (in red), and O^{18} curve from Bassinot and others (1994). Highstands of sea level correspond to warmer interglacial periods while lowstands correspond to cooler glacial periods. Major unconformities develop during lowstands of sea level. Age ranges for unconformities are based on Ponti and others (2007). Note that this age model does not incorporate McDougall and others (2012). Depth scale on logs is feet below ground surface. Modified from Ehman and Edwards (2014) Figure 6.

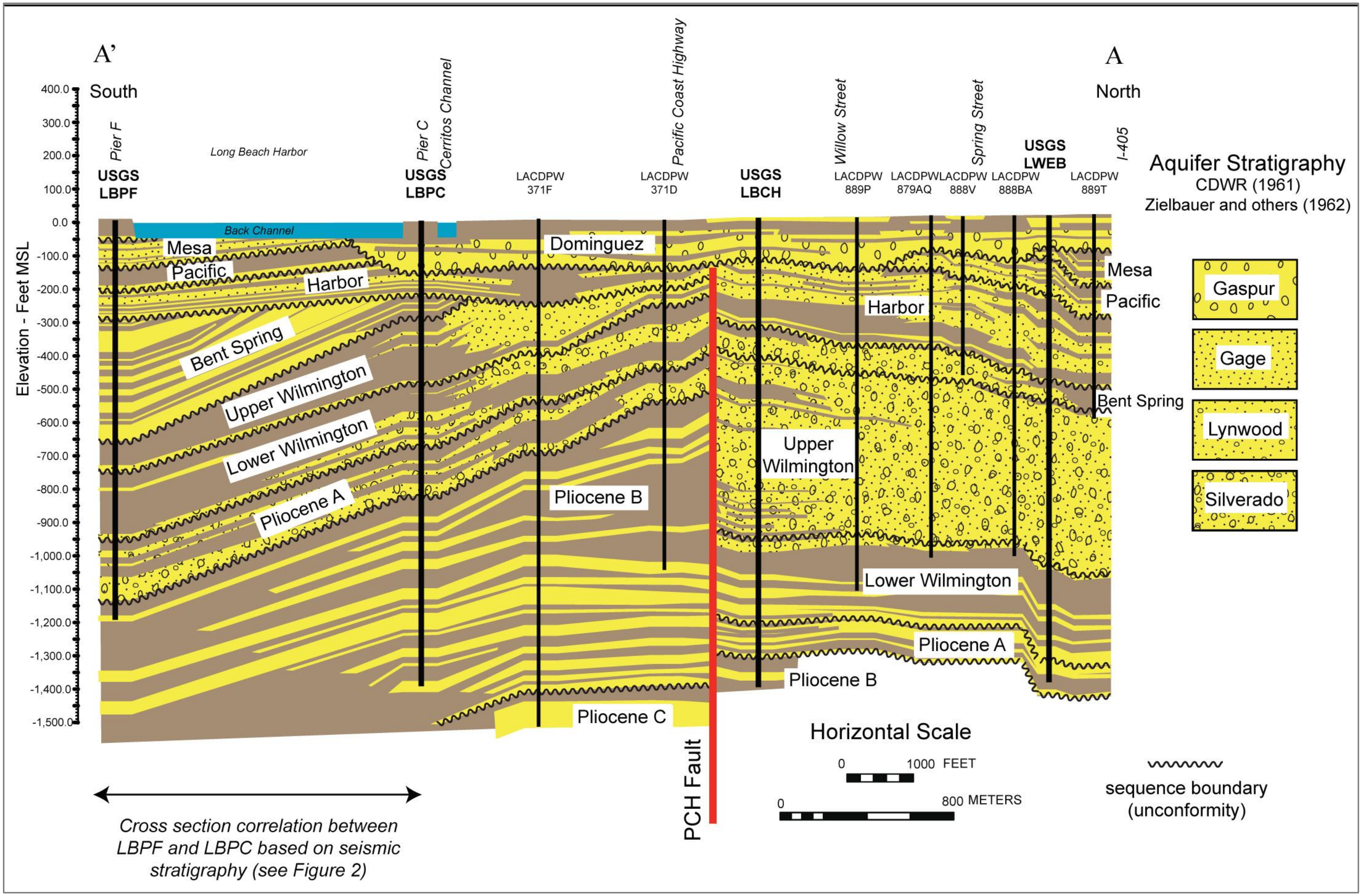

Figure 6. Simplified sequence stratigraphic cross section A - A' (see Figure 1 for location). Yellow indicates aquifer sand and gravel while brown indicates aquitard silt and clay. Note that Silverado aquifer is in different sequences north and south of the PCH Fault. Figure modified from Figure 8 of Edwards and others (2009) and Figure 14 of Ehman and Edwards (2014).

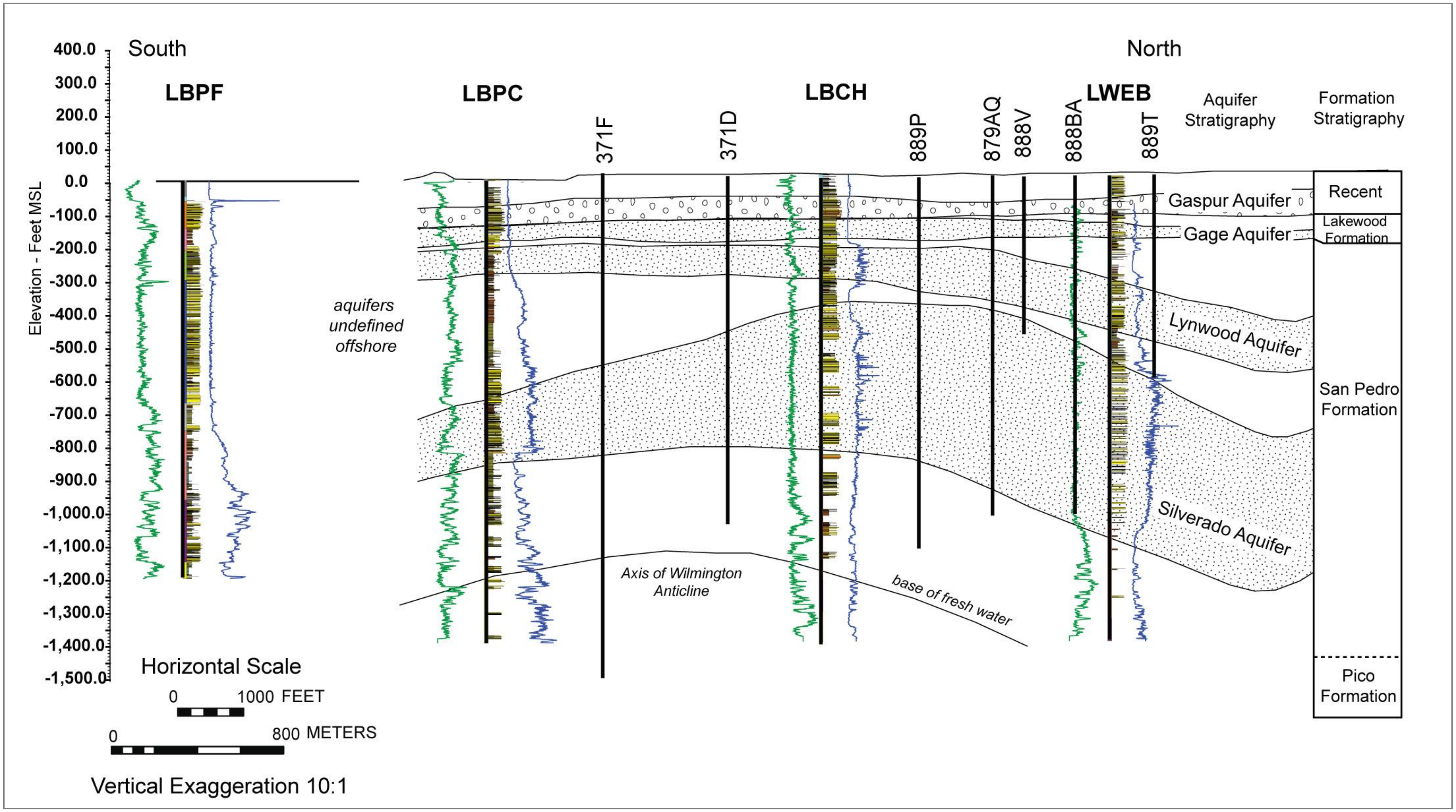

Figure 7. Southern portion of cross section K - K' from California Department of Water Resources (1961) showing aquifer stratigraphy and lithostratigraphy of the Wilmington - Long Beach area as interpreted prior to this investigation. Cross section is modified to show wells projected from cross section A - A' (Figure 6). Graphic grain-size-and geophysical logs are shown for USGS wells LBPF, LBPC, LBCH, and LWEB. Note that aquifers are shown as relatively continuous blankets of sand/gravel. Modified from Ehman and Edwards (2014) Figure 2.

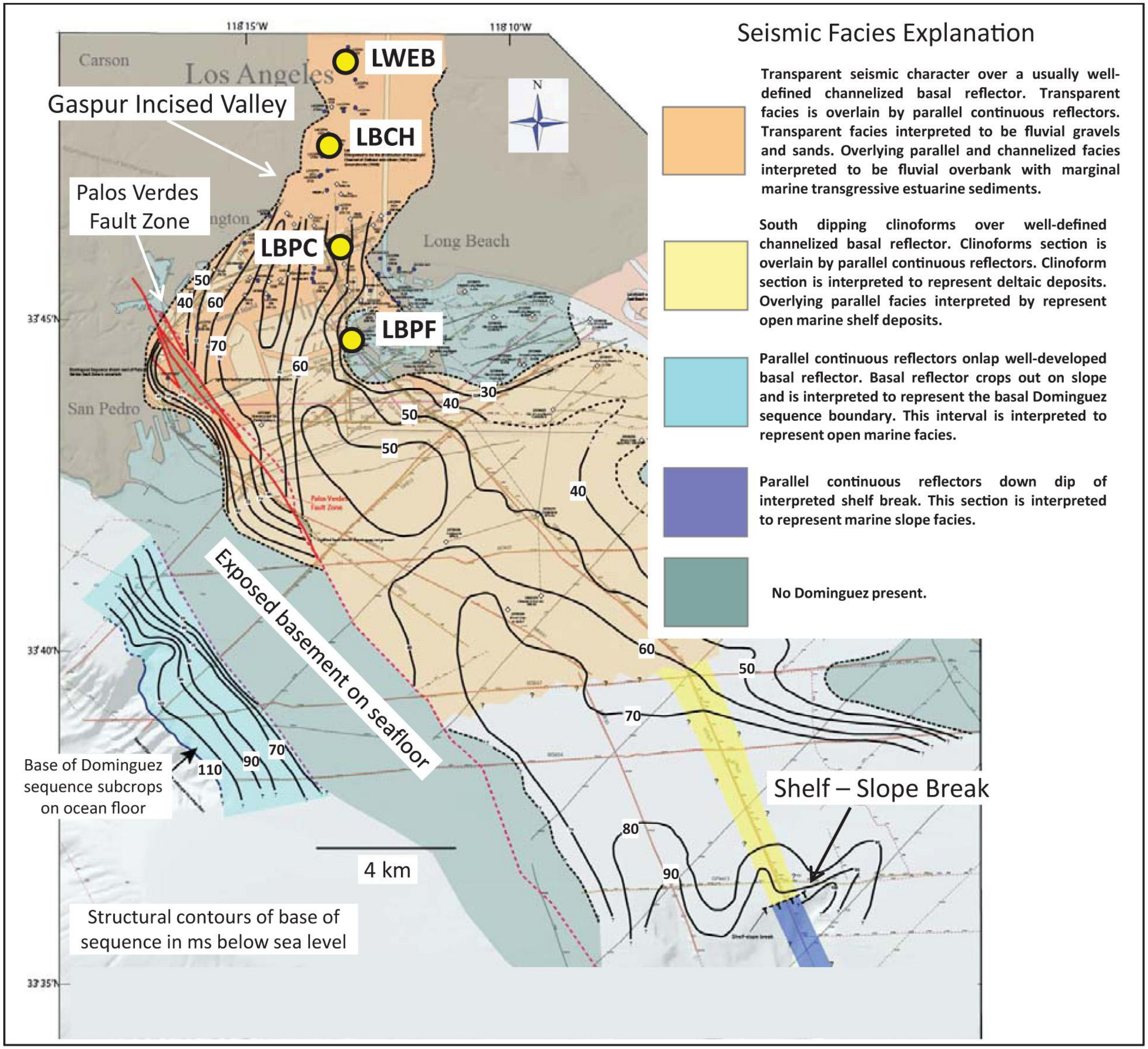

Figure 8. Seismic Facies Map Dominguez Sequence. Modified from Sheet 18 of Ehman and Edwards (2014).

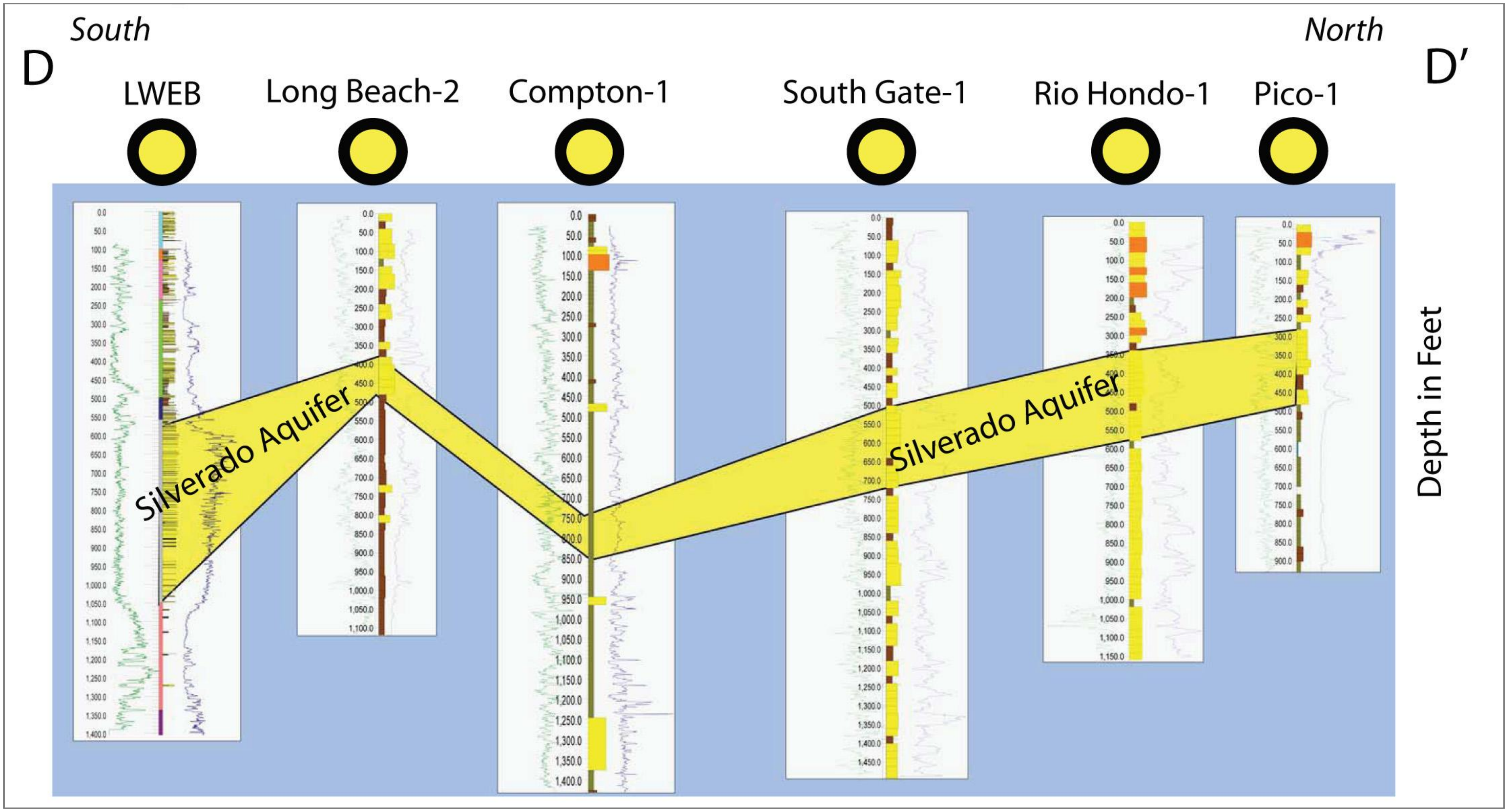

Figure 9. Regional Silverado aquifer well log cross section through major WRDSC monitoring wells showing the existing correlation of the Silverado aquifer from the West Coast Basin (LWEB) into the Central Basin. The type Silverado well, 4/13-23G2 identified in Poland and others (1956), is present in the Wilmington - Long Beach area and located within ½ mile of LWEB well (Figure 1). Figure modified from Ehman and Edwards (2014) Figure 16a.

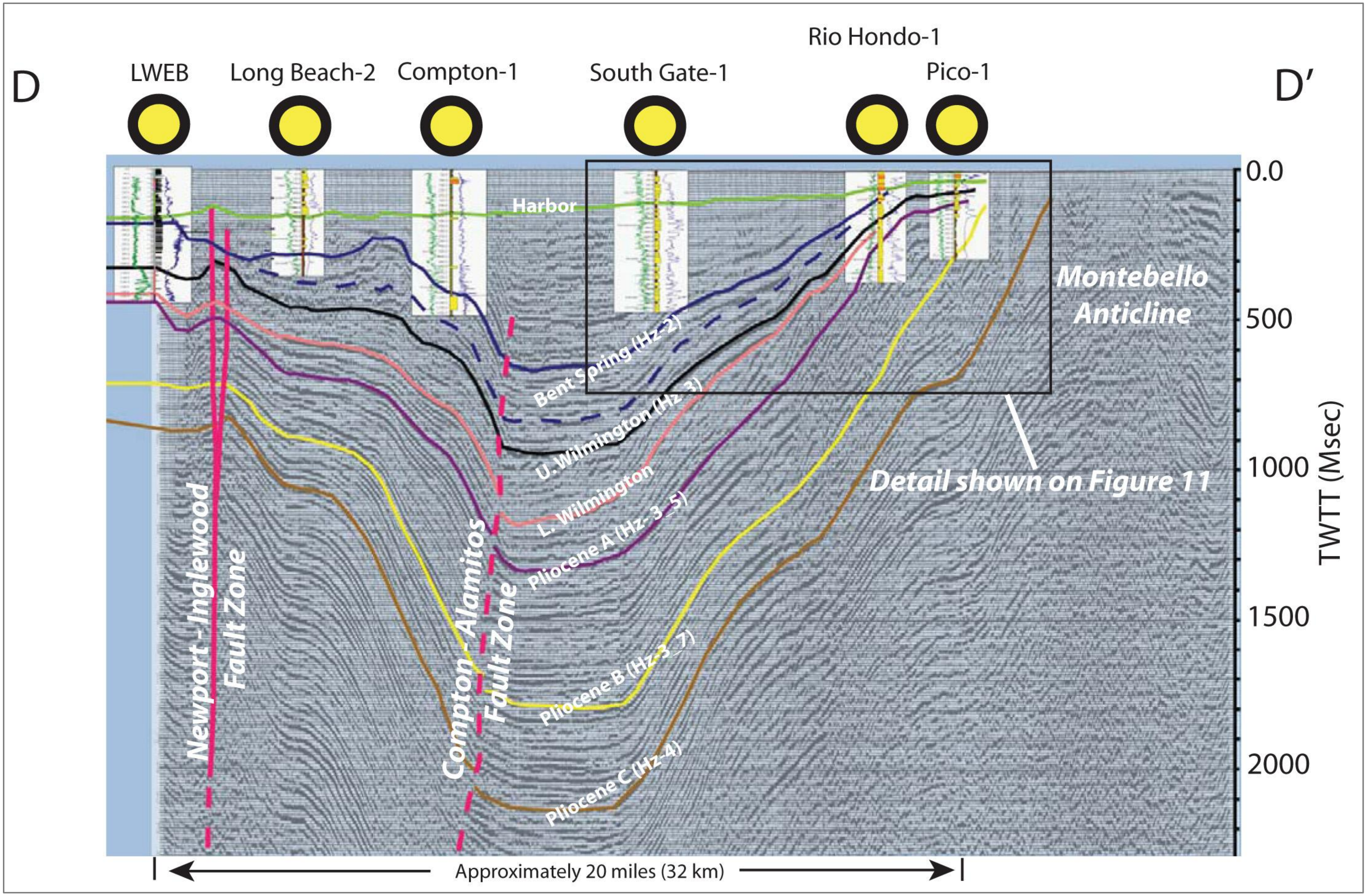

Figure 10. Texaco seismic reflection lines AA-2 and AA-3 tied to WRDSC monitoring wells. Figure modified from Ehman and Edwards (2014) Figure 16b.

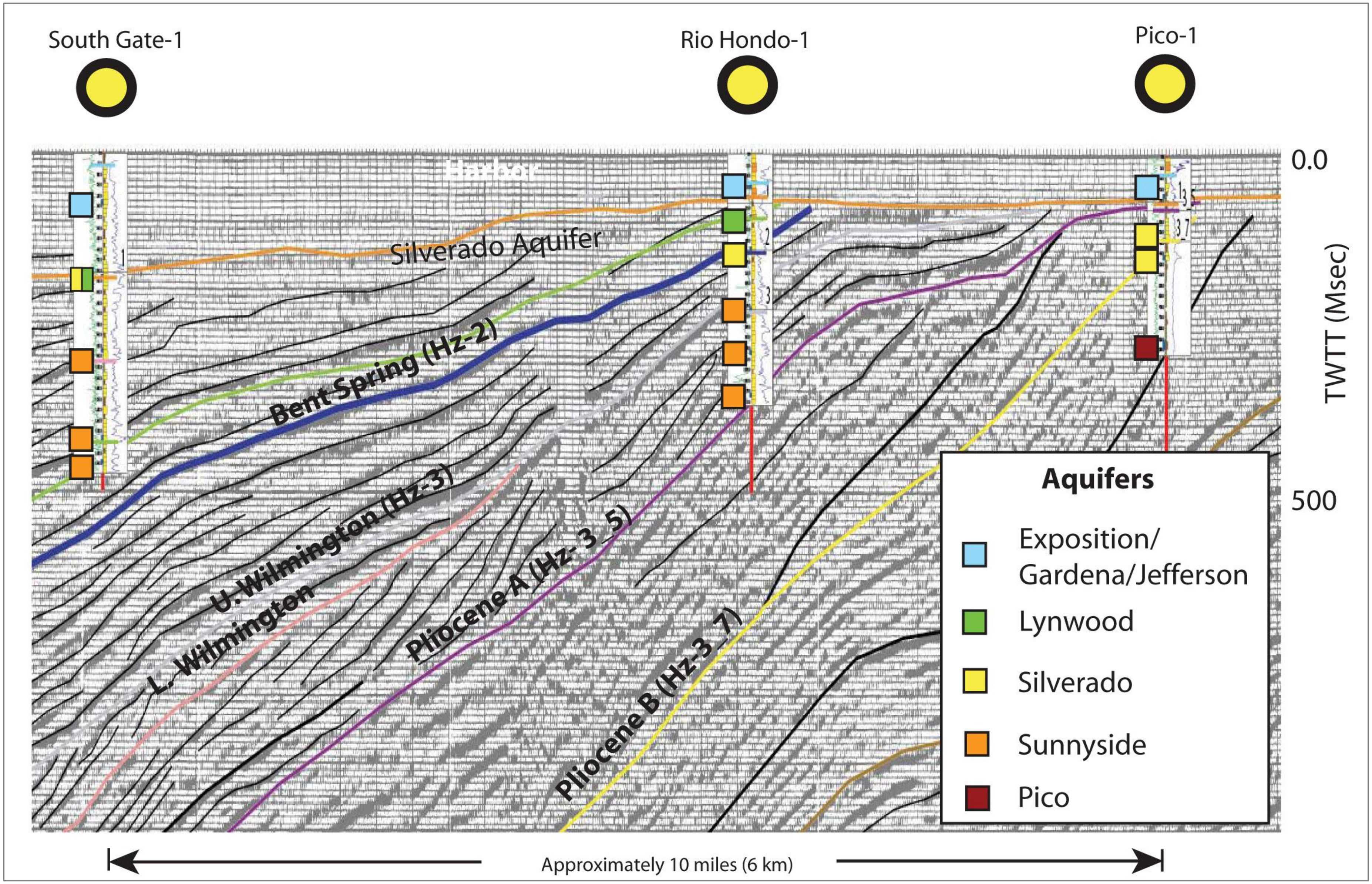

Figure 11. Detail of portion of Figure 10, showing the screened aquifers as discussed in Reichard and others (2003) and the seismic stratigraphic correlation. Figure modified from Ehman and Edwards (2014) Figure 16c.