ANALYSIS OF ACTIVE BLIND THRUST AND FOLD HAZARDS IN THE SOUTHERN LOS ANGELES BASIN FROM SHALLOW AQUIFERS AND AIRBORNE SWATH-MAPPED DEM'S

FINAL TECHNICAL REPORT
NEHRP AWARD 02HQGR0100

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Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number (Recipient, insert award number). The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

This report is a condensed version of Sean Sundermann's (2004) Masters Thesis completed at the University of Colorado, Boulder under the supervision of Prof Karl Mueller and Daniel Ponti of the USGS. Additional information is provided from other NEHRP funded projects to Mueller. Figure numbers retain ordering in Sundermann (2004).

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Abstract

This project combines borehole data and digital topography) to determine uplift rates of active folds within the LA Basin by mapping Quaternary aquifers. Our work places a slower slip rate across the Compton-Los Alamitos trend, based on folding of the Sunnyside aquifer than previous work by Shaw and Suppe (1996). Given an age of 720 ka for the aquifer and the width of its backlimb at this level, we calculate a slip rate on the Compton thrust of 0.51 - 0.56 mm/yr, or about a third the rate determined for older Pliocene strata. The recency of folding across the structure in Los Alamitos appears to be greater than ~12 +/-5 ka, based on a lack of folding across the Gaspur aquifer as (CPT) borings in Los Alamitos. Uplift measured across the Compton trend in Rossmoor is defined as ~38.7 m of structural relief across the Lakewood formation and ~191 m across the Upper San Pedro formation. A second profile measured near Los Altos suggested ~47 m of relief across the Lakewood formation and ~152 meters across the Upper San Pedro. Aquifer surfaces constrained by well logs and seismic profiles across the Compton trend in Los Alamitos suggest 30.1 – 45.7 m of uplift across the 330 ka Gage (base of Lakewood Formation) and ~ 200 m of relief across the Silverado (base of Upper San Pedro Formation). Based on limb dips on depth-corrected seismic profiles (which we use as a proxy for the dip of the underlying Compton thrust ramp) we assign slip rates on the CLA trend as 0.31 mm/yr, 0.38 mm/yr and 0.32 mm/yr for the Lakewood Formation. We assign slip rates on the trend as 0.67 mm/yr, 0.54 mm/yr and 0.71 mm/yr for the Upper San Pedro Formation across the three profiles measured. Comparison of relief across the Compton Los Alamitos trend suggests the fault is decreasing in slip rate between 750 ka and 330 ka. Mapping of the forelimb of the San Joaquin Hills anticline indicates abrupt changes in its strike where segments include a NW-SE trending segment in the El Toro embayment, a 9 km long segment trending EW that marks the northern edge of Newport Mesa and a 21 km-long, NW-SE trending segment between Huntington Mesa and Long Beach. The northmost extent of the San Joaquin Hills anticline is mapped near Signal Hill, between Los Alamitos and Long Beach. Previous mapping of the southernmost Compton-Los Alamitos trend, as interpreted by Shaw and Suppe (1996), is interpreted here as the northern end of the forelimb of the San Joaquin Hills anticline. The geomorphology of marine terraces deformed across the San Joaquin Hills also indicate that this active fold grows above a newly developed fault prior to 330Ka, and rapidly propagates northward to nearly the port of Los Angeles after 122 Ka along a reactivated fault. Eastward migration of the locus of folding in the forelimb of the San Joaquin Hills suggest the underlying blind thrust propagated upward between ~6.2 and 9.6 km for a range of fault dips between 40 and 60°. Offshore bathymetric data suggest the eastern margin of the Santa Catalina Basin is formed by folding of the backlimb of the San Joaquin Hills. Alternatively this sharp bathymetric rise may mark folding above a wedge thrust tip defined by the east vergent San Joaquin Hill's and the underlying Oceanside detachment of Rivero et al., 2000. Mapping of late Quaternary strata folded across the Anaheim Nose confirm it is an 18-km long, northwest-trending anticline formed above a SW-verging blind thrust. A

transect oriented N42°E across the Anaheim Nose suggests 55.3 m of relief of the Lakewood formation and 82 m of relief across the Upper San Pedro formation yielding uplift rates of 0.17 +/- 1.0 mm/yr for the Lakewood and 0.11 +/- 0.3 mm/yr for the Upper San Pedro formation. This indicates an increase in uplift rate between 750 ka and 330 ka and may suggest the Anaheim Nose is accommodating increased shortening in a NE-SW direction across the Los Angeles Basin.

Introduction

Blind thrusts underlie regions undergoing contraction in the Los Angeles Basin and are expressed at the surface only as active folds (Stein and Yeats, 1989; Shaw and Suppe, 1996; Schneider et al., 1996; Shaw and Shearer, 1999; Oskin et al., 2000; Dolan et al., 2003). Seismic hazards posed by active thrusts are assessed in the Los Angeles Basin by a number of means, all of which are aimed at placing constraints on fault slip rates, earthquake recurrence and fault geometry and segmentation (Dolan et al., 1995; Shaw and Suppe, 1996; Shaw and Shearer, 1999). Research into the relationship between fault slip, fault geometry and fold growth thus provides insight into the occurrence of earthquakes produced on these structures. Large earthquakes originating on blind thrusts within Southern California have occurred in the past century, illuminating their geometry and potential for seismic hazard and include the Mw5.9 1987 Whittier Narrows earthquake and the Mw6.8 1994 Northridge earthquake.

Research into blind thrusts in the Los Angeles Basin prior to these events was minimal because their hidden, subsurface nature concealed their true hazard. Subsurface data such as seismic reflection profiles, well logs and instrumentally recorded seismicity are used to define fault slip rates and segmentation by analysis of compressive growth structure in fault-related folds above blind faults that do not cut the surface (Shaw and Suppe, 1996; Shaw and Shearer, 1999; Rivero et al., 2000; Allmendinger and Shaw, 2000). Because direct examination of blind thrust faults is typically not possible, attention is aimed at fault-related folds formed above them, which are used as a proxy for fault slip.

This project incorporates a combination of subsurface structural data (from boreholes) and surface tectonic geomorphology (from digital topography) to determine rates of fold growth and the geometry of fault-related folds within the basin. Work undertaken for this thesis focused primarily on mapping late Quaternary deposits across the basin to assess strain produced by folding. This was aimed at identifying the trend and extent of folds, uplift rates across them and the age of folded late Quaternary deposits. This was accomplished by: 1) using water well logs to map chronostratigraphic units of late Quaternary aquifers 2) analysis of topographic geomorphology to more accurately locate fold hinges and rates of folding and 3) synthesis of structural data to estimate the dip of underlying thrusts, calculate slip rates and estimate their potential for producing future damaging earthquakes.

Project Focus

The main purpose of this award was to define the late Quaternary depositional history of the Los Angeles Basin and the record of folding above several active blind thrusts. We sought to determine the timing and uplift histories of these blind faults and the risk they pose for future earthquakes in densely populated regions. Work undertaken included mapping sequence stratigraphic boundaries across the basin as they act as strain markers for subsurface tectonic deformation. Structural aspects of the thesis were aimed at determining the lateral extent, kinematic history and lateral propagation of active folds. Correlation of aquifers throughout northern Orange County with USGS FOQUS-LA wells also helped constrain the ages of these deposits and their relationship with the global eustatic record and subsidence in the Los Angeles Basin.

Sequence Stratigraphy

Previous work in sequence stratigraphy in the Los Angeles Basin has been largely aimed at interpretation of offshore sediments for petroleum exploration. Sequences are defined as a succession of genetically related strata bounded by unconformities that are deposited between inflection points in the eustatic sea level curve (Van Wagoner et al., 1988). A sequence can be subdivided further based on the eustatic record. Stratal wedges deposited during individual eustatic cycles are termed system tracts, which can be further divided into parasequences. A parasequence is a conformable succession of related strata bounded by surfaces representing changes in water depth (deposited during a single base-level cycle) (Prothero and Schwab, 1996). It has been established that cycle boundaries indicate the transition from base-level fall to base-level rise. High frequency cycles can be mapped across multiple facies tracts and include multiple vertical facies successions and are therefore chronostratigraphic units (Kerans & Tinker, 1997 and Mitchum & Van Wagoner, 1991). Strata that accumulate are affected by the rate accommodation space is created, basin subsidence, and sediment flux. When accommodation is more rapid than infilling, as during a rise in sea level, sequences of retrogradational strata step landward. When accommodation rate is less than the deposition rate, or sea level recedes, and sediment flux exceeds subsidence, progradational sequences step seaward. Equilibrium is achieved when the accommodation area is equal to sediment flux and the parasequence forms an aggradational stacking pattern.

During a sea level lowstand, continental shelves are typically exposed as the shoreline regresses. Erosion is an important process during sea level lowstands, as sediment is transported seaward in fluvial environments towards the receding shoreline. As sediment is transported, new channels are incised into the exposed shelf and preexisting sea cliffs, or shoreline angles. The exposed shelf is incised by fluvial channel networks that transport sediment to the existing shoreline forming fan deltas. When the sedimentation rate exceeds channel capacity or the incision rate, overbank sediments are deposited in interchannel areas. As sea level transgresses, these channels are the first to infill with sediment as a result of the rising base level. During sea level lowstands that occur at lower elevations than previous lowstands, unconformities may develop during both glacial episodes.

During sea level highstands sediment supply slows in relation to creation of new basin accommodation space. The fluvial channels incised during the lowstand will infill first as the base level rises. Parasequences aggrade upward in retrogradational stacking patterns and coarse sediment supply slows in deeper water marine environments. Sediments deposited in these deeper marine settings may then include condensed sections of clay, silt or pelagic shale. As eustatic changes shift to a highstand system track, the shoreline recedes and rivers carrying sediment further seaward and may produce a progradational sequence of deltaic clinoforms. Unconformities that bound parasequences, are commonly attributed to higher rates of erosion. Rates of erosion may be even higher above actively uplifting folds which alter seafloor bathymetry and affect patterns of sedimentation and basin subsidence.

Characterization of Late Quaternary Aquifers

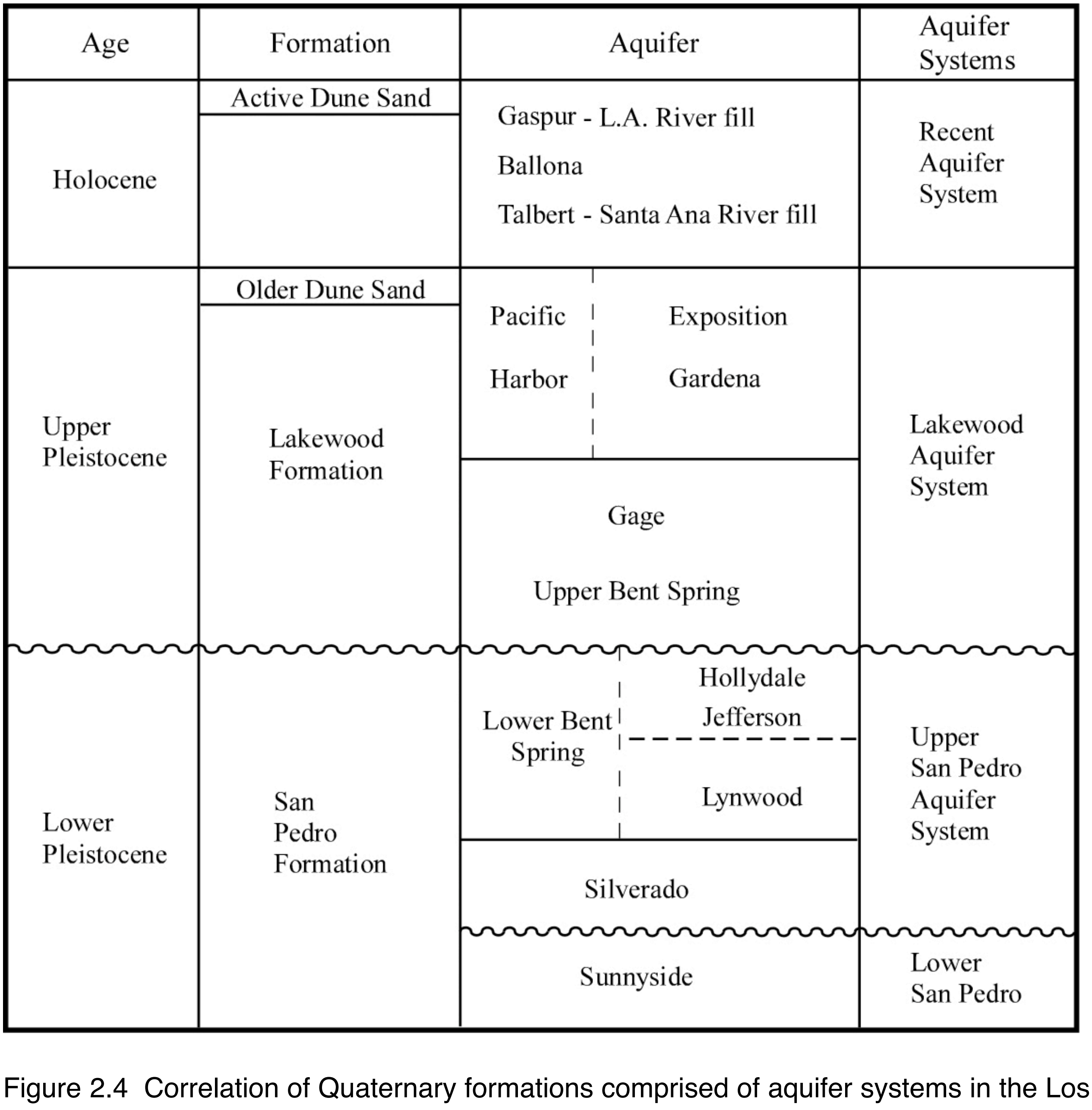
Early Pleistocene strata in the Los Angeles Basin were deposited under shallow, but continuously marine conditions. Younger, late Pleistocene strata were more strongly influenced by eustatic sea level change and were deposited under a mix of shallow marine and terrestrial (fluvial) conditions. Deposition of late Pleistocene sediment in the Los Angeles Basin is influenced by eustacy, uplift of active structures and deposition along rivers and within alluvial fans. Eustatic processes most strongly affect late Pleistocene sedimentation in the western part of the basin, as evidenced by abrupt changes in grain size in vertical sections, angular unconformities, and interfingered marine and nonmarine deposits (Yerkes et al., 1965, FOQUS). The most detailed record of late Pleistocene deposition in the basin has been provided by wells drilled by the Orange County and Los Angeles Water Districts and the U.S. Geological Survey into gravels and finer-grained deposits that control the hydrologic characteristics of this region (Yerkes et al., 1965, FOQUS). Mapping and correlation of these aquifers with the eustatic record provides an important method of measuring recent folding during the last ca. 750 Ka and allows uplift and fault slip rates to be determined for a number of active fold and blind thrust trends.

Late Pleistocene Strata

Late Pleistocene units defined by biostratigraphy in wells drilled for petroleum exploration in the Los Angeles basin are subdivided into the Pico, San Pedro and Lakewood Formations (older to younger) (Yerkes, 1965; Ponti, 1989) (Figure 2-4). Water-bearing gravels in these formations are further subdivided into hydro stratigraphic units grouped by water chemistry and hydraulic connectivity. Work by the USGS has subdivided late Quaternary deposits into an aquifer system with four members that include the Lower San Pedro, Upper San Pedro, Lakewood and Recent. Aquifers are subdivided by aquitards, saturated but largely impermeable units that restrict transport of water between permeable units. Hydrostratigraphic units are defined by pump tests, aquifer production records and radiogenic tracers injected into the basin.

The San Pedro formation overlies the Pico formation. The lower San Pedro Formation is correlated to the Sunnyside aquifer, while the Upper San Pedro Formation is correlated to the Silverado aquifer (base of Upper San Pedro), Lynwood and

Hollydale-Jefferson aquifers (Poland, 1959; Ponti, 1989). The overlying Lakewood Formation is subdivided into the Gage, Gardena and Exposition Aquifers, whereas Holocene strata are grouped into the Gaspur, Bollona and Talbert Aquifers (Figure 2-4). Correlation and mapping of chronostratigraphic surfaces or sequence stratigraphic boundaries was focused on the Upper San Pedro and the Lakewood aquifer systems. Available well data was not sufficient to allow accurate mapping of Holocene (i.e. Gaspur aquifer) or Lower San Pedro (i.e. Sunnyside aquifer).



Age	Formation	Aquifer		Aquifer Systems
Holocene	Active Dune Sand	Gaspur - L.A. River fill Ballona Talbert - Santa Ana River fill		Recent Aquifer System
Upper Pleistocene	Older Dune Sand Lakewood Formation	Pacific Harbor	Exposition Gardena	Lakewood Aquifer System
		Gage Upper Bent Spring		
Lower Pleistocene	San Pedro Formation	Lower Bent Spring	Hollydale Jefferson	Upper San Pedro Aquifer System
			Lynwood	
		Silverado		
		Sunnyside		Lower San Pedro

Figure 2.4 Correlation of Quaternary formations comprised of aquifer systems in the Los Angeles Basin. Each aquifer system is comprised of several aquifers except the Lower San Pedro. Correlating these aquifers to the eustatic record permits use of aquifers as chronostratigraphic units.

Silverado Aquifer

The Silverado aquifer is defined as a 75-meter thick coarsening upward sequence of fine-grained sand and sandy-gravel (Bulletin 104) correlated with the lower portion of the Upper San Pedro formation. These strata are interpreted to have been deposited under continuous shallow marine conditions and do not appear to have been exposed to erosion or fluvial sedimentation during sea level highstands. Individual parasequences of the Silverado aquifer are approximately 60 – 150 meters thick and coarsen upward. The Silverado aquifer is correlated to the Marine O^{18} Stage 16 or older with a maximum age of 600 ka (Ponti, 2002). Resistivity logs that record the Silverado aquifer define a gradually coarsening-upward sequence of strata that are increasingly permeable towards the top of the unit.

Gage Aquifer

The Gage aquifer is correlated with strata at the base of the Lakewood formation that lie stratigraphically above an angular unconformity identified throughout the western part of the Los Angeles basin (Yerkes, 1965). The Lakewood formation, in contrast to the San Pedro formation, consists of thinner packages of basal marine coarse sands that fine upward into coastal marsh or non-marine deposits (Ponti, 2002). The unconformity defined at the base of this unit was likely reoccupied during consecutive marine lowstands. Younger strata deposited immediately above the unconformity are comprised of basal sands deposited in shallow marine environments. Reworking of strata deposited above the unconformity make the age of these deposits uncertain, leading the Department of Water Resources for L.A. County to group all upper Pleistocene strata as Lakewood Formation and assign a broad age range of 100 to 500 ka. More recent work, including boreholes (USGS FOQUS-LA) and amino acid analyses (Ponti, 1989) suggest basal strata in the lower Lakewood are 330 ka in age, and were deposited during the Marine Stage 9 sea level highstand (Figure 2-4).

Shaley sands that comprise the lowermost part of the Gage aquifer are interpreted to have been deposited in shallow marine conditions. The sequence grades upward into tidal flat or coastal estuarine deposits that in turn grade upward into beach and estuarine deposits. The sequence is commonly capped by fluvial overbank deposits (Ponti, 2002). A 50-meter section of fluvial gravel deposits and near-shore marine units tied to the Marine Stage 9 sea level highstand is the Gage aquifer as interpreted in a U. S. Geological Survey borehole in Long Beach (Ponti, personal communication). The assumption is made here that the gage is the same across the basin. Sheet-like sequences of sand apparent in electric logs may record amalgamations of different eustatic cycles, although the base of the sequence is generally considered about to be ~ 330 ka in age (correlated to the Marine Stage 9 highstand). The sequence generally fines upward. Resistivity logs suggest the sequences coarsen abruptly across its base and fines upward through 15–18 meter thick sequence of finer sands.

Although the aquifers listed above were mapped across the basin in early studies to correlate water-bearing aquifers (USGS Bull 104, 1961), considerable effort is currently aimed at developing a detailed database of lithostratigraphic information and age constraints based on continuously cored boreholes (USGS FOQUS-LA). Current efforts are aimed at defining whether the aquifers form continuous sheets across the entire basin, or whether the coarse-grained gravel units are part of a more complex series of shingled deposits and channels that were deposited and reworked during intervals of sea level rise and fall. Of particular concern is the time-transgressive nature of formations defined solely on the basis of microfossil biostratigraphy.

Well Log Data

Well data used for this study included 380 older drillers logs in Los Angeles County (Department of Water Resources, 1961), 490 modern wireline logs and cores in Orange County made available from the Orange County Water District and 33 wells drilled in the basin in the past few years by the USGS for its Focus On Quaternary Stratigraphy (FOQUS) research program (Figure 2-12). Wells in Los Angeles County were digitized from georeferenced documents (Department of Water Resources, 1961) and existing GIS databases provided by the Orange County Water District for Los Angeles County Depths to the top and base of aquifers were digitized from existing cross sections

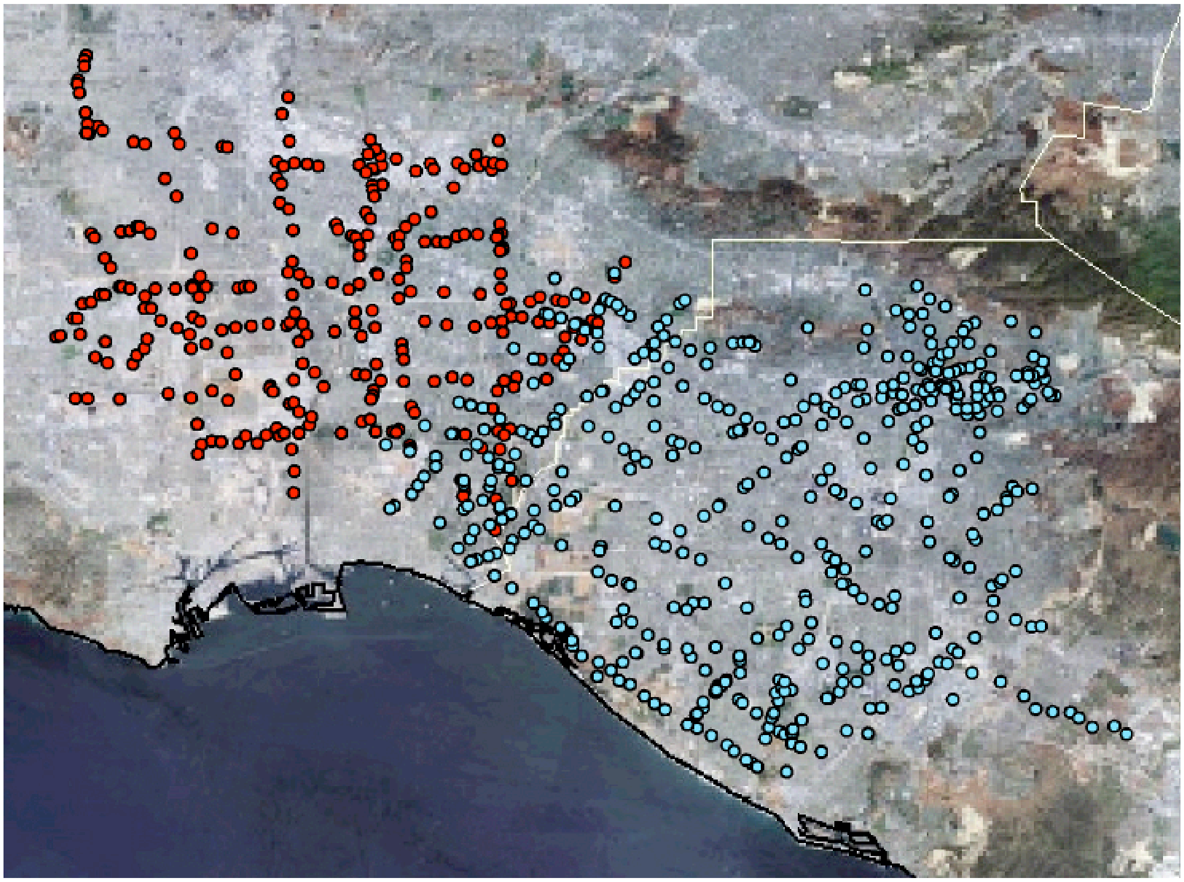


Figure 2.12 Locations of water wells used in study. Orange County Water District data shown in blue, data from Los Angeles County (see Bulletin 104) shown in red. Points draped over satellite image of Los Angeles Basin region.

(Department of Water Resources, 1961). Structure contour maps were created for the Sunnyside, Silverado, Lynwood, Gage/Gardena, Exposition/Artesia, and Gaspur (oldest to youngest) from this database. Overlap of the dataset of more modern wireline logs from Orange County into the southern portion of the area covered by the older LA county wells published in USGS Bulletin 104 (Department of Water Resources, 1961) allowed us to compare these two datasets. Wells from the USGS FOQUS-LA dataset that were located in Long Beach were used to correlate sequence stratigraphic boundaries and aquifers defined in the Orange County dataset. Geographic location and well logs were provided by the USGS. GIS coverages of aquifer contacts penetrated by wells were projected onto OCWD cross-sections provided by the OCWD to constrain uplift rates on individual structures. Electric logs were also provided for selected wells to validate electronic log character of individual aquifers and the subsea elevations throughout the basin.

Wells from the Orange County Water District were included in the geodatabase as the primary data source for assessing active folding of the Compton-Los Alamitos, Coyote, Santa Fe Springs, San Joaquin Hills and Anaheim folds. Geographic locations of the wells were supplied as a GIS coverage by the water district. Lithologic, water monitoring and electronic logs were used to develop cross sections across active folds. Besides electric log character, aquifers were correlated with well screen data that recorded water chemistry and piezometric surfaces. Electronic logs generally consisted of spontaneous potential and resistivity logs, but a few wells included gamma ray or single-point resistivity.

Lithostratigraphy vs. Hydrostratigraphy

The Orange County Water District's interest in water flow mapping through aquifers, or hydrostratigraphy, results in aquifer correlations that follow a combination of peizometric surfaces and lithostratigraphic information. These piezometric surfaces frequently cross aquifer boundaries and follow gradients of water flow in the basin. Remapping of aquifers based on electric log patterns, borehole data from USGS FOQUS wells and industry seismic data was used to characterize sequence stratigraphic boundaries throughout the southern Los Angeles Basin in Orange County. This work forms the core subsurface dataset used in this thesis to evaluate late Quaternary folding and attendant seismic hazards posed by blind thrusts. Lithologic basal indicators provide guides to locating stratigraphic boundaries with our assumptions bolstered by hydrostratigraphy.

Interpolation Methods

Characterization of folded late Quaternary deposits for this thesis is dependent on the spacing of available well data. Data points were interpolated using a variety of methods to test whether gridded surfaces matched curvature of fold limbs defined by reflections on seismic reflection profiles. Grid interpolations were constructed in ArcGIS 8.1 using the Geostatistical Analyst 8.1 extension. The kriging method was chosen from the comparative analysis for the interpolations. Several semivariogram models were tested for comparison of the range and error analysis. The root-mean-square error associated with the semivariogram models is smallest for the spherical model, and was therefore chosen as the optimum kriging model. The grids were completed using a lag interval of 0.017083 (Lakewood) and 0.02222 (Upper San Pedro), a nugget of 188.17 and the major range was 0.11049 (Lakewood) and 0.13394 (Upper San Pedro). The grid cell size geostatistically computed from the random sampling is 100 meters. Despite the use of the kriging method, surfaces mapped across the basin contain error associated with the spacing of well points. Sampling of wells across fold limbs by wells typically smooth abrupt fold hinges.

Tectonic Geomorphology

The tectonic geomorphology of the Los Angeles Basin provides an important means of assessing patterns of uplift along active folds. Geomorphic indicators of uplift in the basin include folds elevated above the surrounding flood plain, such as Coyote Hills and San Joaquin Hills, as well as more subtle features such as deformed stream channel networks, marine terraces and broad, gently inclined fold limbs (Christoffersen, et al., 2000; Grant, et al., 1999; Mueller, 1997; Shaw, et al., 2000; Shaw and Shearer, 1999; Shaw and Suppe, 1996; Walls, et al., 1998; Yeats, et al., 2001). Access to 10-meter digital elevation models, 5-meter terrain models provided by Interferometric Side Aperture Radar, and very high-resolution side-scan sonar from offshore regions allows detailed analysis of this region. Analysis of geomorphic features in the Los Angeles Basin undertaken for this study was aimed at mapping active fold limbs and assessing rates of uplift.

Topographic Analysis

For analysis of topography in Orange County, high-resolution surface topography was derived from Interferometric Side Aperature Radar (IFSAR) to map features produced by Late Pleistocene and Holocene fault-related folding above the Santa Fe Springs and West Coyote blind thrust segments**.** Digital elevation models produced by IFSAR have a horizontal resolution of 5 meters and a vertical resolution of 30 centimeters. Although significantly modified by urbanization (i.e. the data also images buildings and vegetation), fold scarps are apparent along the entire length of the forelimb of the West Coyote segment where they form a curved (concave towards the north) surface trace (Figure 3-1). The western segment is characterized by a narrow, sharp scarp where it is crossed by a transect of seismic and well data acquired to assess relief uplift across the fold (Dolan et al, 1995; Shaw and Shearer, 1999; Shaw et al., 2000; Yeats et al., 2001; Dolan et al., 2003). The northwest trending line of relief corresponds to the forelimb of the West Coyote anticline. Figure 3-3 illustrates the forelimb of west coyote in an oblique image viewed toward the north. The scarp is incised by a NE trending drainage, apparent as the area of white and yellow at the top of the image. The total relief along the seismic line measured from the DEM is 9-meters. A 400 foot wide zone defines the scarp at the forelimb with approximately 5 meters of relief in this zone. A topographic profile constructed from the 7.5' quadrangle confirms this surface expression of the West Coyote forelimb.

Topography produced by recent folding across the Santa Fe Springs segment is less pronounced. Relief is less apparent at this location, and may be due to burial of the scarp by overbank deposits derived from the San Gabriel River. The forelimb of the Santa Fe Springs fold also appears to be considerably wider than farther east along the coyote folds. Topography generated from folding on the forelimb of the Santa Fe Springs forelimb is most apparent along a scarp near the southern portion of the city of Santa Fe Springs. (The scarp over the eastern segment. measured from the DEM is approximately 1.9-meters high. The western portion of the Santa Fe Springs fold segment displays much lower relief. The forelimb of the fold can be traced to a point 4 km west of the San Gabriel River, the western limit of the IFSAR data available for this study. Whereas the morphology of the scarp at west Coyote is narrow and abrupt on the IFSAR imagery, the forelimb of the Santa Fe Springs segment is much broader and more diffuse, except for the higher section along its eastern extent. The presence of a paired set of scarps across the forelimb of the Santa Fe Springs fold suggests that shear is heterogeneously distributed across it. Variation in scarp morphology along strike is greatest along the Santa Fe Springs segment, where two arcuate lobes are apparent east and west of the San Gabriel River.

In addition to mapping relief across fold scarps, high-resolution DEMs were used to define segmentation of the underlying thrust faults. Of particular interest was whether tear faults might exist that might limit lateral propagation of individual earthquake ruptures. Topographic analysis indicates the forelimb of the Santa Fe Springs trends East-West suggested by subsurface mapping of the thrust surface (Shaw and Shearer, 1999). The forelimb of the Santa Fe Springs anticline exhibits an abrupt change in its trend west of the San Gabriel River. This is interpreted as a soft linkage, or segment boundary that is unlikely to limit rupture propagation. The forelimb of the Coyote Fold has a curved trace that overlaps the trace of the forelimb of the Santa Fe Springs anticline. Given the subsurface geometry of the thrusts beneath these folds, this geometry suggests the underlying thrusts are stacked in the shallow subsurface which may limit linkage during thrust earthquakes (Shaw and Shearer, 1999).

Basin Subsidence versus Uplift

Subsidence of the Los Angeles Basin occurs at scales of varied wavelength. As noted earlier, broad wavelength subsidence of the central basin has occurred relative to surrounding areas throughout the Cenozoic. Subsidence is the result of several processes. Loading of the basin from aggradation of localized depocenters such as the Santa Ana fan occurs at scales of several tens of kilometers. Flexural loading from thrusts in the basin also induces localized subsidence as indicated by down warped (e.g. flexed) strata in their footwall (Schneider et al, 1996; Yeats et al, 2001). Larger thrusts, such as Coyote and Santa Monica, have documented flexural signals (Schneider et al., 1996; Yeats, 1965). Flexural loading from thrusts is clearly not the only source of far-field subsidence in the Basin that is centered over northern Orange County. Data from LARSE (Roy and Clayton, 2000) suggest the presence of a dense root at the base of the seismogenic crust in the central basin that is likely to drive subsidence of this region. Perhaps more importantly, the Los Angeles Basin does not appear to undergo regional, late Quaternary uplift documented in the Peninsular Ranges further south. This uplift has been attributed to replacement of the mantle lid in the eastern Peninsular Ranges based on flexural modeling and the history of uplift along the Pacific coastline between Orange County southward to nearly the Vizcaino Peninsula in Baja California. Related to modern extension in the Gulf of California and Salton Trough, the topography of the western Peninula Ranges is thus interpreted as a rift flank uplift driven largely buoyancy of the upper mantle (Mueller et al. In review). The uplift extends across the entire Peninsular Ranges and results in total uplift of about 100 m along the Pacific coastline, producing the extensive tracts of marine terraces in Orange and San Diego Counties. Noteably this pattern of regional uplift appears to end at about the latitude of the southern Los Angeles Basin, consistent with its position relative to the northern end of the Salton Trough.

Marine Terraces

Marine terraces provide important horizontal datums of known age that can be used to assess uplift and lateral propagation of active folds. Marine terraces may also provide high-resolution records of lateral uplift and how it may have varied over time for specific structures. Terraces exposed along the Pacific coastline result from uplift driven by both the regional processes discussed previously and local uplift produced by geologic structures. Marine terraces consist of an abrasion platform cut into hillslopes during sea levels highstands or lowstands. The landward margin of platforms are paleo-sea cliffs eroded by wave action during the highstand. Abrasion platforms typically dip gently seaward from the sea cliff. The width of individual platforms is related to both the duration of the highstand in question (and the subsequent one) and the susceptibility to erosion of rock underlying the region. As new terraces are uplifted, they become subsequently exposed and begin to erode. The distribution of terraces around folds is a product of both uplift and lateral propagation of these structures. For folds that grow under uniform uplift rates but increase in length with time, the marine terraces should decrease in age down their plunging terminations.

Well-preserved terraces that contain datable material allow their paleo-elevations to be determined by comparison with highstands defined by the global eustatic record. Molluscan fauna dated by amino acid racemization methods can provide control, although unknown thermal processes may affect reaction kinetics lending to inaccurate age determinizations. Faunal assemblages can also be used to identify warm-water fauna that correlate with interglacial episodes that lead to sea level highstands.

Uranium series dating of corals is based on the tendency of these organisms ability to incorporate microscopic amounts of uranium from seawater. After the coral integrates the uranium, the parent isotope begins to decay into isotopes of thorium-230 and protactinium-231. U-series dating methods provides the most independent and accurate means of determining the age of sediments deposited above abrasion platforms during sea level highstands.

San Joaquin Hills

The San Joaquin Hills are a northwest-trending elongate upland that forms the southwestern boundary of the Los Angeles basin. The San Joaquin Hills are the topographic expression of a northwest-trending anticline originally defined between San Juan Capistrano and Huntington Mesa (Vedder, 1975). The anticline exhibits lesser uplift but actually extends further northward from Huntington Mesa to Landing Hill. The San Joaquin Hills are bounded by the right-lateral Newport-Inglewood fault zone that extends from offshore south of the San Joaquin Hills to the base of the Santa Monica Mountains. The San Joaquin Hills are faced by the coastline of the Pacific Ocean along the southwest–facing flank. A series of uplifted marine terraces is incised into the southwest flank of the anticline that has been well dated by amino acid (Barrie et al, 1992) and U-series age determinizations (Grant et al, 1999). Marine terraces exposed on the southwest flank of the San Joaquin Hills extend northward and wrap around the plunging terminization of the fold near Newport Bay. Broad, gently northeast-dipping terraces extend northeast of Newport Bay, parallel to the coastline. U-series dating suggest these terraces, which include Newport Mesa, Huntington Mesa and Bolsa Chica were formed during the Marine stage 5e (122ka) sea level highstand. A narrow lower terrace adjacent to the coast is identified by U-series dating as forming during the stage 5a (78ka) highstand.

3-D Fold Growth as a Proxy for Fault Displacement

Fault-related fold theory relates the geometry of folds to displacement on underlying blind thrusts. This and the presence of well-preserved marine terraces on the fold allow its lateral propagation history to be defined. A longitudinal topographic profile, drawn parallel to the trend of the San Joaquin Hills suggests that deeply eroded terraces at the fold's crest step downward abruptly to the northwest (figure 3-7). Assuming a constant uplift rate (e.g. Barrie, 1992) terraces at the crest of the anticline are about 1.25 Ma in age. A broad, much less eroded terrace, interpreted to form during the marine stage 9 (ca 330ka) highstand wraps around the nose of the anticline in the city of Irvine and Corona Del Mar (figure 3-8). Although folded downward across the forelimb of the fold, the marine stage 9 terrace lies at an elevation of 88.4 m at the fold crest in Corona Del Mar. Given the distance between the 1.25 Ma crest of the fold and the location of stage 9 shoreline angle in Corona Del Mar, the San Joaquin Hills propagated 3.47 km towards the northwest in 920 ka. Using a dip of 40 -60 ° for the underlying thrust map, this yields a displacement to length ratio of 0.11 – 0.08. The distance of 2.8 km between the stage 9 shoreline angle and the stage 5e, 122 ka, shoreline angle is the distance the San Joaquin Hills fault has propagated in 208 ka. This yields a displacement to length ratio of 0.02 – 0.015. Based on available age determinations, the stage 5e terrace stretches 27.5 km from its shoreline angle in Corona Del Mar to Cypress, east of Anaheim, the stage 5e terrace records a nearly instantaneous lateral propagation at a maximum of 122 ka. This records a fundamental change in the mechanics that govern lateral propagation of the San Joaquin Hills, interpreted as being related to reactivation of a pre-existing fault. Reactivation of a preexisting fault is supported by the history of the Newport Inglewood fault. The Newport Inglewood has a parallel trend to the San Joaquin Hills and interpreted to reactivate preexisting faults that are probably extensional in origin, given the history of the basin.

Folding of the Stage 9 Terrace in Irvine

The marine stage 9 terrace preserved near Irvine is folded downward across the forelimb of the San Joaquin Hills anticline (Figure 3.9). Although a deeply incised

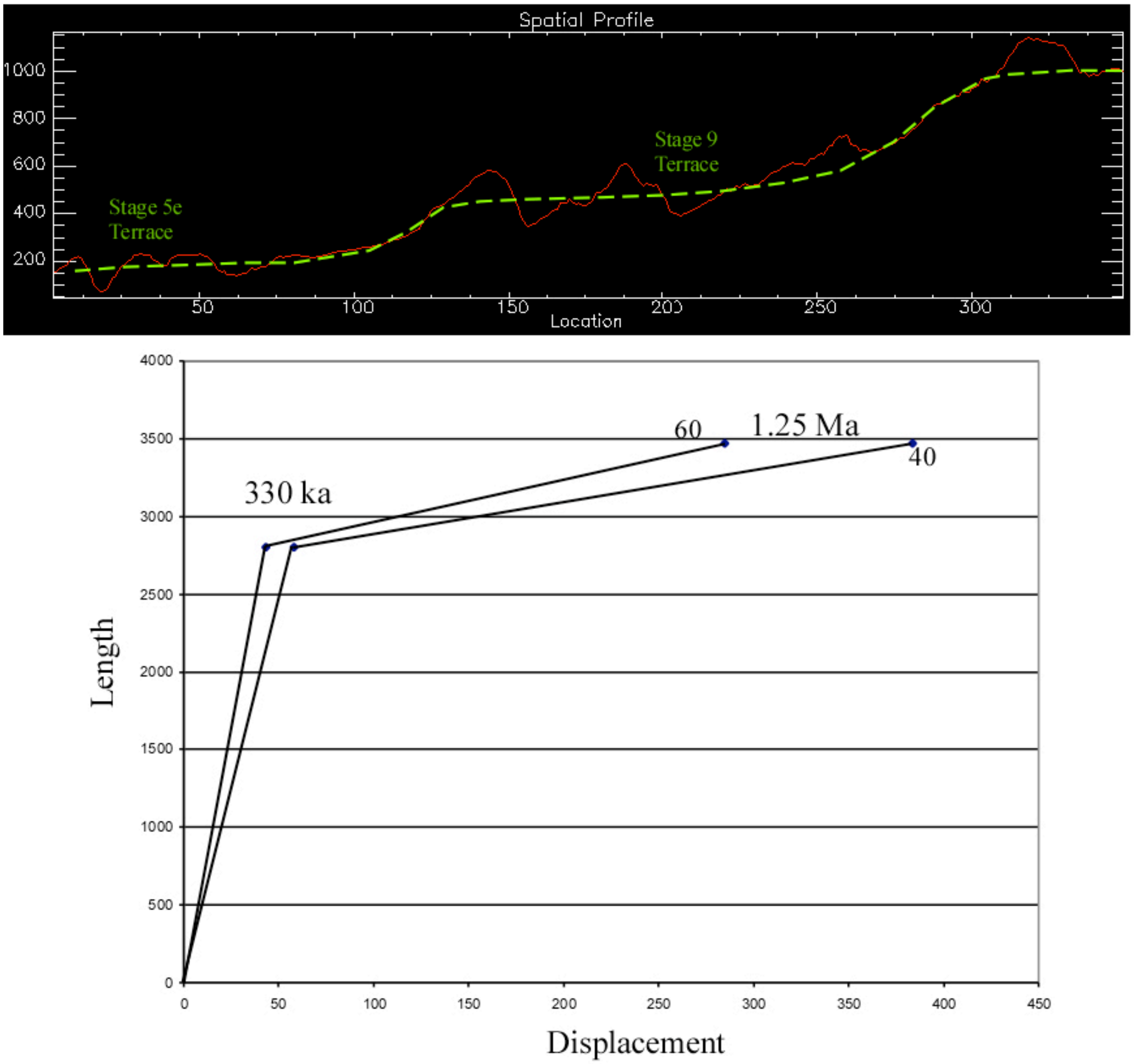


Figure 3.7 Top section is a longitudinal profile along the crest of the forelimb of the San Joaquin Hills viewed to the north. A best fit line marks the marine stage 5e terrace on the left, with the Stage 9 terrace in the center and older (1.25Ma? terraces on the right). Bottom chart shows displacement to length ratio along the fold based on assumptions

for ramp angle (shown for 40 and 60 degree dipping thrust). Key in this image is the rapid increase in rates of lateral propagation of the fold after 330 Ka, which we attribute to linkage of an early thrust plane with a preexisting fault.

stream drainage channel (Bonita Creek) cuts across the forelimb of the fold where it is incised by the terrace, a narrow strip of downfolded terrace is clearly preserved with an attendant shoreline angle. The terrace shoreline angle lies approximately 2.4 km southeast of the CU Irvine campus.

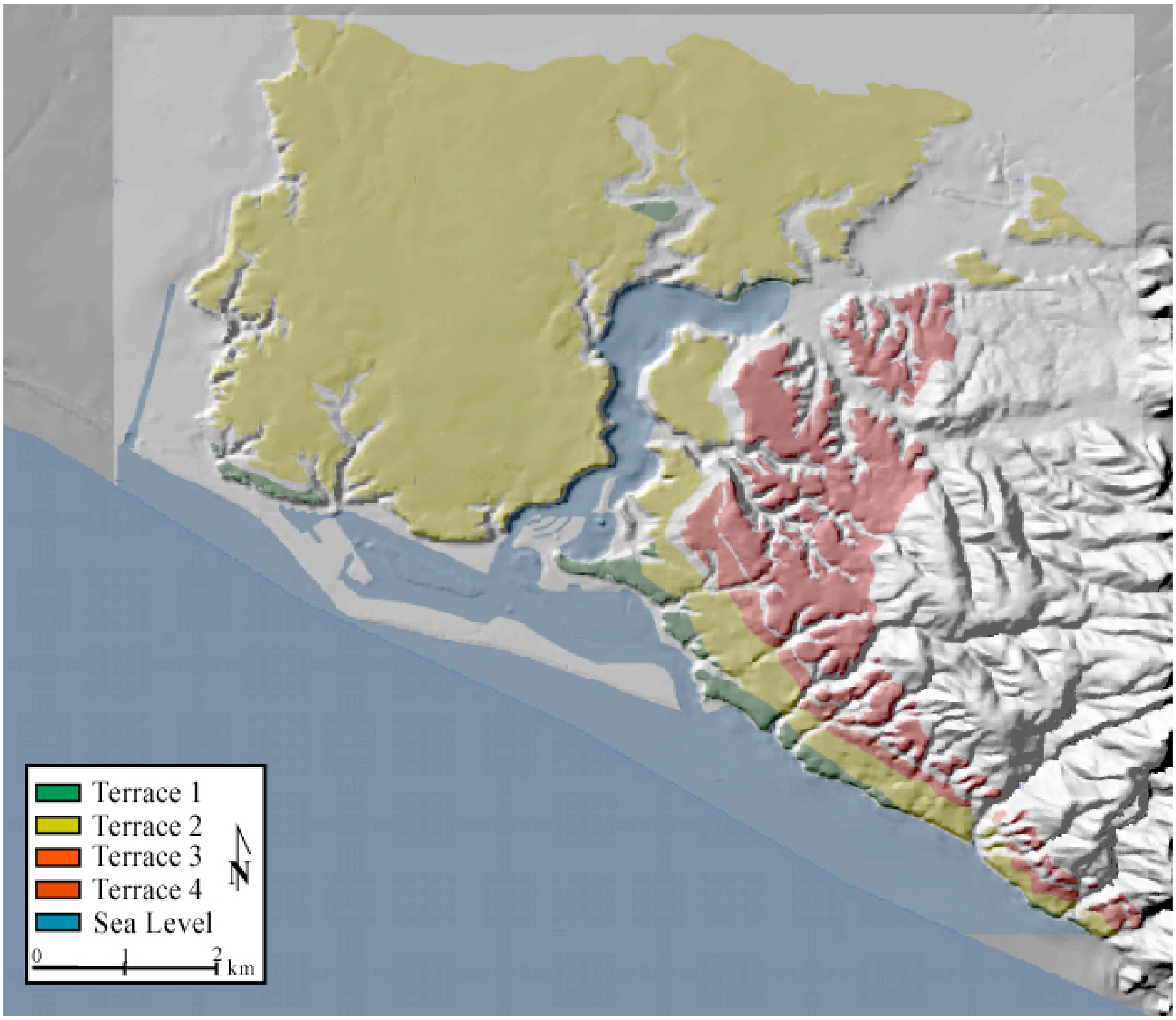


Figure 3.8 Nadir view of marine terraces mapped over the San Joaquin Hills anticline. Terrace 1 = Marine Stage 5a or 5c (83 and 105Ka), Terrace 2 = Marine Stage 5e (122Ka) and Terrace 4 = Marine Stage 9 (330 ka). A narrow terrace exposed on the north side of the anticline in Irvine (incised by north flowing Bonita Creek) previously was mapped at Marine Stage 7 is here mapped at Stage 9. See subsequent oblique scene of this area.

3.7.2 Bathymetric Constraints on Backlimb Geometry

The lack of an apparent backlimb in the San Joaquin Hills could indicate the fold grows as a monocline, but bathymetric data gathered across the Santa Catalina Basin, and the modern abrasion platform (e.g. the shelf located immediately west of the coastline) suggests its backlimb is defined by the seafloor. Based on this bathymetry, and the sense of vergence of the San Joaquin Hills, the eastern margin of the Santa Catalina Basin is interpreted as the backlimb of the San Joaquin Hills. Alternatively this sharp bathymetric rise may mark folding above a wedge thrust tip defined by the east vergent San Joaquin Hill's and the underlying Oceanside detachment of Rivero et al., 2000. The bathymetric rise could instead be interpreted as the shelf slope; however the acute slope angle rising from the Santa Catalina Basin toward the modern abrasion platform suggests a tectonic aspect. The active uplift of the backlimb, or wedge structure is necessary to maintain the sharp bathymetric rise despite aggradation of fan deposits from the major rivers of the basin, stemming back to the Pleistocene.

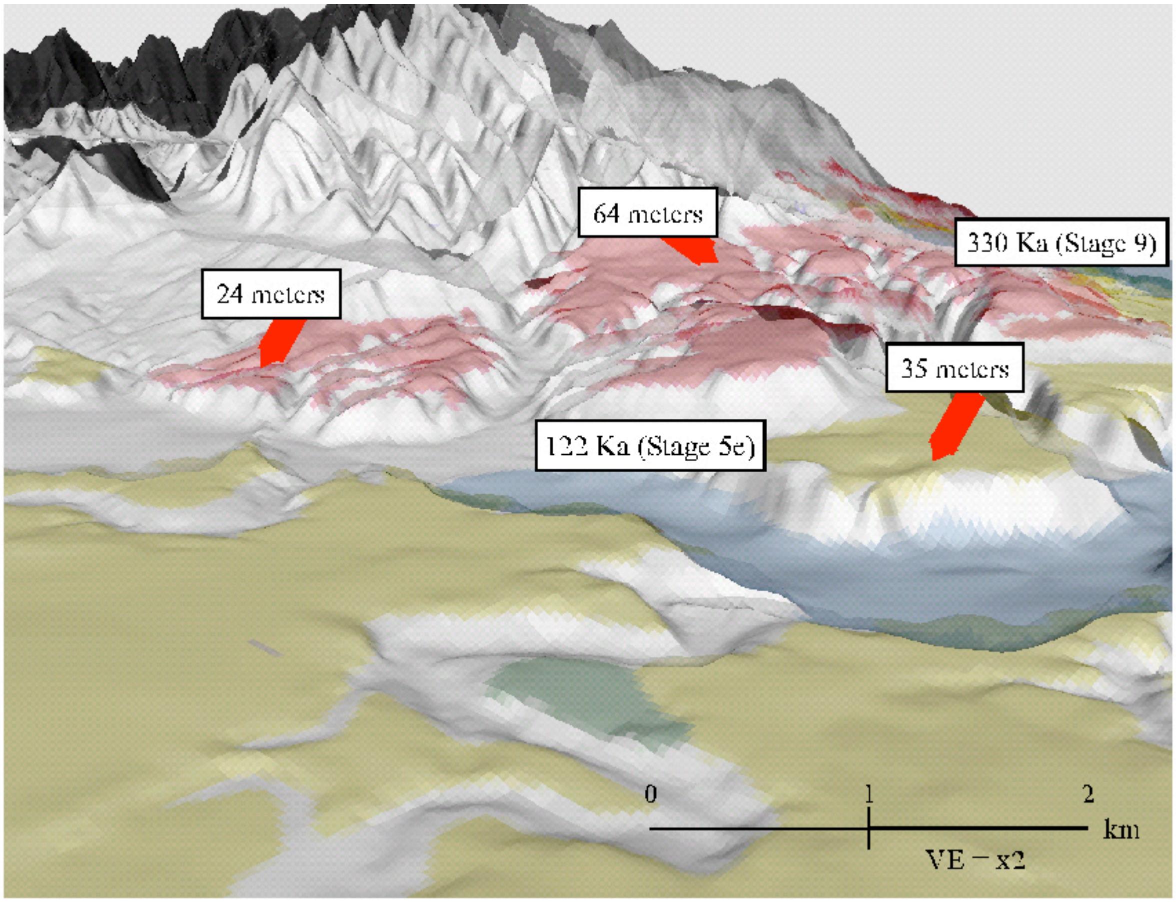


Figure 3.9 Oblique scene of northern San Joaquin Hills. Blue is Newport Bay, Yellow Stage 5e terrace, pink Stage 9 terrace. Note decrease in elevation of Stage 9 terrace across Bonita Creek of about 40 meters.

Drainage networks

Drainage networks were mapped with DEM's derived from archival 1940's era topographic maps in the software package Rivertools. As part of a general analysis of stream channel networks, stream orders were mapped to assess patterns of erosion across the fold. Stream channel networks are used to map the topographic crest of the fold, which is not correlated with the upper edges of fold limbs. Northwest-trending drainage channels, including Bonita Creek drain the northwest-plunging termination of the fold, as is expected for an anticline that propagated towards the northwest (see earlier discussion on propagation history).

Folding of Antecedent Channels Across the San Joaquin Hills Since 122ka

An antecedent drainage flows into the 122 ka terrace of the eastern edge of Newport Mesa. This drainage no longer carries into Newport Bay and has been defeated by folding across the forelimb of the San Joaquin Hills**.** The resulting water gap has a longitudinal stream drainage profile that can be used to map the upper edge of the forelimb of the fold at 5e time. As stated previously, this important constraint allows upward propagation of the underlying blind thrust to be estimated between 330 and 122 ka. Topographic relief measured down the down-folded portion of the wind gap is 65-meters, which is a minimum measure of the vertical component of shear imparted into the forelimb since 122ka.

Using the crest of the wind gap as the forelimb crest at 122 ka provides insight into how the fault has propagated since 330 ka. The marine terraces on the southwest flank of the San Joaquin fold wrap around its northwest corner implying the axial surface defined by the sharply curved part of the terrace is an inactive axial surface. The forelimb crest for the marine stage 9 terrace is preserved in the terrace above Big Canyon in Corona Del Mar. The distance between the stage 9 forelimb crest and the stage 5e crest is 4.81 km. Using a dip on the San Joaquin Hills fault of 40 - 60°, calculation of the amount of fault propagation yields a value of 6.28 – 9.62 km. Further analysis provides a propagation to slip ratio for this time. Again using the fault dip values and the uplift calculated earlier between the stage 9 and stage 5e terrace of 37.2 m yields slip rates of 0.21 – 0.28 mm/yr. Dividing the values for fault propagation by the slip values yields P/S ratios of 108 for a 40° fault and 224 for a 60° fault. These P/S ratios are extremely high and are interpreted as related to slip on reactivated faults, consistent with very rapid northward propagation as defined by the 122Ka 5e marine terrace that extends from Newport Bay to nearly the port of San Pedro.

Structural Analysis of Active Folds

Structure contour mapping of late Quaternary deposits of known age allows assessment of folding above active blind thrusts in the Los Angeles Basin. Uplift can then be coupled with other subsurface data that constrain fault dips to estimate fault slip rates. These rates can then be used with regressions that relate earthquake magnitude and fault size to estimate earthquake recurrence for the structures studied. In a first order analysis, we use the lateral extent of fold trends defined by deformation of late Quaternary deposits along with seismological constraints on the depth of the brittle crust to estimate fault area.

Units mapped in this study across the Los Angeles Basin include the base of the Upper San Pedro Formation and the base of the Lakewood Formation. The Upper San Pedro Formation base is equivalent to the Silverado aquifer (correlated to the Oxygen Isotope Marine Stage 17) with a maximum age of 750 ka (Ponti, personal communication). The Lakewood Formation base is equivalent to the Gage aquifer (correlated between the Oxygen Isotope Stages 5 and 9 marine transgression) with a maximum age of 330 ka for the basal unit of the Gage. As discussed above, the assignment of these ages may contain significant errors. If the unconformity defined at the base of Lakewood results from reoccupation by more than one highstand, its age may range from 200 to 500 ka (Ponti, 2002). The broad terrace that extends across the plunging termination of the San Joaquin Hills near Irvine is assigned an age of 330 ka based on dating of the adjacent stage 5e terrace, amino acid racemization data (Barrie et al, 1992) and its elevation based on a constant uplift rate and uplift of younger dates terraces. Based on comparison with the global eustatic record, this terrace may also have formed during the marine stage 11 highstand, and thus may be somewhat older (i.e. 425 ka). The age of the Upper San Pedro formation is assigned to the 750 ka marine stage 17 sea level highstand based on correlation with the eustatic record. We suggest the likely error associated with this age assignment is ~±150 ka based on the possibility the terrace may also have formed during the stage 15 highstand of 600 ka.

In this study, the Silverado and Gage aquifers are defined by water wells, electronic well logs and the 2-D seismic profiles. Well spacing affects measurement of structural relief, in particular where the upper and lower hinges of fold limbs are poorly defined. Seismic data, available across the Compton-Los Alamitos trend, however allows relatively more accurate characterization of fold limbs, at least for the 750 ka Silverado that is imaged by it. We assign measurement errors of ~±30 m for the depth of the Lakewood Formation and ±50m for the Upper San Pedro Formation based on average well spacing and range of curvatures for fold hinges. The following sections outline constraints for estimating seismic hazards posed by the Compton-Los Alamitos, Santa Fe Springs, Coyote Hills San Joaquin Hills and Anaheim anticlines.

Compton-Los Alamitos

Recent analysis of the Compton Los-Alamitos trend were motivated by the recognition of compressive growth architecture apparent on industry seismic reflection profiles (Shaw and Suppe, 1996) (Figure 4-1). Fault slip estimated from compressive growth architecture across the Compton trend was 4 km. Shaw and Suppe (1996) used folding across the top of the Pico formation (2.5 Ma) to indicate a slip rate of 1.4 +/-0.4 mm/yr (Shaw and Suppe, 1996). Recent work by Mueller et al. (2002) places a much slower slip rate across the trend, based on folding of the Sunnyside aquifer, which is identified on depth-corrected seismic lines that cross the central portion of the trend, and using borehole data from the DWR (Department of Water Resources, 1961). Given an age of 720 ka for the aquifer and the width of the corresponding fold limb(s) on the seismic profiles, Mueller et al. (2002) calculates a slip rate on the Compton thrust of 0.51 - 0.56 mm/yr, or about a third the rate determined for older Pliocene strata. The recency of folding across the structure in Los Alamitos appear to be greater than ~12 +/- 5 ka, based on a lack of folding across the Gaspur aquifer as defined by core penetrometer test (CPT) borings.

Figure 4-2 is an oblique 3-D view of the Lakewood and Upper San Pedro depositional surfaces and surface topography that illustrates the continuous northeast-southwest trend of the Compton-Los Alamitos fold trend. The southern end of the fold extends into Orange County and coincides with the central fold segment defined by Shaw and Suppe (1996). Subsurface mapping indicates this field trend is a separate structure independent from the Newport-Inglewood and trend of the San Joaquin Hills.

Uplift measured across the Compton trend in the city of Rossmoor is defined as ~38.7 m of structural relief across the Lakewood formation and ~191 m across the Upper San Pedro formation. A second profile measured across the Compton trend near Los Altos suggested ~47 m of relief across the Lakewood formation and ~152 meters across the Upper San Pedro (Figure 4-3). Mueller et al. (2002) mapped aquifer surfaces constrained by well logs and seismic profiles across the Compton trend in Los Alamitos. Their profiles show 30.1 – 45.7 m of uplift across the 330 ka Gage (base of Lakewood Formation) and ~ 200 m of relief across the Silverado (base of Upper San Pedro Formation). Based on limb dips on depth-corrected seismic profiles (which we use as a proxy for the dip of the underlying Compton Los Alamitos thrust ramp) we assign slip rates on the CLA trend as 0.31 mm/yr, 0.38 mm/yr and 0.32 mm/yr for the Lakewood Formation. We assign slip rates on the trend as 0.67 mm/yr, 0.54 mm/yr and 0.71 mm/yr for the Upper San Pedro Formation across the three profiles measured. Comparison of relief across the Compton Los Alamitos trend suggests the fault is decreasing in slip rate between 750 ka and 330 ka (Figure 4-4). This supports CPT data from Mueller et al. (2002) that suggests the fault has been inactive since deposition of the 15 ka Gaspur aquifer.

Santa Fe Springs

The Santa Fe Springs anticline comprised the central segment of the Puente Hills thrust system, and extends from Norwalk eastward to Whittier (Figure 1-2). The Santa Fe Springs fold has recently been identified as the structure that accommodated shortening during the Whittier Narrows earthquake (Shaw and Suppe, 1996; Allmendinger and Shaw, 2000). Mapping of the fault plane suggested it dips gently 27° north and is overlain by a trishear fault propagation fold (Allmendinger and Shaw, 2000). The long-term slip rate across Santa Fe Springs is defined as 0.5-0.9 mm/yr based on deformation of strata interpreted as 1.6 Ma in age (Shaw and Shearer, 1999) (Figure 4-5). The age of the deposit is very poorly constrained and may vary in age by as much as ~0.5 ma. Higher rates are estimated from geodetic constraints that suggest as much as 2.0 mm/yr are accommodated across the Puente Hills blind thrust system (Walls et al., 1998). Measurement of relief apparent in late Quaternary deposits folded across Santa Fe Springs was only undertaken for the Lakewood formation due to sparse well coverage (Figure 4-6). Correlation of the Lakewood formation on the eastern part of the Los Angeles Basin is different because these deposits are largely fluvial in origin and difficult to correlate from marine equivalents for the west. The Santa Fe Springs transect of wells used to define relief across the anticline extends 4 km between USGS well 3S11W9D001 and Chev-RC1 (Figure 4-3). About 42 meters of relief is apparent in Lakewood age strata yields an uplift rate of 0.13 +/- 0.7 mm/yr for the last 330 ka. Using the fault dip from Shaw and Shearer (1999) of 25° yields a slip rate of 0.3 +/-0.2 mm/yr. This lies well below the range of slip rates of 0.5 –0.9 mm/yr from previous work (Shaw et al., 2000; Yeats, et al., 2001). Figure 4-7 shows several profiles derived across the Santa Fe Springs fold interpreted from Los Angeles County water well data. An additional segment of folding appears to the north of the Carfax seismic line in the Gage and Lynwood aquifers. Figure 4-8 illustrates how this second kink increases the total uplift measured across the 330 ka and 650 ka surface. The kink is not seen in the Gaspur aquifer. The slip rate to 0.2 mm/yr between 650 ka and 330 ka and 0.27 mm/yr between 330 ka and 15 ka. This may indicate uplift across the structure has recently increased. The increase to a 1.0 mm/yr slip rate between 15 ka to present supports this interpretation.

Coyote Hills

The Coyote Hills comprises the easternmost segment in the 40 km long Puente Hills thrust system, and extends from La Mirada to Placentia. The fault dip has been determined as 19° - 22° based on seismic reflection data (Shaw and Shearer, 1999; Christofferson et al, 2000) (Figure 4-9). Seismic data acquired over the forelimb of West Coyote Hills along Trojan Way illustrates folding of late Quaternary strata (Figure 4-10). Folding of the Nomlaki Tuff (3.4 +/-0.3 Ma, Sarna-Wojcicki, et al, 1991) across the forelimb of the West Coyote fold suggests the underlying blind thrust slips at a rate of 1.2 - 1.4 +/-0.5 mm/yr (Sarna-Wojcicki, et al, 1991; Yeats et al., 2001).

A 2 km transect over the Coyote Hills forelimb was measured between F-Coyo2 and OCWD-AIR1 (Figure 4-11, 4-12). The spacing of well data was not closely spaced enough to accurately measuring relief across the Upper San Pedro formation deformed across the Coyote Hills fold. Measurement of the Lakewood formation folded across Coyote is 55.3 m; this yields an uplift rate of 0.17 +/- 0.9 mm/yr. Given a fault dip of 25° (Shaw and Shearer, 1999) the average fault slip rate on Coyote is 0.4 +/-0.25 mm/yr for the past 330 ka. This is significantly lower than previous slip rates (Yeats et al., 2001).

San Joaquin Hills

The San Joaquin Hills forelimb extends into the Orange County dataset along the trend of the reactivated fault uplifting the 122 ka terrace (Figure 4-13). Subsurface mapping indicates abrupt changes in the strike of the forelimb of the San Joaquin Hills anticline. Distinct segments include a Northwest-Southeast trending segment in the El Toro embayment, a 9 km long segment trending more East-West that lies along the northern edge of Newport Mesa and a 21 km-long, Northwest-Southeast trending segment between Huntington Mesa and Long Beach. The northwesternmost extent of the San Joaquin Hills anticline is mapped near Signal Hill, between Los Alamitos and Long Beach. Previous mapping of the southernmost Compton-Los Alamitos trend, as interpreted by Shaw and Shearer (1996), is interpreted here as the northern end of the forelimb of the San Joaquin Hills anticline.

Anaheim

Mapping of late Quaternary strata folded across the Anaheim Nose confirm it is an 18-km long, northwest-trending anticline formed above a southwest-verging blind thrust (Figure 4-14). A transect oriented N42ºE across the Anaheim Nose suggests 55.3 m of relief of the Lakewood formation and 82 m of relief across the Upper San Pedro formation (Figure 4-15). This yields uplift rates of 0.17 +/- 1.0 mm/yr for the Lakewood and 0.11 +/- 0.3 mm/yr for the Upper San Pedro formation. This indicates an increase in uplift rate between 750 ka and 330 ka and may suggest the Anaheim Nose is accommodating increased shortening in a NE-SW direction across the Los Angeles Basin.

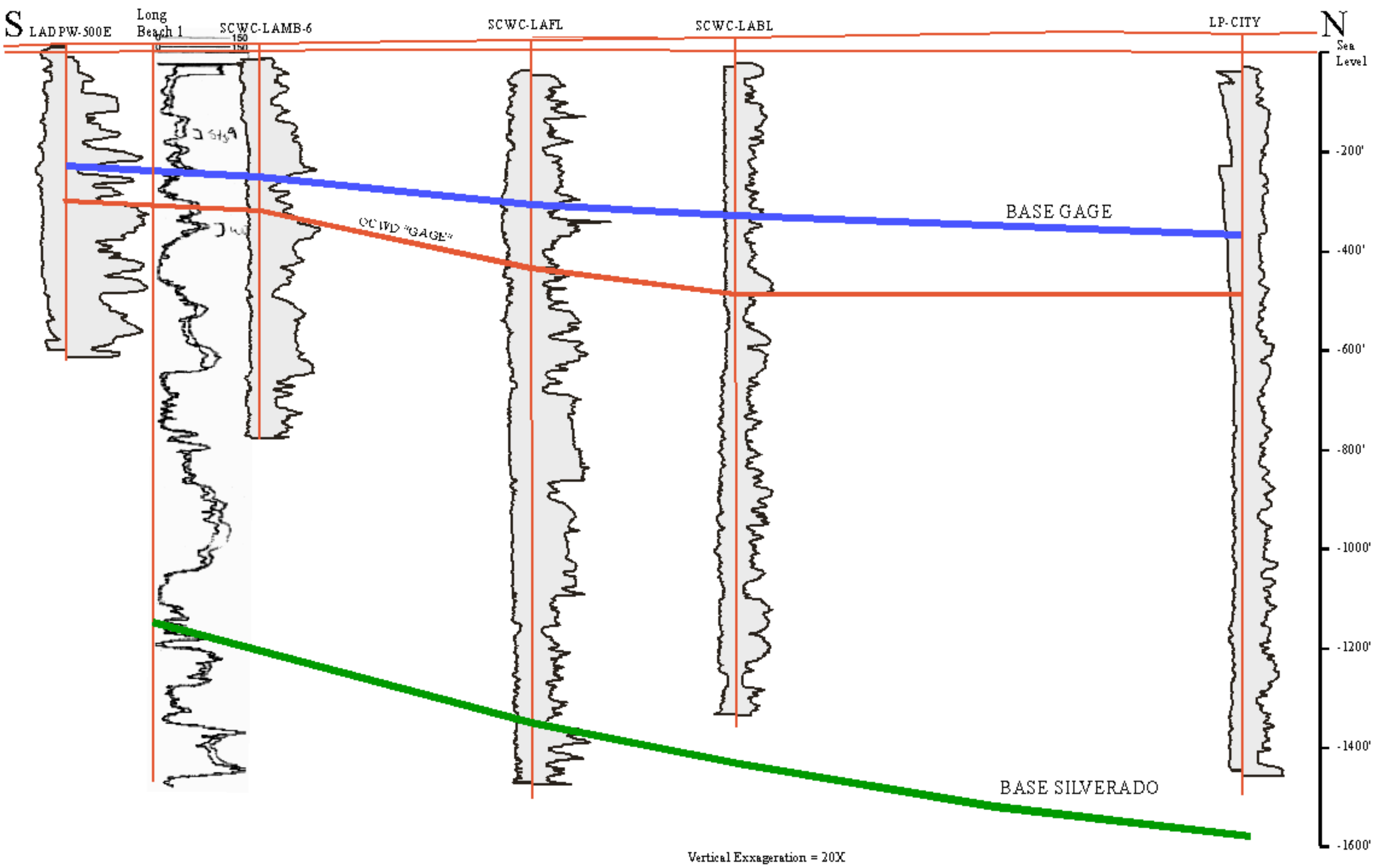


Figure 4-3 - Cross section across the Compton-Los Alamitos fold from Orange County Water District electronic wells and one USGS borehole (Long Beach-1). Fold transect lies in Rossmoor.

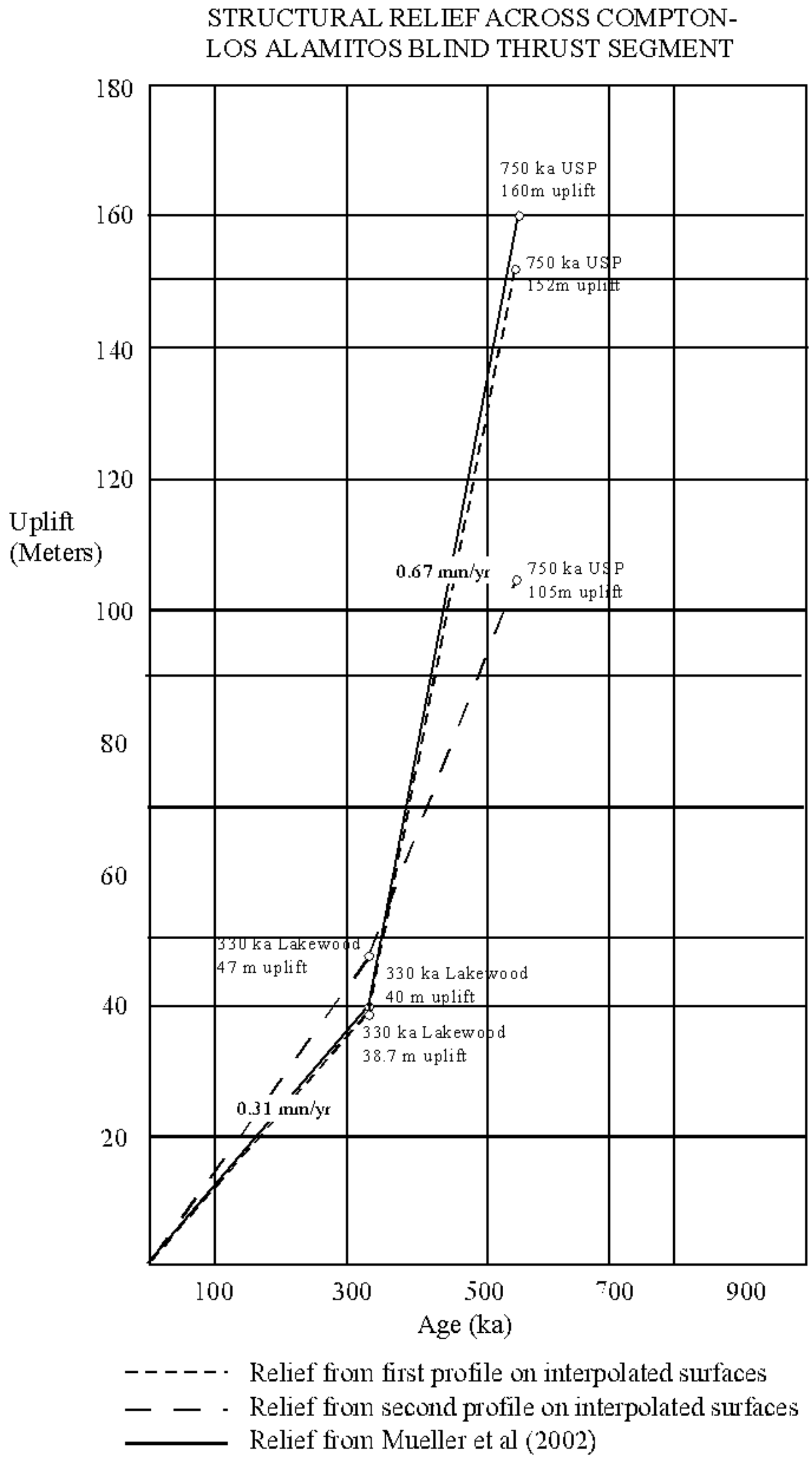


Figure 4-4 - Uplift plot for three transects across Compton_Los Alamitos

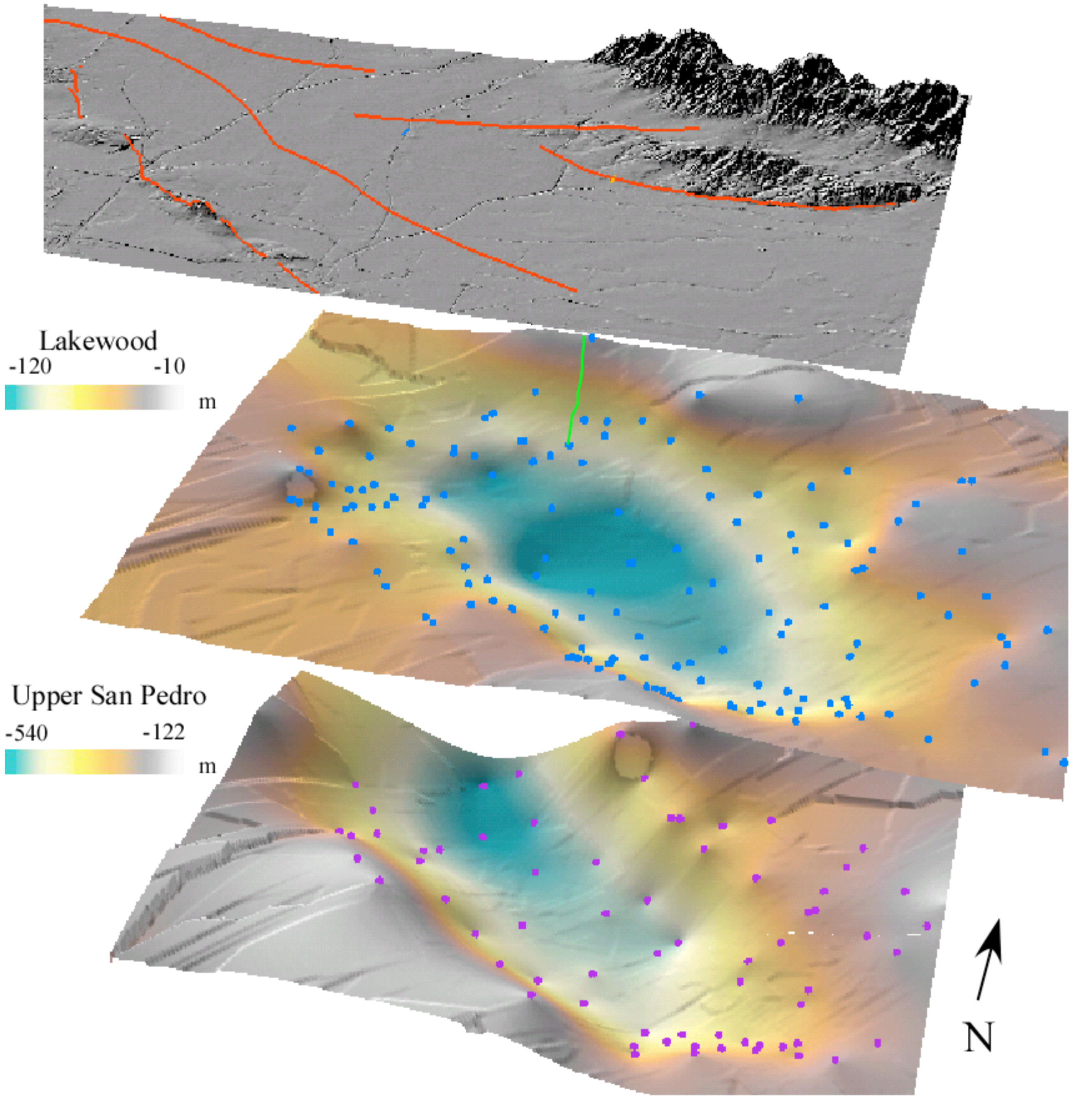


Figure 4-6 - Oblique 3-D view of the Upper San Pedro Formation, Lakewood Formation, and surface topography with wells (points in blue) and faults traces (red lines) viewed to the north. The green line on the lakewood surface indicates the location of the measured transect across the forelimb of the Santa Fe Springs anticline. The orange line on the topography surface is the location of the Trojan Way seismic line and the blue line is the location of the Carfax seismic line.

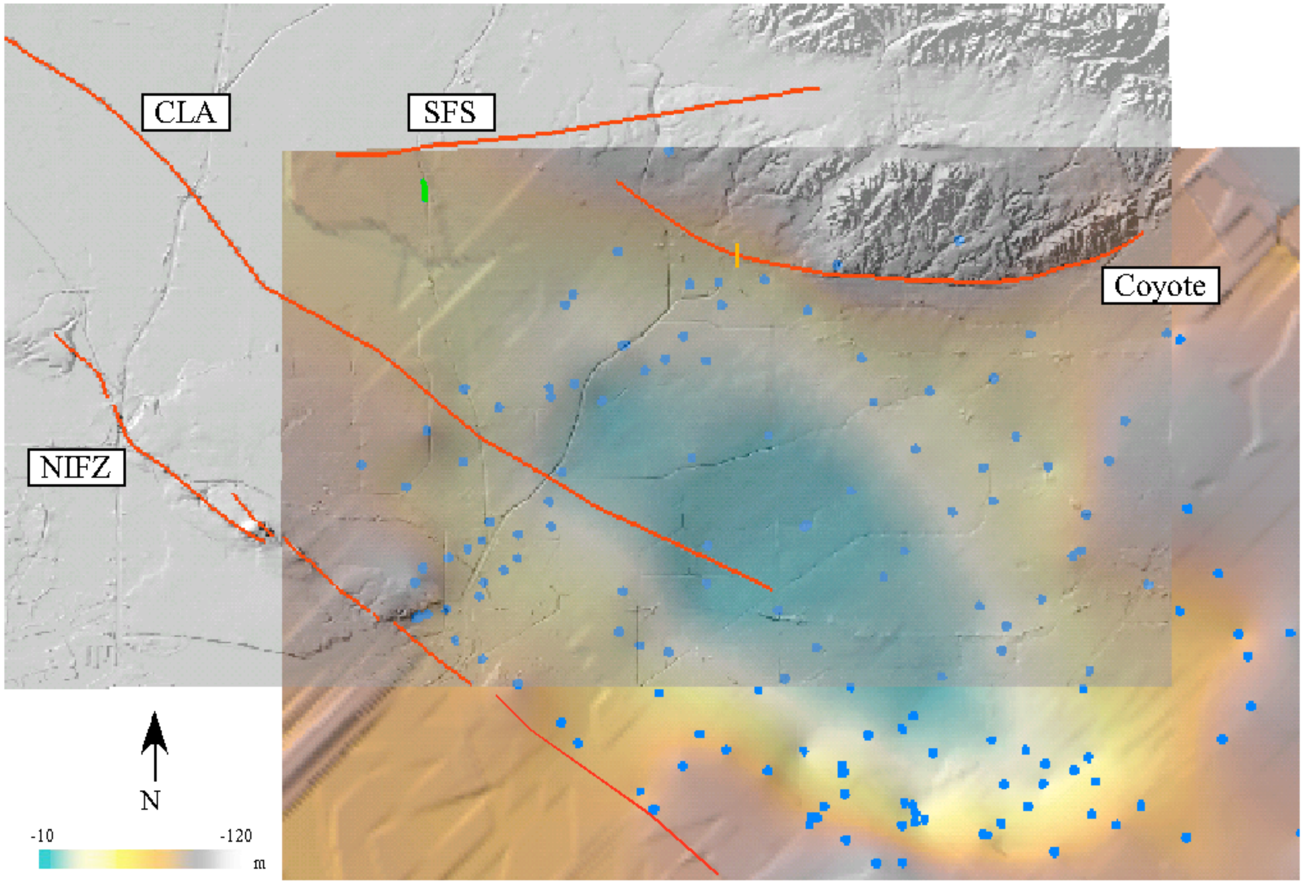


Figure 4-12 - Nadir 3-D view of the Lakewood and topography with wells (points in blue) and faults traces (red lines) from a southeast perspective. Overlap of topography shows accurate projection of the Coyote Hills, Compton-Los Alamitos and several restraining bends along the Newport Inglewood fault. The short green and orange lines represent the location of seismic on Carfax Ave. and Trojan Way, respectively. The deep central trough, in blue, is shown trending northwest between the Newport Inglewood and the Puente Hills

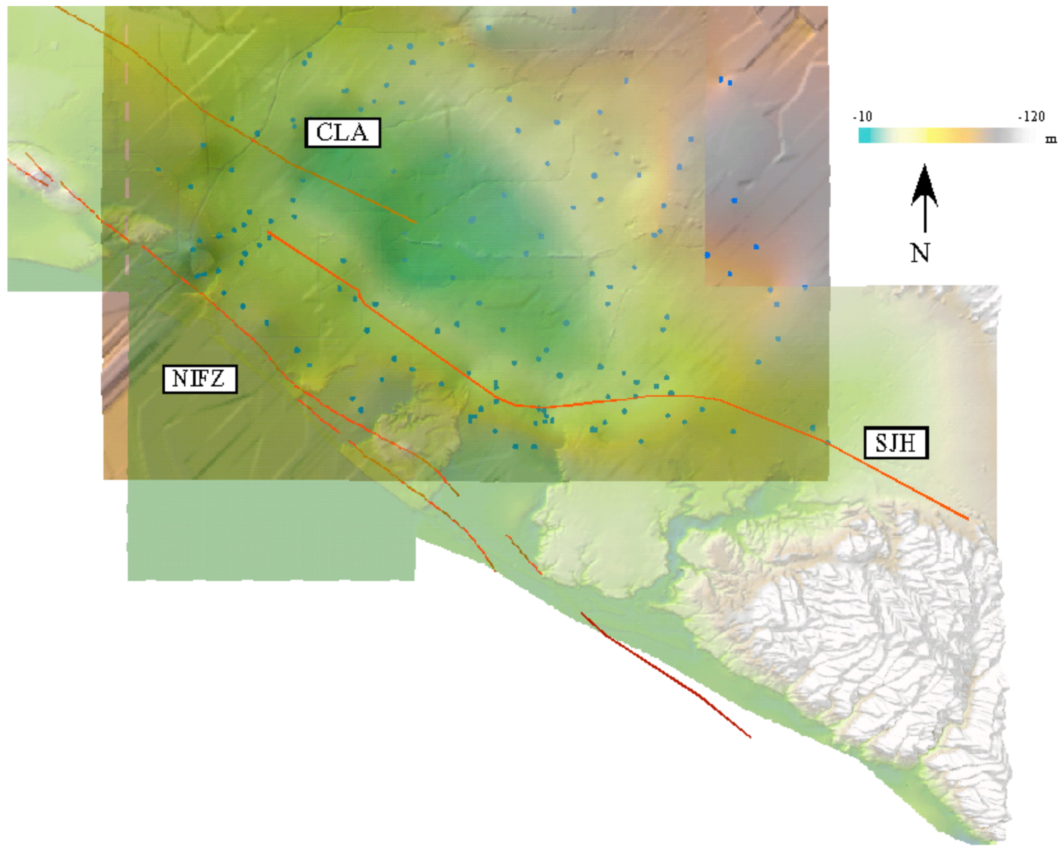


Figure 4-13 - Nadir 3-D view of the Lakewood and topography with wells (points in blue) and faults traces (red lines) from a southeast perspective. Overlap of topography shows accurate projection of the Coyote Hills, Compton-Los Alamitos and several restraining bends along the Newport Inglewood fault. The short blue and green lines represent the location of seismic on Carfax Ave. and Trojan Way, respectively. The deep central trough, in blue, is shown trending northwest between the Newport Inglewood and the Puente Hills. The backlimb of the San Joaquin Hills is also evident at bottom right, trending northward where it is buried by the San Pedro Bay fluvial deposits.

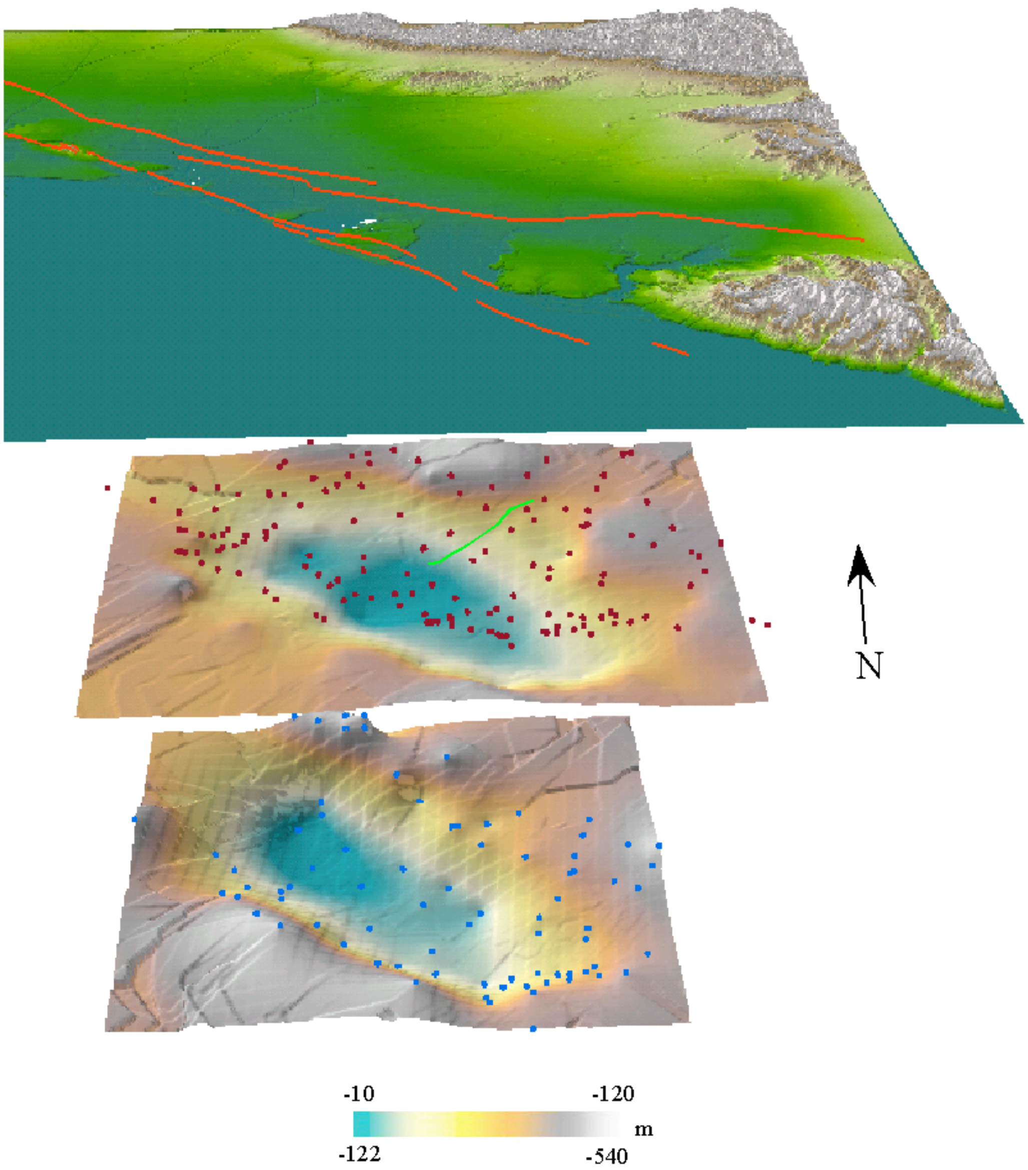


Figure 4-14 - Oblique 3-D view of the Upper San pedro, Lakewood, and topography with wells (points in blue) and faults traces (red lines) from a southeast perspective. The green line on the lakewood surface indicates the measured transect for the Anaheim Anticline forelimb. Topographic expression of the fold has been buried by the Santa Ana fan, extending from the northeast corner.

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Nontechnical Report

Mapping of subsurface deposits in the Los Angeles Basin suggests the Compton-Los Alamitos trend is an active fold that is currently growing by earthquakes at about a third of the rate proposed by previous studies. Deformation has instead occurred during Late Quaternary time across San Joaquin Hills blind thrust, expressed as a fold (the San Joaquin Hills) in Orange County. Uplift rates defined by sedimentary deposits across the San Joaquin Hills anticline are similar to rates defined by uplifted seabeds, or marine terraces and suggest it extends from near Signal Hill, through El Toro to San Juan Capistrano. The locus of deformation above the San Joaquin Hills has shifted to the NE recently, suggesting slip is occurring on an underlying blind thrust, similar to that which grew in the Northridge earthquake (i.e. a buried thrust that terminates upward as a fold that adsorbs strain at shallow levels).