Fault displacement and fold contraction estimated by unfolding of Quaternary strata, onshore and offshore Ventura basin, California

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Non-technical Summary

We mapped the geometry of deformed layers along faults bounding onshore and offshore Ventura basin. Results to date indicate a continuous onshore-offshore Oak Ridge fault, and a complex stack of thrust faults along the northern margin of Ventura basin. Repetition of a folded ~1.8 million year layer across the Pitas Point-North Channel fault represents N-S shortening varying along strike from near zero (near Carpinteria and south of Goleta) to over 4 km (south of Santa Barbara). Additional shortening is accommodated across the Red Mountain fault and due to folding above the Pitas Point-North Channel fault. Unfolding of digital maps is underway that will quantify how variation of shortening along the trend of the system is related to vertical-axis rotation of crustal blocks and to left-lateral slip components along faults that are curved (arcuate) in map view.

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INVESTIGATIONS UNDERTAKEN

Introduction

The objective of the project is to quantify the amounts, directions, and rates of movements on prominent faults in the region of the offshore Ventura basin, California (Santa Barbara Channel), and the adjoining part of the onshore Ventura basin (Fig. 1). We will also quantify the contraction due to folding, which is related to slip on both blind and surface faults. This region is traversed by the same structural trends responsible for the M>7 1812 earthquake, M6.3 1925 Santa Barbara earthquake, the M6.7 1971 San Fernando earthquake and the M6.7 1994 Northridge earthquake. In our original NEHRP project, we focused on the Oak Ridge fault (Sorlien and Kamerling, 1998). The Oak Ridge fault has been interpreted either as an active fault that cuts to seismogenic depths onshore and offshore (Yeats, 1988; Huftile and Yeats, 1995; Kamerling and Nicholson, 1996), or alternatively as being detached at a few kilometers depth onshore, and not being a fault offshore (Suppe and Medwedeff, 1990; Shaw and Suppe, 1994). We have shown that the onshore Oak Ridge fault is kinematically and geometrically-linked to folding along an offshore S-dipping fault (Sorlien and Kamerling, 1998, Sorlien and others, in press). Three-dimensional views have been constructed in order to communicate complex three-dimensional structure (http://quake.crustal.ucsb.edu/vbmrp), including a view of a deeper structural level done as part of this renewal project (Fig. 2). In this renewal project, we extend our study to the N-dipping faults along the north margin of Santa Barbara Channel. These faults include the Pitas Point-North Channel fault and the north and south branches of the Red Mountain fault (Fig. 3).

Unfolding and Map Restoration

Structure-contour maps are constructed, digitized, and gridded, then these maps are unfolded (using the UNFOLD software), and the flattened surfaces is fit back together using an interactive graphics program (Gratier and others, 1991; Gratier and Guillier, 1993). Comparing the restored surfaces to the present-day deformed surfaces gives the finite displacement during

Quaternary time, and restoring both surfaces allows us to determine how displacement has changed with time. The Quaternary restorations will also be compared to a restoration of older strata in the same area (Sorlien and others, in press; Gratier and others, 1999). Contraction due to folding for each fault or fold block is also calculated by the UNFOLD program. Detailed discussion of the method is given in Gratier and others, 1991, 1999).

Mapping by Sorlien and others (in press), Jennings (1994), Hopps et al. (1995), Kamerling and Sorlien (1999)

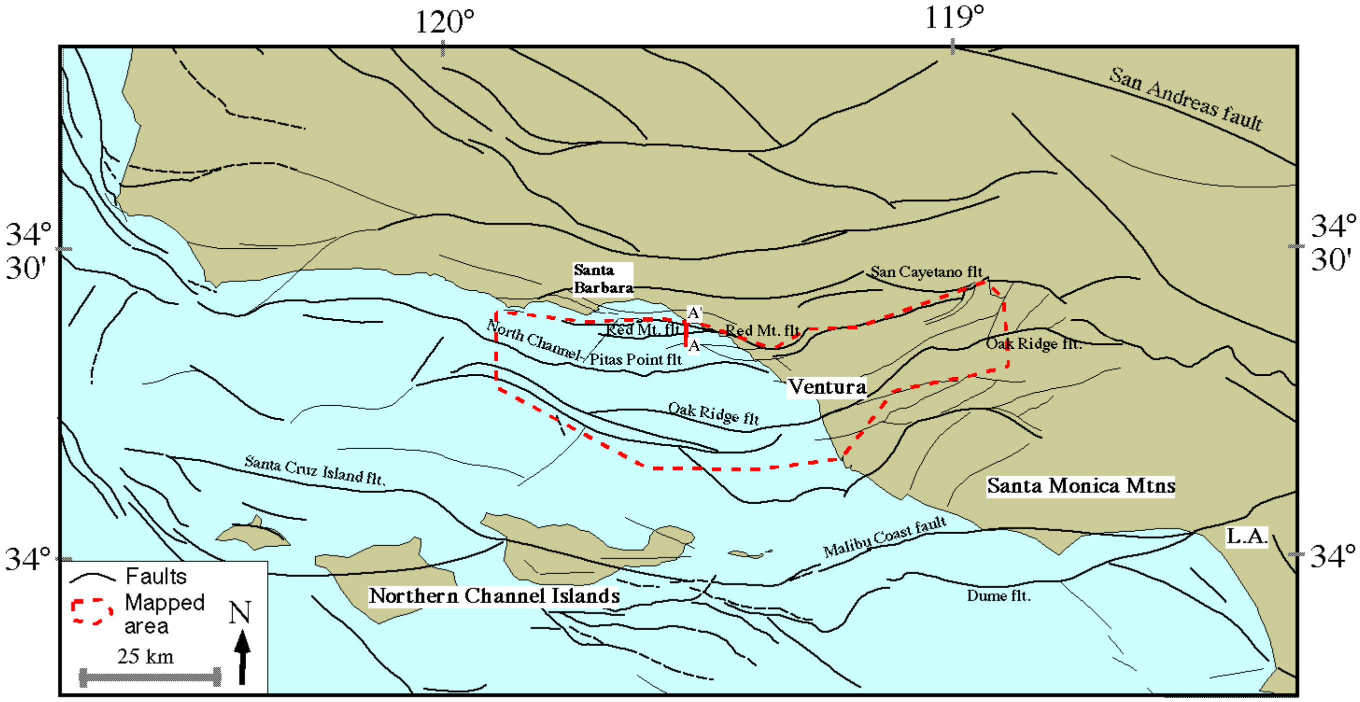

Figure 1: Mapping in onshore Ventura basin is from Hopps et al., 1995, and is on several subsurface horizons. Offshore mapping is by Sorlien and others (in press), and is on Miocene horizons, except south and east of the Northern Channel Islands faults are mapped at the seafloor. Mapping in northern Santa Barbara Channel is by Kamerling and is projected upwards to near the sea floor. Other mapping from Jennings (1994). The area outlined in red has been mapped by us on the top Lower Pico horizon (~1.8 Ma).

RESULTS

A depth structure contour map of the ~1.8 Ma top Lower Pico Formation (top Venturian faunal stage) was created for onshore Ventura basin using numerous cross sections in the Hopps data set (Hopps and others, 1995; Nicholson and others, 1997), published cross sections from Yeats and others (Yeats, 1981, 1983, 1988; Huftile and Yeats, 1995, Grigsby, 1986), and geologic maps (e.g. Dibblee, 1992). This map was extended offshore into the eastern Santa Barbara Channel using industry seismic reflection data, well data, and sea floor geology. We have digitized this map in travel time as far west as 119° 45'; the travel time map is being finalized as far west as 120° (Fig. 4). An average velocity map to the top Lower Pico Formation has been created for the area south of the Pitas Point-North Channel fault using velocity surveys from wells. The travel time map and the velocity map will each be gridded and the grids then multiplied to result in a digital depth structure-contour map. There is much less velocity control north of the Pitas Point-North Channel fault, and therefore a general velocity function related to travel time below the sea floor will be used for depth conversion. Dense NOAA bathymetry data will be used as part of this depth conversion.

Part of the digitized onshore map has been gridded and unfolded. Work with Jean-Pierre Gratier indicated problems with the grids produced by the software GMT (Wessel and Smith, 1991) if a fine grid interval is used (relative to the horizontal distance between digitized contours). Rather than using a coarse 1 km grid, we are investigating other approaches to gridding before proceeding with restoring the maps.

We have updated our web page (http://quake.crustal.ucsb.edu/vbmrp), adding the text of our AGU abstract (Kamerling and Sorlien, 1999) and 2 supplementary figures, Figures 1 and 2. Additional information may be added to this page in advance of preparation of our final NEHRP report.

Interpretation and Discussion

The structure and kinematics of the Oak Ridge fault is discussed in our 1998 technical report (Sorlien and Kamerling, 1998), and we here focus on the faults along the northern margin of offshore Ventura basin. The N-dipping Pitas Point fault and the North Channel fault are interleaved or stacked along the same E-W trend, while the south branch of the offshore Red Mountain fault is a separate parallel structure 6 km to the north. Fault plane reflections from these faults were observed on 3D and 2-D seismic lines and faults were also detected by repeated sections and abrupt dip changes in wells (Fig. 3). Shallow thrusts, folds, and south dipping reverse faults occur in the hanging wall and the footwall of the Pitas Point-North Channel fault

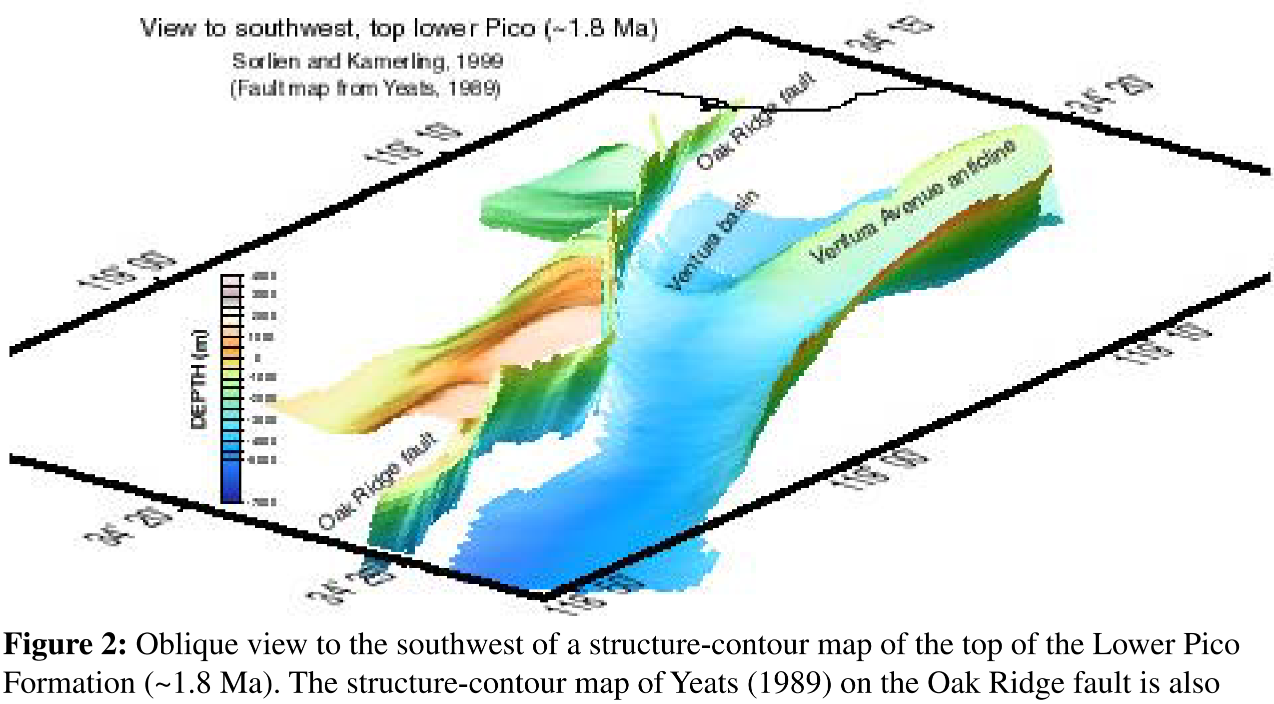

Figure 2: Oblique view to the southwest of a structure-contour map of the top of the Lower Pico Formation (~1.8 Ma). The structure-contour map of Yeats (1989) on the Oak Ridge fault is also shown. Similar 3-D views of the structure along the Pitas Point- North Channel fault and the Red Mountain fault are being prepared.

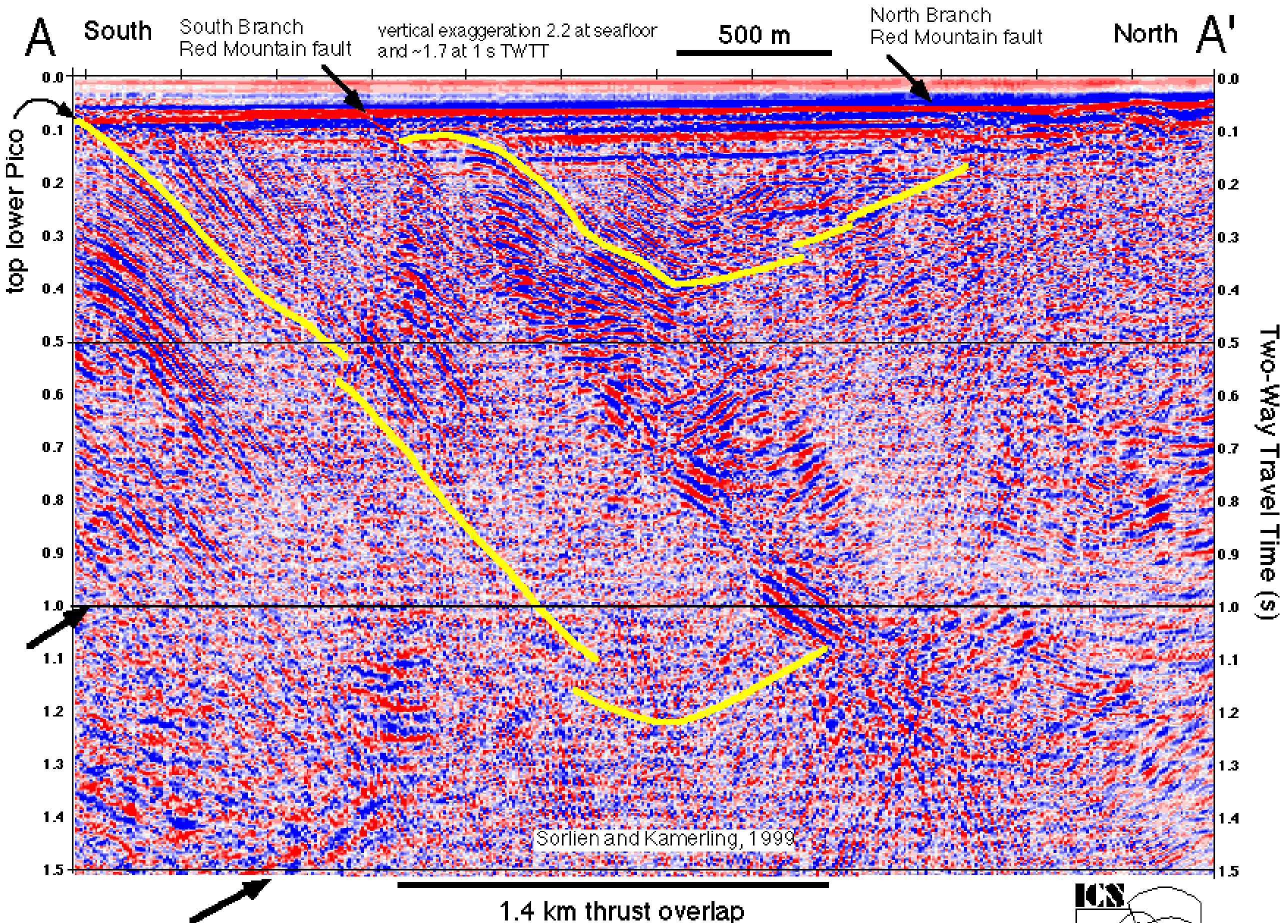

Figure 3: Upper part of migrated industry seismic reflection profile across the south branch of the Red Mountain fault. Interpreted horizon is the ~1.8 Ma top lower Pico Formation. South-dipping faults indicated by arrows are the Hobson fault (Edwards, 1998) and, beneath, a strand of the Padre Juan fault. Profile located in Figures 1 and 4. The Pitas Point-North Channel fault is also characterized by fault-plane reflections.

(e.g., Edwards, 1998). The Red Mountain fault splays into two main branches near the Carpinteria coast. The northern branch decreases in displacement to the west and continues as far west as offshore Goleta where it may die into folding. The south branch decreases in displacement to the west and dies out in a syncline south of Santa Barbara (Fig. 3). Shortening across the Pitas Point-North Channel fault and hanging wall structures increases westward from near Pitas Point to a maximum south of Santa Barbara (Fig. 4). Thus as displacement on the Red Mountain fault is decreasing westward the displacement on the Pitas Point-N. Channel fault is increasing. Displacement on one fault is compensating for the other. The Pitas Point and Red Mountain faults may merge with depth, detaching the intervening upper crustal block. Abrupt changes in shortening and fault-fold style along the strike of the Pitas Point-North Channel fault occur across NE-SW cross faults. Vertical axis block rotation of the segmented detached blocks can transfer slip from one fault to the other. Shortening of the 1.8 Ma horizon due to fault slip and folding across the Pitas Point-North Channel trend locally exceeds 5 km south of Santa Barbara, and exceeds 1 km across the south Branch of the Red Mountain fault south of Carpinteria. Ongoing unfolding and restoration of the digital map will allow slip, block rotation, and shortening to be quantified, and the structural-kinematic interpretation to be validated.

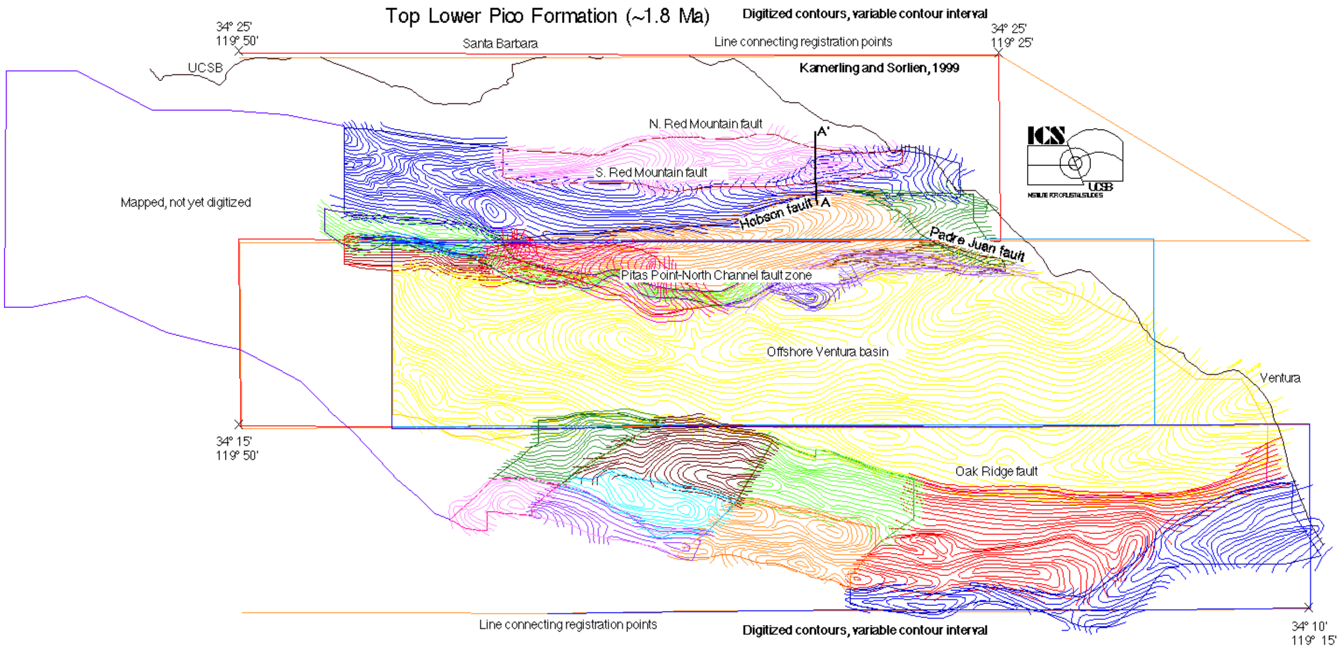

Figure 4: The ~850 digitized contours of our travel-time structure-contour map of the top Lower Pico Formation (~1.8 Ma). The contour interval is not constant because many infill contours were added. Fine gridding requires that the horizontal distance between digitized contours be small. The horizontal and vertical lines connect registration points. Different parts of this map are digitized on different scans, and will be transformed to a geographic reference frame separately. On this figure, there is a slight mismatch between certain fault blocks. Nevertheless, this figure can be used for fault and fold trends, and the outline of fault blocks can be compared to give approximate thrust overlap across faults. Note that contours are digitized beyond fault boundaries because this helps the gridding process. The onshore part of this map was completed in depth and is found in Sorlien and Kamerling (1998).

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Data Availability

The industry seismic reflection data used in this project are not available. Well data, including velocity surveys, are public and available from Industry sources such as Rileys, or from the U.S. Minerals Management Service in Camarillo, California. Low resolution cross sections from the Hopps and others (1995) data set are on the web (http://quake.crustal.ucsb.edu/hopps), and high-resolution onshore structure contour maps and cross sections are available to researchers (see Nicholson and others, 1997). The digital map of the 1 Ma horizon is available on the USGS-NEHRP web site (http://erp-web.er.usgs.gov, then go to annual reports, volume 40, Southern California, Sorlien and Kamerling 1998). Figures and eventually digital maps will be made available on our web site: http://quake.crustal.ucsb.edu/vbmrp.