Map restoration of folded and faulted late Cenozoic strata across the Oak Ridge fault, onshore and offshore Ventura basin, California

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ABSTRACT

The Ventura basin lies within the east-west–trending active fold-and-thrust belt of the western Transverse Ranges, California. This basin has been the site of significant earthquakes on structures within it and bordering it. The purpose of our study is to identify the main structures in the basin and its borders and to quantify their rate of deformation. Our study includes the onshore and offshore Ventura basin, the arcuate basin-bounding Oak Ridge reverse fault, and the Oxnard shelf to the south. Shortening, fault-slip, and crustal-block motions were studied using a three-dimensional map-restoration technique. Structure-contour maps on the 6 Ma surface and other horizons were digitized and restored to the initial horizontal state by unfolding them using the computer program UNFOLD and then fitting the unfolded surfaces across faults. Comparing the restored and present configuration allows us to estimate total net finite displacements relative to a fixed horizontal reference line.

Average post–5 Ma shortening rates estimated from our restoration are slower than both post–1 Ma rates and present rates determined by global positioning systems. Most shortening due to folding in the onshore basin is post–1 Ma, although slip on the Oak Ridge fault has occurred both before and after 1 Ma. Displacement due to faulting and folding includes left-lateral strike-slip motion on the northeast-southwest coastal segment of the Oak Ridge fault and associated clockwise rotation of the adjacent Ventura basin. The Oxnard shelf is bordered to the south by mountains and islands that have been previously interpreted as folds above thrust-fault ramps. This onshore-offshore block moves as one continuous thrust sheet. Similarly, beyond the well-studied onshore fault, a kinematically continuous offshore Oak Ridge–Mid-Channel left-oblique fault system is interpreted to continue at least an additional 100 km westward beneath the Santa Barbara Channel.

Keywords: faulting, kinematics, restoration, Santa Barbara Channel, Ventura basin.

INTRODUCTION

The western Transverse Ranges province of southern California is characterized by east-west–trending folds and faults that contrast with the regional northwest-southeast structural trends that predominate in California (Fig. 1). The province is bounded on the east by the San Andreas fault and on the north and south by northwest-southeast–trending structures of the Coast Ranges and California borderland. These active northwest-southeast faults constitute part of the Pacific–North American plate boundary, the most active participating structure being the San Andreas fault. The Ventura basin is an elongate depression that bisects the western Transverse Ranges between Point Conception and the San Gabriel fault. It formed in post-Miocene time and is superposed on Miocene rift basins and on a Mesozoic–early Cenozoic forearc basin (e.g., Yeats, 1987). The post-Miocene strata alone range from 2 km thickness in the west to 8 km in the east (Figs. 2 and 3; Yeats, 1988).

The western portion of the Ventura basin underlies the northern Santa Barbara Channel (Fig. 1). In the east (onshore), the basin is bordered by the north-dipping San Cayetano and Red Mountain reverse faults on the north and by the south-dipping Oak Ridge reverse fault on the south (Yeats, 1983, 1988; Huftile, 1991; Huftile and Yeats, 1995). The Red Mountain fault extends westward offshore north of and parallel to the Pitas Point–North Channel fault system (Kamerling and Sorlien, 1999). These north-dipping faults form a left-stepping en echelon array (Gratier et al., 1999). This onshore-offshore system is characterized by high rates of Pliocene–Quaternary north-south contraction and rapid Quaternary fault slip and may be capable of relatively frequent large earthquakes (Namson and Davis, 1988; Huftile and Yeats, 1995; Hornafius et al., 1996). South of the Oak Ridge fault, the Oxnard shelf has been only slightly deformed during late Cenozoic time, and it can be considered a relatively stable block (Yeats, 1987). The Oxnard shelf is bounded to the south by an arcuate south-dipping Miocene normal fault (Sulphur Springs fault in Fig. 1, called the proto–Simi fault of Huftile and Yeats, 1996).

The anomalous structural trends in the western Transverse Ranges are due to both clockwise crustal rotation and compression within a restraining bend in the San Andreas fault. Paleomagnetic data have been interpreted to indicate about 95° of clockwise vertical-axis rotation of the western Transverse Ranges since about 17 Ma (Kamerling and Luyendyk, 1985; Luyendyk, 1991). This rotation was accompanied by regional Miocene extension on both sides of the rotating blocks (Kamerling and Luyendyk, 1985; Legg, 1991; Crouch and Suppe, 1993; Sorlien et al., 1999b). Rifting of Baja California from mainland Mexico and creation of the restraining bend of the San Andreas fault resulted in initiation of north-south transpression across the plate boundary at

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GSA Bulletin; July 2000; v. 112; no. 7; p. 1080–1090; 7 figures.

about the end of the Miocene (5.3 Ma; e.g., Atwater, 1989). This transpression has resulted in common reactivation of diversely striking Miocene normal-separation faults as reverse-separation faults, broad downwarping in places, and inversion of half-graben basins into anticlines in others (Yeats, 1987; Clark et al., 1991; Seeber and Sorlien, 2000 [GSA *Bulletin*, this issue]). It is this post-Miocene strain that is the subject of our paper. We are pursuing two questions: (1) What structures absorbed the post-Miocene strain in the Ventura basin region? and (2) What was the rate of strain on these structures? These questions bear upon the structural history of the region, the processes by which this basin has deformed, and

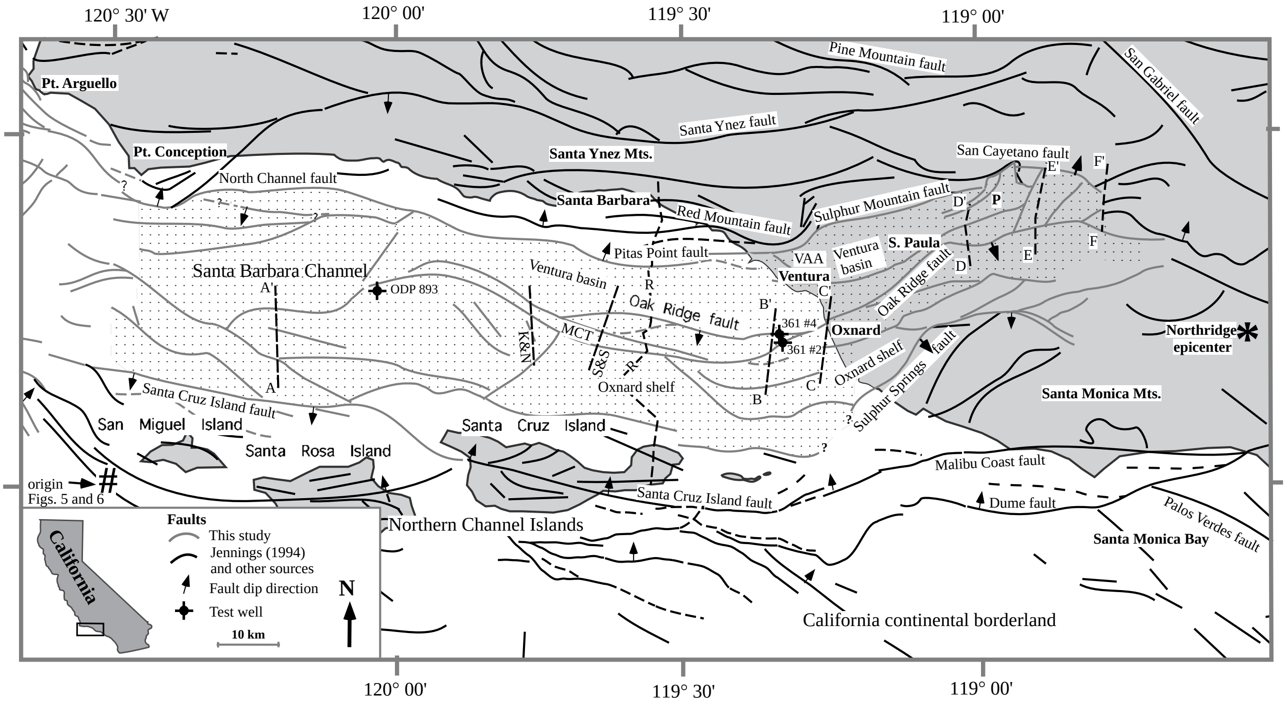

Figure 1. Regional fault map of the western Transverse Ranges, including the Santa Barbara Channel, California. The locations of Figure 6 (A–A′), the published cross sections in Figures 3 and 7 (B–B′ through F–F′), cross section S&S in Shaw and Suppe (1994), cross section K&N in Kamerling and Nicholson (1996), and cross section R by Redin et al. (1998) are shown. P—Pagenkopp fault; MCT—Mid-Channel trend; #—the origin point for Figures 4 and 5. The region that we unfolded is indicated by the dot pattern. Part of the San Cayetano fault is shown at its footwall cutoff of the top of the Fernando Formation. Faults are from Jennings (1994), Kamerling and Sorlien (1999) for the offshore Red Mountain fault, and this study.

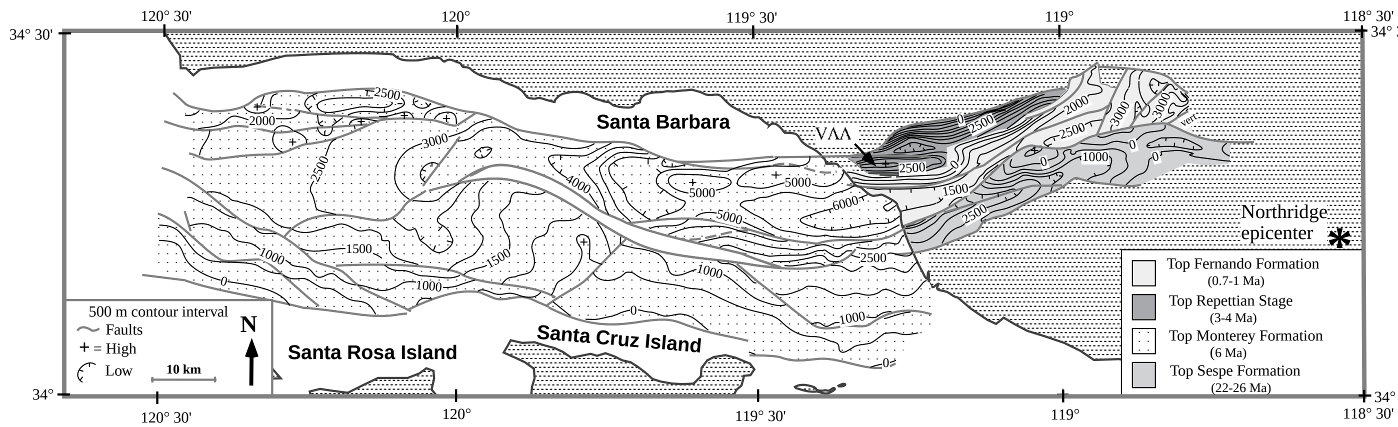

Figure 2. Present-day, deformed depth maps of four horizons for the restored region (see Legend). The horizons are projected where eroded (erosion is restored). Contours at an interval of 305 m (offshore) or 152 m (onshore) were digitized for unfolding. The onshore maps are available at http:/quake.crustal.ucsb.edu/hopps, and a map of the top of the Monterey Formation similar to our interpretation was published by Heck (1998). This figure was recontoured by hand at a 500 m interval. The top of the Fernando Formation is generally just above the 1 Ma horizon of Yeats (1988) in the west part of the Ventura basin, although it is older in the east; the top of the Repettian Stage is Pliocene, top of the Monterey Formation is ca. 6 Ma, and top of the Sespe Formation is about late Oligocene (ca. 26 Ma; older in west and younger in east). VAA—Ventura Avenue anticline; vert.—an area of vertical beds at the east edge of the figure.

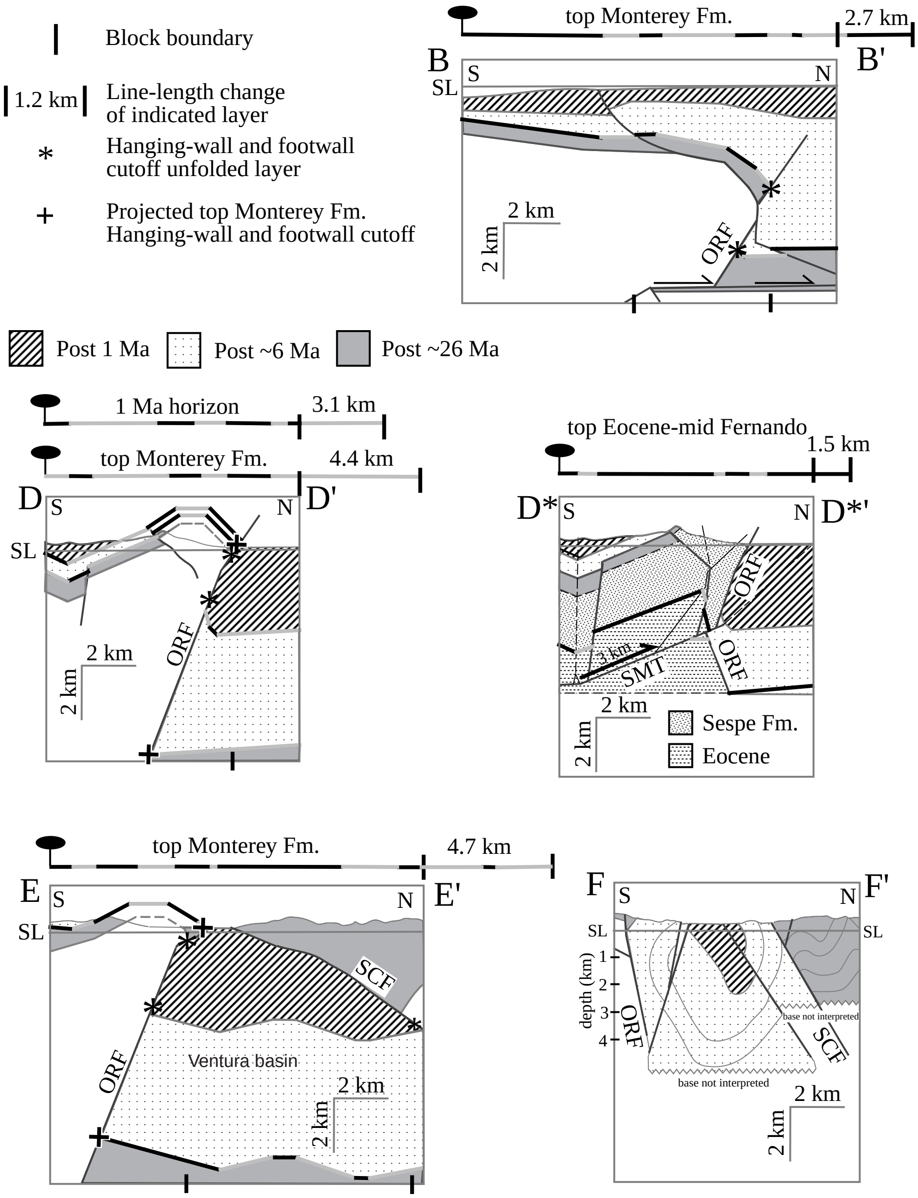

Figure 3. Depth sections, located in Figure 1, that are simplified and/or modified from published sections. SL is sea level. All sections are the same scale and have no vertical exaggeration. The top of the Monterey Formation is at the base of the dotted post–6 Ma interval, and the 1 Ma horizon is at the base of the striped post–1 Ma interval. The top of the Monterey Formation and (in one case) the 1 Ma horizon are represented by alternating gray- and black-line segments. These segments are laid flat and drawn in the same gray and black pattern above the profile. The amount of shortening due to faulting and folding can be determined at any location along a profile by matching the line segments. This shortening is along a profile and need not correspond to the change in map-view area found from unfolding. Cross section B–B′ is simplified from Huftile and Yeats (1995). Wells in block 361 near Oxnard and Ventura (Fig. 1) and a nearby industry seismic-reflection profile confirm the general shape and depth of the top of the Monterey Formation across the Oak Ridge fault. Cross section C–C′ is shown in Figure 7. D–D′ is from Yeats (1988), and E–E′ is from Yeats (1983). D*–D*′ is the Suppe and Medwedeff (1990) modification of the Yeats (1988) D–D′ cross section. Post–1 Ma shortening due to folding can be estimated from older horizons because the beds are parallel in D*–D*′. SMT is South Mountain thrust of Suppe and Medwedeff (1990). The arrow indicates that 3 km of slip is predicted using fault-propagation fold theory (the distance between axial surfaces where they intersect the fault). On cross section D–D′ and E–E′, the top of the Sespe Formation (late Oligocene) is unfolded south of the fault (*—hanging-wall cutoffs), and a horizon above the 1 Ma horizon is unfolded north of that fault (*—footwall cutoffs). The post–6 Ma shortening (the horizontal distance between the + on the sections) was approximated by adding the stippled block in Figure 5. Our modification of D–D′ from the original in Yeats (1988) includes planar downdip projection of the Oak Ridge fault and interpretation of the 6 Ma horizon, based on a basin strike section in Yeats (1983). This modification is essentially identical with that of Huftile and Yeats (1996). The San Cayetano fault (SCF) is not included in the line-length restoration of E–E′. Cross section F–F′ is modified from Yeats et al. (1994).

the seismic hazards to be expected here. A focus of our analysis is the role of the Oak Ridge fault in post-Miocene deformation.

METHOD

Comparison of Three-Dimensional Map Restoration to Cross-Section Balancing

The use of geological strata as crustal deformation markers implies that the strata can be restored to their initial state and that the initial and final state can be compared in order to estimate the finite deformation and displacement. This approach also allows the geometric and kinematic compatibility of the structures to be tested. Map restoration techniques (Schwerdtner 1977; Cobbold, 1979) complement the balanced cross-section techniques (Dahlstrom 1969; Hossack, 1979). Both approaches assume mass, volume, and surface or length conservation.

Restoration of cross sections and maps are both based on the flexural folding assumption (constant layer thickness during the deformation). This assumption is applied in two different ways: (1) *cross sections*—conservation of layer length and area in cross sections, and (2) *maps*—layer length and surface-area conservation of folded sheets (Gratier et al., 1991).

Balanced cross-section techniques search for the best compatibility of the structures at depth (within a plane-strain assumption), whereas surface-unfolding techniques test map compatibility including, for example, the fit between restored hanging-wall and footwall cutoffs along faults (Gratier and Guillier, 1993). Information on the finite displacement deduced from the two methods is different. Balanced cross sections give information on the displacement in vertical planes. Due to the required plane-strain assumption, restoring a series of parallel balanced cross sections gives parallel displacement directions in map view. The map restoration technique gives a map view of the finite displacement that includes nonparallel displacement vectors. Map restoration is theoretically more correct for regions with block rotation because the balanced cross-section technique assumes plane strain parallel to the section and no vertical axis rotation. Map-restoration techniques have been applied that use a simple two-dimensional untilting (Audibert, 1991; Rouby et al., 1993) or that use a three-dimensional unfolding process (UNFOLD program; Gratier et al., 1991).

Unfolding of Deformed Horizons to Estimate Strain

The details of the computer program UNFOLD and the technique of map restoration have been published (Gratier et al., 1991, 1999; Gratier and Guillier, 1993), and only a general description of the technique is given here. Structure-contour maps of a reference competent layer are digitized and gridded for each fault block. The XYZ grid is organized as neighboring triangles, and the computer program UNFOLD lays the triangles flat. Misfits between the flattened triangles and the holes defined by its neighbors are minimized by translation and vertical axis rotation in an iterative process (Gratier et al., 1991). The program UNFOLD produces a map of a misfit statistic and an average value of this statistic (see Gratier and Guillier, 1993, for details). The value of the misfit can be compared to that obtained by unfolding a folded piece of paper (a layer with no stretching parallel to the neutral surface; Gratier and Guillier, 1993). The program also calculates the percent of shortening for each individual fault block.

Given accurately contoured maps and layer surface-area conservation, the main errors in map restoration come from uncertainty about the exact location of the faulted edges of the surface, particularly where reverse faulting creates overlaps. If too little surface overlap is interpreted for the reverse or thrust fault, a void will appear in the map restoration and cross sections can be reinterpreted to eliminate that void (example in Gratier and Guillier, 1993). Automatic fitting programs are available that seek a balance between gaps and overlaps in the outlines of the restored blocks (Audibert, 1991; Rouby et al., 1993). In our approach, one edge of the deformed (present) map is chosen as a fixed reference line, and the outline of each unfolded block is manually and sequentially fit to their neighbors across faults using an interactive graphics program (Gratier and Guillier, 1993). In areas such as the Ventura basin with steep fold limbs and thrust overlap, it is more likely to miss part of a layer than to draw excess area, and therefore voids are more frequent than overlaps. Manual fitting allows one to incorporate the confidence of the interpretation of thrust overlap or the width of steep fold limbs and allows reinterpretation of the available data.

Comparison between the restored and present state allows the finite displacement field to be drawn with respect to the fixed reference line. Estimates of local block rotations with respect to the reference line are obtained by rotating the flattened block outlines to achieve a best fit between neighbors. The results are local estimates of shortening for each block and a regional displacement field derived from fitting all blocks by translation and rotation. Strike-slip motion can be inferred if a fault is arcuate or if the fault terminates and the horizontal motion is accounted for by shortening or extension. For example, the Hosgri fault dies out into tight folds on its east side near Point Arguello and Point Conception (located in Fig. 1). Flattening these folds restores right-lateral motion on the Hosgri fault (Sorlien et al., 1999a).

Unfolding and map restoration is analogous to taking a folded and torn rug, unfolding different pieces of that map, and then fitting the flat pieces back together. If the map of the rug can be unfolded without stretching or creasing it, then the map and our assumptions of area and volume conservation (no layer-parallel shortening or stretching) are permissible interpretations. Map restoration can be applied as a kinematic test relating one cross section or profile to the next, in order to quantify the lateral evolution of slip along arcuate faults and folds. In cases with the curved map-view displacement field associated with local block rotation, the balanced cross-section technique cannot be used, and map restoration is the only way to balance the structures.

Three-Dimensional Map Restoration and Thin-Skinned Structural Models

Both three-dimensional map restoration and cross-section restoration quantify shortening. For thick-skinned tectonic models (planar faults cutting entire brittle crust; Yeats, 1993) and thin-skinned fault-propagation fold models (e.g., Suppe and Medwedeff, 1990), all the fault slip is absorbed by folding or thrust overlap along the structural trend. This shortening would be restored during either cross-section restoration or three-dimensional map restoration. However, in the thin-skinned, fault-bend fold model, most of the slip is transferred beyond the structural trend (Suppe, 1983). This slip is accounted for by shortening only if the map or cross-section restoration includes the entire thin-skinned system. Map restoration can examine lateral changes in slip on a fault-bend fold if, for example, it is linked by a tear fault to a restored fault-propagation fold.

Map restoration can be applied as a kinematic test for the diverse interpretations of the structure of the Oak Ridge trend and modeled blind faults to its south. In particular, we contrast the interpretation that the onshore Oak Ridge fault is unimportant and has been passively folded by a fault propagation fold (e.g., Suppe and Medwedeff, 1990) against the model for an active high-angle reverse fault (e.g., Yeats, 1988). The offshore part of the Oak Ridge trend has been treated as an active axial surface, not a post-Miocene reverse fault (Shaw and Suppe, 1994). Alternatively, the Oak Ridge oblique-reverse fault continues offshore (Huftile and Yeats, 1995; Kamerling and Nicholson, 1996; Stone, 1996).

ANALYSIS AND INTERPRETATION

We determined the net finite strain since 6 Ma for a set of deformed fault blocks mapped within the Ventura basin, both onshore and offshore beneath the Santa Barbara Channel (Fig. 2). Ideally, the geometry of a single 6 Ma horizon would be known through the entire region. This is not the case due to the extreme vertical motions across onshore Ventura basin. The 6 Ma horizon is eroded in the hanging walls of the major reverse faults and is too deeply buried to map beneath parts of onshore Ventura basin. If two horizons are parallel, unfolding either will result in identical estimates of shortening. Published cross sections indicate that the mapped horizons that we restored are subparallel to a ca. 6 Ma horizon in the particular areas in question; it is irrelevant if these layers are nonparallel elsewhere. Despite having to make these adjustments, the 6 Ma reference horizon is the most reliable for regional reconstructions that include eroded areas, partly because it includes the total Neogene contraction. This restoration of total transpressional deformation serves as a reference for studies of younger strata (Kamerling et al., 1998; Sorlien and Kamerling, 1998).

Map restoration is especially applicable to the Ventura basin, where the Oak Ridge fault is arcuate, and the cross-sectional geometry changes dramatically along strike (Fig. 3). The assumption of no layer-parallel stretching is met because very low values (0.005) of the fitting statistics were obtained for our unfolding of the horizons in Figure 2, similar to the values expected by flattening a folded piece of paper (see Gratier and Guillier, 1993, for discussion of permissible val-

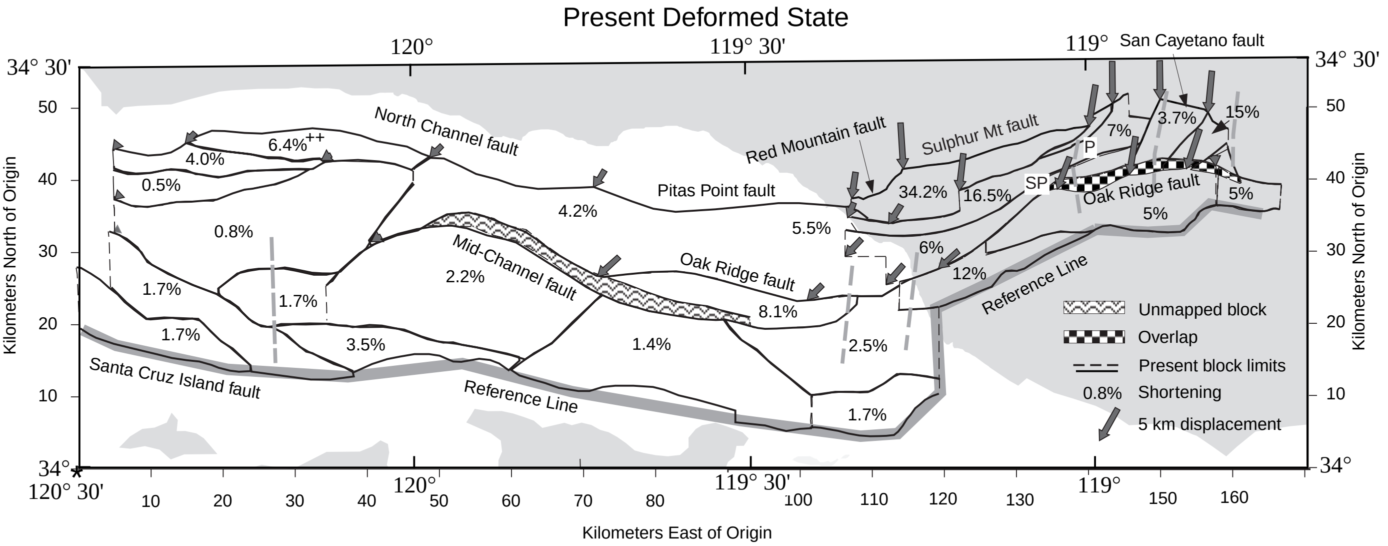

Figure 4. Present-day fault and fold blocks (thin black polygons) that were unfolded. The black arrows give the net finite displacement with respect to a line along the southern edge of the unfolded region. The displacements are inferred by comparing unique points on the present-day map to the same point on restored surfaces (Fig. 5); The numbers shown as % indicate the horizontal shortening in all directions that is quantified by unfolding for each block, and this number does not include shortening due to faulting. The direction of maximum horizontal shortening is perpendicular to fold trends (Fig. 2). Thrust overlap of the top of the Sespe Formation (south) over the top of the Fernando Formation (north) in the eastern part of the study area is represented by the checkerboard pattern. An unrestored block (zig-zag fill) is also shown. Straight north-south and east-west boundaries are limits of unfolded blocks, not faults, and are shown dashed. Boundaries that are faults are shown as solid lines and are also drawn in Figure 1. P—Pagenkopp fault; SP—Santa Paula. Land areas are shown as light-gray shading, and cross sections in Figures 3, 6, and 7 are shown as dashed medium-gray lines.

ues of the fitting statistic). Finite displacement is shown with respect to a southern reference-line location within the little-deformed onshore and offshore Oxnard shelf block because a reference line along the northern edge of Ventura basin would be in the middle of a deformation belt. We are studying the Oak Ridge fault in this paper, and the displacement arrows in Figures 4 and 5 near this fault do not represent any deformation along the north margin of Ventura basin.

Offshore

We modified and restored a structure-contour map of the top of the Monterey Formation (ca. 6 Ma; Barron, 1986) in the Santa Barbara Channel. This map had been constructed by Grant McHattie and others at Mobil Oil Corporation. Correlation of electric (gamma, resistivity, and spontaneous potential) and stratigraphic ("mud") logs confirmed that the depth of the Monterey top is correct at wells. We checked the Mobil correlations of the top of the Monterey Formation through an ~2 km grid of industry multichannel-reflection data. The resulting structure-contour map (offshore part of Fig. 2) is similar to that recently published by Heck (1998). Interpretation of seismic-reflection profiles indicates that, except for the Oak Ridge–Mid-Channel trend (latter is MCT of Fig. 1), faults are high angle with small vertical separation of the top of the Monterey Formation, and, therefore, its overlap across reverse faults is minor (zero to perhaps 100 or 200 m; Fig. 6).

Steep dips along the Mid-Channel trend (MCT on Fig. 1; see Kamerling and Nicholson, 1996) are poorly imaged in seismic reflection data, making the structure difficult to interpret. Because of this, we did not map or unfold a fault block along the Mid-Channel trend (wavy pattern in Fig. 4). The unrestored shortening across this block and its boundaries is seen as a gap in the unfolded map (stipple in Fig. 5). It is still possible to unfold and restore a rug with a hole in it as long as we know how to connect the unfolded rug at either side of the hole, and especially if we also know how wide the hole is at several locations. A significant shortening along profile A–A′ (Fig. 6) beyond what was restored is highly unlikely. The fitting of blocks west of the "hole" should therefore be accurate. Section B–B′ and our interpretation of a nearby industry seismic-reflection profile and wells indicate that the gap should be about 2 km to the east of the hole (Figs. 3 and 5). About 2 km of shortening across the west-northwest–striking Mid-Channel trend (the "hole") is incorporated in our fitting of unfolded blocks. This amount of shortening is consistent with cross sections (Kamerling and Nicholson, 1996; Redin et al., 1998; indicated by "K&N" and "R," respectively, in Fig. 1).

Onshore

Numerous well data and outcrop information were used by Hopps et al. (1995) to construct the onshore maps on Quaternary and Pliocene horizons north of the Oak Ridge fault and on the top of the Sespe Formation (late Oligocene–early Miocene?) immediately south of that fault (Nicholson et al., 1997; see Fig. 2[1]). Our reference horizon is the approximate age equivalent of the ca. 6 Ma top of the Monterey Formation (called the Modelo Formation south of the Oak Ridge fault; Yeats, 1988). South of the Oak Ridge fault, the ca. 6 Ma horizon is eroded away at many locations; there, the top of the underlying Sespe Formation was used. Cross sections indicate that the top of the Sespe Formation and the ca. 6 Ma horizon are nearly parallel in the hanging wall immediately south of the Oak Ridge fault (B–B′, D–D′, and E–E′; Fig. 3). If two horizons are parallel, folding must have occurred after deposition of the upper horizon, and unfolding either of them will produce identical estimates of shortening. Therefore, the majority of resolvable deformation in this area is post–6 Ma, and the top of the Sespe

[1]Unpublished maps and cross sections are available on the Internet at http://loquake.crustal.ucsb.edu/hopps/. These maps and cross sections are shown at low resolution; the 1:48 000-scale data are still proprietary but are available to researchers under signed agreement.

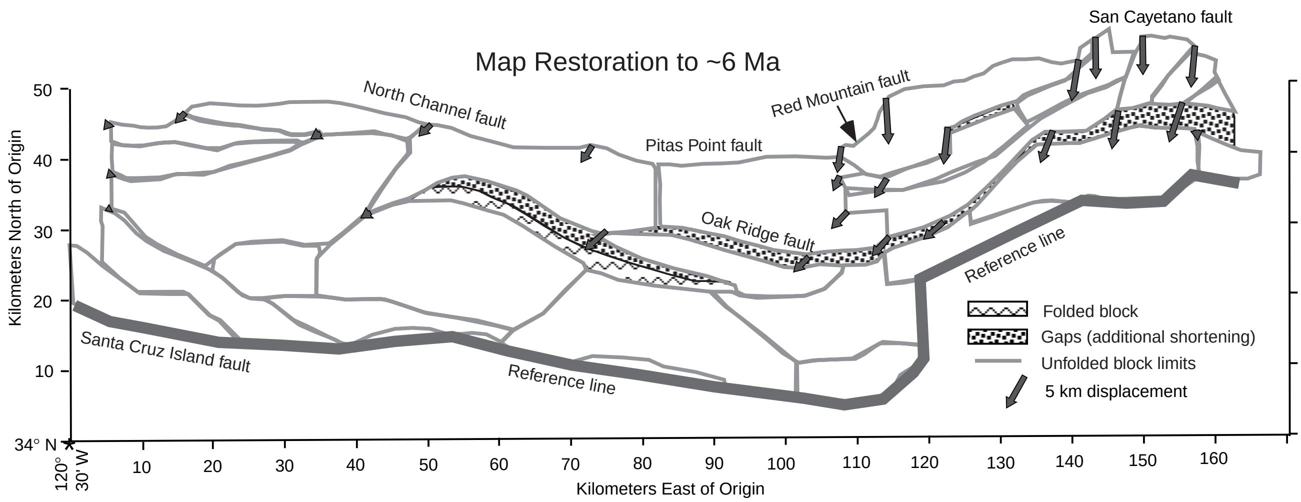

Figure 5. The retro-deformed (unfolded) fault blocks (gray outlines). The stippled blocks (with heavy dots) represent additional shortening that was added during fitting of the unfolded blocks. These stippled blocks include the shortening across the Mid-Channel trend that was not mapped or restored. It represents the part of the thrust overlap of the ca. 6 Ma horizon not accounted for in Figure 4 (checkerboard pattern), and it also includes the length of a vertical-to-overturned fold limb near the east edge of the restored area (F–F′ in Fig. 3). The finite displacement vectors are the same as in Figure 4. Figure 5 can be compared with Figure 4 on a light table using common reference lines.

Formation can be used as a proxy for the ca. 6 Ma horizon where it is eroded.

Maps of the top of the Fernando Formation (top of the Pico Formation in Hopps et al., 1995) and top of the Repettian Stage were unfolded north of the onshore Oak Ridge fault (Fig. 2). The top of the Fernando Formation is time transgressive and is older in the east (Yeats, 1977), but it is located just above the 1 Ma horizon of Yeats (1988) in the study area. Deformation of the two horizons is essentially the same (Fig. 2 for top of the Fernando Formation; see http://quake.crustal.ucsb.edu/vbmrp and Yeats, 1989, and Kamerling et al, 1998, for the 1 Ma horizon). The top of the Repettian Stage is time transgressive, being ca. 3.4 Ma northwest of the Santa Barbara Channel (Clark et al., 1991) and ca. 2.5 Ma in Los Angeles basin (Blake, 1991). Our assumptions only require that folding postdate the Repettian Stage for the block mapped on that horizon along the northern margin of Ventura basin (Fig. 2). The ca. 1 Ma horizon is very nearly parallel to the underlying ca. 6 Ma horizon on published cross sections (Fig. 5; Huftile and Yeats, 1995, 1996), implying that folding within west Ventura basin is post–ca. 1 Ma. Post–ca. 6 Ma thrust overlap is interpreted from published and unpublished cross sections (Fig. 3; D–D′; Nicholson et al., 1997), and this overlap is accounted for during the fitting of unfolded blocks by adding a gap (stippled block in Fig. 5). The ca. 6 Ma horizon has greater vertical separation and thrust overlap than the 1 Ma horizon in D–D′ (Fig. 3); therefore, fault slip occurred here between 6 and 1 Ma. We assume that this slip occurred without pre–ca. 1 Ma footwall folding below well control. If there is older footwall folding or if the Oak Ridge fault flattens with depth (i.e., is listric), then we have underestimated shortening due to folding and thrust overlap.

DISCUSSION

Fold and Fault Compatibility and Mechanism of Shortening

Our reconstruction (Fig. 5) is one possible geometric solution that represents the best fit between all of the unfolded blocks. The black arrows in Figures 4 and 5 connect the map-view locations of the edges of the 6 Ma horizon in the fault blocks with the present location of these edges. The arrows represent the net horizontal displacement with respect to the reference line since 6 Ma. The south-to-southwest displacement ranges from a few hundred meters in the west, to ~2 km along the Mid-Channel trend, to 5 to 6 km in the east. The local change in map-view area for each fault block is given in Figure 4; surface area is conserved. Note that these shortening values are averages for entire unfolded blocks and do not include contraction across faults along the block boundaries.

Both published cross sections and our restored depth-contoured surfaces show that most shortening in the mapped areas is by reverse faulting and that little shortening has been absorbed by folds, except immediately adjacent to the Oak Ridge fault and south of the Sulphur Mountain fault (Figs. 1 and 2). Folding represents only a few hundred meters of shortening in western Santa Barbara Channel and slightly more than 1 km at the coast and across the onshore Ventura basin and Oxnard shelf in the east. Folding absorbs about 4 km of shortening above blind faults south of the Sulphur Mountain fault, including the Ventura Avenue anticline (Figs. 2, 4, and 5; Huftile, 1991). This lateral variation in shortening is reflected in the total structural relief (elevation change) of the top of the Monterey Formation across the restored area due to faulting and folding. Structural relief increases from 2 km on cross section A–A′ in the west to almost 10 km on section E–E′ in the east (Figs. 3 and 6).

The best-fit modeled southward displacement of the footwall cutoff along the Red Mountain and San Cayetano faults has been about 6 km with respect to the southern reference line (Fig. 4). The modeled displacement does not, however, include shortening due to slip on the Red Mountain and San Cayetano faults or folding in the hanging wall north of these faults. Post–1 Ma thrust overlap across the San Cayetano fault along E–E′ is more than 7 km (Fig. 3), and is at least 9 km since 6 Ma (Huftile and Yeats, 1996). Adding 9+ km to the ~5 km of shortening restored along E–E′ results in total shortening of more than 14 km across Ventura basin. Both this thrust overlap and unfolding of the hanging wall were included in the more regional restoration of Gratier et al. (1999).

Block Rotations and Fault Slip

The displacement field drawn in Figures 4 and 5 shows that crust moved relatively south from the San Cayetano fault toward the Oak Ridge fault and was deflected southwest or clockwise

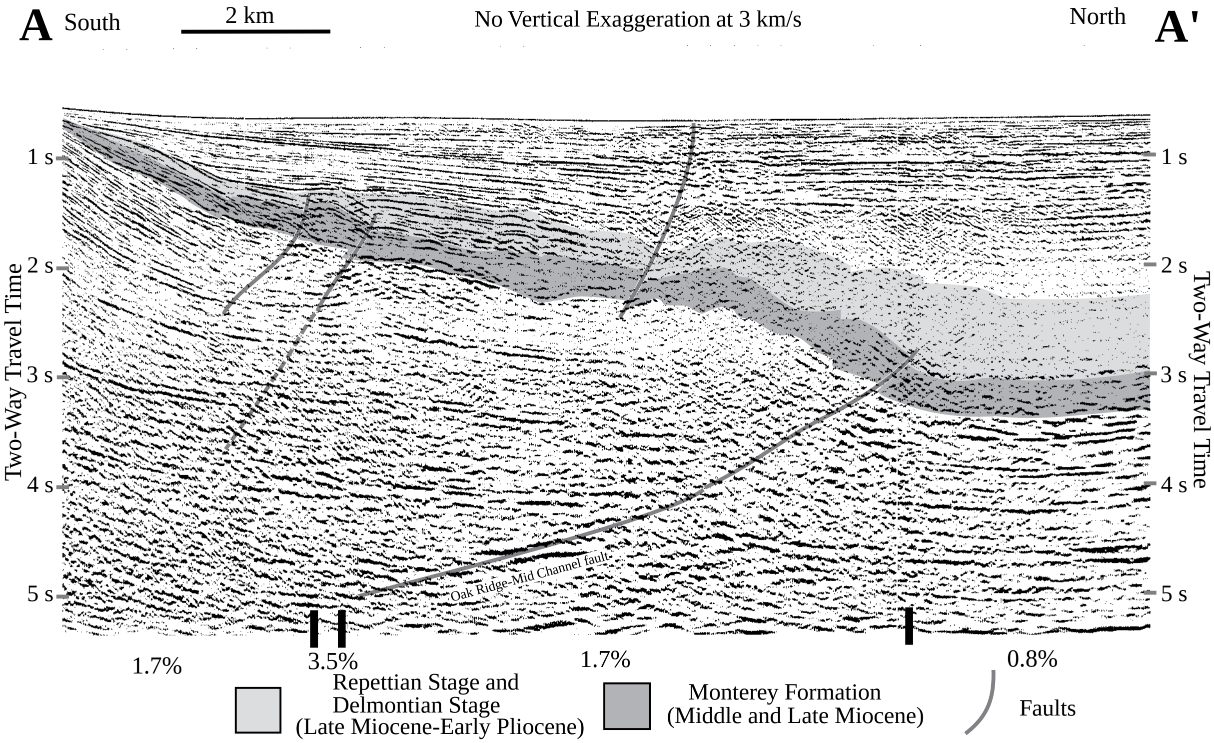

Figure 6. A north-south–migrated multichannel-seismic reflection profile in western Santa Barbara Channel (location shown in Fig. 1). The approximate edges of the fault blocks are shown by heavy vertical black lines on the bottom of the profile. Percentage of shortening in the blocks is also shown (see Fig. 4). This industry profile is of a more recent vintage than those used to create and evaluate the structure-contour map. Discontinuities or reflections that we interpret to be faults form the block boundaries in Figures 4 and 5. The top of the Monterey Formation was unfolded; little thrust overlap seems possible. This minimal post–6 Ma shortening across the western continuation of the Oak Ridge–Mid-Channel fault system helps determine what is possible farther east.

along the nearly vertical, northeast-striking segment of the Oak Ridge fault instead of overriding the Oxnard shelf. Left-lateral displacement is required across this segment of the Oak Ridge fault because there is little shortening or extension perpendicular to the fault. A clockwise vertical axis rotation of about 6° is seen by comparing the restored orientation of the long, narrow block immediately north of the Oak Ridge fault to its present orientation (Figs. 4 and 5). Smaller coherent blocks would result in larger local clockwise rotations in the area of maximum curvature in the strike of the Oak Ridge fault, and any regional rotation of the block containing our reference line must be added to the local rotations determined from our restoration. Paleomagnetic measurements have been used to infer rapid Quaternary vertical-axis, clockwise-block rotation within the Ventura basin in this area (Liddicoat, 1992), and global positioning system (GPS) measurements indicate that these rotations continue today (Donnellan et al., 1993). This vertical-axis rotation provides a mechanism to transfer slip across the Ventura basin and is related to the strong east plunge of the Ventura Avenue anticline (Fig 2; Sorlien and Kamerling, 1998).

There is independent geologic evidence for left-lateral slip on the northeast-southwest part of the Oak Ridge fault. Yeats and Taylor (1989) estimated a 3.5 km component of left slip based on offset of a facies change in the ca. 1 Ma horizon across the Oak Ridge fault near Santa Paula (SP in Fig. 4), with this facies change being projected in the air where eroded south of the fault. Our estimate of ~3 km of post–6 Ma southwest displacement is less than the Yeats and Taylor (1989) post–1 Ma estimate of left separation in the same area. Unfolding and restoration of the map of the 1 Ma horizon of Yeats (1989) by Kamerling et al. (1998) shows that post–1 Ma left slip must be less than 2 km unless a left-lateral shear zone cuts the Ventura basin in the footwall of the Oak Ridge fault. The northeast-southwest segment of the Oak Ridge fault aligns with a northeast-southwest segment of the Pagenkopp fault along the northern margin of Ventura basin (Fig. 1), suggesting that such a left-lateral shear zone is possible (Sorlien and Kamerling, 1998). Alternatively, Yeats and Taylor (1989) overestimated the left-lateral component of slip. We use the shortening due to faulting and folding across east-west segments of the Oak Ridge fault to determine the left-lateral displacement across the northeast-southwest coastal segment, and do not incorporate the Yeats and Taylor (1989) piercing point or the inferred shear zone. In our results a minimum 3 km of left slip on the northeast-striking segment of the Oak Ridge fault is linked to oblique left-reverse slip on the west-northwest–striking Mid-Channel trend offshore (Figs. 1 and 4).

Timing and Rate of Deformation

The top of the Monterey Formation and the early Pliocene horizons are parallel or nearly parallel over wide areas on offshore reflection profiles (Kamerling and Nicholson, 1996; Redin et al., 1998; Sorlien et al., 1998). Early Pliocene compressional-fold growth is interpreted in those areas where the top of the Monterey Formation is not parallel to early Pliocene strata (B–B′ in Fig. 3, and A–A′ in Fig. 6). We interpret continuing post–6 Ma transtension (e.g., McGroder et al., 1994), if present at all, to have been relatively minor and localized, and, therefore, Figure 4 does represent displacement since initiation of contraction. Work in and around the western Transverse Ranges indicates that contraction did not initiate until between 5.3 and 4.5 Ma (Clark et al., 1991; Schneider et al., 1996). In addition, Repettian Stage (early Pliocene) strata thin onto folds bounding the northern Los Angeles basin on cross sections of Wright (1991). Furthermore, Repettian Stage strata onlap the regional fold limb south of the Oak Ridge fault in the Santa Barbara Channel (Fig. 6; Redin et al., 1998). Thus, the shortening and displacement indicated in Figures 4 and 5 may represent post–5 Ma deformation, and the rates that will be discussed are averaged over 5 m.y.

Average rates of north-south shortening since 5 Ma are ~1 mm/yr across the onshore restored region, and ~3 mm/yr if including slip on the San Cayetano fault, with an additional 0.5 mm/yr if the folding of Miocene strata in the hanging wall north of the San Cayetano fault is restored (see cross section in Yeats, 1983). The maximum average slip rate is less than both the post–1 Ma rates of contraction estimated from cross sections and less than geodetic estimates of present contraction. Uniaxial northeast convergence across the eastern Santa Barbara Channel (including the offshore Ventura basin) is presently occurring at rates ranging between 4.9 and 6.4 mm/yr (Larsen et al., 1993; Larson and Webb, 1992). GPS data indicate approximately north-south shortening rates across the onshore Ventura basin of about 7 mm/yr (Donnellan et al., 1993), similar to the post–1 Ma geologic rates. Post–ca. 1 Ma horizontal shortening ranges from 6.6–8.3 km (near B–B′) to 10.2–11.5 (near F–F′) (Huftile and Yeats, 1995, 1996). It seems certain that deformation rates across the Ventura basin are higher during the past 1 m.y. than previously.

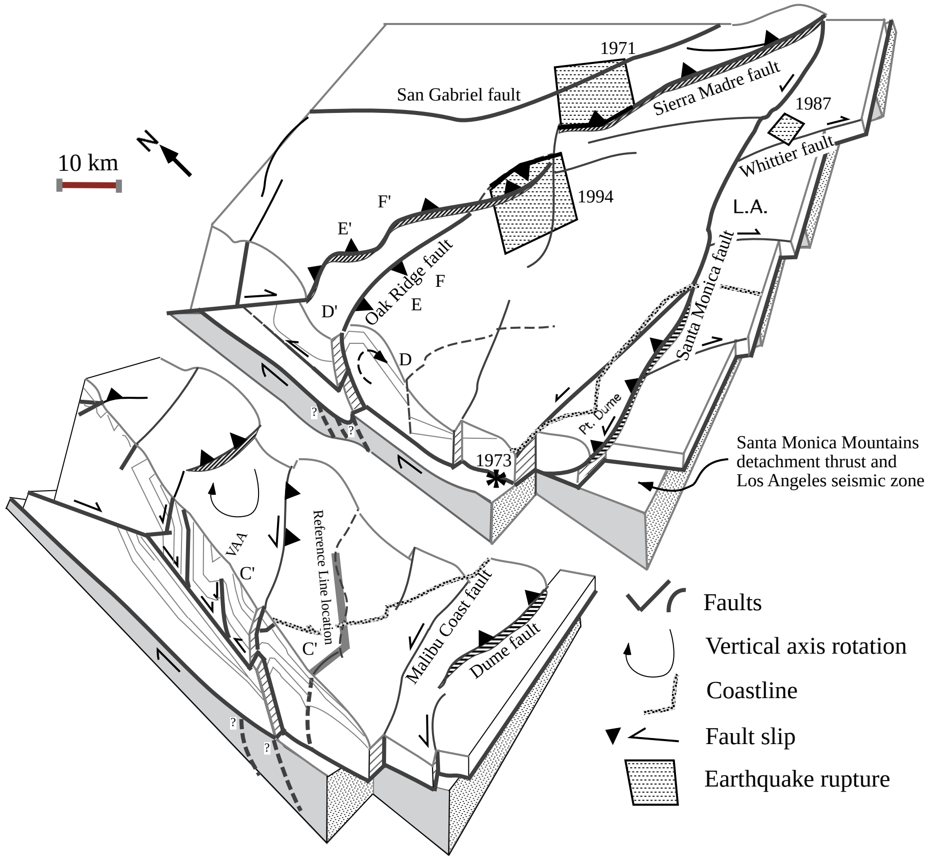

Figure 7. Block diagram of onshore Ventura basin and adjoining areas. The map surface is simplified from Figure 1 but is approximately to scale, although the surface relief is exaggerated. The cross sections are modified from Huftile and Yeats (1995; C–C′) and Yeats (1988; D–D′); C–C′ is approximately to scale but has been skewed for the oblique view; D–D′ is not to scale. Earthquake rupture locations are given by year and are simplified from U.S. Geological Survey and Southern California Earthquake Center (1994). Folding is shown only selectively. The locations of cross sections from Figure 3 are given by letters. Displacement transfer by clockwise rotation of a detached crustal block, combined with motion of a south-directed thrust wedge, is represented in the foreground. VAA—Ventura Avenue anticline.

Structural Compatibility

Map restoration is a tool that allows a kinematic test of the diverse interpretations of onshore and offshore Ventura basin structure. The simplified cross sections in Figure 3, all drawn to the same scale, show that the structure changes dramatically along strike. Yet, the deformation is dependent and, thus, a combination of possible motions of crustal fault blocks that result in the interpreted shortening on cross sections must exist. Our model is one kinematically possible interpretation, and we explore below some of its implications.

Displacement Associated with the Eastern East-West–Striking Part of the Oak Ridge Fault

Published interpretations of the onshore Oak Ridge fault include a very active steep and planar fault (Yeats, 1983, 1988; Huftile and Yeats, 1996) or, alternatively, a preexisting north-dipping normal fault that has been passively folded through vertical by a north-verging fault-propagation fold (Namson and Davis, 1988; Suppe and Medwedeff, 1990). In the former interpretation, the Oak Ridge fault cuts steeply to seismogenic depths. In the latter interpretation, the active south-dipping fault flattens at a depth of 5 or 6 km so that an earthquake hypocenter on this fault could be located far south of its surface trace (Fig. 3; D–D′ vs. D*–D*′). The amount of post–6 Ma shortening along D–D′ (Fig. 3) is 4.4 km in the steep- and planar-fault model of Yeats (1988). The reinterpretation of the same section as a fault-propagation fold by Suppe and Medwedeff (1990) results in estimates of 3 km of total reverse slip, of which only about 2.2 km is accounted for as shortening across the associated Quaternary fold (D*–D*′ in Fig. 3). About 0.7 km of extension occurs across a north-dipping normal fault on D*–D*′, with a greater extension if the fault is projected to the ca. 6 Ma horizon (Fig. 3). This extension must be Pliocene in age in the Suppe and Medwedeff (1990) interpretation because the Fernando Formation is involved. The maximum total post–6 Ma shortening across D*–D*′ is then 2.2 – 0.7 = 1.5 km. Our modeled 3 km of post–6 Ma left-slip motion on the Oak Ridge fault near Santa Paula is based on shortening across east-west segments of that fault, and is independent from and can be compared with the estimated post–1 Ma 3.5 km left separation (5.2 km of true slip) of Yeats and Taylor (1989). Using the net 1.5 km shortening in the interpretation of Suppe and Medwedeff (1990, D*–D*′) in our map restoration would result in less than a third of the left slip interpreted by Yeats and Taylor (1989). The fault-propagation fold model of Suppe and Medwedeff (1990) can only be compatible with the Yeats and Taylor (1989) slip estimate if there are several kilometers of post–1 Ma left-lateral displacement transfer across Ventura basin from the Pagenkopp fault. The original Yeats (1988) interpretation of E–E′ is more compatible with the estimate of 3.5 km of left slip; it requires less displacement transfer.

Deformation and Displacement in the Eastern Ventura Basin

Cross section F–F′, from Yeats et al. (1994), shows a syncline with a vertical to overturned south limb that is 5 km wide (Fig. 3). An additional 2 km or more of eroded fold limb must be projected into the air in order that the cross section be retro-deformable. Thus, at least 7 km of shortening is accounted for by this fold limb. The width of a vertical fold limb is the same as the shortening absorbed in that limb. Therefore, an additional 5 km of shortening was absorbed in the vertical north limb of this fold. Cross section E–E′ (Fig. 3) is only 10 km to the west of F–F′, yet strata in the Ventura basin are subhorizontal. The minimum 12 km of shortening in the fold on F–F′ laterally evolves into about 5 km of thrust overlap across the Oak Ridge fault, and some of the at least 9 km of thrust overlap across the San Cayetano fault (post–ca. 6 Ma in age). Consequently, lateral compatibility implies that a tear fault or lateral ramp affects the San Cayetano fault between sections F–F′ and E–E′. This is a good example of lateral evolution from folding and high-angle reverse faulting (F–F′) to thrust faulting (E–E′), and unfolding and map restoration is an efficient method for studying this geometry.

Displacement Transfer Between the Onshore and Offshore Ventura Basin

Our estimates for slip on the deep Oak Ridge fault beneath eastern Santa Barbara Channel are half those of Huftile and Yeats (1995), although we agree on total post-Miocene slip on the shallow fault. Huftile and Yeats (1995) proposed that a detachment surface near 8 km depth connects the Oak Ridge fault offshore with folding in the Ventura Avenue anticline to the north. Using deformation-rate estimates over the past 0.5 m.y. for the anticline, they interpreted that the detachment has undergone 2.5 km of slip since that time. We agree with the Huftile and Yeats (1995) interpretation of section B–B′ offshore (Fig. 3), which shows 2.7 km of shortening associated with the Oak Ridge structure itself. The 2.5 km of slip on the detachment thrust must be added to this 2.7 km for a total of 5.2 km of shortening across the deep Oak Ridge fault in the interpretation of Huftile and Yeats (1995, shown below the flat detachment on B–B′ in Fig. 3). This translates to 6.0 km of slip on a 30°-dipping fault.

Our map restoration, however, indicates that less horizontal motion is associated with the Oak Ridge fault at B–B′ than is required by the Huftile and Yeats (1995) model or than is present across east-west segments of the onshore Oak Ridge fault (Figs. 4 and 5). Shortening across the Santa Barbara Channel, including the folds and faults along the northern margin of the Channel, increases to the east from a hinge located near Point Arguello (Gratier et al., 1999). Shortening across the Oak Ridge fault and in adjacent folds should thus decrease from 4.4 km at D–D′ by about 20% to 3.5 km at B–B′ (Figs. 1 and 3). Faulting and folding across the offshore Oak Ridge fault absorbs 2.7 km of shortening, so that only 0.8 km of excess shortening is available for displacement transfer on a detachment.

The 2.4 to 2.5 km of dip slip calculated by Yeats (1988) across the Oak Ridge fault since the end of deposition of the Saugus Formation (presumed to be 0.5 Ma in this area) was apparently used by Huftile and Yeats (1995) to infer 2.5 km of displacement transfer on a flat fault to the west. However, the Oak Ridge fault dips 70° at section D–D′ so that the dip slip is much greater than the shortening; the corresponding horizontal shortening is less than 900 m. Vertical motions, unlike horizontal motions, can diminish gradually as a simple tilt or diminish abruptly across a cross fault. Folding in the hanging wall of the Oak Ridge fault along section D–D′ contributes up to 0.4 km of shortening (Fig. 3) for a maximum shortening of 1.3 km (0.9 + 0.4 km). Reducing this value by 20% for the regional hinge motion results in a maximum 1 km of shortening available for displacement transfer at B–B′. This 1 km of inferred post-Saugus slip on the blind fault can be added to the 2.7 km of shortening seen on the shallow fault for a total of 3.7 km post–6 Ma slip on the deep offshore Oak Ridge fault. Late Quaternary slip rates on the offshore Oak Ridge fault must be less than half that implied by Huftile and Yeats (1995) to be compatible with our restoration and with this logical argument. The 2.5 km of shortening accommodated in the Ventura Avenue anticline (Huftile and Yeats, 1995) could be related to 1 km of north-directed displacement transfer combined with additional shortening related to a south-directed tectonic wedge (Fig. 7). If, on the other hand, additional left slip is transferred across the Ventura basin from near the Pagenkopp fault to the Oak Ridge fault near Santa Paula, as discussed above, then the additional horizontal motion required by the Huftile and Yeats (1995) model might be available. Geological and geophysical studies should be focused on the area of the inferred left-lateral shear zone to search for direct evidence of its existence (Kamerling et al., 1998).

The Oak Ridge Structure as a Reverse Fault or Active Axial Surface above the Thrust Ramp

Huftile and Yeats (1995) proposed that the offshore Oak Ridge structure is a reverse fault (see also Kamerling and Nicholson, 1996). Alternatively, the offshore Oak Ridge trend has been interpreted by Shaw and Suppe (1994) to be an active axial surface that is related to the kink in the hypothesized Channel Islands thrust ramp at depth. Slip of 11 km is proposed for this blind thrust (Shaw and Suppe, 1994). The Santa Monica Mountains and northern Channel Islands have been proposed to be an anticlinorium resulting from slip on a north-dipping ramp in a continuous thrust-fault system (Davis and Namson, 1994; Seeber and Sorlien, 2000 [GSA *Bulletin*, this issue]). Part of the north limb of this anticlinorium is seen in Figures 2, 3, and 6.

Our own interpretation of the seismic-reflection and well data is that there is a significant south-dipping reverse fault along the offshore Oak Ridge trend. We modeled the faults and the displacement to be continuous (in space) between the onshore and the offshore Oak Ridge fault and the Mid-Channel trend (Fig. 1). The results of our map restoration require that the onshore Oak Ridge fault continues offshore, unless there is a large displacement transfer zone or tear fault across the Oxnard shelf between the onshore and offshore cross sections (D–D′ and C–C′; Figs. 3 and 7). No such tear fault or displacement transfer is seen in the pattern of faults and folds (Figs. 1 and 2). Displacement is transferred between the Oak Ridge fault and Mid-Channel trend by folds, local block rotation, and connecting faults so that shortening is at a local minimum at the location of the Shaw and Suppe (1994) cross section (Fig. 5; cross section S&S in Fig. 1).

Shaw and Suppe (1994) proposed a north-northeast–striking sinistral-displacement transfer zone along the southeast margin of their Channel Islands thrust and did not discuss the relationship of the Channel Islands thrust to the Santa Monica Mountains thrust (name used by Dolan et al., 1995). If these two proposed north-dipping fault ramps are not connected, then the interpretation of Shaw and Suppe (1994) requires a tear fault or shear zone with 11 km of left slip extending from the San Cayetano fault across the Ventura basin and cutting the Oxnard shelf. No such structure can be seen with the available data (Fig. 2; http://quake.crustal.ucsb.edu/hopps; Heck, 1998). Instead, we propose that the Channel Islands thrust, if it exists, must be the western continuation of the Santa Monica Mountains thrust, with a left bend or tear fault between them (also, J. Shaw, 1997, personal commun.). Our map restoration cannot directly evaluate the existence of the proposed Santa Monica Mountain–Channel Islands thrust because we have not restored across the southern limit of that structure. We can say that the hanging wall of this thrust (if it exists) must have a uniform or smoothly west-decreasing displacement with respect to the footwall over the entire restored area.

CONCLUSIONS

Our application of the map-restoration technique produces a kinematically and geometrically admissible model for the onshore and offshore Ventura basin that relates block motions and fault-slip vectors across the entire 160-km-long region. Within the studied area, the total shortening due to folding and faulting since ca. 6 Ma is about 6 km in the east and a few hundred meters in the west. Most of the shortening is absorbed by reverse faulting and folds associated with reverse faults. Analysis of published and unpublished cross sections indicates that there has been more post–6 Ma contraction across the San Cayetano–Red Mountain fault system and its hanging wall than across the Oak Ridge fault and the Ventura basin. Post–1 Ma and present rates of contraction are both higher than the average rate since shortening commenced ca. 5 Ma.

There is a north-south direction of displacement in onshore Ventura basin and northeast-southwest displacement near the coastal section of the Oak Ridge fault. South-moving material is deflected and escapes to the southwest along the preexisting northeast-southwest edge of the Oxnard shelf–Santa Monica Mountains block, rather than deforming or overriding this resistant block. The modeled displacement of block boundaries indicates clockwise block rotation north of the onshore Oak Ridge fault in the Ventura basin and left-lateral slip on northeast-striking segments of that fault.

The shortening across east-west–trending segments of the Oak Ridge fault decreases gradually from about 5 km in the eastern (onshore) part to about 3.5 km beneath eastern Santa Barbara Channel (1 km of this shortening is transferred to the north) to near zero beneath the western Santa Barbara Channel. The Oxnard shelf–Santa Monica Mountains block is continuous with the offshore Oxnard shelf (southern Santa Barbara Channel), and map restoration favors a continuous onshore and offshore Oak Ridge fault. Therefore, either (1) the north-dipping Channel Islands thrust and Santa Monica Mountains thrust proposed by other authors do not exist, or (2) these structures are moving together as one giant thrust system. In the latter case, the Oak Ridge fault is a left-oblique reverse fault in the hanging wall of these blind thrust faults.

Part of the reason that conflicting interpretations exist here is that geometric and kinematic analysis has not been done in both cross section and map view. The use of the map restoration technique is demonstrated to be an efficient tool to test the compatibility of folded and faulted structures when the plane-strain assumption needed for balanced cross sections is not valid. This is the case in the Transverse Ranges, where the horizontal displacement field map includes common nonparallel displacement directions.

ACKNOWLEDGMENTS

Jim Galloway (of the Minerals Management Service), Ron Heck, Marc Kamerling, Craig Nicholson, and Nano Seeber provided geologic and geophysical input. Bob Yeats, M. Meghan Miller, Ray Weldon, Delphine Rouby, Peter Vrolijk, Joan Fryxell, and an anonymous reviewer provided constructive comments on various versions of this manuscript. The GMT software of Wessel and Smith (1991) was used to prepare and view data. Petroleum industry data have been critical to this study. Grant McHattie and others at Mobil Oil created the depth structure-contour map in the offshore, and Robert Hindle and Howard Stark (with T. Hopps) prepared the onshore maps. We thank Mobil Oil Exploration and Producing U.S., Incorporated, for partial support and permission to use maps and data. This research was supported by the Southern California Earthquake Center (SCEC), which is funded by National Science Foundation Cooperative Agreement EAR-8920136 and U.S. Geological Survey Agreements 14-08-0001-A0899 and 1434-HQ-97AG01718. The SCEC contributions number for this paper is 502, and the Institute for Crustal Studies contribution number is 0257-69TC.

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MANUSCRIPT RECEIVED BY THE SOCIETY NOVEMBER 12, 1996
REVISED MANUSCRIPT RECEIVED OCTOBER 1, 1998
MANUSCRIPT ACCEPTED JULY 27, 1999

Printed in USA