Deep crustal structure and tectonics in the offshore southern Santa Maria Basin, California

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ABSTRACT

Reprocessed deep-penetration seismic reflection profiles across the offshore southern Santa Maria Basin suggest a complex history of tectonic deformation. The top of subducted oceanic crust, imaged at the north end of EDGE line RU-10, is disrupted and eventually disappears to the south. Farther south, a strong lower crustal reflection ramps up and may reflect a possible north-dipping low-angle detachment, or a change in crustal geometry associated with the subducted Morro Fracture Zone. Above a time-transgressive unconformity, Miocene and younger sediments onlap to the south and water bottom deepens, suggesting a major regional tilt reversal in post-Miocene time. Below the unconformity, basement is displaced by largely northwest-striking normal faults that we believe form tilted crustal blocks; it is possible that Cretaceous and Paleogene sections are preserved in resulting half-grabens. Some of these normal faults, including splays off the outer Santa Lucia Bank fault system, were reactivated as minor reverse faults in post-Miocene time. There is no evidence that requires any post–17.5 Ma tectonostratigraphic terrane boundary through this area; rather, much of the structure of the southern Santa Maria Basin appears to be continuous with the rotated Western Transverse Ranges and northern Channel Islands.

INTRODUCTION

The offshore Santa Maria Basin occupies a strategic position along the active continental margin of western North America. The region has undergone early Tertiary subduction, Miocene extension, and post-Pliocene transpression (Atwater, 1989; McCulloch, 1989). In 1986, an 80 km north-south multichannel seismic reflection line, RU-10, was shot across the basin as part of the EDGE Program (Fig. 1) (Ewing and Talwani, 1991). Other EDGE lines shot farther north reveal strong, discontinuous, landward-dipping reflections in the midcrust that are interpreted to have resulted from the earlier episode of east-dipping Paleogene subduction (e.g., Meltzer and Levander, 1991). Of particular interest in the southern offshore Santa Maria Basin are (1) the extent to which similar crustal features (such as the inferred top of subducted oceanic crust) are seen farther south, (2) the nature of the middle to lower crust and its possible control on basin evolution, (3) the relation between offshore structure and near onshore deformation associated with the tectonic rotation and uplift of the Western Transverse Ranges (Luyendyk et al., 1985), and (4) the location and orientation of several inferred tectonostratigraphic terrane boundaries thought to traverse this area (Howell et al., 1987; McCulloch, 1989).

Here we present preliminary results from the processing and interpretation of RU-10 and part of an east-west tie line (USGS-3) to an adjacent deep stratigraphic COST well (OCS 78-164) (Fig. 2) (Isaacs et al., 1989). Additional seismic profiles shot in 1978, 1979, and 1990 (Fig. 2) were also used to help provide a more comprehensive regional analysis of subsurface crustal structure. For reference, a generalized stratigraphic section modified for the southern Santa Maria Basin is shown in Figure 3 and includes inferred correlations with various seismic units identified on USGS-3 at the COST well.

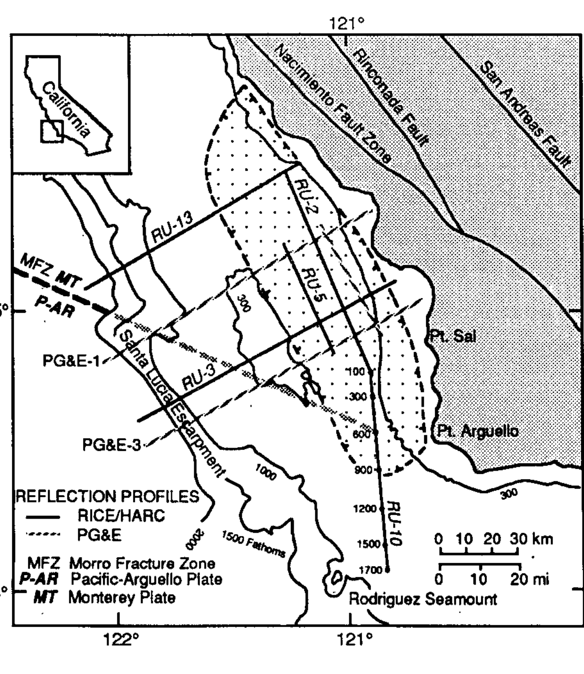

Figure 1. Map showing bathymetry and location of EDGE seismic reflection lines. Pacific-Arguello and Monterey plates and Morro Fracture Zone are from Lonsdale (1991) and Atwater (1989). Stippled area represents offshore Santa Maria Basin (after McCulloch, 1989).

DATA AND ANALYSIS

Along RU-10, data from 180 channels were recorded to 16 s. Data for USGS-3 were collected in 1979 and consist of 24 channels recorded to 7.8 s. Both data sets were severely contaminated by strong water-bottom and peg-leg multiples associated with various reflectors at all crustal levels. The data were significantly improved, however, by careful reprocessing that largely consisted of detailed velocity analyses (at intervals of 1 km) and a wide range of different time-varying *f-k* filters to reduce the high levels of coherent noise on the final stacked section. All stacked sections were compared to unfiltered versions to identify possible artifacts introduced by the *f-k* filtering. Interpretations were performed on both migrated and unmigrated record sections, although resolution is poor on migrated records below about 4.0 s because of low signal-to-noise ratios. We show the unmigrated data from RU-10 (Fig. 4A[1]) because RU-10 is primarily a strike line to the regional structure and because migration artifacts from multiple residuals still contaminate the deep record even after filtering. However, a line drawing of the migrated depth section (Fig. 4C) and migrated versions of USGS-3 (Fig. 5[1]) are shown as well. To distinguish deep crustal reflections, relative trace amplitudes were preserved as much as possible; thus, *no* automatic gain control is applied to any data shown in Figures 3–5.

RECORD SECTIONS

RU-10

The general character of RU-10 is very similar to other seismic lines shot during the EDGE program (e.g., Meltzer and Levander, 1991). A well-defined sedimentary sequence onlaps or downlaps onto a strong regional reflector lo-

[1]Figures 4 and 5 are a loose insert accompanying this issue.

cated at about 1.4–1.8 s (Fig. 4), and is identified at the COST well as a middle Miocene sequence boundary (Fig. 3). Along the western margin of the Santa Maria Basin, this sequence boundary is a time-transgressive unconformity; sedimentary units directly above the reflector at the northern end of RU-10 represent Miocene rocks of the Monterey Formation, whereas toward the south (beyond shot point [SP] 900) units are likely of Pliocene age or younger. Water depth currently increases to the south; therefore, the area may have undergone a net regional tilt reversal since Miocene time, or, alternatively, deposition became progressively unrestricted toward the south. Below the strong reflector, the lower Miocene section thins or may be missing locally. Thus, in many places along RU-10, this strong reflector may be considered to be at or near the base of the Miocene section and may onlap—or be indistinguishable from—an earlier regional unconformity at about 17.5 Ma (e.g., Bohacs, 1990). Alternatively, this reflector may mark the top of middle Miocene volcanic rocks, because well 496 No. 1, 5 km west of RU-10 (SP 350, Fig. 4), drills elements of the Obispo Tuff just below this boundary.

The sedimentary sequence above the strong reflector exhibits minor fault-related folding (near SP 900, Fig. 4) associated with splays off the Santa Lucia Bank fault system and other minor disruptions that may be associated with possible near-vertical faults (SP 160, Fig. 4). Below the sequence boundary, reflections are generally more discontinuous and chaotic, making interpretation difficult. However, some coherent reflectors are evident below this boundary, suggesting that basement is deeper than previously interpreted along this profile (Levander and Henrys, 1989). This is consistent with the results from several deep offshore test wells that typically drill, near the northern end of RU-10, from Miocene-age rocks into material that is either the Point Sal ophiolite or metamorphosed basement rocks of the Franciscan Formation, whereas farther south and east of RU-10, substantial Paleogene section is present and basement is not encountered, even at drill depths of more than 3000 m (Fig. 2).

In the lower crust, starting at the northern end of unmigrated RU-10 (Fig. 4B), strong, discontinuous, nearly horizontal reflections are observed at about 5.0–5.6 s (R1) and again at 6.6–7.2 s (R2) south to about SP 600, where they disappear and are replaced by strong, north-dipping deep crustal reflections that ramp up from about 9.0 s to about 6.5 s near SP 1300 (R3). The nearly horizontal mid-crustal reflections (R1) at the northern end of RU-10 appear to correlate with the inferred top of subducted oceanic crust interpreted farther north, based on ties to RU-2, RU-3, and RU-13 (Meltzer and Levander, 1991; Ewing and Talwani, 1991). These mid-crustal reflections become disrupted and disappear by about SP 600, suggesting that the subducted oceanic crust may no longer be a coherent structure underlying the continental margin by the latitude of Point Arguello. The discontinuity in deep crustal structure near SP 600 correlates with the projected intersection with the subducted Morro Fracture Zone (Figs. 1 and 4C). Other reflections observed on RU-10 at mid-crustal levels may reflect additional sets of faults with apparent south (R4) and north (R5) dips at moderate to steep angles (Fig. 4).

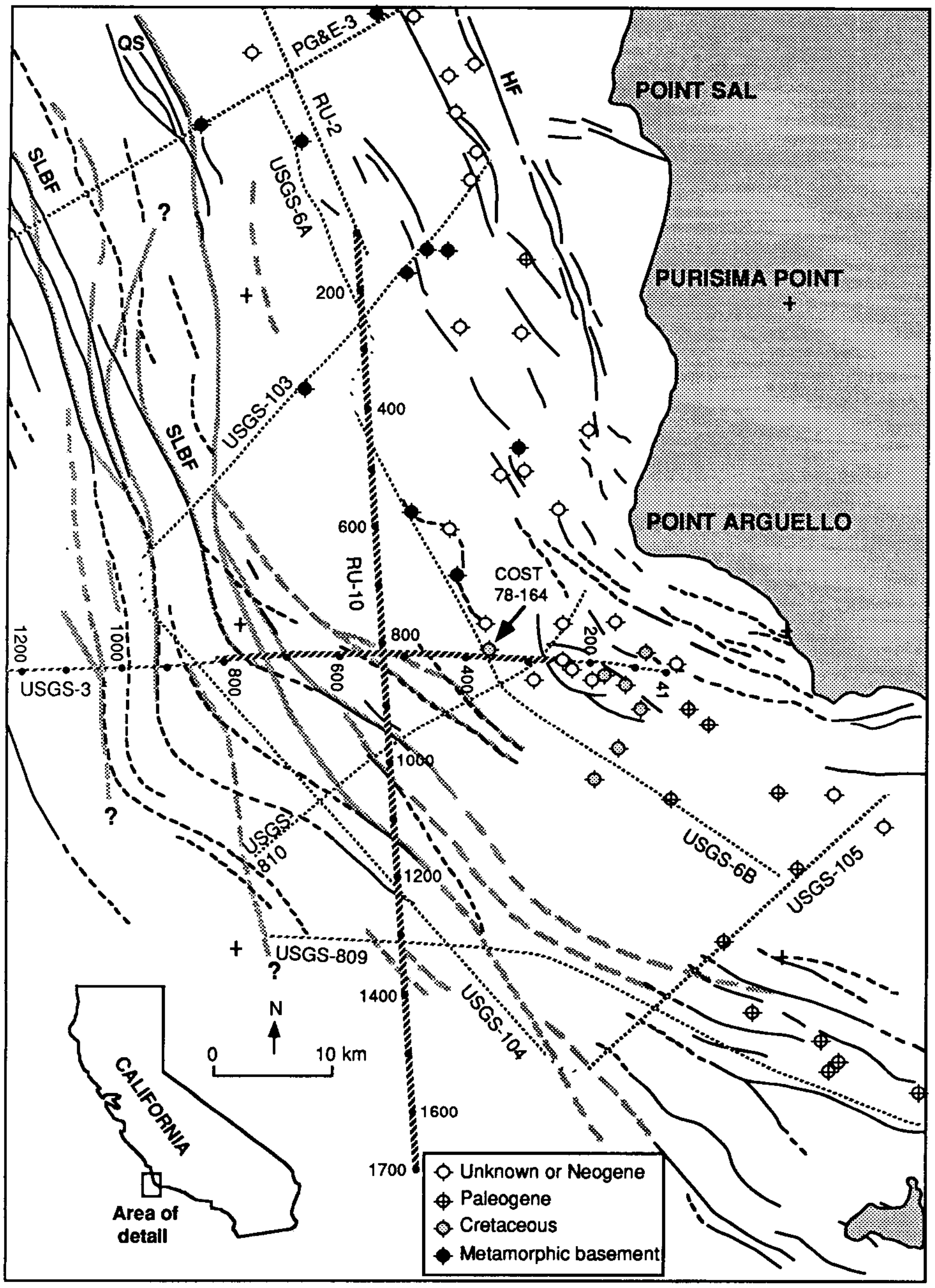

Figure 2. Location of RU-10 relative to other deep (>7.8 s) seismic lines shot in 1978, 1979, and 1990 that provide ties to various deep offshore test wells, particularly COST stratigraphic well OCS 78-164. Mapped post-Pliocene faults (black lines) are largely combinations of inferred strike-slip and reverse faults that break sea floor. Along western margin of Santa Maria Basin, gray lines are preliminary locations of older faults—mapped on basis of available multichannel and single-channel data—that offset mid-Miocene sequence boundary and exhibit largely down-to-east normal separation. Exploratory drill holes that penetrate metamorphic (Franciscan?) basement, Cretaceous, or Paleogene section are identified. SLBF—Santa Lucia Bank fault; QS—Queenie structure; HF—Hosgri fault.

USGS-3

USGS-3 extends from just south of Point Arguello due west to the base of the continental slope (Fig. 2). A part of USGS-3, extending from SP 240 to SP 800, is shown in Figure 5. From the tie with RU-10 (SP 530) east to the deep stratigraphic COST well (SP 365), the middle Miocene sequence boundary drops down toward the central axis of the basin.

Above this boundary, relatively undeformed sedimentary sequences thicken toward the east and to the west onlap the broad basement high that defines the western margin of the Santa Maria Basin. Below this boundary, the seismic record suggests a pattern reminiscent of a series of tilted crustal blocks defined by faults interpreted with largely down-to-the-east normal separations. These tilted crustal blocks preserve a significant lower sedimentary section (including possible Cretaceous and Paleogene units) that also becomes increasingly thick toward the COST well (Fig. 5).

Above the middle Miocene boundary, the younger sedimentary section is mildly folded, consistent with similar evidence for a regional change from Miocene extension (transtension?) to transpression along the plate boundary in post-Miocene time (e.g., Clark et al., 1991). On the basis of data in USGS-3, the amount of crustal shortening across the western margin of the southern Santa Maria Basin is small (<2%), and is largely accommodated by relatively small amplitude, long-wavelength folds, rather than by fault reactivation or the development of new (oblique?) reverse faults, although some reverse dip-slip faulting is present (e.g., SP 450, Fig. 5) (Crouch et al., 1984).

DISCUSSION

On the basis of the analysis and interpretation of RU-10, USGS-3, and other seismic lines, two important observations can be made relative to the structure in the upper and lower crust, respectively. The first is that, in the upper crust, significantly different stratigraphic sections are present to the north and south along the western edge of the southern Santa Maria Basin. Near the northern end of RU-10, much of the Miocene section is present, but units of Paleogene or Cretaceous age are absent. Toward the southern end of RU-10, however, much of the Miocene section thins or may be missing locally, whereas farther east, toward the western end of the Santa Barbara Channel, wells drill a nearly complete Paleogene section and basement is significantly deeper (Fig. 2). These observed spatial differences in record sections have been previously used to infer the presence of several tectonostratigraphic terrane boundaries across the southern Santa Maria Basin (Howell et al., 1987; McCulloch, 1989). Although the presence of possible terrane boundaries cannot be precluded, there are no seismic data that necessitate large lateral (strike-slip) movement of basement terranes to explain such stratigraphic differences; in fact, the contrary is true.

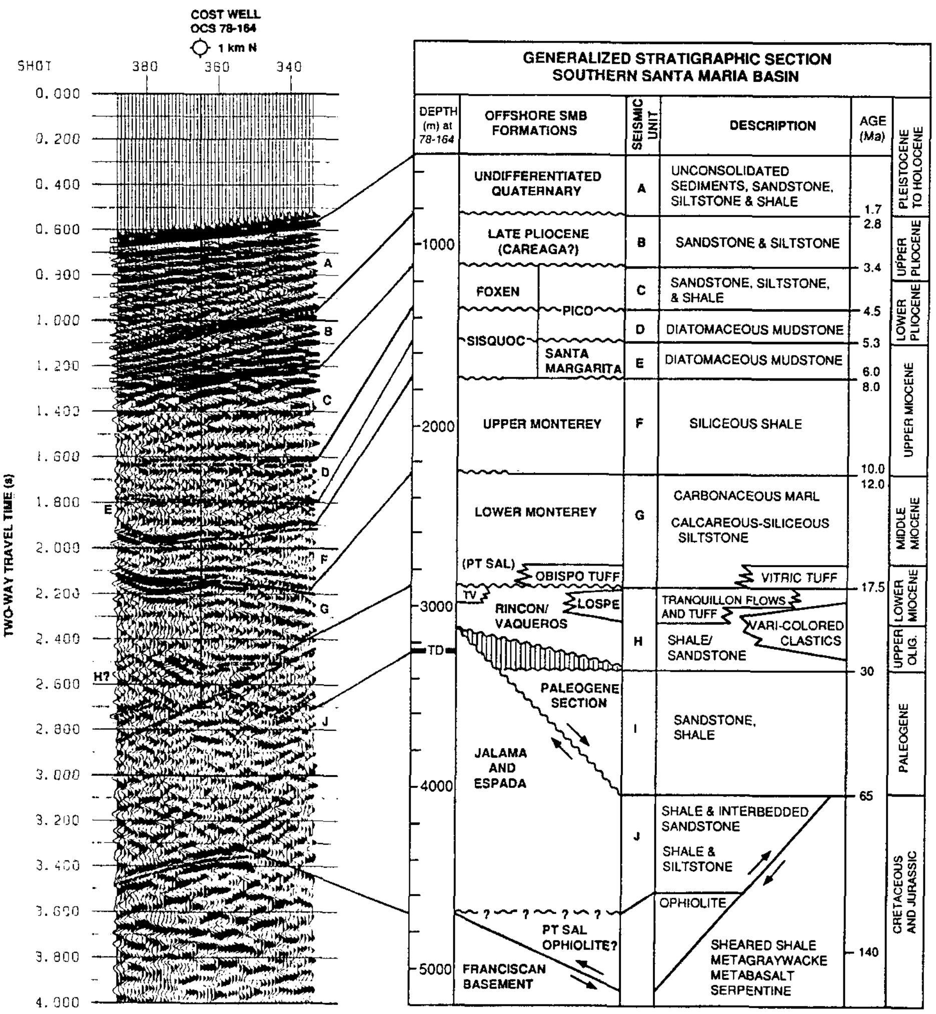

Figure 3. Generalized stratigraphic section for southern Santa Maria Basin (SMB), modified after Isaacs et al. (1989), Bohacs (1990), and Clark et al. (1991). Age correlations of seismic units A–J are indicated in section of USGS-3 at tie with COST well OCS 78-164. TV—Tranquillon Volcanics; TD—total depth of COST well.

The thinned Miocene and lower Pliocene section at the southern end of RU-10 appears to be simply the result of pinch-out owing to onlap or downlap. Neither the sedimentary section nor the strong regional reflector exhibit any major discontinuity that could be attributed to a significant high-angle tectonostratigraphic terrane boundary. Similarly, the presence or absence of lower Miocene, Paleogene, and/or Cretaceous sedimentary rock along the southwestern Santa Maria Basin can be attributed to local processes of uplift, subsidence, sedimentation, and erosion across an older set of pre-Pliocene normal faults, rather than to any major lateral tectonic offset. The western margin of the Santa Maria Basin may be thus defined by a set of largely down-to-the-east normal-separation faults that are probably of Miocene age (Fig. 5). Some of these faults have been reactivated in post-Miocene time with minor reverse, oblique-reverse, or possibly strike-slip components (black lines, Fig. 2), including major strands of the Santa Lucia Bank fault system. Preliminary mapping of the older set of normal faults (gray lines, Fig. 2) that displace the middle Miocene sequence boundary indicates that they are contiguous with faults in the western Santa Barbara Channel, and suggests a continuity of structure between the southern Santa Maria Basin and the rotated northern Channel Islands.

The second important observation, which relates to the first, concerns structure in the lower crust and its implications for the evolution of the Pacific–North American plate boundary. As the Pacific plate approached western North America, the intervening Farallon plate began to fragment (Atwater, 1989; Lonsdale, 1991), forming the Monterey and Arguello microplates at about magnetic anomaly 10 time (30 Ma). Relative to the Pacific plate, spreading rates slowed and directions changed to become more southeasterly, as if the Monterey microplate became partly coupled to cratonic North America. Monterey and Arguello plate motions were sufficiently different from each other that a left step developed along the Pacific spreading ridge, requiring right oblique-reverse motion along the transform plate boundary that became the Morro Fracture Zone (T. Atwater, 1991, personal commun.). Spreading between the Pacific and Monterey plates apparently ceased just after anomaly 6 time (19 Ma), before the ridge was fully subducted, leaving a piece of partially subducted Monterey plate attached to the Pacific plate (Fig. 1). Pacific-Arguello spreading proba-

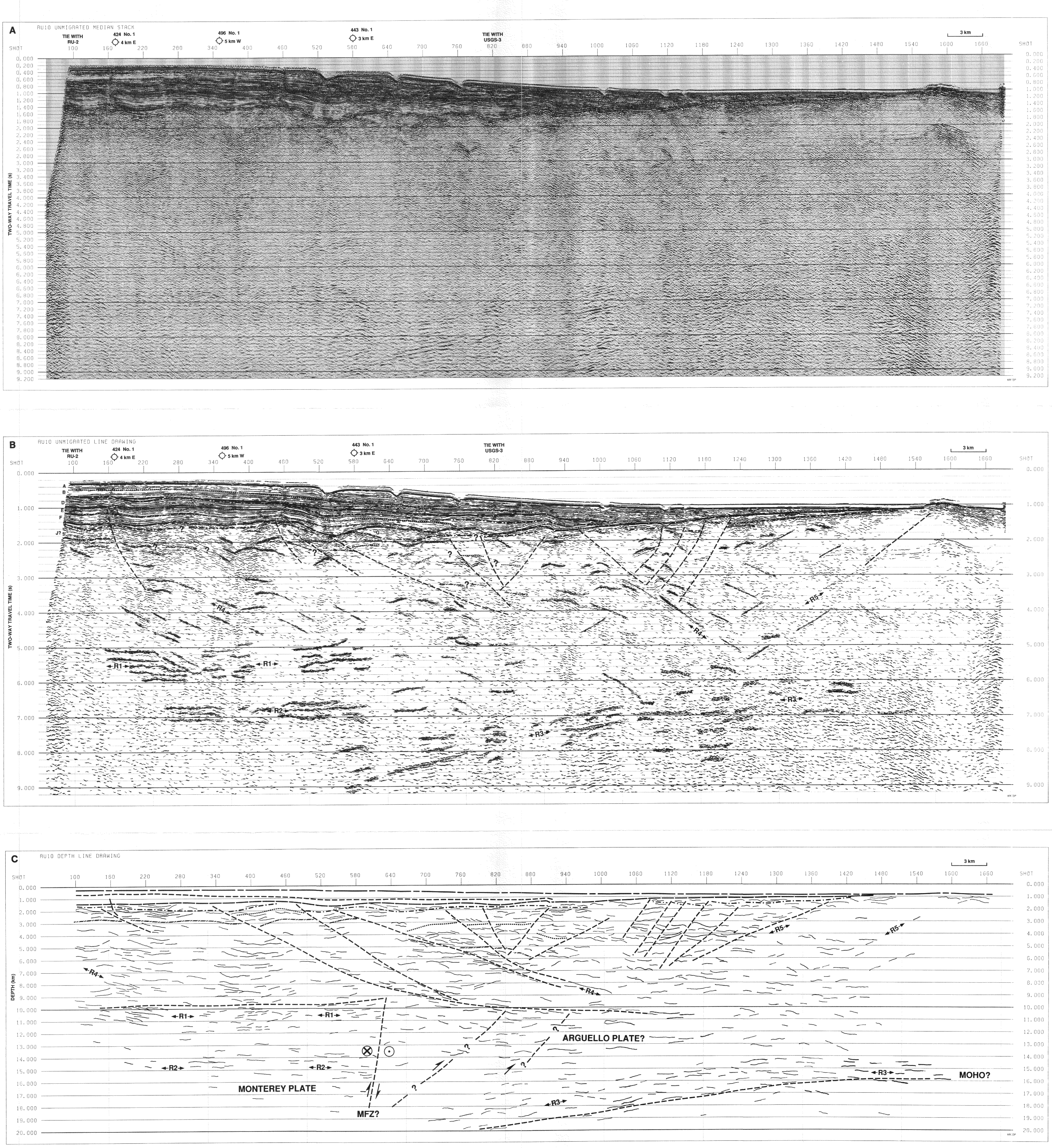

Figure 4. A: Unmigrated seismic reflection line RU-10 showing data. B: Automatic line drawing of data with interpretation. C: Line-drawing of corresponding migrated depth section. Time sections shown are plotted with relative trace amplitudes preserved; no automatic gain control. Vertical exaggeration in time sections is ~1:1 for velocity of 6 km/s. Ties to wells have allowed identification of several regional Neogene unconformities, and, in isolated areas, top of metamorphic basement (Franciscan Formation or Point Sal Ophiolite).

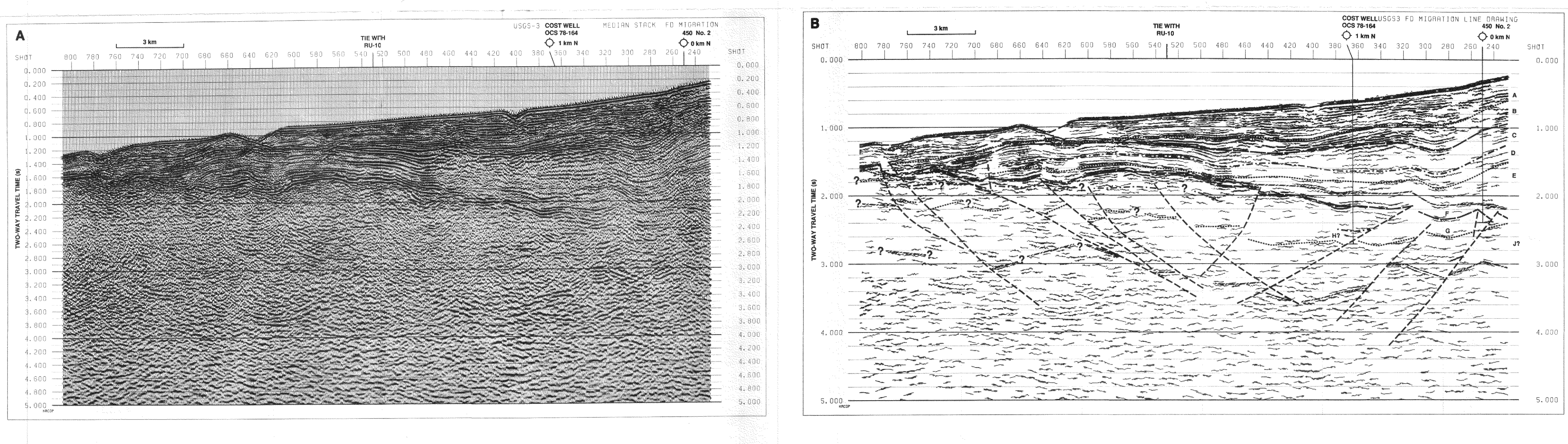

Figure 5. Part of migrated USGS-3 line shot in 1979. A: Data. B: Automdic line drawing of data with interpretation. Time sections shown are plotted with relative trace amplitudes preserved; no automatic gain controlSame vertical exaggeration as in Figure 4. This line ties RU-10 directly to deep COST well OCS 78-164, and shows presence of increasingly thicksedimentary section to east. Letters A–J: refer to Figure 3.

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bly continued longer, but exactly when it stopped and exactly where the subducted(?) fossil spreading ridge may be found (if it exists) is unknown.

The Morro Fracture Zone, which formed the southern boundary to the Monterey microplate, is a relatively straight topographic feature that disrupts the Santa Lucia Escarpment and can be traced under the continental margin as far east as its inferred intersection with RU-3 and PG&E-3 (Fig. 1) (Ewing and Talwani, 1991; McIntosh et al., 1991; Meltzer and Levander, 1991). On the basis of the observed changes in deep crustal structure seen in RU-10, we suggest that the Morro Fracture Zone may continue even farther to the southeast. Thus, the subhorizontal crustal reflections (R1 and R2) inferred to be within (or on top of) the east-dipping oceanic Monterey paleomicroplate are truncated at about SP 600 owing to their extrapolated intersection with the Morro Fracture Zone. South of SP 600, apparent low-angle north-dipping deep crustal reflections (R3) are observed. On the basis of revised crustal models from the limited offshore seismic refraction data (e.g., Tréhu, 1991), these north-dipping reflections may represent Moho (or at least modified lower crust), because anomalously high velocities (approaching 8.0 km/s) are inferred at depths as shallow as 18–20 km. The unusual topography and the shallow depth of the presumed Moho on RU-10, south of inferred intersection with the Morro Fracture Zone, may be the result of mantle material that has upwelled within the remnant Pacific-Arguello fossil spreading ridge or possibly within a slab window, if the fossil ridge is located west of RU-10. Alternatively, the apparent north-dipping zone of deep-crustal reflections (R3) could simply represent (1) a low-angle detachment or decollement associated with some earlier process of terrane accretion (Howell et al., 1987), (2) differential tectonic rotations between the upper and lower crust (e.g., Luyendyk et al., 1985), or (3) more recent crustal shortening associated with the post-Miocene uplift and reverse faulting of the western Transverse Ranges (cf. Namson and Davis, 1990).

If the discontinuity in deep crustal structure near SP 600 is indeed associated with the Morro Fracture Zone, then this interpretation requires that any lower crustal strike-slip motion between the Pacific and North American plates be inboard of RU-10 and east of the Santa Lucia Bank fault system (Fig. 2). Thus, either the Santa Lucia Bank fault system has accommodated little right-lateral strike slip, or, if it has, this motion must be necessarily restricted to the shallow crust, i.e., decoupled so as not to disrupt the inferred Morro Fracture Zone in the lower crust. This restriction is further inference for the lack of any major *high-angle* throughgoing tectonostratigraphic terrane boundary across this area, but may imply that much of the shallow deformation and subsidence within the offshore Santa Maria Basin is detached, as previously suggested by Crouch et al. (1984). Thus, we suggest that the subducted Monterey microplate exists as a coherent crustal feature under much of the offshore continental margin (as far south as Point Arguello), and that a likely candidate for a detachment surface (if required) is the top of this subducted plate. Farther south, however, it is not clear what remnants of the previous paleo-subduction zone are present. Pacific-Arguello spreading apparently stalled (or was subducted) at about anomaly 5D time (17.5 Ma) (Lonsdale, 1991), which would place the fossil ridge close to the Rodriguez Seamount (Fig. 1) and close to the intersection of RU-10 with the extrapolated Morro Fracture Zone.

SUMMARY

Reprocessed images of RU-10, USGS-3, and preliminary well ties suggest that the western margin of the Santa Maria Basin appears to be defined by an older set of largely down-to-the-east normal separation faults, some of which have been reactivated in post-Miocene time with minor reverse separations. Total crustal shortening since Miocene time across the southwestern Santa Maria Basin is small (<2%) and is largely accommodated by minor folding. There is no seismic evidence that requires any major *high-angle* stratigraphic discontinuity along RU-10. The stratigraphic contrasts observed at the northern and southern ends of RU-10 appear to reflect largely local conditions of deposition, erosion, and preservation across the older set of normal faults, rather than any large-scale lateral transport along a regional terrane boundary.

Various reflections from the lower crust are seen in RU-10 below 5 s. North of SP 600, some of these deep reflections are interpreted to represent the segmented top of subducted oceanic crust. Farther south, beyond SP 600 (Fig. 4), these subhorizontal reflections are disrupted or disappear, as would be expected if the Morro Fracture Zone intersects the record section at this point. Beyond SP 600, RU-10 images a set of strong north-dipping deep reflections that we interpret as a relatively shallow low-angle Moho. If this correlation is valid, then this necessarily implies that the partially subducted Monterey microplate may underlie the continental margin only as far south as Point Arguello, and that any large-scale lateral displacements between the Pacific and North American plates in the lower crust must be localized east of RU-10 and the Santa Lucia Bank fault system.

REFERENCES CITED

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N, p. 21–71.

Bohacs, K.M., 1990, Sequence stratigraphy of the Monterey Formation, Santa Barbara County: Integration of physical, chemical, and biofacies data from outcrop and subsurface, *in* Keller, M.A., and McGowan, M.K., compilers, Miocene and Oligocene petroleum reservoirs of the Santa Maria and Santa Barbara–Ventura basins, California: SEPM Core Workshop No. 14, p. 139–201.

Clark, D.H., Hall, N.T., Hamilton, D.H., and Heck, R.G., 1991, Structural analysis of late Neogene deformation in the central offshore Santa Maria Basin: Journal of Geophysical Research, v. 96, p. 6435–6458.

Crouch, J.K., Bachman, S.B., and Shay, J.T., 1984, Post-Miocene compressonal tectonics along the central California margin, *in* Crouch, J., and Bachman, S.B., eds., Tectonics and sedimentation along the California margin: Pacific Section, Society of Economic Paleontologists and Mineralogists Special Publication 38, p. 17–36.

Ewing, J., and Talwani, M., 1991, Marine deep seismic reflection profiles off central California: Journal of Geophysical Research, v. 96, p. 6423–6434.

Howell, D.G., Champion, D.E., and Vedder, J.E., 1987, Terrane accretion, crustal kinematics, and basin evolution, southern California, *in* Ingersoll, R., and Ernst, G., eds., Cenozoic basin development of coastal California (Rubey Volume 6): Englewood Cliffs, New Jersey, Prentice-Hall, p. 242–258.

Isaacs, C.M., Jackson, L.L., Stewart, K.C., and Scott, N., III, 1989, Analytical components of Miocene and early Pliocene cuttings from the Point Conception deep stratigraphic test well, OCS-CAL 78-164 No. 1, offshore Santa Maria Basin, southern California: U.S. Geological Survey Open-File Report 87-75, 28 p.

Levander, A.R., and Henrys, S.A., 1989, Crustal structure of the offshore Santa Maria Basin and Transverse Ranges (California) from seismic reflection data [abs.]: Eos (Transactions, American Geophysical Union), v. 70, p. 1312.

Lonsdale, P., 1991, Structural patterns of the Pacific floor offshore of Peninsular California, *in* Dauphin, J., ed., Gulf and Peninsula provinces of the Californias: American Association of Petroleum Geologists Memoir 47.

Luyendyk, B.P., Kamerling, M.J., Terres, R.R., and Hornafius, J.S., 1985, Simple shear of southern California during Neogene time suggested by paleomagnetic declinations: Journal of Geophysical Research, v. 90, p. 12,455–12,466.

McCulloch, D.S., 1989, Evolution of the offshore central California margin, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N, p. 439–469.

McIntosh, K.D., Reed, D.L., Silver, E.A., and Meltzer, A.S., 1991, Deep structure and structural inversion along the central California continental margin from EDGE seismic profile RU-3: Journal of Geophysical Research, v. 96, p. 6459–6474.

Meltzer, A.S., and Levander, A.R., 1991, Deep crustal reflection profiling offshore southern central California: Journal of Geophysical Research, v. 96, p. 6475–6492.

Namson, J., and Davis, T.L., 1990, Late Cenozoic fold and thrust belt of the southern Coast Ranges and Santa Maria Basin, California: American Association of Petroleum Geologists Bulletin, v. 74, p. 467–492.

Tréhu, A., 1991, Tracing the subducted oceanic crust beneath the central California continental margin: Results from ocean bottom seismometers deployed during the 1986 Pacific Gas and Electric EDGE experiment: Journal of Geophysical Research, v. 96, p. 6493–6506.

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