# COCORP seismic profiles near Coalinga, California: Subsurface structure of the western Great Valley

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## ABSTRACT

COCORP seismic reflection profiles collected in 1977 on the west side of the San Joaquin Valley near Coalinga in southern California provide information on the Cenozoic and Mesozoic structures in the subsurface of the western Great Valley. The data show evidence of significant normal faulting during the Cretaceous, when this part of California was the site of a forearc basin. Neogene compression, probably associated with transform motion on the nearby San Andreas fault system, may be reactivating these pre-existing faults in a reverse sense and causing the active folding of the southern Coast Ranges. The recent Coalinga earthquake sequence that began on May 2, 1983, appears to correspond to movement on the high-angle reverse fault within the basement that is inferred from the COCORP lines.

## INTRODUCTION

The Coalinga area is located at the western edge of California's Great Valley, a large elongate basin that stretches about 700 km north-south (Fig. 1). Most of the sedimentary rocks that have filled this basin since Late Jurassic time and the basement beneath them are exposed only around the edges of the Great Valley (e.g., Blake and Jones, 1981). The thick Cenozoic strata conceal the essentially unknown deep structure of the valley. The east side of the Great Valley clearly lies upon the down-tilted edge of the Sierra Nevada block (e.g., Ingersoll, 1982), but the nature of the basement of the western flank has long been a problem. The boundary between the Great Valley sediments and the Franciscan complex to the west of Coalinga is marked by a zone of dismembered fragments of the Coast Range ophiolite thought to be parts of Jurassic oceanic lithosphere (e.g., Hopson et al., 1981). The prevailing interpretation is that this boundary represents the site of a Mesozoic subduction zone (e.g., Ernst, 1970), commonly called the Coast Range thrust.

COCORP (Consortium for Continental Reflection Profiling) collected deep seismic reflection profiles in the Coalinga area along two lines shot in the summer of 1977 (see Fig. 2). COCORP seismic reflection lines suggest that the Cretaceous strata beneath the Coalinga area were faulted before the deposition of Tertiary sediments; these pre-existing faults may control the orientation and nature of Neogene and Quaternary tectonic features. The recent Coalinga earthquake sequence that began on May 2, 1983, is a manifestation of the active tectonics of the area, and many of the larger events appear to correspond to movement on high-angle basement faults that are inferred from the COCORP lines.

## GEOLOGIC AND TECTONIC SETTING

Descriptions of the tectonic events that have molded the geology of the Coalinga area are both complex and controversial. Most recent studies have interpreted the Franciscan Complex as a Late Jurassic to Miocene subduction complex deposited in an active trench, and the structurally overlying Great Valley strata as forearc basin deposits located on the western flank of the active Sierra Nevada arc complex and adjacent oceanic crust represented by the
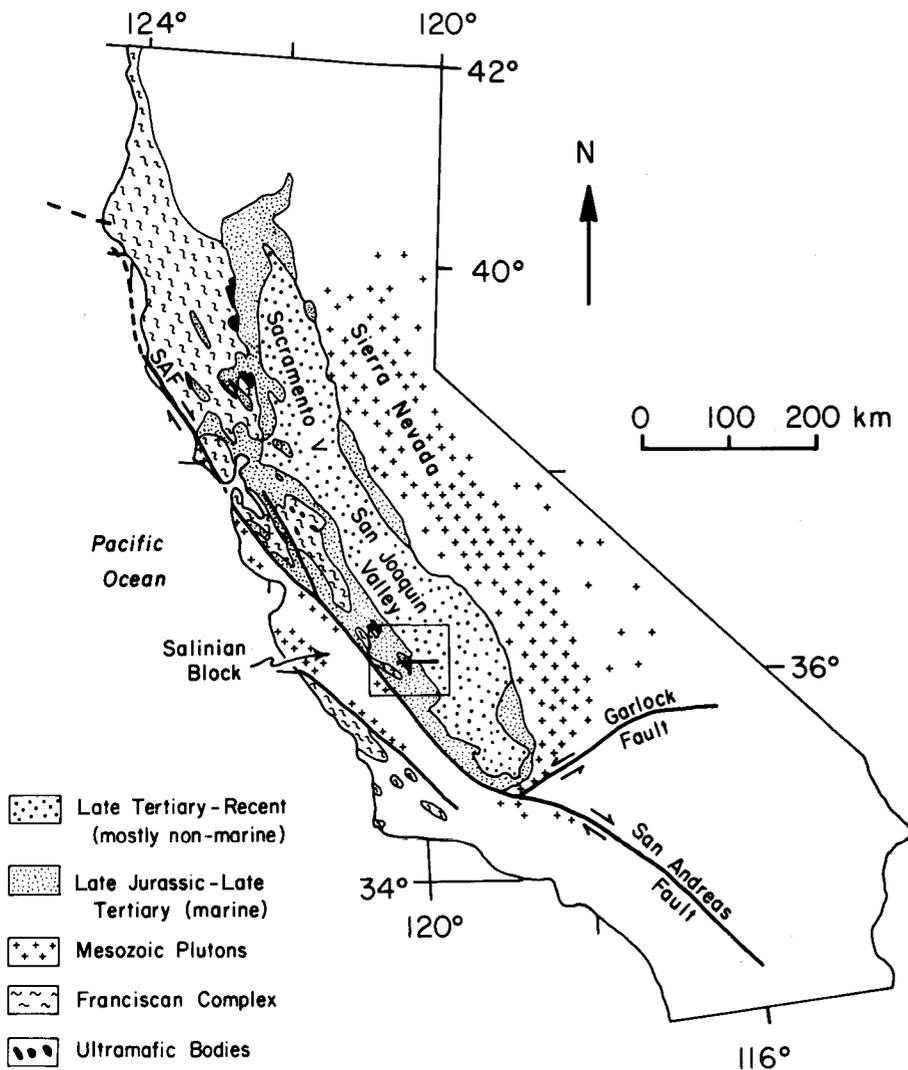


Figure 1. Generalized tectonic map of California, showing tectonic setting and location of COCORP Coalinga lines. Boxed area is shown enlarged in Figures 2 and 3.

Figure 2. Generalized geologic map of Coalinga area and location map for COCORP lines, showing complex folding and faulting in Coast Ranges west of Coalinga and exposures of strata interpreted to lie beneath Coalinga lines (modified from Fowlkes, 1982).
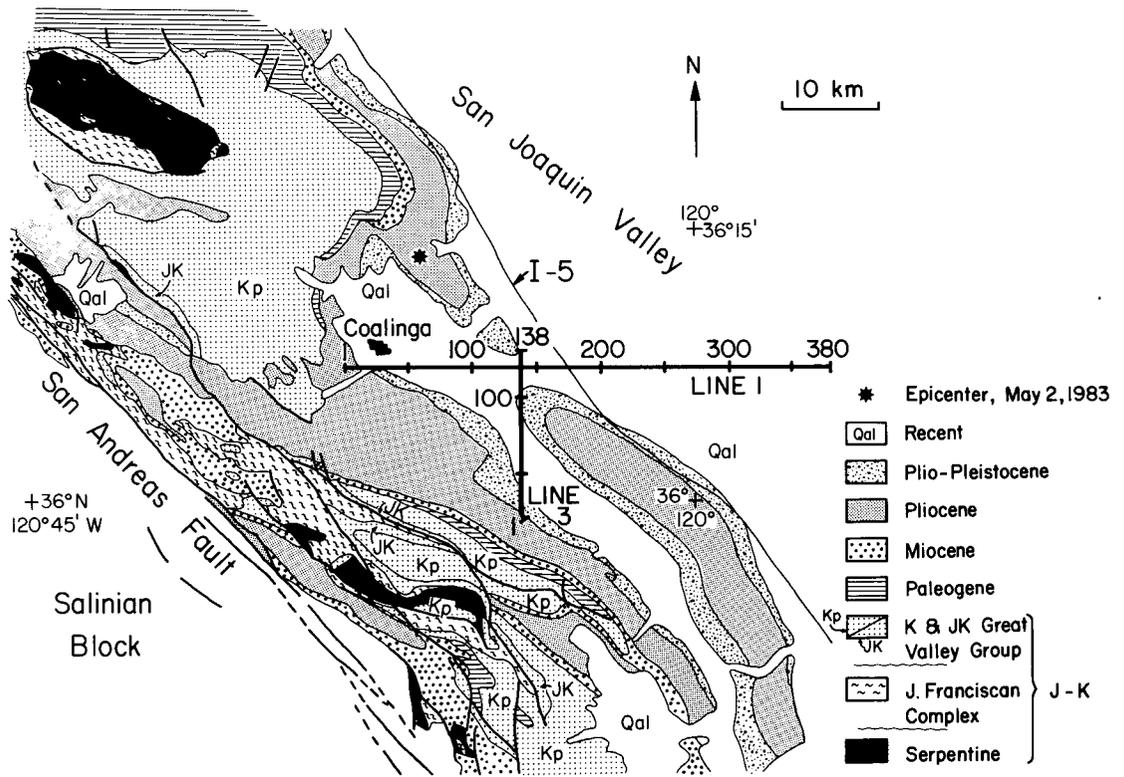
Coast Range ophiolite (e.g., Ernst, 1970; Dickinson, 1981; Fig. 1). The details of this model are in dispute, especially the nature of the Great Valley basement and the influence of large-scale Mesozoic strike-slip motion.

The Great Valley Sequence, renamed the Great Valley Group by Ingersoll (1982), spans Late Jurassic through Cretaceous time. In the Coalinga area, the Great Valley Group is exposed in the hills just west of the city, where the entire section is tilted to a steep east dip (e.g., Fowlkes, 1982; Fig. 2). Lower Tertiary deposits include both deep-water shales and continental-shelf deposits that lie disconformably on the Mesozoic section. During Oligocene and Miocene time, uplift in the Coast Ranges isolated the San Joaquin basin from the Pacific Ocean as a shallow inland sea (Page, 1981; Fowlkes, 1982). Pliocene-Pleistocene time was marked by an acceleration in the rate of movement along the San Andreas and in the amount of folding in the southern Coast Ranges (Page, 1981). Total thickness of the Tertiary section penetrated by wells in the Coalinga area is about 3.5 km. Pleistocene fluvial and lacustrine deposits are the youngest strata folded and exposed in the Kettleman Hills and Coalinga Nose anticlines. Quaternary terraces west and east of Coalinga are also deformed, indicating ongoing deformation of the western edge of the San Joaquin Valley (King and Stein, 1983).

Faulting in the Coalinga area is dominated by the San Andreas strike-slip fault system (see Fig. 3). There are also several high-angle re-
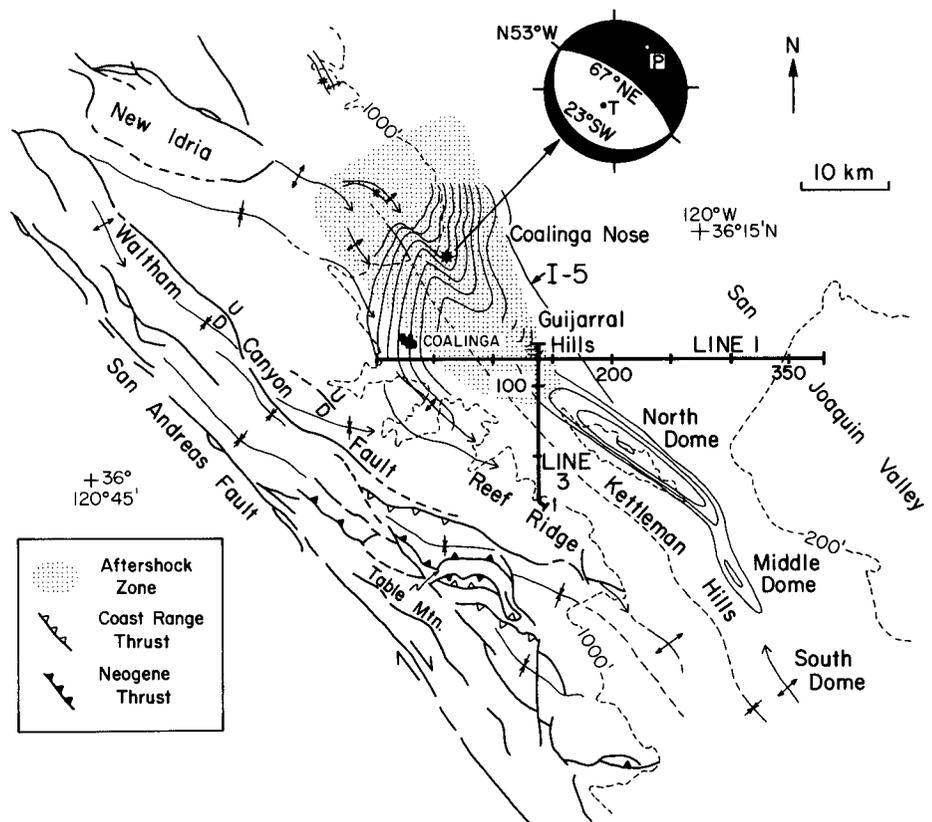


Figure 3. Generalized tectonic map of Coalinga area, showing major faults and fold axes, topographic contours (dashed lines), 500 m structural contours (solid lines) on top of Eocene Kreyenhagen Formation derived from wells in Coalinga and Kettleman Hills oil fields, location and focal mechanism of May 2, 1983, Coalinga earthquake ($M_L$ = 6.7), and its aftershock zone through June 12, 1983.

verse faults between Coalinga and the San Andreas, most notably the enigmatic Waltham Canyon fault that shows Quaternary movement; moderate-sized earthquakes have occurred in the Coast Ranges near Coalinga (Jennings, 1975; Fowlkes, 1982; Eaton, 1983). There are only minor faults in the hills adjacent to the San Joaquin Valley, including the Kettleman Hills and Coalinga Nose.

## COCORP DATA ACQUISITION AND INTERPRETATION

Two Vibroseis (trademark of CONOCO, Inc.) reflection lines were shot in the Coalinga area during May and June of 1977—a 50-km-long east-west Line 1 and a 15-km-long north-south Line 3 (Figs. 2, 3). The short Line 3, discussed only briefly here, is covered more completely in Fielding et al. (1983), which also contains a more detailed discussion of the data processing. A 48-channel recording system was used with a 134-m station spacing, producing near and far offsets of 0.6 km and 6.7 km, respectively. Vibrating every station (five or six vibrators × 16 sweeps/station) resulted in nom-

inal 24-fold data. The data were collected and originally processed under contract to CO-CORP by Compagnie Générale de Géophysique (CGG). The data presented here have been extensively reprocessed on COCORP's Megaseis computer system at Cornell. The section displayed here (Fig. 4) is not migrated, so dipping reflections on the time section have shallower dips and are displaced down-dip from their true positions in the earth. Constant velocity migrations performed on the data show, however, that the major features of the section are qualitatively correct (compare Figs. 4 and 6). See Fielding et al. (1983) for a more detailed discussion of the data processing.

The most prominent feature of both of the COCORP Coalinga lines is the set of reflections that runs continuously between about 2 and 3.5 s through the length of both lines (Fig. 4). These reflections are by far the highest amplitude events on the sections; events above and below are of lower amplitude and are less continuous. There are a few ambiguous deep reflections on Line 1 at about vibration point (VP) 350, which are not discussed here.

### Stratigraphic Correlation

Stratigraphic control from wells in the large Coalinga and Kettleman Hills oil fields is excellent (e.g., American Association of Petroleum Geologists, 1957, 1959). Depths to formation tops from two wells, each about 750 m on either side of Line 1, were averaged, converted to an approximate time section (using the interval velocities derived from processing), and projected onto Line 1 at VP 138 (see Fig. 5). The strong, ringing return at 2–3 s at VP 138 is probably reflected from the interlayered shale and sandstone of the early–middle Miocene and Eocene strata penetrated by the wells, which would provide numerous interfaces of high impedance contrast. Both wells bottomed in the lower Eocene section at depths of 3.1 and 3.3 km below sea level. The thickness of the Paleogene section is projected down-plunge to VP 135 from another well 7 km north of Line 1, which bottomed in the Upper Cretaceous section at a depth of 3.25 km (American Association of Petroleum Geologists, 1959; Fig. 5).

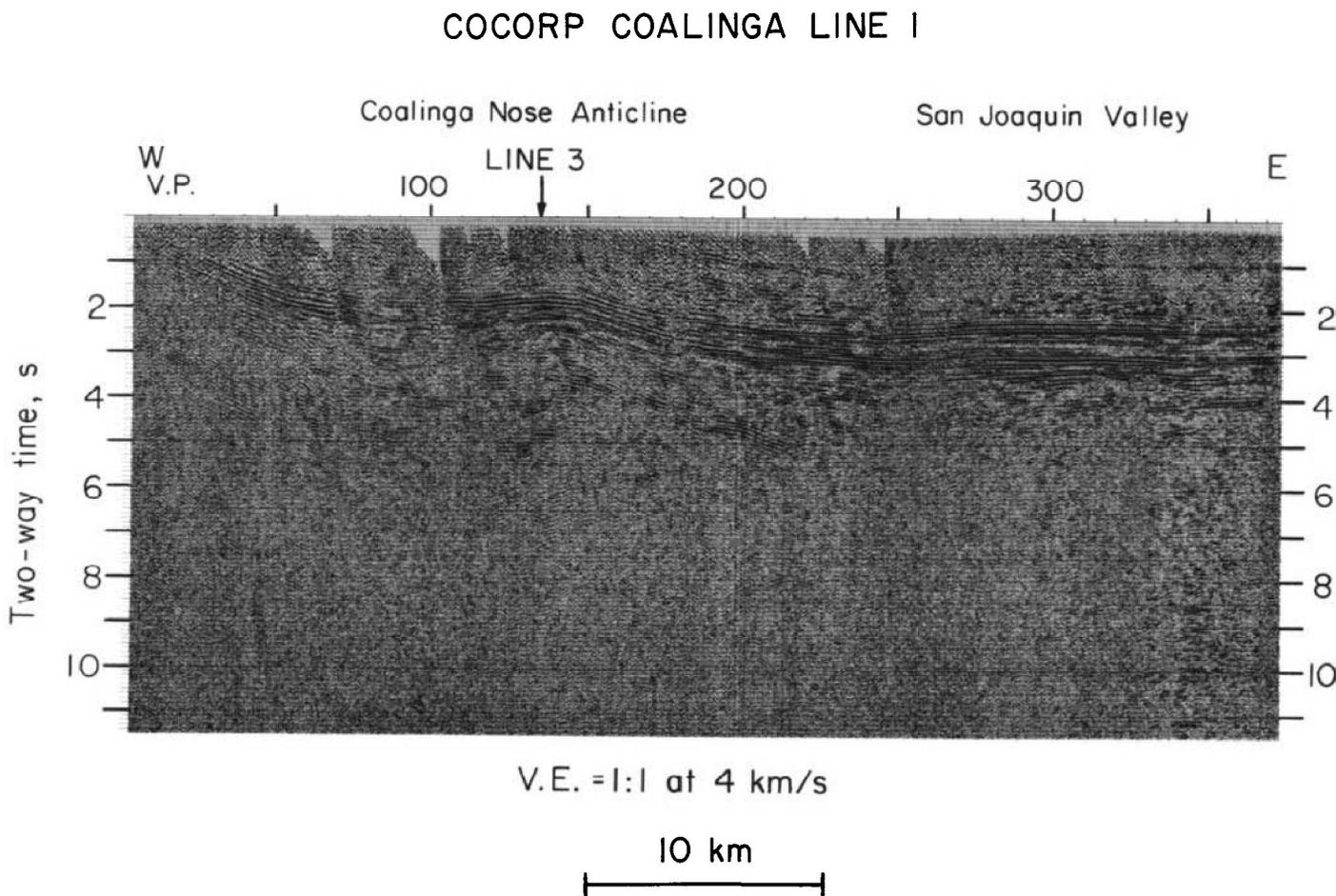The Great Valley Group exposure just off



Figure 4. COCORP Coalinga Line 1. Time section is not migrated or deconvolved. Trace amplitude balancing with window of 0.5 s has been applied before stack. High-amplitude, continuous reflections are from lower Tertiary section. Note deformation of Cretaceous section reflectors beneath strong Tertiary reflections at east end.

the western end of the line has a minimum stratigraphic thickness of 6–8 km down to the faulted base at the Waltham Canyon fault (Fowlkes, 1982; Figs. 3, 5). If this entire thickness is present farther east beneath the Tertiary section, then the base of the Great Valley Group would be at a depth of 9.5–11.5 km, or about 5–6 s on the seismic time section (dashed and dotted line in Fig. 5). This is the approximate time at which the deepest relatively continuous events are seen on the western one-third of the section. The thickness of the interpreted Great Valley Group, based on the depth of the deepest layered reflections and the depth to basement interval velocities, is much less in the eastern part of Line 1.

## Structures

The first-order structure visible on both of the COCORP Coalinga lines is the upwarping of the entire sedimentary section west and south of Coalinga. A large amount of this ongoing upwarping is pre-Pliocene, as the dip of the Pliocene and later strata west of Coalinga is much less than that of the Miocene and earlier strata. The angular unconformity between the Pliocene and the Miocene strata is visible both on the surface (Fig. 2) and on the west end of Line 1 (Fig. 5). Upwarping of the Great Valley Group occurs along the entire western side of the Great Valley and may be related to underthrusting of the Franciscan Complex (Dickinson, 1981) or to movements along the San Andreas fault system (Page, 1981).

Superimposed on this broad synclinal upwarping is a smaller anticline, down-plunge from the Coalinga Nose, with an axis at about VP 145 on Line 1 (Figs. 4, 5). The folds in the Coalinga area have a moderately complex, three-dimensional structure, as shown in Figure 3 by the structural contours derived from closely spaced oil wells (Dodd, 1931; Kaplow, 1945; Hunter, 1951). Line 1 passes through the structural saddle between the Coalinga Nose and the Kettleman Hills North dome. Both the Coalinga Nose and the Kettleman Hills North dome are asymmetric, with steeper southwest limbs. The southwest limb of the Coalinga Nose reaches a dip of more than 70° at its northern end, whereas the northeastern limb dips only 15°. As the Coalinga Nose plunges southward toward Line 1, it flattens and becomes more symmetrical. The Kettleman Hills North dome also flattens as it passes beneath the COCORP lines. The involvement of Pliocene-Pleistocene strata indicates that these folds are young tectonic features.

The asymmetric nature of the Coalinga Nose and recent leveling data suggest that the fold probably formed as a drape over a basement fault (e.g., Stearns, 1978; Reches and Johnson, 1978; Stein, 1983). The Tertiary strata are not significantly faulted in the Coalinga Nose or the Kettleman Hills North dome at the surface (Dodd, 1931; Kaplow, 1945), and they appear to be continuous on Line 1 at least down to 2.5 s. The Great Valley Group strata down to about 3.5 s on migrated seismic sections also appear largely unfaulted within the resolution of the COCORP data (about 100 m), though reflections from them are less continuous. The data from both COCORP lines are consistent

with the interpretation of the fold as a combination of drape folding and buckling of the sedimentary section over a high-angle, eastward-dipping, reverse fault in the basement (see Fig. 5); the data appear to rule out a southwest-dipping blind thrust in the upper 8–12 km beneath the lines. The basement displacement beneath Line 1 is probably less than that beneath the Coalinga Nose or the Kettleman Hills North dome, in view of the reduced amplitude of the folds where they are crossed by the COCORP lines. This inferred basement faulting may be a reactivation of a pre-existing normal fault or faults, as will be discussed below.

The deeper reflections of the eastern half of Line 1 show significant Cretaceous-age faults that may have affected later deformation. Beneath VP 335, event A and event B, correlated as the same reflecting layer, are offset, with the western block relatively uplifted (Fig. 5). A normal fault at about 4 s that dips 50°–70° eastward, with 1 km or so of offset, fits the data best, but the orientation (especially the strike) of the fault is poorly constrained. A high-angle reverse fault dipping 60°–80° to the west is also possible. Minor folding of the reflecting layers above events A and B suggest that the fault is high-angle. The fault movement probably occurred mostly during the Cretaceous, as the overlying Tertiary strata are not disrupted. The lowermost reflections from the Tertiary section pinch out against the structurally higher western block on both sides.

West of VP 300, the reflections from the Cretaceous strata dip increasingly westward to
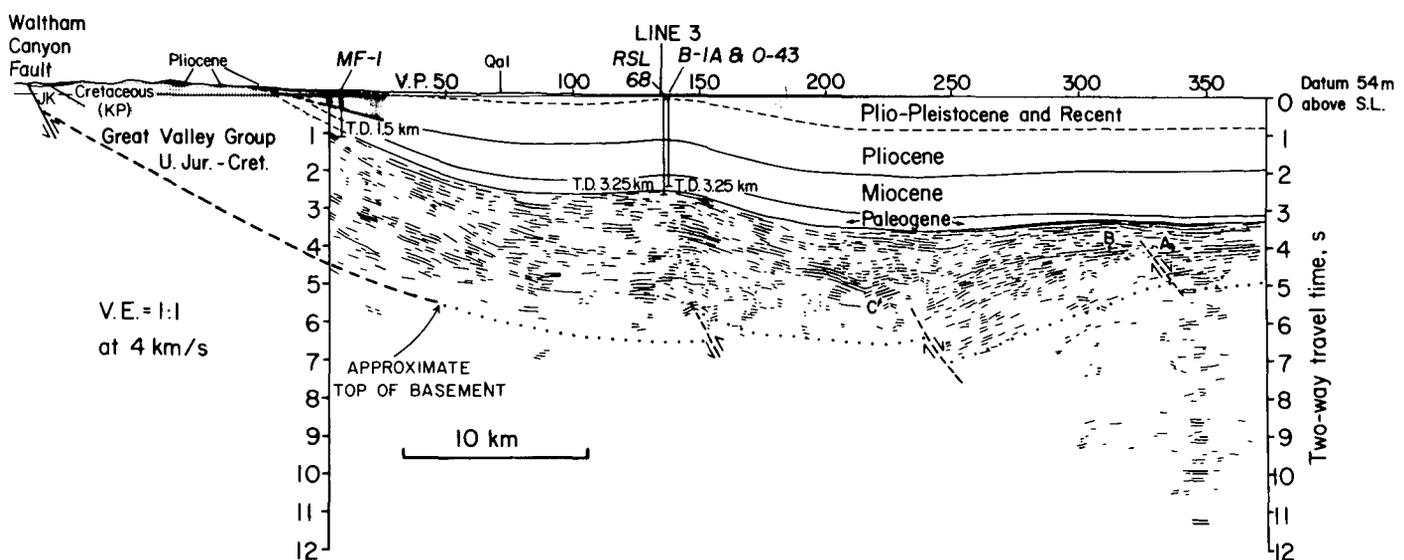


Figure 5. Interpretation of COCORP Line 1 (unmigrated), showing surface topography and geology, stratigraphic interpretation of reflections from Cenozoic section, line drawing abstracted from deeper reflection interpreted as from Great Valley Group, inferred basement faults, and approximate location of basement (dashed where projected and dotted where inferred). Note offset between events A and B (correlated as same strata), and wedge-shaped package of reflectors extending to event C, similar to seismic expression of half-grabens on extended basement. Wells projected onto section are Oils, Inc. of Calif. "Magnet Fee" -1 (MF-1), R. S. Lytle 68 (RSL 68), Chevron "Bourdieu" 1A (B-1A), and Univ. Cons. "Orr" 43 (0-43). Total depths (T.D.) in meters below sea level (S.L.).

form a wedge-shaped sequence (see Figs. 4, 5, 6). This feature is partially obscured by the noise associated with Interstate 5, but discontinuous dipping events extend all the way to event C at VP 225. These events dip fairly steeply (as much as 30° apparent dip in the plane of the section); thus, their true position is considerably updip from their location on the unmigrated time section. Constant velocity migrations show that event C migrates to about VP 245 and dips about 30° (Fig. 6); if the seismic line is not perpendicular to the strike of the strata, the true dip would be steeper. The other reflections from the wedge also steepen and become more continuous on the migrated sections.

The bottom of the wedge is not obvious on the seismic section; the lowermost reflections fade out into the background noise. The fanning pattern of the basin fill requires some deformation of the basement beneath the wedge during deposition of the strata and suggests an extensional half-graben, perhaps with a normal fault near VP 240 (see Figs. 5, 6). The shape and size of the wedge-shaped sequence is somewhat similar to features imaged on present-day passive continental margins that have been interpreted as half-grabens (e.g., Bally, 1981). Here also, the deformation

stopped before the deposition of the lower Tertiary strata. The wedge occurs at the axis of the San Joaquin syncline and in the transition zone between the thick Great Valley Group to the west and the thin Great Valley Group to the east, possibly representing the edge of the continental-thickness crust during the deposition of the Great Valley Group.

The structures described above from the COCORP lines are different from the structures imaged on a reflection line purchased by the U.S. Geological Survey (USGS) that cross the south end of the Kettleman Hills South dome some 50 km southeast (Wentworth et al., 1983; Fig. 3). In particular, the wedge-shaped package of reflections is not present on the USGS line, indicating that the Cretaceous structures beneath the Great Valley do not continue that far south. In addition, there is clear evidence for a low-angle, west-dipping thrust at 3–7 km depth in the core of the Kettleman Hills South dome in the USGS data. Since the COCORP data rule out a similar shallow thrust in the gap between the Coalinga Nose and the Kettleman Hills North dome, the structural style beneath the apparently continuous line of Kettleman Hills anticlines (see Figs. 2, 3) must vary along strike. Further reflection lines across the Kettleman Hills North and

Middle domes might resolve the nature of such changes. These structural changes along strike in the western side of the San Joaquin Valley emphasize the complexity of the tectonics and the dangers of extrapolation along strike.

**Coalinga Earthquake Sequence**

An earthquake sequence began on May 2, 1983, about 10 km northeast of Coalinga and about 30 km northeast of the San Andreas fault. The hypocenter of the main event on May 2 ($M_L$ = 6.7) has been located by the USGS at a depth of 10.5 km on the axis of the Coalinga Nose anticline, about 15 km along strike northwest of Line 1; it was followed by thousands of aftershocks (Eaton, 1983; see Fig. 3). The aftershocks extended across Line 1 and the end of Line 3 (Fig. 3). The thrust-type focal mechanism for the main shock shows almost pure horizontal compression; the two nodal planes both strike N53°W. One plane dips 67°NE, the other 23°SW (Eaton, 1983; see Fig. 3).

Projecting the fault plane of the May 2 earthquake onto the COCORP siesmic section is hazardous for several reasons. The complex aftershock activity indicates that deformation occurred throughout a large volume, as the thick sedimentary section adjusted to basement

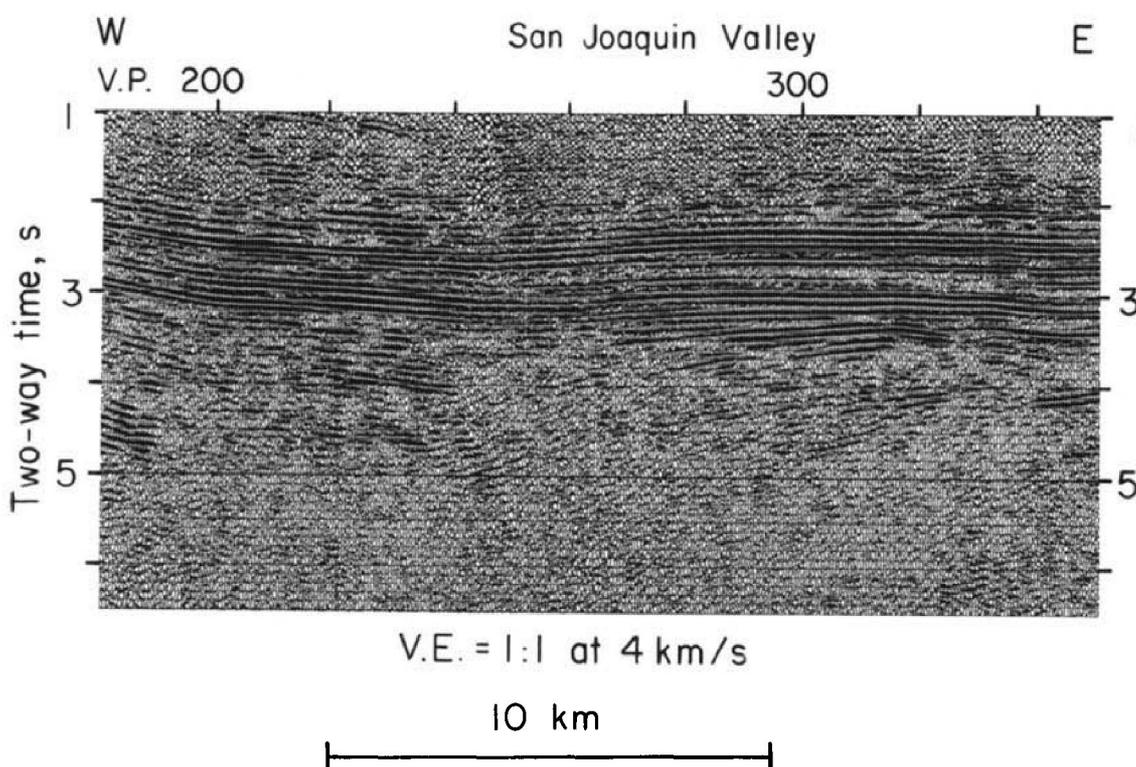## MIGRATION OF THE EASTERN PART OF COCORP COALINGA LINE 1

**Figure 6. Migrated time section of east end of COCORP Coalinga Line 1. Trace amplitude balancing with window of 0.5 s and surface-consistent, automatic-residual statics have been applied before stack and migration. Migration was at constant velocity of 5 km/s. Note enhanced continuity, up-dip movement, and increased dip of events in wedge-shaped sequence between VP 245 and VP 300 compared to Figure 4.**

displacement. Aftershocks do not suggest movement along a single fault plane (Eaton, 1983; Reasenberg et al., 1983). The Coalinga Nose anticline plunges more than 2 km and changes shape and amplitude considerably between the location of the main shock and Line 1 (Kaplow, 1945; American Association of Petroleum Geologists, 1959; Fig. 3). Nevertheless, the interpretation of the anticline as a drape fold over a high-angle basement fault is consistent with interpretation of faulting along the steep northeast-dipping nodal plane for the main Coalinga earthquake.

## CONCLUSIONS

Very strong, continuous reflections from mid–early Tertiary marine strata can be followed through the length of COCORP Coalinga seismic reflection Lines 1 and 3. Lower amplitude reflections from strata of the Upper Jurassic–Cretaceous Great Valley Group are less continuous but can also be traced in the subsurface along both seismic profiles. Unambiguous lower crustal reflections were not detected on the COCORP Coalinga lines, possibly owing to attenuation of the seismic energy by the thick overlying sediments. Structures are visible within the reflections from the sedimentary layers, and they record tectonic events that have affected the Coalinga area since the Late Jurassic. Cretaceous extension along basement normal faults is suggested by the disruption of Cretaceous strata. The folds in the Coalinga area are subparallel to the San Andreas, an orientation not expected in "wrench-fault" tectonics (Page, 1981). The inferred Cretaceous faults may have been reactivated as reverse faults during the Neogene compressional episode to form the line of drape-fold anticlines on the west side of the San Joaquin Valley, including the Coalinga Nose and the Kettleman Hills.

The recent Coalinga earthquake sequence indicates that deformation is continuing in the Coalinga area, and the complexity of the anticline under which the earthquakes occurred prevents a simple projection of the earthquake fault plane onto the seismic section of Coalinga Line 1. However, the inferred high-angle basement faults beneath the Coalinga area are consistent with the interpretation of reverse faulting along the steep northeast-dipping nodal plane for the May 2, 1983, Coalinga earthquake. In such an interpretation, recent reverse fault slip may be a reactivation of a pre-existing normal fault or faults. The results described here emphasize the important role of deep subsurface faults in the active compressional tectonics of the regions adjacent to the San Andreas fault system.

## REFERENCES CITED

American Association of Petroleum Geologists, Pacific Section, 1957, Correlation section across central San Joaquin Valley–San Andreas Fault to Sierra Nevada foothills, California: American Association of Petroleum Geologists correlation section, 1957 series.
—— 1959, Correlation section longitudinally north-south through westside San Joaquin Valley from Coalinga to Midway Sunset and across San Andreas Fault into southeast Cuyama Valley, California: American Association of Petroleum Geologists Memoir correlation section, 1959 series.
Bally, A. W., 1981, Atlantic-type margins, in Bally, A. W., compiler, Geology of passive continental margins: History, structure, and sedimentologic record (with special emphasis on the Atlantic margin): American Association of Petroleum Geologists Education Course Note Series no. 19, p. 1–48.
Blake, M. C., Jr., and Jones, D. L., 1981, The Franciscan assemblage and related rocks in northern California: A reinterpretation, in Ernst, W. G., ed., The geotectonic development of California (Rubey Volume 1): Englewood Cliffs, New Jersey, Prentice-Hall, p. 306–328.
Dickinson, W. R., 1981, Plate tectonics and the continental margin of California, in Ernst, W. G., ed., The geotectonic development of California (Rubey Volume 1): Englewood Cliffs, New Jersey, Prentice-Hall, p. 1–28.
Dodd, H. V., 1931, Recent developments in the Kettleman Hills field: California Oil Fields, v. 17, no. 1, p. 5–44.
Eaton, J. P., 1983, Seismic setting, location, and focal mechanism of the May 2, 1983 Coalinga earthquake, in Borcherdt, R. D., ed., The Coalinga earthquake sequence commencing May 2, 1983: U.S. Geological Survey Open-File Report 83-511, p. 20–26.
Ernst, W. G., 1970, Tectonic contact between the Franciscan melange and the Great Valley Sequence: Crustal expression of a late Mesozoic Benioff Zone: Journal of Geophysical Research, v. 75, p. 886–902.
Fielding, E. J., Barazangi, M., Brown, L., Oliver, J., and Kaufman, S., 1983, COCORP seismic reflection profiles near the 1983 Coalinga earthquake sequence: Deep structures, in The 1983 Coalinga, California earthquakes: California Division of Mines and Geology Special Publication 66, p. 137–149.
Fowlkes, E. J., 1982, An educational guidebook to the geologic resources of the Coalinga District, California: Coalinga, California, West Hills College, 260 p.
Hopson, C. A., Mattinson, J. M., and Pessagno, E. A., 1981, Coast Range ophiolite, western California, in Ernst, W. G., ed., The geotectonic development of California (Rubey Volume 1): Englewood Cliffs, New Jersey, Prentice-Hall, p. 418–510.
Hunter, G. W., 1951, Guijarral Hills oil field (Fresno County): California Oil Fields, v. 37, no. 1, p. 13–19.
Ingersoll, R. V., 1982, Initiation and evolution of the Great Valley forearc basin of northern and central California, U.S.A., in Leggett, J. K., ed., Trench-forearc geology: Geological Society of London Special Publication 10, p. 459–467.

Jennings, C. W., 1975, Fault map of California, with locations of volcanoes, thermal springs and thermal wells: California Division of Mines and Geology, California Geological Data Map Series, Map No. 1, scale 1:750,000.
Kaplow, E. J., 1945, Coalinga oil field (Fresno County: California Oil Fields, v. 31, no. 2, p. 5–22.
King, G.C.P., and Stein, R. S., 1983, Surface folding, river terrace deformation rate and earthquake repeat time in a reverse faulting environment: The Coalinga, California, earthquake of May 1983, in The 1983 Coalinga, California earthquakes: California Division of Mines and Geology Special Publication 66, p. 165–176.
Page, B. M., 1981, The southern Coast Ranges, in Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 329–417.
Reasenberg, P., Eberhart-Phillips, D., and Segall, P., 1983, Preliminary views of the aftershock distribution of the May 2, 1983, Coalinga, earthquake, in Borcherdt, R. D., ed., The Coalinga earthquake sequence commencing May 2, 1983: U.S. Geological Survey Open-File Report 83-511, p. 27–37.
Reches, Z., and Johnson, A. M., 1978, Development of monoclines: Part II. Theoretical analysis of monoclines, in Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 273–311.
Stearns, D. W., 1978, Faulting and forced folding in the Rocky Mountain foreland, in Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1–38.
Stein, R. S., 1983, Reverse slip on a buried fault during the 2 May 1983 Coalinga earthquake: Evidence from geodetic elevation changes, in The 1983 Coalinga, California earthquakes: California Division of Mines and Geology Special Publication 66, p. 151–163.
Wentworth, C. M., Walter, A. W., Bartow, J. A., and Zoback, M. D., 1983, Evidence on the tectonic setting of the 1983 Coalinga earthquakes from deep reflection and refraction profiles across the southeastern end of Kettleman Hills, in The 1983 Coalinga, California earthquakes: California Division of Mines and Geology Special Publication 66, p. 113–126.