

Basement Faults Beneath the Western Great Valley of California
Based on COCORP Seismic Reflection Profiles near Coalinga

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Summary

COCORP, the Consortium for Continental Reflection Profiling, collected deep seismic reflection profiles along two lines in the Coalinga area of central California during May and June of 1977 (see Figure 1). These reflection data shed some light on the deep Cenozoic and Mesozoic structures in the subsurface and suggest the existence of basement faults beneath the 1983 Coalinga earthquake sequence, and the western San Joaquin Valley. The collection and processing of the reflection data are covered in more detail in Fielding and others (1983), and the geologic background and stratigraphic interpretation of the data are covered in Fielding and others (1984); these topics will be covered only briefly here.

The COCORP data are most consistent with faulting on the high-angle nodal plane of the May 2, 1983 main shock focal mechanism (see Figures 2, 4 and 5), and the continuity of reflections from the folded sedimentary layers across the axis of the Coalinga Nose-Kettleman Hills North Dome (KHND) anticline indicates that major movement on faults has not broken through about the upper 6 km of the sedimentary section at the latitude of the COCORP lines. The presence of low-angle, southwest-dipping thrust faults to the southwest of the Coalinga Nose anticline is ruled out in the upper 8-10 km by the continuity of reflections from presumed sedimentary layering (see Figures 2, 3 and 4). A southwest-dipping thrust fault deeper than 10 km cannot be ruled out, but there are no deeper reflections in the COCORP data to suggest such a fault.

We have interpreted and inferred several faults beneath the axis of the San Joaquin Valley, with significant movement during the Cretaceous, as high-angle normal faults that affected the basement and the overlying sediments. The Late Cenozoic and ongoing surface folding and subsurface reverse faulting, highlighted by the recent Coalinga earthquake sequence, may be the result of the reactivation of these

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inferred high-angle basement faults; hence pre-existing faults may be controlling the compressional deformational style of the western Great Valley in the Coalinga area.

Discussion

Figure 1 shows the locations of the two COCORP Coalinga lines on a tectonic map of the area with structural contours, faults, fold axes, and the May 2, 1983 main shock location and focal mechanism and the preliminary spatial extent of the aftershock zone (Eaton, 1983; Reasenbergs and others, 1983). The main, 50 km long, east-west Line 1 runs from the hills southwest of the city of Coalinga, due east across the Coalinga Nose-KHND anticline, and out into the San Joaquin Valley. It passes about 15 km to the southeast of the May 2 main shock epicenter along the strike of the Coalinga Nose anticline (also called Anticline Ridge), and crosses the southern end of the aftershock zone. Note that there is about 2 km of plunge and a considerable decrease in amplitude along the fold axis, as shown by the structural contours on the Eocene Kreyenhagen formation, derived from the closely spaced oil wells of the Coalinga and Kettleman Hills oil fields (Figure 1); this would suggest that the underlying fault offset is less and/or deeper than it is where the main shock occurred.

The short, 15 km north-south crossline, labelled Line 3, starts at the base of Keef Ridge, southeast of Coalinga, and runs due north across the end of the Kettleman Hills North Dome. Common depth point, or CDP, coverage on Line 3 extends only to vibration point 113, or VP 113--the station numbering used on this and the other figures--so the CDP stack does not quite cross Line 1. The results presented here are from extensive reprocessing done on the Megaseis computing facility at Cornell University during 1982 and 1983--before and after the May 2 main shock--and followed a standard processing sequence. A detailed stacking velocity (approximately equal to RMS velocity for shallowly dipping layers) analysis was performed; a plot of the interval velocities derived from the processing of Line 1, can be found in Fielding and others (1983).

Figure 2 shows the CDP stack for Line 1. The scale is approximately equal for the horizontal and vertical axes, assuming a velocity of 4 km/s (close to the average velocity of the sedimentary section) for the conversion of the two-way travel time to depth. There are several caveats to remember in the interpretation of these data. Because the dominant frequency of the reflections detected in these data is 10-15 Hz, with a wavelength of 200-400 m, the resolution of these

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data is about 50-100 m. Fault offsets or other structures smaller than 50 m or 1/4 wavelength might not be detectable.

Figures 2 and 3 show unmigrated CDP stacks, which means that dipping reflections are apparently displaced down-dip, and appear to have shallower dips than the true position of the reflectors in the earth. In addition, Lines 1 and 3 cross the Coalinga Nose-KHND structure at about 40 and 50 degree angles, respectively, so that the reflection points are probably not directly below the surface traces of the lines. For Line 1, this means that the east-dipping reflections are actually bouncing somewhat south of the line, and appear to have slightly shallower dips than they would if they were in the plane of the section. The combined corrections for the migration and the off-strike section take reflections with apparent dips of 20 degrees to true dips of about 35 degrees.

Figure 3 shows the unmigrated CDP stack for Coalinga Line 3. This crossline runs from the steeply dipping strata of the Reef Ridge anticline, due north across the north end of the Kettleman Hills North Dome. The continuity and slight north dip of the sedimentary reflectors across the syncline here clearly rules out a southwest-dipping thrust fault, at least in the upper 5-6 s, or down to about 8-10 km depth. Subhorizontal reflections are assumed to be from the same sedimentary section as is interpreted beneath about VP 90 of Line 1.

Figure 4 shows the interpretation of Coalinga Line 1. The strong reflectors in the Tertiary section are shown in this figure with their identified ages only, derived from the exposed surface geology off the west end of the line, and from several nearby oil wells (see Fielding and others, 1984 for the geologic map and stratigraphic description). In the lower part of the section, consisting mostly of the Upper Jurassic through Cretaceous Great Valley Group, the seismic data have been abstracted as a line-drawing. No wells have penetrated deeply into the Cretaceous section, so the exposed thickness of 8-10 km has been projected down-dip from the hills west of Coalinga, placing the approximate bottom of the sedimentary section and the top of basement at the depth indicated by the dashed line, where projected down-dip, and the dotted line, where inferred from the deepest reflections received.

Notice the offset between event A and event B, which are correlated as the same stratigraphic horizon by their seismic expression; this offset requires about a kilometer of movement on an inferred fault. The best fit to the observed truncations, and to the folding of the overlying sediments is with a high-angle normal fault dipping to the east. The dip

beneath the sedimentary section just 10-15 km to the east of the CN-KHND axis, the simplest interpretation of the 1983 Coalinga main shock focal mechanism is that movement occurred on the high-angle northeast-dipping nodal plane determined by Eaton (1983; see Figure 1). As described in detail by Stein and King (1984), the repetition of about a thousand earthquakes of the magnitude of the 1983 earthquake would produce the observed fold amplitude and shape.

Reflections from a fault with a 50 or 60 degree dip would probably not be detected on a seismic reflection line, and if it were, it would appear displaced significantly down-dip to the northeast on the unmigrated seismic sections. As mentioned earlier, the continuity of reflections from the sedimentary layers folded over the anticlinal axis rules out large (> 50 m) fault displacements certainly in the upper 4 km, and probably in the upper 6 km, where the fold is crossed by COCORP line 1. This is consistent with the elastic dislocation modelling of the coseismic surface deformation measured on levelling lines and long-term deformation of terraces along streams which cross the Coalinga Nose (Stein and King, 1984).

Figure 5 shows two highly schematic cross-sections along Line 1, portraying two of many possible geometries of basement faults, which satisfy the observed structures in the overlying sedimentary section shown in the COCORP data. Cretaceous faults in the preferred figure 5a are high-angle normal faults, and would be similar to growth-fault adjustments seen in other deep sedimentary basins. Cretaceous listric reverse-faults and/or strike-slip faults could also explain the rotation and deformation of the Cretaceous strata, as shown in figure 5b. In both cases, the pre-existing faults may be controlling the deformational style of the Pliocene to Recent folding of the Coalinga Nose-KHND anticline.

It is not unreasonable to compare the general active deformational style of the Coalinga area, and possibly the whole western Great Valley, to the active deformation of the Zagros fold belt in western Iran. The Zagros orogenic belt is the result of the Miocene to present continental collision of the Arabian plate with the Iran crustal blocks at the edge of the Asian plate. Shortening of the Zagros belt is being accommodated both by folding of the relatively thick (6-10 km) sedimentary section, and by thrust faulting of the basement, as indicated by numerous medium-sized earthquakes. The basement faulting in the Zagros appears to be strongly decoupled from the overlying folded sedimentary section by a relatively thick (about 1 km) salt layer located at the base of the sedimentary cover. As appears to be the case in the

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and, especially the strike, are not well constrained. In addition, strike-slip movement on the basement faults cannot be detected in the seismic data.

To the west of events A and B on Line 1, there is a wedge-shaped package of reflectors which dip increasingly westward, extending to event C. A migrated version of this feature can be found in Fielding and others (1984). The tilting of the probably Cretaceous sediments in this wedge requires significant rotation of the underlying basement, at least 30 degrees, depending on the unconstrained strike of the dipping strata. The wedge has a seismic expression similar to half-grabens imaged on other reflection profiles, and occurs in the same position as a wedge of material with velocities near 5 km/s shown on the U.S.G.S. refraction line some 15 km to the north (Walter, this volume; Wentworth and others, this volume). The essentially undeformed overlying Tertiary section indicates that fault movement on both of the interpreted basement faults described above ended before the Tertiary (see Figures 2 and 3).

The fault beneath the Coalinga Nose anticline, shown in Figure 4, is inferred from several sources: from the COCORP data, the focal mechanism of the 1983 Coalinga main shock from Eaton (1983), and dislocation modelling of coseismic elevation changes by Stein and King (1984). COCORP lines 1 and 3 show continuous reflections from the apparently little deformed sedimentary layering of the Great Valley Group and the Tertiary section to the west and south, respectively, of the Coalinga Nose-KHND anticlinal axis to depths of about 6 seconds two-way travel time or 8 to 10 km (Figures 2 and 3). This rules out significant fault offsets greater than the approximate 50-100 m resolution of the reflection data within the observed sedimentary section. Beneath the sedimentary reflectors, extensive reprocessing of the reflection data revealed no evidence of any southwest dipping reflections, as might be expected if there were a low-angle fault zone at depth. Seismic reflection data has been very successful in imaging low-angle faults in other areas (e.g., Wentworth and others, 1983; and this volume; Allmendinger and others, 1984), so the absence of reflections here may be significant, assuming that some seismic energy is penetrating through the thick overlying sedimentary section.

The shape of the Coalinga Nose-KHND anticline both outcropping at the surface and revealed in the seismic reflection lines across the fold axis is quite similar to forced folds and drape folds seen on seismic lines in the Laramide province (e.g., Sacrison, 1978). Because there is good evidence for high-angle Cretaceous basement faults

Coalinga earthquake sequence, the main shocks of medium-sized ($M_s = 6-7$) events in the Zagros are located in the uppermost part of the basement and are not associated with surface faulting; however, many aftershocks do occur within the overlying sedimentary section. Hence, it is tempting to speculate that numerous, and mostly unmapped, active faults may exist beneath the western edge of the Great Valley. The seismic hazard potential of such "blind" faults should be carefully evaluated.

Acknowledgements

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References Cited

- Allmendinger, R., Sharp, J., von Tish, D., Serpa, L., Brown, L., Kaufman, S., Oliver, J., and Smith, R.B., 1983, Cenozoic and Mesozoic structure of the eastern basin and range from COCORP seismic reflection data: *Geology*, v. 11, p. 532-536.
- Eaton, J.P., 1983, Seismic setting, location, and focal mechanism of the May 2, 1983 Coalinga earthquake, in Borchardt, R.D., ed., *The Coalinga earthquake sequence commencing May 2, 1983*: U.S. Geological Survey Open-File Report 83-511, p. 20-26.
- Eaton, J.P., Cockerham, R., and Lester, F., 1983, Study of the May 2, 1983 Coalinga earthquake and its aftershocks, based on the USGS seismic network in northern California, in *The 1983 Coalinga, California Earthquakes: California Division of Mines and Geology Special Publication 66*, p. 261-273.
- 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.

- Fielding, E.J., Barazangi, M., Brown, L., Oliver, J., and Kaufman, S., 1984, COCORP seismic profiles near Coalinga, California: Subsurface structure of the western Great Valley: *Geology*, v. 12, p. 268-273.
- Reasenber, P., Eberhart-Phillips, D., and Segall, P., 1983, Preliminary views of the May 2, 1983, Coalinga earthquake, in Borchardt, R.D., ed., *The Coalinga earthquake sequence commencing May 2, 1983*: U.S. Geological Survey Open-File Report 83-511, p. 20-26.
- Sacrison, W.R., 1978, Seismic interpretation of basement block faults and associated deformation, in Matthews, V., III, ed., *Laramide folding associated with basement block faulting in the western United States*: Geological Society of America Memoir 151, p. 39-49.
- Stein, R.S., and King, G.C.P., 1984, Seismic Potential Revealed by Surface Folding: 1983 Coalinga, California, Earthquake: *Science*, v. 224, p. 869-872.
- Walter, A., Velocity structure near Coalinga, California: this volume.
- Wentworth, C.M., Zoback, M.D., and Bartow, J.A., Structure at the west side of the San Joaquin Valley, California, from seismic reflection profiles: this volume.

Figure Captions

Figure 1:

Generalized tectonic map of the Coalinga area, showing location of COCORP lines, major faults and fold axes, topographic contours (dashed), 500m structural contours 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 main shock and its aftershock zone through June 12, 1983.

Figure 2:

COCORP Coalinga Line 1: time section is not migrated or deconvolved. Trace amplitude balancing with a window of 0.5 s applied before stack. High-amplitude, continuous reflections are from Lower Tertiary section. Note structures in Cretaceous section reflectors beneath the strong Tertiary reflections.

Figure 3:

COCORP Coalinga Line 3: time section is not migrated or deconvolved. Trace amplitude balancing with a window of 0.5 s applied before stack. Note sharp upwarping toward Reef Ridge on south end and limb of Kettleman Hills North Dome on north end. Relatively continuous, presumably unfaulted, reflectors can be seen down to 5-6 s (10-12 km) in syncline in the middle of the line.

Figure 4:

Interpretation of COCORP Line 1 (unmigrated), showing surface topography and geology, stratigraphic interpretation of reflections from the Cenozoic section, line drawing abstracted from deeper reflections interpreted as from the 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, and wedge-shaped package of reflectors extending to event C. Wells projected onto section are identified in Fielding (1984).

Figure 5:

Schematic drawings of two possible interpretations of the subsurface structure and tectonic setting of the Coalinga area, consistent with the COCORP data on the overlying sedimentary section. Basement faults deformed the Great Valley Group, and one may be reactivated under the Coalinga Nose anticline.

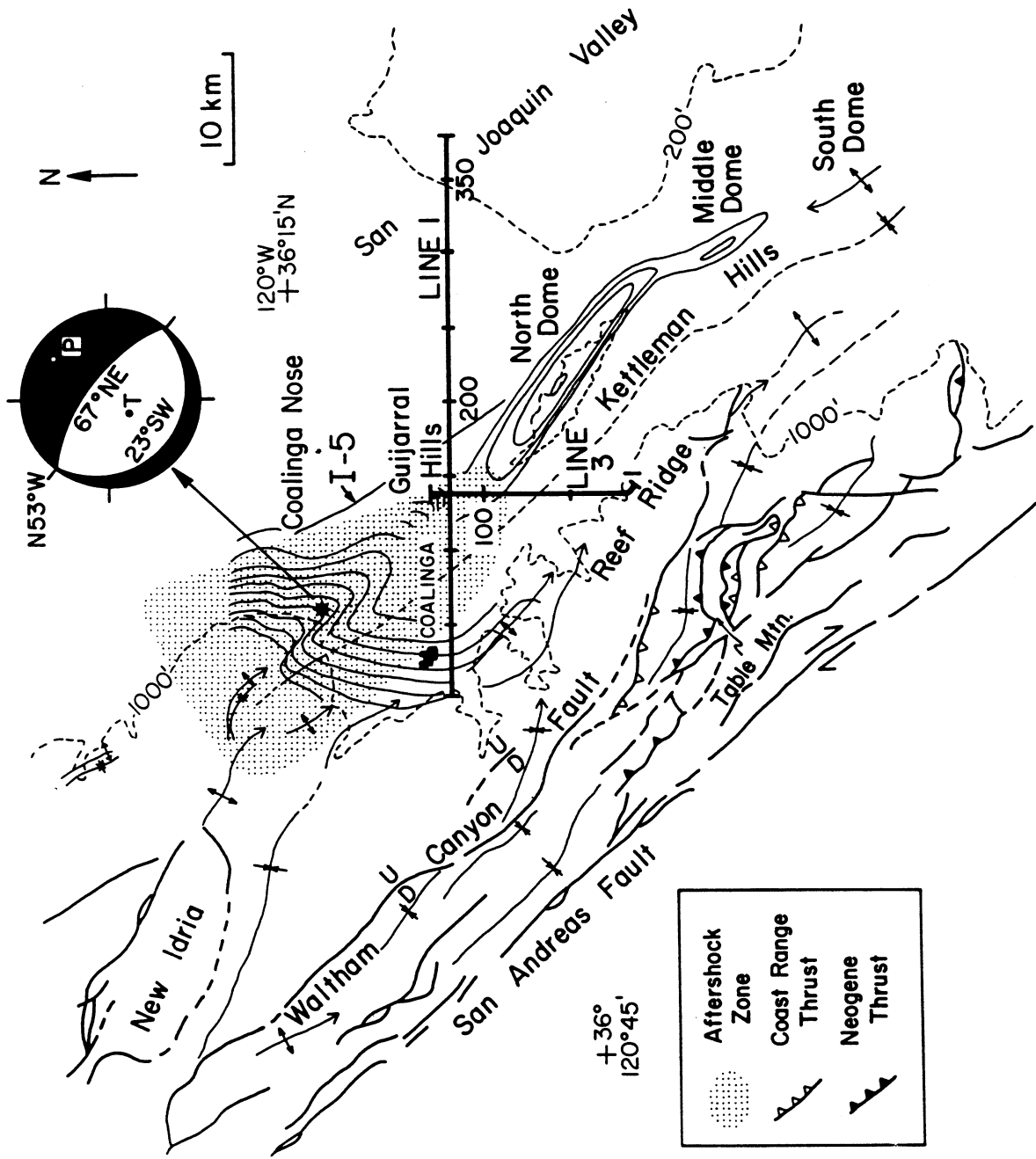
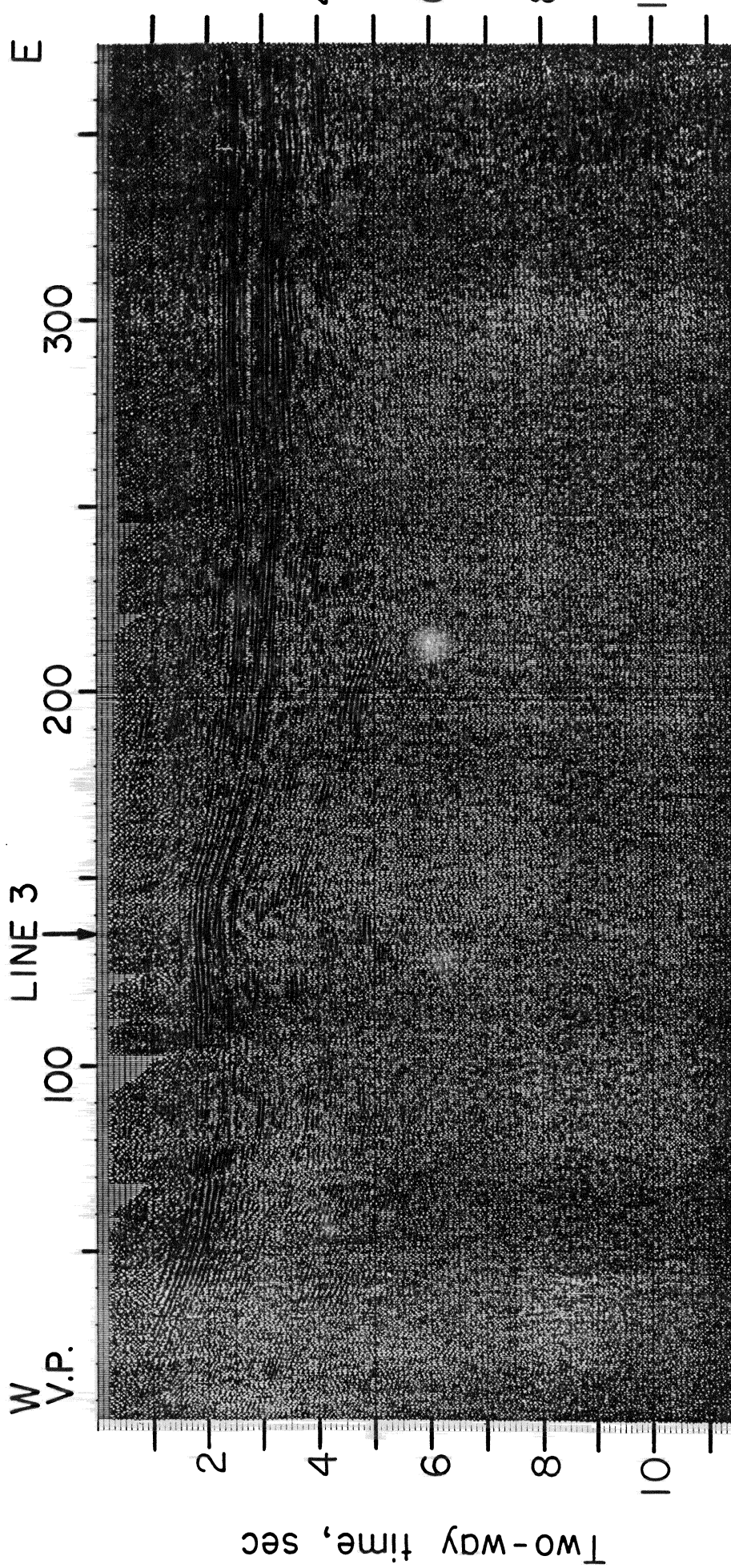


Fig. 1

COCORP COALINGA LINE I

Coalinga Nose Anticline San Joaquin Valley



V.E. = 1:1 at 4 km/sec

10 km

Figure 2

Fig.

COCORP COALINGA LINE 3

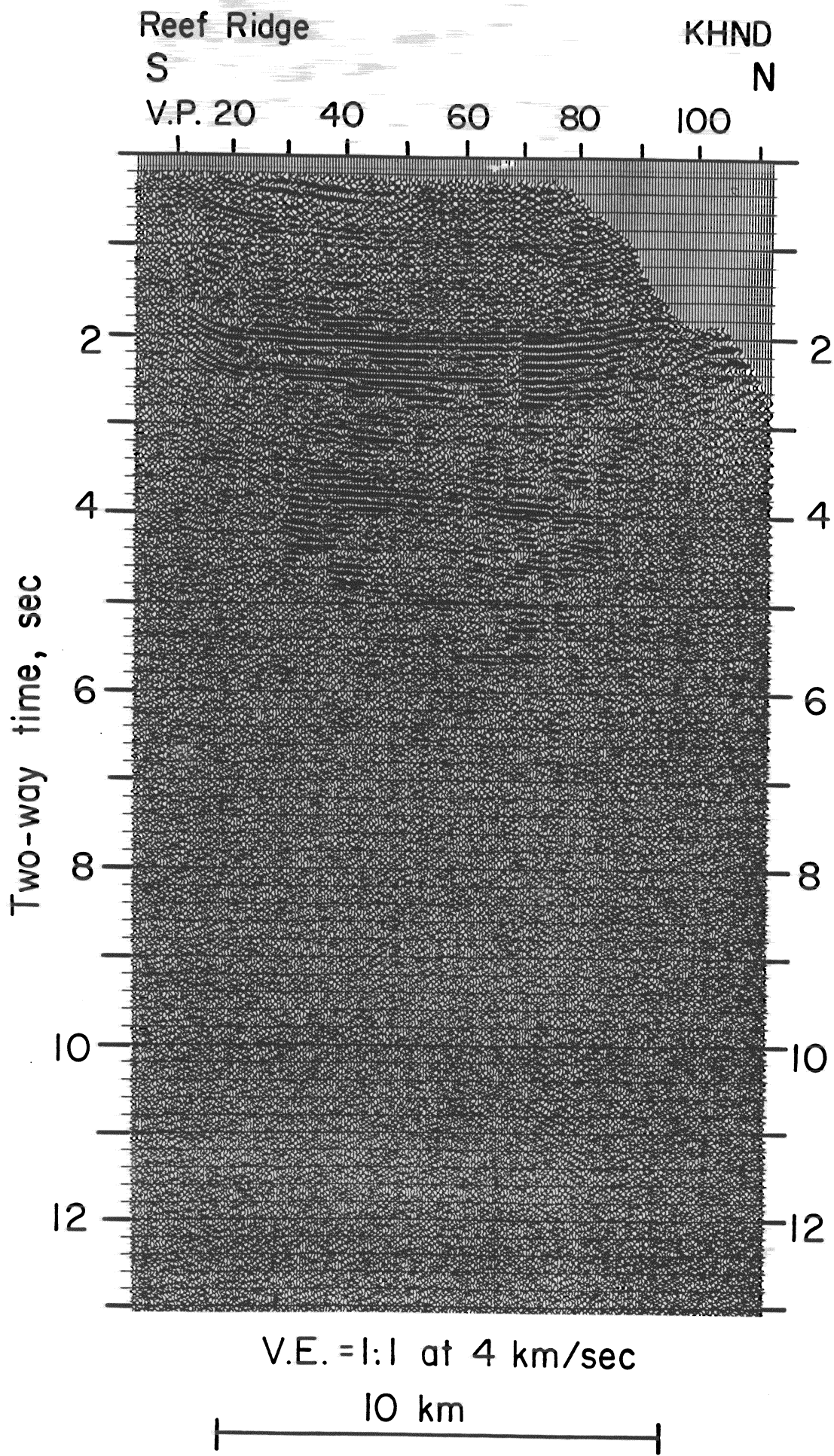


Fig. 3

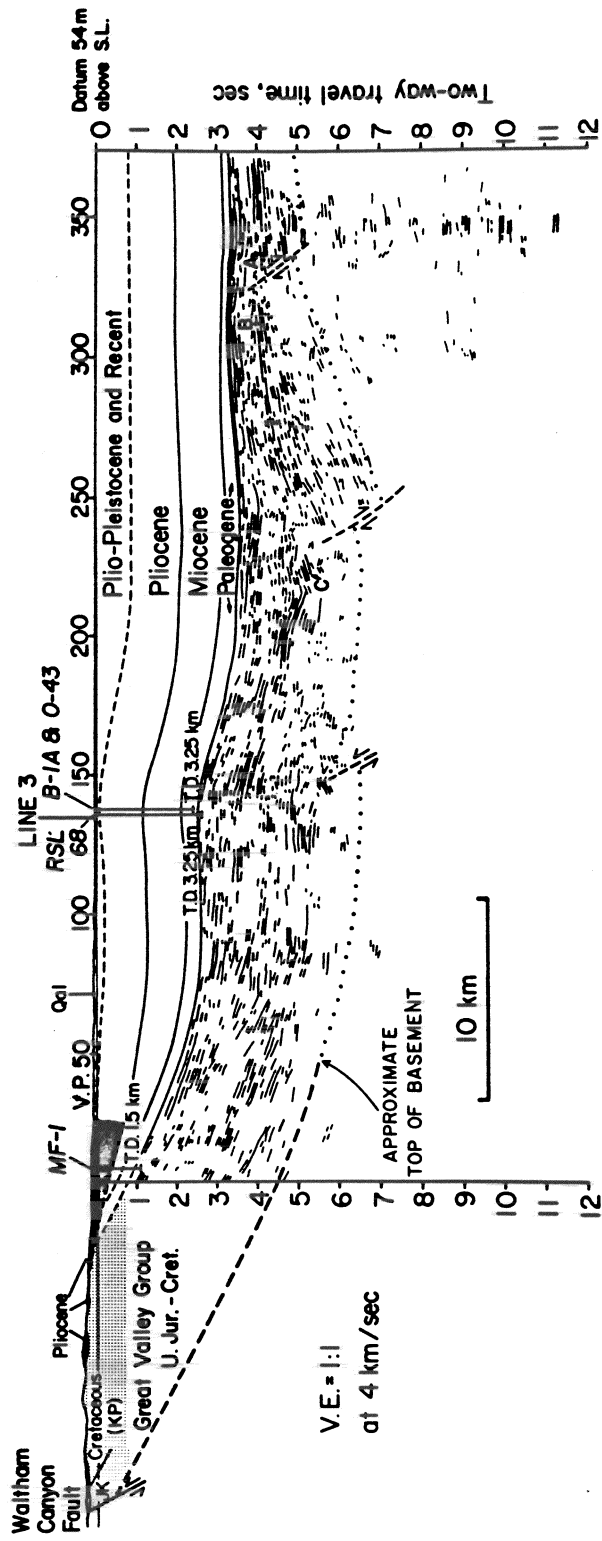


Fig. 4

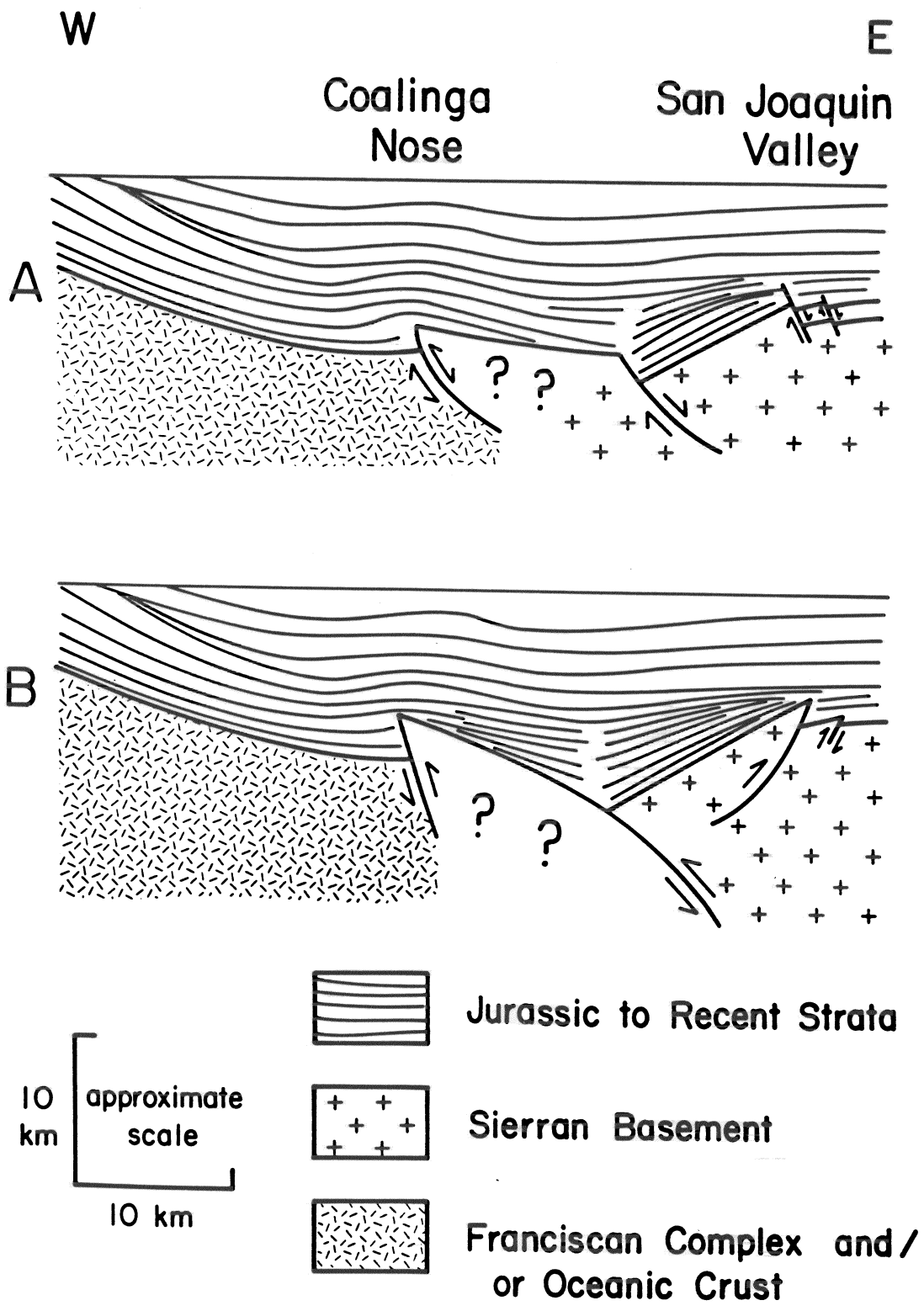


Fig. 5