

COCORP SEISMIC REFLECTION PROFILES NEAR THE 1983 COALINGA
EARTHQUAKE SEQUENCE: DEEP STRUCTURES

by

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ABSTRACT

COCORP seismic reflection lines shot in the Coalinga area in 1977 delineate deep Cenozoic and Mesozoic structures in the subsurface of the western San Joaquin valley beneath the 1983 earthquake sequence. The data imply several faults interpreted to be high-angle normal faults with significant movement during the Cretaceous, and provide constraints on the deep structure of the Neogene fold system under which the recent earthquakes occurred. The reverse faulting indicated by the earthquakes in the sequence may be reactivating the pre-existing, high-angle, basement faults that are inferred from the COCORP data.

INTRODUCTION

COCORP (Consortium for Continental Reflection Profiling) collected two deep seismic reflection profiles in the area south and east of the City of Coalinga during the summer of 1977. Line 1 runs east-west just south of Coalinga for some 50 km from the base of the hills out into the San Joaquin valley, and Line 3 runs north-south for 15 km from Reef Ridge to the north end of the Kettleman Hills North Dome (KHND) (see Fig. 1). Line 1 passes about 15 km to the southeast of the May 2, 1983 epicenter. The main strand of the San Andreas fault system, which lies about 25 km to the southwest of the COCORP Coalinga lines, was crossed by COCORP's Parkfield Line 2, which was collected along with the the Coalinga lines (see Long, 1981).

These COCORP seismic reflection surveys were carried out to provide information on the deep structure of the western side of the Great Valley. The Coalinga area was chosen because of excellent stratigraphic control from exposures of the Mesozoic and Cenozoic sections in the hills west of Coalinga and from the numerous oil wells in the area. The re-entrant of the San Joaquin valley in the Coalinga area also allows seismic crews to get closer to the Coast Ranges and the San Andreas fault system, without working over high topographic relief, than is the case for other areas on the west side of the Great Valley.

The COCORP Coalinga profiles show strong reflections from Tertiary and Cretaceous strata that imply deep basement structures in the Coalinga area. Reflections from the approximately 3.5 km thick Tertiary deep and shallow marine section (AAPG, 1959; Fowlkes, 1982)

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show the effects of the Neogene folding that has greatly modified the western side of the San Joaquin valley. This folding is closely associated in space and time with deformation of the southern Coast Ranges and strike-slip motion along the San Andreas fault system (Page, 1981). Reflections from the 6-8 km thick Upper Jurassic to Cretaceous Great Valley Group (GVG, previously called the Great Valley Sequence -- see Ingersoll, 1982) indicate significant faulting during the deposition of these deep marine turbidites, probably along high-angle normal faults. The recent Coalinga earthquake sequence, beginning May 2, 1983, is a manifestation of the continuing active tectonics of the area, and many of the deep reverse-fault mechanisms detected during the sequence may be reactivations of the high-angle Cretaceous faults that are inferred from the COCORP lines. A more detailed discussion of the geologic and tectonic setting of the Coalinga area can be found in Fielding and others (1983) and in other articles in this volume.

DATA ACQUISITION AND PROCESSING

Two Vibroseis (trademark CONOCO, Inc.) reflection profiles were collected in the Coalinga area during May and June of 1977: a 50 km east-west main line and a 15 km north-south crossline (see Fig. 1). Line 1 runs due east from the base of the hills west of Coalinga through the gap between the Gujarral Hills and the KHND and out into the San Joaquin valley. Line 3 starts at the base of Reef Ridge and runs due north across the end of the KHND to the Gujarral Hills. Common depth point (CDP) coverage on Line 3 extends only to vibration point (VP) 112, so the CDP stack for Line 3 does not cross Line 1. Data was recorded on a 48-channel recording system with 134 m station spacing, producing minimum and maximum source-to-receiver offsets of 0.6 km and 6.7 km, respectively. For Line 1, vibrator sweep (10-32 Hz) time and recording time were adjusted to produce 24 s of correlated data; the Line 3 vibrating and recording times produced 20 s of data. Vibrating every station (5 or 6 vibrators X 16 sweeps/station) resulted in nominal 24-fold CDP stacks, except at the eastern end of Line 1, where vibrating through the spread resulted in CDPs with a maximum 46-fold.

The data were originally collected by Compagnie Generale de Geophysique (CGG) under contract to COCORP and processed under contract by the Geodigit Division of CGG. The data presented here have been extensively reprocessed at Cornell using the Megaseis processing facility, starting with the demultiplexed and Vibroseis correlated VP gathers. The standard sequence followed in the reprocessing includes elevation statics corrections, CDP gathering, trace amplitude balancing, mute and velocity analyses, normal moveout (NMO) corrections, and stacking. Mutes were applied before and after NMO.

Detailed velocity analysis was performed in two stages. Velocity spectra and constant velocity stacks were used to pick an initial set of velocity functions; then variable velocity stack and moved out CDP gather panels, perturbed from the initial velocity functions by increments of 2.5 percent, were used to refine stacking (approximately equal to rms) velocities every 20-50 CDPs (about every 10-25 stations) depending on changes in structure. Velocity control is generally very good down to 4 or 5 s because of the strong reflections and the relatively long receiver array. Interval velocities calculated from the rms velocities with the Dix equation (Dobrin, 1976) have been smoothed and contoured in Fig. 2. Interval velocities are

sensitive to small changes in rms velocities, so the expected error in interval velocities is greater than 10 percent (considerably greater error expected over short intervals has been partially removed by smoothing).

More advanced processing, performed on these data, includes deconvolution, automatic residual statics, and migration. Short periodicity multiples (ringing) are very strong on both Coalinga lines, causing events close together in time to appear as one multicyclic event and also causing some low-amplitude events to be obscured by nearby reflections of high amplitude. Predictive deconvolution strongly attenuates the ringing and increases the resolution of the reflection data, but it also introduces some waveform distortion of the Vibroseis correlated pulse that appears to attenuate some genuine events. Elevation statics were not a problem owing to the lack of relief (less than 260 m) along the lines, but the continuity of the reflections was significantly improved by a surface-consistent, automatic-residual-statics program, which presumably corrected for varying near-surface delays in the Recent alluvium. The time sections displayed in Figs. 3 and 4 are not migrated, so dipping reflections on the sections have shallower dips and are displaced horizontally from their true positions in the plane of the section. However, constant velocity migrations performed on the data show the major features of the seismic sections to be only slightly changed by migration. Cultural noise was somewhat of a problem on these lines, especially where the main line passed within 2 km of the City of Coalinga and where it crossed Interstate 5 (see Fig. 1). There were also agricultural pumps operating near the lines, introducing coherent noise in some areas along the lines. The effects of this noise were sharply reduced by normalizing the amplitudes along and between the traces before stacking (trace amplitude balancing).

COCORP DATA INTERPRETATION

Both of the COCORP Coalinga lines show a prominent set of reflections that runs continuously through the length of the lines between about 2 and 3.5 s (Figs. 3 and 4). These reflections are by far the highest amplitude events on the two sections; other events above and below them are weaker and less continuous. In general, reflections are strongest where the layering is horizontal and where the stack fold is highest, as expected. A more detailed interpretation of the data will be published in Fielding and others (1983).

Stratigraphic Correlation

Stratigraphic control from wells in the Coalinga, Gujarral Hills, and Kettleman Hills oil fields is excellent (e.g. AAPG, 1959). Depths to formation tops from two nearby (about 750 m away) wells were averaged, converted to an approximate travel time (using interval velocities) and projected onto Line 1 at VP 138 (see Fig. 5). The upper layers of the section, identified as Pliocene and Plio-Pleistocene to Recent in the wells, extend to about 1.5 km depth, or 1.2 s on the time section. The long COCORP receiver array is not conducive to good imaging of these less-continuously bedded upper strata, because it is optimized for deeper reflections.

The upper half of the high-amplitude continuous reflections correlates with Miocene strata, while the lower half corresponds to the rest of the Lower Tertiary section down to a depth of 3.5 km (about 2.5 s) at VP 138. Thickly interbedded sandstone and shale layers of Miocene and Eocene age probably provide numerous interfaces of high impedance contrast that produce the observed high-amplitude reflections. The 6-8 km minimum stratigraphic thickness of the Upper Jurassic-Cretaceous GVG exposed west of Coalinga, projected down-dip under Line 1 (Fig. 5), would extend to a depth of 9.5-11.5 km approximately corresponding to the deepest relatively continuous events at 5-6 s on the seismic profile. This is also near the depth at which the interval velocities reach 6 km/s (Fig. 2).

Structures

The first-order structure seen on both Line 1 and Line 3 is the upwarping of the sedimentary section toward the Coast Ranges west and south of Coalinga. Plio-Pleistocene strata and even Quaternary terraces are involved in the upwarping, indicating ongoing deformation (Fowlkes, 1982; Fig. 5). Upwarping on the southern end of Line 3 is especially sharp, with dips measured in the Reef Ridge area up to 70°. Superimposed on this upwarping is the anticline under which the recent earthquake sequence occurred, which has an axis at about VP 145 on Line 1 and at about VP 110 on Line 3 (Figs. 1, 3, and 4). The southeast limb of the KHND appears on the north end of Line 3. The moderately complex, three-dimensional structure of this fold is shown by the structural contours derived from closely spaced oil wells (Dodd, 1931; Kaplow, 1945; Hunter, 1951; Fig. 1). The COCORP lines run through this fold on the structural saddle between the northward-plunging KHND and the southward-plunging Coalinga Nose anticline.

The asymmetric, monoclinical shape of this fold suggests that it may have been formed as a drape fold over a steep basement fault (e.g., Stearns, 1978; Reches and Johnson, 1978). The Tertiary strata reflections appear to be continuous over this fold on Line 1 at least down to 2.5 s (down to 3.5 s on migrated seismic sections). The GVG also appears largely unfaulted, though reflections from that depth are less continuous on the seismic section. The COCORP data are consistent with the interpretation of this fold as a combination of drape folding and buckling of the sedimentary section over a high-angle, eastward-dipping, reverse fault in the basement, and probably rule out a blind thrust interpretation. The displacement on the fault beneath Line 1 is probably less than that beneath the Coalinga Nose or KHND, in view of the plunge of the overlying folds. The inferred basement fault may be a reactivation of a pre-existing normal fault, as will be discussed below.

The deeper reflections of the eastern half of Line 1 show evidence of significant Cretaceous age faults that may be affecting Late Cenozoic to Recent faulting. Beneath VP 335, events A and B are offset, with the western block relatively uplifted (see Fig. 5). The orientation (especially the strike) of the fault is poorly constrained by this single seismic profile, but the preferred interpretation is that a normal fault exists at approximately 4 s and dips 50°-70° eastward in the plane of the section with about a kilometer of offset (possibly 3 km of offset with different event correlations). A reverse fault dipping to the west cannot be ruled out, but minor drape folding of the reflecting strata above event A suggest a east-dipping,

high-angle, normal fault. The overlying Tertiary reflectors are not disrupted, indicating that the fault motion probably took place during the Cretaceous. The uplifted western block is overlapped by the lowermost Tertiary layers.

West of VP 300, the reflections from the Cretaceous strata dip increasingly westward, forming a wedge-shaped sequence (see Figs. 3 and 5). Although this feature is partially masked by the traffic noise from Interstate 5, discontinuous dipping events occur as far west as event C at VP 225. Because these events are dipping fairly steeply (up to 30° of apparent dip in the plane of the section), their true location is updip from their location on the unmigrated section (Fig. 3). Assuming that the seismic line is close to perpendicular to the strike of these strata, the preliminary constant velocity migrations show that event C migrates to around VP 245 and dips 30° west. If the section is far from perpendicular to the strike of the reflectors, their true dip could be much greater.

The bottom of the wedge-shaped sequence is not unambiguously imaged on the COCORP section; the lowermost reflections are gradually lost in the background noise. The data do not well constrain the position of the bounding fault or faults, but the major structural relief occurs between VP 240 and VP 270 (Fig. 5). The fanning pattern of the reflecting strata requires significant rotation (perhaps 30°) of the underlying basement during their deposition. The shape and size of this wedge-shaped sequence is similar to several sequences imaged on passive continental margins, which have been interpreted to be half-graben basins. Here also, the overlying Tertiary strata are not deformed, indicating that the probable normal faulting ended during the Cretaceous.

Deep Reflections

Although lower crustal reflections are rare on the COCORP Coalinga lines, a particularly curious set of possible deep reflections were imaged on Line 1 at about VP 350 between 8.5 and 11.2 s. The amount of moveout across the receiver array of these events is too small for simple multiples of reflections higher in the section, but without crossline control, reflected refractions or out-of-the-plane reflections ("side-swipe") cannot be ruled out. A detailed study of the amount of attenuation within the thick sedimentary section and the effects of cultural noise presently underway may explain why lower crustal reflections were not observed elsewhere on the Coalinga lines. Refraction studies suggest that the Moho is located at about 25-km depth in this area, falling within this zone of deep reflections.

The Coalinga Earthquake Sequence

The May 2, 1983 Coalinga earthquake ($M_L=6.5$) began a sequence of thousands of aftershocks beneath the Coalinga Nose and KHND anticlines (Reasenber and others, 1983; and other papers in this volume; see Fig. 1). The aftershocks appear to define a volume that extends across COCORP Line 1 to the end of Line 3. The May 2 hypocenter has been located at a depth of 10.5 km on the axis of the Coalinga Nose anticline (Eaton, 1983; and this volume), only about 15 km northeast along the strike of the anticline from

the crossing of Line 1 (Fig. 1). However, projecting the fault plane of the May 2, 1983 main shock directly onto the COCORP reflection section is hazardous for several reasons.

The apparent complexity of the spatial distribution of the aftershock activity indicates that deformation is occurring throughout a large volume, perhaps as the thick sedimentary section accommodates probable basement faulting along one or more faults. The moderately complex, three-dimensional shape of the Coalinga Nose anticline (Fig. 1) also precludes a simplistic model of the basement fault geometry. The anticline plunges more than 2 km and flattens out considerably (from 60° dip to less than 10° dip on the southwest limb) between the hypocenter of the main shock and COCORP Line 1 (Kaplou, 1945; AAPG, 1959; Fig. 1). The anticline shape suggests that the amount of structural relief is greater under the Coalinga Nose and the KHND than under Line 1; in addition, the KHND lies about 2 km west of the projection of the Coalinga Nose, suggesting an en echelon basement fault pattern. The COCORP profiles pass through the structural saddle between the two folds at about a 45° angle to their strike. Nevertheless, there are some tentative short, but relatively high-amplitude, events and possible diffraction patterns at 5-6.5 s beneath VP 140 on Line 1 that may indicate a fault-disrupted zone at a depth of 8.5-12 km. A high-angle fault plane reflection would be located much farther east on the unmigrated seismic section in view of the nature of unmigrated sections and the angle that the profile makes with the probable strike of the fault. The interpretation of the anticline on Line 1 as a combination of drape folding and buckling over a high-angle basement fault is consistent with the interpretation of the steep NE-dipping nodal plane of the May 2 main shock being the fault plane.

CONCLUSIONS

COCORP deep seismic reflection profiles in the Coalinga area provide some important constraints on the structure of the basement beneath the thick sedimentary section. Reflections from deformed Cretaceous strata provide evidence for significant fault movements during deposition of the GVG, most likely along an east-dipping series of high-angle normal faults. This early deformation does not affect the thick overlying Tertiary section, but the pre-existing faults could well have controlled the orientation and nature of Late Tertiary and Quaternary faulting and folding in response to Neogene tectonic stresses in the area. COCORP Line 1 shows that the Coalinga Nose anticline continues down plunge with reduced amplitude, and suggests that the fold is primarily a drape fold over a high-angle basement fault or faults. The inferred reverse fault slip may be reactivating a pre-existing normal fault. The COCORP data also indicate that the Tertiary strata involved in the Coalinga Nose folding are largely unfaulted down to at least a depth of 3.5 km, and that the uppermost Cretaceous strata are probably not significantly faulted down to about 5 km depth, which constrains the amount of displacement on the underlying fault. The complexity of the folds prevents a simple projection of the May 2 main shock onto the seismic reflection section, but the inferred high-angle basement faults are consistent with the interpretation of reverse faulting along the steep NE-dipping nodal plane of the earthquake. The possibility of earthquake recurrence on such deep basement faults beneath the thick sedimentary section of the western part of the Great Valley should be considered in any future seismic risk evaluation of the region.

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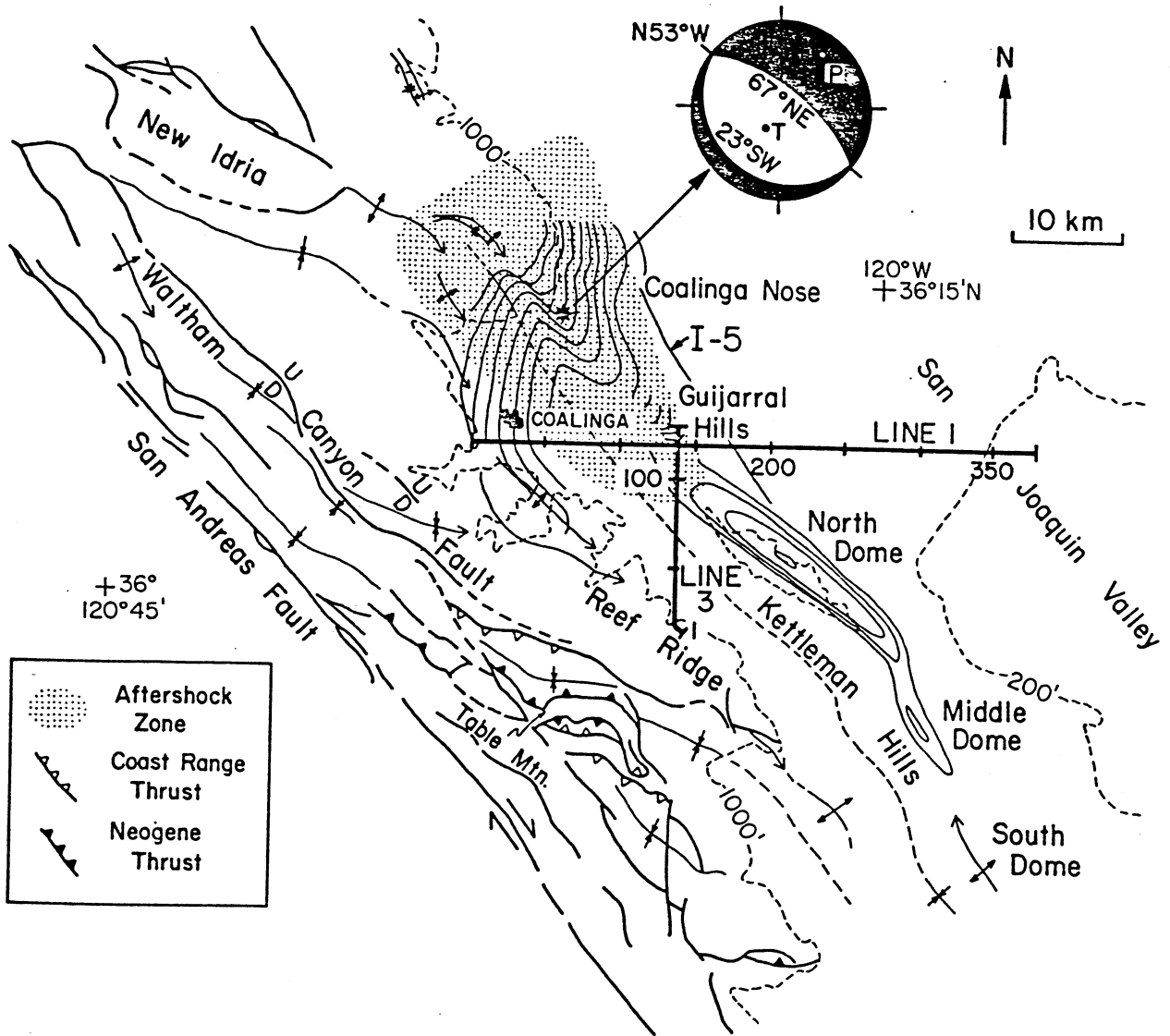


Fig. 1: Generalized tectonic map of the Coalinga area, showing location of COCORP lines, major faults and fold axes, topographic contours, 500 m structural contours on Eocene formation derived from wells in Coalinga and Kettleman Hills oil fields, location and focal mechanism of May 2, 1983 Coalinga earthquake ($M_L=6.5$) and its aftershock zone through June 12, 1983.

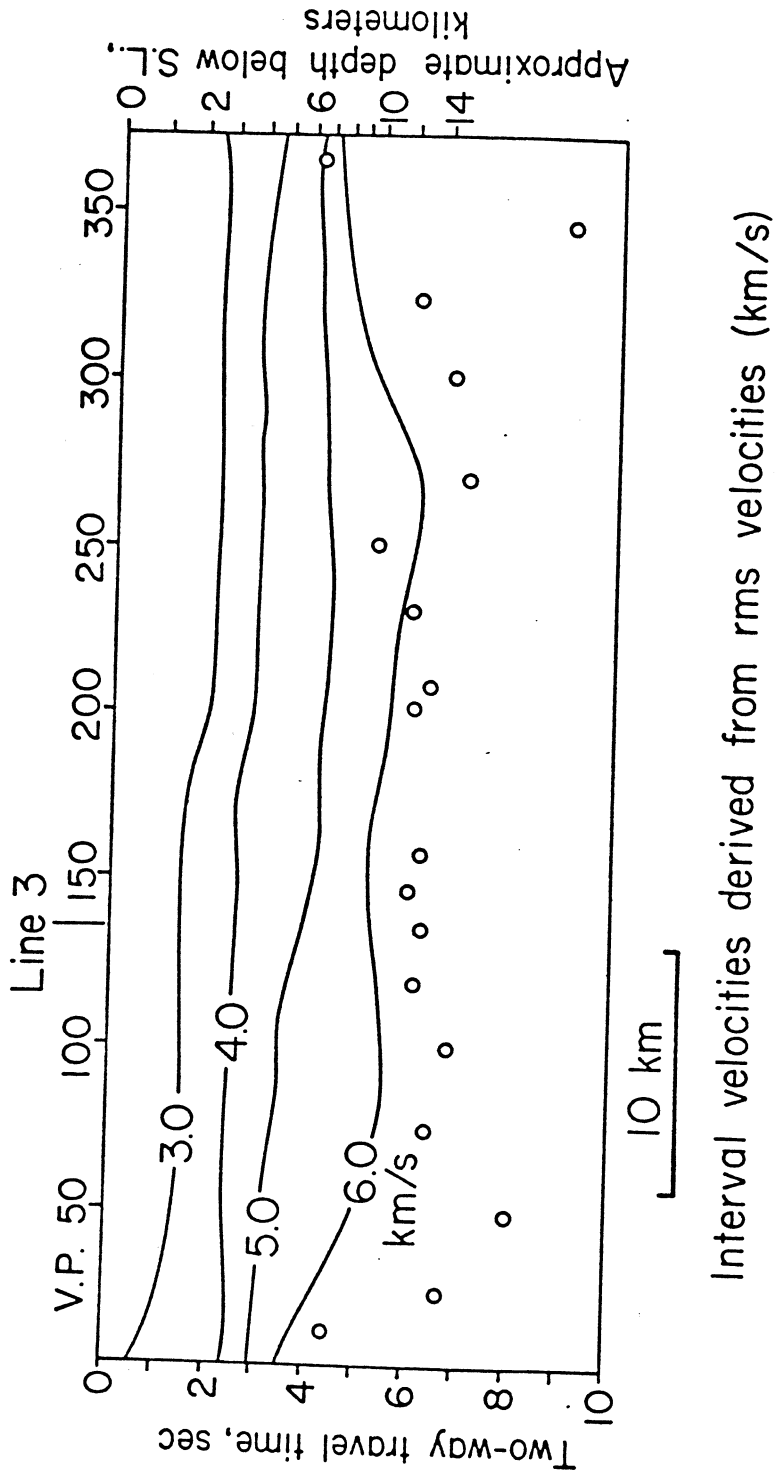
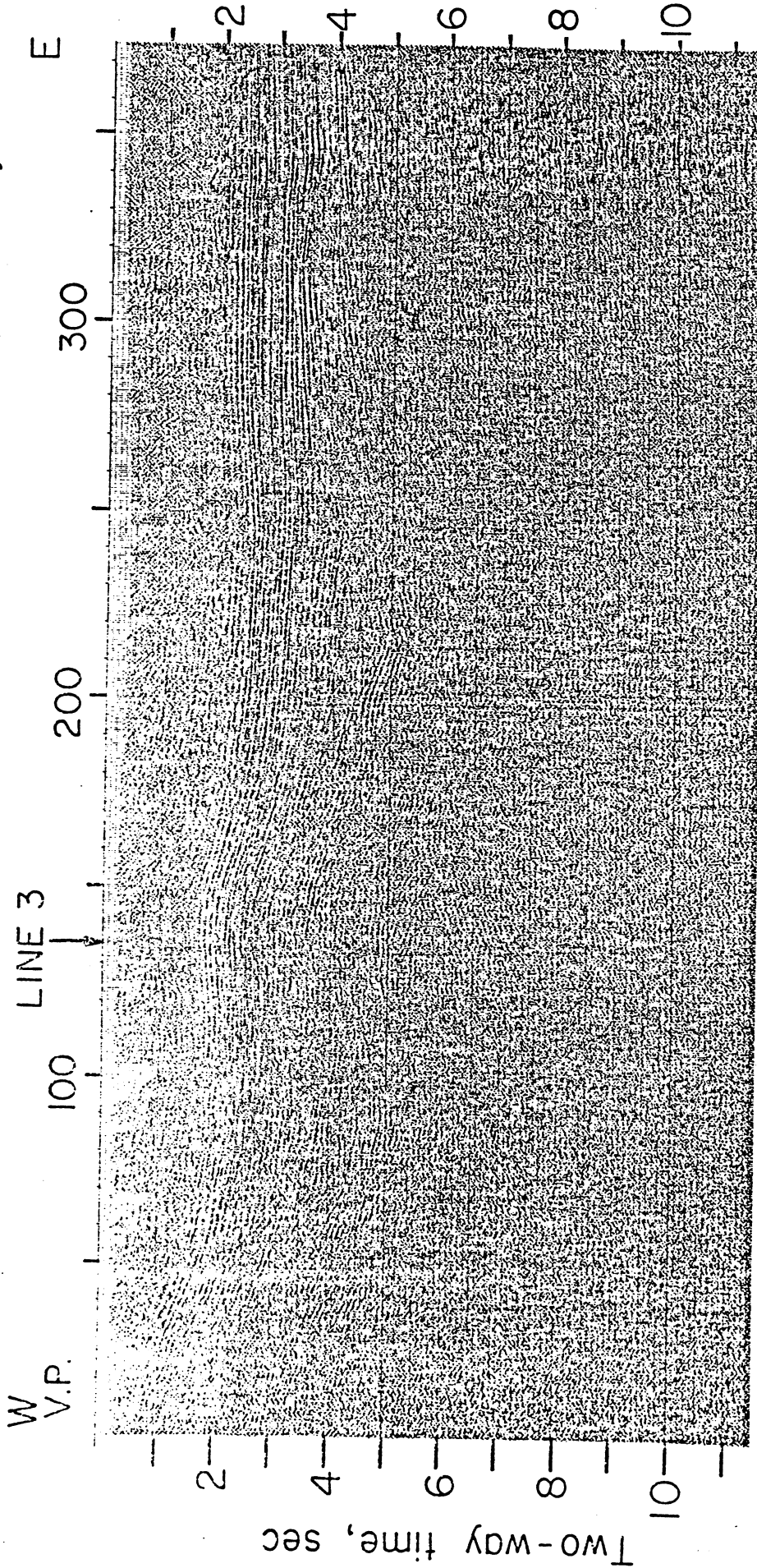


Fig. 2: Generalized contours of the interval velocities for COCORP Line 1 derived from the stacking (rms) velocities used in processing. Interval velocities are very sensitive to small changes in rms velocities, so these contours are only approximate. Crystalline basement is inferred near 6 km/s contour. Circles indicate deepest points at which a rms velocity was measured.

COCORP COALINGA LINE 1

Coalinga Nose Anticline San Joaquin Valley



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

10 km

Fig. 3: COCORP Coalinga Line 1: time section is not migrated or deconvolved. Trace amplitude balancing with a window of 0.5 s has been applied before stack. High-amplitude, continuous reflections are from Lower Tertiary section. Note structures in Cretaceous section reflectors beneath the strong Tertiary reflections.

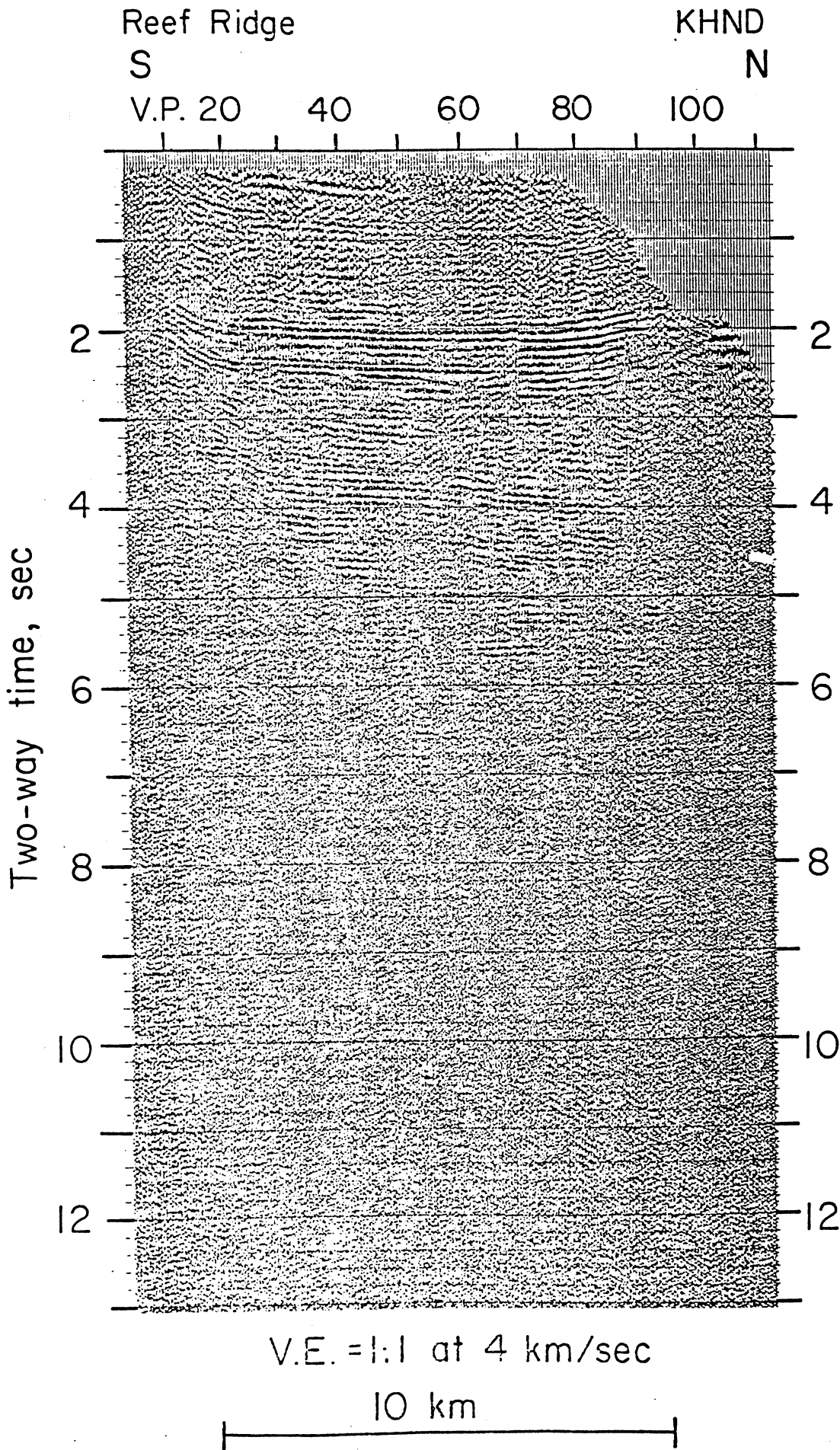


Fig. 4: COCORP Coalition Line 3: time section is migrated or deconvolved. Trace amplitude balanced with a window of 0.5 applied before stack. Note sharp upwarping toward Reef Ridge on south end and limb of Kettleman Hill North Dome (KHND) on north end. Flat part of section correlates with about V.P. 80 on Line 1.

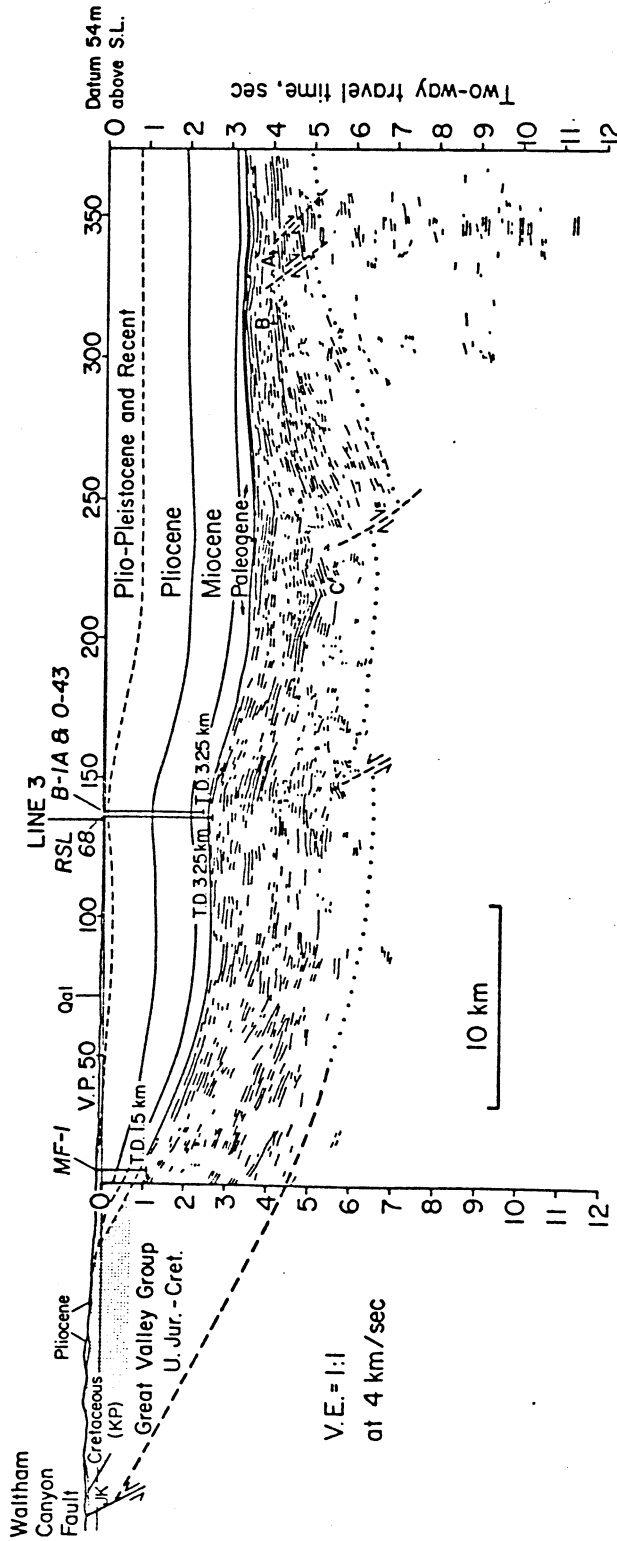


Fig. 5: Interpretation of COCORP Line 1 (unmigrated), showing surface topography and geology, stratigraphic interpretation of reflections from the Cenozoic section, line drawing abstracted from Upper Jurassic - Cretaceous section reflections, inferred basement faults and approximate location of basement. Note offset between events A and B, and the wedge-shaped package of reflectors extending to event C. 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 (O-43). Total depths (T.D.) in km below S.L.