TECTONICS, VOL. 5, NO. 2, PAGES 293-320, APRIL 1986

THE DEEP CRUSTAL STRUCTURE OF THE MOJAVE DESERT, CALIFORNIA, FROM COCORP SEISMIC REFLECTION DATA

M. J. Cheadle[1], B. L. Czuchra[2], T. Byrne[3], C. J. Ando[4], J. E. Oliver, L. D. Brown, and S. Kaufman

Department of Geological Sciences, Cornell University, Ithaca, New York

P. E. Malin[5]

Department of Geological Sciences, University of Southern California, Los Angeles

R. A. Phinney

Department of Geological and Geophysical Sciences, Princeton University, New Jersey

Abstract. COCORP seismic reflection profiling in the western and northern Mojave Desert of southern California has revealed the presence of numerous major low-angle reflecting horizons within the crust. These complex, though laterally continuous, horizons are interpreted to represent major southwesterly dipping crustal fault zones, and as such they place important constraints on the tectonic evolution of the region. The uppermost horizon is interpreted to be the Rand thrust, which, where exposed, places Precambrian and Late Cretaceous crystalline rocks over possibly younger Pelona-Rand-Orocopia Schist. This reflecting horizon extends for 25 km southwest of the Rand Mountains where it appears to be truncated at a depth of about 7.4 km by another horizon, which may be a later low-angle normal fault. The other reflecting horizons are not traceable to the surface, and so greater ambiguity remains in their interpretation. The most prominent of these horizons occurs at midcrustal depths (15±6 km), exhibits a "ramp and flat" geometry, and extends over the northern area of the Mojave survey into the Basin and Range Province. A lower horizon, at depths of 20-30 km in the northern part of the survey area, is antiformal and appears to terminate above a flat and relatively continuous Moho-depth horizon. The crust-mantle transition appears to be represented by a continuous series of reflections which occur at about 10 s (33 km) in the north of the survey and at about 8-9 s (26-29 km) in the south. These reflections are offset in the vicinity of the town of Mojave. The deep intracrustal fault zones inferred from the COCORP survey may represent (1) the deep crustal continuation of the system of Mesozoic thrusts which crops out in southern Nevada and southeastern California, (2) Late Cretaceous to Early Cenozoic, northeast-vergent thrusts related to the uplift of the Pelona-Orocopia-Rand Schist, or (3) low-angle normal faults related to Early Miocene, northeast-southwest directed crustal extension. The COCORP survey also traversed the major strike-slip faults

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[1]Now at Department of Earth Sciences, Cambridge University, United Kingdom.
[2]Now at Tenneco Oil Company, Lafayette, Louisiana.
[3]Now at Department of Geological Sciences, Brown University, Providence, Rhode Island.
[4]Now at Shell Development Company, Houston, Texas.
[5]Now at Marine Sciences Institute, University of California at Santa Barbara.

Paper number 5T0765.
0278-7407/86/005T-0765$10.00

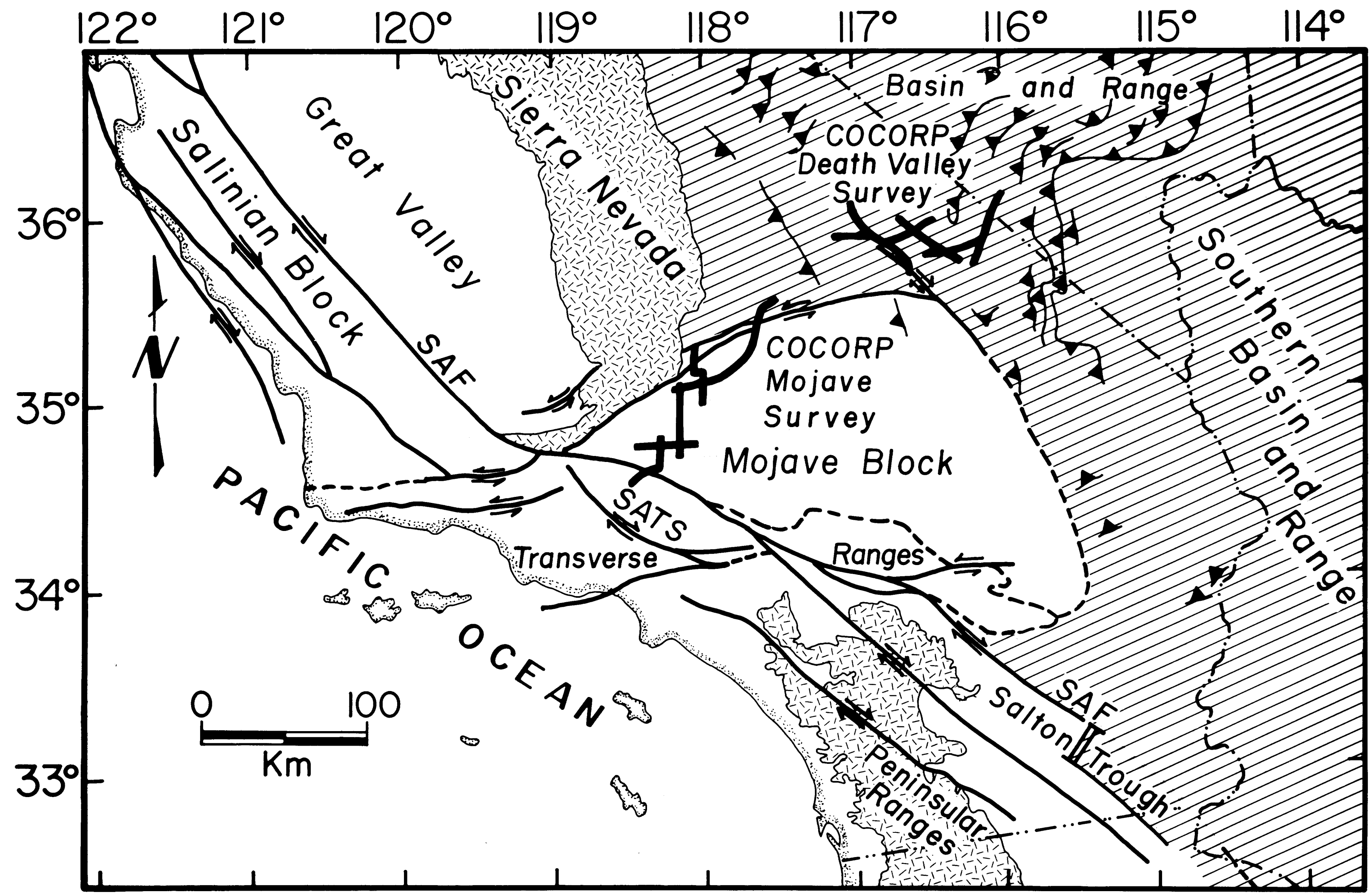

Fig. 1. Geological map of the major physiographic provinces of southern California and the locations of the COCORP seismic reflection lines. Abbreviations (faults are in bold type): SAF, San Andreas fault; SATS, San Andreas transform system. Dashed pattern, outcrop of the Sierra Nevada and Peninsula Ranges batholiths, which are both part of the Mesozoic batholithic belt that includes much of the Mojave and the Salinian blocks [Hamilton, 1969]; lined pattern, Basin and Range Province, not extended into the Mojave block for clarity; thrust symbols, Mesozoic thrust belt.

that bound the Mojave block. The San Andreas fault zone appears to truncate reflectors at depths of 6, 8 and 20 km within the Mojave basement, suggesting that it is a major vertical feature which extends to at least 20 km depth. Conversely, the Garlock fault does not offset an underlying reflecting horizon which occurs at 9 km depth and therefore appears to be a relatively shallow crustal feature.

INTRODUCTION

The Mojave Desert region of southern California is located at the junction of several of the major tectonic provinces of the southwestern United States (Figure 1). It is a wedge-shaped region where bedrock exposure is dominated by granitic rocks of the Mesozoic batholithic belt that extends along the western margin of North America. The Mojave block is bounded to the north by the Garlock fault and the extensional Basin and Range Province, and to the south and west by the San Andreas transform system. East-vergent thrusts of Mesozoic age extend across its eastern margin, which is marked by a series of northwest trending geophysical anomalies (Bouguer gravity and seismic), and a change in physiography and crustal thickness [Dokka, 1980]. At one time or another, each of these tectonic regimes has played an important role in the evolution of the Mojave block. Recent detailed surface geological studies such as those by Miller [1977], Dokka [1980], and Glazner [1981], and the pioneering seismic reflection experiments of Dix [1965], have begun to elucidate the fundamental structural nature of the block.

Six deep seismic reflection profiles were recorded within the western Mojave Desert region (Figure 2) during the winter and spring of 1982 by the Consortium for Continental Reflection Profiling (COCORP) in an effort to further understand this complex region. The survey revealed several extensive southwesterly dipping horizons, or zones of reflections, at two-way travel times corresponding to various depths within the crust of the Mojave block (Figure 3). These horizons are often multicyclic and vary in continuity, the less continuous horizons consisting of discrete events which are laterally correlative and are subparallel to the more continuous horizons. They are interpreted to be major fault zones. However, whether these fault zones are brittle faults or discrete ductile shear zones is unclear, not being determinable from seismic reflection data alone.

Three regional tectonic models which involve either northeast-directed overthrusting or northeast-southwest-directed extension are considered in terms of the COCORP results. Each model attributes the primary cause of the reflecting horizons to a different tectonic episode, either (1) Mesozoic thrusting, (2) Late Cretaceous to Early Cenozoic thrusting related to the uplift of the Pelona-Orocopia-Rand Schist, or (3) Early Miocene crustal extension.

TECTONIC SETTING

Although the Mojave block is defined largely by the San Andreas and the Garlock faults, these geological features have played a relatively minor role in the evolution of the crust within the Mojave block compared to earlier Cenozoic and Mesozoic tectonic events [Burchfiel and Davis, 1981].

One important Mesozoic event was the voluminous intrusion of granitic rocks which form part of the major Mesozoic batholithic belt of western North America. This belt represents the remains of one or more fluctuating "Andean-type" magmatic arcs [Hamilton, 1969] which overprinted most of the earlier Precambrian and Mesozoic structures that once existed within the western and central Mojave Desert. In the eastern Mojave region, major east vergent thrusting was coeval with, and possibly related to, the evolution of this magmatic arc [Burchfiel and Davis, 1972; 1975]. These thrusts may have been part of a major Mesozoic thrust belt that once extended into the Mojave block [Burchfiel and Davis, 1981].

Magmatic activity and accompanying arc-related thrusting ended about 80 Ma [Burchfiel and Davis, 1981]. The Rand thrust cuts granites dated at 85 Ma indicating that the Rand Schist was emplaced beneath Precambrian and Mesozoic crystalline rocks no earlier [Silver et al., 1984]. Uplift of the Rand Schist to shallow crustal levels may have occurred at a substantially later time. The Rand Schist outcrops in the Rand Mountains and is correlated with the Pelona-Orocopia Schist of southern California [Ehlig, 1968; Haxel and Dillon, 1978]. Although the Pelona-Orocopia-Rand Schist is distinctive in

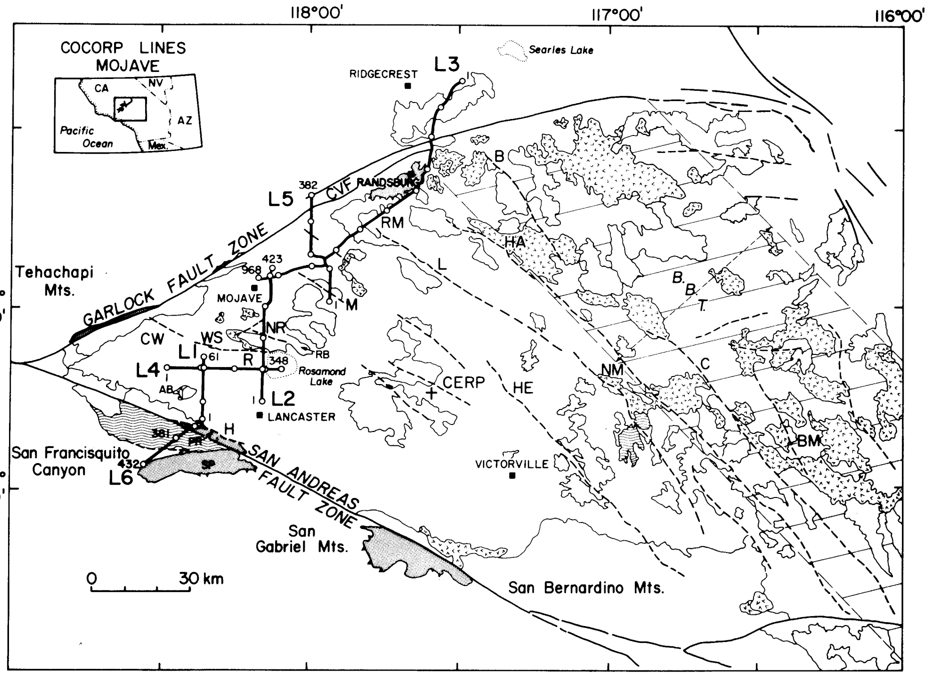

Fig. 2. Generalized geologic map of the Mojave Desert showing the positions of the COCORP seismic reflection lines. Inset shows position of map in southern California. Dotted pattern, Rand-Pelona-Orocopia Schist; v pattern, Tertiary sediments and volcanics; wavy pattern, Precambrian outcrops; white, Mesozoic granites; unshaded, alluvium; dashed lines, Barstow Bristol Trough (B.B.T.). Faults are shown as bold lines. Abbreviations for faults are B, Blackwater fault; C, Camprock fault; CVF, Cantil Valley fault; CW, Cottonwood fault; H, Hitchbrook fault; HA, Harper Valley fault; HE, Helendale fault; L, Lockhart fault; M, Muroc fault; NR, North Rosamond fault; R, Rosamond fault; WS, Willow Springs fault. Abbreviations for mountains are AB, Antelope Buttes; BM, Bullion Mountains; NM, Newberry Mountains; PR, Portal Ridge; RB, Rosamond Buttes; RM, Rand Mountains; SP, Sierra Pelona. Position of CERP (COCORP Extended Research Program) survey is marked by a cross.

outcrop, its genesis and history are enigmatic [Mukasa et al., 1984]. COCORP line 3 traverses the surface outcrop of the Rand Schist.

Uplift and erosion of the Mojave block at about 45 Ma is suggested by Ar^{40} blocking temperatures determined from biotite-bearing plutons in the central Mojave Desert [Miller and Sutter, 1982]. This apparent uplift is also supported by the lack of Early Cenozoic sediments in the Mojave Desert. From such evidence Hewett [1954] estimated that the Mojave block underwent approximately 3 km of erosion during the Early Cenozoic.

In the early Miocene (23-20 Ma), the central Mojave block underwent an intense period of detachment faulting and associated high-angle normal faulting [Dokka, 1980]. This period was characterized by rapidly evolving tectonic basins and the onset of copious volcanism, centered about the Barstow-Bristol trough (Figure 2) [Dokka and Glazner, 1982].

Since mid-Miocene times the Mojave block has been influenced by the San Andreas strike-slip fault system. The combined effect of the lateral displacements along both the San Andreas and Garlock faults has resulted in a north-south compressive regime [Hill, 1954; Bohannon and Howell, 1982], and in the development of northwest trending right-lateral strike-slip faults within the eastern and central Mojave Desert [Dibblee, 1961]. On the basis of paleomagnetic studies in southern California, Luyendyk et al. [1980] predicted substantial displacement on these faults. However, Dokka [1983] suggested that the faults have relatively minor displacements, ruling out large lateral shearing within the Mojave block during the late Cenozoic, although rotation of the Mojave block as a whole cannot be discounted.

DATA ACQUISITION AND PROCESSING

The locations of the six COCORP deep seismic reflection profiles recorded during the Mojave Desert survey are shown in Figure 2. These profiles form a network of lines, approximately 300 km in total length, which runs southwest across the Mojave Desert, from Searles Lake north of the Garlock fault to San Franscisquito Canyon south of the San Andreas fault. Together, they provide three-dimensional seismic reflection coverage of the western and northern Mojave block.

Table 1 lists the data acquisition parameters that were used by Petty Ray Geophysical, a division of Geosource Inc., during the recording of each line. The data were processed at Cornell University using a MEGASEIS (TM Seiscom Delta) seismic processing system following the sequence outlined in Table 2. In addition to the three-dimensional information provided by cross-line control, common depth point (CDP) scatter resulting from crooked line geometries was exploited to provide supplementary information about the three-dimensional geometry of the reflectors imaged by the survey. Extensive F-K filtering was also required to remove surface waves from shot point gathers recorded within sedimentary basins. This filtering, along with careful muting and velocity analysis, considerably enhanced the appearance of the shallow data.

The quality of the data collected in the survey is generally good; prominent reflections occur at two-way travel times corresponding to all depths within the crust. However, occasional vertical strips or "panels" of numerous "ringing" events are present on some of the unmigrated stacked sections, particularly in areas of low stacking fold. Examples of these "panels" are visible on line 2 (VP 340 to VP 400, Figure 3), on line 3 (VP 340 to VP 480 and VP 850 to VP 900, Figures 3 and 6), and on line 4 (VP 1 to VP 50 and VP 250 to VP 300, Figures 3 and 8). The abrupt termination of these "panels" (for example, the "panel" visible on line 3 between VP's 340 and 480), and the presence within the "panels" of events with differing dips and hence differing raypaths, suggests that the "panels" may be artifacts of anomalous near surface conditions such as variation in vibrator coupling and/or the shallow generation of pegleg multiples. However, no correlation has been detected between the occurrence of the panels and changes in the mapped surface geology. Preliminary deconvolution suggests that some of the "ringing" may be removed by further processing.

During data analysis, particular attention was paid to distinguishing diffractions and sideswipe (reflections from out of the plane of the section) from reflections that originated from structures within, or near to, the plane of the section. Diffractions were recognized at many levels within the sections; however, sideswipe proved to be a minor problem despite the presence of major structural features, such as the San Andreas and Garlock faults, in close proximity to the lines.

The data in this paper are presented as line drawings which have been abstracted from the seismic sections, augmented with examples of the sections themselves. Although most of the data presented here are unmigrated, both three-dimensional hand-, and two-dimensional hand- and computer-migrated sections have been used as interpretive aids.

COCORP DATA: RESULTS AND INTERPRETATIONS

The COCORP Mojave seismic data are characterized by discrete, but mostly discontinuous, horizons or zones of reflections which appear to represent gently dipping, near-planar structures at several levels within the crust of the Mojave block (Figure 3). Many of these bands are multicyclic with a duration of up to 1 s of two-way travel time. They consist of numerous short reflections which are laterally correlatable over large portions of the survey.

Figure 3 is a schematic representation of the seismic sections recorded during the survey. Each section is adjacent to the sections which cross it in order to facilitate the discussion of the continuous nature of the reflecting horizons. The sections (Figures 3, 4, 6, 7, and 8) were displayed so that the upper parts have approximately equal horizontal and vertical depth scales. Consequently, the lower parts of the sections are horizon-

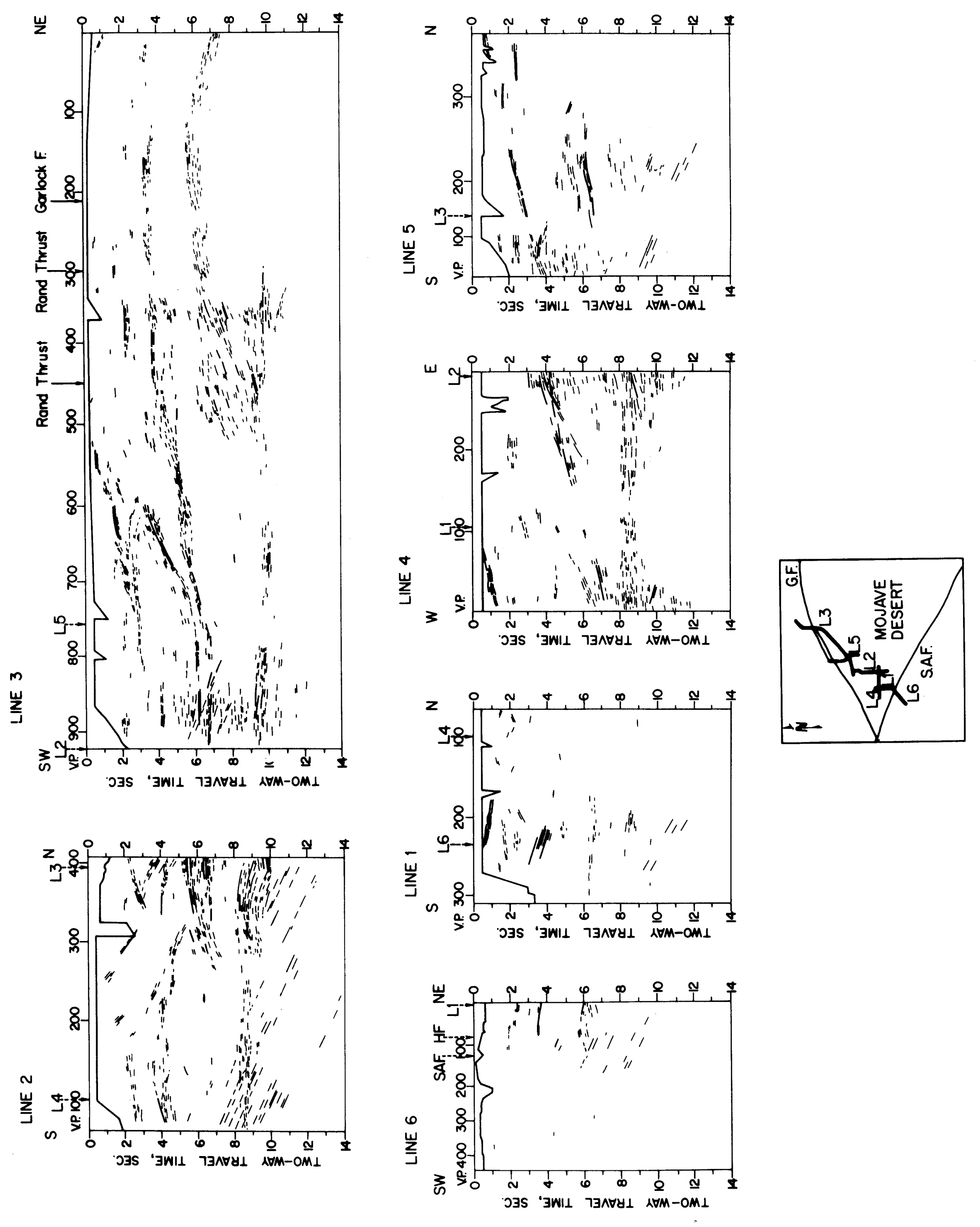

Fig.3a. Interpretive line drawings of the seismic sections for the COCORP Mojave Survey (Figure 3). Numbers along the top of the sections are VP (vibration point) numbers which correspond to those on Figure 2 (100 VP's = 10 km), except for line 6 where 100 VP's = 5 km). For approximate depth multiply by one half the average velocity, which is about 6.0 km/s ÷ 2 = 3 for most of the section. DF, diffractions. The inset shows the relative position of the lines.

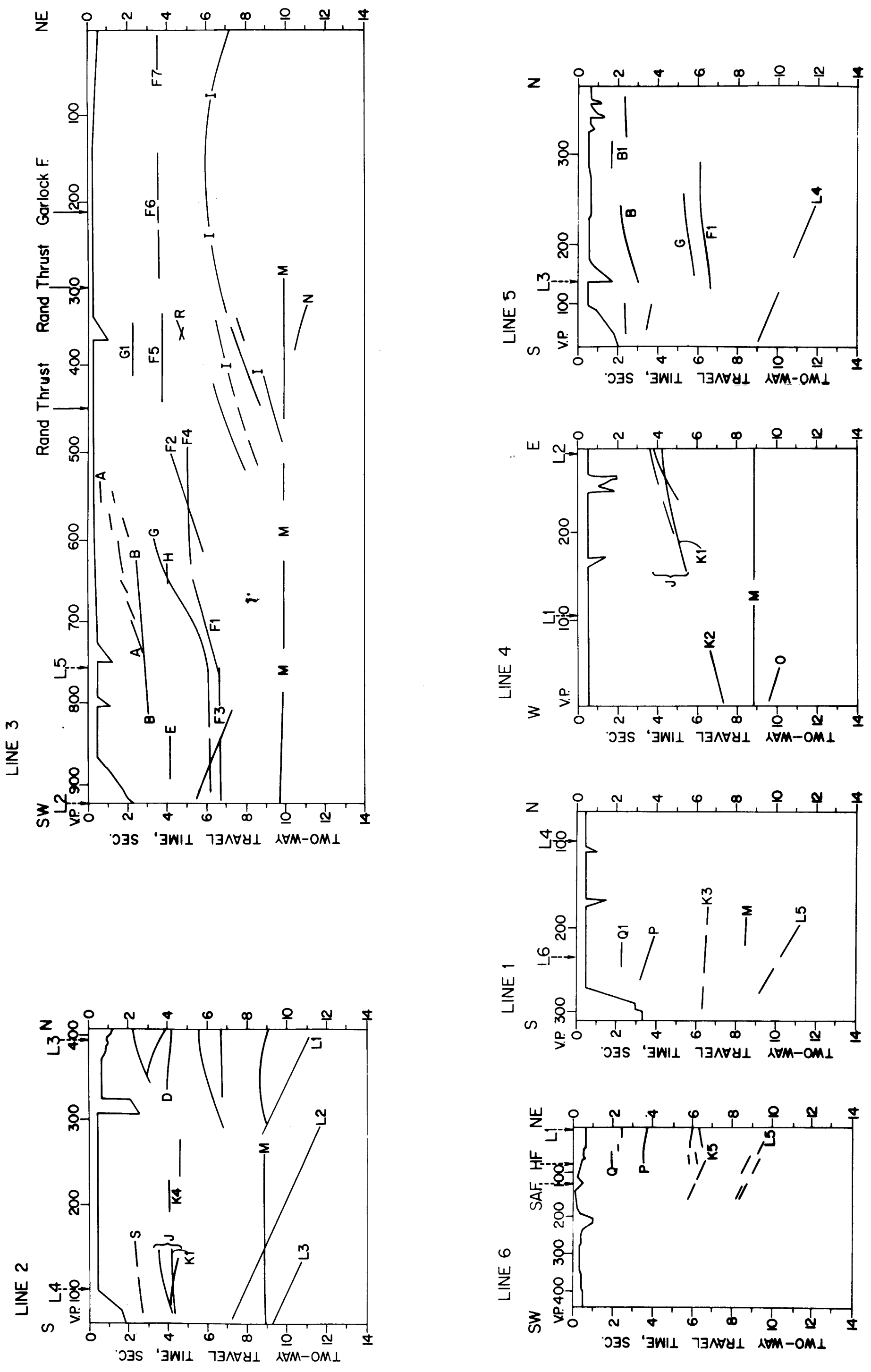

Fig. 3b. Index to features in Figure 3a that are discussed in text.

TABLE 1. Data Acquisition Parameters

Parameter	Description
Source	Vibroseis (trademark CONOCO,Inc.), nominal 5 vibrators 8 sweeps per vibration point (line 5: 4 sweeps) 8-32 Hz upsweep, 32-s duration (lines 4 and 6: 16 s) 100.6 m spacing (line 6:50.3 m) 149 m array length with 5 vibrators or 134 m with 4 vibrators
Receiver	100.6 m station spacing (line 6: 50.3 m) 96 channels 98.1 m geophone array length (24 elements) nominal distance: near station 503 m (line 6: 251.5 m) far station 10,058 m (line 6: 5,026 m)
Recording	52 s recording time (lines 4 and 6: 32 s) 20 s correlated record length 8 ms sample rate 48 (nominal) fold
Direction of Shooting	line 1: north to south; VP 61 to VP 280, push spread to south line 2: south to north; VP 101 to VP 323, pull spread to north VP 324 to VP 343, vibrate through spread line 3: northeast to southwest; VP 1 to VP 868, pull spread to southwest line 4: west to east: VP 1 to VP149, push spread to east VP 150 to VP 290, vibrate through spread line 5: south to north; VP 101 to VP 382, pull spread to north line 6: northeast to southwest; VP 229 to VP 244.5, vibrate off-line on line 1, into spread on line 6 VP 245 to VP 344.5, vibrate off-line on line 1, into fixed spread on line 6 VP 151 to VP 442, pull spread to south

Parameters apply to all lines unless otherwise stated.

tally exaggerated by about 1.5:1. As a general rule, 1 s of two-way travel time corresponds to approximately 2 to 2.8 km from 0 to 2 s and 2.8 to 3.3 km from 2 to 10 s on the sections. Two-way travel times are used throughout this paper in order to describe the depth of an event. All dips quoted in this paper are approximate and based on three-dimensional migrations unless otherwise specified. Copies of the Mojave data set may be obtained as outlined by Kaufman [1984].

The Rand Thrust

The Rand Mountains in the northern Mojave Desert (Figure 2) expose the Rand Schist [Hulin, 1925; Dibblee, 1967], an isoclinally folded sequence of metavolcanic and metasedimentary rocks of oceanic affinity and continental provenance, which has been correlated with the Pelona and Orocopia Schists of southern California [Hershey, 1912; Ehlig, 1968; Haxel and Dillon, 1978]. All outcrops of the

TABLE 2. Processing Sequence

Steps	Descriptions
1	demultiplex
2	Vibroseis correlation
3	velocity (FK) filter
4	edit and tailmute noisy shot point gathers
5	crooked line geometry (CDP spacing = 50.3 m except line 6 = 25.15 m)
6	elevation statics
7	gather
8	balance trace amplitudes, 1 s window
9	velocity analysis
10	normal moveout correction
11	mute
12	trace sum, line 6 only
13	stack
14	frequency filter
15	automatic gain control, 1 s window
16	display (Figures 4, 6, 8)
17	migration
18	display (Figures 4, 7)

Sequence applies to all lines unless otherwise stated

Pelona-Orocopia Schist are domal in form with no visible basement, and appear to lie in tectonic contact with overlying Precambrian crystalline and Mesozoic igneous rocks.

The Pelona-Orocopia Schist was metamorphosed during thrusting at depths of 20-30 km [Graham and England, 1976; Haxel and Dillon, 1978; Graham and Powell, 1984]. It has since been uplifted, reaching the surface during early Cenozoic times [Haxel and Dillon, 1978]. Although the protolith of the Pelona-Orocopia Schist is dated at >160 Ma [Mukasa et al., 1984], the original tectonic setting and the mechanisms of emplacement and uplift of the Schist are uncertain [Burchfiel and Davis, 1981; Jacobson, 1983; Mukasa et al., 1984; Tosdal et al., 1984]. Regional tectonic models suggest that the Schist may represent either an underthrust extension of the Franciscan Complex [Crowell, 1968, 1981; Yeats, 1968a, b; Burchfiel and Davis, 1981]; the overthrust remains of a now closed oceanic rift or intra-arc basin [Ehlig, 1968; Haxel and Dillon, 1978; Tosdal et al., 1984]; the overthrust remains of a pull-apart rift basin once located at the junction of the sinistral Mojave-Sonora Megashear and the continental margin [Tosdal et al., 1984]; or a pre-Late Jurassic exotic addition to North America that was deformed and metamorphosed prior to being sutured to the continent [Vedder et al., 1983; Mukasa et al., 1984]. However, the apparent age of the Pelona-Orocopia Schist protolith (>160 Ma) casts doubt on the underthrust Franciscan model, because the Franciscan Complex is Upper Jurassic to Tertiary in age [Mukasa et al., 1984].

The Rand Schist crops out as a broad northwest-southeast trending antiform [Dibblee, 1967] over most of the Rand Mountains. Ehlig [1968] has suggested that the schist lies in thrust contact with the overlying gneissic and granitic rocks, inferring that the contact, the Rand thrust, is also antiformal. In the northeastern part of the Rand Mountains, the Rand thrust has been mapped as a zone of mylonites [Vargo, 1972] between the antiformal Rand Schist and the overlying Precambrian paragneisses (the Johannesburg Gneiss [Hulin, 1925]). In the southwestern Rand Mountains, Silver et al. [1984] have mapped a southwest dipping (10-40°) thrust zone of granite over schist marked by a 5 to 75 m interval of distinctive, mylonitic, grey carbonate-rich quartzofeldspathic gneiss, and have shown the thrust to be younger than 85 Ma, the age of a granite in the upper plate. In addition, an intrusive granite, dated at 73 ± 3 Ma, contains hornfelsed xenoliths of the schist suggesting that the

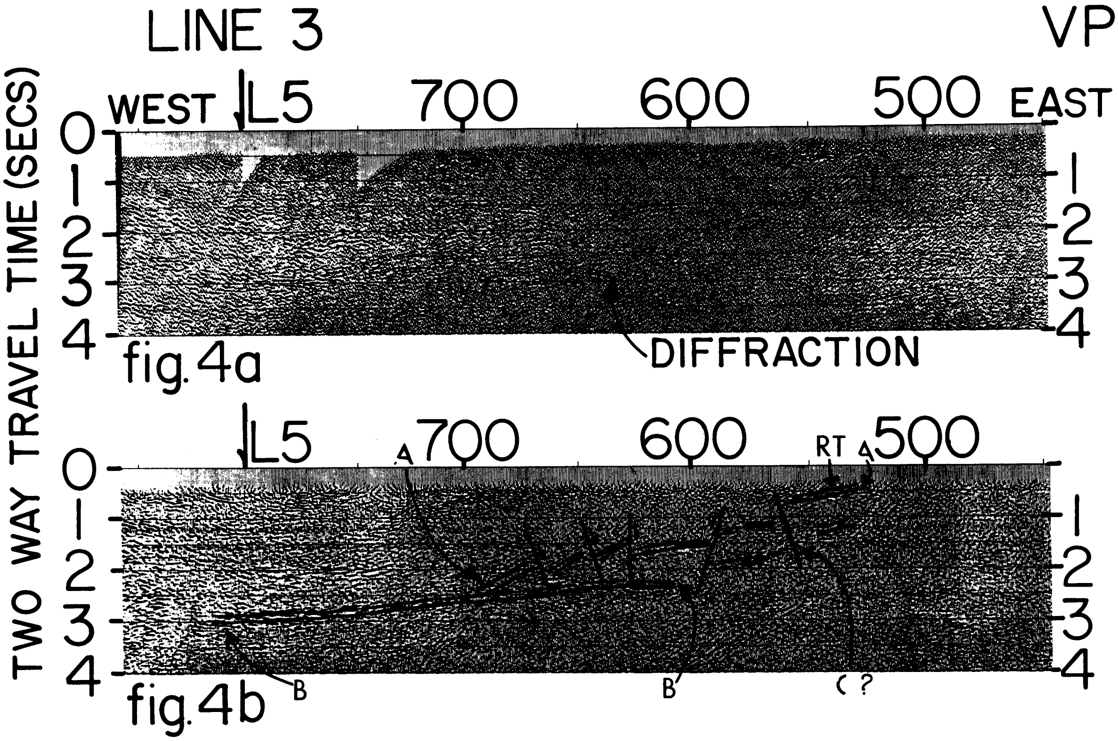

Fig. 4. Detail of the middle part of COCORP Mojave line 3. The lower section is migrated with interpretation and shows the inferred Rand thrust and related structures. The upper section is unmigrated and unmarked. Horizontal and vertical scales are approximately 1:1. Lettered reflections are discussed in text. RT, Rand thrust.

Rand Schist was metamorphosed prior to that date [Silver et al., 1984].

Line 3 traverses the Rand Mountains and crosses the inferred surface trace of the northeastern limb of the Rand thrust at VP 300 and the southwestern limb of the thrust at VP 450 (Figure 2). A complex zone of numerous southwesterly dipping reflections which extends from VP 520 at 0.5 s (1 km) to VP 820 at 3.0 s (8 km) is visible on line 3 (Figures 3, 4). In detail, the zone consists of a series of short, discontinuous, relatively strong reflections (horizon A in Figures 3b and 4b) which run from VP 520 at 0.5 s (1 km) to VP 740 at 2.8 s (7.4 km), below which extends a diffuse series of subhorizontal reflections (horizon B in Figures 3b and 4b). Horizon B extends from VP 600 at 2.5 s (6.5 km) to VP 820 at 3.0 s (8 km) on line 3 and is also visible on line 5, a crossline which intersects line 3 southwest of the Rand Mountains at VP 750 (Figure 2). This horizon (B) has a true dip of approximately 20° south and is distinct between VP 120 at 3.0 s (8 km) and VP 240 at 2.0 s (5 km) on line 5 (Figure 3). Event B1 (Figure 3) may be the continuation of the horizon further to the north on line 5.

The positions of horizons A and B relative to the inferred surface trace of the southwestern limb of the Rand thrust, and the absence of similar shallow reflections in other parts of the data, suggest that at least one of the horizons consists of reflections from the Rand thrust. Figure 4 is an interpretation of this complex feature. Horizon A may be projected to the surface approximately at the inferred surface outcrop of the Rand thrust (VP 450) and is therefore interpreted to represent the thrust. The horizon is interpreted to be cut extensively by high-angle normal faults which may correlate with high-angle normal faults mapped in the vicinity of the Rand Mountains [Morehouse, 1984; Silver et al., 1984], and to be truncated at depth by the more continuous horizon B. Therefore the

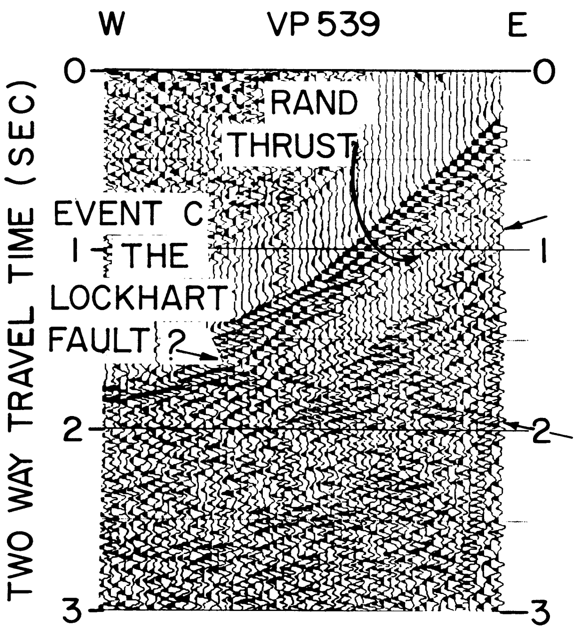

Fig. 5. Shot point gather showing the reverse moveout event that is interpreted to be a reflected refraction from a high-angle normal fault or a splay of the Lockhart Fault, and the event that is interpreted to be the Rand thrust. Shot point gather has had AGC (Automatic Gain Control) with a 1-s window applied. See Figure 2 for location.

Rand thrust, at least with these data, cannot be traced throughout the Mojave block. Horizon B is difficult to trace westward beyond VP 820; however, event E on the western end of line 3 and event D on the northern end of line 2 may represent its southwesterly continuation (Figure 3). Diffractions at the eastern end of horizon B, below VP 630 on line 3, at 2.5 s (Figure 4a) suggest that horizon B terminates abruptly and therefore may also be faulted.

Event C on Figure 5 exhibits reverse-moveout on the shot point gathers. It may originate from one of the faults which cuts horizons A and B, and can be interpreted as a reflected refraction [Sheriff and Geldart, 1982] from a steeply dipping fault that projects to the surface approximately at VP 585 on line 3, cutting the Rand thrust at VP 575. The event (C) may originate from a splay of the Lockhart fault (Figure 2), a Late Cenozoic northwest-trending strike-slip fault [Dibblee, 1961] or one of the high angle normal faults mapped to the south of the Rand Mountains [Morehouse, 1984; Silver et al., 1984].

The identity of horizon B is unknown. However, since some of the inferred faults which offset horizon A do not offset horizon B, horizon B is interpreted to be more recent structure than A. It may represent a thrust related to the emplacement of the Rand Schist or, alternatively, it may be a later extensional detachment which truncates the Rand thrust. Both horizons A and B are interpreted to have been offset by late Cenozoic faults east of VP 600 (Figure 4).

There is no recognizable reflection from the northeastern continuation of the Rand thrust on line 3 between VP 300 and VP 220. This absence may be due to (1) a lack of sufficient impedance contrast between the Johannesburg Gneiss, with its associated mylonites, and the schist; (2) the possible extreme structural complexity of the northeastern limb of the thrust, or, more likely, (3) the thrust lying above the minimum depth (about 1 km) for imaging seismic events in this survey.

Mid- and Deep-Crustal Structure

The mid- and deep-crustal data are characterized by discrete bands of reflections, some of which are more continuous and laterally extensive than the horizons described above (Figure 3). However, these mid- and deep-crustal horizons are not traceable to the surface within the survey, and so some ambiguity is inherent in their interpretation. On the basis of their form and extent, and in consideration of the regional geology, the most likely causes of these reflections are either tectonic or lithological contacts such as fault zones or the bottoms of batholiths. Fault zones are commonly accepted as possible seismic reflectors [e.g., Smithson et al., 1979; Allmendinger et al., 1983], and Lynn et al. [1981] have considered the possibility that layering at the bottoms of granitoid batholiths may also generate good seismic reflections.

Event F (Figures 3 and 6) is a complex midcrustal horizon on line 3, which extends from VP 350 at 3.7 s (10 km) to VP 808 at 7 s (22 km). Migration of horizon F (Figure 7) clearly shows that it has a steplike geometry with two southwesterly dipping segments, below VP's 755 to 595 (F1) and VP's 525 to 440 (F2), between three apparently horizontal segments, VP's

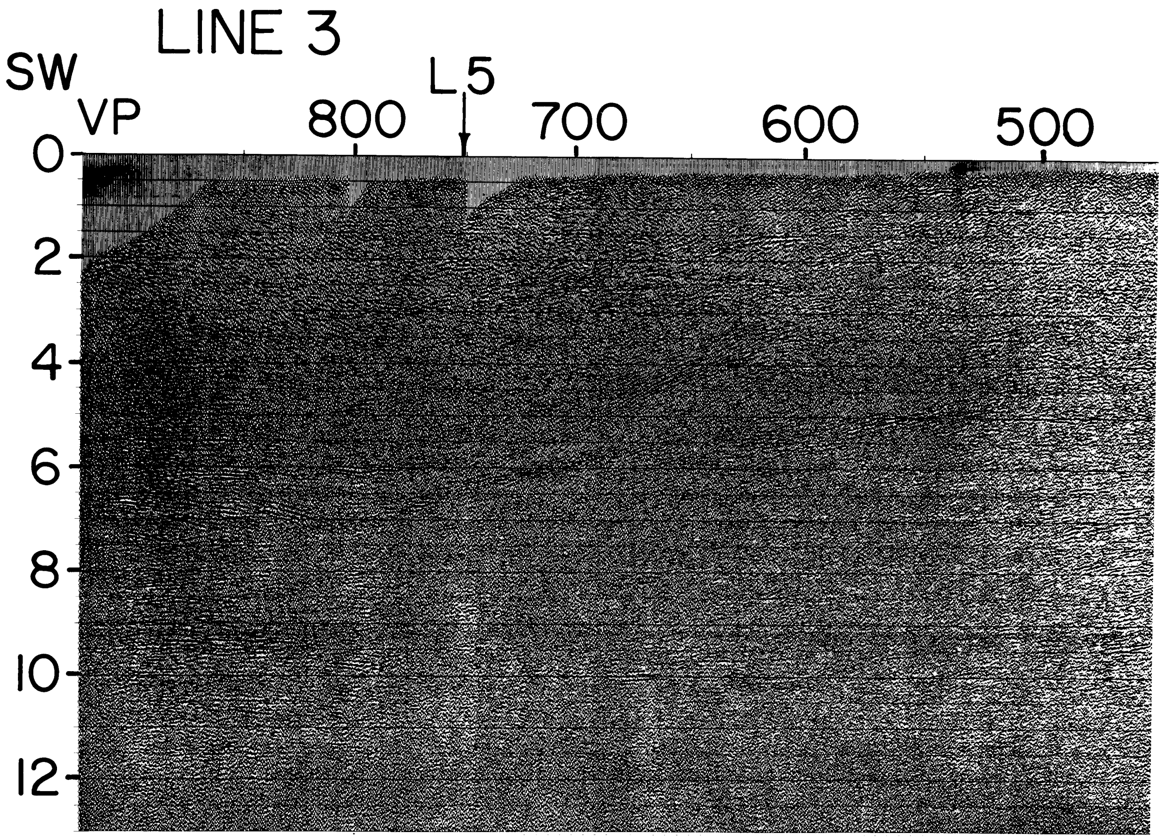

Fig. 6. Line 3, stacked section of the entire line, top 13 s of data only.

808 to 755 (F3), VP's 595 to 525 (F4), and VP's 440 to 350 (F5). The bend in line 3 at VP 360 (Figure 2) provides three-dimensional control which confirms that segment F5 is horizontal; therefore, it seems reasonable to suggest that the other two segments with no apparent dip (F3 and F4) may also be horizontal. Crossline control provided by line 5 shows that segment F1 dips at approximately 30° to the south-southwest and implies that F2 dips at approximately 26° to the south-southwest (assuming that both F1 and F2 have the same strike). As there is no evidence for large upper crustal velocity variations above horizon F which might explain its apparent shape, the horizon is interpreted to exhibit a large-scale "ramp and flat" geometry. Furthermore, it seems too regular to be a folded, originally more planar horizon. Ramp and flat geometry is commonly shown by the thrusts of foreland thrust belts [Dahlstrom, 1970] and is not considered to be characteristic of batholithic contacts. Consequently, the geometry of horizon F suggests that the horizon consists of a series of reflections from a crustal penetrating fault zone. The dip of the ramps (segments F1 and F2) implies that the fault zone is either a north-northeast vergent thrust fault or a south-southwesterly dipping extensional fault.

Since events F6 (VP 300 to VP 150, line 3) and F7 (VP 50 to VP 10, line 3) occur along the northeastward projection of segment F5 (Figure 3) at a similar two-way travel time, they are interpreted to be reflections from the northeastern continuation of this fault zone. Event F8 on the northern end of line 2 (VP 320 to VP 400) and on the southwestern end of line 3 (VP 830 to 890) occurs at the same two-way travel time as segment F3 and may also be from the inferred fault zone. These correlations suggest that the fault zone is traceable over approximately 100 km of the survey and therefore appears to be a major crustal feature.

The presence of such a structure, extending from depths of 9 to 22 km, has significant ramifications for the deep

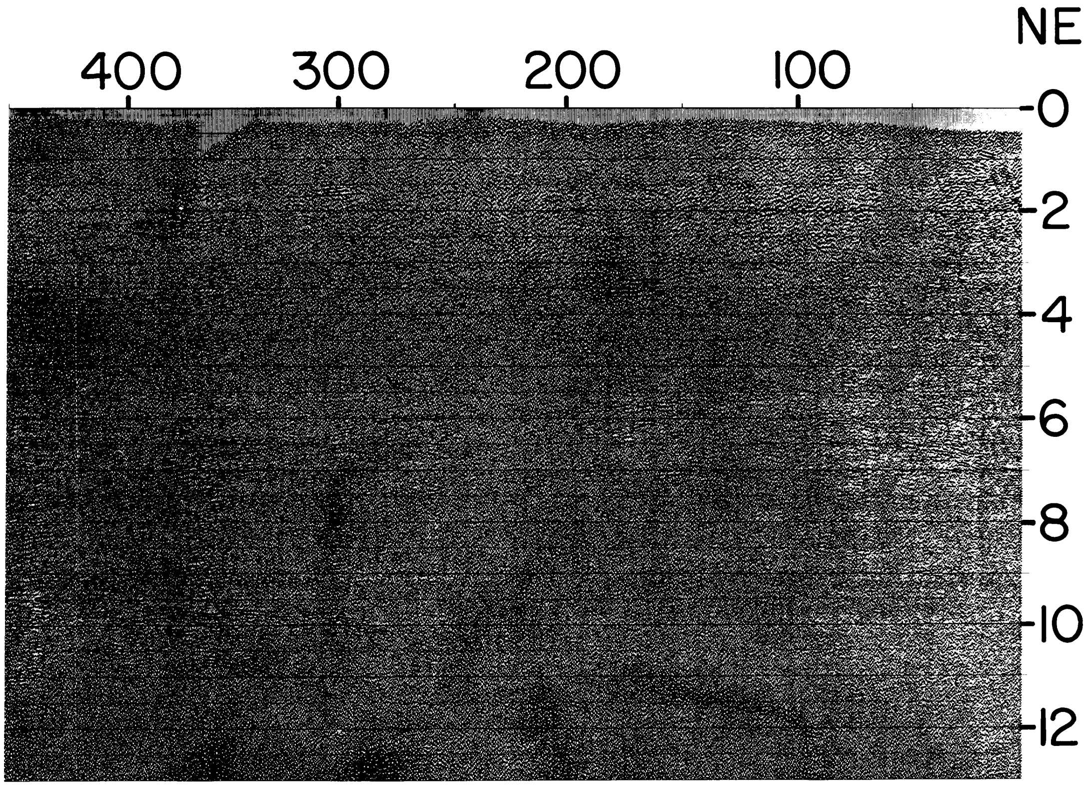

Figure is shown at the same scale as the line drawings in Figure 3.

structure of the crust of the northern Mojave block. If the flats are layer parallel [e.g., Elliott and Johnson, 1980], it may be inferred that the crust in this area is inhomogeneous, consisting of subhorizontal, interlayered competent and incompetent rocks. Some regional geologic models hypothesize a suture between two different crustal blocks [Haxel and Dillon, 1978; Vedder et al., 1983; Mukasa et al., 1984] in the region where horizon F occurs. However, the regular ramp and flat geometry of this structure would perhaps not result from the juxtaposition of two highly irregular crustal blocks.

Above horizon F on line 3 is horizon G, a less extensive horizon which extends from VP 900 at 6.2 s (19 km) to VP 560 at 3 s (9 km), (Figures 3, 6 and 7). Horizon G has a ramplike geometry similar to horizon F, and the migrated section (Figure 7) suggests that it truncates the short event H below VP 620 at 4 s (12.0 km). These geometrical relationships and the fact that crossline control by line 5 shows that horizon G has a similar strike to horizon F (Figure 3), suggest that horizon G is a related fault zone.

On the northeastern half of line 3, below horizon F, is an arcuate zone (I in Figure 3; also see Figure 6) of numerous short, discontinuous reflections. Zone I has a maximum duration of 0.5 s and a more diffuse character than the other horizons on line 3. It is visible below VP 1 at 7 s (22 km), and rises up to 5.5 s (18 km) below VP 150, just north of the Garlock fault. South of the Garlock fault, zone I gently descends to 6.5 s (20 km) below VP 340, where it merges with an upwardly convex wedge of reflections which extends down to 8-9.5 s (26-30 km) between VP's 450 and 600. This wedge of reflections terminates above a series of horizontal Moho-depth reflections (M in Figure 3). The bend in line 3 at VP 360 (Figure 2) allows an average local dip of 28° southwest to be calculated for the wedge.

The same wedge of reflections is visible on wide-angle seismic reflection data collected by the COCORP Extended Research Program (CERP) Mojave survey south of the

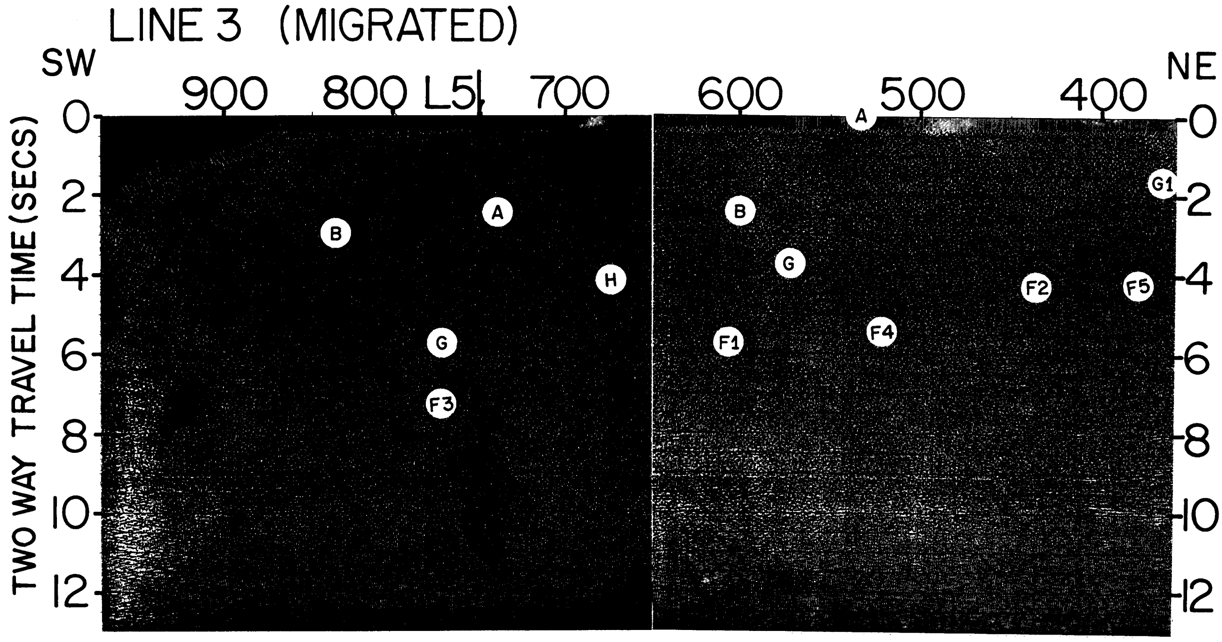

Fig. 7. Line 3, migrated section, VP's 350-980, top 13 s of data. Lettered reflections are discussed in text. Figure is shown at the same scale as the line drawings in Figure 3.

Rand Mountains [Roy Chowdhury et al., 1983]. These data were recorded in-line, 70 km to the south of VP 360 on line 3 (Figure 2) from the same vibration signals generated during the course of shooting COCORP line 3 (VP's 271-368). The CERP data show that the wedge has an apparent dip of 35° to the south in the area just south of VP 360 on line 3 (Figure 2), which is consistent with the form of the wedge seen on line 3. The convex-upward curvature of the wedge of reflections is suggestive of diffraction tails. Three-dimensional control is insufficient for detailed three-dimensional migration. However, after two-dimensional migration, the wedge maintains the same overall form. Horizon I and the wedge of reflections may originate from a major lithological discontinuity, for example from the top or bottom of a major intrusion [Lynn et al., 1981], or they may represent a complex fault zone.

Other distinct horizons are also visible on the seismic sections, but their equivocal form and limited extent make them more difficult to interpret. The zone of numerous events, J on line 4 (VP 140 at 5.6 s (18 km), to VP 300 at 4 s (12 km)) and on line 2 (VP 50 to VP 150 at 4 s (12 km)) consists of a series of interfering events which appear to have hyperbolic curvatures (Figures 3 and 8). Some of these events may be diffractions from out of the plane of the section; however, the most prominent event (K1) of zone J on line 4 (Figure 8) projects across an area (VP 80 to VP 150) of low signal-to-noise ratio to event K2 (VP 1 to VP 80 at 7 s, or 22 km) and hence is long enough to eliminate the possibility that it is a diffraction tail. The crossline control provided by line 2 suggests that K1/K2 dips to the west-southwest at approximately 25°.

Three-dimensional extrapolation of horizon K1/K2 calls attention to events K3, K4, and K5, which have dips and two-way travel times that are consistent with their forming part of horizon K1/K2 (Figure 3). Horizon K1/K2 is relatively isolated from the other prominent horizons and does not have a diagnostic geometry such as the ramps and flats of horizon F. However, the horizon does extend over 60 km of the survey and is structurally higher than horizon F (Figure 9). Horizon K1/K2 may represent a lithological boundary such as the bottom or top of a batholith [Lynn et al., 1981] or may represent a tectonic structure, possibly related to horizons A, B, F, and G.

Some of the horizons previously discussed (F, G, K) extend into, but are not

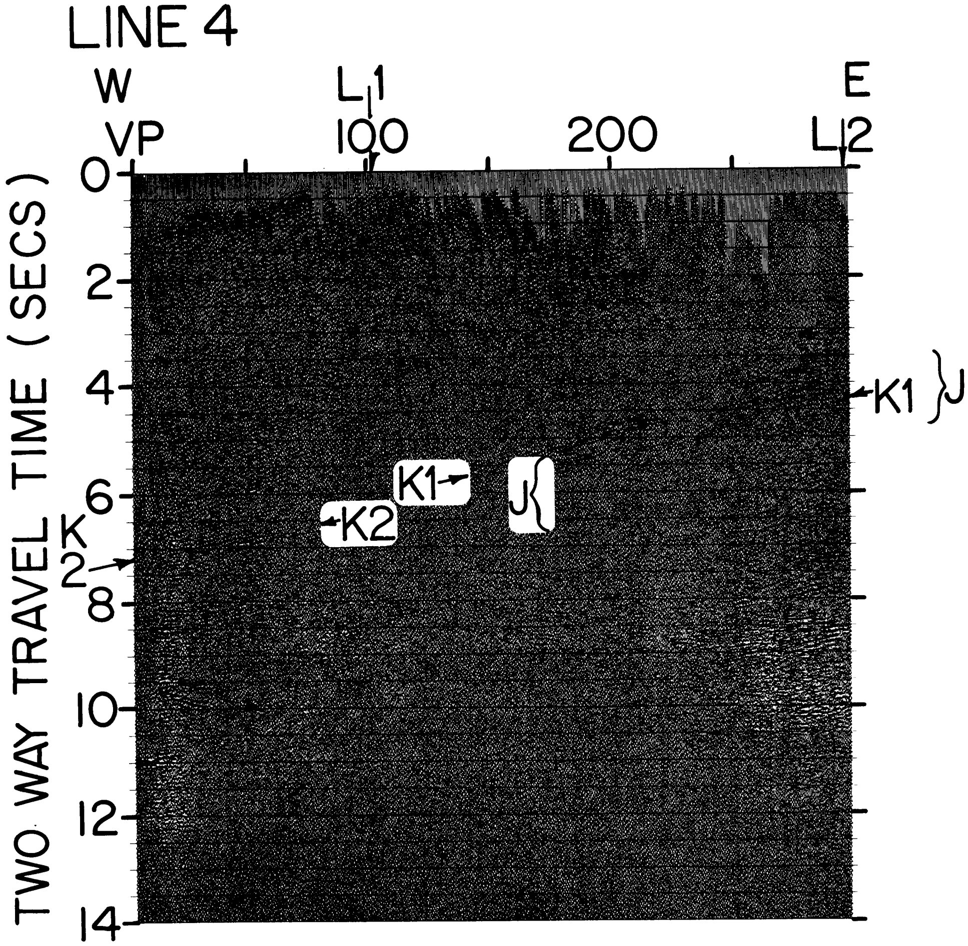

Fig. 8. Line 4, stacked section of the entire line, top 14 s of data only. Lettered reflections are discussed in text. Shown at the same scale as the line drawings in Figure 3.

traceable through, a vertical zone of numerous diffractions and reflections on the western end of line 3 (VP 820 to 948) and on the northern end of line 2 (VP 320 to 410) (see Figure 3). This vertical zone may represent a region of extreme geological complexity within the crust of the Mojave Desert. It may correlate eastward with a similar, though less distinct vertical zone on line 5 (VP 50 to 120) (Figure 3), across which reflection continuity is disrupted.

Lines 1, 2, 5 and 6, all north-south trending lines, show a series of deep (8 to 16 s), northward dipping (35°) events which appear to extend from the lower crust into the mantle with constant dip (L1, L2, L3, L4, L5, Figure 3). The average velocity difference between the crust and the upper mantle (about 1 km/s) determined from refraction studies [Roller and Healy, 1963; Prodehl, 1979] should cause an apparent change in the dip of these events if they are in fact reflections from within the plane of the section. Since the events maintain constant dip and do not all migrate (two-dimensional) to above 10 s (the approximate two-way travel time corresponding to Moho depths), they cannot be reflections from within the plane of the section and may be sideswipe or reflected refractions. Without more three-dimensional control, the origin of these events cannot be determined; however their orientations eliminate the Garlock, San Andreas, or San Gabriel faults as a source of sideswipe.

Moho Depth Reflections

The presence of numerous reflections between 8.5 and 10 s two-way travel time

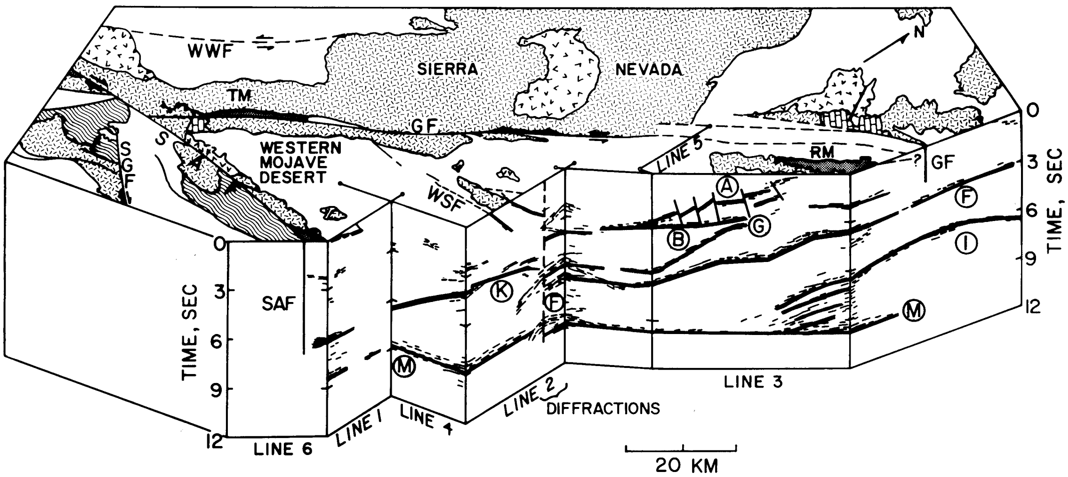

Fig. 9. Summary block diagram showing major interpreted features of the Mojave survey. Abbreviations: GF, Garlock fault; SAF, San Andreas fault; SGF, San Gabriel fault; WSF, Willow Springs fault; WWF, White Wolf fault. RM, Rand Mountains; THM, Tehachapi Mountains; A and B, Rand thrust and related horizon; M, Moho; F, G, I, and K, middle and deep crustal horizons. Dotted pattern, Rand-Tehachapi Schist; wavy pattern, Precambrian rocks; brick pattern, Paleozoic sediments; v pattern, Tertiary volcanic and sedimentary rocks; dashed pattern, Mesozoic granites.

(28-33 km) is a conspicuous feature of much of the Mojave data. These reflections are aligned and mostly horizontal. They occur as both individual reflections and as packets of reflections of up to 1 s duration. The reflections define a discontinuous horizon M (Figure 9) which is also horizontal, a feature which distinguishes M from the predominantly southwesterly dipping horizons previously discussed. Horizon M is the deepest prominent horizon revealed by the survey. For consistency, the position of horizon M will be referred to the bottom of each of the individual reflections or packets of reflections which comprise it.

On the northern part of the survey, horizon M occurs at approximately 10 s two-way travel time (33 km) and, although discontinuous, can be traced along line 3 from VP 280 to VP 960 into the vertical zone of numerous reflections (described previously) on the northern end of line 2. South of this vertical zone, horizon M occurs between 8-9 s (26-29 km), extending across the rest of line 2 and as a weak zone across line 4. "Panels" of numerous "ringing" events (discussed earlier) partially obscure horizon M on either end of line 4. An event on line 1 at 8.5 s (28 km) (M1) may also be correlated with horizon M, suggesting that the horizon extends beneath most of the Mojave survey area (Figure 9).

The change in two-way travel time to horizon M, from 9.5-10 s on line 3 to 8.5-9.0 s on the southern part of line 2 (Figure 3), occurs below the vertical zone of numerous reflections and diffractions previously discussed (VP's 320 to 410 on line 2). Average crustal velocities calculated from the reflection data are well constrained at upper crustal levels and show little variation across the entire survey. Interval velocities are poorly constrained at lower crustal depths because of the relatively short receiver spread length used by the COCORP survey. However, a 1-s change in the two-way travel time to horizon M, due solely to lower crustal velocity variation would require a change in lower crustal velocity of approximately 2.0 km/s. Such a velocity variation is both unlikely and incompatible with the range of lower crustal velocities calculated from the available refraction data [Roller and Healy, 1963; Hadley and Kanamori, 1977; Prodehl, 1979]. Therefore this change in travel time to horizon M appears to represent a real change in depth. The occurrence of the Moho offset below the vertical zone of numerous diffractions and reflections raises the possibility that an apparently

TABLE 3. Moho Depth from Seismic Refraction Experiments in the Mojave Desert

Experiment	Author(s)	Depth to Moho, km	Approximate Two-Way Vertical Reflection Travel Time Calculation From the Refraction Models, s
USGS Lake Mead to Santa Monica Bay	Roller and Healy [1963]	26-30 (central Mojave Desert to Lake Mead)	8.7-9.4
USGS Lake Mead to Santa Monica Bay	Prodehl [1979]	35-29 (eastward shallowing)	13.2-9.7
USGS Mojave to Barstow	Prodehl [1979]	30-31 (westward shallowing)	9.7-10.3
USGS Barstow to Ludlow	Prodehl [1979]	31-29 (eastward shallowing)	10.7-9.4
USGS China Lake to Santa Monica Bay	Prodehl [1979]	37-31 (northward shallowing)	13.8-10.7
USGS Ludlow to Nevada Test Site	Prodehl [1979]	28-35 (southward shallowing)	9.9-11.7
Caltech Network Mojave Desert	Hadley and Kanamori [1977]	34-30 (eastward shallowing)	10.5-9.6

Two depths, corresponding to the beginning and end of the line, are given where the Moho is interpreted to be dipping. The two-way travel times correspond to these depths.

near vertical crustal-penetrating feature, perhaps a major fault, exists near the northern end of line 2 in the vicinity of the town of Mojave.

Horizon M occurs at depths appropriate for the crust-mantle transition as defined by seismic refraction experiments across the Mojave Desert [Roller and Healy, 1963; Hadley and Kanamori, 1977; Prodehl, 1979], which suggest Moho depths of 26 to 32 km (see Figure 10 for the locations of the refraction surveys). Vertical, Moho two-way travel times calculated from the refraction models within the Mojave Desert range from 8.7 to 10.7 s (Table 3), and are broadly consistent with the range of times recorded by the COCORP survey to the base of horizon M (8.5-10.5 s). In fact, the Moho itself may correspond to the base of horizon M, as noted in other seismic reflection surveys [Barton et al., 1984]. The zone of reflections which comprise horizon M may represent a transitional crust-mantle boundary, possibly similar to that reported by Meissner [1973] on seismic reflection profiles recorded in Germany. Some of the local differences between two-way travel times to the Moho calculated from the refraction models and from the COCORP data may result from the problems of interpreting refraction data in regions of variable crustal thickness. For example, the USGS China Lake to Santa Monica Bay refraction experiment extends across three separate provinces of different crustal thicknesses: the Transverse Ranges, the Mojave block, and the Basin and Range Province [Prodehl, 1979]. Thus, it is perhaps not surprising that it predicts a slightly deeper Moho than that suggested by the COCORP survey (Table 3; Figure 10).

The reflection character of horizon M varies over the length of the survey. On line 4 the horizon is a weak multicyclic zone spanning over 1 s (VP's 50 to 220), whereas on line 3 (VPS 500-800) the horizon is less pronounced, or even absent (Figure 3). These lateral changes may be caused by varying attenuation within the overlying crustal material; however, some of this lateral variation may represent the variable nature of the crust-mantle boundary [Herzberg et al., 1983].

Reflections from similar depths (9.9 s, or about 32 km) recorded by Dix [1965] in the southeastern Mojave Desert (Figure 10) may also be from the crust-mantle transition. The widespread presence of horizon M on the Mojave COCORP survey, and the

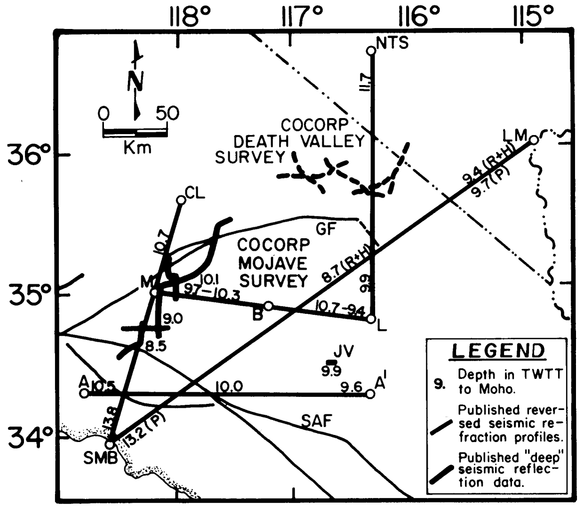

Fig. 10. Schematic map of the Mojave region showing seismic reflection and refraction lines. Numbers refer to the two-way vertical travel times, in seconds, to the Moho at that part of the reflection or refraction line. Where there are two published models for the same refraction survey, R & H indicates time determined from the model of Roller and Healy [1963], P indicates time determined from the model of Prodehl [1979]. Shot point localities are in bold type: B, Barstow; CL, China Lake; JV, Johnson Valley; L, Ludlow; LM, Lake Mead; M, Mojave; NTS, Nevada Test Site; SMB, Santa Monica Bay. A, A' mark the epicenters of earthquakes used by Hadley and Kanamori [1977] for their refraction profile. GF, Garlock fault; SAF, San Andreas fault.

presence of reflections from a similar depth on Dix's survey, suggest that the crust-mantle transition is a good reflector beneath the Mojave block.

A number of events occur near horizon M, but the relationship between these adjacent events and M is difficult to interpret. Some of the adjacent events occur below M, for example N on line 3, and O on line 4 (Figure 3), whereas others occur above M, specifically, the wedge of reflections of horizon I on line 3 (Figure 3). The events which occur below horizon M are of limited extent and cannot be three-dimensionally constrained by the seismic data, hence they may be "sideswipe" from shallower structures.

Migration shows that the south-dipping wedge of reflections that forms part of horizon I (line 3), extends toward, but does not cross the approximately flat-lying horizon M (a similar relationship between the lower crust and the upper mantle has been observed across the southern Indian craton [Roy Chowdhury and Hargraves, 1981]). The discordance between horizons M and I and the apparent termination of horizon I raises the intriguing possibility that horizon M is younger than I. Such a geometrical relationship may be explained by (1) movement of the crust of the Mojave block relative to the mantle on horizon M, (2) transformation of old crust into new mantle, obliterating deep crustal structures below horizon M, or (3) simply that horizon I does not extend to Moho depths.

Horizon M cannot be traced further than VP 280 on line 3 although horizon I (Figure 3) continues further to the north. The absence of horizon M from VP 280 to VP 1 on line 3 appears to be unrelated to horizon I. Moho-depth reflections at similar two-way travel times are also recorded on the COCORP Death Valley survey, 50 km to the northeast of line 3 [DeVoogd, in press, 1985], suggesting that the absence of Moho-depth reflections on the northern end of line 3 may not be significant.

The San Andreas Fault Zone

The COCORP Mojave Survey traverses the San Andreas fault zone in the north-central Transverse Ranges, where it changes direction from its usual N40°W trend to a N75°W trend to form the "Big Bend" (Figure 1). Line 6 crosses the fault 15 km west of Lancaster and runs from north of the Hitchbrook fault (VP 1), across the San Andreas fault zone, then southwest to San Francisquito Canyon (VP 432, Figure 2). No fault plane reflections are recognized on the seismic section; however, the presence of a fault zone is perhaps indicated by the apparent termination of reflections K5, P and Q (line 6, Figure 3) just to the north of the surface expression of the San Andreas fault zone (VP 118).

Event Q (line 6) occurs at 2.2 s (6 km) and extends from VP 1 to VP 100 (Figure 3). It is weak and discontinuous and is offset 0.4 s to 1.8 s below VP 50. This event correlates with event Q1 on line 1, which occurs at a similar depth (2 s) where the two lines cross (Figure 3).

A more pronounced event on line 6 (P on Figure 3) occurs at 3.6 s. This doublecycle event, between VP 1 to VP 70, is also visible as a multicyclic event on line 1 (VP 210 to VP 260, P1 in Figure 3). The multicyclic character of event P1 is interpreted to be an artifact, because the principle character of the vertical zone in which it occurs (VP 210 to VP 240), is very similar to the 'panels' of numerous ringing events discussed earlier. Calculation of a true dip of 35° northwest for the reflector from which events P and P1 originate suggests that the events have a large component of "sideswipe." Anomalously low stacking velocities of 3.8 km/s for P further suggest that the reflections are "sideswipe" from a relatively shallow reflector. The reflector probably lies beneath Portal Ridge, 6 km to the southeast of VP 1 on line 6, and does not extend beneath the surface trace of the San Andreas fault. It may be a low-angle fault splay related to the San Andreas fault zone, or alternatively, may represent structure within the Pelona Schist of Portal Ridge.

Event K5 on line 6, at 6 s (20 km), has already been correlated with horizon K. It also does not extend southwest of approximately VP 60.

No major reflections are visible to the south of the San Andreas fault zone on line 6, although short lineups are present on some of the shot point gathers recorded along this line. This lack of major reflections may be due in part to the complex geometry of line 6 (part of which was shot off-line due to adverse weather), and/or to the extreme structural complexity of the basement of the San Gabriel Mountains over which the southern part of line 6 was shot. However, the apparent terminations of events P, Q, and K5 north of VP 100 suggest that the San Andreas fault zone extends down to at least 20 km without an appreciable northeasterly dip.

The Garlock Fault

The Garlock fault, first recognized by Hess [1910], is a major east to northeast trending sinistral strike-slip fault at least 265 km long, which forms the boundary between the Sierra Nevada and Basin and Range terranes and the Mojave block (Figure 2). The fault consists of two segments, a northeasterly trending western segment, and a more easterly trending eastern segment. These two segments overlap in the vicinity of Koehn Lake forming the Cantil Valley pull-apart basin [Clark, 1973; Aydin and Nur, 1982]. Up to 64 km of left-lateral strike slip displacement has been recognized on the eastern segment of the fault [Smith, 1962; Smith and Ketner, 1970; Davis and Burchfiel, 1973]. However, less is known about the total displacement on the western segment [LaViolette et al., 1980]. The COCORP survey crosses the Garlock fault twice. Line 5 crosses the western segment at the southeastern end of the Cantil Valley (VP 340), and line 3 crosses the eastern segment to the northeast of Randsburg (VP 220) (Figure 2).

Displacement of a strike-slip fault, such as the Garlock fault, will create an apparent vertical offset on any dipping horizon which it cuts if that horizon has a strike which is not parallel to the strike of the fault. Therefore, the depth, extent and geometry of the mid-crustal horizons F and I (previously discussed) which pass under the surface trace of the Garlock fault (Figures 3 and 6) together with the known left-lateral offset on the fault itself, place constraints on the maximum depth to which the central portion of the fault extends. The horizons F (3.3 s) and I (5.8 s) extend below the surface trace of the Garlock fault on line 3 (Figure 3) and are traceable for approximately 100 km and 50 km, respectively (Figure 9). If the occurrence of reflections F6 and F7 along the projection of horizon F (Figure 3) is fortuitious and the reflections are unrelated, then the Garlock fault may dip southwards to approximately 20 km depth, merging into the dipping reflections of horizon I (Figure 3). The Garlock fault would therefore be a deep crustal feature. However, as discussed earlier, it is more likely that reflections F1-F8 are from a continuous structural horizon and therefore constrain the depth of the Garlock fault. The geometries of horizons F and I, as shown by lines 3 and 5, are complex with both horizons having a component of dip parallel to the Garlock fault. Based on the projection of event F1 on line 5 to the inferred vertical trace of the Garlock fault, horizon F has an average dip of 11° parallel to the Garlock fault. The absence of horizon I on line 5 and its apparent dip on line 3 suggests a dip of at least 16° parallel to the Garlock fault for this horizon. The ages of horizons F and I are not known and consequently some displacement on the Garlock fault may have occurred prior to their formation. However, Carter [1982] has suggested that about 43 km of the total displacement of approximately 64 km on the eastern segment of the fault has occurred since Middle Pliocene time. Assuming that horizons F and I are older than Pliocene in age (a reasonable assumption considering the tectonic history of the region [Burchfiel and Davis, 1981], and assuming that there is no large component of dip-slip displacement on the Garlock fault, the 43 km of left-lateral displacement on the Garlock fault should yield a 2-s (6 km) apparent vertical offset of horizon F, and 3-4 s (10-13 km) apparent vertical offset of horizon I. No such large offsets are observed for these horizons (Figures 3 and 6). In fact, the maximum apparent vertical offsets allowed by the discontinuous nature of the horizons is of the order of 0.4 s (1.5 km), implying that the Garlock fault in the vicinity of Randsburg is a relatively shallow feature confined to the upper 9 km of the crust.

The behavior of faults at depth is poorly understood, and it is possible that displacement on the Garlock fault may be distributed over a large area by brittle deformation and/or ductile flow. If the displacement were distributed over a large area, a significant change in depth to horizons F and I, albeit a more gradual one, would still result.

The distribution of microearthquake hypocenters (M_L<5.5) in California suggests that the transition from frictional to quasi-plastic behavior in quartz-bearing crust (defined as the depth above which 90% of the microearthquakes occur) occurs at around 10 km in areas of high to normal heat flow [Sibson, 1982] such as the Mojave Desert region. The eastern segment of the Garlock fault is relatively aseismic compared to the western segment of the fault [Astiz and Allen, 1984]. However, the seismicity is comparatively high in the vicinity of the Cantil Valley, where the COCORP survey crosses the surface trace of the fault. Astiz and Allen [1984] report that all seismic events within a 25 km wide zone centered on the Garlock fault occur above 15 km depth and 90% occur above 9 km (L. Astiz, personal communication, 1983).

The actual geometry of the Garlock fault at depth is unknown; however, it is possible that the fault extends vertically down to 9 km and terminates at horizon F. Horizon F, or at least the part of it to the north of the Garlock fault, may therefore be a low-angle detachment above which extension is occurring within the Basin and Range Province [e.g., Stewart, 1983; Burchfiel et al., 1983]. This would require that horizon F originated as an older structure, possibly a thrust, that has been reactivated north of the Garlock fault since the Middle Pliocene [Cheadle et al., 1986].

Problematic Events

Several events of limited lateral extent from different crustal levels have not been discussed in the preceding sections, for example R on line 3 and S on line 2 (Figure 3). These events are too short or too isolated to be easily related to any of the major horizons described. Some of these short events may be segments of additional, more continuous horizons which have low impedance contrasts and hence are not imaged well; for example, event G1 on line 3 could correlate with horizon G on the same line (Figure 3). Alternatively, the short events may be a combination of reflections from older structures, both lithologic and tectonic, which have been disrupted by the later and now more continuous structures, and sideswipe from complex younger structures.

TECTONIC IMPLICATIONS

Figure 9 is a schematic block diagram which shows the major features of the Mojave survey and their relationship to the known bedrock geology of the region. The bands of reflections (horizons A, B, F, G, I, K, and M) and the vertical discontinuity described in the earlier sections of the paper are readily visible. Apart from horizon A, which can be traced nearly to the surface and which is inferred to be the Rand thrust, and horizon M, which can be correlated with the Moho as defined by refraction experiments, the identities of the horizons are speculative.

The relationship of horizon B to horizon A and the geometries of horizons F and G suggest that they are tectonic in origin. Unlike horizons A and B, horizons I and K have no characteristic geometry and may represent lithological or tectonic discontinuities.

In this section three tectonic models (Figure 11) based on the results of the COCORP survey and on the current geological knowledge of the region are pre-

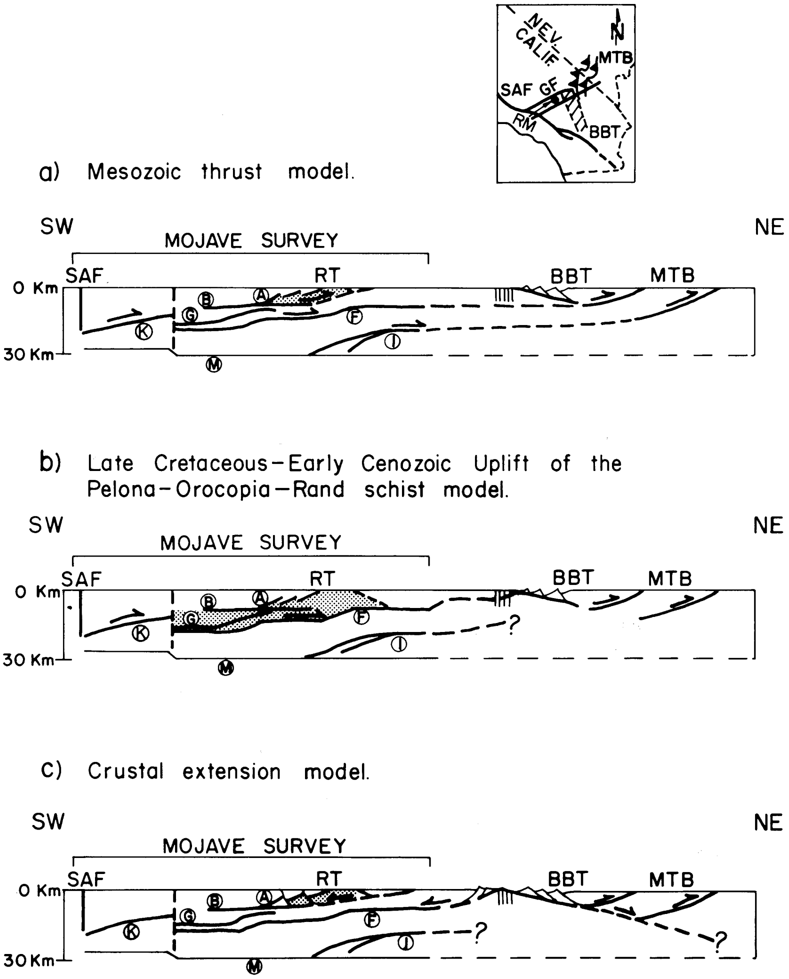

Fig. 11. Summary cross sections of three possible models for the horizons visible on the COCORP Mojave sections. Inset map shows location of cross sections. Abbreviations: BBT, Barstow-Bristol Trough; GF, Garlock fault; M, Moho; MTB, Mesozoic thrust belt; RM, Rand Mountains; RT, Rand thrust; SAF, San Andreas fault; dotted pattern, Rand Schist. Letters refer to major horizons in text. In both models 2 and 3, the shading represents the minimum extent of the schist. The crust below the shading may or may not consist of Pelona-Orocopia Schist.

sented. All three models assume a complex structural history for the Mojave Desert region which involved at least two compressional events (Mesozoic thrusting, and the Late Cretaceous to Early Cenozoic metamorphism and emplacement at depth of the Pelona-Orocopia-Rand Schist) and an early Miocene extensional event. The mechanism of uplift of the Pelona-Orocopia-Rand Schist is poorly constrained and may be related to an additonal early Cenozoic compressional event. The models differ concerning which structural episodes caused the features observed on the seismic profiles, and thus, on the relative importance and timing of thrusting and extension.

Mesozoic Thrusting

The mid and lower crustal horizons (F, G, I, and K in Figure 9) may represent the root zone of the system of Mesozoic thrust faults which extendinto southern Nevada and southeastern California. Burchfiel and Davis [1981] summarized the temporal and the spatial relationships of the component thrust faults in this part of the Cordilleran orogen. The compressional deformation ranges in age from Triassic to Late Cretaceous with the last major deformational event being represented by the early Late Cretaceous Keystone-Muddy Mountains thrust system of southern Nevada [Sutter, 1968; Fleck, 1970].

Most of the Mesozoic thrust faults in the eastern Mojave Desert are east-vergent and are mapped in granitic and crystalline rocks. Hence the thrusts would be expected to have originally extended westward into the Mojave block, possibly in the manner suggested in Figure 11a. Assuming that the Rand Schist correlates with the Pelona-Orocopia Schist, the Mesozoic thrust model requires that the protolith of the Schist was metamorphosed, at depth, to the west of the Mojave Desert region (outside the COCORP survey) and that the Schist was overthrust along horizon B above the older Mesozoic thrusts in a relatively thin-skinned manner (Figure 11). The more continuous form of the Mesozoic thrusts relative to the Rand thrust may be explained by faulting of the Rand thrust during overthrusting or by shallow, late Cenozoic deformation which affected the Rand thrust, but did not affect the deeper Mesozoic thrusts.

Late Cretaceous-Early Cenozoic Uplift of the Rand-Pelona-Orocopia Schist

Despite an age of at least 160 Ma for the protolith of the Pelona-Orocopia Schist [Mukasa et al., 1984], the emplacement and metamorphism of the schist below the Vincent thrust system occurred after 80 Ma and probably between 50 and 60 Ma ago based on ages obtained from upper plate rocks, from the schist and from mylonites in the thrust zone [Carter and Silver, 1971; Ehlig et al., 1975; Conrad and Davis, 1977]. The Rand-Tehachapi Schist may have been metamorphosed and emplaced beneath Late Cretaceous granites [Silver et al., 1984] somewhat earlier, prior to the intrusion of minor granites, dated at 74.8 Ma [Kistler and Peterman, 1978] and 73 3 Ma [Silver et al., 1984], into the Rand Schist. However, despite this discrepancy in the ages of metamorphism and emplacement, the Pelona-Orocopia Schist and the Rand-Tehachapi Schist are still believed to be correlative based on similarities of lithology [Ehlig, 1968; Haxel and Dillon, 1978].

In Figure 11a the major horizons (F, G and possibly I and K) are interpreted to be thrusts related to the uplift of the Rand Schist to high crustal levels. Both the Rand thrust, and the Rand Schist below it, are interpreted to have been uplifted by displacement on horizon F and thus the antiformal outcrop of the Rand thrust may be explained as a ramp anticline. This model implies that the deformation related to the uplift was "thick skinned," affecting most of the crust in the region of the survey. Indeed the similarity between anomalous K-Ar [Ehlig et al., 1975; Miller and Morton, 1980] and $^{40}Ar/^{39}Ar$ dates [Miller and Sutter, 1982] which may represent uplift ages over large parts of the region [Frost and Martin, 1983] and the age of metamorphism of the protolith of the Pelona-Orocopia Schist [Ehlig et al., 1975; Conrad and Davis, 1977], suggest that the metamorphism and uplift of the schist may be related to one structural episode. Alternatively, the event which led to the metamorphism of the protolith of the schist may be distinct from the uplift event. In this case model 2 is irrelevant to the question of how the protolith was emplaced at depth.

No reflections are seen from the Portal Ridge (Figure 2) Schist body [Dibblee, 1967; Haxel and Dillon, 1978], perhaps because of its close proximity to the San Andreas fault. This body may be a sliver of Pelona-Orocopia Schist caught up within the San Andreas fault and is therefore not depicted in Figure 11. In addition, the origin of the protolith of the Rand, and hence of the Pelona-Orocopia-Rand Schist, is not constrained by the structures seen on the seismic sections and any of the numerous models for its origin may be relevant. Thus the protolith of the Schist may have originated in a back arc, intra-arc, pull-apart, or rift-basin [Ehlig, 1968; Haxel and Dillon, 1970; Mukasa et al., 1984; Tosdal et al., 1984], or in a deep ocean basin [Vedder et al., 1983; Mukasa et al., 1984] or represent underthrust Franciscan material [Crowell, 1968, 1981; Yeats, 1968a, b; Burchfiel and Davis, 1981]. Regardless of which model for the protolith's origin is accepted, the schist was clearly involved in a major Late Cretaceous to Early Cenozoic period of eastward directed overthrusting according to the model 2 interpretation.

It is possible that events later than those considered in models 1 and 2 have affected the Mojave Desert region and are responsible for some or all of the major structures visible on the seismic data. One such event is the Early to Mid-Cenozoic, major west-directed thrusting proposed by Silver [1982, 1983] on the basis of the geochemical, geochronological and tectonic stratigraphy of southern California. However, the ramp and flat geometry of horizon F and the southwesterly dips of the other major horizons visible on the COCORP seismic sections do not support Silver's model, which predicts southeasterly dipping thrusts.

Crustal Extension

Model 3 (Figure 11c) offers another possible interpretation of the structures visible on the Mojave survey, in which horizon F and possibly horizon B are low-angle normal faults which formed during an intense period of extension that affected the Mojave block during the early Miocene (23-20 Ma). This period of extension has been documented by Dokka, [1980], who recognized part of a regionally developed extensional fault complex in the Newberry Mountains of the east-central Mojave Desert.

The extension was dominantly to the northeast (N 50°, E). However, in the Bullion Mountains southeast of the Newberry Mountains (Figure 2) extension was apparently bidirectional [Dokka 1980], with movement occurring both to the northeast (N 50°, E) and to the southwest (S 50°, W). This distribution of extension directions implies that a low-angle normal fault underlying these mountains should be antiformal in nature, dipping both to the northeast and southwest.

The mapped extensional terrain is located 100 km to the southeast of the COCORP survey (Figure 2). It occurs within the Barstow-Bristol trough (Figure 2), a northwest-trending belt of Miocene and Pliocene volcanic and sedimentary rocks [Gardner, 1980; Glazner, 1981]. Dokka and Glazner [1982] identified this trough with the surface expression of the extension, which allows the extensional complex to be extrapolated along strike to within a few kilometers of the COCORP survey (Figure 2). This extrapolation and the crustal-penetrating detachment hypothesis of Wernicke [1981] form the basis of model 3.

If the Barstow-Bristol trough represents the axis of a bidirectional extension terrain then the detachments may have broad antiformal geometries. This interpretation is supported by Dokka's [1980] observations in the Bullion Mountains, and such an antiformal geometry is analogous to that postulated for the Snake Range décollement in western Utah by Miller et al. [1983].

In model 3, horizon F is interpreted to be the southwestern limb of a postulated antiformal low-angle normal fault. This limb must lie almost wholly within the granitic basement of the Mojave block, being similar in this respect to the northeasterly dipping detachment mapped by Dokka [1980] in the central Mojave Desert, which also penetrates granitic basement. Although the ramp and flat geometry shown by horizon F is typically considered to be indicative of thrust faults, such a geometry may also be a feature of extensional faults [Dahlstrom, 1970; Allmendinger et al., 1983]. The difference in the dip direction of horizon F (S 15°W) and Dokka's extension direction (S 50°W) may be due to the folded nature of the detachment; similar folding has been mapped by Dokka in the Newberry Mountains.

An extensional model is further supported by the apparent normal faulting of the Rand thrust above horizon B (Figure 4), which suggests that horizon B is a higher level low-angle normal fault. Most of the faults which cut the Rand thrust do not appear to affect horizon B; however, below the Rand Mountains both horizons appear to be cut by possibly later high-angle normal faults or strike-slip faults. High-angle faults have been mapped by Morehouse [1984] and Silver et al. [1984] and may be similar to faults mapped as cutting the low-angle normal faults in the Barstow-Bristol trough [Dokka, 1980].

This model provides no constraints on the uplift of the Rand Schist to shallow crustal levels, nor on the events associated with the high pressure metamorphism of the Schist. Furthermore, some of the horizons, for example G, I, and K, may represent now disrupted structures related to earlier thrusting. The amount of the southwesterly displacement of the upper plate along the detachment is not known, although some of the major westward displacement of the Mojave Desert granitic terrain suggested by Silver [1982, 1983] could be explained by such southwesterly dipping extensional faults.

The regional Miocene extension may be related to the Neogene northward migration of the unstable Mendocino triple junction along the California coast. Dickinson and

Snyder [1979] and Ingersoll [1982] recognized that such an unstable configuration necessitates regional extension in at least one of the surrounding lithospheric plates and that extension in the North American plate is most likely. This suggestion is further supported by the apparent correlation of the migrating Mendocino fracture zone with the onset of bimodal Tertiary volcanism and detachment faulting in the southwestern United States [Glazner and Supplee, 1983].

All of the models require that horizon F was reactivated during the late Cenozoic (Middle Pliocene to Recent) Basin and Range extension as a west dipping detachment to the north of the Garlock fault. It is also possible that horizon F is an entirely Late Cenozoic detachment related to the west-dipping detachments of Death Valley and surrounding areas [e.g., Stewart, 1983]. However, this hypothesis is geometrically more complex, requiring the accomodation of large amounts of Late Cenozoic upper crustal extension north of the Garlock fault, but not to the south. Since the dip direction of horizon F is approximately parallel to the trend of the Garlock fault, horizon F cannot simply be the rooted continuation of the extensional faults to the north of the Garlock fault.

Summary

The three models considered in this section each depict a different structural interpretation and tectonic origin for the major crustal horizons that have been delineated by the COCORP Mojave survey. Since the three major tectonic events upon which the models are based occurred at different times, it is worth emphasizing that the reflection horizons visible on the seismic sections may be the result of the superposition of these three major tectonic events. Some of the shorter horizons may represent disrupted earlier structures.

Of course, the possibility exists that some of the major crustal horizons seen on the seismic sections represent earlier Precambrian or Paleozoic structures. However, it seems reasonable that any such early structure would have been highly disrupted by the complex Mesozoic and Cenozoic events of the region, and that the later overprints are more likely to be preserved.

CONCLUSIONS

COCORP deep seismic reflection profiling in the Mojave block, California, has yielded significant new information on the structure of the Mojave crust and provides an insight into the tectonic evolution of southern California. The major results of the survey are as follows:

1. The seismic character of the crust of the Mojave block is dominated by low-angle, southwesterly dipping, linear bands of reflections which can be traced over large distances, suggesting the presence of numerous, gently dipping, crustal structures.

2. The southern extension of the Rand thrust has been delineated for the first time. It is a complexly faulted, southwesterly dipping, low-angle structure which extends for 25 km southwest of the Rand Mountains, where it appears to be truncated by a younger or possibly coeval structure. Therefore the Rand thrust cannot be traced, at least with these data, throughout the Mojave block.

3. A major southwesterly dipping mid-crustal horizon, F on line 3 (Figure 9), exhibits a well-defined ramp and flat geometry, extends from 9 to 22 km in depth and can be traced for over 100 km from the Basin and Range Province into the northwestern Mojave Desert. The ramp and flat geometry is consistent with either a northeast vergent thrust fault, or a southwesterly dipping, low-angle normal fault.

4. A series of complex, sometimes multicyclic, Moho-depth reflections is visible on the seismic sections at 8-10 s (28-33 km). These events define a horizon which may represent the crust-mantle transition. This horizon occurs at approximately 33 km in the northwest part of the COCORP survey and shallows, relatively abruptly, to about 28 km below the northern end of Mojave line 2, remaining at about 28 km beneath the rest of that part of the western Mojave block covered by this survey.

5. The presence of numerous diffractions and the apparent termination of three of the major horizons (G, I, and K) in a vertical zone above an apparent offset in the crust-mantle transition on line 2 suggests a major vertical crustal penetrating feature, presumably a fault.

6. The apparent termination of a deep crustal structure above the crust-mantle

transition raises the possibility that the crust-mantle transition may be an "active" feature and that either (1) the crust of the Mojave block may have moved laterally relative to the underlying mantle, or (2) an older and deeper portion of the crust has been transformed into new mantle.

7. The San Andreas fault is a major, vertical feature which appears to truncate crustal structures within the Mojave block down to depths of 20 km and does not appear to have an appreciable northeasterly dip.

8. The eastern strand of the Garlock fault in the vicinity of Randsburg is interpreted to be a relatively shallow crustal feature which is confined to the upper 9 km of the crust by the continuous midcrustal horizon seen on Mojave line 3. It does not appear to be a crustal-penetrating fault as has been formerly suggested [Davis and Burchfiel, 1973].

In summary, the COCORP Mojave survey has delineated major dipping, horizontal, and vertical structures within the Mojave block. Many of these features may correspond to Mesozoic or Cenozoic thrusts. However, the presence of extensive, gently southwesterly dipping structures, a well-defined, possibly "young" Moho and a shallow Garlock fault also raises the possibility, subject to confirmation by future studies, that major extensional structures exist within the Mojave block and therefore that the Mojave block may indeed have been the southwestern continuation of the extensional Basin and Range Province.

Acknowledgments. As with all COCORP projects, this paper represents the combined efforts of many individuals both inside and outside the project. We would especially like to thank J. C. Crowell for help with setting up the survey. We would also like to thank C. Allen, L. Astiz, R. K. Dokka, S. L. Klemperer, R. Renner, D. Sarewitz, L. T. Silver, J. Willemin, S. T. Wray and R. S. Yeats for providing preprints and/or helpful discussions of these data and the geology of the Mojave Desert region of California. C. E. Jacobson and B. Wernicke are also thanked for constructive reviews. In addition we would like to thank all of the members of COCORP both past and present. The COCORP project is supported by National Science Foundation grant EAR-82112445. Data collection was carried out by crew 6834 of Petty-Ray Geophysical, a division of Gesource Inc. The data were processsed on the MEGASEIS (trademark, Seiscom Delta, Inc.) computing system of Cornell University. Cornell Department of Geological Sciences contribution 803.

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C. J. Ando, Shell Development Company, P.O. Box 481, Houston, TX 77001.
L. D. Brown, S. Kaufman, and J. E. Oliver, Department of Geological Sciences, Cornell University, Ithaca, NY 14853.
T. Byrne, Department of Geological Sciences, Brown University, Providence, RI 02912.
M. J. Cheadle, Department of Earth Sciences, Cambridge University, Cambridge CB3 OEZ, United Kingdom.
B. L. Czuchra, Tenneco Oil Company, P.O. Box 51345, Lafayette, LA 70505.
P. E. Malin, Marine Sciences Institute, University of California at Santa Barbara, Santa Barbara, CA 93106.
R. A. Phinney, Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544.

(Received August 1, 1984;
revised October 3, 1985;
accepted October 3, 1985.)