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GEOMETRIES OF DEEP CRUSTAL FAULTS: EVIDENCE FROM THE COCORP MOJAVE SURVEY

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Abstract. Several reflecting horizons imaged during deep seismic reflection profiling in the western and northern Mojave Desert are interpreted as fault zones which penetrate the deep crust of that region. The most prominent is a complex, though laterally correlatable midcrustal horizon (9-20 km) which extends over the northern area of the Mojave Survey into the Basin and Range Province and is interpreted to be a major southwesterly dipping crustal fault zone. Its shape resembles ramp and flat geometry, which suggests that deep "faults" in crystalline terranes can have geometries similar to thrusts mapped in foreland thrust belts.

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. The change in two-way travel time to this horizon, the base of which is interpreted to be the Moho, provides evidence for a fault which offsets the Moho.

The COCORP survey also traversed the two major strike-slip faults that bound the Mojave block. The San Andreas fault zone, though poorly constrained by the seismic data, appears to be a major vertical feature separating Mojave basement, with numerous discontinuous reflections down to 30 km depth, from basement to the south, which is devoid of such reflections. Conversely the Garlock fault appears to be a relatively shallow feature, extending to less than 9 km depth, because it does not offset an underlying reflecting horizon.

Introduction

Deep seismic reflection profiling over the continents, in conjunction with earthquake [Sibson, 1982; Chen and Molnar, 1983] and crustal rheological studies [Sibson, 1983; Kusznir and Park, 1984], has begun to provide important information about the geometry and extent of major faults or shear zones at depth. However, many questions still remain: How deep do discrete faults penetrate? What do strike-slip faults look like at depth? Are the "rules of faulting" derived from surface geological mapping in foreland thrust belts [Dahlstrom, 1970; Boyer and Elliot, 1982] applicable at depth?

This paper describes results from the COCORP Mojave survey that pertain to the above questions by discussing briefly the detailed geometry of possible low-angle, intracrustal fault zones in the Mojave block, the possiblity of faults at Moho depths and the depth and geometry of two major strike-slip faults, the San Andreas and Garlock faults. In this paper the term "fault zone" refers to major, low-angle structures imaged by the seismic survey. Whether these structures are brittle faults or discrete ductile shear zones is unclear and cannot be determined from seismic data.

Burchfiel and Davis [1981] reviewed the geology of the Mojave block, which appears to be a predominantly crystalline province dominated by Mesozoic granites which intrude Precambrian crust and overlying Paleozoic cover rocks. The presence within the region of the Pelona-Orocopia-Rand Schist, whose age, origin, and mode of emplacement remain enigmatic [Mukasa et al., 1984; Burchfiel and Davis, 1981], gives an indication of the geological complexity of the Mojave block. Several relatively shallow (1-2 km) Tertiary basins have been superimposed on this older crystalline basement [Dibblee, 1967].

In 1982 the Consortium for Continental Reflection Profiling (COCORP) collected six deep seismic reflection profiles totalling 300 km in length within the Mojave Desert region (Figure 1). The results and processing of this survey are described in detail by Cheadle et al.

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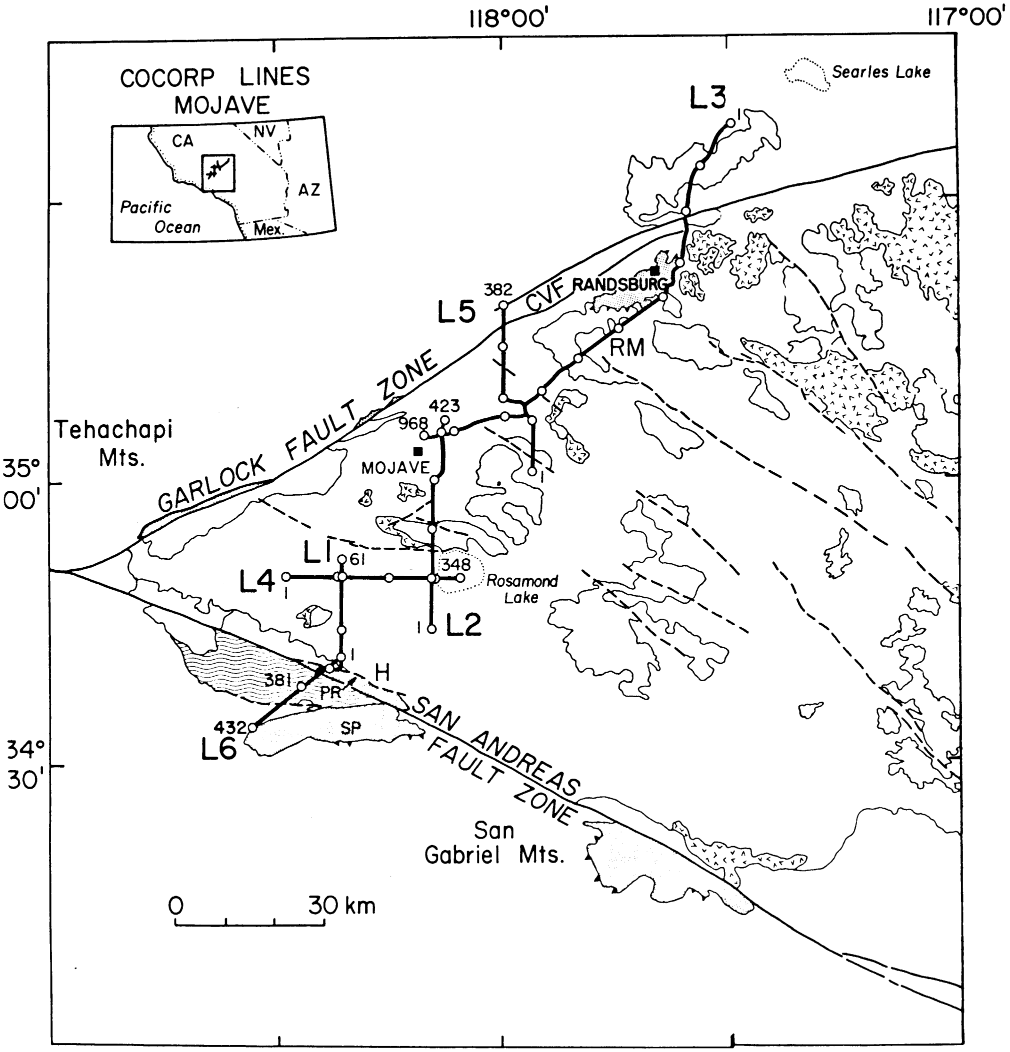

Fig. 1. Generalized geologic map of the Mojave Desert showing the positions of the COCORP seismic reflection lines. Inset shows position of map in southern California. Dotted pattern = Rand-Pelona-Orocopia Schist; V pattern = Tertiary sediments and volcanics; wavy pattern = Precambrian outcrops; white = Mesozoic granites; unshaded = alluvium; faults shown as bold lines. Abbreviations for faults are: CVF, Cantil Valley fault; H, Hitchbrook fault; abbreviations for mountains are: PR, Portal Ridge; RM, Rand Mountains, SP, Sierra Pelona.

[1985]. The survey revealed several major southwesterly-dipping reflecting horizons and a prominent Moho-depth horizon which appears to be offset beneath the northwestern Mojave Desert (Figure 2). The uppermost of these horizons can be traced to the surface and has been identified as the Rand thrust; however, the deep horizons are not traceable to the surface. Cheadle et al. interpreted these deeper horizons to be major fault zones and proposed three models for their origin. The horizons may be 1) the westward deepening 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 emplacement of the Pelona-Orcopia-Rand Schist; or 3) low-angle normal faults related to early Miocene northeast-southwest directed crustal extension.

Results

The Geometry of the Mid- to Deep-Crustal Reflecting Horizon

Figure 2 summarizes the COCORP Mojave data, and delineates the major reflecting horizons

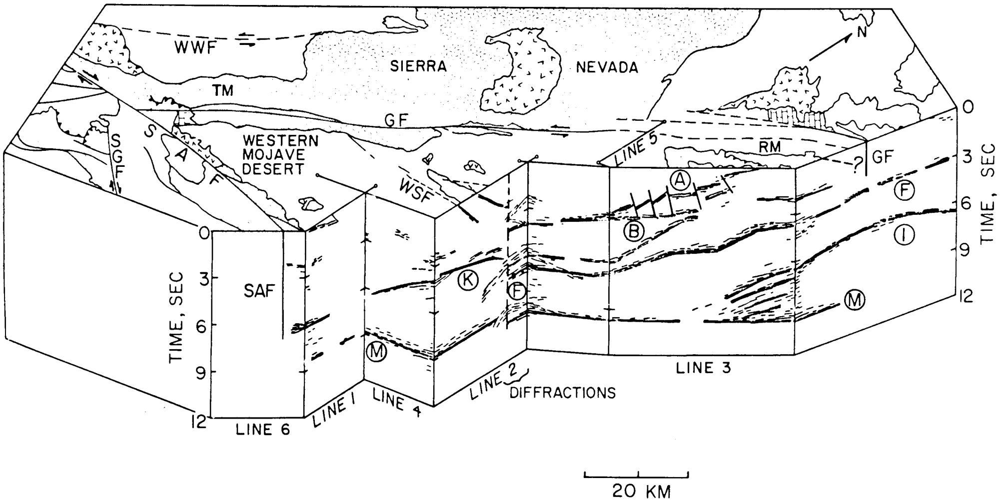

Fig. 2. Summary block diagram showing major interpreted features of the Mojave survey. Abbrevations: GF, Garlock fault; SAF, San Andreas fault; SGF, San Gabriel fault; WSF, Willow Springs fault; WWF, White Wolf fault; R = Rand Mountains; THM, Tehachapi Mountains; A and B = Rand thrust and related horizon; M = Moho-depth horizon; F, I, and K = Mid- 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.

identified by Cheadle et al. [1985]. The reflecting horizons are discontinuous, consisting of discrete, but laterally correlative, events which are often multicyclic with a duration of up to 1 s two-way travel time (TWTT). Most of these horizons cannot easily be correlated with the known surface geology because they are not traceable to the surface over the length of the survey. In this respect the data are typical of many other deep seismic reflection profiles [Gibbs et al., 1984; Klemperer et al., 1985]. When interpreting such data, care must first be taken to distinguish diffractions, sideswipe and reflected refractions from "real" reflections. Then, often only a combination of the characteristic geometry and extent of the reflections, and

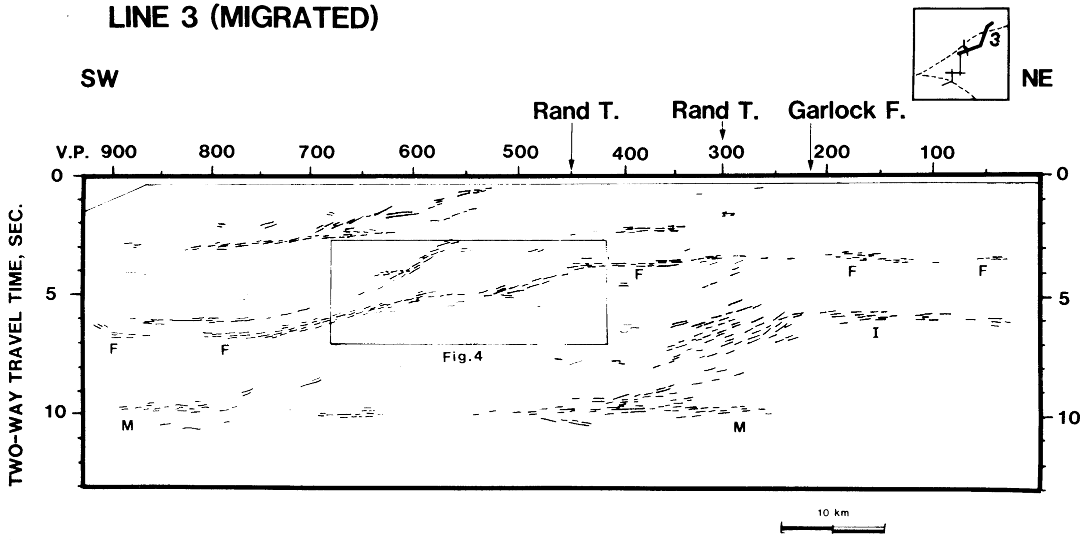

Fig. 3. Line 3: line drawing of the complete migrated line. Lettered reflections are discussed in the text. Numbers along top of section are VP numbers which key to figure 1. Scale is 1:1 for 4.5 km/s. To convert vertical scale to approximate depth scale multiply TWTT by 3 km/s.

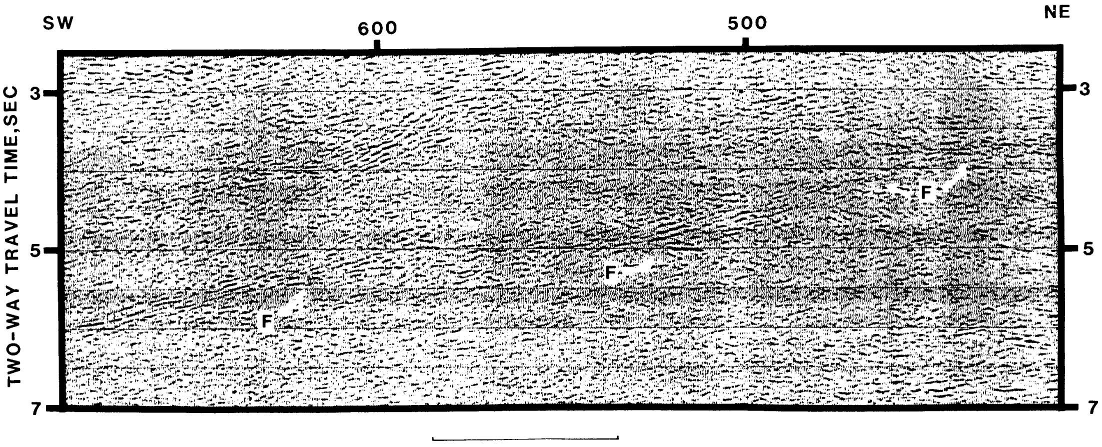

Fig. 4. Detail of COCORP Mojave Line 3, VPs 420-680, illustrating reflections discussed in text (2.8 to 7 s TWTT only). Scale is 1:1 for 4.5 km/s. To convert vertical scale to approximate depth scale multiply TWTT by 3 km/s.

the geological history of the region can provide an indication of their origin. Such an approach suffers from the limitations of current geological knowledge. For example the form of the bottom of a batholith, the form of a continent-continent suture, and the geometries of faults at depth are largely subjects for speculation. In fact, it is questionable whether reflective features with complicated shapes are even recognizable in deep seismic data [e.g., Wong et al., 1982].

Several of the reflecting horizons visible on the Mojave data (Figure 2) are gently-dipping and extend over relatively large distances (> 50 km) and so are plausibly interpreted to be major low-angle faults. Horizon F (Figure 2) is the best example, and the other gently-dipping horizons are described in Cheadle et al. [1985]. On Line 3 (Figure 3) horizon F is interpreted to extend from VP 50 at 3.2 s TWTT to VP 900 at 6.8 s TWTT, and therefore it is traceable over approximately 100 km of the survey to depths of at least 20 km.

Three-dimensional control on the geometry of horizon F is provided by the network of seismic lines that cross F. Two-dimensional wave equation migration of the data employing interval velocities calculated from the data for the upper crust, and refraction velocities [Roller and Healey, 1963; Prodehl, 1979] for the lower crust, indicate that horizon F on Line 3 (Figures 3 and 4) has a ramp and flat geometry typical of thrusts in foreland thrust belts and possibly characteristic of low-angle normal faults [Dahlstrom, 1970]. The ramps dip at approximately 30° south-southwest, an angle characteristic of the ramps of thrust faults exposed at the surface [Boyer and Elliot, 1982]. The dip directions of the ramps imply that the fault zone is either a north-northeast-vergent thrust fault or a low-angle normal fault along which the direction of movement was to the south-southwest. Further seismic reflection profiling is required to trace this structure to the surface and thus distinguish between these two possibilities.

The identification of horizon F is based on its extent and form and on the geology of the region. If this interpretation is correct, it suggests that the geometry of major, deep thrust or normal faults can be similar to the geometry of thrusts mapped in foreland thrust belts and that they can exhibit this geometry in crystalline terranes. The existence of major thrusts with ramp and flat geometry in crystalline terranes has been suggested by Bartley [1981] and Hodges et al. [1982] for the Scandinavian Caledonides.

Moho Depth Reflections

A conspicuous feature of much of the Mojave data is the presence of a series of horizontal reflections between 8.5 and 10 s TWTT (28-33 km). These events occur as both individ-ual reflections and as packets of reflections of up to 1 s duration, and they define a discontinuous horizon M (Figure 2) which is mainly horizontal [Cheadle et al., 1985]. Horizon M is distinguished from the other predominantly southwesterly-dipping horizons seen in the Mojave data by its depth and its lack of an apparent dip.

Cheadle et al. [1985] compared the two-way travel times to horizon M with two-way travel times to the Moho calculated from the crustal models derived from refraction data across the Mojave Desert. They concluded that horizon M occurs at depths appropriate for the crust-mantle transition and that the Moho itself may corre-

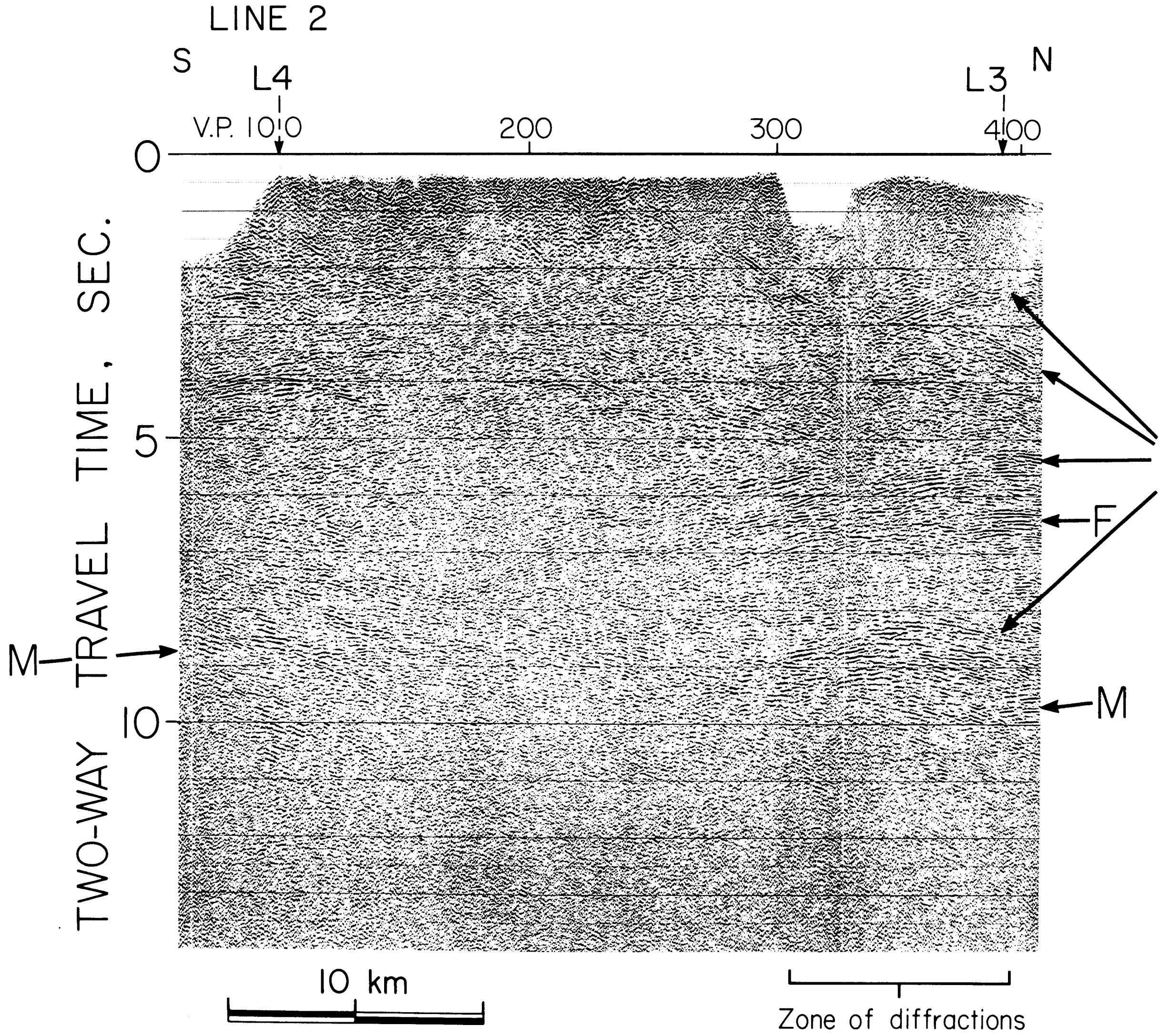

Fig. 5. Line 2: unmigrated time section. Numbers along top of section are VP numbers which key to figure 1. Scale is 1:1 for 4.5 km/s. To convert vertical scale to approximate depth scale multiply TWTT by 3 km/s. Abbreviations: D, Diffractions; F, Horizon F; M, Horizon M.

spond to the base of horizon M, as suggested by other seismic refraction surveys [Barton et al., 1984].

There is an abrupt change in TWTT to the base of horizon M from 9.5-10 s on Line 3 (Figure 3) and the northern part of Line 2 (Figure 5) to 8.5-9.0 s on the southern part of Line 2 (Figures 2 and 5). Realistic crustal velocity variations cannot explain this change in TWTT, therefore it probably reflects a real change in depth to the Moho. This Moho offset occurs below a complicated vertical zone of numerous diffractions and reflections on Line 2, through which none of the intracrustal horizons (B, F and K, Figure 2) can be traced (Figure 5), suggesting that a near-vertical, crustal penetrating fault exists near the northern end of Line 2 in the vicinity of the town of Mojave. A strike-slip fault, possibly the northern continuation of the Mojave-Sonoran Megashear [Silver and Anderson, 1974] or a proto San Andreas fault [Graham, 1976], is a possible identity. Faults which offset the Moho have been reported from active collisional orogens [the Himalayas and the Apennines - Hirn et al., 1984; Morelli, this volume] and stable cratons [India - Roy Chowdhury and Hargraves, 1981].

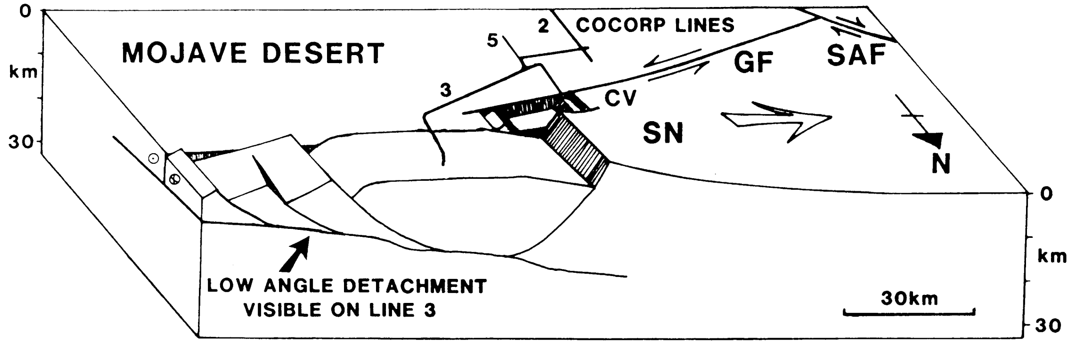

Fig. 6. Schematic model, based on Wernicke (1981) and Stewart (1983), illustrating the possible relationship of the Garlock fault to the low-angle detachment (horizon F) discussed in the text. Abbreviations: GF, Garlock fault; SAF, San Andreas fault; CV, Cantil Valley; SN, Sierra Nevada.

Strike-Slip Faults

The geometry of strike-slip faults at upper crustal levels is relatively well-known. However, the deep crustal geometry of strike-slip faults is poorly understood. Sibson [1983] reviewed the possible configuration of strike-slip faults at depth and concluded that they either merge into steeply-dipping shear zones which may remain constant in width, or alternatively may widen with depth or, less likely, merge into subhorizontal decoupling horizons.

The imaging of vertical or very steeply dipping faults, particularly strike-slip faults, is a major problem in deep seismic reflection profiling. Without fault plane reflections, which are virtually impossible geometrically, diffractions and reflected refractions can sometimes be used to suggest the presence of very steep faults. But perhaps the best constraints on the shape and depth of strike-slip faults are provided by marker horizons (for example, sedimentary or structural reflections) which may be truncated by the fault or pass under the surface trace of the fault. Unfortunately, such marker horizons are often rare on deep seismic profiles.

The COCORP Mojave survey crossed two major strike-slip faults, the San Andreas and Garlock faults, and both appear to show different geometries. The Garlock fault appears to be confined to the upper crust by two reflection horizons, I and F, which pass beneath its surface trace without any apparent offset (Figure 2), though the reflections which comprise the horizons vary in amplitude and continuity [Cheadle et al., 1985]. The geometry of the Garlock fault above horizon F is unknown because marker events, fault plane reflections, diffractions or reflected refractions, which might delineate its geometry are absent. 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 associated with extension within the Basin and Range Province (Figure 6). Such a low-angle detachment may be an older thrust which has been reactivated to the north of the Garlock fault during Basin and Range extension.

A shallow Garlock fault is consistent with field mapping of the eastern end of the fault by Burchfiel et al. [1983], who suggest that the Garlock fault is a shallow tear fault bounding the Kingston Range Detachment to the north. It is also compatible with models of detachment faulting in the Death Valley region [for example, Stewart, 1983].

The San Andreas fault is poorly constrained by the seismic data, but the presence of reflections down to 30 km depth to the north of the fault and the complete absence of reflections to the south of the fault within the San Gabriel Mountains (Figure 2) is consistent with the San Andreas fault extending as a vertical feature down to at least 30 km.

Two other deep seismic profiles cross the San Andreas fault and are equally disappointing: the COCORP Parkfield Line [Long, 1981] and the USGS San Benito County Line [McEvilly, 1981]. Both lines provide little information about the detailed geometry of the San Andreas fault, but they reveal gently-dipping midcrustal reflections and a Moho-depth reflection within the Salinian block to the west of the fault and few reflections from the Franciscan terrane to the east. Removal of the late Tertiary displacement of the San Andreas fault suggests that the Salinian block may once have been contiguous with the Mojave block [Graham, 1978] and therefore that the reflectors imaged by the COCORP Parkfield and USGS lines may represent the continuation of the major low-angle structures imaged by the COCORP Mojave survey. The similar depth Moho reflections support this speculative interpretation.

Conclusions

COCORP deep seismic reflection profiling in the Mojave Desert of Southern California has revealed deep crustal structures which provide constraints on the relatively poorly understood subject of the geometry and extent of deep crustal faults. The data reveal:

1) Several major low-angle faults within the Mojave block, one of which may exhibit ramp and flat geometry to depths of 20 km. This suggests that faults may develop ramp and flat geometries at depth within crystalline terranes.
2) That the Moho may be offset, possibly by a major strike-slip fault, in the Mojave region.
3) That some major strike-slip faults, such as the Garlock fault, are relatively shallow crustal features. The San Andreas fault is poorly imaged, but the data is consistent with it extending to at least 30 km depth.

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