

Structure of the central Death Valley pull-apart basin and vicinity from COCORP profiles in the southern Great Basin

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ABSTRACT

COCORP deep seismic reflection profiles in the vicinity of the central Death Valley pull-apart basin in southeastern California provide three-dimensional information on the subsurface of an active extensional terrane. Variations in the orientation and density of reflectors indicate that the crust and upper mantle of the region is divisible into three seismic zones which may represent regions of differing lithology, rheology, or both. The reflections in the upper ~5 s (15 km) of the data have gentle to moderate dips; between 5 and 10 s, reflections are predominantly subhorizontal; and below ~10 s (30 km), there are no notable reflections. The boundaries between the above reflecting zones are marked by prominent reflecting horizons which are continuous throughout the survey region.

The observed reflection geometries resemble those predicted by the crustal model of the region proposed by Wright and Troxel (1973) on the basis of geological studies. In addition, many of the upper-crustal reflectors can be traced directly to mapped features. Based on those correlations, the upper reflecting zone (0–5 s) is interpreted to be a region of brittle deformation with the various upper-crustal reflectors interpreted as faults and basin sediments. The reflecting horizon at the base of the upper zone appears to be the lower boundary of the faulted upper crustal blocks and, it has been suggested that it locally includes partially molten rock. The observed geometries and amplitudes of reflec-

tions from the lower crust (15–30 km depth or 5–10 s two-way traveltime) are consistent with the model of Wright and Troxel for a ductilely deformed and intruded lower crust. The prominent reflecting horizon at the base of that zone is designated the reflection Moho and the seismically transparent lowest zone appears to correspond to the upper mantle.

The seismic data define a zone of faults (referred to here as the “Wingate Wash fault zone”) which appears to form the southern boundary of the central Death Valley basin and also may have provided a conduit for the migration of magma from a mid-crustal magma body to the surface. The Wingate Wash fault zone appears to intersect the southern Death Valley fault zone and the frontal faults of the Black Mountains in the subsurface beneath the youngest volcanic edifice in the region. Those three fault zones appear to separate the Panamint, Owlshhead, and Black Mountain upper-crustal fault blocks. From the available data, a reconstruction of the possible fault-block movements during the time of basin subsidence is presented. That reconstruction suggests that the central Death Valley basin formed as a result of the combined down-to-the-east rotation and northwest translation of the fault blocks in manner similar to that proposed by Reches for other parts of the Basin and Range.

INTRODUCTION

The Consortium for Continental Reflection Profiling (COCORP) collected 250 km of deep seismic reflection data in the vicinity of Death Valley, California (Fig. 1). Those data provide three-dimensional information on the configuration of upper-crustal fault blocks, as well as other features of the crust and upper mantle,

associated with the development of the central Death Valley pull-apart basin and surrounding region. The main focus of this paper is on the major structural features, particularly the faults, in and around the basin. Further discussion of the detailed geology and its expression in the COCORP seismic data are in preparation (Wright and others, 1987; and unpub. data); other aspects of the seismic data, including information on crustal magmatism (de Voogd and others, 1986a; 1988), the role of extension in the evolution of continental crust (Serpa and de Voogd, 1987), and the possible relationships between the Mojave and Death Valley COCORP data (Serpa, 1987, 1988), are discussed in detail elsewhere.

The central Death Valley basin is unusual in that many of its structural features are well exposed at the surface (Fig. 2) rather than being buried beneath sediments as is typical of extensional basins. For that reason, it is possible to relate upper-crustal reflectors to the surface geology of the basin. Thus, the interpretation of the seismic data and the resulting crustal model of the survey area presented in this paper are based to a large extent on the correlation of the seismic data with existing surface data.

STRUCTURAL FEATURES OF THE DEATH VALLEY REGION

The most obvious structural features of the Death Valley region are the west-dipping normal faults that bound east-tilted fault blocks of various sizes (Noble and Wright, 1954; Hunt and Mabey, 1966; Wright and Troxel, 1973). These faults and the fact that the fault-bounded blocks commonly contain late Cenozoic sedimentary and volcanic rocks, which are also tilted to the east, have long been accepted as evidence that the region has undergone severe

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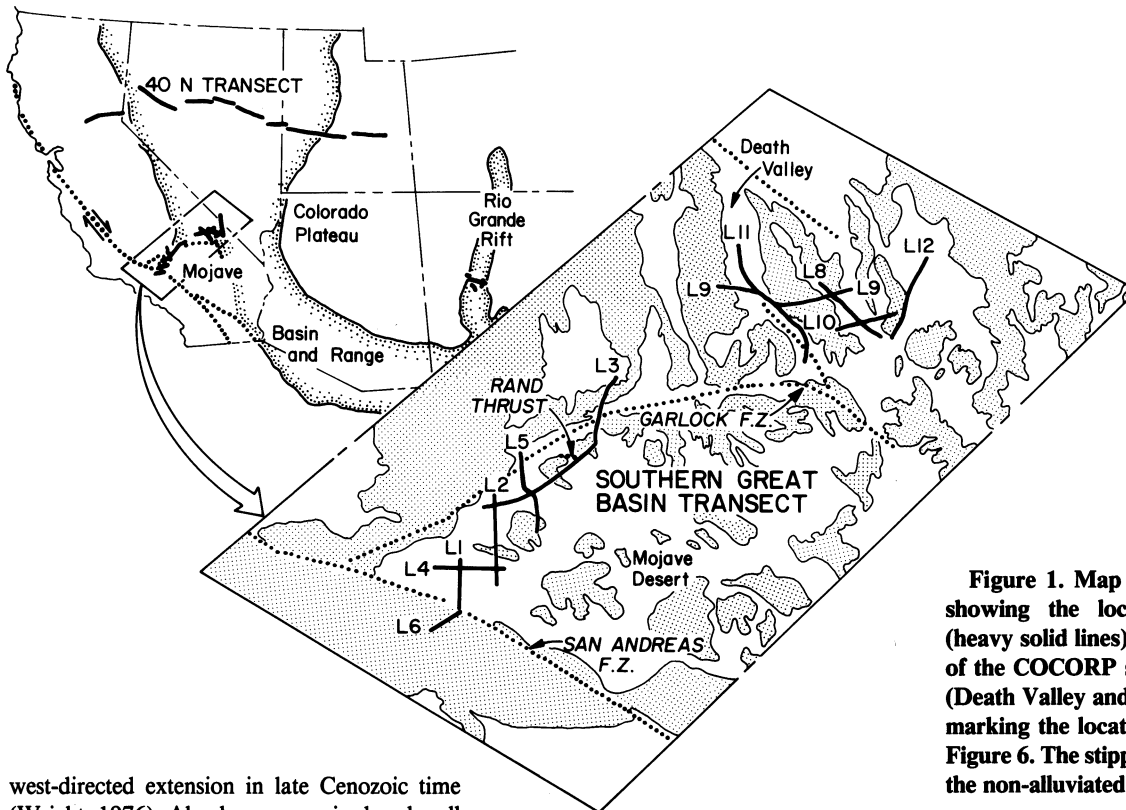


Figure 1. Map of the western United States showing the location of COCORP profiles (heavy solid lines). The inset shows the location of the COCORP southern Great Basin transect (Death Valley and Mojave areas), with triangles marking the locations of seismic data shown in Figure 6. The stipple patterns in the inset indicate the non-alluviated areas.

west-directed extension in late Cenozoic time (Wright, 1976). Also long recognized and well documented in this region are major zones of wrench faults, which, like the normal faults, displace late Cenozoic rock units and thus have been active contemporaneously with the normal faults (Burchfiel and Stewart, 1966; Hill and Troxel, 1966). Foremost among these are the northeast- to east-trending, left-lateral Garlock fault zone and the northwest-trending, right-lateral faults that occupy southern Death Valley and Furnace Creek Wash (Fig. 1).

Burchfiel and Stewart (1966) first emphasized the relationship between the normal and wrench faults when they proposed that the central Death Valley basin marked an area of crustal extension between the en echelon terminations of active segments of the southern Death Valley and Furnace Creek fault zones, as shown in Figure 3. They coined the term "pull-apart basin" for such a feature. A similar geologic setting was later proposed for the central Death Valley igneous field (Wright and Troxel, 1971).

Also implicit in the configuration and sense of movement on the Garlock and Furnace Creek fault zones is the conclusion that the crust in the triangular area between the two fault zones has been extended by a greater amount than the crust to the south and northeast. The Panamint Mountains compose, by far, the largest single fault block in the eastern part of that area and apparently define a massif that has existed, relatively intact, since the middle Proterozoic. In

late Cenozoic time, the block was extended by movement along normal faults exposed on the eastern slope of the mountains (Fig. 2). Most of the faults dip gently westward (Hunt and Mabey, 1966); others dip steeply to gently eastward to northeastward. Most of the latter are exposed in the southeasternmost part of the mountains, some of them being recorded on profiles 9 and 11 (Figs. 1, 2, and 4). The over-all effect of late Cenozoic deformation on the Panamint Mountains block, and even whether the block should be considered autochthonous or allochthonous, however, continues to be debated.

The concept of an allochthonous Panamint Mountain block originated with Noble (1941), who suggested that a low-angle regional fault, his "Amargosa thrust," lies at a shallow depth beneath the Panamint Mountains. He later discarded this interpretation (Noble and Wright, 1954), but others, including Hunt and Mabey (1966), Stewart (1983), Hamilton (1987), and Wernicke (1987a, 1987b) have continued to accept it. Stewart (1983), in particular, has suggested that the Panamint Mountains block has moved northwestward from an original position above the Black Mountains and Greenwater Range.

The seismic data presented here provide evidence (1) that the principal surface above which

the Panamint Mountains block has moved in late Cenozoic time dips northwestward as well as westward and extends to mid-crustal levels and (2) that the Panamint Mountains block has been displaced in a more northwesterly direction than previously assumed. The COCORP profiles also provide evidence that an east-thickening wedge of Cenozoic layered rocks underlies the floor of central Death Valley. Such a wedge supports the interpretation that the Panamint Mountains block extends beneath much of central Death Valley and that the block has been rotating, down to the east, as it moves away from the Black Mountains block.

The interpretation of the seismic data is discussed in subsequent sections of this paper. The following is a brief description of the data acquisition and processing which led to the data interpretation.

THE COCORP DEATH VALLEY SURVEY

The COCORP Death Valley survey consists of five seismic profiles. California lines 8 through 12 (L8 to L12 in Fig. 1), with a combined length of 250 km. Two of the profiles, lines 9 and 10, trend east-west, perpendicular to the strike of the tilted mountains and intervening valleys. The remaining three profiles, lines 8, 11,

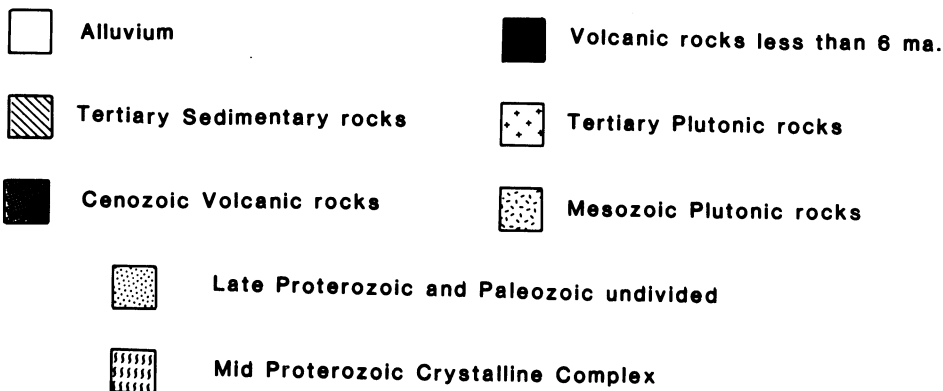
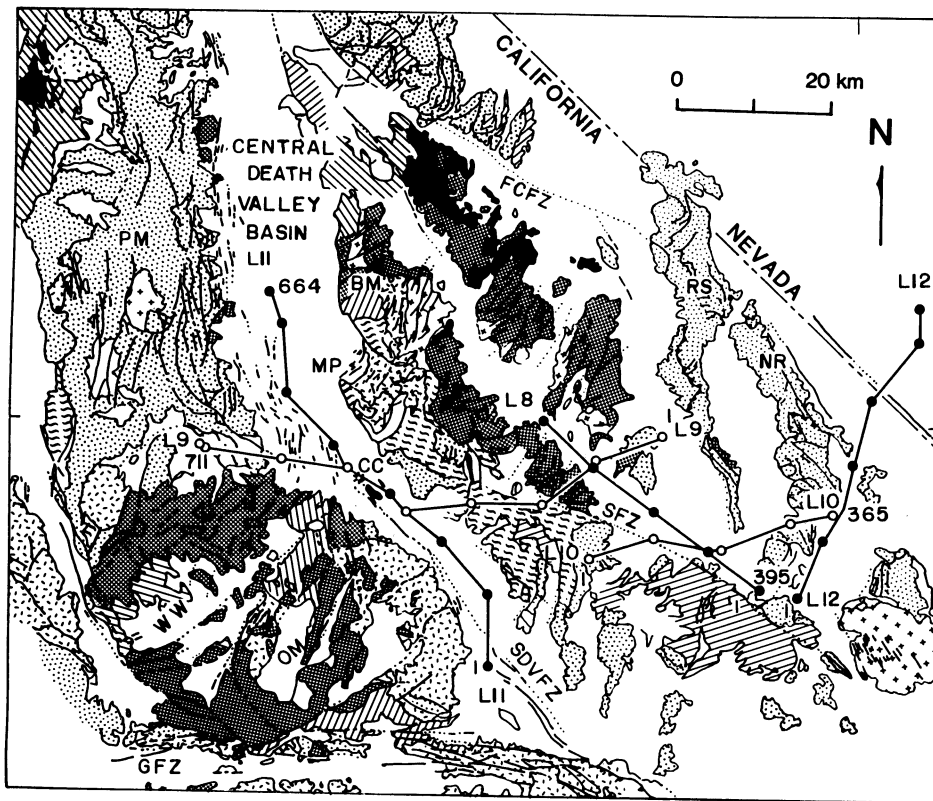


Figure 2. Generalized geologic map of the Death Valley area (after Wright and Troxel, 1973). The COCORP profiles (L8 through L12) are shown with circles indicating the vibrator source locations (VP's). CC indicates the location of a 690,000-yr-old basaltic cinder cone, MP is the Mormon Point turtleback surface, DVFZ is the southern Death Valley fault zone, FCFZ is the Furnace Creek fault zone, and SFZ is the Sheephead fault zone.

and 12, trend approximately north-south and lie within the basin regions. The various profiles intersect at three key locations: the southern end of the central Death Valley basin (lines 9 and 11), near the Sheephead fault zone (lines 8, 9, and 10), and near the eastern margin of the Nopah Range (lines 10 and 12); these provide three-dimensional information on the geometry of reflectors in those areas.

Data Processing

The well-exposed structural features which make Death Valley an ideal place to study crustal extension also make it a less than ideal place for the collection of seismic reflection data. The topography is rugged, and the surface conditions are variable. Elevation changes of more than a kilometer occur along seismic profile 9

(Fig. 1). The final stacked section of line 9, however, shows features that are similar to those observed on the other Death Valley profiles which were collected in areas of low topographic relief. Thus the elevation static correction (Table 1), which was based on the measured velocities of shallow refracted arrivals in the COCORP field data (see Alter, 1985, for a discussion of the COCORP refraction velocities), appears to have removed the major topographic effects from the data.

Parts of line 9 and all of the other Death Valley seismic profiles were located in the basins and those data were affected in varying ways by the unconsolidated basin fill. In particular, undesired surface-wave and back-scattered energy were recorded on nearly all of the profiles. In addition, the quality of the data collected along profile 11 appears to be further degraded by noise which may be related to some combination of salt corrosion of the geophone connections, intermittent high gusty winds, the passage of heavy ore trucks, or other unidentified factors which occurred during data collection. Similar noise problems have been reported (Rundle and others, 1985; Cheadle and others, 1986) for seismic data collected in the desert regions of southern California, and the processing of those data is similar to that used in Death Valley and discussed below.

The Death Valley seismic profiles were collected and initially processed (Table 1) in a manner similar to many other COCORP profiles (Serpa and others, 1984). After the initial

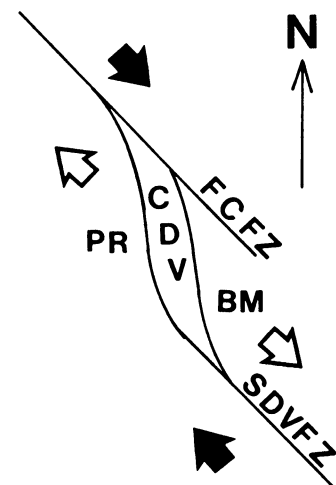


Figure 3. Pull-apart basin model (modified from Burchfiel and Stewart, 1966). CDV is the Central Death Valley basin, FCFZ is the Furnace Creek fault zone, and SDVFZ is the southern Death Valley fault zone. Arrows indicate the displacement directions in the vicinity of the basin.

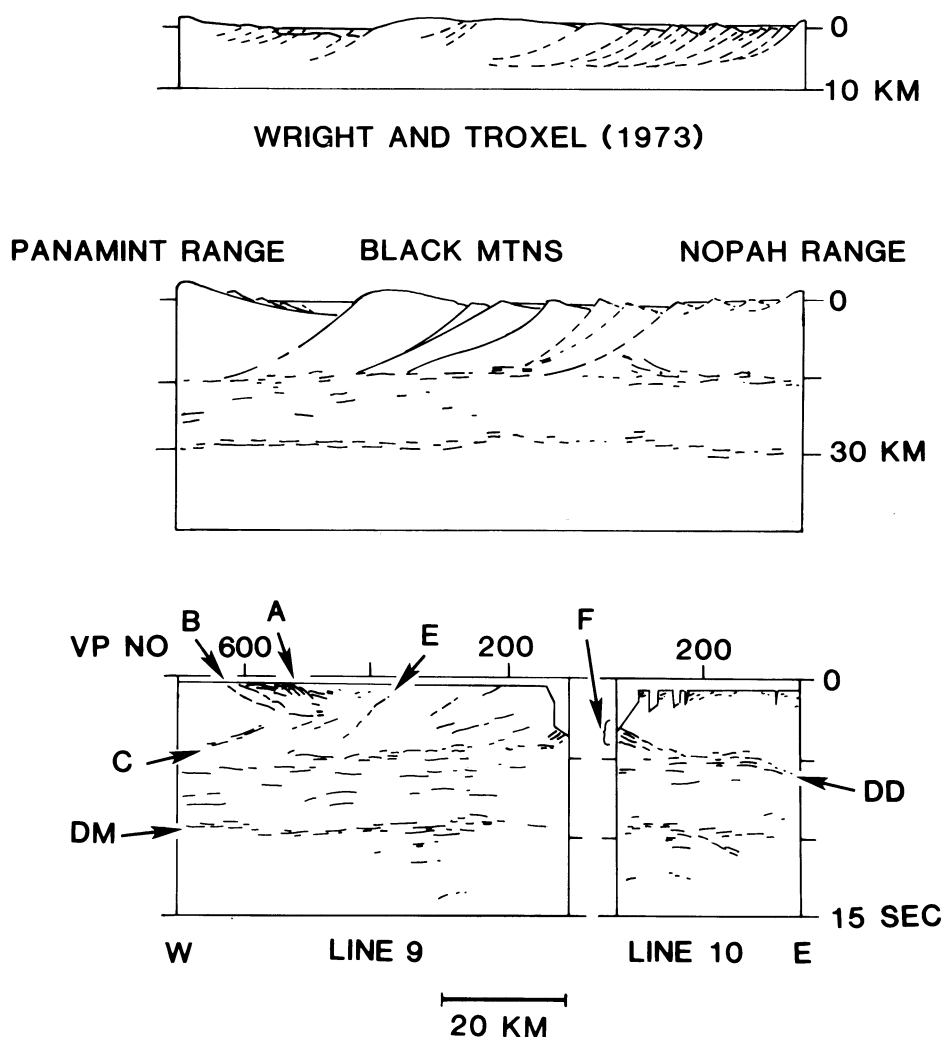


Figure 4. Line drawing of the Death Valley seismic profiles 9 and 10 (bottom). An interpreted geologic cross section based on the seismic data and surface geology is shown directly above the line drawing. At the top of the figure, there is a geologic cross section (modified from Wright and Troxel, 1973), based on the surface geology between 5 and 20 km north of the seismic profiles.

TABLE 1. DATA ACQUISITION PARAMETERS

Sample rate	8 ms	Vibroseis sweep frequencies	8-32 Hz
Station spacing	100 m	Spread configuration	off end
Near offset	500 m	Far offset	10,160 m
Correlated data length	16 s		
FINAL PROCESSING		INITIAL PROCESSING	
Demultiplex and correlate field data Mute air wave and refracted arrivals Pie-slice velocity filter Variable bandpass frequency filter Sort into common mid-point files Elevation statics (1 km datum*) Deconvolution Velocity analysis Normal moveout and mute Stack Display (true amplitude and gain balanced [†]) Migrate [†]		Demultiplex and correlate field data Mute air wave and refracted arrivals Sort into common mid-point files Elevation statics (sea-level datum) Deconvolution Velocity analysis Normal moveout and mute Stack Display (true amplitude, gain balanced)	

*A 600-m/sec shift was applied to line 11 after stack to give it an apparent 1-km datum because the surface of the profile is below sea level.

[†]Gain balancing and migration are not included in Figure 5.

processing, however, the Death Valley stacked sections showed numerous areas where the signal-to-noise ratio appeared to be low. To minimize the noise in the data, both narrow-band-pass-frequency filters and pie-slice velocity filters were applied to the field data. After filtering and other reprocessing (Table 1), the appearance of the stacked sections was significantly improved. The reprocessed sections are the ones which were released by COCORP (Kaufman, 1984). The only difference between those released sections and the ones shown in this paper (for example, Figs. 5, 6, 7, and 8) is that our figures are based on true relative amplitude displays (for example, Fig. 5), some of which have had a correction applied for spherical divergence and exponential gain, rather than the standard Automatic Gain Correction (AGC) used in the released sections (see, for example, Dobrin, 1976; and Waters, 1981, for a discussion of different types of amplitude corrections).

Plots of the frequency spectrum were prepared from field files such as those shown in Figure 9. These plots showed that low-frequency surface waves were particularly severe when both the source and the receivers were located on the unconsolidated basin sediments in the survey area. Low-frequency noise, possibly mechanical noise generated by the source trucks, also appeared to dominate many of the seismic traces that were recorded within ~2.5 km of the source. The upper limit of the low-frequency noise from all sources varied between 12 and 18 Hz. Between 18 and 28 Hz, the amplitude spectra were relatively flat, except on parts of line 11. Prominent amplitude peaks, above 28 Hz, however, were observed in the amplitude spectra of nearly all of the data. On the northern half of line 11, where the source vibrators were located on evaporite deposits, coherent energy with a frequency range of 24 to 32 Hz appeared to dominate the upper 3 to 5 sec of the data. That high-frequency energy may be the result of reverberations of the seismic signals within the evaporite layers or spurious electronic signals related to salt corrosion of the receiver cables, or both.

The low- and high-frequency noise was removed from the data with a band-pass frequency filter which varied in a manner determined by the quality of the field files. The maximum frequency range of the seismic data after filtering is 17 Hz (12 to 28 Hz), and the frequency range of the northern half of line 11, where the noise problems were severe, is only 7 Hz (18 to 24 Hz) after filtering. The layering of the shallow-basin sediments and the geometries of many of the upper-crustal faults which are discussed in this paper are shown more clearly in the filtered data than in the unfiltered data. For

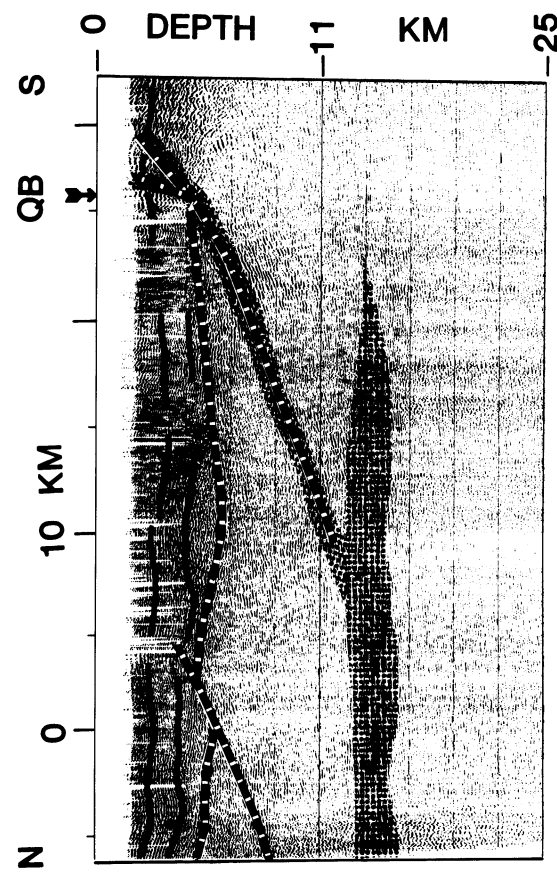
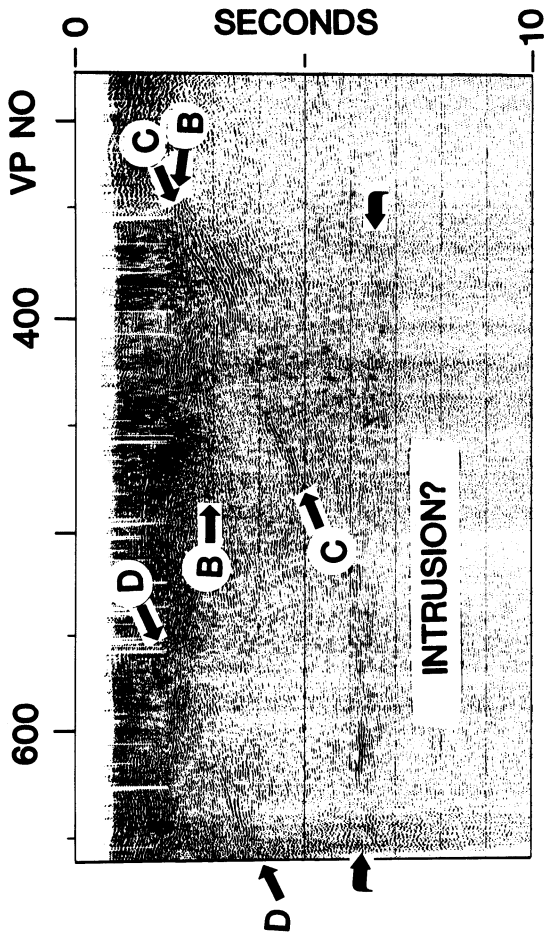


Figure 5. Section of seismic profile 11. The data are filtered (see text), but no amplitude correction has been applied. QB indicates the surface position of a 690,000-yr-old cinder cone, and curved arrows indicate the inferred position of the inferred magma body discussed in the text. The geologic interpretation of the data is shown below, with solid lines indicating the trend of the basin-fill reflectors; dashed lines indicate faults and the base of the basin fill, and stippled areas indicate the inferred location of intrusions.

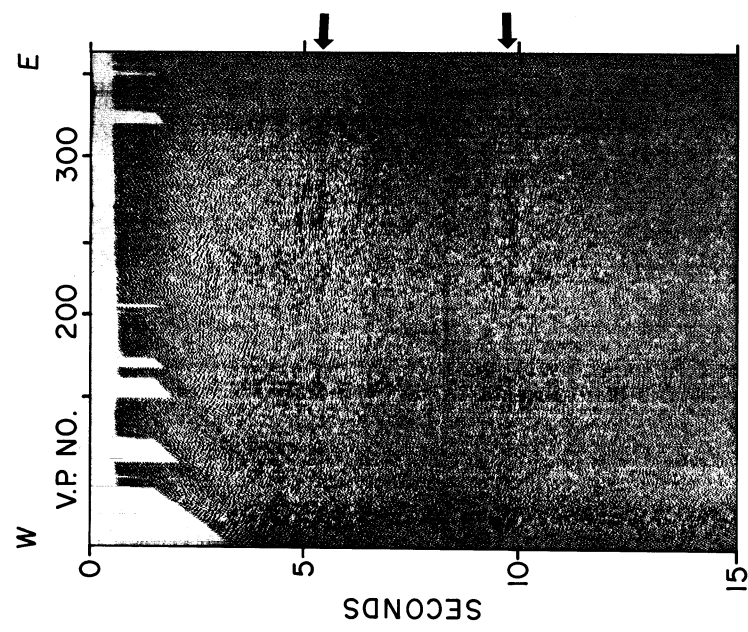


Figure 6. Death Valley line 10, with arrows marking the positions of the mid-crustal reflecting zone (5 sec) and the reflection Moho (10 sec).

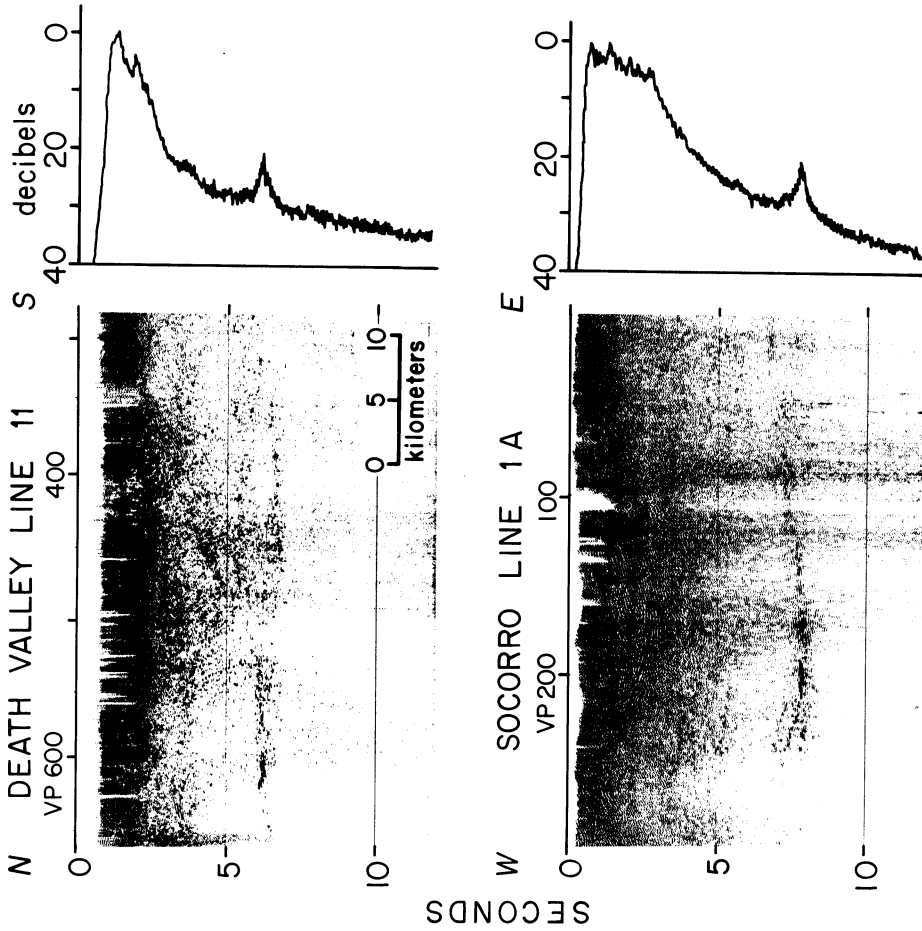


Figure 7. Comparison of Death Valley line 11 (unfiltered) and Rio Grande rift high-amplitude reflections (modified from de Voogt and others, 1986).

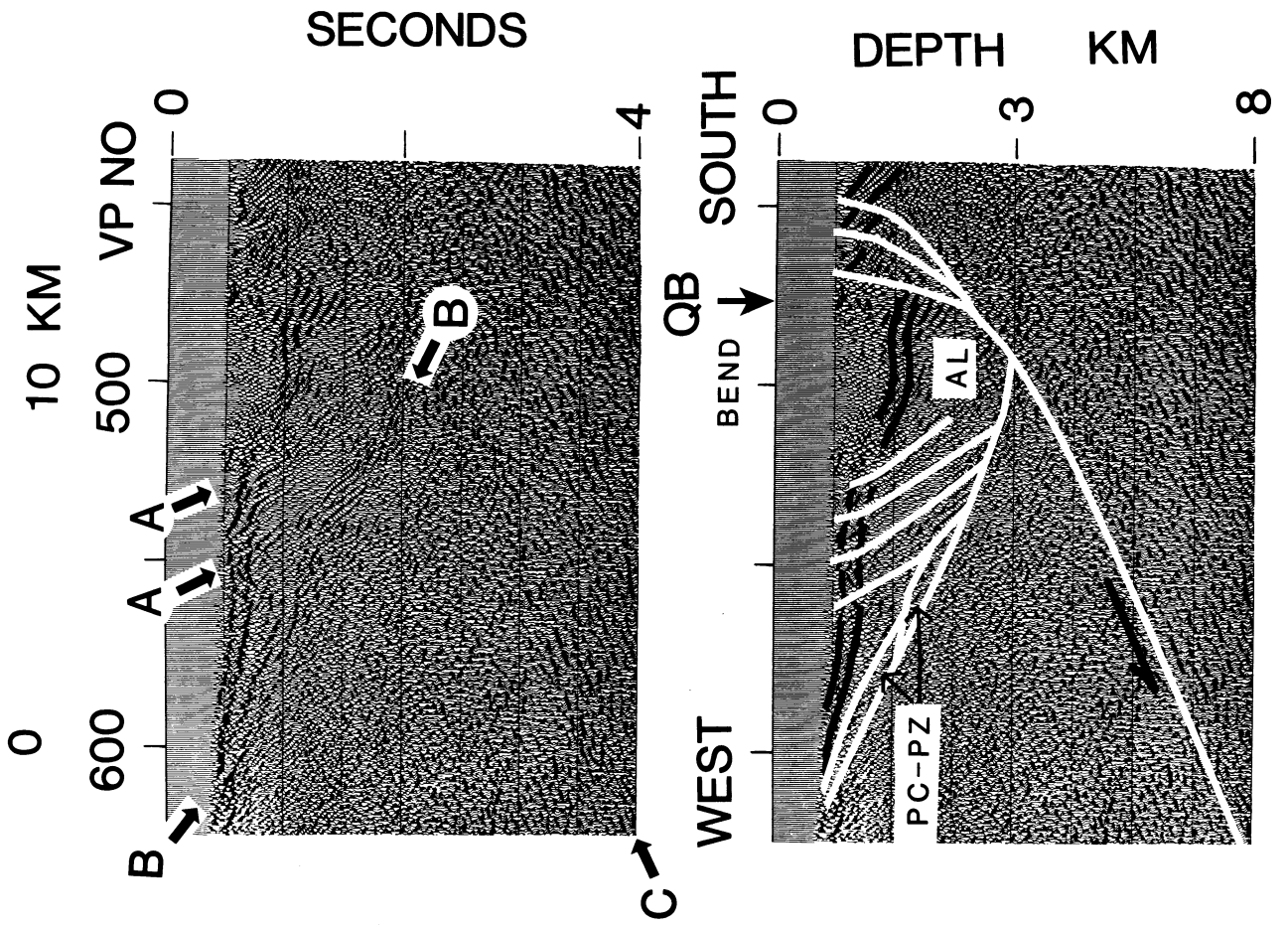


Figure 8. Migrated section of seismic profile 9. The data are filtered, and an automatic gain correction (AGC) has been applied. QB indicates the surface position of a 690,000-yr-old cinder cone. Other letters are discussed in the text. The lower section shows the geologic interpretation of the seismic data, with white lines indicating faults and the basin bottom. Solid black lines show the trend of the basin-fill reflectors; PC-PZ indicates the location of inferred Precambrian and Paleozoic sedimentary rocks faulted against the bottom of the basin. AL indicates the area of late Cenozoic basin deposits.

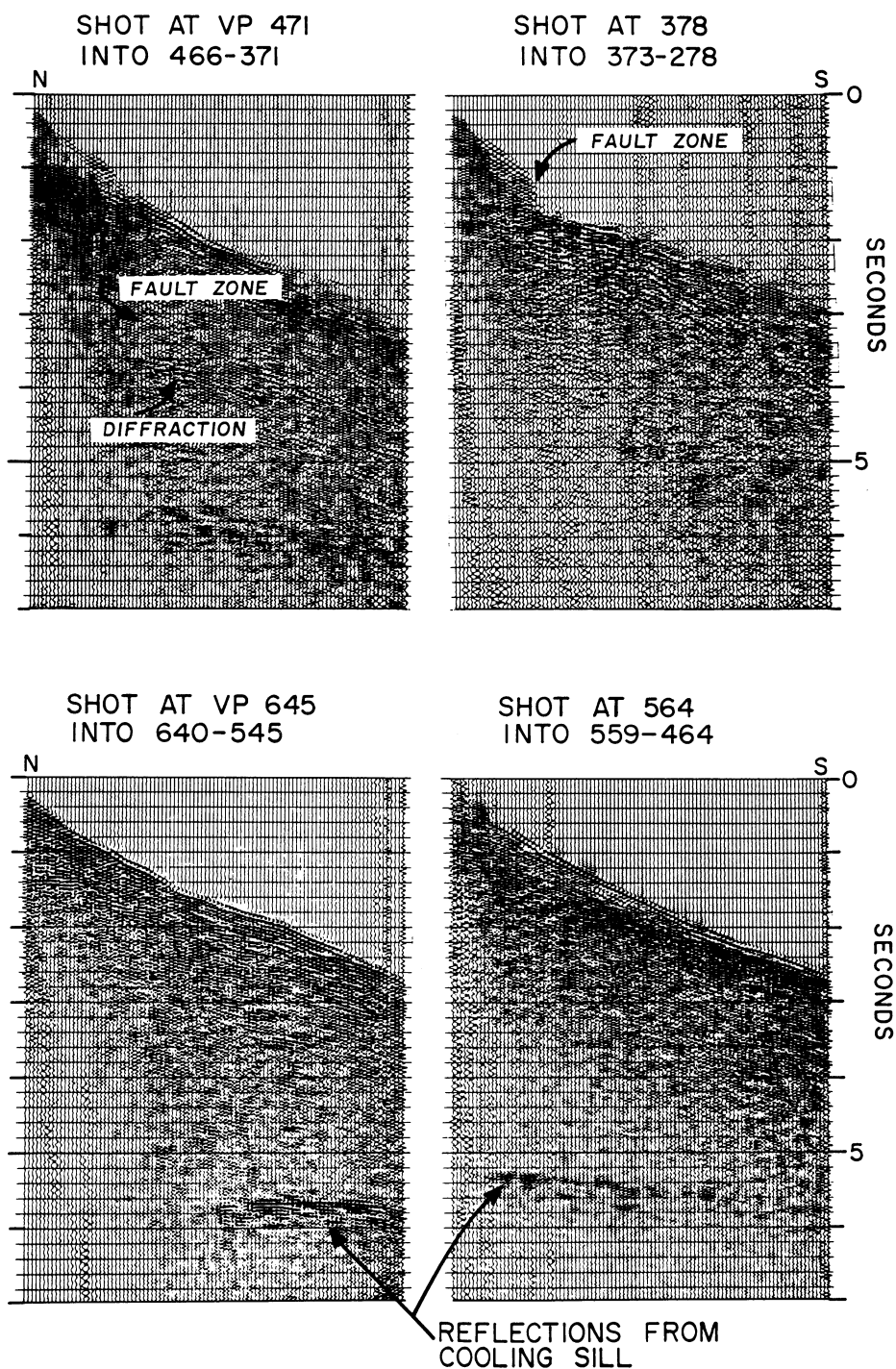


Figure 9. Field files from Death Valley line 11 showing some of the features discussed in the text. The fault zone indicated in the upper two files corresponds to event C in other figures.

studies of the reflection characteristics, such as that conducted by de Voogd and others (1986a), however, the frequency range of the filtered data is too narrow. For that reason, the unfiltered data (Fig. 7) were used for that study.

Frequency-wave number (F-K) plots (Dobrin, 1976, chap. 6) were also prepared from some of the field files. These F-K plots indicated the presence of back-scattered and surface-wave

energy in the seismic data. A pie-slice velocity filter (Embrece and others, 1963), designed from the F-K plots, was used to remove seismic energy with an apparent velocity less than, or equal to, that of the first refracted arrival (an average velocity of 2.7 km/sec) from all of the field files. The pie-slice filtered field files show numerous short, horizontal events (generally continuous over 3 to 7 traces). These horizontal

events are assumed here to be artifacts (coherent signals unrelated to the subsurface geology) of the filtering because they do not appear in the unfiltered files. These artifacts give the final stacked sections a slight subhorizontal grain (not distinct enough to be indicated in any of the sections displayed in this paper) but do not produce any events which could be misinterpreted as reflections.

The processing that was used to produce the final stacked sections of the Death Valley data is not typical COCORP processing. In particular, the use of a pie-slice velocity filter is generally avoided because it may produce artifacts, such as those shown by Howard and Danbom (1983), which could be misinterpreted as reflections. A significant amount of both high- and low-frequency information has been removed from the final stacked sections, and this also may result in some interpretational errors. The improved quality of the filtered data, however, appears to justify the use of the filtering to display the stacked data. Throughout the interpretation of the data, the unfiltered field files and stacked sections were compared with the filtered sections to insure that the interpreted events were reflections and not artifacts of the data processing.

In addition to the processing discussed above, two-dimensional migrated sections, such as that shown in Figure 8, were prepared for all of the Death Valley profiles. Because the two-dimensional migration will not correct reflections from outside the vertical plane of the seismic profiles to their proper relative position in the seismic sections, the three-dimensional subsurface positions and orientations of some reflectors were determined using the unmigrated seismic sections (for example, Fig. 5) as discussed below.

Three-Dimensional Analysis of Reflector Geometries

In the areas where two profiles intersect, reflections from the same subsurface source can be correlated and their three-dimensional orientations estimated. De Voogd and others (1986b) described a method, similar to that developed by Slotnick (1959), for estimating the strike and dip of a reflecting plane imaged on two nonparallel seismic lines. That method was used in this study to estimate the subsurface orientations and positions of reflectors B, C, and E (Figs. 4, 5, 8, and 10), which are imaged on both lines 9 and 11 near the southern end of the central Death Valley basin.

The three-dimensional analysis described by de Voogd and others (1986b) is based on the assumption that the velocity of rocks above the reflecting plane is constant and that the dip angle can be measured accurately from seismic depth

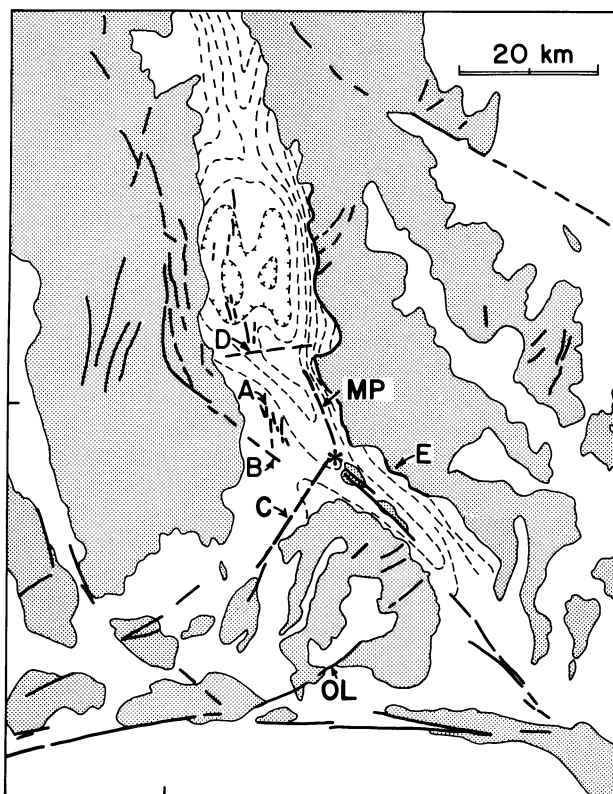


Figure 10. Map of the central Death Valley area showing the position of inferred faults (heavy dashed lines) and other features discussed in the text. Heavy solid lines are mapped faults, and shaded areas are mountains (modified from Wright and Troxel, 1973). The dashed lines within the basin area are 5-mGal gravity contours reported by Mabey (1963). The general geology and the location of the COCORP profiles are omitted for clarity. Those features are shown in Figure 2. OL is the Owl Lake fault zone, and MP is the Mormon Point turtleback fault. Other letters are discussed in the text.

sections. Because of noise in the data and the three-dimensional nature of the reflectors, however, the velocity structure of Death Valley is not well constrained by the seismic data. Thus uncertainties in the subsurface velocities used to convert seismic traveltimes to depths and the inherent assumption that the velocity is constant above the reflector are recognized to be potential sources of error in this analysis. Seismic modeling of portions of the Death Valley data (de Voogd and others, 1988) indicates that the latter problem is not a significant source of error. To determine the effects of the depth uncertainties, we used two different velocity estimates (Table 2), derived from both the inferred lithologies and the stacking velocities of nearby horizontal reflectors, to convert the traveltimes to depths.

For example, constant velocities of both 5.0 and 6.5 km/sec, between 3 and 4 sec, were used to study event C. The strike estimate (N28°E) for C did not change with the two different velocity models. However, the true dip estimate changed from 22NW to 29NW degrees for ve-

locities of 5.0 and 6.5 km/sec, respectively. Because those velocities are reasonable (Press, 1966) for the lithologies (that is, carbonates, quartzites, granites, and gneisses) present in the surrounding mountains and inferred to be present at depths corresponding to traveltimes of 2.0 to 6.5 sec, the true dip is taken to be 25NW \pm 4 degrees. Similarly, the strike and dip of events B and E were estimated to be N54°W 32°NE (\pm 2 degrees of dip) and N10°E 30°W (\pm 5 degrees of dip), respectively. The estimated orientations of these three events agree closely with those of nearby mapped features. Thus, those and other aspects of the interpretation are constrained by surface observations.

DESCRIPTION AND INTERPRETATION OF THE SEISMIC DATA

In order to discuss the data in terms of the subsurface geology, the two-way traveltimes must be converted to depths using some estimate

of the subsurface velocities. As mentioned above, the velocities are not well constrained by the Death Valley seismic data. For depth conversion, therefore, a relatively simple velocity model, 6 km/sec for the inferred crystalline rocks and 3 km/sec for the inferred basin sediments, is assumed. Those velocities appear to be reasonable in terms of previously published refraction studies (Roller and Healy, 1963), the velocities estimated from the seismic data, and the nature of the rocks exposed in the region. That velocity model, however, does not take into consideration the velocity variations which give rise to the reflections observed in the data. The true depths will therefore vary to a greater extent than indicated in this discussion.

A line drawing of all of the Death Valley profiles is shown in Figure 11, and Figures 5, 6, 7, and 8 show examples of the data. There are two prominent subhorizontal zones of reflections (Figs. 6 and 11) observed on all of the seismic profiles. Those zones occur at traveltimes of 5.0 ± 1.5 sec and 10.0 ± 1.0 sec (\sim 15 and \sim 30 km, respectively). The reflection horizons separate the seismic data into areas of differing seismic characteristics (geometry, spacing, and amplitude of reflections) and thus appear to define three distinct regions in the subsurface of Death Valley and vicinity. Those regions are described and discussed in the following sections.

The Upper Crust in Death Valley

Events in the upper 5 sec of the Death Valley seismic data can be subdivided into three basic reflection groups: (1) a localized region on lines 9 and 11 of closely spaced, layered reflections; (2) widely spaced, dipping reflections of varying strength and continuity observed on nearly all of the profiles; and (3) the basal zone of prominent subhorizontal reflections which separate the upper-crustal reflectors from those of the lower crust.

Upper-Crustal Layered Reflections. Layered reflections are observed in the upper 2 sec (\sim 3 km) between VP's 350 and 664 on line 11 (Fig. 5) and between VP's 465 and 600 on line 9 (Fig. 8). The traveltimes to the top and bottom of the layered reflection sequences are the same on lines 9 and 11 where those profiles intersect. They thus appear to be from the same geologic source. On line 9, the east dips of the individual reflections within this group increase with depth. On line 11, the layered reflections show some traveltime variations but are essentially subhorizontal.

The location of the layered reflectors corresponds to the area north and west of cinder hill

TABLE 2. INTERVAL VELOCITIES

2-way traveltimes	Inferred rock type	Range of estimated interval velocities
0.0-2.0 s	Alluvium, evaporites	1.5-4.0 km/sec
0.0-2.0	Volcanics, crystalline rocks, pre-Tertiary sedimentary rocks	4.5-5.5
2.0-6.5	Crystalline and sedimentary rocks	5.0-6.5
6.5-10.0	Crystalline rocks	6.0-7.5
10.0-16.0	Upper-mantle rocks	7.5-8.5

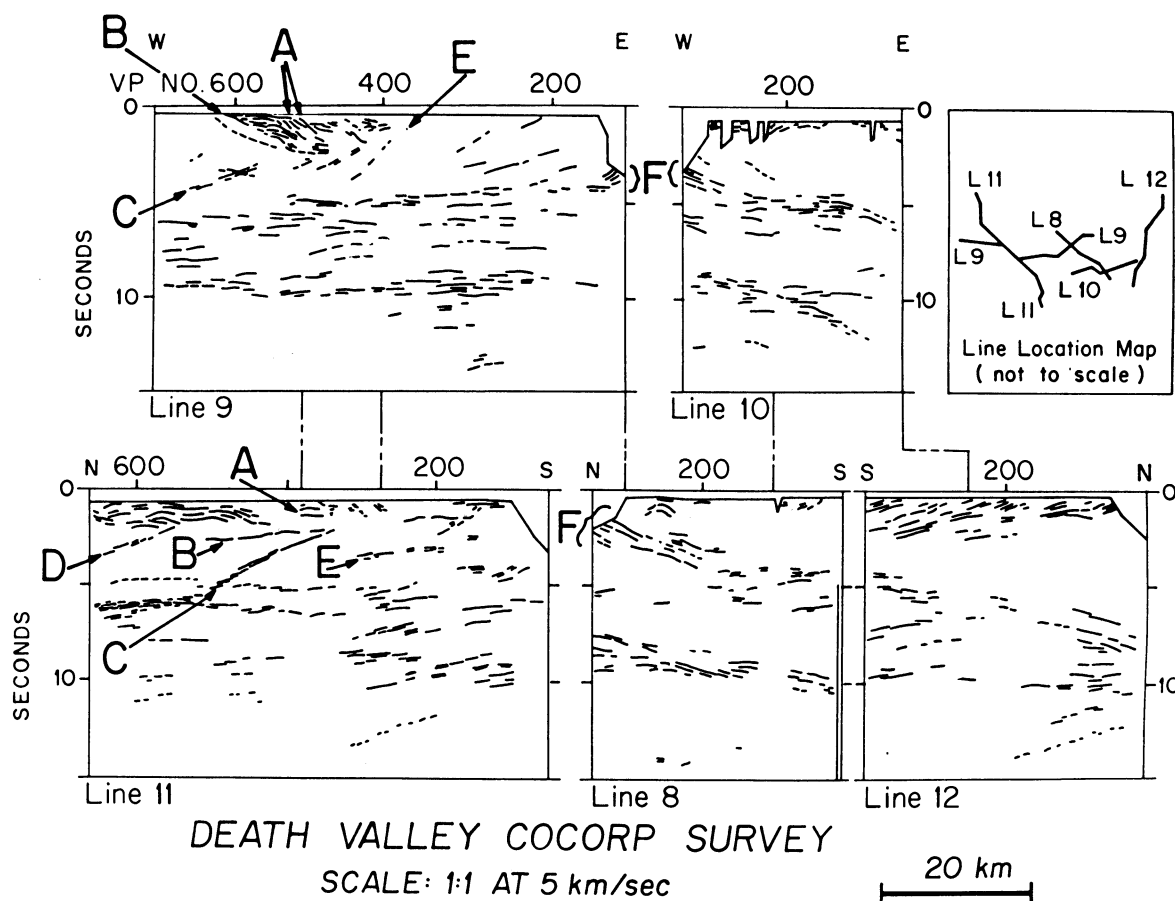


Figure 11. Line drawing of the Death Valley seismic profiles. Letters are discussed in the text.

(CC in Fig. 2) which Burchfiel and Stewart (1966) define as the central Death Valley pull-apart basin. It is also the area where gravity data (Mabey, 1963) indicate that the basin fill is deeper than that of nearby basins. Mabey (1963) suggests that the basin is a half-graben with a maximum 3-km thickness of sediments along the eastern margin, and the fanning dips of the reflectors are similar to those observed in seismic data from half-grabens (Serpa and others, 1984). Thus the layered reflections are interpreted to be from the basin sediments.

Upper-Crustal Dipping Events. Examples of the dipping events (labeled A through F) are shown in Figures 4, 5, 8, and 11. Events A and B appear to be confined to the upper 4 km (2.5 sec) of the crust, whereas the remaining events (C through F) are inferred to extend throughout the upper 15 km (5 sec) of the crust. Events C and D are prominent on true amplitude displays (Fig. 5), and thus they appear to be from subsurface boundaries where rocks of greatly differing material properties (velocity, density, or both) are in contact. In contrast, A and E are relatively weak events which are discernible, but not prominent, on displays of the data in which the

gain has been adjusted to enhance reflection strength (Fig. 8). B and F are prominent on all displays but do not show the unusually high amplitudes of events C and D. Several other dipping reflections (not labeled) are present in the upper 5 sec of the seismic data (Fig. 11). These unlabeled events vary in strength between those of events B and E.

Most of the dipping reflectors are interpreted to be faults. That interpretation is based in part on the observation that the reflectors truncate or offset other reflectors recorded in the data. The main basis for the interpretation, however, is the correlation of reflectors with mapped faults.

Events A appear to be typical of the shallow faults mapped in the region. On line 9 (Fig. 8), they dip to the east within the basin and project to a set of north-trending normal faults mapped in the Quaternary alluvium (Fig. 10). Thus events A are interpreted to be the subsurface continuation of those mapped faults. Using the north strike of the mapped faults and their apparent dips on line 9, the true dips of the faults are estimated to average 35 degrees east. The moderate dip of events A and their termination above horizon B are consistent with the geome-

tries of many of the shallow faults described by Wright and Troxel (1973).

Similarly, event B can be traced, on line 9, to the exposed boundary between the sedimentary cover rocks and the igneous basement rocks (Figs. 2 and 8) of the Panamint Range. The estimated N54°W strike and 32°NE dip suggest that B is a continuation of a curved fault mapped on the eastern flank of the Panamint Range (Fig. 10). Because event B passes beneath A without offset and projects to the boundary between the crystalline and sedimentary rocks, B is interpreted here to be a master fault along the top of the basement, similar to those described by Wright and Troxel (1973).

Near the intersection of lines 9 and 11 (the southeastern side of the basin), reflector B (Figs. 5 and 8) appears to mark the base of the layered sequence. Thus it is interpreted to be the bottom of the basin in that area. Between VP's 450 and 664 on line 11 and VP's 540 and 610 on line 9, however, B appears to be separated from the base of the layered reflectors by intervening zones which are seismically transparent. The lack of coherent reflectors within the intervening zones could be explained by the presence of clas-

tic sediments (Sangree and Widmier, 1977) in that part of the basin. On line 9, however, the transparent zone projects to the mapped pre-Tertiary sedimentary rocks and thus is interpreted to be the faulted sedimentary rocks (Figs. 2, 5, and 8). The transparent zones on line 11 may also indicate the presence of buried blocks of faulted rock near the base of the unconsolidated sediments.

Shallow faults, similar to those discussed above, are also interpreted to lie beneath the alluvium along line 12 (Fig. 11). In that area, there are numerous curved and gently south-dipping reflectors in the upper 2.5 sec (4 km) of the seismic data. Because the two-dimensional migration did not improve the continuity of these events nor separate crossing events, the shallow reflectors are inferred to be located outside the vertical plane of the seismic section. The apparent dip directions (south and southwest) are consistent with the mapped (Wright, 1974) orientations of the shallow faults in the Precambrian and Cambrian rocks of the adjacent Nopah Range. Thus the seismic data suggest that those mapped faults continue beneath the alluvium on the east side of the Nopah Range.

Shallow faults are mapped throughout the area of the COCORP profiles, but only in the areas discussed above do they appear to be imaged in the seismic data. There are two possible explanations for the absence of shallow fault-plane reflectors elsewhere in the data. One is that the juxtaposed lithologies may not have significantly different velocities and densities, and thus no reflection is generated. The second is that the faults may penetrate less than 500 m into the subsurface. Reflections from the upper 500 m of the crust were obscured by shallow refracted energy in the seismic data and, therefore, were muted (set to zero) during the data processing. Thus faults which penetrate less than 500 m into the subsurface are not indicated in the processed seismic data.

Wright and Troxel (1973) observe that most of the faults in the Death Valley region are shallow, occurring primarily in the sedimentary cover rocks. They also describe a number of widely spaced fault zones in the area which appear to penetrate well into the crystalline basement. Reflections C through F in the seismic data are inferred to be from such deep faults. In particular, west-dipping faults are mapped between the tilted mountain blocks throughout the Death Valley area. West-dipping reflectors observed on profiles 9 and 10 (Fig. 4) appear to correlate with those mapped faults and to extend to depths of 9 to 18 km (3 to 6 sec) in the crust. All of the deep, west-dipping fault-plane reflectors appear similar in that they are weak but clearly identifiable against the seismically transparent crystalline rocks.

Event E (Figs. 4 and 10) appears to be typical of the west-dipping fault-plane reflectors. It is imaged in both profiles 9 and 11 near their intersection. The strike and dip of this inferred fault is estimated from the seismic data to be N10°E 30°W. Event E projects to a sequence of mapped normal faults located along the western side of the Black Mountains (Fig. 10). The estimated strike of E agrees well with the north trend of those mapped faults, and thus reflector E is interpreted to be a subsurface continuation of those faults.

The interpretation of the events labeled F in Figure 11 is complicated by the fact that those events are observed only near the ends of profiles where there was a large offset between the source and receivers during data collection. When the refracted arrivals were muted from those data, a significant amount of shallow information was lost. As a result, events F cannot be reliably projected to the surface. Their location on the eastern side of the Black Mountains and their apparent east and north dips, however, are consistent with those of the proposed Sheephead fault detachment. Wright and others (1987) suggested that the Sheephead fault zone (Fig. 2) is a remnant of a detachment which formed prior to the current episode of extension in Death Valley. The subsequent deformation of the region has obscured much of the surface evidence for the detachment, and the seismic data provide the first subsurface evidence for its existence.

There are two zones of prominent dipping reflectors, events C and D (Fig. 11), that do not appear to correlate directly with mapped faults. Event C consists of a set of subparallel reflections and associated diffractions (Figs. 5, 7, 8, and 11) which can be traced between 2 and 6 sec (3 and 15 km, respectively) in both lines 9 and 11. Its position at 2 sec on both profiles (VP 470 on line 9 and VP 350 on line 11) coincides closely with the location of a sharp offset and a change in the velocity of the shallow refracted arrivals (Fig. 9). Because the basin-fill reflectors do not appear in the seismic data south of that area, C is interpreted to be the basin-bounding fault zone. Event C dips ~25 degrees northwestward to extend beneath the basin sediments and thus appears to be a zone of normal or dip-slip faults.

The N28°E strike of event C projects it into the topographic low of Wingate Wash, which separates the Panamint Range from the Owlshhead Mountains (Fig. 10). Several short faults with approximately the same orientation as C have been detected in the Tertiary volcanic flows of Wingate Wash (Wagner, 1988) (Fig. 2). These features, including event C, provide evidence that Wingate Wash is fault controlled. We therefore collectively designate those faults

as the Wingate Wash fault zone and observe that it apparently separates the Panamint Mountains block in the north from the Owlshhead Mountain block to the south.

Event D (Figs. 5, 10, and 11) lies ~25 km north of C in line 11. The seismic data in this area do not provide three-dimensional control, and D cannot be traced to an exposed feature. Event D, however, truncates layered reflectors near the bottom of the basin, and its subsurface position coincides with a west-trending gravity gradient (Mabey, 1963) (Fig. 10). The direction of decreasing gravity values across this gradient is consistent with the apparent displacement, north side down, across D. D is thus inferred to be a west-trending (that is, parallel to the gravity gradient) zone of dip-slip faults.

There is no geologic evidence to suggest that, below the basin sediments, rocks of distinctly different density or elastic properties are juxtaposed across faults. The presence of apparent fault-plane reflections in the seismic data, however, indicates that such juxtapositions are possible. Alternatively, the reflections may be related directly to materials within the faults. The presence of hot springs in the vicinity of Death Valley (Higgins, 1980) indicates that hydrothermal fluids may be circulating along fault zones and, as discussed by de Voogd and others (1986a) and in the following section, there is evidence to suggest that the Wingate Wash fault zone and possibly other fault zones have acted as conduits for magma traveling in the upper crust. Thus the impedance contrasts associated with the fault reflectors are inferred here to be due to the juxtaposition of differing lithologies across the fault zones or the presence of fluids, hydrothermal alteration products, intrusions, brecciated or mylonitized rocks, or some combination of those features within the fault zones.

The Mid-crustal Reflecting Zone. At a travelt ime of 5.0 ± 1.5 sec (15 km) on all of the profiles, there is a prominent zone of reflections. On line 12, the mid-crustal zone can be traced from a depth of ~15 km in the southwest to a depth of 25 km in the northeast. Elsewhere the mid-crustal reflecting zone shows travelt ime variations consistent with a subhorizontal source. That is, the reflections are latest (6.5 sec) beneath the sediments of central Death Valley and fastest beneath the mountain ranges. Although some travelt ime variations may be related to changes in the depth of the source zone, the major variations appear to be due to the variations in the velocity of the overlying material.

The reflecting zone varies in thickness from 3 to 5 km (1 to 2 sec) and typically includes 2 to 3 distinct reflecting bands. It is most prominent in a 30-km-long region beneath the surface of the central Death Valley basin (Fig. 5). In that area, the amplitudes of the reflections are, on the av-

erage, 10 dB higher than those measured at comparable times elsewhere in the seismic data (de Voogd and others, 1986a). de Voogd and others compared those measured amplitudes, as well as the frequency content and continuity of the reflections, with those of reflections from an inferred magma body (Sanford and others, 1973; Brocher, 1981) in the Rio Grande rift (Figs. 1 and 7). Because these two reflecting sequences appeared to be similar, de Voogd and others suggested that the Death Valley reflections also are from a deep magma body. That interpretation is further supported by the observation that the moderately dipping reflectors of the Wingate Wash fault zone (C in Fig. 5) connect the inferred magma body to the youngest known (Crowe and others, 1983a) volcanic feature in the area, a 690,000-yr-old (R. Drake, 1986, oral commun.) cinder cone.

Based on the geochemistry of the cinder cone basalts (hawaiites), Crowe and others (1983b) suggested that the basalts were derived from a shallow magma source. They interpreted the location of the magma source to be near the base of the crust, following the model of Herzberg and others (1983). The geochemistry, however, does not exclude the possibility that the source magma was within the crust (Morrison and others, 1985). The cinder cone basalts are therefore interpreted here to be derived from the inferred mid-crustal magma body beneath central Death Valley. Because the Wingate Wash fault zone can be traced between the cinder cone and the inferred magma body, it is inferred to have provided the path for the magma migration.

There is no evidence to suggest that the mid-crustal reflecting zone is associated with molten rocks in other parts of the Death Valley region. It is possible, however, that outside of central Death Valley the mid-crustal reflections are from cooled intrusions. Similarly, the observation that none of the inferred fault plane reflectors can be traced below the mid-crustal zone indicates that the zone may be either a deep detachment, as proposed by Wright and Troxel

(1973), or a zone of transition between the brittle upper crustal rocks and a ductile lower crust, or both. Based on a possible correlation of this mid-crustal reflecting zone with a similar zone of reflections recorded in COCORP profiles from the Mojave desert region, Serpa (1988) also suggested that the horizon represents a subsurface feature which formed near the base of the crust prior to the current episode of extension and was uplifted to its present position during the past 6 m.y. Some combination of the above interpretations also provide possible sources for the mid-crustal horizon observed in the Death Valley seismic data. Additional data will be required before a unique interpretation of the mid-crustal reflecting horizon or the deep-crustal reflectors, discussed below, can be presented.

Lower Crust and Upper Mantle of Death Valley

Below the mid-crustal reflecting horizon, there is a region of subhorizontal reflectors (Fig. 11) which extends to a depth of ~30 km (10 sec). Within that region, reflectors are numerous, and many individual reflectors are prominent. None can be traced over horizontal distances greater than 15 km, however. The absence of continuous horizons may indicate that the lower crust is deformed, either as a result of the recent extension or some earlier event, or both. Alternatively, igneous activity, possibly associated with the inferred mid-crustal magma

body, may have disrupted pre-existing layered features of the lower crust. We prefer the interpretation that the lower crustal reflectors are the result of both ductile deformation and intrusive activity related to the recent extension in Death Valley, because that interpretation is consistent with (1) previous inferences on the nature of the lower crust in Death Valley (Wright and Troxel, 1973) based on surface information; (2) the interpretation (de Voogd and others, 1986a) of magma at mid-crustal depths and possibly in the upper mantle (discussed below); and (3) previous models of crustal rheology in the Basin and Range province (Meissner and Strehlau, 1982).

The base of the lower crustal region is marked by a prominent reflecting horizon which has a two-way travelt ime of 10 ± 1 sec (30 km). That travelt ime is consistent with the predicted travelt ime for the Mohorovičić discontinuity based on nearby seismic refraction studies (Roller and Healy, 1963; Johnson, 1965; Prodehl, 1979). Thus it is, by definition (Klemperer and others, 1986), the reflection Moho and also may represent the boundary between the upper mantle and the lower crust. There are no prominent reflections with travelt imes greater than the reflection Moho. There are diffractions on lines 10, 11, and 12 (Fig. 11), however, which may indicate irregularities along the reflection Moho.

In the Death Valley data, the reflection Moho is generally only a few cycles wide (Fig. 6). Thus it appears to be a sharp boundary rather than the

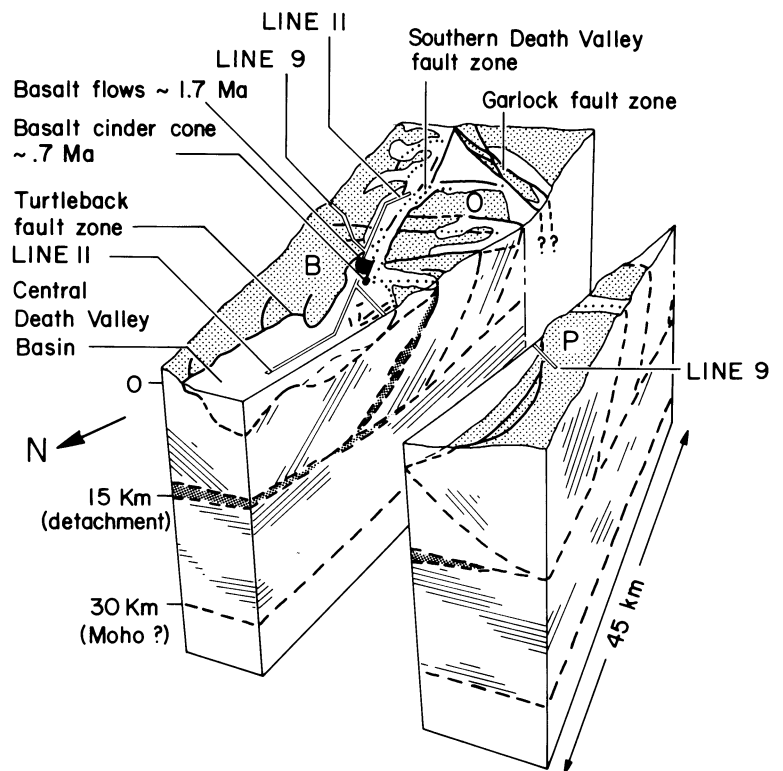


Figure 12. Block diagram of the southern end of the CDV basin showing the major crustal geologic features interpreted from the combined surface and seismic reflection data. The fine lines in the areas of the upper and lower crust indicate the general trend of reflectors in those areas, dark stipple indicates the inferred magma plumbing system, and light stipple indicates the exposed areas of the mountain blocks. B = Black Mountains, P = Panamint Range, and O = Owlshead Mountains.

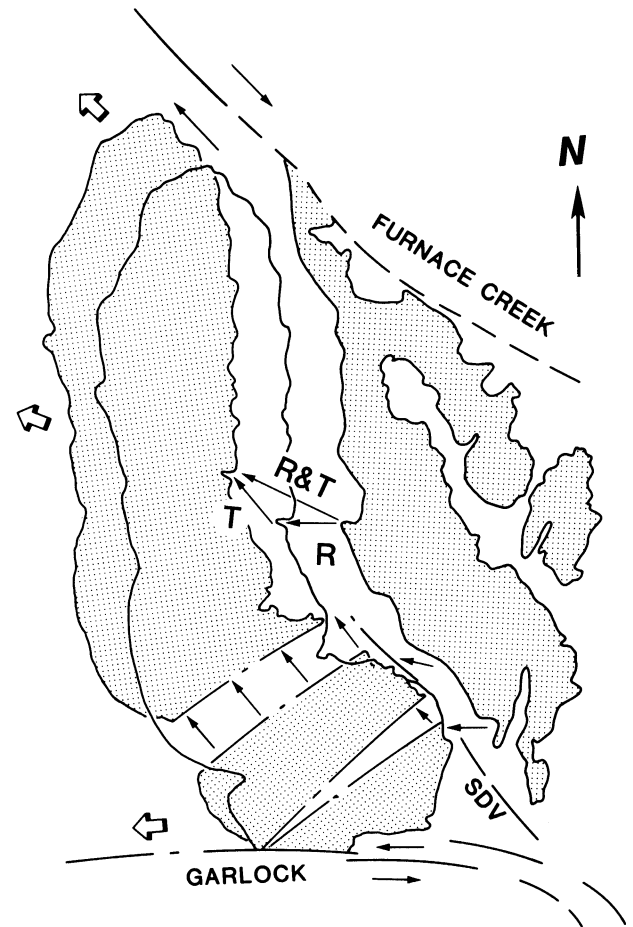
transitional Moho inferred (Meissner, 1973) to characterize the base of continental crust in many other parts of the world. De Voogd and others (1988) observed an abrupt decrease (3 dB) in the amplitude of the recorded seismic energy at the base of the reflection Moho. This change in amplitude indicates that energy is penetrating to the reflection Moho that is not returning to the surface. That may indicate that there are no reflecting boundaries at sufficiently shallow depths within the mantle to return energy to the surface geophones during the recording time of the survey, or that all of the energy is attenuated at the reflection Moho boundary. That observation, combined with the narrow width of the reflecting zone, suggests that the reflection Moho in Death Valley represents a distinct change in the material properties of the deep rocks.

The Death Valley reflection Moho has approximately the same traveltime and, thus, a depth (± 5 km) approximately equal to the reflection Moho imaged in COCORP data from the northern Mojave desert (Cheadle and others, 1986) and the northern Basin and Range (Klemperer and others, 1986). Because the amounts and times of late Cenozoic crustal extension vary significantly between the Mojave block, Death Valley, and the northern Basin and Range province (Davis and Burchfiel, 1973; Wright, 1976), but the time to the reflection Moho appears to be relatively constant throughout the region, it is unlikely that the reflection Moho in the Great Basin is a pre-extensional feature which has been uplifted to its present depth as a result of crustal thinning. The reflection Moho in the Great Basin is therefore inferred, here, to be related to the late Cenozoic extension in the western United States.

Klemperer and others (1986) also suggested that the reflection Moho in the northern Basin and Range is younger than the crust and might represent a zone of magma located near the base of the crust. That interpretation is consistent with the geometry and seismic character of the reflection Moho, as well as the tectonic setting and the inferred presence of magma in the crust, in the southern Great Basin. Alternatively, the sharp reflection Moho may represent the base of lower crustal intrusions, a deep detachment zone, or a metamorphic phase boundary.

In summary, many of the features observed in the seismic data are inferred to be the result of igneous activity and deformation related to the extension of the Death Valley region. A block diagram showing the interpreted structure of the central Death Valley basin is shown in Figure 12. In Death Valley, the extensional features are well exposed at the surface, and the correlation of the seismic and map data allows a reconstruc-

Figure 13. Reconstruction of inferred fault block movements in the vicinity of central Death Valley. Small arrows show the direction of movement indicated by the surface and seismic data across individual faults. R is the movement due to the fault-block rotations, T is the movement due to the fault-block translations, and R&T are the combined movement due to the simultaneous rotation and translation. Large arrows indicate the inferred general pattern of fault-block movements resulting from displacements across all of the faults in the area.



tion of the nature of upper-crustal fault-block movements during the recent episode of extension. That reconstruction is discussed below.

BLOCK FAULTING AND THE EVOLUTION OF THE CENTRAL DEATH VALLEY BASIN

The combined geologic and geophysical data in the vicinity of Death Valley (Figs. 2 and 10) indicate that two types of fault-block movements have occurred during the late Cenozoic crustal extension of the Death Valley region. The first type is the rotation of the fault blocks, down to the east (Fig. 4). That rotation accompanies a westward horizontal displacement of the Panamint and Owshead Mountain blocks (R in Fig. 13) relative to the Black Mountain block and dip-slip displacements along the frontal faults of the Black Mountains. Because the horizontal movements related to the rotations of the fault blocks are subparallel to the trend of the Garlock strike-slip fault zone, they may contribute to the left-lateral offset of features across the Garlock, as suggested previously by Davis and Burchfiel (1973).

The second type of fault-block movement is

the northwest-directed translation (T in Fig. 13) indicated by the dip-slip displacement across the northeast-trending faults, such as those of Wingate Wash. The right-lateral strike-slip displacement across the southern Death Valley fault zone is due to the translation of the Owshead Mountain block relative to the Black Mountain block. Similarly, the northwest translation of the Panamint block contributes to the right-lateral offset of features across the Furnace Creek fault zone.

Both the northwest-directed translation of the fault blocks and their westward movement, related to the rotation, were widely recognized prior to this study. Previous models for the basin subsidence, however, have focused primarily on one type of fault-block movement, either the translation (Figs. 3 and 14A) (Burchfiel and Stewart, 1966) or the rotation (Figs. 4 and 14C) (Wright and Troxel, 1973). The identification in the COCORP seismic data of the Wingate Wash fault zone between the Panamint and Owshead Mountain blocks indicates that the basin subsidence is the result of the simultaneous rotation and translation (R & T in Fig. 13) of the fault blocks.

The fanning east-dip of the basin sediments is

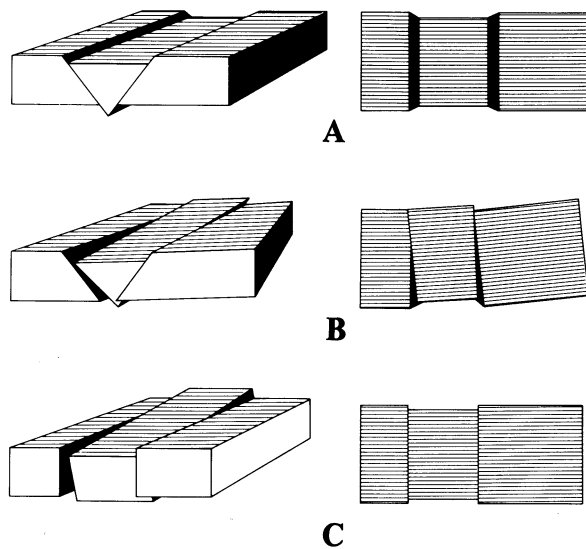


Figure 14. Schematic block diagram of the types of fault-block displacements during extension. A = pure translation, B = combined rotation and translation such as that inferred in Death Valley, and C = pure rotation.

evidence that the Panamint block was rotating down to the east during the time those sediments were being deposited. The Owlhead block also may have been rotating at the time of the basin formation. The gravity (Fig. 10) (Mabey, 1963) and the seismic (Fig. 11) data, however, indicate that the sediments that fill the basin between the Owlhead and Black Mountains are less than 1 km thick. Thus the Owlhead block appears to have rotated significantly less than did the Panamint block. Because the Owlhead block projects beneath the southern side of the Panamint block, along the Wingate Wash fault zone, the differential rotation between the two fault blocks could not have occurred unless the Panamint block also moved to the north (the translation) during rotation, in a manner similar to that shown in Figure 14B.

As a result of the simultaneous rotation and translation of the Panamint block, the displacements across the turtleback surfaces and the Wingate Wash faults include both a dip-slip and a strike-slip component. That observation is consistent with the northwest trend and plunge of linear features mapped (Curry, 1954; Otton, 1976) on the surfaces of the Black Mountain faults. Similarly, because the directions of the fault-block movements appear to vary throughout the area, many of the faults are oblique-slip faults.

The reconstruction suggests that the fault blocks along the northern side of the Garlock fault zone are moving predominantly toward the west relative to the Black Mountains. The north dips (and possibly south dips) of the northeast-trending faults between the Garlock and Furnace Creek fault zones, however, add a northward component of displacement to each of the fault blocks, and that displacement increases to-

ward the north. Because, at the same time the blocks are moving to the west in association with their rotation, each fault block is also moving to the north with the accumulated displacement of all of the fault blocks south of its position, as well as an additional amount away from the block immediately to the south, the net direction of displacement of the fault blocks changes, radially, from west to northwest between the Garlock and Furnace Creek fault zones.

The varying directions of the horizontal displacements, indicated by the reconstruction (Fig. 13), appears to provide a geologic example of the three-dimensional strain that was proposed (Reches, 1978) previously on the basis of theoretical calculations for the block faulting in the western United States. Within the area of the reconstruction, the fault blocks appear to be moving away from the projected intersection of the Garlock and Furnace Creek fault zones. The trend and sense of displacement across those two nonparallel strike-slip systems (Fig. 1), over distances of several hundred kilometers, suggest that the directions of the fault-block movements in the vicinity of Death Valley are typical of the entire region between the Furnace Creek and Garlock fault zones.

CONCLUSIONS

Figure 12 shows the major crustal features indicated by the seismic data in the vicinity of the central Death Valley basin. The geologic interpretation presented here is based in large part on the correlation of reflectors imaged in the seismic data with mapped surface features. The geometries and locations of many of the reflectors confirm elements of the subsurface geology

previously inferred (Wright and Troxel, 1973) from surface studies (Fig. 4) and provide insight on the structural evolution of the region during severe Cenozoic extension (Fig. 13). These data suggest that the subsidence of the central Death Valley basin is the result of the simultaneous rotation and translation of the upper-crustal fault blocks during extension.

There has been considerable recent discussion (Wernicke, 1987a, 1987b; Serpa, 1988; Wright and others, 1987) regarding two possible models for the pre-extensional position of the Panamint Mountains block. One model would place the Panamint directly above the Black Mountain block prior to the formation of the central Death Valley basin (Stewart, 1983; Wernicke, 1987a, 1987b). The other model places the two fault blocks adjacent to each other prior to the basin subsidence (Noble and Wright, 1954; Wright and Troxel, 1973). The seismic data indicate that the Panamint Mountains block is now at least 15 km thick and do not show evidence for the shallow detachment within the Panamint that Stewart (1983) suggested should exist. The estimate of the thickness of the Panamint is based on the depth to which faults along the eastern and southern boundaries of the mountains can be traced in the seismic sections. In addition, the shallowest feature which appears to be regionally continuous in the seismic data is the mid-crustal reflecting zone which passes beneath both the Panamint and Black Mountain blocks in the manner originally suggested for a fault-block detachment in the model of Wright and Troxel (1973). It may be possible to modify the Stewart (1983) model to accommodate these observations (B. Wernicke, 1987, personal commun.), but at this time the model of Wright and Troxel appears to be most consistent with the seismic data. We therefore prefer that model.

The moderately dipping faults, tilted fault blocks, and asymmetrical basin imaged in the Death Valley seismic data are similar to features observed in COCORP profiles from the northern Basin and Range province (Allmendinger and others, 1987; Klemperer and others, 1986). In Death Valley, the interpretation of the seismic data is unusually well constrained by the surface geology and the intersecting seismic profiles. The three-dimensional nature of the block faulting is therefore more evident in Death Valley than elsewhere in the western United States. Focal mechanisms derived (Smith and Sbar, 1974) from earthquakes in the Basin and Range, however, often indicate oblique- or strike-slip displacements in areas where predominantly normal faults are mapped. Those focal mechanisms and the varying orientations of faults (Stewart and Carlson, 1978) throughout the Great Basin indicate that the complex pattern of

block faulting observed in Death Valley may be typical of many other parts of the western United States.

Reflections from a depth of ~15 km beneath the basin are inferred (de Voogd and others, 1986) to be from a partially molten intrusive body. Magma from that intrusive body appears to have traveled to the surface, 690,000 yr ago, along the moderately dipping faults of Wingate Wash. Thus the seismic data appear to provide an image of the upper-crustal plumbing system used during the migration of basaltic magmas. Because volcanic flows are commonly located along fault zones (Stewart and Carlson, 1978) and dikes have been mapped (Allmendinger and Jordan, 1984; Crowe and others, 1983b) within faults in many parts of the western United States, moderately dipping fault/conduits, such as that imaged in the Death Valley seismic data, may be a common feature of the Great Basin region.

Most geophysical profiles and geologic cross sections in extensional terranes are oriented perpendicular to the trend of mountains and basins because that orientation is generally assumed to provide the most information on the extensional features. As a result, crustal extension is often viewed as a two-dimensional process. The reconstruction of the fault-block movements, as well as the evidence for the magma body and the fault/conduit, however, is based primarily on the information provided by the seismic profiles which trend parallel to the mountains and basins in Death Valley. The Death Valley seismic data, combined with the surface geology, thus provide a rare three-dimensional view of extensional structures, and that view suggests that crustal extension is a more complex process than the two-dimensional models have indicated.

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