Crustal extension and magmatic processes: COCORP profiles from Death Valley and the Rio Grande rift

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ABSTRACT

New crustal-scale information on the interaction between normal faulting and magmatic activity is provided by recent COCORP deep seismic reflection profiles in Death Valley, California, and by reprocessing of the COCORP data from the Socorro area of the Rio Grande rift, New Mexico. The most striking feature on the seismic sections from these areas is a prominent, subhorizontal series of reflectors at mid-crustal depth. Previous studies have suggested that thin tabular magma bodies lie within the mid-crustal reflective zones. In addition, because they are traced without apparent offset beneath faults both mapped at the surface and interpreted from the COCORP data, these mid-crustal horizons are here inferred to be detachments or zones of tectonic decoupling.

Upper-crustal Cenozoic faults do not appear to penetrate deeper than 15 km in Death Valley and 13 km in the Rio Grande rift. In Death Valley, these faults are relatively planar, with moderate dips (20° to 35°), and appear to bound large basement rocks. One such zone of normal faults can be traced from the magma body inferred at 15 km depth beneath central Death Valley to the surface location of a 690,000-yr-old basaltic cinder cone. Listric and low- to moderate-angle normal faults are evident on the reprocessed New Mexico data and constitute the structural component of upper-crustal extension. In particular, a listric master fault traceable to depths as great as 13 km is inferred to underlie the Albuquerque basin. Unlike the Death Valley data, no faults are observed to merge with the Socorro magma body per se. Rather, subhorizontal to moderately west-dipping packages of reflections are imaged between the base of the faulted upper crust (13 km depth) and the mid-crustal magma body (about 20 km depth).

The middle crust marks a major rheological boundary between the faulted upper crust and a ductile lower crust extending by penetrative flow and intrusion. Events seen in the middle and lower crust are generally subhorizontal, and prominent layering is observed. A band of reflections attributed to the crust-mantle boundary is evident on most seismic sections. The upper mantle appears seismically transparent. On some of the profiles, the events attributed to the base of the crust are the deepest in a series of strong and continuous reflections, at least one of which is a layer of magma. This association supports the suggestion that magmatic intrusions are a probable cause for the high reflectivity observed in the deep crust of many extensional terranes.

INTRODUCTION

Deep faults and mid-crustal magma bodies are interpreted from seismic reflection profiles collected by COCORP (Consortium for Continental Reflection Profiling) in two areas of late Cenozoic extension, the Rio Grande rift near Socorro (New Mexico) and the Death Valley area of the southern Great Basin (California). This study includes heretofore unpublished COCORP profiles across the late Cenozoic Socorro cauldron complex. The seismic data provide new crustal-scale information on the interaction between normal faulting and magmatic activity and on the link between upper and lower crustal extension. Other results of the Rio Grande rift and Death Valley surveys are summarized here, but more detailed discussions can be found in Brown and others (1980a), de Voogd and others (1986a), and Serpa and others (1988).

Much controversy remains in explaining how crustal extension is accommodated at depth, and the literature includes numerous models, such as (1) a subhorizontal, mid-crustal decoupling zone of ductile rheology (Stewart, 1971; Eaton, 1982), together with a significant flux of mantle-derived magmas into the crust (Gans, 1987); (2) anastomosing shear zones or "lenses" (Hamilton, 1982; Kligfield and others, 1984); and (3) crustal-penetrating shear zones (Wernicke, 1981). Seismic reflection profiling does not uniquely support any one model of crustal extension (Allmendinger and others, 1987). The model proposed in this paper for the New Mexico and Death Valley areas belongs to category 1 above, where magmatic activity is an important factor in crustal extension and evolution.

The most prominent feature of the seismic profiles of this study is a subhorizontal mid-crustal band of unusually strong reflections (G and DVBS, Figs. 1 and 2). The strong mid-crustal reflector G (Fig. 1), believed to be the tabular magma body previously inferred and mapped from earthquake studies in the Socorro region by Sanford and others (1973), was identified on the COCORP profiles by Brown and others (1979). The relationship between magmatic activity and normal faulting, however, was unclear after the initial contractor processing of the data. The early results (Brown and others, 1980a; Cape and others, 1983) also failed to identify normal faults deep within the basement, leaving questions about the style of extension beneath the sedimentary section and the nature of structures associated with the Socorro magma body largely unresolved. This new investigation was motivated by success with reprocessing and reanalysis of New Mexico (Abo Pass) line 1, where a Cenozoic fault surface could then be traced to a depth of at least 10 km (de Voogd and others, 1986a), and by more recent COCORP profiles which suggest a previously unrecognized mid-crustal magma body beneath central Death Valley (de Voogd and others, 1986b; DVBS, Fig. 1).

The middle crust is of particular interest because it is the locus of a

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Geological Society of America Bulletin, v. 100, p. 1550–1567, 15 figs., 1 table, October 1988.

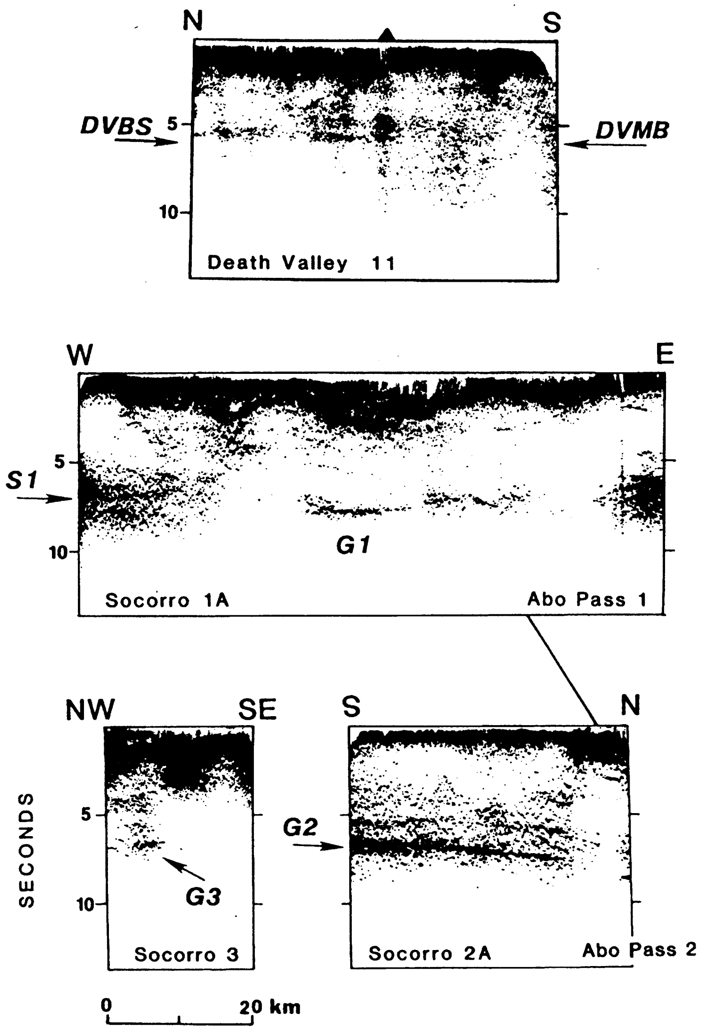

Figure 1. True amplitude sections from Death Valley line 11 (top) and the Rio Grande rift COCORP data; exponential gain applied to the upper 3 s to partially correct for geometrical spreading; unusually bright reflections DVBS, G1, G2, and G3 are attributed to partially molten rocks (Brown and others, 1980a; de Voogd and others, 1986b). This high reflectivity is more quantitatively illustrated in Figure 2. The basement also appears quite reflective beneath the flanks of the rift basin (western part of Socorro line 1A and eastern part of Abo Pass line 1); however, this seemingly high reflectivity is most likely not due to the presence of magma, and other explanations such as a much higher signal-to-noise ratio outside the rift basin and/or constructive interferences due to fine layering have been discussed by de Voogd and others (1986a). In the western part of Socorro line 1A, coherent reflection segments can be correlated at about 7 s to suggest the presence of a subhorizontal mid-crustal horizon S1 (discussed in text).

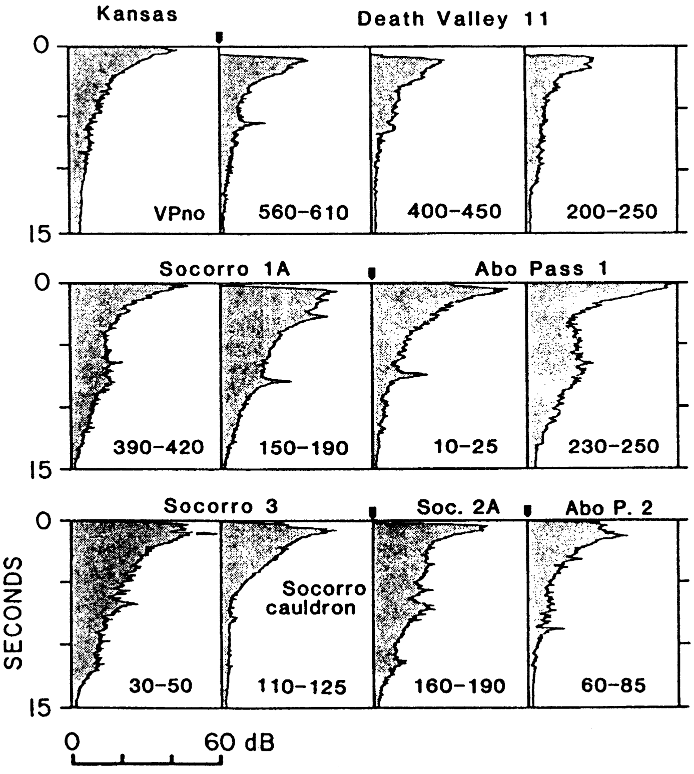

Figure 2. Average seismic amplitude versus time curves calculated from the stacked sections shown in Figure 1 and plotted versus two-way traveltime; included here for comparison with a cratonic area where numerous basement structures are imaged, the top left curve is calculated from Kansas COCORP line 3 (Brown and others, 1983); although the Kansas sections have very good data quality and show coherent reflected energy down to at least 14 s (~45 km), the corresponding decay curve is quite smooth and does not indicate highly reflective zones comparable to the New Mexico or Death Valley mid-crustal events.

major change in mode of extension, between a faulted upper crust and a sheared and intruded lower crust. It is imaged on reflection profiles and also thought to be widely exposed in Eocene through Pliocene "core complexes" (Gans and others, 1985; McCarthy, 1986), where it is seen to include sharp discontinuities separating brittlely faulted upper-plate rocks from variably metamorphosed and ductilely deformed rocks in the lower plate (Crittenden and others, 1980). The existence of a transition from brittle to ductile deformation is also expected on the basis of laboratory and earthquake data. This transition may be a sharp boundary (Meissner and Strehlau, 1982) or a transitional boundary a few kilometers thick, perhaps a ductile shear zone (Sibson, 1983; Tullis and others, 1982). Both the Socorro and the Death Valley magma bodies occur at similar depth, and within, or at the base of, the laterally continuous zone of reflections that separates the faulted upper crust from the relatively layered lower crust. Thus, the magma may have been trapped at the base of a major rheological boundary. Because both mid-crustal reflecting zones pass, without apparent offset, beneath faults showing late Cenozoic normal displacement, the mid-crustal reflective bands are interpreted to be zones of detachment (Serpa and others, 1988; this paper).

Various geological and geophysical studies have emphasized the compositional and rehological heterogeneity of the lower crust (for example, Fountain and Salisbury, 1981; Kay and Kay, 1981). Magmatic and tectonic processes proposed as mechanisms of crustal evolution are reviewed in Kay and Kay (1986). Magmatic underplating and associated replacement of the mantle lithosphere have been shown theoretically to be a physically reasonable process to create continental crust (Furlong and Fountain, 1986). The COCORP results provide new evidence that the

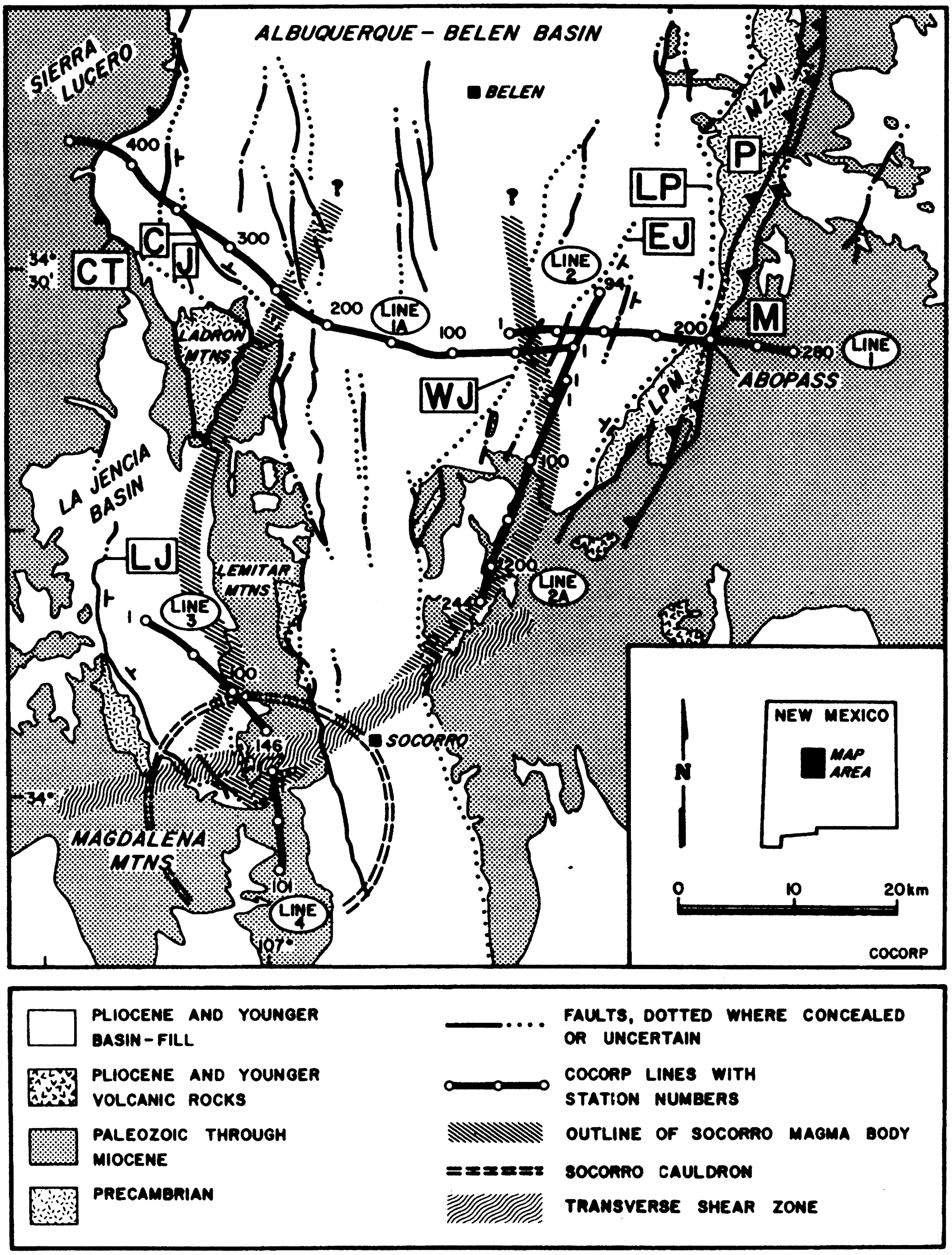

Figure 3. Location of COCORP New Mexico surveys; geology sketched from Kelley (1977) and Machette (1978); approximate extent of Socorro mid-crustal magma body drawn from Sanford and others (1977) and Rinehart and others (1979). Faults labeled CT, C, J, WJ, EJ, LP, P, M, and LJ are the Comanche, Coyote, Jeter, West Joyita, East Joyita, Los Pinos, Paloma, Montosa, and La Jencia, respectively (named after Kelley, 1977); LPM and MZM are the Los Pinos and Manzano Mountains, respectively.

lower crust in the two regions of Cenozoic extension discussed hereafter is extensively intruded.

In the following sections, we present a description of the seismic data, with special emphasis on deep features and on new results from the Rio Grande rift. The Death Valley profiles are discussed in more detail in Serpa and others (1988). We will argue that, in both areas, a distinct, subhorizontal tectonic boundary exists at mid-crustal levels, and that the deep crustal layering observed on the seismic sections is probably igneous in origin. Because the emplacement of magmatic intrusions represents a major input of heat, likely to affect crustal rheology, the relationship between magmatism and mode of extension is an important topic for study, and the central theme of this paper.

TECTONIC SETTING AND PREVIOUS INTERPRETATIONS OF THE NEW MEXICO COCORP SURVEYS

The Rio Grande rift is a north-northeast–trending succession of en echelon basins and fault-block ranges that include the Albuquerque-Belen basin, and the Ladron and Lemitar Mountains (Fig. 3). Crustal extension began 27 to 32 Ma (Chapin, 1979) and is continuing at the present time as suggested by recent fault scarps, seismic activity, high heat flow, contemporary uplift, and the presence of an extensive mid-crustal magma body (Fig. 3; Sanford and others, 1973). Magmatic activity in the Socorro area results in earthquake swarms and surface deformation (Sanford and others, 1979; Reilinger and others, 1980; Larsen and others, 1986). Shallow dikes (less than 10 km depth), possibly rising from the top of the main magma chamber, have been inferred from detailed studies of the microearthquake data (summarized in Sanford, 1983). In the Socorro area, therefore, there is substantial evidence that, at various crustal levels, intrusive activity is associated with current tectonic deformation.

Two major episodes of rifting are documented from stratigraphy and the ages of volcanics (Chapin and Seager, 1975; Chamberlin, 1981): (1) a late Oligocene to early Miocene period of rapid extension resulting in large low-angle and listric normal faults and strongly rotated beds and (2) from mid-Miocene to present, slower extension resulting in less tilting and steeper normal faults. East of the Ladron Mountains, the Popotosa deposits and interbedded volcanics have been uplifted and tilted (10° to 60° dip; Kelley, 1977) during early stage of rifting. The younger syn-rift basin-fill of the upper Santa Fe Group overlies the Popotosa separated by an angular unconformity. The Santa Fe Group mainly consists of Miocene-Pliocene gravels, arkoses, and tuffs commonly covered by Quaternary alluvial sands and gravels (Foster, 1978). The subhorizontality of the Santa Fe Group in the Albuquerque basin (tilts less than 10° or 15°; Kelley, 1977; Chamberlin and others, 1983) argues against major listric faulting during late rift stage. Recent studies (summarized by Baldridge and others, 1984) suggest that several low-angle faults with normal displacement (for example, the Jeter fault, Fig. 3) are truncated by younger, steeper normal faults that offset Miocene strata.

The Socorro-Magdalena cauldron complex (Fig. 3), a series of 8 overlapping cauldrons, formed early in the history of rifting (27 Ma) and produced voluminous outpourings of silicic ash-flow tuffs. Cauldron collapse and resurgent doming were followed by a period of volcanic quiescence, during which the cauldron was buried by conglomerates and sediments of the Popotosa Formation. Volcanic activity was renewed 12 to 7 Ma, when rhyolitic domes, flows, and tuffs were emplaced. The most recent deposits are predominantly coarse basin fill but include basaltic lava flows as young as 4 m.y. (Chapin and others, 1978). Most of the faults mapped in the vicinity of this extrusive complex are normal faults, younger than the cauldrons, with a dominant trend N10°–25°W, and down-to-the-west motion (Osburn and others, 1981). Older faults are likely to exist buried beneath younger volcanic units.

Although the most obvious features of the Socorro region are related to late Cenozoic extension, older structures are conspicuous. Major northeast- and east-southeast–trending crustal lineaments of pre-Cenozoic origin are the most prominent regional structures in the Precambrian rocks (Chapin and others, 1978). Two of these, the Morenci and Capitan lineaments, intersect in the Socorro area. In general, voluminous volcanic centers (for example, Datil Mogollon, Jemez) are located where the rift intersects these transverse shear zones. The Socorro-Magdalena cauldron complex lies along the Morenci lineament (Chapin and others, 1978).

COCORP surveys in the Socorro area (Fig. 3) consist of an east-west transect in the Albuquerque-Belen basin (lines 1 and 1A), supplemented by a cross line (line 2) that provides some three-dimensional information, a north-south profile (line 2A) that extends line 2 to the south, across the Socorro mid-crustal magma body, and two short lines heretofore unpublished (lines 3 and 4) that constitute a north-south profile in the La Jencia basin and Lemitar-Chupadera Mountains, and that transect the Socorro cauldron.

Extensive Tertiary faulting is conspicuous on the seismic sections. Previous interpretations of the east-west transect (lines 1 and 1A; Brown and others, 1980a) confirm the existence of a shallow bench (Hubell-Joyita bench, in Kelley, 1977) beneath the southeastern portion of the Albuquerque basin. The thickness of the syn-rift basin fill varies greatly along the COCORP profiles from 0 (Precambrian outcrops; Fig. 3) to 1,500 m at Vibration Point (VP) 80 of line 1 or 4,000 m at VP 170 of line 1A (Fig. 4a; Brown and others, 1980a). Substantial basement topography is also indicated by gravity (Cordell, 1978) and aeromagnetic data (Cordell, 1976). The western and eastern boundaries of the main rift basin (Fig. 3) are crossed by line 1A around VP 420, and line 1 around VP 185, respectively. The section from line 1A (Fig. 4a) clearly demonstrates that the western edge of the Albuquerque basin is at the Comanche fault (Brown and others, 1980a), inferred to be a Laramide thrust (Kelley, 1977). The Ladron Mountains (Fig. 3) is a west-tilted uplifted block.

To the east, a marked lateral change in seismic character is observed on line 1 across the surface location of the Los Pinos fault (Fig. 4a), the basin-bounding fault (Kelley, 1977). The near-vertical zone, apparently devoid of continuous reflections, that bounds the eastern side of the basin has been shown by de Voogd and others (1986a) to be most likely an artifact of processing data which span the large lateral contrast in shallow seismic velocities across the Los Pinos fault, rather than being representative of some deeply penetrating geological structure, for example, an intrusion or a fault zone. Cape and others (1983) interpreted migrated versions of lines 1 and 1A to indicate that shallow (upper 5 or 6 km) listric faults may be the dominant structures of the rift basin but could not constrain deeper extension. Based on reprocessing and synthetic seismic modeling of line 1, de Voogd and others (1986a) suggested that synthetic and antithetic Cenozoic normal faults sole into or are truncated by a northwest-dipping listric master fault (labeled H, Figs. 4a and 4b) which bounds the eastern side of the basin and projects toward the surface position of the Los Pinos fault. This master fault can be traced to a depth of at least 10 km beneath the basin (VP 1 of line 1). It will be argued here that this fault may continue westward and underlie the entire southern Albuquerque basin.

REPROCESSING OF THE NEW MEXICO COCORP DATA

The New Mexico surveys originally received only the basic processing treatment that was available under the contractor arrangements in effect during COCORP's early years (1975–1980). The initial interpretation of line 1A by Brown and others (1980a) also relied upon reprocessed sections from Digicon, which were superior to the initial processing for the sedimentary section. Reprocessing on Cornell's MEGASEIS (TM Seiscom Delta) substantially improved the New Mexico stacked sections (Figs. 4, 5, and 6). Most of this improvement is attributed to pre-stack processing (FK filtering and deconvolution; Figs. 7 and 8) and subsequent careful velocity analysis. Data-acquisition parameters and initial contractor processing sequences are described in Brown and others (1980a) and summarized in Table 1 along with the reprocessing sequence.

For all of the seismic data reproduced in this paper, the vertical axis is two-way traveltime, and the horizontal scale is chosen so that the sections are 1:1 for a seismic velocity of 5 km/s. To alleviate the difficult task of reducing large seismic sections into prints suitable for publication, the sections in Figures 4a and 4c have a coherency filter applied after stack (Zheng and Brown, 1988). All interpreted events, however, are also clear on the sections before such filtering, and selected details of the unfiltered seismic sections are shown in Figures 5 and 6.

The following describes a few aspects of the data analysis and reprocessing that were deemed essential in the new interpretation presented in this paper. Events brought out in reprocessing are generally identifiable as

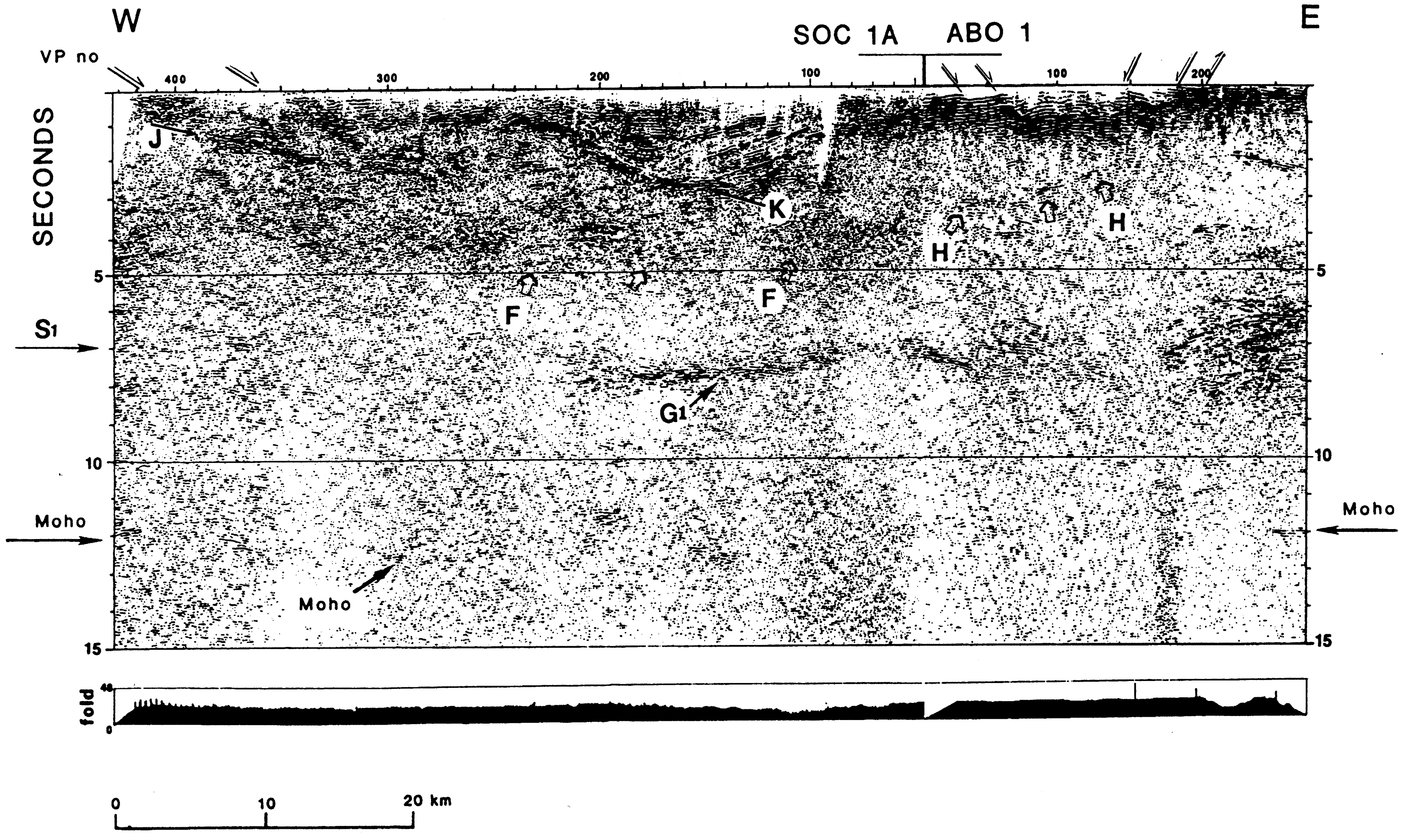

Figure 4. Upper 15 s of the totality of the reprocessed New Mexico COCORP profiles; sections in Figures 4a and 4c have a coherency filter applied; labeled features are discussed in text. Nominal fold is 2,400%, but the actual fold of the processed data varies due to numerous skips (for example, across the Rio Grande River on line 1A), crooked line geometry and editing of noisy traces.

(a) Transect across the Rio Grande rift (Abo Pass line 1 and Socorro line 1A combined); layered reflections in the upper 2 s include both synrift and older deposits and are offset by several Cenozoic normal faults; events labeled H and F are interpreted as reflections from a major fault, discussed in text; G1 is a reflection from the top of the Socorro magma body.

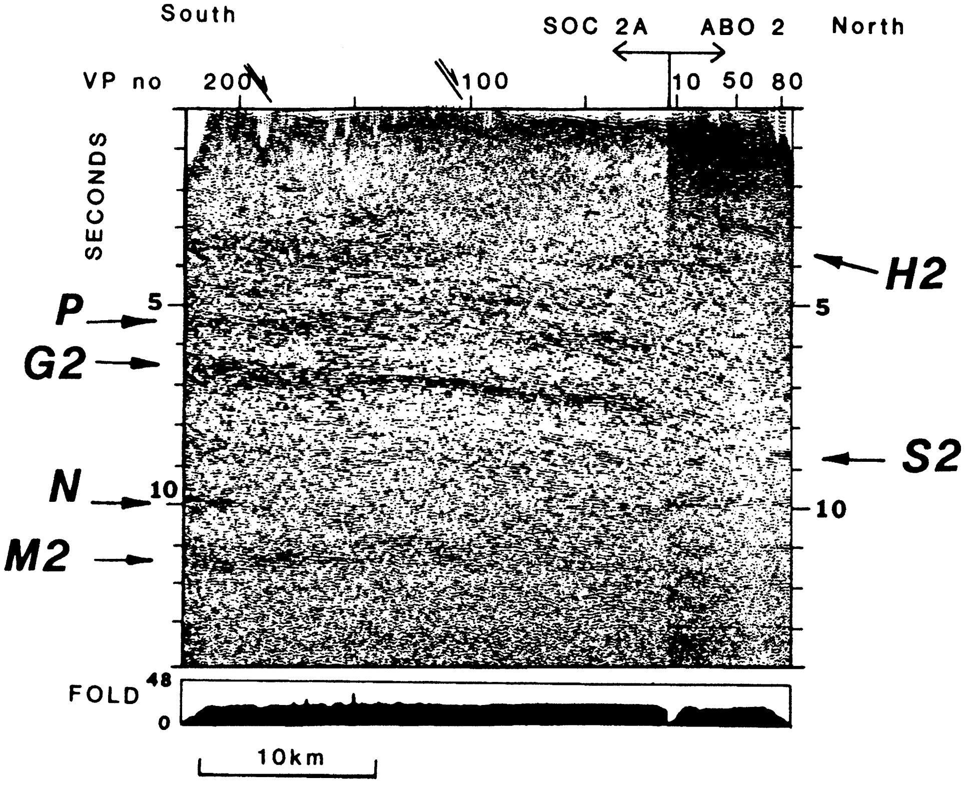

Figure 4b. Abo Pass cross-line 2, combined with Socorro line 2A; event labeled H2 correlates with series of reflections H on line 1 (Fig. 4a).

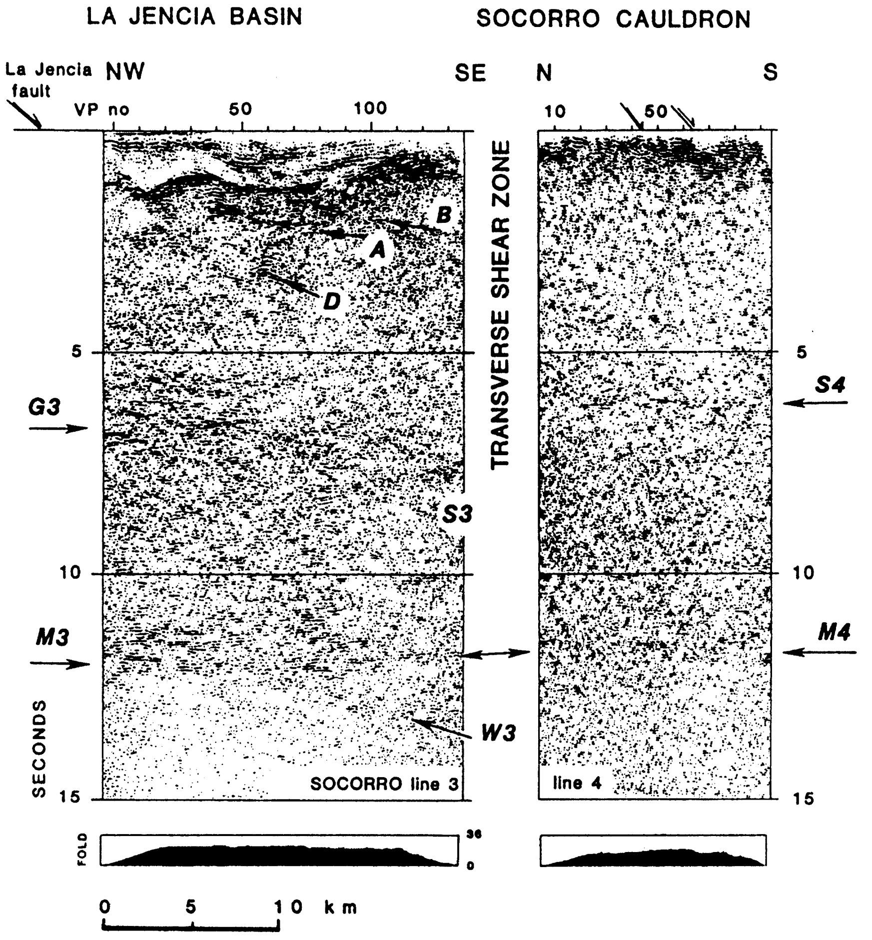

Figure 4c. Socorro lines 3 and 4; events A and B are interpreted as fault-plane reflections; the apparent north dip of A beneath VP 70 may be a velocity pulldown effect; event S4 is more evident on the shot-point gather shown in Figure 7.

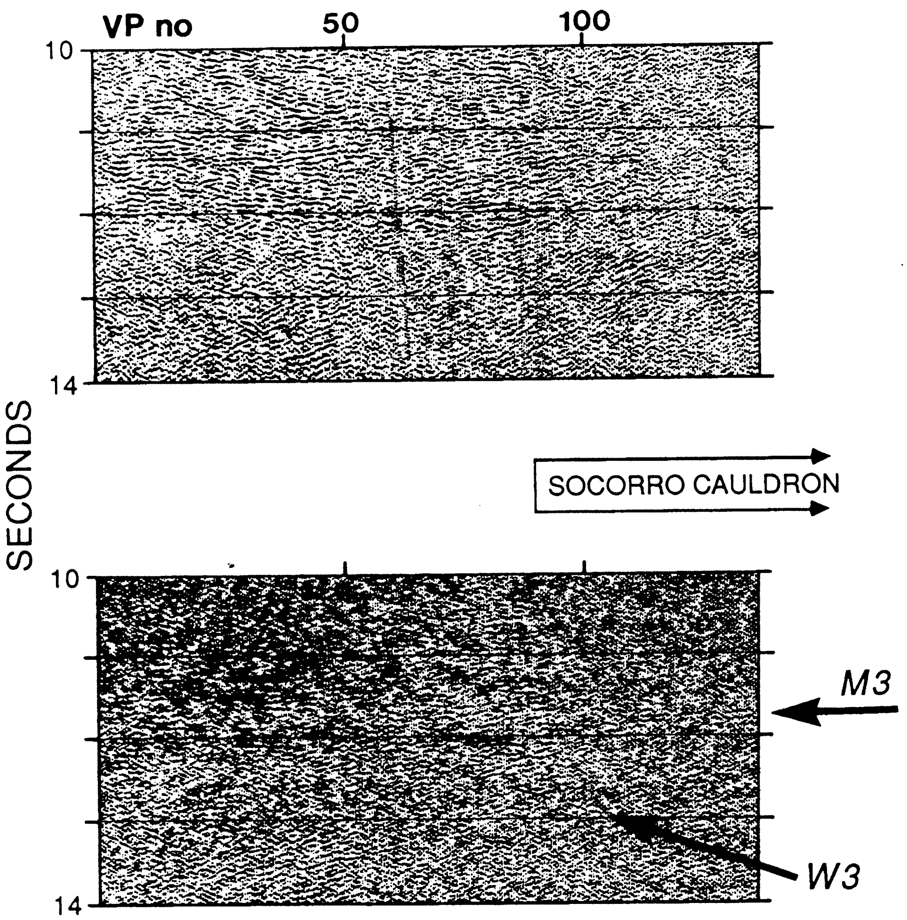

Figure 5. Deeper portion of the seismic section from line 3, showing differences between the contractor processing (top) and the reprocessing discussed here without coherency enhancement (bottom); VP numbers (on top) are located in Figure 3; both sections are displayed with the same automatic gain control and bandpass filter; M3 is inferred to be the reflection Moho, argued here to be continuous across the Socorro cauldron; dipping reflection W3 migrates above M3 for a velocity of 6 km/s.

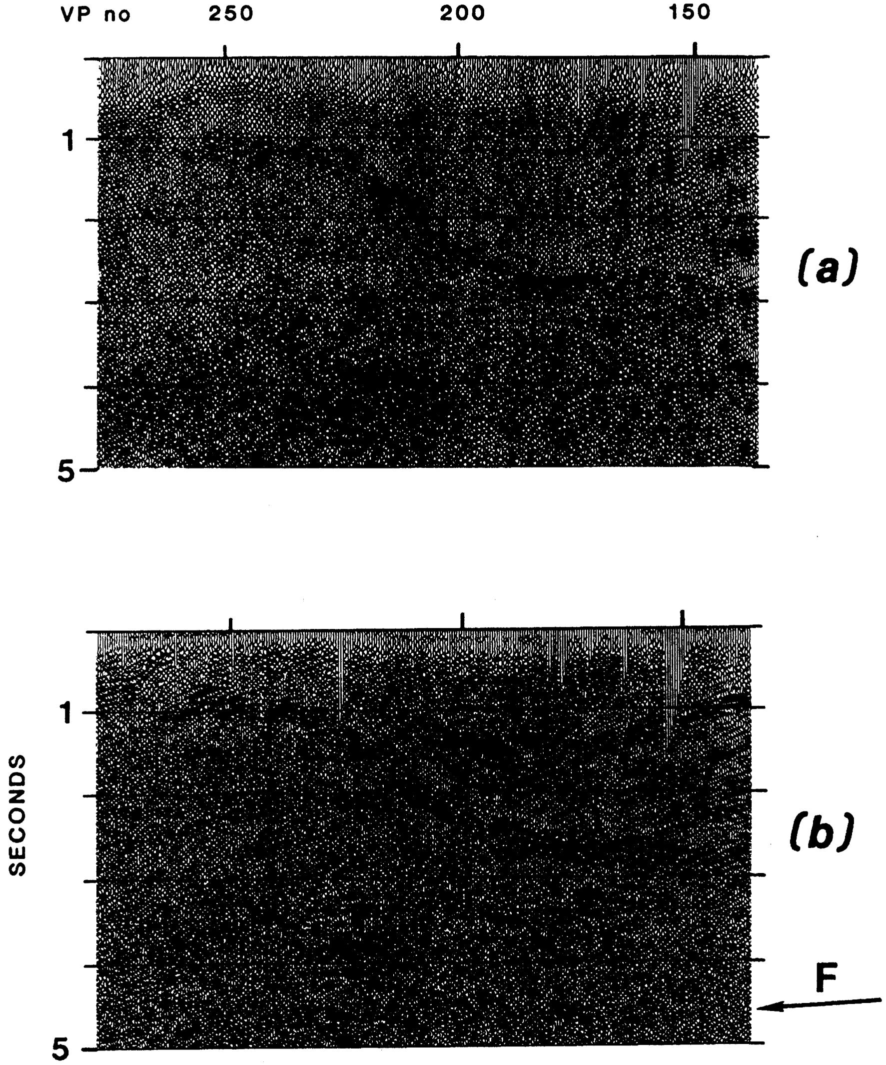

Figure 6. Detail of the seismic section from line 1A; VP numbers (on top) are located in Figure 3.

(a) Original contractor processing.

(b) Same section reprocessed at Cornell; improvement of the shallow section is attributed to better velocities and deeper post-NMO mutes; improvement of the data from the basement is attributed to the pre-stack deconvolution; series of subhorizontal reflections F between 4 and 5 s is discussed in text.

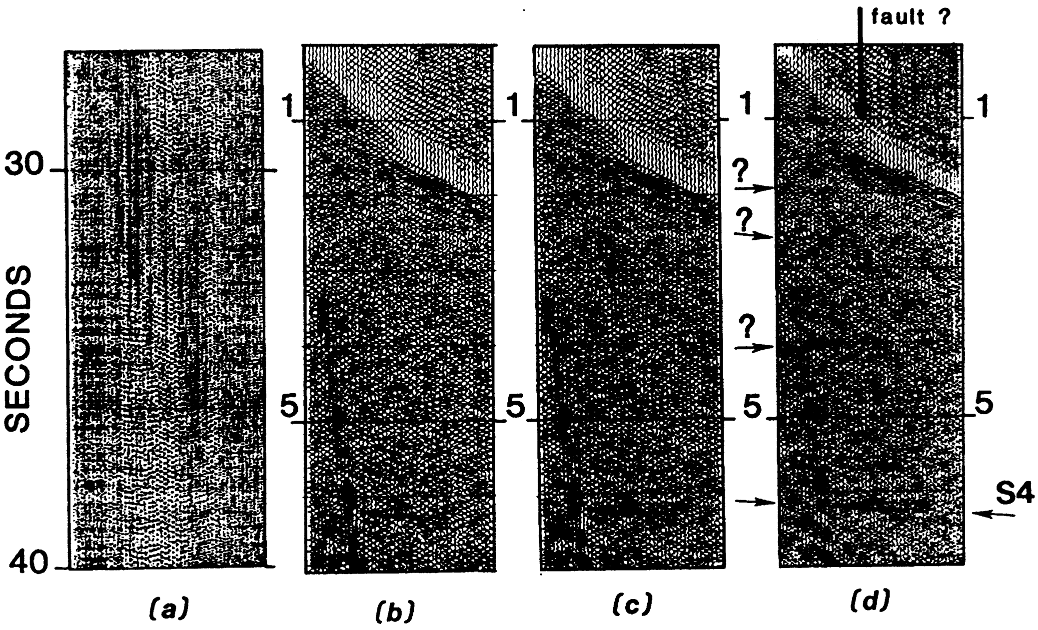

Figure 7. Shot-point gather from Socorro line 4 shown at different processing stages; source at VP 42 into VP's 47 to 94 (Fig. 4); trace spacing is 134 m; horizontal arrows point to possible reflections brought out by the reprocessing; event S4 is discussed in text.

(a) Before correlation; note numerous flat events that cannot be real seismic arrivals because of their constant arrival time across the spread; these noise bursts have an average dominant frequency of 25–28 Hz. No similar noise was encountered on the other New Mexico profiles.

(b) Correlated tape released by the contractor.

(c) After recorrelation at Cornell; here, noisy parts of the records were zeroed or filtered before correlation.

(d) After recorrelation and deconvolution. Although 7c does not appear much better than 7b, subsequent processing such as deconvolution gave better results when using recorrelated records as in the case of 7c.

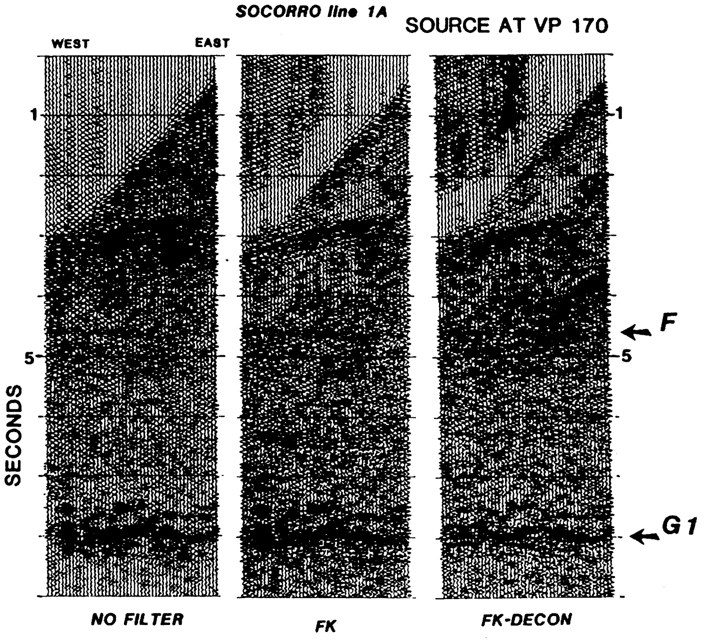

Figure 8. Shot-point gather from line 1A before and after FK filtering; deconvolution after FK filtering provided much improvement; trace spacing is 134 m, and near offset is 670 m. Surface waves and aliased energy were removed by a frequency-wavenumber (FK) domain filter developed at Cornell by C. Caruso (unpub. data). This FK filter was designed to minimize the aliasing problems and reduce the artifacts that result from simple pie-slice filters (Embree and others, 1963). Filtering parameters were selected from FK plots of shot-point gathers. Note reflection F, also labeled on stacked section in Figure 4a and discussed in text.

TABLE 1. PROCESSING AND REPROCESSING SEQUENCES FOR THE COCORP RIO GRANDE RIFT SEISMIC DATA

Initial contractor processing	Cornell reprocessing (Figs. 4, 5, 6)
Trace editing and amplitude balancing	
	FK filtering (except Abo Pass lines 1, 2)
	Bandpass filtering
Deconvolution	Deconvolution (parameters varied along profiles)
Static corrections	
Velocity analysis: generally higher stacking velocities	
Mute before dynamic corrections	Mute before and after dynamic corrections
Automatic residual statics	
Final stack bandpass filtering	
	Coherency filtering (Figs. 4a and 4c)
	Migration attempted with poor results (see text)

Note: the source consisted of 4 or 5 vibrators generating a 10- to 32-Hz linear sweep. Except for line 4, where about one-third of the uncorrelated shot records were found to be contaminated by recording noise bursts of unknown origin (Fig. 7), we used data that were demultiplexed and correlated by the contractor in 1977.

individual reflections on shot-point gathers, and it should be noted that study of shot-point gathers (that is, unstacked data; Figs. 7, 8, and 9) was a critical factor in the interpretation. Both "true amplitude" (Fig. 1) and gain-balanced sections (Fig. 4) were produced (Table 1). To generate the "true amplitude" sections of Figure 1, no FK filter was applied, and true amplitude relationships from trace to trace were preserved by applying surface-consistent amplitude corrections calculated from the unstacked data. Predictive deconvolution applied before stack was particularly helpful in the deeper part of the sections where signal-to-noise ratio is quite low. Besides suppressing multiples and compressing the seismic wavelet, deconvolution can significantly reduce both random and some coherent

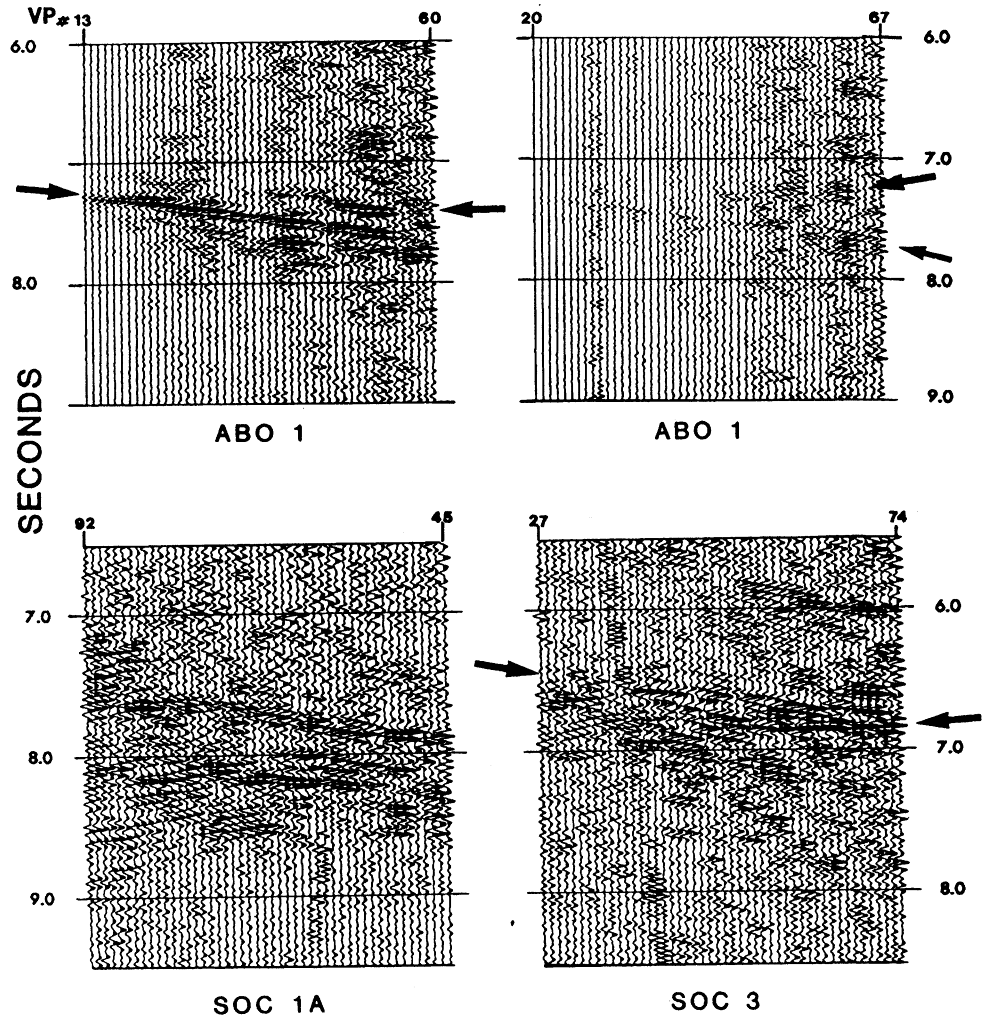

Figure 9. True-amplitude display of shot-point gathers showing details of the Socorro magma body; VP numbers plotted on top are located on map of Figure 3 and on stacked sections of Figure 4. A shot-point gather from Death Valley is shown in Figure 14.

noise, resulting in a much improved seismic section as has been shown with other COCORP data (Zhu and Brown, 1986). Figure 7 shows an example where a deep event (S4) is revealed much more clearly after deconvolution. Subsequent processing steps such as velocity analysis or residual static calculations were substantially aided by the pre-stack deconvolution.

The sections shown here are not migrated, because the conventional time-migration schemes available for this study cannot properly handle laterally complex structures (Larner and others, 1981; Peddy and others, 1986) and deep seismic data in general (Warner, 1987). Instead, synthetic sections were computed with the AIMS modeling package (TM Geoquest International) to evaluate migration and velocity pull-down effects and to constrain the interpretation.

Because the seismic lines are often subparallel to mapped faults (Fig. 3), reflections coming from out of the plane of section (side swipe) are likely to be present in the data. Only at one location, the intersection of lines 1 and 2, could strike and dip of structures be estimated (de Voogd and others, 1986a), and the strikes estimated from the seismic data were consistent with the trends of faults mapped at the surface. In this paper, when reflections are correlated with mapped structures, as is the case for most upper-crustal events, "true" dips are estimated from the seismic data by extrapolating at depth the strikes mapped at the surface.

Reflections are more prominent and continuous on the reprocessed sections (Figs. 4, 5, and 6), and features are imaged that were not apparent on the initial sections (for example, W3, M3 in Fig. 5; F in Fig. 6). Although many of the reflections discussed hereafter may exist in the initial sections, the reprocessed sections place both better and new constraints on the tectonic interpretation of the data.

MID-CRUSTAL MAGMA ACCUMULATION

The Socorro Magma Bodies

The prominent series of reflections observed between 7 and 8 s throughout most of the Rio Grande rift survey (labeled G1, G2, and G3; Figs. 1 and 4) correspond in depth (18 to 22 km) with an unusually strong S-wave reflector previously inferred to be an extensive sill-shaped magma body (Sanford and others, 1973, 1977). Therefore, events G are interpreted as being reflections from the top of the Socorro magma body (SMB) (Brown and others, 1979). Since the initial work of Sanford and others (1965 and 1973), numerous geophysical studies have supported their interpretation and provided some constraints on depth (18–22 km), thickness (less than 1 or 2 km), and lateral extent (at least 1,700 km^2; Rinehart and others, 1979) of this zone of partially molten material (for a review, see Sanford and others, 1983). The New Mexico COCORP surveys provide detailed information on the geometry of the main body and associated structures. Brocher's study (1981b) of the amplitude and frequency content of the COCORP reflections indicates a partially molten, multilayered intrusion. Only one or two magma layers are required to explain events seen on most of line 2A. A series of magma pods (each 30 to 40 m in thickness) rather than a few continuous layers, however, best explain the extreme lateral variation in frequency dependence of the reflectivity at the eastern edge of the intrusion on line 1 (Brocher, 1981b). The following is a description of structures associated with the magma body, as they appear on the reprocessed sections.

Reflections are attributed to the SMB on the basis of their depth and unusually high amplitude relative to reflections from similar depths (10 dB higher or more, estimated from unstacked data). Such reflections are readily seen on true amplitude displays of shot-point gathers (Fig. 9) and on the stack sections (Figs. 1 and 4). These reflections are more or less continuous between VP 10 of line 1 and VP 250 of line 1A, and along all of line 2A. The southernmost lobe of the SMB is imaged on line 3 between VP's 1 and 95. No bright reflections readily attributable to the SMB are observed on line 4. Reflections from the SMB are particularly strong and continuous on line 2A (Figs. 1 and 4b). As line 2A runs parallel to the average strike of most mapped geological features (Fig. 3), raypath distortion due to shallow structural complexity is probably less severe than on line 1A, resulting in better imaging of the middle and lower crust. Dipping structures, such as those inferred in the upper crust along line 1A, will produce subhorizontal reflections on a profile parallel to their strike.

The COCORP data confirm previous inferences from microearthquake S-wave reflection points that the top of the SMB is fairly flat, with a maximum relief of less than 0.5 km (Rinehart and others, 1979). Both the earthquake data and COCORP line 2A indicate that the SMB dips about 6° to the north. The apparent relief on reflector G1 (line 1A, Fig. 4a) is a velocity pull-down effect due to the varying thickness of the overlying low-velocity graben fill. The SMB does not appear to be offset by any of the faults imaged in the upper crust, an aspect discussed below.

The margin of the SMB is imaged on four different profiles (lines 1, 2, 1A, and 3; Fig. 3). To the west, on line 1A, the SMB appears to split into a broad zone of subhorizontal reflections (VP's 200–250, Fig. 4a). To the east (line 1, VP's 1–50; Figs. 4a and 9), it corresponds to a series of complex seismic events of various dips and curvatures at about 7 s. Similar features are observed to the north (line 2–2A) and to the south (line 3, Fig. 9). Several of the shot-point gathers in Figure 9 show two continuous events at similar arrival times but having different normal moveout, attributable to differences in reflectors dip. Apparently dipping events are imaged at the edges of the bright reflection series G that define the SMB on the seismic sections. These dipping events could be explained by features out of the plane of section (side swipe), by complex ray paths, or by multiples generated in shallower structures. All shot-point gathers were examined to look for dipping events such as those shown in Figure 9, but these were found only at the margins of the SMB. In particular, they do not necessarily correlate with the location of the overlying low-velocity troughs capable of generating complex raypaths resulting in multiple arrivals having different moveout. Therefore, at the margin of the SMB, dipping features may exist that merge with, splay off, or are truncated by the SMB. These reflectors that appear to be connected with the SMB are similar to features imaged on the Death Valley data and interpreted (this paper) as the intersection of a mid-crustal intrusion and an upper-crustal magma conduit. Therefore, dipping events as those shown on Figure 9 and observed at several locations at the margin of the SMB may represent magma-migration paths. Unlike the Death Valley data (discussed in a section below), however, there is no evidence for faults merging with the SMB. Rather, we will argue that faulting appears to be restricted to the upper 13 km of the crust in the Albuquerque basin.

Small intrusive bodies may be present above the southern end of the main mid-crustal body (Sanford and others, 1977) in an area which corresponds to one of the largest and most dense clusters of seismic activity in the region (Sanford, 1983). Microearthquakes give a large data base which has been used to map these shallower bodies (Johnston, 1978; Wallace, 1978; Frishman, 1979; Roach, 1982). These authors propose "anomalous regions" containing thin discontinuous dikes of magma and corresponding to a very small volume of molten material. Such near-vertical features of limited lateral extent would correspond to point diffractors and therefore might not be imaged on COCORP profiles. A relatively high amplitude event at about 4 s on line 3 (D, Fig. 4c) first interpreted as a shallow magma chamber (Brown and others, 1980b) is now thought to be a surface-wave side swipe. This artifact was essentially removed by deconvolution and stacking with our revised velocities and is not as prominent on the reprocessed section. Thus, none of the shallow bodies inferred above the SMB could be identified on the COCORP data.

The SMB appears to be truncated and to step downward on line 2 (S2, Fig. 4b) and line 3 (S3, Fig. 4c). Events S2 and S3, although of small lateral extent, have a high seismic amplitude, comparable to that of G, and they occur approximately a second later than G (that is, possibly 2 or 3 km deeper). Lines 1 and 1A (Figs. 3 and 4a) show that the eastern edge of the SMB trends north-northeast, about 45° away from line 2 (Fig. 3). Therefore, S2 may be a side swipe from the edge of the magma layer, and the apparent down-faulting of the margin of the SMB on line 2 is most likely an artifact. The southernmost lobe of the main sill (Fig. 3) can be correlated with a bright reflection only beneath VP's 1–95 of line 3 (G3, Fig. 4c). This is in slight disagreement with the outline of the SMB proposed by Sanford and others (1977) (Fig. 3). This apparent discrepancy may be explained if event G3 comes from a reflector slightly off the plane of section, a likely candidate being the margin of the SMB as drawn in Figure 3. A weaker but more or less continuous reflection can be traced south of VP 95 (line 3) and on line 4 (S4, Figs. 4c and 7) between 6 and 7 s. This weak, subhorizontal reflection S4, which extends beneath the Socorro cauldron and correlates in depth with the mid-crustal horizon defined by the SMB, is underlain by a bright event at 7.7 s (S3, Fig. 4c). As S3 is 1 s deeper than G3, the mid-crustal reflective zone appears to be offset by at least 3 km across the cauldron. This apparent offset could be a structural offset. It might also be a velocity pull-down effect if, as found by Ward and others (1981), the velocity above S3 is 0.7 km/s lower than that above G3. Since no comparable offset affects lower crustal reflections M3 (Fig. 6), we conclude that G3 correlates with S4, and S3 represents either a deeper reflector, possibly from a small magma body, or a side swipe from one of the small upper crustal intrusions mentioned above. No vertical offset of series of reflections G could be documented from the above examination of the seismic data.

The Death Valley Bright Spot

Although the existence of partially molten rocks beneath Death Valley is not as well constrained as in the Socorro area, the Death Valley COCORP profiles (Fig. 10) provide new insight into the relationship between magmatic processes and normal faulting. The most striking feature seen on these profiles is a 30-km-long, subhorizontal zone of unusually strong reflections between 5.5 and 6.5 s (approximately 15 km) on the northern end of line 11 (labeled DVBS on Figs. 1 and 11). This amplitude anomaly (or seismic "bright spot") is remarkably similar to reflections G just described on the Socorro profiles (Fig. 1). On the basis of the strong amplitudes (Fig. 2), relatively broad band reflectivity, the similarity between the Death Valley and the Rio Grande rift bright spots, and the evidence for young volcanism in Death Valley (Wright and Troxel, 1984), the Death Valley bright spot is reasonably suggested to represent partially molten material at mid-crustal depth (de Voogd and others, 1986b). Details of data acquisition, processing, and analysis of the Death Valley profiles can be found in Serpa and others (1988).

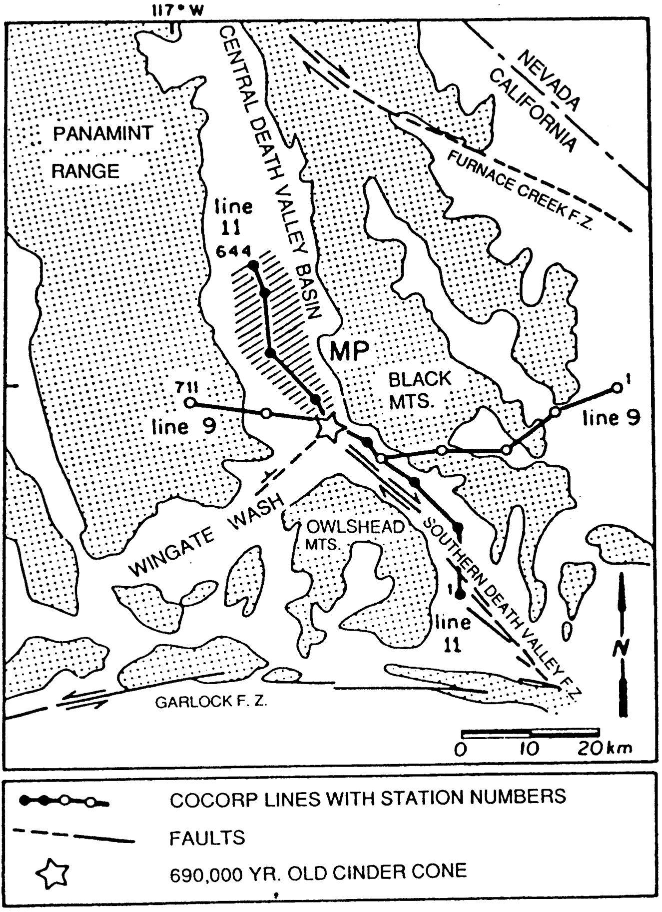

Figure 10. Location of COCORP Death Valley lines 9 and 11; geology sketched from Wright (1974); stipple indicates ranges; white indicates young basins; diagonal lines indicate approximate extent of Death Valley bright spot; MP is Mormon Point turtleback.

A dipping reflector (C, Fig. 11) can be traced between the inferred magma body and a 690,000-yr-old basaltic cinder cone. Thus, the Death Valley profiles may image, perhaps for the first time, the upper-crustal plumbing system associated with a deep basaltic intrusion. In addition, the seismic data show that C is a normal fault (Wingate Wash fault; Serpa and others, 1988). Therefore, magma from the mid-crustal intrusion may have traveled to the surface, 690,000 yr ago and, possibly, 1.5 m.y. ago, along a moderately dipping fault (C) or the intersection of normal fault C with the southern Death Valley strike-slip fault zone.

BASEMENT FAULTING

Rio Grande Rift

In the Rio Grande rift, Cenozoic normal faulting is evident from offsets across Phanerozoic strata on lines 1, 1A, and 3 (Fig. 4). Originally interpreted as depositional contacts deformed by progressive differential subsidence across steep normal faults (Brown and others, 1980a), J and K (Fig. 4a) have also been interpreted as fault-plane reflections (Cape and others, 1983). The shallow faults interpreted by Cape and others, however, leave open the question of how the underlying basement accommodates extension. Presumably, a deeper set of faults must exist. Here, we focus on deep features (such as H and F; Figs. 4a, 6, and 8) revealed by the reprocessing as possible clues to the nature of this deeper extension. Reprocessing and synthetic seismic modeling of line 1 (de Voogd and others, 1986a) suggest that synthetic and antithetic Cenozoic normal faults may sole into a northwest-dipping listric detachment (H, Figs. 4a and 4b) which bounds the eastern side of the basin and reaches a depth of ~10 km beneath the southern Albuquerque basin.

The original section of line 1A shows no indication of an extension of a master fault such as H to the west. Reprocessing of line 1A, however, revealed a prominent package of reflections between 3 and 6 s (F, Figs. 6 and 8) beneath the northern extension of the Ladron horst. Although their arrival time and apparent dip vary along line 1A, these reflections are correlatable on the reprocessed section from line 1A and may be traced (Fig. 4a) from beneath the Sierra Lucero to the west to about VP 110. East of VP 110, the data quality deteriorates for a 5-km-wide zone, possibly due to traffic noise as line 1A crosses a major highway, and to drop in fold across the Rio Grande River (around VP 100). Consequently, deep events cannot be unambiguously traced between lines 1A and 1. Additional difficulties in interpreting this transect come from the complexity of the shallow structures and the resulting velocity pull-down effects and ray-path distortions.

A two-dimensional model for line 1A (Fig. 12a) was derived from the depth to Precambrian basement, and shallow velocities were estimated from Brocher's (1981a) study of COCORP refracted arrivals. In the central part of the basin, a large, buried intra-graben horst is interpreted as the northward extension of the Ladron Mountains (Fig. 3), an uplifted block of Precambrian basement. Dips of about 30° have been mapped around the Ladron. Because of three-dimensional effects, the relief on this horst at the location of the COCORP transect may not be as extreme as suggested by the seismic section from line 1A (Wu, 1986). Zero-offset (single-fold) synthetic seismic sections were used to quantitatively illustrate migration and velocity pull-down effects. The model in Figure 12a postulates that reflector F is continuous and subhorizontal beneath the basin. Yet its seismic image (Fig. 12b) shows substantial velocity pull-down beneath VP 160 and a broad antiformal shape beneath the Ladron. Comparison of the synthetics in Figure 12b with the actual data (Fig. 4a) shows that velocity pull-down effects alone can explain the discontinuous appearance of series of reflections F on the seismic section. In particular, reflections H and F are correlatable without the large offsets observed in the Phanerozoic section and responsible for the Precambrian basement topography. The lack of vertical offset of low-angle to subhorizontal reflectors that underlie the rift basin beneath 8 and 13 km (H, F, line 1A; Figs. 4a and 6) precludes substantial displacement along steeply dipping normal faults. Therefore, despite some ambiguity in the interpretation of line 1A due to the lack of three-dimensional control and the resulting uncertainty on true dip of some key reflectors, low-angle normal faults (such as H or F) appear to accommodate extension within the basement.

Similarities in the location and orientation of Tertiary features with earlier Laramide trends suggest that rifting may have reactivated older structures (Chapin and Seager, 1975). The ramp-like geometry of fault F–H is reminiscent of compressional structures. Similar geometries have been documented on the basis of seismic data for extensional structures possibly, but not necessarily, reactivating compressional structures (Allmendinger and others, 1983). The low-angle Cenozoic normal fault inferred here to underlie the southern Albuquerque basin projects to the surface in the vicinity of the Paloma and Montosa thrusts (Fig. 3), suggesting possible reactivation of these Laramide structures, although this is not required by the COCORP data (de Voogd and others, 1986a).

Both the inferred fault system H–F and the SMB appear to merge with the prominent layering observed beneath the western rift margin

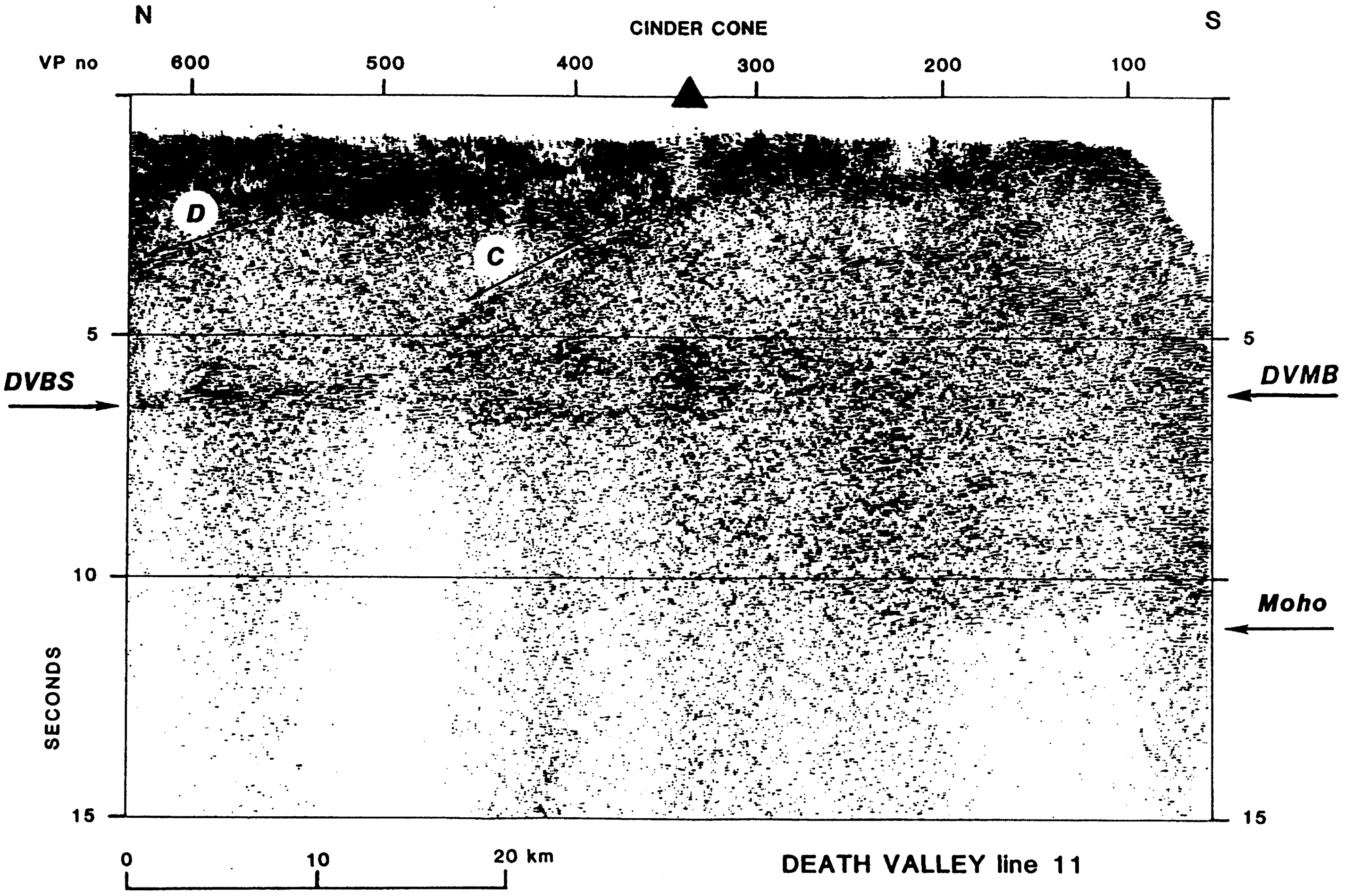

Figure 11. "True-amplitude" section of Death Valley line 11; exponential gain applied to the upper 3 s to partially correct for geometrical spreading; coherency filter applied for display purposes; the unusually strong mid-crustal reflector beneath VP's 340–640 and labeled DVBS is interpreted as a magma body; prominent mid-crustal reflections are also evident to the south (DVMB); events C and D are interpreted as normal faults; C is also inferred to be a magma conduit; note the abrupt vertical change in reflectivity at the base of the crust; lower-crustal reflections are also present in the northern half of the profile on gain-balanced displays but are not seen on this "true-amplitude" section because of the high reflectivity of the mid-crust.

and the edge of the Colorado Plateau. Within this layering, a strong reflector stands out on the true amplitude section of line 1A (S1, Figs. 1 and 4a). S1 may represent either a continuation or splay of fault system F, or the westward extension of the mid-crustal boundary seen in refraction data (Olsen and others, 1979) and discussed in a section below.

Structures attributable to Cenozoic rifting are also conspicuous on Socorro line 3 (Fig. 4c). Line 3 crosses the northern margin of the Socorro cauldron around VP 110. This coincides with a marked deterioration of the quality of the seismic data (Fig. 4c). Although the lack of continuous reflectors beneath the cauldron margin can be attributed to intense structural deformation during the late Cenozoic volcanic episodes (7- to 12-m.y.-old rhyolite at Socorro Peak; Chapin and others, 1978), this change in seismic character also coincides with a sharp decrease in fold, a change in the surface conditions, and the proximity of a highway. The general degradation in data quality evident on the southern portion of the stacked section of line 3 (Fig. 4c) is also observed on shot-point gathers. This results in a gradually poorer signal-to-noise ratio to the south rather than clear truncation of reflectors. Average amplitude versus traveltime decay curves calculated along line 3 within and outside the Socorro cauldron are remarkably different (bottom-left plots of Fig. 2). The traveltime at which amplitude ceases to decrease can be interpreted as an indication that the transient source-generated energy has decreased sufficiently to allow the background noise to dominate the record. The depth corresponding to this time is therefore a guide to signal penetration (Mayer and Brown, 1986). Only strong reflections, if any, will be seen beneath that depth. The curve calculated between VP's 110–125 of line 3 (Fig. 2) shows a relatively short time to approximately ambient noise, contrasting with the continued decay of the seismic energy to the north. The relative lack of reflections on the southern end of line 3 therefore may well be attributable to lack of signal penetration rather than geologic homogeneity.

Two faults are interpreted on line 3 (Fig. 4c). Two reflections (labeled A and B in Fig. 4c) can be traced within the basement and project upward toward the truncations and offsets of layered reflections that define the two faults in the Phanerozoic section. Reflection A projects upward 2 or 3 km north of the beginning of line 3, toward the surface location of the La Jencia fault. Event B projects to the surface at VP 40 of line 3. No fault

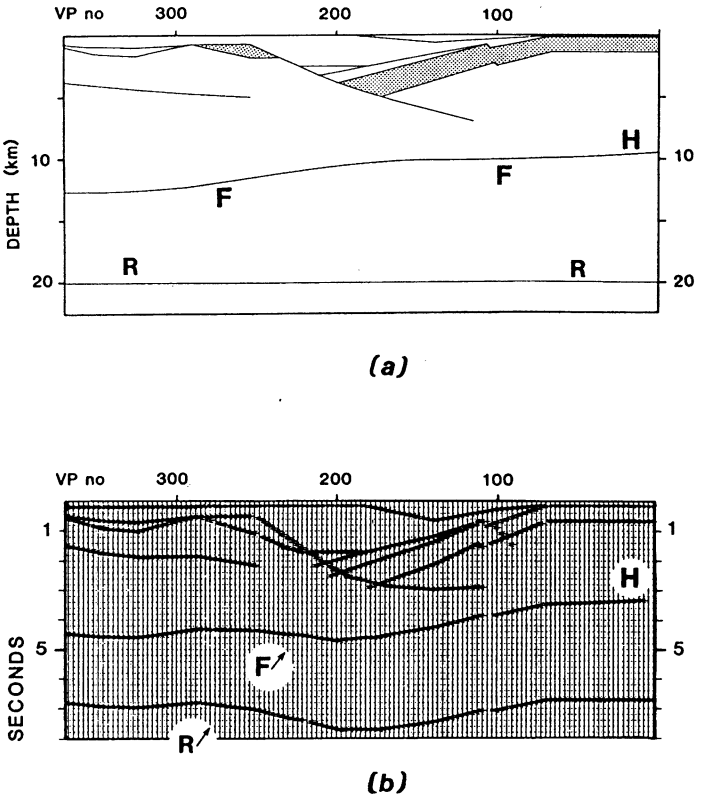

Figure 12. Synthetic seismic modeling of portion of line 1A; (a) input model; the position of H is constrained by detailed modeling of line 1 (de Voogd and others, 1986a); (b) normal-incidence seismic section of the above model; R is a flat reference horizon introduced in the model to illustrate velocity pull-down effects beneath the rift basin.

is mapped at this point, although faulting is indicated by the offset of shallow reflectors. The La Jencia fault displaces alluvial deposits of Holocene to middle Pleistocene age (Machette, 1982) along the western margin of the La Jencia basin (Fig. 3). Machette has suggested that the La Jencia is a major range-bounding fault that may offset Miocene rocks by as much as several thousand meters. From the surface geology, the strike of the La Jencia fault is at an angle of 50° with the seismic line; therefore, the true dip of the inferred fault plane reflection A is approximately 35° (see Fig. 5 of de Voogd and others, 1986a). Tertiary strata are vertically offset by at least 1 km. Although the strike of reflector B cannot be determined without additional seismic profiling, the seismic data from line 3 suggest that two listric normal faults, the La Jencia fault and a previously unrecognized fault farther to the east, mark the western edge of a large tilted block which may include the Socorro-Lemitar range.

Analysis of line 4 is limited by complex terrane, rugged topography, shortness of profile, and unusual recording noise (Fig. 7). Although the end of line 3 and the beginning of line 4 are only 4 km apart, events cannot be unequivocally traced between the 2 seismic sections (Fig. 4c). Because of low signal-to-noise ratio, however, this lack of reflection continuity between the two profiles does not prove that the northeast-trending transverse shear zone that is mapped (Chapin and others, 1978; Fig. 3) between these profiles corresponds to a near-vertical feature that disrupts the whole crustal column. Reflections from Moho depth, evident along line 3 (Fig. 5), may also exist on line 4 (Fig. 4c), although much weaker. As discussed above, a somewhat continuous reflection at 6.5 s on line 4 (S4, Figs. 4c and 7) is correlated to the mid-crustal reflective horizon which includes the SMB. The shortness of lines 3 and 4, however, makes it difficult to interpret features imaged on the seismic sections in a regional perspective.

Within the Socorro cauldron complex (that is, south of VP 110 of line 3), no faults with large vertical displacement are observed on the seismic data (Fig. 4c). The voluminous rhyolitic extrusive activity ending 7 Ma may have obscured earlier rift structures. The "domino-style" structures documented by Chamberlin (1983) in the Lemitar Mountains are most likely too shallow (a few hundred meters to a kilometer) to be imaged on the COCORP profiles. Two normal faults, with small down-to-the-south displacement, are inferred from offsets in the seismic data to surface near VP's 45 and 70 of line 4 (Fig. 4c). They appear to correspond to the young normal faults mapped by Osburn and others (1981).

The north edge of the Socorro cauldron also coincides with the south margin of the SMB as inferred from the COCORP data. On line 3 (Fig. 4c), the SMB stops abruptly beneath VP 100. An unusually bright deep reflection is observed between VP's 100 and 130 (S3, Fig. 4c), and may represent a deeper magma body, as discussed in a previous section. The lateral continuity of upper crustal reflections A and B (Fig. 4c) and deep reflection series M3 (Fig. 5) argue against a steep fault being responsible for the vertical offset between events G3 and S3 (Fig. 4c). Lower crustal reflections are prominent on line 3 and may also exist at a similar depth on line 4 (Fig. 4c).

The relationship between upper-crustal late Cenozoic normal faulting and the SMB is unclear. The east-west transect (lines 1, 1A) that provides the most information on fault geometry shows no identifiable reflection between about 13 km and the 20-km-deep SMB. On the north-south profile (line 2A), strong reflections (labeled P and N in Fig. 4b) parallel the SMB at depths of about 15 km and 28 km over a lateral distance of at least 20 km. This prominent layering may indicate that within this zone, distributed ductile pure shear accommodates extension.

Death Valley

A different situation may prevail in Death Valley, where faults appear to terminate along a prominent subhorizontal zone of reflections at mid-crustal depth (DVBS and DVMB on Fig. 11). The inferred mid-crustal magma body (DVBS) lies within this zone. In this paper, we briefly review the evidence presented in detail by Serpa and others (1988) for deep-fault geometry beneath the central Death Valley basin (COCORP lines 9 and 11, Figs. 11 and 13) in order to later compare these results with the Rio Grande rift data.

Central Death Valley has been interpreted as a pull-apart basin formed by oblique extension between the en echelon southern Death Valley and northern Death Valley–Furnace Creek strike-slip fault zones (Burchfiel and Stewart, 1966; Wright and Troxel, 1973; Stewart, 1983). COCORP surveys in that area (Fig. 10) show that the mountain blocks appear to be tilting and translating along a series of widely spaced, moderately dipping faults which can be traced from the surface to mid-crustal depth (15–16 km), where they sole into, or are truncated by, a subhorizontal detachment (that is, the lower boundary to a set of faults) (Serpa and others, 1988). Beneath this zone of decoupling, the lower crust exhibits a subhorizontal structural and/or compositional fabric (Fig. 11). The inferred magma body is emplaced within the mid-crustal band of reflections.

Both the surface geology (Wright and Troxel, 1973; Wright and others, 1981) and the seismic data indicate two distinct levels of faulting. Shallow faults (less than 4 km deep) appear to terminate near the top of the crystalline basement and, thus, are interpreted to be the result of the collapse of the layered rocks above the tilting crystalline fault blocks (for example, A in Fig. 13). These shallow faults may sole into low-angle faults

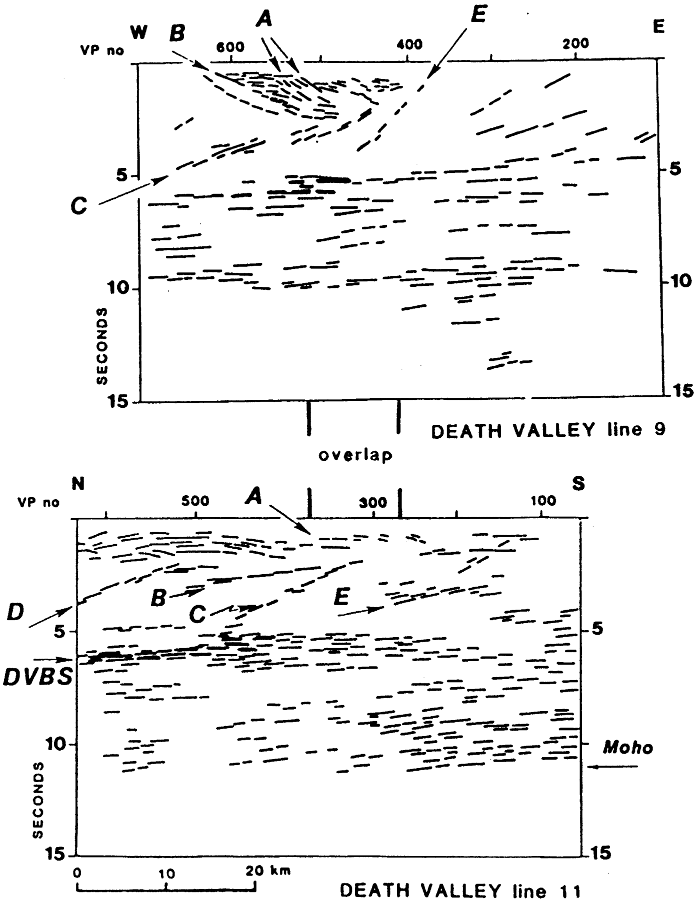

Figure 13. Simplified line drawings of Death Valley lines 9 and 11 (adapted from Serpa and others, 1988).

that mark the top of the basement (for example, B in Fig. 13). A deeper set of faults bound crystalline basement blocks. Reflector E (Fig. 13) is interpreted to be the subsurface continuation of normal faults mapped along the western side of the Black Mountains (Fig. 10).

Two prominent dipping reflections (C and D, Figs. 11 and 13) can be traced between about 3 and 15 km depth but do not correlate directly with mapped faults. Because they truncate layered reflections, C and D are interpreted as normal faults (Serpa and others, 1988). Fault zone C appears to bound the southeastern side of the central Death Valley basin (line 9, Fig. 13). Reflections attributed to this fault zone can be traced between 1.5 and 5 s, after migration at 6 km/s, on two intersecting and overlapping profiles (COCORP lines 9 and 11; Fig. 13).

A critical issue for the present study is the relationship between fault zone C and the mid-crustal detachment. Both events are clearly seen on several shot-point gathers along the profile (de Voogd and others, 1986b; Serpa and others, 1988). The shot gather in Figure 14 shows two reflected arrivals that can be traced across the 10-km spread length at similar arrival times (between 5 and 6 s) but having different normal moveout. The moveout of these two events was modeled using an average velocity of 3.8 km/s for the basin fill and 6.1 km/s for basement rocks (Fig. 14). The moveout of the upper event (DVBS) is consistent with it being from a subhorizontal horizon at a depth of 15 km, possibly with a slight dip to the south. The underlying seismic event has no significant moveout and matches arrival from a north-dipping (about 20° dip) reflector merging with the horizontal reflector beneath VP 495, but trending at 60° from the strike of the seismic line. Therefore, these two reflections are reasonably identified as DVBS and fault/conduit C, respectively. The above study suggests that fault C does not extend beneath reflector DVBS, but rather appears to sole into the mid-crustal intrusion. This result supports the interpretation of Serpa and others (1988) that the molten intrusion is part of a regional zone of detachment which constitutes the lower boundary of the upper-crustal fault blocks.

MID-CRUSTAL BOUNDARY

The reflections identified with the top of magma bodies (G and DVBS in Fig. 1) have been shown to merge into much weaker, subhorizontal reflections at approximately the same depth (for example, S1, S4 in Fig. 4, and DVMB in Fig. 11). Therefore, in both the Rio Grande rift and Death Valley, correlatable if not continuous reflective horizons exist at mid-crustal depths, possibly extending well beyond the margins of the magma bodies. These horizons separate two distinct crustal domains: the upper crust is characterized by reflections from inferred faults of various dips; in contrast, reflections from the middle and lower crust are generally subhorizontal. This relatively abrupt change from moderately dipping (15°–40°) events to subhorizontal events does not appear to be an artifact of the technique. For example, dips up to 40° should be recordable down to an unmigrated depth of 10 s provided that the seismic profile is more than 25 km long (Lynn and Deregowski, 1981). Furthermore, a few dipping events are recorded at times greater than 7 s in the Death Valley (Serpa and others, 1988) and perhaps the New Mexico data (this paper), and dipping reflections from lower-crustal levels have been observed on other seismic profiles (Lynn and others, 1983; Jones and Nur, 1984; Matthews and Cheadle, 1986; Moss and Mathur, 1986). The COCORP data therefore indicate that the crust of these two regions is divided into a brittle upper crust apparently decoupled from a ductile middle and lower crust. The mid-crustal horizons, where magma appears to accumulate, lie at the base of basement fault blocks (in Death Valley), or a few kilometers below (in the Rio Grande rift).

Refraction profiling has established that distinct upper- and lower-crustal layers (respective P-wave velocities of 6.0 and 6.4 km/s) exist in this part of the Rio Grande rift (Toppozada and Sanford, 1976; Olsen and others, 1979). The boundary between these two crustal columns of different physical properties is between 18 and 20 km depth. It may correspond to weak reflections such as S1 (Figs. 1 and 4a) or S4 (Fig. 4c). The magma body coincides with a thin low-rigidity zone which top coincides, in depth, with this increase in crustal velocity (Olsen and others, 1982). Magma in the Socorro area may thus be accumulating just below a major crustal discontinuity (Sanford and Einarsson, 1982). No refraction data are available for Death Valley. A subhorizontal mid-crustal reflecting zone, however, is traced on the COCORP profiles throughout most of the Death Valley area and may here also correspond to a regionally extensive crustal boundary (Serpa and others, 1988).

In extensional terranes, the maximum depth of seismicity has been taken as evidence for the depth of the brittle-ductile transition (Meissner and Strehlau, 1982; Sibson, 1983; Smith and Bruhn, 1984). Instrumental studies of the seismicity of the Rio Grande rift, with special emphasis on the Socorro area, indicate a sharp cutoff in the number of hypocenters between 11.5 and 14 km (4 to 5 s two-way traveltime). Most of the earthquakes occur between 6.5 and 11.5 km (2.5 to 4 s), and none is observed deeper than 13 or 14 km (Sanford and others, 1983; Jaksha and Sanford, 1986). This suggests a rheological boundary at about 13 km depth, which is also the maximum depth of faulting interpreted from the COCORP profiles. A relatively shallow brittle-ductile transition has also

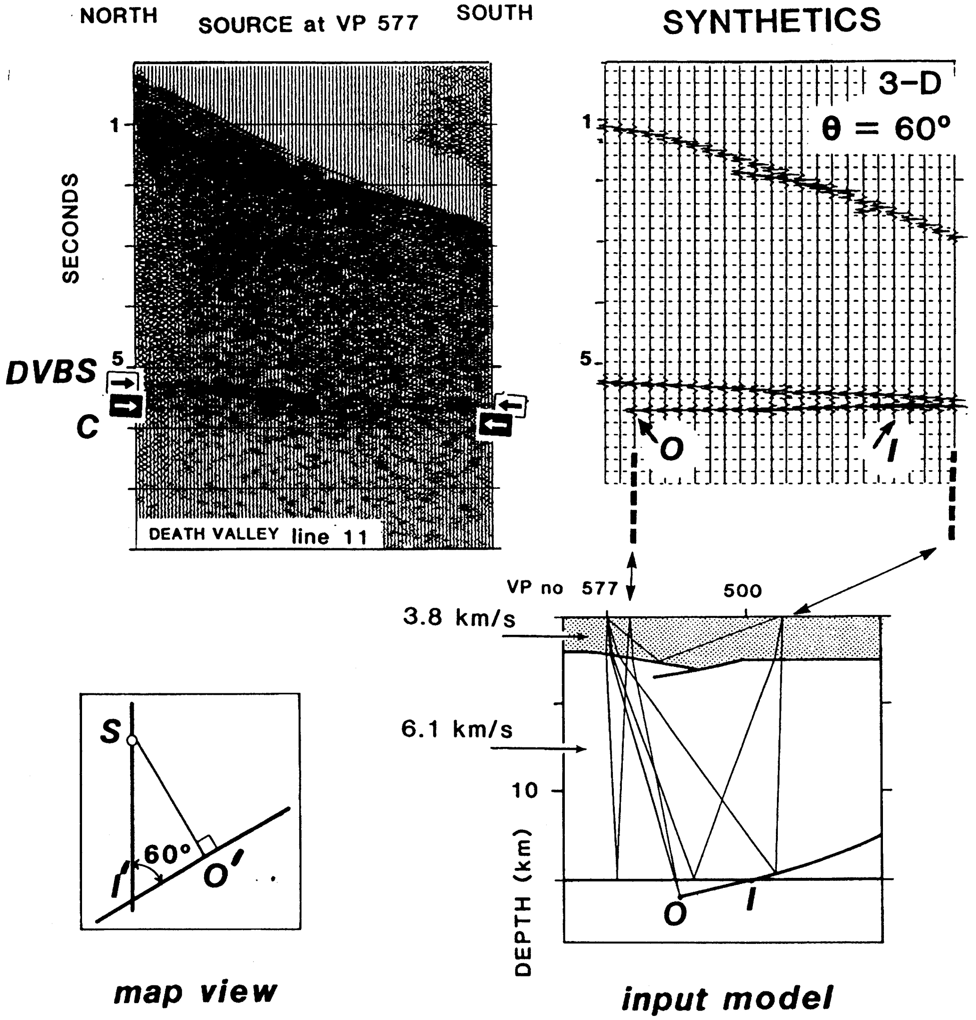

Figure 14. Shot-point gather from Death Valley line 11 interpreted to show the intersection between the mid-crustal magma body (DVBS) and the Wingate Wash fault zone (C) (Figs. 10 and 11). The approximate shape of the basin in the input model is taken from the interpretation of Serpa and others (1988). I′ and O′ are the surface projections of points I and O, respectively, that lie on fault plane C. Serpa and others concluded that the trend of fault zone C strikes at about 60° from the seismic line, but the AIMS modeling package available to us is only two dimensional. Therefore, the input model is corrected for side-swipe effect by extending fault plane C slightly beneath DVBS. The good agreement between the synthetics and the data shows that with proper consideration of side-swipe effect, fault plane C does not have to extend deeper than DVBS (or about 15 km depth).

been proposed by Jiracek and others (1987) on the basis of modeling of magnetotelluric data. No similar data sets are available for Death Valley.

The two magma bodies discussed here occur at similar depths and within laterally correlatable if not continuous zones of reflections that separate the faulted upper crust from the relatively layered lower crust. The magma may thus have been trapped at the base of the brittle upper crust. The observation of a brittle-ductile transition at mid-crustal depths is consistent with previous models for crustal processes in the Basin and Range province (Eaton, 1982; Smith and Bruhn, 1984; Gans, 1987). In contrast, in other zones of continental extension where deep seismic reflection data are available (Matthews and Cheadle, 1986; Keen and others, 1988), large, low- to moderate-angle normal faults persist as single zones of displacement through the entire lithosphere. Wernicke (1986) suggested that the formation of decoupling horizons in the crust is not necessary to accommodate changes from brittle to ductile rheology. The presence of magmatic intrusions may be the key factor that controls the existence and depth of decoupling horizons into which faults may sole. Therefore, differences in style of continental extension could be explained by differences in heat flow and magmatic activity.

DEEP CRUSTAL LAYERING AND THE MOHO

On the Death Valley gain-balanced seismic sections discussed by Serpa and others (1988), a deeper reflecting horizon is observed beneath the inferred mid-crustal detachment at a depth of ~30 km (between 10 and 11 s) and is interpreted to be the reflection Moho. The "true amplitude" sections of line 11 shown in Figures 1 and 11 give a somewhat different impression of the base of the crust. The series of subhorizontal events that characterize the lower crust in this area end abruptly at about 11 s. Beneath the relatively reflective lower crust, the upper mantle appears seismically transparent. The boundary between these two regions is quite sharp along most of line 11 (Fig. 11). Although a cessation of coherent reflections at some characteristic traveltime has been observed in other COCORP data (Mayer and Brown, 1986), the amplitude decay curve of line 11 (top right plot of Fig. 2) shows this decrease in seismic energy to be unusually large and abrupt (a step down of at least 3 dB). Absence of returned seismic energy after a certain depth can be due to insufficient signal-to-noise ratio or to geologic homogeneity. The magnitude and abruptness of the decrease in average seismic amplitude at 11 s on line 11 suggest that it is not the result of insufficient signal penetration. Rather, it indicates that, beneath Death Valley, the base of the crust may be a sharp boundary.

In the Rio Grande rift, correlatable and often continuous subhorizontal events form a reflective band between 11 and 12 s (about 33 to 36 km). Below this zone, there is a marked absence of reflections. The dipping event seen on line 3 (W3, Fig. 5) migrates above this zone. As depths to Moho of 33 to 38 km (11–13 s) are given by wide-angle explosion seismology (Toppozada and Sanford, 1976; Olsen and others, 1979), the base of the series of reflections labeled "M" (Figs. 4 and 5) is inferred to represent the crust-mantle boundary. Lateral variations in the seismic

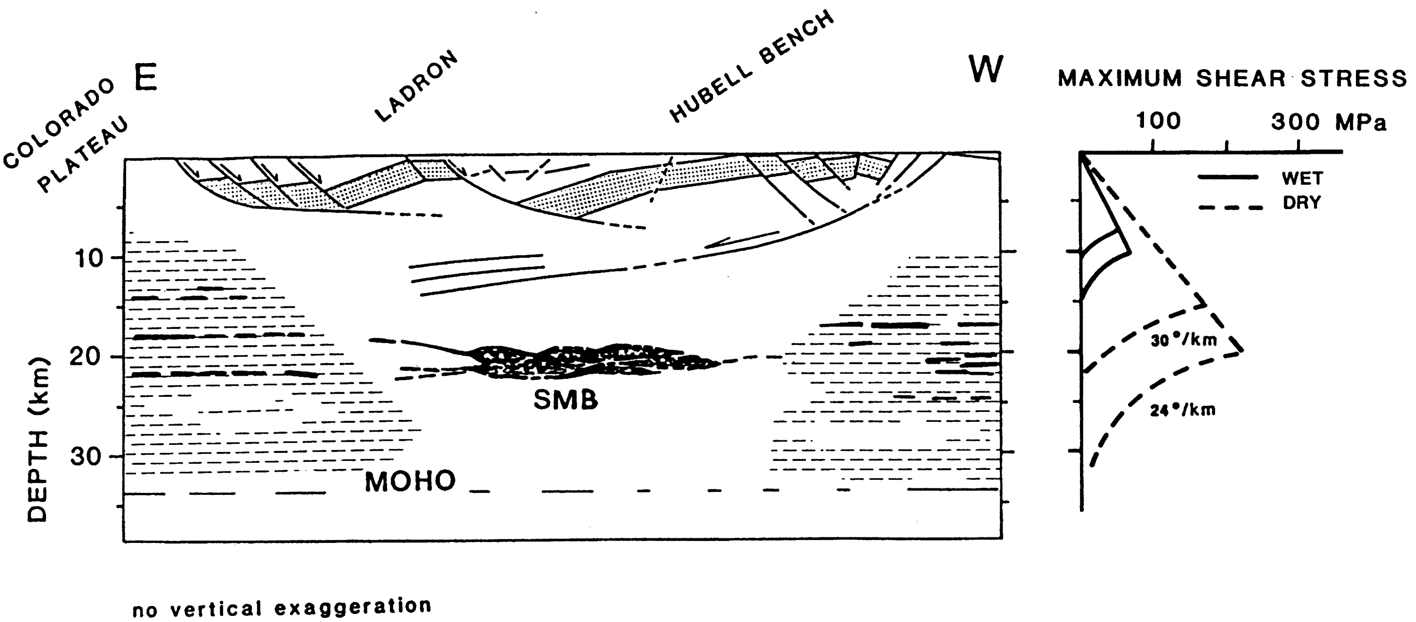

Figure 15. Cross section across southern Albuquerque basin; drawn to scale from the COCORP data; arrival times were approximately converted to depth using velocities determined from COCORP refracted arrivals and well data for the sedimentary section; constrained by the synthetic seismic model of Figure 12; dotted blocks represent pre-rift strata. Plotted to the right are maximum shear stress versus depth curves for quartz rheology, adapted from Meissner and Strehlau (1982), for an average strain rate of 10^{-15} s^{-1} (Morgan and Golombek, 1984), and for two geothermal gradients, 24° and 30°/km (~70 and 90 mW/m^2, respectively); the approximate depth of the brittle-ductile transition inferred from the COCORP data (10 to 15 km) falls between the respective maxima of these curves.

character of reflection series M may not be significant considering the complexity of the overlying structures and the narrow bandwidth of the deep data. No demonstrable offset is observed along M.

The reflection Moho is most prominent on lines 2A and 3 (Figs. 4b, 4c, and 5). On line 3, lower-crustal reflections are continuous beneath the transverse shear zone and across the edge of the 7-m.y.-old Socorro cauldron. These observations suggest that the reflection Moho observed on line 3 is a young feature, evolving on a short time scale in response to tectonic and magmatic processes. Similarly, on line 2A (Fig. 4b), the Moho does not dip to the north like mid-crustal reflections G2 or P but rather appears subhorizontal. Models where the Moho is an intrusive boundary, possibly the result of magmatic underplating or ponding at the base of the crust, predict a sharply defined, subhorizontal Moho (Fyfe, 1974; Herzberg and others, 1983). These types of models have been shown to be consistent with the seismic reflection data available from extensional terranes, although other models for the origin of the Moho, such as a metamorphic boundary or a shear zone, cannot be ruled out (Klemperer and others, 1986).

In the Death Valley and Rio Grande rift data, subhorizontal reflections observed between 14 km and Moho depth do not show offsets matching displacements documented along the upper crustal Cenozoic normal faults. Therefore, the deep layering, best observed on Death Valley line 11 (Fig. 11; Serpa and others, 1988) and Socorro line 2A (Fig. 4b), must have formed during Cenozoic extension, or represent older features which were significantly reactivated during Cenozoic extension. Similar observations have been made on the Basin and Range COCORP data (Klemperer and others, 1986; Hauge and others, 1987; Potter and others, 1987), where this deep layering may represent intrusions or shear zones related to Cenozoic extension. Pervasive subhorizontal layering in the middle and lower crust has been observed beneath several core complexes and shown to represent zones of mylonite (Reif and Robinson, 1981; Robinson, 1982; Hurich and others, 1985). In other areas, diabase sills have been drilled (Harrison and others, 1985; Potter and others, 1986). Relic sedimentary layering is also a possibility, supported by the metasedimentary origin of some deep crustal xenoliths in the southern Rio Grande rift (Padovani and Carter, 1977). No xenoliths data are available in the vicinity of the COCORP profiles, however, and a recent worldwide compilation of xenoliths data indicate that the lower continental crust is dominated by mafic rocks (Griffin and O'Reilly, 1987). On line 2A, event M2, attributed to the base of the crust, is the deepest of a series of strong and continuous reflections that extend from 4 to 12 s and that sandwich a layer of magma; therefore, intrusive activity is a likely cause of the reflectivity of the pervasive subhorizontal fabric seen on line 2A. Shot-point gathers from line 1A (Fig. 9) also show that the bright reflection G1 attributed to magma is, in places, sandwiched between less strong but continuous reflections. The conformity between the trend of overlying reflecting segments (for example, P on line 2A, Fig. 4b) and the magma body may suggest that the sill follows a "stretch" crustal fabric, and zones of mylonites may also contribute to the reflectivity of the lower crust. The spatial association between reflective lower crust and magmatic intrusions, however, is direct evidence of the potential importance of underplating in crustal growth and evolution (Serpa and de Voogd, 1987).

CONCLUSIONS

Fundamental differences appear to exist between upper and middle or lower crust in the Rio Grande rift and in Death Valley, two active continental rift zones where COCORP deep seismic reflection data are available. Evidence for basement penetrating faults is revealed on the reprocessed Socorro sections, including a low-angle master fault traceable to mid-crustal depth beneath the Albuquerque basin. A generalized model of the crust in the vicinity of the New Mexico profiles is proposed in Figure 15 and summarizes the results of this study. This model is based on the

COCORP data but is also supported by published geophysical and geological observations.

In both rifts, a mid-crustal boundary, prominent on the seismic sections, does not appear to be cut by any of the faults mapped at the surface or inferred from the seismic data. It is suggested that major faults do not continue into the lower crust but rather sole into subhorizontal shear zones in the mid-crust. In these two areas, therefore, the mid-crust is a structural boundary, perhaps a brittle-ductile transition. The middle and lower crust exhibits a subhorizontal structural and/or compositional fabric. In Death Valley, and perhaps also in the Rio Grande rift, décollement or decoupling of the upper crust occurs on a regional scale. The locally unusually strong reflectivity of the mid-crustal boundaries is thought to be due to magma accumulation along the zone of decoupling.

The Rio Grande rift and Death Valley COCORP data are compatible with models of crustal extension where brittle upper crust is underlain by lower and middle crust characterized by laminar flow and intrusion. The prominent layering observed in the middle and lower crust includes at least one layer of magma, thereby supporting the suggestion that magmatic intrusions are the likely cause of the strong subhorizontal reflections observed in the deep crust of many extensional terranes. This reflective crustal column stops, uniformly and often rather abruptly, at the approximate Moho depth defined by refraction experiments. The data support models where the reflection Moho is a young feature, related to Cenozoic magmatism and extension. The magmatic activity documented by this study is a major component of lower-crustal extension and evolution.

ACKNOWLEDGMENTS

We thank C. Chapin, E. Hauser, and D. Nelson for helpful discussions. Carlene Merey helped in reprocessing Socorro line 1A. We thank Cary Caruso for the use of his FK filter, and Li Zheng for the use of his coherency filter. Comments from G. Bassi, C. E. Keen, R. Phinney, and two anonymous reviewers significantly improved the revised manuscript. Field data were collected by Crew 6834 of the Petty-Ray Geophysical Division of Geosource, Inc. The data were processed on the MEGASEIS (TM Seiscom Delta) system at Cornell University. This work was supported by the National Science Foundation Grants EAR-82-12445 and EAR-84-18157. B. de Voogd received additional support in the form of a scholarship of the Society of Exploration Geophysicists Foundation.

REFERENCES CITED

Allmendinger, R. W., Sharp, J. W., Von Tish, D., Serpa, L., Kaufman, S., Oliver, J., and Smith, R. B., 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data: Geology, v. 11, p. 532–536.

Allmendinger, R. W., Hauge, T. A., Hauser, E. C., Potter, C. J., and Oliver, J., 1987, Tectonic heredity and the layered lower crust in the Basin and Range province, western United States, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London Special Publication no. 28, p. 223–246.

Baldridge, W. S., Olsen, K. H., and Callender, J. F., 1984, Rio Grande rift: Problems and perspectives: New Mexico Geological Society, 34th Field Conference, Guidebook, p. 1–12.

Brocher, T. M., 1981a, Shallow velocity structure of the Rio Grande rift north of Socorro, New Mexico: A reinterpretation: Journal of Geophysical Research, v. 86, p. 4960–4970.

——— 1981b, Geometry and physical properties of the Socorro, New Mexico, magma bodies: Journal of Geophysical Research, v. 86, p. 9420–9432.

Brown, L. D., Krumhansl, P. A., Chapin, C. E., Sanford, A. R., Cook, F. A., Kaufman, S., Oliver, J. E., and Schilt, F. S., 1979, COCORP seismic reflection studies of the Rio Grande rift, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 169–174.

Brown, L. D., Chapin, C. E., Sanford, A. R., Kaufman, S., and Oliver, J., 1980a, Deep structure of the Rio Grande rift from seismic reflection profiling: Journal of Geophysical Research, v. 85, p. 4773–4800.

Brown, L. D., Allmendinger, R. W., Kaufman, S., Oliver, J., Chapin, C. E., and Sanford, A. R., 1980b, Magma bodies, transverse faulting, and deep crustal structure from COCORP surveys across a Cenozoic cauldron in central New Mexico: Geological Society of America Abstracts with Programs, v. 12, p. 393.

Brown, L. D., Serpa, L., Setzer, T., Oliver, J., Kaufman, S., Lillie, R., Steiner, D., and Steeples, D., 1983, Intra-crustal complexity in the U.S. midcontinent: Preliminary results from COCORP surveys in N.E. Kansas: Geology, v. 11, p. 25-30.

Burchfiel, B. C., and Stewart, J. H., 1966, "Pull-apart" origin of the central segment of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439–442.

Cape, C. D., McGeary, S., and Thompson, G. A., 1983, Cenozoic normal faulting and the shallow structure of the Rio Grande rift near Socorro, New Mexico: Geological Society of America Bulletin, v. 94, p. 3–14.

Chamberlin, R. M., 1981, Cenozoic stratigraphy and structure of the Sorocco Peak volcanic center, central New Mexico: A summary: New Mexico Geology, v. 3, p. 22–24.

——— 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico, A summary: New Mexico Geological Society, 34th Field Conference, Guidebook, p. 111–118.

Chamberlin, R. M., Osburn, G. R., Chapin, C. E., Machette, M. N., Barker, J. M., Hawley, J. W., Cather, S. M., Osburn, J. C., and Anderson, O. J., 1983, New Mexico Geological Society, 34th Field Conference, Guidebook, p. 29–59.

Chapin, C. E., 1979, Evolution of the Rio Grande rift, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 1–5.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas: New Mexico Geological Society, 26th Field Conference, Guidebook, p. 297–321.

Chapin, C. E., Chamberlin, R. M., Osburn, G. R., White, D. W., and Sanford, A. R., 1978, Exploration framework of the Socorro geothermal area, New Mexico: New Mexico Geological Society Special Publication No. 7, p. 115–130.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geological Society Special Publication 6, p. 62–70.

——— 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073–1090.

Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, 490 p.

de Voogd, B., Brown, L. D., and Merey, C., 1986a, Nature of the eastern boundary of the Rio Grande rift from COCORP surveys in the Albuquerque basin, New Mexico: Journal of Geophysical Research, v. 91, p. 6305–6320.

de Voogd, B., Serpa, L., Brown, L., Hauser, E., Kaufman, S., Oliver, J., Troxel, B. W., Willemin, J., and Wright, L. A., 1986b, Death Valley bright spot: A midcrustal magma body in the southern Great Basin, California?: Geology, v. 14, p. 64–67.

Eaton, G., 1982, The Basin and Range province: Origin and tectonic significance: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 409–440.

Foster, R. W., 1978, Selected data for deep drill holes along Rio Grande rift in New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 236–237.

Fountain, D. M., and Salisbury, M. H., 1981, Exposed cross-sections through the continental crust: Implications for crustal structure, petrology, and evolution: Earth and Planetary Science Letters, v. 56, p. 263–277.

Frishman, M. S., 1979, Use of linear inversion techniques to study Poisson's ratios in the upper crust in the Socorro, New Mexico, area: New Mexico Institute of Mining and Technology, Geophysics Open-File Report 27, 85 p.

Furlong, K. P., and Fountain, D. M., 1986, Continental crustal underplating: Thermal considerations and seismic-petrologic consequences: Journal of Geophysical Research, v. 91, p. 8285–8294.

Fyfe, W. S., 1974, Archaean tectonics: Nature, v. 249, p. 338.

Gans, P. B., Miller, E. L., McCarthy, J., and Ouldcott, M. L., 1985, Tertiary extensional faulting and evolving ductile-brittle transition zones in the northern Snake Range and vicinity: New insights from seismic data: Geology, v. 13, p. 189–193.

Gans, P. B., 1987, An open-system, two-layer crustal stretching model for the eastern Great Basin: Tectonics, v. 6, p. 1–12.

Griffin, W. L., and O'Reilly, S. Y., 1987, Is the continental Moho the crust-mantle boundary?: Geology, v. 15, p. 241–244.

Hamilton, W., 1982, Structural evolution of the Big Maria Mountains, northwest Riverside County, southeastern California, *in* Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, p. 1–28.

Harrison, J. E., Cressman, E. R., and Kleinkopf, M. D., 1985, Regional structure, the Atlantic-Richfield-Marathon Oil No. 1 Gibbs borehole, and hydrocarbon resource potential west of the Rocky Mountain trench in northwestern Montana: U.S. Geological Survey Open-File Report 85-249.

Hauge, T., Allmendinger, R., Caruso, C., Hauser, E., Klemperer, S. L., Opdyke, S. S., Potter, C., Sanford, W., Brown, L., Kaufman, S., and Oliver, J., 1987, Crustal structure of western Nevada from COCORP deep seismic reflection data: Geological Society of America Bulletin, v. 98, p. 320–329.

Herzberg, C. T., Fyfe, W. S., and Carr, M. J., 1983, Density constraints on the formation of the continental Moho and crust: Contributions to Mineralogy and Petrology, v. 84, p. 1–5.

Hurich, C. A., Smithson, S. B., Fountain, D. M., and Humphreys, M. C., 1985, Seismic evidence of mylonite reflectivity and deep structure in the Kettle dome metamorphic core complex, Washington: Geology, v. 13, p. 577–580.

Jaksha, L. H., and Sanford, A. R., 1986, Earthquakes near Albuquerque, New Mexico, 1976–1981: Journal of Geophysical Research, v. 91, p. 6293–6303.

Jiracek, G. R., Rodi, W. L., and Vanyan, L. L., 1987, Implications of magnetotelluric modeling for the deep crustal environment in the Rio Grande rift: Physics of the Earth and Planetary Interiors, v. 45, p. 179–192.

Johnston, J. A., 1978, Microearthquake frequency attenuation of S phases in the Rio Grande rift near Socorro, New Mexico: New Mexico Institute of Mining and Technology, Geophysics Open-File Report 24, 84 p.

Jones, T. D., and Nur, A., 1984, The nature of seismic reflections from deep crustal fault zones: Journal of Geophysical Research, v. 89, p. 3153–3171.

Kay, R. W., and Kay, S. M., 1981, The nature of the lower continental crust: Inferences from geophysics, surface geology, and crustal xenoliths: Reviews of Geophysics and Space Physics, v. 19, p. 271–297.

——— 1986, Petrology and geochemistry of the lower continental crust: An overview, *in* Geological Society of London Special Publication No. 24, p. 147–160.

Keen, C. E., Boutilier, R., de Voogd, B., Mudford, B., and Enachescu, M., 1988, Crustal geometry and extensional models for the Grand Banks, eastern Canada: Constraints from deep seismic reflection data, *in* Beaumont, C., and Tankard, A. J., eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 101–115.

Kelley, V. C., 1977, Geology of the Albuquerque basin: New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p.

Klemperer, S. L., Hauge, T. A., Hauser, E. C., Oliver, J. E., and Potter, C. J., 1986, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40°N seismic-reflection transect: Geological Society of America Bulletin, v. 97, p. 603–618.

Kligfield, R., Crespi, J., Naruk, S., and Davis, G.I.H., 1984, Displacement and strain patterns of extensional orogens: Tectonics, v. 3, p. 577–609.

Larner, K. L., Hatton, L., Gibson, B. S., and Hsu, I-C., 1981, Depth migration of imaged time sections: Geophysics, v. 46, p. 734–750.

Larsen, S., Reilinger, R., and Brown, L. D., 1986, Evidence of ongoing crustal deformation related to magmatic activity near Socorro, New Mexico: Journal of Geophysical Research, v. 91, p. 6283–6292.

Lynn, H. B., and Deregowski, S., 1981, Dip limitations on migrated sections as a function of line length and recording time: Geophysics, v. 46, p. 1392–1397.

Lynn, H. B., Quam, S., and Thompson, G. A., 1983, Depth migration and interpretation of the COCORP Wind River, Wyoming, seismic reflection data: Geology, v. 11, p. 462–469.

Machette, M. N., compiler, 1978, Preliminary geologic map of the Socorro 1°×2° quadrangle, central New Mexico: U.S. Geological Survey Open-File Report 78–607.

——— 1982, Quaternary and Pliocene faults in the La Jencia and southern part of the Albuquerque-Belen basins, New Mexico: Evidence of fault history from fault-scarp morphology and Quaternary geology: New Mexico Geological Society, 33rd Field Conference, Guidebook, p. 161–169.

Matthews, D. H., and Cheadle, M. J., 1986, Deep reflections from the Caledonides and Variscides west of Britain and comparison with the Himalayas, *in* Barazangi, M., and Brown, L., eds., Reflection seismology: A global perspective: Washington, D.C., American Geophysical Union Geodynamics Series, Volume 13, p. 5–19.

Mayer, J. R., and Brown, L. D., 1986, Signal penetration: Basin and Range to Colorado Plateau: Geophysics, v. 51, p. 1050–1054.

McCarthy, J., 1986, Reflection profiles from the Snake Range metamorphic core complex: A window into the mid-crust, *in* Barazangi, M., and Brown, L. D., eds., Reflection seismology: The continental crust: Washington, D.C., American Geophysical Union Geodynamics Series, Volume 14, p. 281–292.

Meissner, R., and Strehlau, J., 1982, Limits of stresses in continental crusts and their relation to the depth-frequency distribution of shallow earthquakes: Tectonics, v. 1, p. 73–89.

Morgan, P., and Golombek, M. P., 1984, Factors controlling the phases and styles of extension in the northern Rio Grande rift: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 13–20.

Moss, F. J., and Mathur, S. P., 1986, A review of continental reflection profiling in Australia, *in* Barazangi, M., and Brown, L. D., eds., Reflection seismology: A global perspective: Washington, D.C., American Geophysical Union Geodynamics Series, Volume 13, p. 67–76.

Olsen, K. H., Keller, G. R., and Stewart, J. N., 1979, Crustal structure along the Rio Grande rift from seismic refraction profiles, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 127–143.

Olsen, K. H., Cash, D. J., and Stewart, J. N., 1982, Mapping the northern and eastern extent of the Socorro midcrustal magma body by wide-angle seismic reflections: New Mexico Geological Society, 33rd Field Conference, Guidebook, p. 179–185.

Osburn, G. R., Petty, D. M., and Chapin, C. E., 1981, Geology of the Molino Peak quadrangle: New Mexico Bureau of Mines and Mineral Resources Open-File Report 139A.

Padovani, E. R., and Carter, J. L., 1977, Aspects of deep crustal evolution beneath central New Mexico, *in* Heacock, J. G., ed., The Earth's crust: Its nature and physical properties: American Geophysical Union Geophysical Monograph Series, Volume 20, p. 19–55.

Peddy, C. P., Brown, L. D., and Klemperer, S. L., 1986, Interpreting the deep structure of rifts with synthetic seismic sections, *in* Barazangi, M., and Brown, L. D., eds., Reflection seismology: A global perspective: Washington, D.C., American Geophysical Union Geodynamics Series, Volume 13, p. 301–311.

Potter, C. J., Sanford, W. E., Yoos, T. R., Prussen, E. I., Keach, R. W., Oliver, J. E., Kaufman, S., and Brown, L., 1986, COCORP deep seismic reflection traverse of the interior of the North American Cordillera, Washington and Idaho: Implications for orogenic evolution: Tectonics, v. 5, p. 1007–1026.

Potter, C. J., Liu, C. S., Huang, J., Zheng, L., Hauge, T. A., Hauser, E., Allmendinger, R. W., Oliver, J. E., Kaufman, S., and Brown, L., 1987, Crustal structure of north-central Nevada: Results from COCORP deep seismic profiling: Geological Society of America Bulletin, v. 98, p. 330–337.

Reif, D. M., and Robinson, J. P., 1981, Geophysical, geochemical and petrographic data and regional correlation from the Arizona State A-1 Well, Pinal County, Arizona: Arizona Geological Society Digest, v. 13, p. 99–109.

Reilinger, R., Oliver, J., Brown, L. D., Sanford, A. R., and Balazs, E. I., 1980, New measurements of crustal doming over the Socorro magma body: Geology, v. 8, p. 291–295.

Rinehart, E. J., Sanford, A. R., and Ward, R. M., 1979, Geographic extent and shape of an extensive magma body at midcrustal depths in the Rio Grande rift near Socorro, New Mexico, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 237–251.

Roach, J. M., 1982, The mapping of shallow magma bodies near Socorro, New Mexico, by use of seismic attenuation: New Mexico Institute of Mining and Technology, Geophysics Open-File Report 42, 91 p.

Robinson, J., 1982, Petroleum exploration in southeastern Arizona: Anatomy of an overthrust play: Rocky Mountain Association of Geologists, p. 665–674.

Sanford, A. R., 1983, Magma bodies in the Rio Grande rift in central New Mexico: New Mexico Geological Society, 34th Field Conference, Guidebook, p. 123–125.

Sanford, A. R., and Long, L. T., 1965, Microearthquake crustal reflections, Socorro, New Mexico: Seismological Society of America Bulletin, v. 55, p. 579–586.

Sanford, A. R., Alptekin, O. S., and Toppozada, T. R., 1973, Use of reflection phases on microearthquake seismograms to map an unusual discontinuity beneath the Rio Grande rift: Seismological Society of America Bulltin, v. 63, p. 2021–2034.

Sanford, A. R., Mott, R. P., Jr., Shuleski, P. J., Rinehart, E. J., Caravella, F. J., Ward, R. M., and Wallace, T. C., 1977, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, *in* Heacock, J. G., ed., The Earth's crust: Its nature and physical properties: American Geophysical Union Geophysical Monograph Series, Volume 20, p. 385–403.

Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1979, Seismicity of the Rio Grande rift, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 145–168.

Sanford, A. R., and Einarsson, P., 1982, Magma chambers in rifts, *in* Palmason, G., ed., Continental and oceanic rifts: American Geophysical Union and Geological Society of America Geodynamics Series, Volume 8, p. 147–168.

Sanford, A., Jaksha, L., and Wieder, D., 1983, Seismicity of the Socorro area of the Rio Grande rift: New Mexico Geological Society, 34th Field Conference, Guidebook, p. 127–131.

Serpa, L., and de Voogd, B., 1987, Deep seismic reflection evidence for the role of extension in the evolution of continental crust: Royal Astronomical Society Geophysical Journal, v. 89, p. 55–60.

Serpa, L., de Voogd, B., Wright, L., Willemin, J., Oliver, J., Hauser, E., and Troxel, B., 1988, Structure of the central Death Valley pull-apart basin from COCORP profiles in the southern Great Basin: Geological Society of America Bulletin, v. 100, p. 1437–1450.

Sibson, R. H., 1983, Continental fault structure and the shallow earthquake source: Geological Society of London Journal, v. 140, p. 741–767.

Smith, R. B., and Bruhn, R. L., 1984, Intraplate extensional tectonics of the eastern basin-range: Inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, p. 5733–5762.

Stewart, J. H., 1971, Basin and Range structure—A system of horsts and grabens produced by deep-seated extension: Geological Society of America Bulletin, v. 82, p. 1019–1044.

——— 1983, Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwestward: Geology, v. 11, p. 153–157.

Toppozada, T. R., and Sanford, A. R., 1976, Crustal structure in central New Mexico interpreted from the Gasbuggy explosion: Seismological Society of America Bulletin, v. 66, p. 877–886.

Tullis, J., Snoke, A. W., and Todd, V. R., 1982, Significance and petrogenesis of mylonitic rocks (Penrose Conference report): Geology, v. 10, p. 227–230.

Wallace, T. C., 1978, Microearthquake swarm activity in the Socorro, New Mexico area: Directed study, Geoscience Department, New Mexico Institute of Mining and Technology.

Ward, R. M., Schlue, J. W., and Sanford, A. R., 1981, Three-dimensional velocity anomalies in the upper crust near Socorro, New Mexico: Geophysical Research Letters, v. 8, p. 553–556.

Warner, M., 1987, Migration—Why doesn't it work for deep data?: Royal Astronomical Society Geophysical Journal, v. 89, p. 21–26.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648.

——— 1986, Whole-lithosphere normal simple shear: An interpretation of deep-reflection profiles in Great Britain, *in* Barazangi, M., and Brown, L. D., eds., Reflection seismology: The continental crust: American Geophysical Union Geodynamics Series, Volume 14, p. 331–339.

Wright, L. A., 1974, Geologic map of the region of central and southern Death Valley, eastern California and southwestern Nevada, *in* Death Valley Region, California and Nevada, Field trip no. 1: Geological Society of America, Cordilleran Section Guidebook, p. 25.

Wright, L. A., and Troxel, B. W., 1973, Shallow-fault interpretation of basin and range structure, *in* DeJong, K. A., and Scholten, Robert, eds., Gravity and tectonics: New York, John Wiley & Sons, p. 397–407.

——— 1984, Geology of the northern half of the Confidence Hills, 15 minute quadrangle, Death Valley region, eastern California: The area of the Amargosa chaos: California Department of Mines and Geology map sheet 34, scale 1:12,000; 31 p. text.

Wright, L. A., Troxel, B. W., Burchfiel, B. C., Chapman, R. H., and Labotka, T. C., 1981, Geological cross section from the Sierra Nevada to the Las Vegas Valley, eastern California to southern Nevada: Geological Society of America Map and Chart Series NC-29M.

Wu, Z., 1986, Shallow structure of the southern Albuquerque basin (Rio Grande rift), New Mexico, from COCORP seismic reflection data, *in* Barazangi, M., and Brown, L., eds., Reflection seismology: A global perspective: Washington, D.C., American Geophysical Union Geodynamics Series, Volume 14, p. 293–304.

Zheng, L., and Brown, L. D., 1988, Application of coherency enhancement to deep seismic reflection data: Geophysics (in press).

Zhu, T., and Brown, L. D., 1986, COCORP Michigan surveys: Reprocessing and results: Journal of Geophysical Research, v. 91, p. 11477–11495.

MANUSCRIPT RECEIVED BY THE SOCIETY MAY 1, 1986
REVISED MANUSCRIPT RECEIVED FEBRUARY 1, 1988
MANUSCRIPT ACCEPTED MARCH 3, 1988
INSTITUTE FOR THE STUDY OF THE CONTINENTS CONTRIBUTION NO. 53

Printed in U.S.A.