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COCORP SEISMIC REFLECTION STUDIES OF THE RIO GRANDE RIFT

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Abstract. Major buried intragraben horsts, large intrusive bodies, deformed metamorphic terrains, the crust-mantle boundary, and a midcrustal zone of magma accumulation are among the geological features apparently resolved by seismic reflection profiling in the Rio Grande rift carried out by the Consortium for Continental Reflection Profiling (COCORP). As part of its program to apply advanced, multichannel seismic reflection techniques to the study of major geological problems of the continental crust, COCORP collected 155 km of 24-fold reflection data near Socorro, New Mexico, in 1975 and 1976, including an 80-km traverse across the rift from the Sierra Lucero on the west to the Manzano Mountains on the east. Stacked reflection sections indicate coherent reflected energy from depths of at least 35 km. From these results the Precambrian basement within the rift is seen to be pervasively disrupted by high-angle normal faults, resulting in substantial buried topography. A major buried horst was discovered in the southwestern part of the Albuquerque Basin, probably correlative with the nearby Sierra Ladron block. The western rift boundary is defined by a reflector dipping eastward at a moderate angle (∿40 °) which intersects the surface at the western edge of the Monte Largo embayment. The eastern rift boundary is associated with a high angle, linear (planar ?) zone defined by lack of coherent reflections and extending to the base of the crust. The basement within the rift is characterized by seismically transparent zones devoid of coherent energy, possibly homogeneous plutons, and zones dominated by numerous short (less than 5 km), discontinuous reflector segments. The latter suggest considerable disruption of structural coherence such as might be expected in a deformed metamorphic terrain. At midcrustal depths a strong, complex P-wave reflector corresponds in depth and dip with a previously inferred magma body. Synthetic seismograms and spectral studies indicate that the observed waveforms are consistent with, but not unique to, models of low velocity partially molten material within the crust. The seismic sections show a complex intermittent zone of layered reflection bands at the base of the crust rather than the simple Moho model often inferred from refraction results. The structural variations in the crust mapped by COCORP reflection profiling may have played an important role in the development and subsequent evolution of the Rio Grande rift.

Introduction

During 1975 and 1976, the Consortium for Continental Reflection Profiling (COCORP) carried out deep seismic reflection surveys near Socorro, New Mexico, to investigate some of the fundamental geologic problems represented by the Rio Grande rift. Using field techniques based on the VIBROSEIS* methods widely used in conventional oil exploration, COCORP collected 155 km of 24-fold reflection data, including a 80-km east-west traverse across the rift in the southern Albuquerque Basin. Details of the data collection and processing procedures are provided by Oliver and Kaufman (1976) and Brown et al. (1979).

In this paper, some of the principal results of COCORP's efforts in the Rio Grande rift are briefly outlined , with particular reference to the results obtained along survey Lines 1, 1A, and 2A (for a more complete discussion of these and other results see Brown et al., 1979). The seismic sections corresponding to these lines provide substantial new information on the nature of the rift boundaries, intra-rift faulting, a midcrustal magma body, and the crust-mantle transition in an area representing the early stages of continental breakup.

Background

The regional geological and geophysical setting of the Rio Grande rift has been reviewed by Chapin (1971), Chapin and Seager (1975), and Cordell (1978). The geology of the Albuquerque Basin, in which the COCORP lines discussed here are located, is reviewed by Kelley (1977). The rift is a major NNE-trending crustal break following the southern Rocky Mountain tectonic belt, which separates the Great Plains from the Colorado Plateau and Basin and Range. Crustal extension began about 32-27 m.y. ago (Chapin, 1979) and has continued to the present, with late Cenozoic rift structures apparently being superimposed upon late Paleozoic and Laramide uplifts (Chapin and Seager, 1975). Volcanism concurrent with extension has occurred mainly along the medial axis and west side of the rift, with periods of greatest activity being from 32 to 20 m.y. ago and from 5 m.y. ago to the present (Chapin and Seager, 1975; Chapin, 1979). Evidence that rifting is continuing at the present time includes an elongate topographic bulge (Cordell, 1978), fault scarps cutting alluvial fans and Pleistocene surfaces (e.g. Kelly, 1977), seismic activity (Sanford et al., 1972), high heat flow (Reiter et al., 1975; Decker and Smithson, 1975), contemporary relative uplift (Reilinger and Oliver, 1976), geophysical measurements indicating the existence of modern magma bodies at shallow and midcrustal depths (Sanford et al., 1977), and gravity results which indicate an anomalous mantle upwarp at the base of the crust (Decker and Smithson, 1975; Ramberg et al., 1978).

Refraction measurements from the Gasbuggy nuclear test indicate an 18 km thick 'upper crust' (V= 5.8 km/sec) overlying a lower crust (V= 6.5 km/sec) bounded by a Moho dipping northward at about 2 degrees (Toppozada and Sanford, 1976). Depth to the crust-mantle transition in the vicinity of COCORP Line 1 is estimated to be about 38 km on the basis of these data. More recent results from the DICE THROW explosions indicate the crust in the vicinity of Line 1 to be closer to 33 km (Olsen et al., 1979). These depths are somewhat greater than the 30 km thickness estimated for Basin and Range crust (e.g. Prodehl, 1977) but

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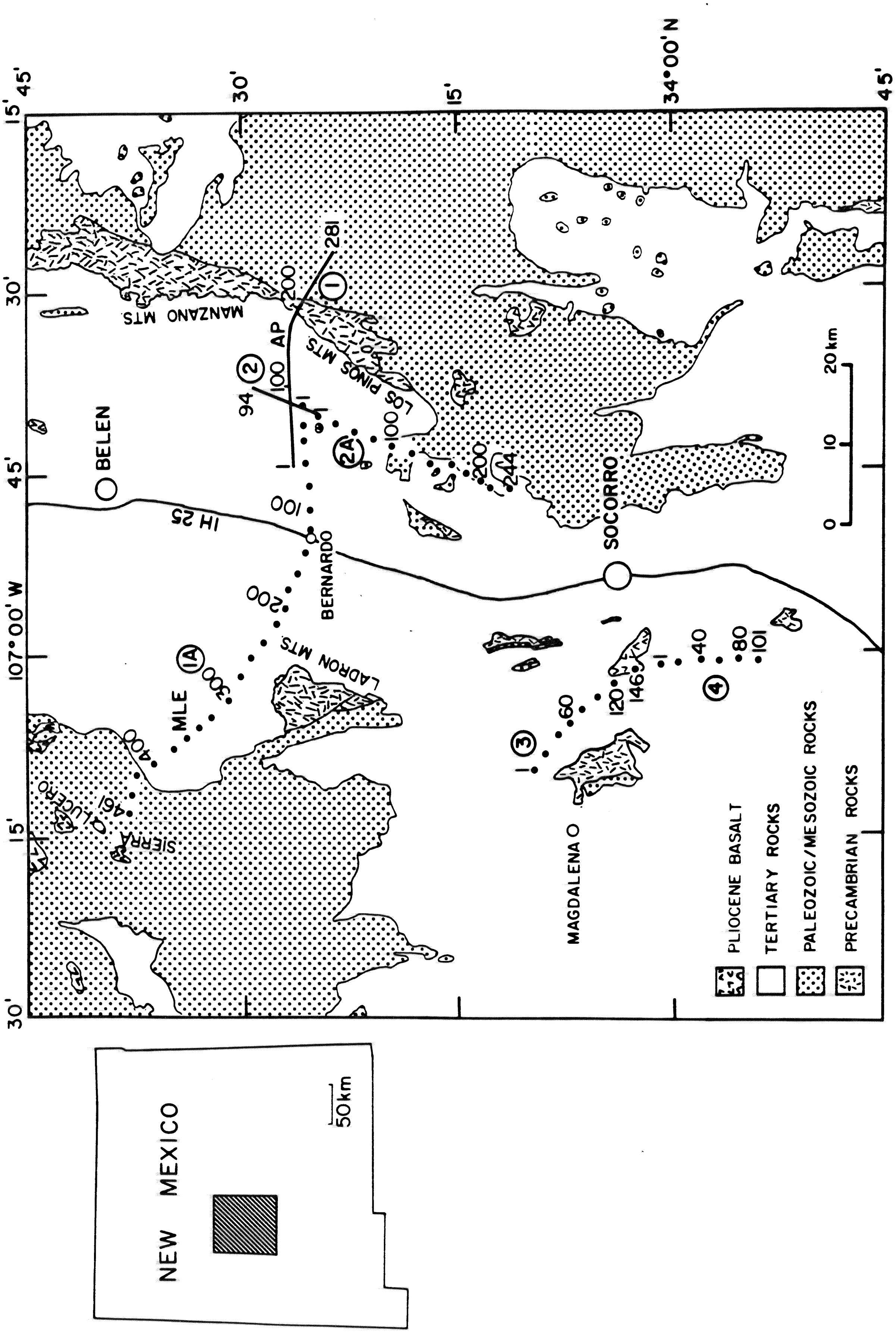


1. Location of COCORP deep seismic reflection profiles in the Rio Grande rift near Socorro, New Mexico. AP = Abo Pass. MLE = Monte Largo embayment.

substantially less than the 53 km crustal thickness suggested for the High Plains (Mitchell and Landisman, 1971)

Of particular interest are the results of microearthquake studies by Sanford and coworkers (Sanford and Long, 1965; Sanford et al., 1973; Sanford et al., 1977) which indicate the existence of an extensive magma body at midcrustal depths. In the vicinity of COCORP Lines 1 and 1A the top of the magma body is estimated from the microearthquake studies to be at a depth of approximately 20 km (Rinehart et al., 1979).

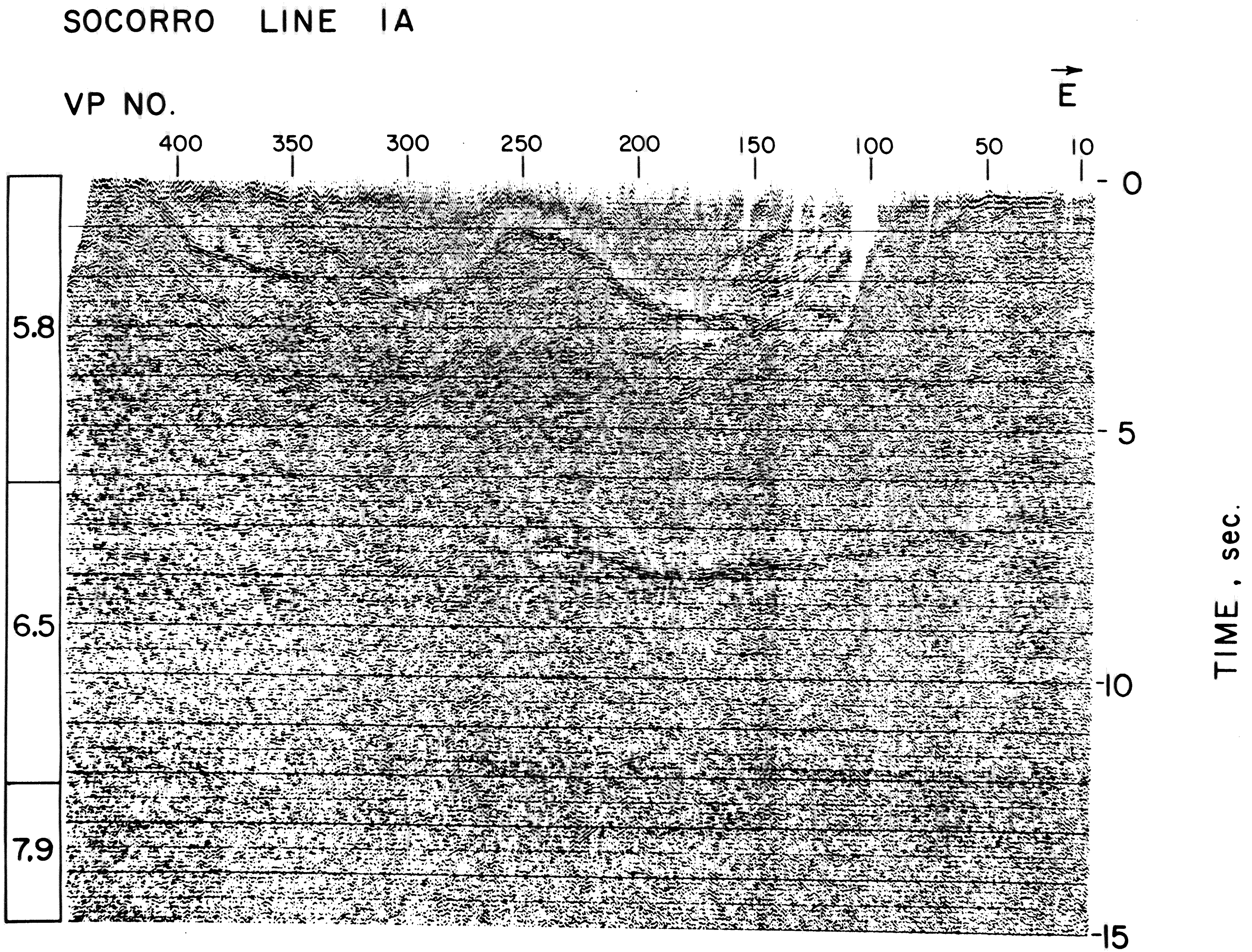
Results

The COCORP seismic time sections obtained in the rift strongly resemble geologic cross sections. However they are subject to numerous interpretational pitfalls because they are unmigrated and generally distorted compared to depth sections because of lateral and vertical velocity variations, and may contain multiples and side reflections. Such effects are of special concern for deep seismic reflection studies because of the low signal-to-noise ratios and complex geology involved. In spite of these complicating factors and the probability that future advances in processing techniques will result in further enhancement of the information contained in these records, the seismic sections represented in Figures 2-6 constitute a substantially more extensive and detailed look at the deep structure of an intracontinental graben than heretofore obtained. Only the first 15 seconds of data are shown in order to conserve space yet retain important structural details. Times on these sections can be converted to approximate depth by multiplying by half the average velocity. For the shallow graben fill, 3.5 km/sec is a proper velocity to use, while for the deeper parts of the records 6 km/sec is more appropriate.

The Rift Boundaries

The eastern rift boundary at Abo Pass is clearly defined on the shallow portions of the seismic sections (Figure 3) by the transition from normal faulted strata beneath the basin (VP 10-180, Line 1) to the nearly reflection-free shallow Precambrian basement beneath the flank. Beneath the surface expression of this boundary (the Los Pinos fault) is a well-defined, steeply dipping zone devoid of reflections. This seismically transparent zone separates the discontinuous reflection character of the deep seismic section beneath the basin from the more continuous character at depth beneath the flank. Although the possibility that this zone is an artifact of near surface wave propagation effects cannot be ruled out, the most plausible interpretation is that it represents real earth structure at depth. It could be due to structural disruption along a major Tertiary normal fault of crustal scale, an igneous intrusion along such a fault, or an ancient flaw in the crust along which Tertiary (and possibly earlier Laramide) faulting was localized. If this zone is the deep expression of the rift boundary fault, it argues strongly against listric models of rift formation (e.g. Woodward, 1977). If the seismic character of this zone is not a result of Tertiary faulting, its coincidence with such faulting is persuasive evidence for control of crustal fracturing by pre-existing weaknesses.

In contrast, the seismic section across the western rift boundary near the Sierra Lucero shows no evidence of a similar transparent zone at depth (Figures 2 and 3). In the shallow section, the boundary is represented by a moderate-angle (∿40° migrated) reflection (note that the shallow section is displayed at between 1.5- and 2.0-to-1 vertical



2. Seismic reflection section obtained along Line 1A. Horizontal scale in terms of Vibrating Points. VP spacing is 134 m. Column at left represents crustal structure determined by refraction (Toppozada and Sanford, 1976).

exaggeration because of the low velocities of the graben fill) which intersects the surface at the western edge of the Monte Largo embayment (VP 420, Line 1A, Figure 1). Since such a shallow fault at this boundary is inconsistent with surface mapping, which indicates predominantly high-angle faulting (Kelley, 1977), this event is most plausibly interpreted as either a composite reflection from the top of a closely-spaced set of step-faults or possibly a reflected refraction. It is also possible that the anomalously low angle is an apparent dip due to traversing the boundary fault at some angle not perpendicular to strike at depth; however, the survey route crosses surface structure (i.e. the edge of the Monte Largo embayment) at nearly a right angle. In either case, the western rift boundary has a substantially different seismic character from the eastern boundary. This difference may be due to possible rheological factors related to the higher heat flow along the western rift margin.

The strong reflector beneath the Monte Largo embayment (at 2.0 sec beneath VP 350 in Figure 3) argues against a listric western boundary fault. If this reflector were downfaulted as much as shown in Figure 3 along a substantially concave fault, it should be strongly tilted down to the west, in opposition to the gentle eastward dip actually observed.

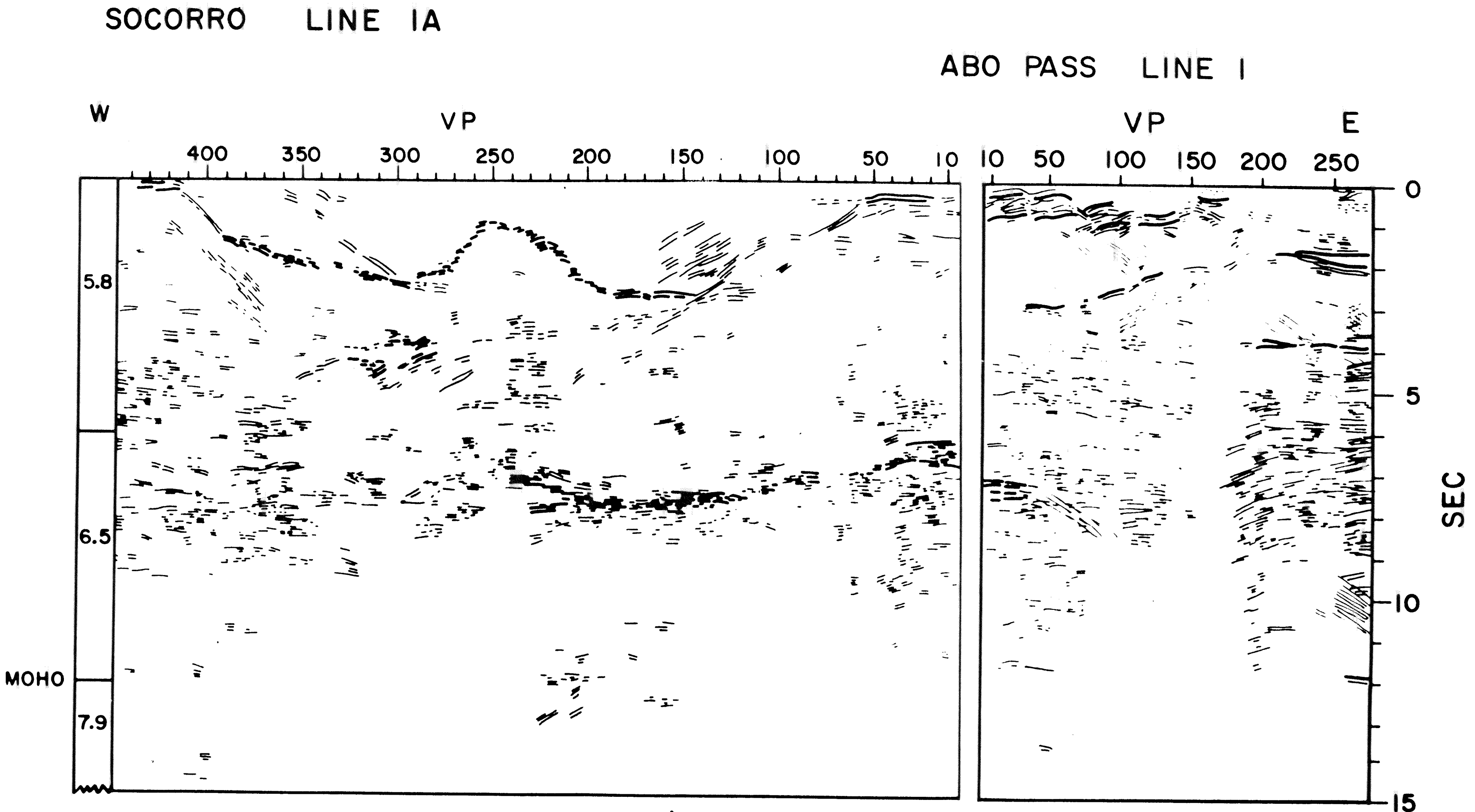
Intrarift Faulting

The shallow reflectors on Lines 1 and 1A are pervasively faulted by generally high-angle (where dip can be determined with confidence) normal faults. The west end of Line 1 displays an especially well developed set of antithetic normal faults (Figure 3) offsetting Phanerozoic strata. Faulting on Line 1A appears to be on a much larger scale. The offset between the shallow reflector at 0.5 sec beneath VP 50 and the strong event at 2.7 sec beneath VP 175 represents at least 4 km of normal faulting (even though these events may not be strictly correlative). The total depth to the 2.7 sec event is 4.8 km. Although some question remains as to the identity of this prominent marker horizon (it may be a Cenozoic volcanic unit or a Paleozoic sedimentary reflector), it does imply considerable fault-generated relief in the crystalline basement beneath the basin.

An outstanding feature on Line 1A is the intragraben horst beneath VP 250. Depth to the top of this structure is 1.5 km, which gives it a relief of 3.3 km with respect to the 2.7 sec reflector. Close inspection of the reflection character of this event (Figure 4) reveals that it is defined, at least on its upper portions, by numerous, en echelon hyperbolae. This pattern may be the result of reflectors truncated by step-faulting, possibly high angle. This horst is located very near the Sierra Ladron block, where Precambrian rocks outcrop within the rift, and may be the subsurface extension of this feature.

Deep Structure

The intrabasement portions of the seismic sections obtained along Lines 1, 1A, and 2A are characterized by substantial inhomogeneity (Figures 2-6). Unlike reflection records for sedimentary sections (e.g. Mitchum et al., 1977), simple correlatable or continuous events are relatively rare. Instead, zones of generally short, discontinuous reflection segments are common (for example, on the west side of Line 1A or between 4 and 7 seconds on Line 2A). In addition, there are zones that appear to have no coherent reflections at all, although later arrivals indicate that sufficient seismic energy has penetrated to such zones. These discontinuous and transparent zones seem to be a rather



3. Line drawing representation of the seismic sections from Lines 1A and 1 which traverse the rift. Standard refraction section shown at left for comparison (Toppozada and Sanford, 1976). VP spacing is 134 m for Line 1A, 100 m for Line 1.

common feature on deep reflection records in general (e.g. Oliver et al., 1976) and have been interpreted as strong evidence for lateral as well as vertical inhomogeneity in the crust (Smithson and Brown, 1977).

Line 2A (Figures 5 and 6) exhibits these characteristics best, possibly because reflections from depth are less disrupted by the simpler, less faulted, near-surface structure along the profile route. Immediately below the shallow (less than 1 sec) relatively continuous reflectors, the upper part of the basement is markedly transparent. This character persists from about 1 sec down to about 4 sec, corresponding to a thickness of about 9 km. Based on similar inferences by Oliver et al. (1976) and Smithson et al. (1977), this transparent zone is interpreted to be an igneous body, possibly a granitic pluton analogous to the Priest and Los Pinos granites exposed in the nearby Manzano and Los Pinos mountains (Stark, 1956).

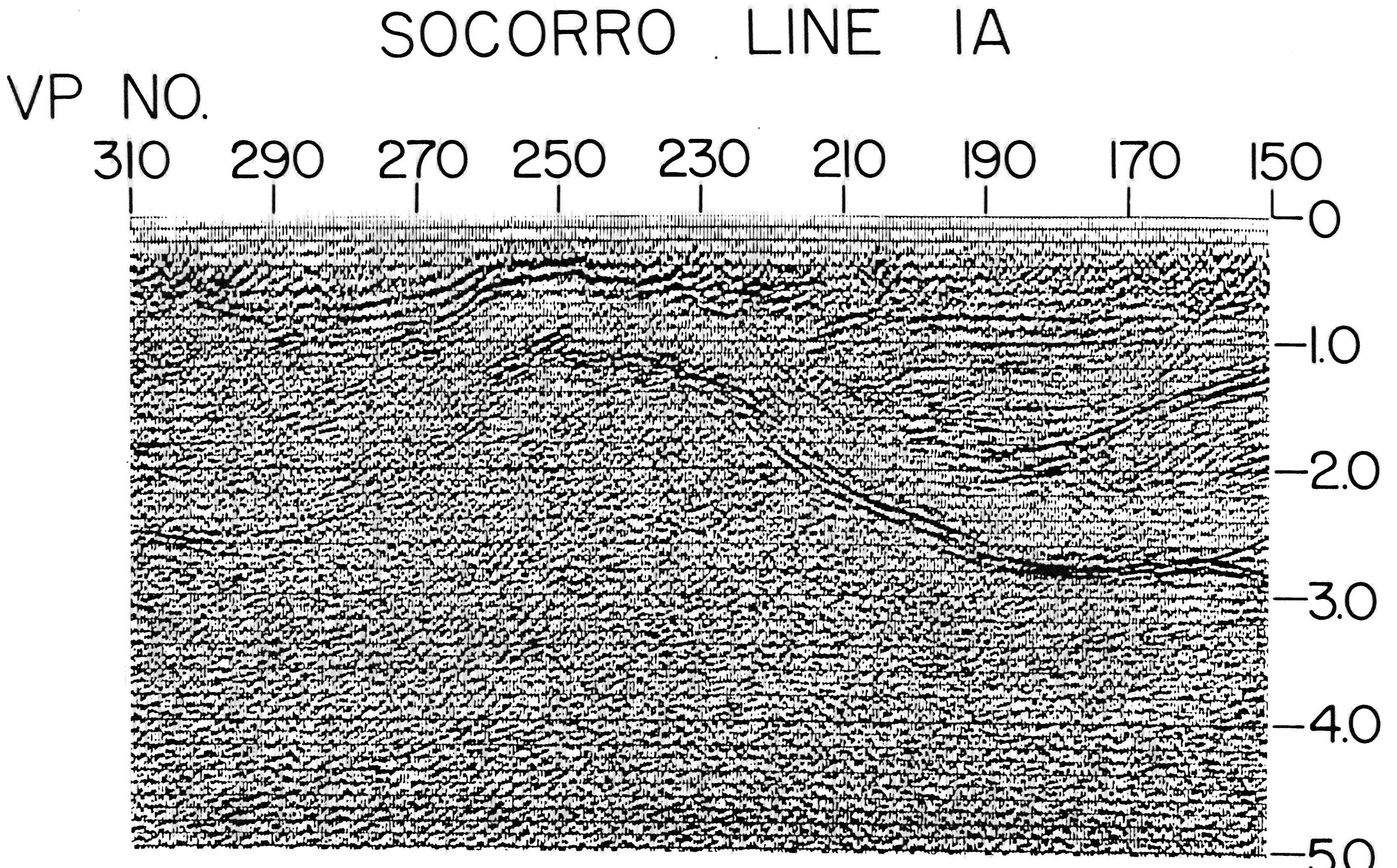
Below the transparent zone, and down to depths at which the signal becomes lost, the seismic section for Line 2A is characterized by numerous discontinuous reflection segments, varying in length, dip, density, and amplitude. The disrupted character of these zones is consistent with the hypothesis that the lower portions of the basement may be a highly deformed metamorphic terrain, whose complexity may equal that exposed in such terrains at the surface (e.g. Smithson and Brown, 1977; Smithson et al., 1977).

Most of these short reflection segments are sub-horizontal, although steep dips might be expected in highly deformed basement rocks (e.g. Anhaeusser, 1978). This apparent sub-horizontal 'fabric' in the basement may be an artifact due to the longer travel path (and consequently greater attenuation) for energy reflected from a steeply dipping event at a given depth compared with that for a near-vertical reflection or to the data processing used, which discriminates to some degree against dipping events (e.g. Phinney and Jurdy, 1979). On the other hand, it may be an essentially accurate representation of preferred orientation in deformed terrains at depth (Bridgewater et al., 1974).

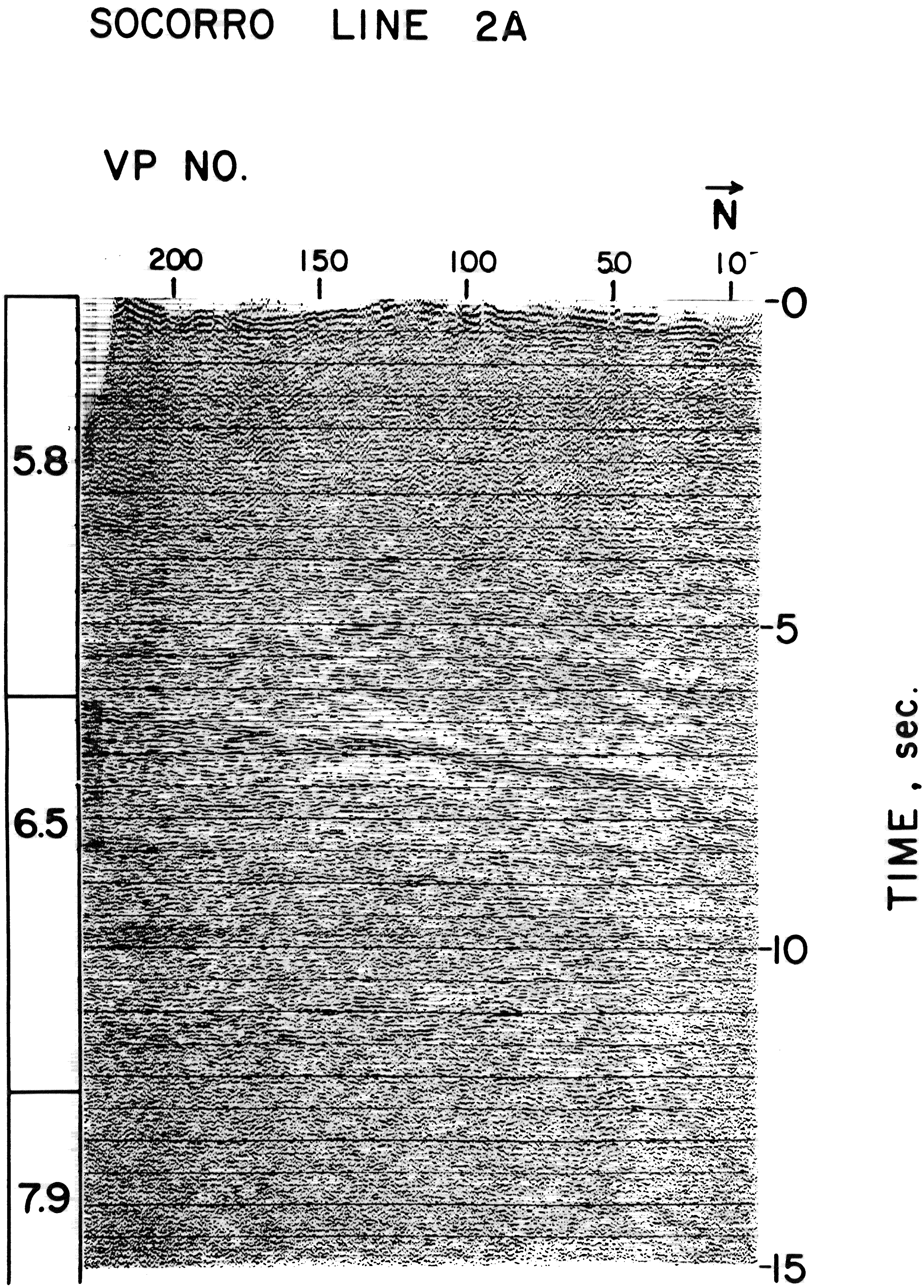
The Magma Body Reflection

The most pronounced event on the deeper parts of the COCORP sections is a complex band of reflections at about 7 sec (Figures 2-6). The apparent relief on the reflector exhibited in Figures 2 and 3 appears to be a velocity pulldown effect due to the varying thickness of overlying graben fill. This reflection sequence appears to terminate as an identifiable unit on the west by splaying out into at least two branches beneath the intragraben horst at VP 250, while on the east it appears to end near VP 50. This event is best displayed on Line 2A (Figures 5 and 6), where it is seen to be strong and complex, varying laterally in amplitude and waveform. It appears to dip northward at about 6 degrees, although some (but not all) of this dip may be due to velocity pulldown by the overlying Tertiary fill. Although the 7 sec event appears to be roughly conformable with certain overlying reflectors, it seems to truncate a flat-lying event just below it (Figure 6). Spectral studies indicate that it is a strong, broad-band reflection, corresponding to a relatively sharp reflector. There is some indication of enhanced attenuation of high-frequency waves passing through it. The amplitude of this event is about 6 db above nearby reflections.

The 7 sec event corresponds in depth and dip with the strong shear wave reflector inferred by Sanford and coworkers to represent the top of a midcrustal magma chamber (e.g. Sanford et al., 1977). Comparison of synthetic seismograms with unstacked reflection recordings (Figure 7)



4. Blow-up of central portion of seismic section for Line 1A showing intragraben horst. Note numerous diffraction hyperbolae defining upper portion of horst. VP spacing is 134 m.



5. Seismic section obtained along Line 2A. VP spacing is 134 m. Standard refraction crustal section at left from Toppozada and Sanford (1976).

indicates that the waveform and amplitude characteristics of this event are consistent with relatively simple models of magma (V=3 km/sec) entrapped in solid crustal material (V = 6 km/sec). On the other hand, properly spaced layers of intermediate velocities typical of crustal rocks might also explain the high amplitudes and waveforms observed. Because of the narrow bandwidth of the returned signal, reflection polarity is difficulty to ascertain. Figure 7 demonstrates that a polarity determination would be of dubious value in any case. Observed waveforms tend to be even more complex than the examples in Figure 7, indicating interference from several reflecting horizons.

The strong 7 sec reflection thus appears to be consistent with, but not requiring, magma at depth. If this reflector is properly identified with the strong shear-wave reflector, and the magma body hypothesis is correct, then these results indicate that it is not a simple body but may be layered and/or discontinuous in places.

The reflection character of this body is consistent with several geometrical models of magma emplacement; resolution of issues such as the location of its 'bottom' (assuming the stronger reflections are from its 'top') depend on whether one favors, for example, a large, connected sill-like intrusive or a zone of accumulation of smaller, disconnected but overlapping magma lenses. Analysis of these data with new processing techniques promises to clarify these and related problems.

The apparent horizontality of the magma body event on Line 1A (once the velocity pull-down effect is removed) suggests that the faulting which resulted in the intrarift horst at VP 250 (Figure 3) with its 3.3 km of relief was accomodated at depths less than 20 km. Alternatively, the lack of apparent offset of the 7 second reflections may be construed as evidence that it was emplaced after the faulting which formed the horst, implying that the reflectors are a relatively recent addition to the crust, as one might expect if it is a still-molten magma body.

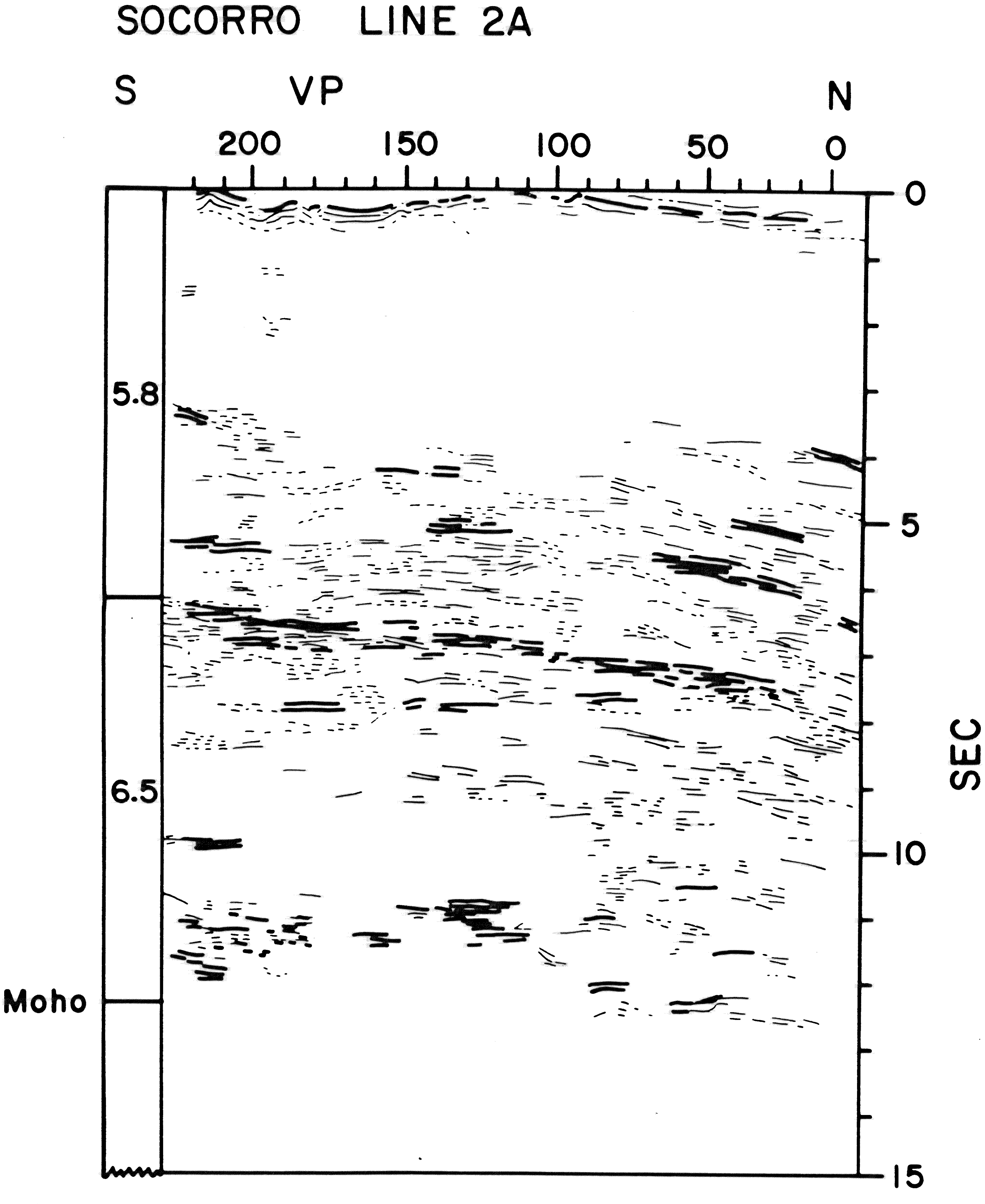
The Crust-Mantle Transition

Conventional seismic refraction techniques indicate that the Moho in the vicinity of the COCORP traverse is located at a depth of 33 to 38 km (Toppozada and Sanford, 1976; Olsen et al., 1979), corresponding to a travel time of between 11 and 13 seconds. Prominent reflections are seen in this time range on Lines 1 and 2A (similar events are lacking on Line 1A, possibly because of the severe near-surface structure effects). These reflections are therefore interpreted to be from the crust-mantle transition.

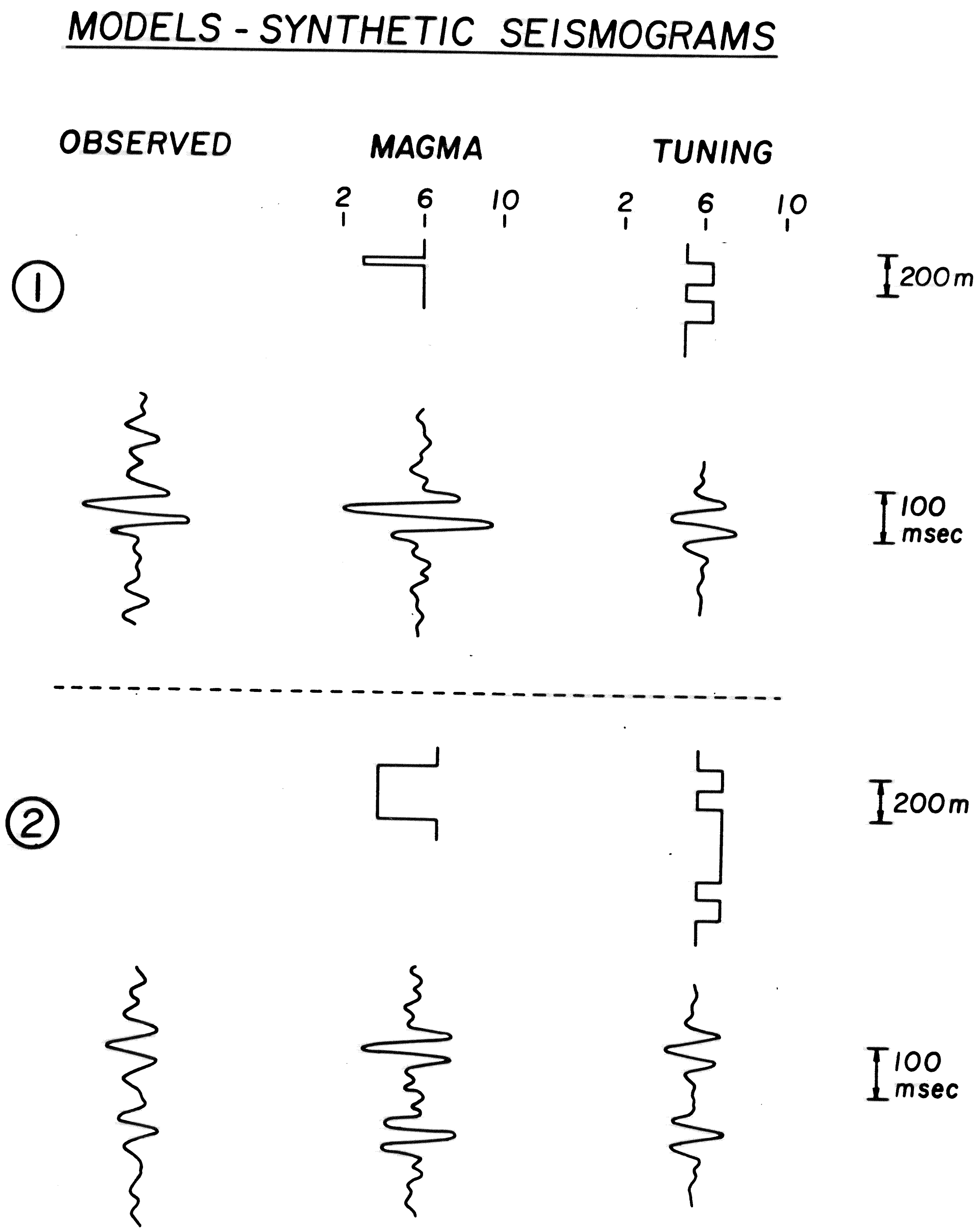
The events on Line 2A define a broad (1-2 sec) zone of short discontinuous reflection segments. The reflections from this zone near the center of Line 2A have layered character, similar to that observed elsewhere (Meissner, 1973). The events near 12 seconds on Line 1 (Figure 3) are relatively strong, especially the east-dipping segment under the flank, and relatively simple. Although signal variations due to overlying structure may affect the appearance of reflections from greater depths, the results of these surveys indicate that the crust-mantle transition is a complex zone which varies both laterally and vertically on a scale of a few kilometers.

Summary and Conclusions

Deep structure in the Rio Grande rift has been successfully mapped by COCORP seismic reflection surveys in the southern Albuquerque Basin. The results of these surveys indicate that:



6. Line drawing representation of the seismic section for Line 2A.



7. Observed and synthetic seismograms corresponding to 7 second reflection on Line 2A and hypothetical reflector models.

1. The shallow basement beneath the Albuquerque Basin is pervasively disrupted by Tertiary normal faults, some with very large offsets (4 km or more).

2. A large, buried intragraben horst, probably correlative with the nearby Sierra Ladron, separates the Monte Largo embayment from the rest of the Albuquerque Basin.

3. The eastern rift boundary appears to be defined by a steeply dipping, seismically transparent zone which extends to the base of the crust. This zone may represent a plane of intense deformation and/or intrusion associated with rifting, or a pre-existing weakness along which rupture was focused.

4. A strong northward-dipping, complex reflector at about 20 km depth corresponds with an inferred magma body beneath the rift.

5. The crust-mantle transition (Moho) beneath the rift is a complex zone of discontinuous, sometimes laminated, reflector units.

6. Numerous seismically transparent zones on the seismic section may indicate homogeneous plutons emplaced in the crust.

7. The majority of the crustal section is characterized by zones of discontinuous reflection character, probably corresponding to deformed and intruded metamorphic terrains.

The picture of an intracontinental rift which emerges from these reflection surveys is consistent with, but more complex than, those previously inferred from gravity (e.g. Decker and Smithson, 1975) or refraction (e.g. Mueller et al., 1969). As new data processing techniques become available, the ambiguities inherent in the interpretation process should diminish accordingly, and further refinements in our knowledge of these important structures should be realized.

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