

# Crustal structure of western Nevada from COCORP deep seismic-reflection data

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## ABSTRACT

The western Nevada segments of the COCORP 40°N deep seismic-reflection survey of the North American Cordillera reveal the geometry of structures of Cenozoic and possibly earlier ages to traveltimes of >10 s, corresponding to depths of >30 km. The most striking feature of the data is a band of prominent reflections, typically at traveltimes of 9.5 to 10.5 s, that are present discontinuously across the entire data set. Few reflections are observed from beneath the base of this reflective zone, which is interpreted as the crust-mantle transition. This "reflection Moho" is inferred to be continuous across the survey area, varying gradually in depth but without resolvable offsets. It appears to have taken its present form or position during basin-range crustal extension. The middle to lower crust in much of the survey area is characterized by discontinuous reflections that are typically subhorizontal and locally dip gently west. These reflections may represent intrusions or shear zones related to basin-range or pre-basin-range extension, but some are likely to be inherited from earlier compressional deformation. Reflections from the upper crust are interpreted as images of basin-fill strata, basin-range normal faults, and Mesozoic and Paleozoic thrusts related to back-arc thrusting and accretion of oceanic and arc-related rocks.

## INTRODUCTION

As part of a regional transect at 40°N latitude across the Cordillera of the western United States (Allmendinger and others, 1983; Nelson and others, 1986; Allmendinger and others, 1987; Potter and others, 1987; E. C. Hauser and others, unpub. data), the Consortium for Continental Reflection Profiling (COCORP) collected 220 km of deep seismic-reflection data in west-central Nevada in the spring of 1983 (Fig. 1). The data record reflections from a broad range of crustal depths, including prominent reflections thought to mark the crust-mantle transition. The

"reflection Moho" is interpreted as a laterally continuous feature with no resolvable offsets that varies gradually in depth from ~29 to 32 km. The apparent continuity and smoothness of the reflection Moho indicate that basin-bounding faults, which have throws of as much as 3 to 4 km or more at the surface, are unlikely to penetrate to mantle depths. Alternatively, the Moho may reform on time scales short in comparison to rates of fault offset, or the faults may penetrate the crust-mantle boundary as diffuse shear zones (Wernicke, 1986). Many reflections from the upper crust are straightforwardly explained as images of basin-fill strata and basin-bounding faults. Others can be interpreted as related to Paleozoic and Mesozoic terrane accretion and subsequent back-arc thrusting. Reflections from middle and lower crustal levels are typically subparallel to the reflection Moho and probably represent features of both basin-range and pre-basin-range ages. COCORP data from western Nevada, surface geology, and earthquake seismology suggest a model of basin-range extension in which the upper 7–15 km of the crust consists of tilted, fault-bounded structural blocks and in which the deeper crust has undergone pervasive extension. This contrasts with interpretations of COCORP and other seismic-reflection data from the Utah Basin and Range (Allmendinger and others, 1983; Smith and Bruhn, 1984), which indicate that low-angle normal faults underlie upper-crustal structural blocks and penetrate at least to mid-crustal depths. The observed smooth geometry of the Moho in western Nevada is interpreted as a product of basin-range lithospheric extension, but whether the pre-extensional shape of the Moho was greatly different from its observed form is not known.

In the following sections, the tectonic setting, data acquisition parameters, and data processing streams are summarized, and the reflection data are described and interpreted. The discussion section focuses on the implications of the data regarding basin-range extension, Mesozoic back-arc thrusting, and earlier Mesozoic and Paleozoic accretion of oceanic and oceanic-arc rocks.

## TECTONIC SETTING

The surface geology of the area of the western Nevada COCORP survey (Fig. 1) records a history including Paleozoic and early Mesozoic accretion of noncontinental terranes; Mesozoic folding, thrusting, and plutonism; and late Cenozoic magmatism and extension. The crust underly-

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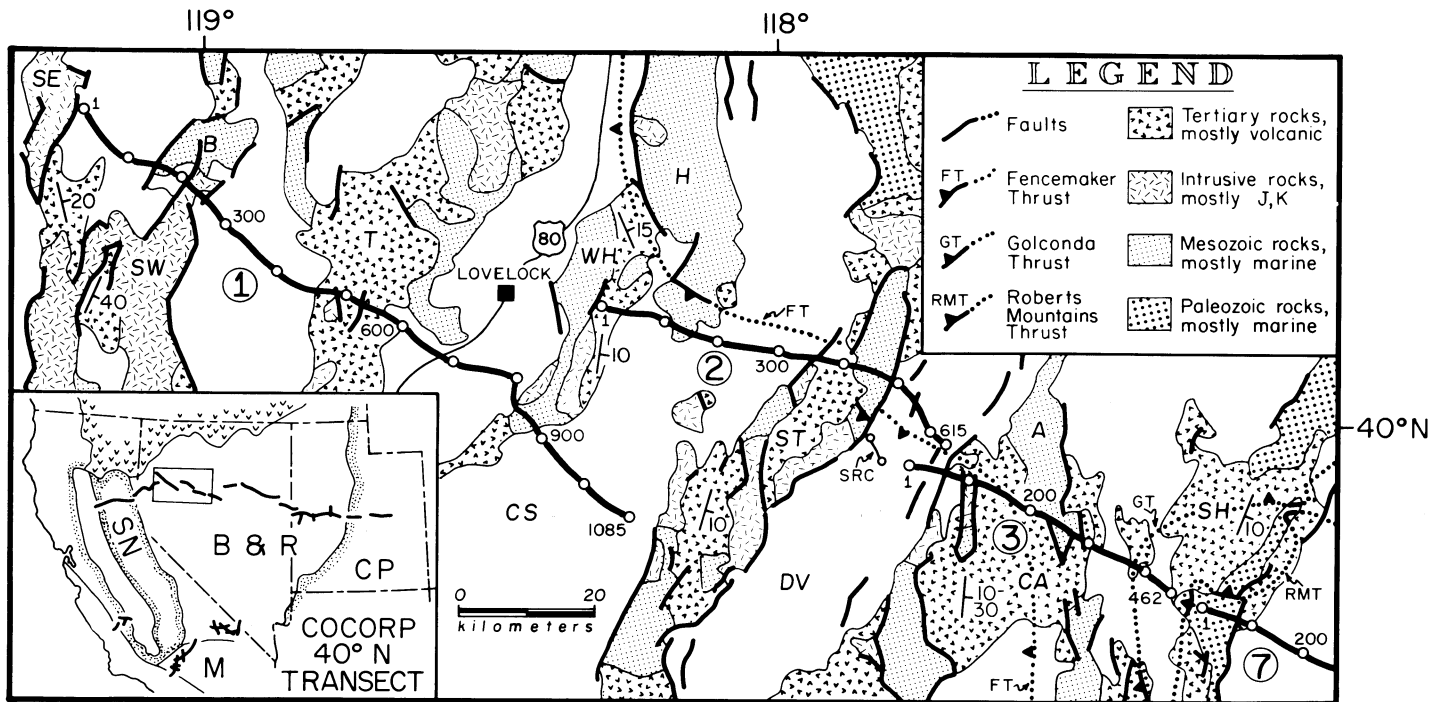


Figure 1. Generalized geologic map showing locations of COCORP Nevada lines 1, 2, and 3. SE, Selenite Range; B, Bluewing Mountains; SW, Shawave Mountains; T, Trinity Range; H, Humboldt Range; WH, West Humboldt Range; CS, Carson Sink; ST, Stillwater Range; DV, Dixie Valley; A, Augusta Mountains; CA, Clan Alpine Mountains; SH, Shoshone Mountains; SRC, route of Southland Royalty Company seismic line. Dip and strike of Tertiary rocks is from Stewart (1978).

ing much of the survey area is thought to have been accreted to the North American continent in middle Paleozoic and earliest Mesozoic time, during the Antler and Sonoma orogenies (Burchfiel and Davis, 1972, 1975; Speed, 1977, 1979a; Johnson and Pendergast, 1981; Speed and Sleep, 1982). Allochthonous eugeoclinal assemblages emplaced during the Antler and Sonoma orogenies, which are exposed at the east end of the survey area, lie astride the continental margin of late Precambrian and Paleozoic age (Stewart and Poole, 1974; Kistler, 1974). After onset of active-margin tectonism to the west, Triassic and Jurassic sediments were deposited on the accreted terranes and imbricated during the middle Jurassic orogeny (Fencemaker thrust of Fig. 1; Speed, 1976, 1978a, 1978b). Cretaceous plutons of the Sierran arc intruded the western and central portions of the survey area (Johnson, 1977; Willden and Speed, 1974). Extensive local Cenozoic igneous activity is evident from exposed Oligocene through Recent volcanic rocks (Stewart and Carlson, 1976). Post-mid-Miocene, west-northwest-east-northeast-oriented extension (Zoback and others, 1981) resulted in the present-day basin-range physiography and the deposition of basin-fill strata (Speed and Moores, 1980). The COCORP survey route crosses the Nevada seismic belt, which experienced historic earthquakes that had magnitudes as great as 7.6 (Jones, 1915; Slemmons, 1957; Ryall and others, 1966). Hypocenters of earthquakes in the Nevada seismic belt are concentrated at depths between 5 and 15 km (Vetter and Ryall, 1983).

Concepts of the geometry and kinematics of structures accommodating crustal extension in the Basin and Range Province include horsts and grabens bounded by planar faults (Stewart, 1971), tilted structural blocks of basin-range pairs bounded by planar or listric normal faults (Stewart, 1971, 1978) and underlain by a mid-crustal detachment (Eaton, 1980), and upper-crustal basin-range structural blocks underlain by low-angle

normal faults (Allmendinger and others, 1983; Anderson and others, 1983; Smith and Bruhn, 1984; Wernicke, 1981, 1985). Extension of the deep crust has been envisioned as plastic deformation and intrusion (Stewart, Eaton) and inclined zones of uniform-sense simple shear (Wernicke). As discussed in a subsequent section, COCORP data from western Nevada favor models of tilted upper-crustal structural blocks 7 to 15 km thick, with pervasive extension at deeper levels.

#### DATA ACQUISITION AND PROCESSING

Three west-northwest-trending seismic-reflection profiles were collected in western Nevada (Fig. 2). No cross-lines were shot in this phase of the survey, but the *en echelon* arrangement of lines 1 and 2 affords some control of the third dimension, and the lines trend approximately normal to the strike of major basin-range structures. A 96-channel recording system was used with a 100-m station spacing, with near and far offsets of 0.3 and 9.8 km, respectively. A 32-s upsweep (8 to 32 Hz) and a listening time of 48 s produced 16 s of common-midpoint (CMP) stacked data, corresponding to a maximum image depth of ~50 km. Vibrating every station (5 vibrators  $\times$  8 sweeps/station) resulted in nominal 4800% data.

Data processing included correlation, refraction statics, editing, frequency filtering, frequency-wavenumber filtering, deconvolution, CMP gathering, velocity analysis, muting, amplitude balancing, normal moveout (NMO) corrections, and stacking. Velocity analysis included displaying CMP gathers moved out at 200- to 1,000-m/s intervals ranging from 1,500 to 10,000 m/s; muting for constant-velocity stacks; generating velocity spectra; and an iterative process of choosing velocity profiles, displaying and muting moved-out CMP gathers, and generating variable-velocity stacks. Stacks were produced from several combinations of



filtering, deconvolution, and velocity analyses; those thought to best represent most features of the data are presented in Figures 3, 4, 5, and 6. The time sections are not migrated because large lateral variations in shallow velocity between basins and ranges cause pull-down effects and ray-path complexities that are not corrected by conventional time-migration techniques (Peddy and others, 1986). Instead, depth sections (Fig. 2b) were created to remove effects of shallow velocity variations on deeper reflections, and selected dipping features were migrated by hand. Dipping reflections in the unmigrated sections displayed herein have shallower dips than, and are displaced downdip from, the features that they image.

### WESTERN NEVADA COCORP DATA

To summarize briefly, COCORP seismic-reflection data from western Nevada (Fig. 2) include sequences of reflections between 0 and 1.5 s traveltimes beneath physiographic basins; a few dipping reflections and diffractions between 1 and 4 s; numerous, mostly subhorizontal reflections between 3.5 and 10 s; a prominent band of reflections at 9.5 to 10.5 s; and a general absence of reflections below 10.5 s. The data are described and interpreted herein, beginning with shallow features.

#### Shallow Features

The late Cenozoic basins that are traversed by the western Nevada COCORP survey are underlain by sequences of reflections (B, Fig. 2a) with maximum traveltimes of ~1.0 to 1.5 s. The reflections within each of these sequences tend to dip uniformly to the east or west (toward the thicker end of each reflection sequence), are locally discontinuous, and form packages that are wedge shaped (Kumiva Valley, Granite Springs Valley, Dixie Valley), synformal at the base (Buena Vista Valley), or complex in shape (Humboldt River Valley). The thicker ends of wedge-shaped sequences occupy sides of basins where basin-bounding faults are mapped (Fig. 1). In Kumiva and Dixie Valleys, faults are also mapped at the thin ends of the reflection sequences, and no basin-bounding faults are mapped where the survey crosses the Humboldt River Valley. Shallow reflections between stations 180 and 200 at line 1 probably represent the

basin-fill sediment and west-dipping fault mapped there, but this small sub-basin appears to be too thin to be well imaged by the data. The reflections stack at velocities of 2.0 to 3.2 km/s, the lowest stacking velocities of the data set.

The shallow reflections from beneath topographic basins are interpreted as images of basin-fill strata of sedimentary and volcanic origin, underlain by volcanic and sedimentary strata that predate basin formation. Most structural basins appear to be asymmetric, with major offset along basement-penetrating faults only at the thick ends of the wedge-shaped reflection sequences (Fig. 2b). Similar geometries of reflection sequences have been observed in seismic-reflection data from several other basins in the Basin and Range Province (Anderson and others, 1983). A 3.5-s reflection profile from the Carson Sink, at the end of the route of the COCORP survey across that basin, shows a wedge-shaped package of reflections that thickens to the east to nearly 3 s traveltimes (Hastings, 1979). (Because weather prevented completion of the east end of line 1, the geometry of the Carson Sink structural basin shown in Figure 2b is taken from Hastings, 1979. Figure 2a is drawn solely from COCORP data.) The Standard-Amoco-S. P. Land Co. no. 1 well, drilled along the route of the reflection survey published by Hastings, revealed that the reflections represent ~2 km of fluvial, lacustrine, and volcanic basin-fill strata, underlain by Oligocene to upper Miocene volcanic and sedimentary strata that predate basin formation and are exposed in nearby ranges (Hastings, 1979). By analogy, basal reflections within the COCORP basin reflection sequences are probably in part from volcanic and sedimentary strata that are exposed in nearby ranges. In particular, down-dip equivalents of volcanic rocks in the east-tilted Humboldt Range probably contribute to disrupted east-dipping and subhorizontal reflections between 0.3 and 1.0 s beneath Buena Vista Valley, as well as the westward-thickening wedge of reflections beneath Dixie Valley. Anderson and others (1983) and Okaya and Thompson (1985) have identified lithologies similar to those of the Standard-Amoco-S. P. Land Co. no. 1 well in a 4-s reflection profile of the west side of Dixie Valley (collected by the Southland Royalty Company; SRC, Fig. 1). Stacking velocities of 2.0 to 3.2 km/s for sub-basinal reflections in the COCORP data are appropriate for unconsolidated sedimentary and volcanic strata (Christensen, 1982). Dis-

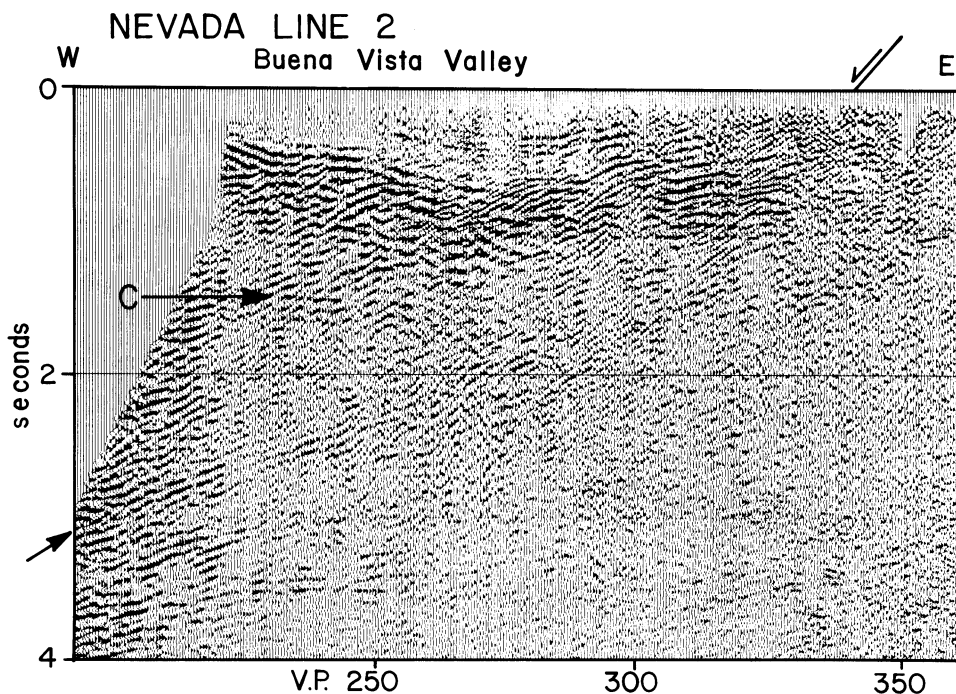


Figure 3. Stacked data from Nevada line 2, enhanced to emphasize sub-basinal reflections interpreted as an image of the basin-bounding fault.

continuities in the reflection sequences may indicate faulting of basin-fill and older Cenozoic strata (Fig. 2b) or may be primary features such as facies changes in sedimentary and volcanic strata.

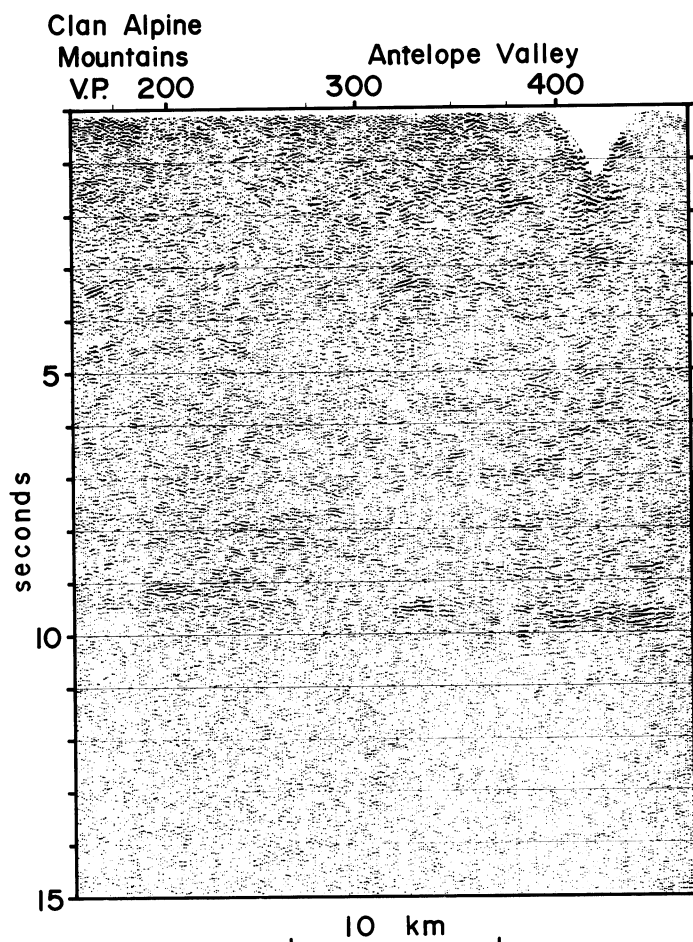
Discontinuous reflections of 2 to 3 cycles are apparent beneath and adjacent to several of the packages of sub-basinal reflections (F, Fig. 2a). In time sections, these reflections dip gently away from the thick ends of wedge-shaped packages of basin-fill reflections. In depth sections, which remove the velocity-pull-down effects of the half-grabens, these reflections dip more steeply and project updip to the thick ends of the sub-basinal reflection packages (see Fig. 6 of Klemperer and others, 1986). For example, the west-dipping multicyclic reflections beneath Buena Vista Valley (Fig. 3) project to the surface at the location of the fault bounding the west side of the Stillwater Range. Hand migration of a depth section indicates that the reflector, interpreted as the basin-bounding fault, is planar to a depth of ~7 km with an apparent dip of 40° west. Other reflections, labeled "F" in Figure 2a, also interpreted as possible images of basin-bounding faults, are short reflection segments that in depth sections suggest moderate apparent dips (40° ± 5° to the east or west). Diffractions beneath Granite Springs Valley and the Humboldt River Valley (D, Fig. 2a) may also mark the locations of basin-bounding faults.

Other features in the upper 4 s of the data include areas of discontinuous west-dipping reflections beneath the Trinity Range, the Clan Alpine Range, and Antelope Valley (A, Fig. 2a). Those beneath the Trinity Range project updip toward exposures of faulted Cenozoic volcanic rocks, Mesozoic intrusive rocks, and deformed metasedimentary rocks and could be related to any of these features, which have not been mapped in detail. The west-dipping shallow reflectors beneath the Clan Alpine Range and Antelope Valley (Fig. 4) project to the surface exposure of Oligocene volcanic strata that are tilted eastward along several west-dipping normal faults (Willden and Speed, 1974; Stewart and McKee, 1977). The easternmost exposures at this latitude of the east-verging Roberts Mountains and Golconda thrusts are mapped in this area (Fig. 1). These reflections may thus represent post-Oligocene normal faults or the upper-crustal expression of Paleozoic and early Mesozoic sutures between accreted terranes (Antleria and Sonomia; Speed, 1979a, 1983) and North America. Figure 2b shows these reflections interpreted as both suture-related thrusts and as normal faults, but the unequivocal correlation of specific reflections with specific surface features would require additional reflection data. These reflectors could also be strata or unmapped thrusts within the Antler and Golconda allochthons or within Mesozoic rocks.

A short subhorizontal reflection (C, Figs. 2a and 3) underlies Buena Vista Valley at 1.5 s traveltimes. This traveltimes is reasonable for a reflector that dips south at moderate dips from the mapped trace of the Fencemaker thrust, which parallels line 2 between stations 100 and 400 (Fig. 1).

### Moho-Depth Reflections

The most striking feature on the seismic sections is a band of prominent reflections (labeled "M" on Fig. 2a), typically 150 to 300 ms thick and at traveltimes of 9.5 to 10.5 s, that marks the transition between an overlying reflective zone and an underlying nonreflective zone (Figs. 4, 5, and 6). The relatively high amplitude of the deepest reflections is evident from their prominence on shot records displayed without amplitude balancing (Fig. 7). These reflections are particularly impressive on lines 1 and 2, although they are weak or absent beneath basins. They are also weak or absent on much of line 3. Their continuity is enhanced by single-fold CMP sections that degrade or eliminate shallowest data (Klemperer and others, 1986). Traveltimes to these reflections are typically greater beneath basins than beneath ranges. These reflections are thought to be from within the plane of the sections because of their lateral persistence across the survey



**Figure 4.** Stacked data from the east end of Nevada line 3. Data are deconvolved before stack and unmigrated. Stacked data are coherency filtered for this display and are shown at a vertical:horizontal scale which is 1:1 for a velocity of 5 km/s. Note the absence of coherent reflections below the bright and laterally persistent reflections at 9–10 s. Subhorizontal reflections dominate the lower crust between 5 and 10 s, but gently west-dipping reflections are abundant in the upper crust.

area and because of control of the third dimension provided by the *en echelon* arrangement of lines 1 and 2.

These deep, prominent reflections are interpreted as the image of a reflector that is laterally continuous, is at Moho depths, and is without resolvable offsets. The reflections are thought to represent a continuous geologic feature because their local absence in the data correlates with areas of shallow, complex structure or general absence of deep reflections. The discontinuity of the deep band of reflections at V.P.'s 1 to 275 and 675 to 800 on line 1 is attributable to attenuation within basinal reflection sequences and refraction at dipping contacts between low-velocity basinal sequences and high-velocity basement. The discontinuity elsewhere (V.P.'s 350 to 500 of line 2; much of line 3) may also be due to near-surface refraction and attenuation because reflections from other traveltimes are also weak or discontinuous. In contrast, in cases in which refracted arrivals on COCORP shot records show little variation in shallow velocities (V.P.'s 300 to 700, line 1), the deep band of reflections appear remarkably continuous. The reflections are thought, as a result of the preliminary

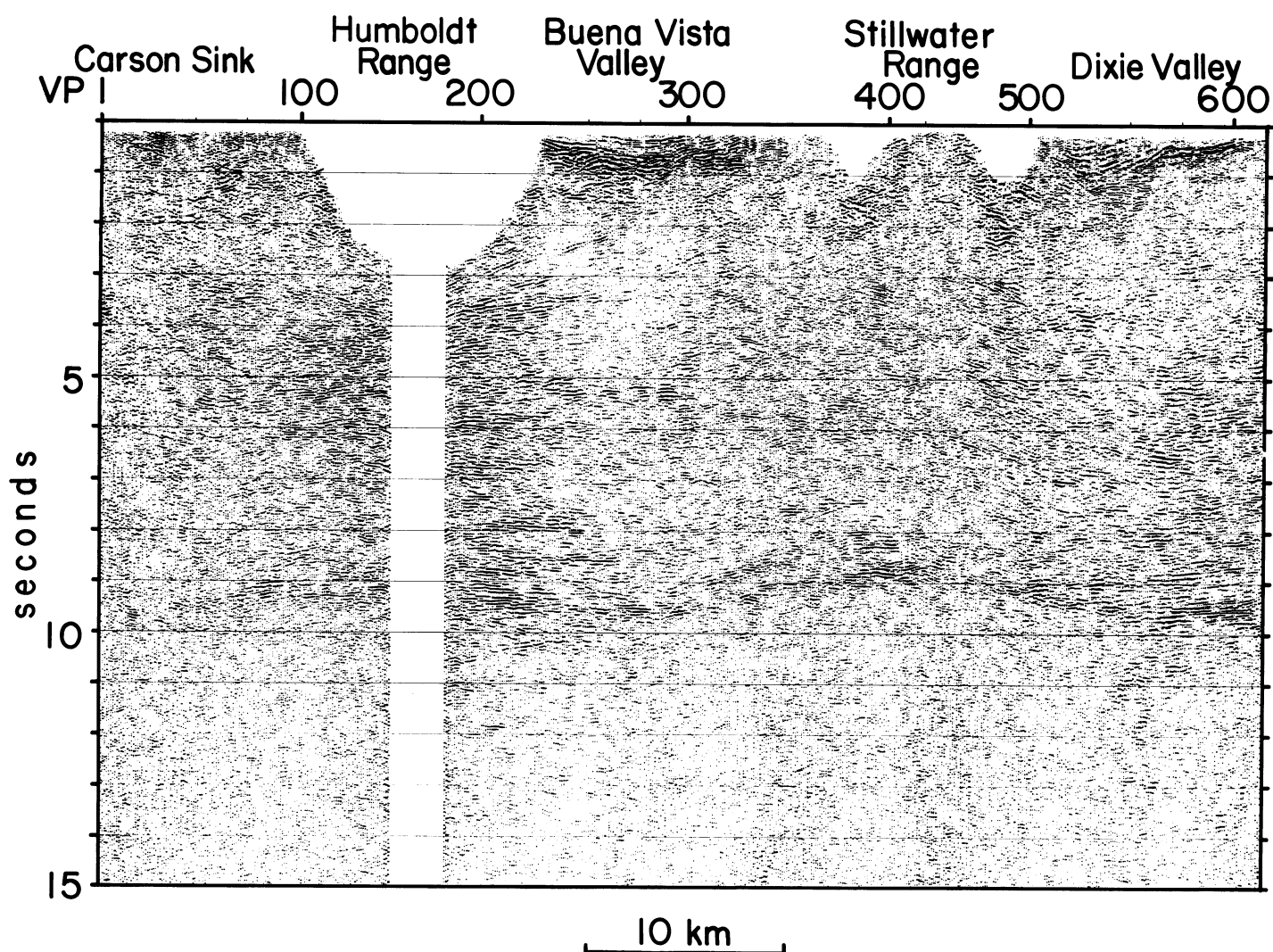


Figure 5. Stacked data of Nevada line 2. Data are deconvolved before stack and unmigrated. These stacked data are coherency filtered for this display and are shown at a vertical:horizontal scale which is 1:1 for a velocity of 5 km/s. Note the absence of coherent reflections below the reflective crust and Moho (M) reflections at 9–10 s. Prominent velocity pull-down is evident below the basins both east and west of the Stillwater Range. Figure 3 is an enlargement of the top central portion of this stack. The higher amplitudes exhibited adjacent to the data gap are largely due to scaling effects next to the gap and below the muted top of the traces.

time-depth conversion represented in Figure 2b, to come from Moho depths. The conversion was based on near-range stacks (1200% nominal fold, with source-receiver ranges <2.5 km, rather than the usual 4800% nominal fold with maximum range of 9.8 km), for which ray paths for each CMP traverse less variable, near-surface conditions. Vertical ray paths were assumed as a first approximation, although actual ray paths were more complex due to refraction within basins and at basin-basement contacts (Fig. 7). Average velocities of basin-fill strata (2.5 km/s) and basement rocks (6.3 km/s) were estimated from COCORP stacking velocities and nearby U.S. Geological Survey (USGS) refraction profiles (Eaton, 1963; Prodehl, 1979), respectively. Traveltimes to basin floors were picked from stacked data. Traveltimes to the band of deepest reflections, which is locally as much as 500 to 600 ms thick, were measured to the most laterally continuous, high-amplitude cycle within the band. The resulting calculated depths to the deep band of reflectors range from 29 to 32 km (Fig. 2b). These are reasonable Moho depths, as discussed below.

The depths may be in error by as much as  $\pm 5\%$  if average basement crustal velocities are 6.0 to 6.6 km/s rather than the 6.3 km/s used in the model. Lateral variations in deep crustal velocities, not well constrained by COCORP data or other available seismic data, would also produce corresponding changes in depth calculations, but such variations are likely to be small compared to shallow lateral variations.

The deep reflections are thought to image a reflector without resolvable offsets (0.5 km or greater; Klemperer and others, 1986) because the local relief on the reflections in the time section disappears in the depth section. This suggests that the local variations in traveltimes result from “velocity pull down” beneath basins rather than from actual local structure on the deep reflector (see Fig. 6 of Klemperer and others, 1986). Studies of the effects of shallow velocity variations on traveltimes to deep reflections using stripping statics and ray-tracing models (Klemperer and others, 1986; Peddy and others, 1986) suggest that the results of the simplified model used here are reasonable.

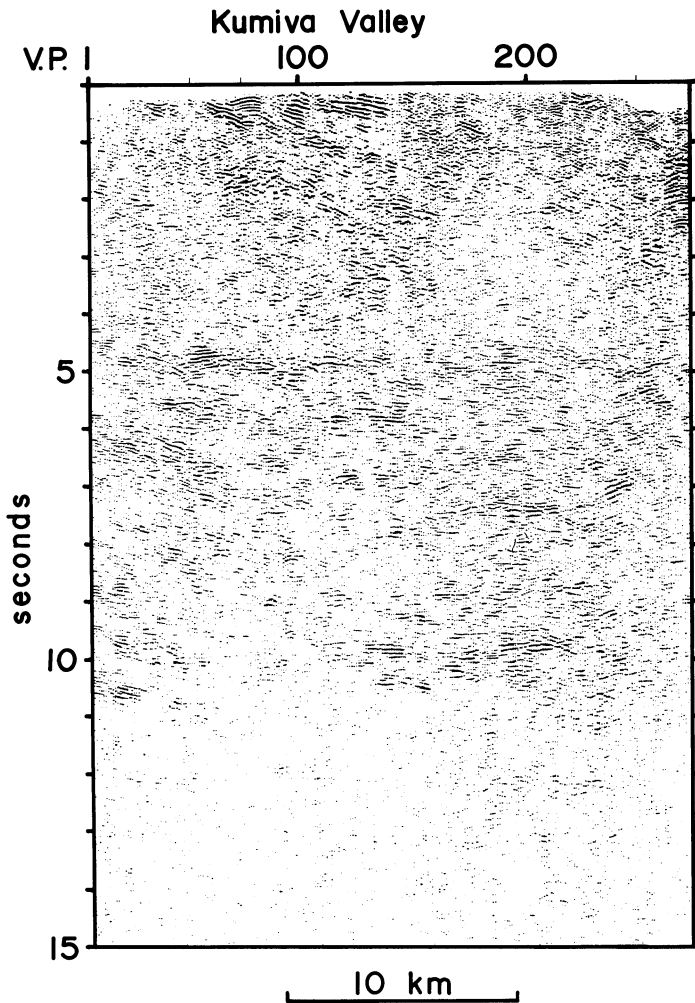


Figure 6. Stacked data of Nevada line 1. Data are deconvolved before stack and unmigrated. These stacked data are coherency filtered for this display and are shown at a vertical:horizontal scale which is 1:1 for a velocity of 5 km/s. Note the absence of coherent reflections below the reflective crust and Moho (M) reflections at 10–11 s (~31–35 km depth). Upper crust down to ~4 s is sparsely reflective except for dipping reflections from Tertiary sediments and volcanics in half-grabens. Lower crust is characterized by subhorizontal reflections, but the data are affected locally by velocity pull-down beneath basins.

Similar Moho-depth reflections are observed in data from the central and eastern Nevada COCORP surveys (E. C. Hauser and others, unpub. data; Potter and others, 1987), and COCORP data from westernmost Nevada and adjacent California (P.L.K. Knuepfer and others, unpub. data) suggest that similar but weaker reflections can be traced westward from the Basin and Range Province to beneath the Sierra Nevada (Nelson and others, 1986). Moho-depth reflections from COCORP basin-range data are the subject of a separate study by Klemperer and others (1986).

The reflections at 9.5 to 10.5 s traveltimes are interpreted as Moho reflections because they represent a prominent, laterally persistent feature at depths similar to Moho depths interpreted from nearby seismic-refraction experiments. The reversed refraction experiment nearest to the COCORP survey route is the USGS survey between Fallon and Eureka,

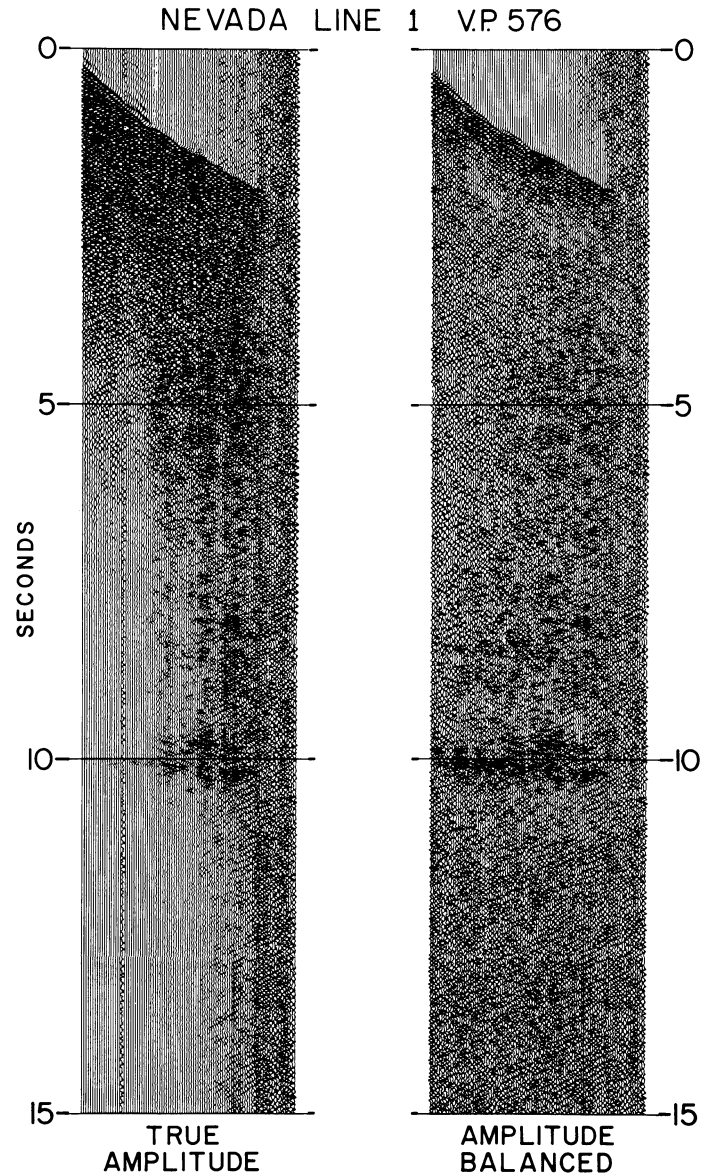


Figure 7. Shot record from Nevada line 1, V.P. 576. Note amplitude of Moho reflection displayed without gain control. Freeway and railroad traffic noise obscures data on far traces.

which crosses western Nevada 60 km south of the COCORP lines (Eaton, 1963). In the initial interpretation of these data (Eaton, 1963), depth to Moho at Fallon was interpreted as 19 km (one-layer model) or 21 km (two-layer model). Prodehl (1979) calculated a 29-km depth to Moho at Fallon from these data using a model that has multiple layers separated by velocity gradients. Unreversed refraction lines fanning northwestward from sources at the Nevada Test Site, if Eaton's (1963) depth estimates are used to resolve the ambiguity between depth and dip of refractors in unreversed data, indicate crustal thicknesses of 19 to 25 km in the COCORP survey area (Priestley and others, 1982). Higher-mode Rayleigh wave data suggest a 25-km crustal thickness for the COCORP survey area (Priestley and others, 1980). If the data of Priestley and others (1982) are keyed to Prodehl's depth estimates, Moho depths are ~28 km (8.9 to 9.0 s vertical two-way time at 6.3 km/s; based on data of Klem-

perer and others, 1986), which are very similar to the depths calculated from COCORP reflection data (29 to 32 km  $\pm$  5%). Despite the uncertainties in time-depth conversion of both the refraction and the reflection data, we conclude that the crust-mantle transition in western Nevada is marked by discontinuities detected by both refraction and reflection and that these discontinuities, although not necessarily identical, are at similar depths. We refer to the COCORP image of the crust-mantle transition thus as the "reflection Moho," restricting the term "Moho" to a discontinuity generally detected by seismic refraction.

### Other Deep Reflections

Numerous, discontinuous reflections are present at traveltimes between 3.5 and 5.0 s and the reflection Moho. These reflections are typically subhorizontal, a few dip gently west or east, and they are commonly subparallel to the reflection Moho. They are as much as 250 ms thick and can be traced for distances of as much as 20 km but more commonly, 5 to 10 km. On line 1, between V.P.'s 400 and 800, few of these reflections were observed, and they are also sparse on much of line 3. In these areas, deep reflections, if any, were of lower amplitude than that of ambient noise levels. Traveltimes to the top of the zone of discontinuous reflections vary from 3.5 s (line 1, V.P. 800, to line 2, V.P. 500) to 5 s (line 1, V.P.'s 1 to 300). Elsewhere, due to sparseness of reflections, the top of this zone is difficult to define.

As many of these reflections are subparallel to the reflection Moho, they are interpreted as "pulled down" in cases in which Moho reflections are similarly "pulled down" due to lateral changes in shallow velocities. After removal of pull-down effects, if the same technique discussed for the reflection Moho is used, only a few of the discontinuous reflections have appreciable dips, most of which are to the west. The reflections between 3.5 to 5 s and the Moho reflections thus probably arise from reflectors that are mostly horizontal and less commonly west dipping, at depths below 10–15 km. Like the reflection Moho, these reflectors are probably more continuous than their reflections indicate, but in the depth section, they do not appear to be continuous for distances  $>20$  km.

These deep reflections have not been traced to surface features, and several interpretations of their origins are compatible with local surface geology and regional geologic history. A variety of sources of these reflections is possible, including mylonitic shear zones (Jones and Nur, 1984), shear zones that juxtapose lithologies with contrasting impedances, subducted sedimentary layers, intrusions, or combinations of these such as intruded shear zones, including features of a variety of ages. Similarly, these predominantly subhorizontal attitudes could be original or deformational fabrics of various ages. Relatively young structures (that is, related to Cenozoic magnetism and extension) are favored candidates, as older structures are likely to have been subsequently deformed. Based on comparison with other deep reflection data, Allmendinger and others (in press) have suggested a Cenozoic age for these reflectors. An older age of origin is suggested by the lateral distribution of these reflections, in that they appear to be more common on lines 1 and 2 than on line 3 (or western line 7; Potter and others, 1987), dying out eastward where accreted crust gives way to rifted Precambrian crust. Their absence on line 3, however, may be an artifact of data acquisition or upper-crustal attenuation or refraction. Until these or analogous reflectors are traced to surface exposures, their nature and origin remain unresolved.

### DISCUSSION

In this section, COCORP data from western Nevada are interpreted to suggest the following model of basin-range extension. Upper-crustal

structural blocks, which display variable cross-sectional geometries and are typically tilted, are 7 to 15 km thick; extension at deeper crustal levels may involve a component of subhorizontal stretching, and the observed geometry of the reflection Moho is probably of basin-range age, although the physical nature of the Moho is not strongly constrained by the data. Implications of the data with regard to pre-basin-range deformation are also discussed.

### COCORP Data and Basin-Range Structures

The COCORP data from western Nevada define the locations, along a transect crossing 7 basins and 6 ranges, of major basin-range normal faults that form the boundaries of upper-crustal structural blocks 10 to 40 km wide at the surface (Fig. 2b). The faults that bound these blocks have undergone offsets as much as 5 km or more, which have vertical components of 3.7 km or more (based on Hastings, 1979), and accommodate significant extension of the upper crust. Upper-crustal extension is also accommodated by internal deformation and tilting of the structural blocks. Geologic mapping of the area (Stewart and Carlson, 1978) shows that these major faults die out along strike, indicating that a cross section a few kilometres north or south of the one constrained by the COCORP data would show somewhat different geometries and boundaries of upper-crustal structural blocks from those shown in Figure 2b.

Upper-crustal structural blocks crossed by the survey display a variety of cross-sectional geometries (Fig. 2b), including tilt-block and horst geometries viewed in earlier studies as characteristic of the Basin and Range Province (Stewart, 1971, 1978; Eaton, 1980). The Bluewing-Shawave Mountains and the Stillwater Range appear to be underlain by horsts, as indicated by the asymmetries of their flanking basins. Ten-degree dips of strata document tilting of the Stillwater Range horst. The West Humboldt Range and the Carson Sink appear to be underlain by a single tilted structural block where crossed by line 1. This is indicated by 10° to 15° eastward dips of mid-Cenozoic volcanic strata in the West Humboldt Range (Stewart, 1978), 10° to 20° eastward apparent dips of basal reflections within the reflection sequence underlying the Carson Sink (from COCORP data and Hastings, 1979), and the structural continuity between the basin and the range indicated by surface geology and COCORP data. The Humboldt Range and Buena Vista Valley may constitute another east-tilted block (Fig. 2b), although a fault may separate them along the range front between stations 100 and 200 of line 2, where logistical problems dictated a gap in coverage. Other structural blocks have also undergone eastward tilting during basin-range extension, as indicated by dips of mid-Cenozoic strata exposed in ranges (Fig. 1) and by apparent dips of basal strata beneath basins calculated from COCORP data (Fig. 2b). The structural block that underlies the Trinity Range and adjacent basins appears broadly arched and, from surface mapping, is internally faulted, but no data regarding dips of exposed mid-Cenozoic strata are available. The structural block underlying the Clan Alpine Range and Dixie Valley appears from surface geology and COCORP data to be cut by numerous faults, mostly west dipping, along which Cenozoic strata of the Clan Alpine Range have been tilted eastward 10° to 30°. Where crossed by the COCORP survey, Dixie Valley does not appear to be underlain by a separate structural block (graben). The depth of the basin increases markedly, however, along strike to the south. COCORP line 2 crosses the west side of Dixie Valley 9 km north of the Southland Royalty Company data, where maximum basin depths appear to be greater than those beneath COCORP line 2 by 0.5 s (0.6 km at 2.35 km/s; from COCORP data and Anderson and others, 1983). South of the COCORP survey route, where its depth is greater, Dixie Valley may be underlain by a graben (as envisioned by Anderson and others, 1983, and by Okaya and

Thompson, 1985) but COCORP line 2 suggests no significant offset of basement between Dixie Valley and the Clan Alpine Range.

In conjunction with data from earthquake seismology, COCORP data suggest that thicknesses of tilted upper-crustal structural blocks are on the order of 7 to 15 km. The horizontal or west dips of most reflectors below depths of 10–15 km contrast markedly with the easterly tilts of exposed Tertiary strata. This disparity suggests that the upper crustal blocks have tilted independently of the lower crust, unless lower-crustal reflectors were fortuitously tilted to predominantly subhorizontal attitudes. Basin-range faults, which define the lateral boundaries of upper-crustal tilted blocks, are traced to depths as great as 7 km in COCORP data and to depths as great as 15 km by earthquake studies (Vetter and Ryall, 1983; K. F. Priestley, 1986, personal commun.). Together, these observations suggest that the upper 7 to 15 km of the crust in the survey area underwent basin-range tilting and extension decoupled from the deeper crust.

The present configuration of the reflection Moho is interpreted as a product of basin-range extension because of its smoothness and continuity in the context of an extended and disrupted upper crust. The contrast between vertical components of offset of the upper crust (as much as 3.7 km) and the lack of resolvable (0.5 km) offsets of the Moho can be explained in several ways. The basin-range faults do not penetrate to Moho depths; the faults penetrate Moho as broad zones of distributed shear (Wernicke, 1985a) with individual offsets <0.5 km; or faults offset the Moho, but the Moho reforms on time scales short in comparison with rates of fault offset. Klemperer and others (1986) argued for a basin-range age of Moho configuration based on the entire COCORP 40°N data set in the context of the regional Phanerozoic tectonic history.

Three hypotheses are offered to explain the configuration of the reflection Moho in western Nevada. All assume that its geometry or position is of basin-range age, but the western Nevada COCORP data do not resolve which aspects of these hypotheses are correct. The first two assume that basin-range faults do not penetrate to the Moho. In hypothesis 1, extension is restricted to the crust. A subhorizontal detachment (zone of simple shear), either along the Moho, within the crust, or within a broad zone including the lower crust and the Moho, accommodates crustal extension above a nonextending deeper layer. In this view, the present Moho may be materially unchanged from that of previous tectonic regimes except for having been uplifted or broadly upward warped during isostatic adjustment to basin-range extension (Thompson and Burke, 1974). In hypothesis 2, both the deep crust and the upper mantle have extended by subhorizontal stretching. In this view, the geometry of the Moho may be little changed from its pre-extension shape, or it may have been smoothed during extension from a more irregular pre-extensional geometry. Pre-basin-range dipping reflectors in the deep crust might have been similarly transposed toward the horizontal during stretching of the deep crust. In hypothesis 3, basin-range faults penetrate to the mantle, but the Moho reforms on time scales that are short in comparison with rates of fault offset, or the faults penetrate the Moho as diffuse shear zones. All of these hypotheses require that the present form of the Moho is a result of basin-range extension, although its pre-basin-range geometry need not have been greatly different from its present geometry. An important difference between the hypotheses is whether crustal extension has (hypotheses 2 and 3) or has not (hypothesis 1) been accompanied by extension of the upper mantle. This issue is not directly resolved by the COCORP data. Models viewing the geologic nature of the Moho in terms of an isochemical phase change, a chemical discontinuity (perhaps along an intrusive contact or shear zone), and elevated pore-fluid pressures are compatible with con-

straints provided by Nevada COCORP data (Klemperer and others, 1986).

The model of basin-range extension that arises from the western Nevada COCORP data is distinctly different from that suggested by COCORP data from western Utah (Allmendinger and others, 1983), where gently west-dipping reflections from upper and middle crustal levels are interpreted as low-angle normal faults of basin-range age. The Utah COCORP data support the extensional model of Wernicke (1981), at least within the upper and middle crust. In contrast, COCORP data from western Nevada suggest that upper-crustal structural blocks may be underlain by a penetratively deformed lower crust and a tectonically active Moho. These data are more akin to extensional models of Stewart (1971, 1978) and Eaton (1980) and Hamilton (1982), in that distributed deformation of the lower crust is indicated. Taken together, COCORP data from western Utah and western Nevada suggest that at 40°N latitude, the kinematics of basin-range extension vary fundamentally across the province.

### COCORP Data and Pre-Basin-Range Structures

As previously discussed, most features of the COCORP data are explained as having originated during or been modified by basin-range extension. Reflections likely to be from pre-basin-range features include those within the upper crust that may be related to the Roberts Mountains, Golconda, and Fencemaker thrusts. The 30° apparent dips of these reflectors on line 3 suggest that the Roberts Mountains and Golconda thrusts penetrate to mid-crustal depths at moderate dips. As the survey route is roughly perpendicular to the traces of surface exposure of these features, these apparent dips are probably good approximations of the true dips. During thrusting, the dips of the faults may have been steeper if the thrusts have been tilted along with exposed east-dipping Cenozoic volcanic rocks. On the other hand, if the thrusts have been reactivated as normal faults, they may have undergone little tilting. Cross-line control would help to relate these reflections to the thrusts and to determine their attitudes with accuracy.

Reflections from the middle and lower crust may also be relics of pre-basin-range compressional tectonics. If thrusts do not root to mantle depths in central Nevada, they may be represented by mid- and lower-crustal reflections on lines 1 and 2. In particular, subhorizontal reflections may represent a Mesozoic intracrustal compressional décollement postulated by Speed (1983). West-dipping reflections may represent ramps of east-verging thrusts of shear zones that accommodated distributed shortening with the lower crust. The deep west-dipping reflectors could also be related to westward subduction of the North American plate beneath migrating island arcs, as envisioned by Speed (1979a) and Speed and Sleep (1982). Features of Paleozoic and Mesozoic origin may have been reactivated as extensional features during basin-range tectonics.

### CONCLUSIONS

COCORP data from western Nevada provide images of crustal features from near-surface to Moho depths, including prominent reflections from the Moho, numerous reflections from the lower crust, sequences of basin-fill strata of basin-range age, and several upper-crustal reflections attributed to basin-range and pre-basin-range faulting. The reflection Moho is interpreted as a continuous feature that varies gradually in depth from ~29 to 32 km but is without resolvable offsets. Its observed geometry

is interpreted to be of basin-range age. The COCORP data suggest that basin-range crustal structure consists of upper-crustal fault-bounded blocks 7 to 15 km thick, beneath which crustal deformation may be more distributed, with subhorizontal zones of shear accommodating lower-crustal stretching, translation of the extending crust across a nonextended mantle, or both. Reflectors that originated before basin-range extension may include thrusts related to Paleozoic and Mesozoic accretion of oceanic and oceanic-arc rocks and later Mesozoic back-arc thrusts and décollements.

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