

Crustal structure of the Basin and Range–Sierra Nevada Transition from COCORP deep seismic-reflection profiling

P.L.K. KNUEPFER* *Institute for the Study of the Continents (INSTOC), Cornell University, Ithaca, New York 14853*

P. J. LEMISZKI *Department of Geological Sciences and INSTOC, Cornell University, Ithaca, New York 14853*

T. A. HAUGE* *INSTOC, Cornell University, Ithaca, New York 14853*

L. D. BROWN

S. KAUFMAN

J. E. OLIVER

} *Department of Geological Sciences and INSTOC, Cornell University, Ithaca, New York 14853*

ABSTRACT

Deep seismic-reflection data collected by COCORP along a 145-km-long line in westernmost Nevada and easternmost California as part of the 40°N latitude transect of the western Cordillera reveal the geometry of three crustal-scale features associated with the Walker Lane and the transition from the Basin and Range extensional province to the Sierra Nevada crustal block. The Walker Lane, a zone of late Cenozoic strike-slip and normal faults crossed in the central third of the line, is underlain by a zone of moderately west-dipping reflections that terminate at a discontinuous mid-crustal zone of subhorizontal reflections extending across most of the line at depths ranging from 14 to 23 km. We interpret the mid-crustal reflections as an active detachment accommodating strike-slip and extensional displacements. It may coincide with the base of the Sierran batholith, a shear zone, and/or the transition from brittle to ductile crustal deformation. The dipping reflections are inferred to be from a moderately dipping (45°) fault that soles in this mid-crustal detachment and accommodates the strike-slip and normal displacement of the northern Walker Lane. Discontinuous reflections at 9.5–10.2 s two-way travel time (28–30 km) on the eastern half of the line are interpreted as the Moho, similar to the Moho imaged by COCORP lines farther east in Nevada. Moho reflections are imaged at 11.0–11.5 s (33–35 km) in the western third of the line, and project westward toward similar reflections as deep as 12–13 s (37–41 km)

beneath the eastern Sierra Nevada, and so the crust appears to thin gradually from the Sierra Nevada into the Basin and Range. The lower crust east of the Walker Lane is relatively highly reflective, characteristic of COCORP data from other Nevada lines, but the lower crust west of the Walker Lane is less reflective, similar to COCORP data from the northern Sierra Nevada. The change in reflectivity of the lower crust also appears to occur gradually, with no sharp offsets or boundaries. On the basis of the COCORP data, therefore, the transition between the Basin and Range and Sierra Nevada appears to be a wide (~100 km) zone of crustal thinning possibly accompanied by a change in deformation fabric that may correspond to changes in lower crustal rheology or degree of deformation. This transition zone is dominated by a moderately dipping fault underlying the Walker Lane and accommodating strike-slip and normal displacement down to a mid-crustal detachment level.

INTRODUCTION

In late 1984, the Consortium for Continental Reflection Profiling (COCORP) completed a deep seismic-reflection profile in westernmost Nevada and easternmost California (Nevada Line 8) that crosses the transition between the Sierra Nevada and Basin and Range physiographic and tectonic provinces, including the right-lateral strike-slip and associated normal faults of the northern Walker Lane. The profile addresses the geometry of the northern Walker Lane and Basin and Range faults, the influence of pre-Tertiary features on present crustal structure, the transition in Moho depths from the Basin and Range to the Sierra Nevada, and possibly the shape at depth of the Sierran batholith.

The COCORP Nevada Line 8 survey crosses a region of relatively simple surface geology (Fig. 1) but complex crustal evolution. The rifted western margin of Precambrian North America, as defined by stratigraphic relationships (Roberts and others, 1958) and the 0.706 ⁸⁷Sr/⁸⁶Sr isopleth (Fig. 1, inset; Kistler and Peterman, 1973), lies well east and south of the survey. The crust underlying the survey area was therefore not part of continental North America in Precambrian time. Its origin is uncertain, due to the lack of exposure of pre-Mesozoic deposits, but the crust is inferred to be of oceanic or arc affinity (Speed, 1979; Oldow, 1983). The crust may have formed in a marginal basin attached to North America (Burchfiel and Davis, 1975), or it may have accreted to North America in the Late Paleozoic to early Mesozoic Sonoman orogeny as part of a volcanic arc terrane ("Sonomia" of Speed, 1979).

During the Triassic and Jurassic, the northwestern Great Basin lay within a marine back-arc basin behind the Sierran volcanic arc (Speed, 1978; Oldow, 1984). The extent of the basin may have been controlled by the location of the oceanic crust in western Nevada (Speed, 1978). In the Late Jurassic and into the Cretaceous, sediments of the back-arc basin were thrust eastward and southeastward over shelf sediments along the Fencemaker-Luning fold and thrust belt (Speed, 1978; Oldow, 1983). The lack of concurrent deformation in the Sierran arc to the west led Oldow (1983) to propose that left-lateral slip along the postulated northwest-trending Pine Nut fault system decoupled the Sierran arc from the fold-and-thrust belt along the North American margin. The trend and location of the Pine Nut fault are similar to those of the late Cenozoic Walker Lane.

Scattered Jurassic plutons were intruded into the shortened Triassic-Jurassic deposits follow-

*Present addresses: (Knuepfer) Dept. of Geological Sciences, State University of New York, Binghamton, New York 13901; (Hauge) Exxon Production Research, P.O. Box 2189, Houston, Texas 77252-2189.

ing Fencemaker thrusting, but emplacement of Cretaceous plutons of the Sierran arc was the main igneous event in the Mesozoic (Bonham, 1969; Oldow and others, 1984). No arc volcanism occurred in the region during the Laramide orogeny (Coney and Reynolds, 1977), but extensive arc-type volcanic activity was renewed in the Oligocene. Most surface exposures in the west half of the line (Fig. 1) consist of Oligocene through Pliocene andesite flows and flow breccias, rhyolitic ash-flow tuffs,

and basalt flows (Bonham, 1969; Stewart and Carlson, 1976).

East-west to east-southeast-west-northwest crustal extension began about 17 Ma in this region (Bonham, 1969) and produced the major north-trending basins and ranges of the eastern portion of the survey region. Concurrently, late Cenozoic right-lateral and normal displacement occurred across northwest-trending faults of the Walker Lane in westernmost Nevada and adjacent parts of California (Nielsen, 1965), begin-

ning about 21–22 Ma in the Pyramid Lake area (Bell, 1984). The survey crosses the northern part of the Walker Lane between VPs 600 and 800 (Fig. 1), in the vicinity of a left step from the Pyramid Lake fault to the Warm Springs fault. Right-lateral displacement across the Pyramid Lake fault has totaled 15–16 km in the past 22 m.y. (Bell, 1984), and strike-slip displacement across the entire northern Walker Lane may be as much as 32 km (Bonham, 1969). Continued activity into the Holocene is documented on the

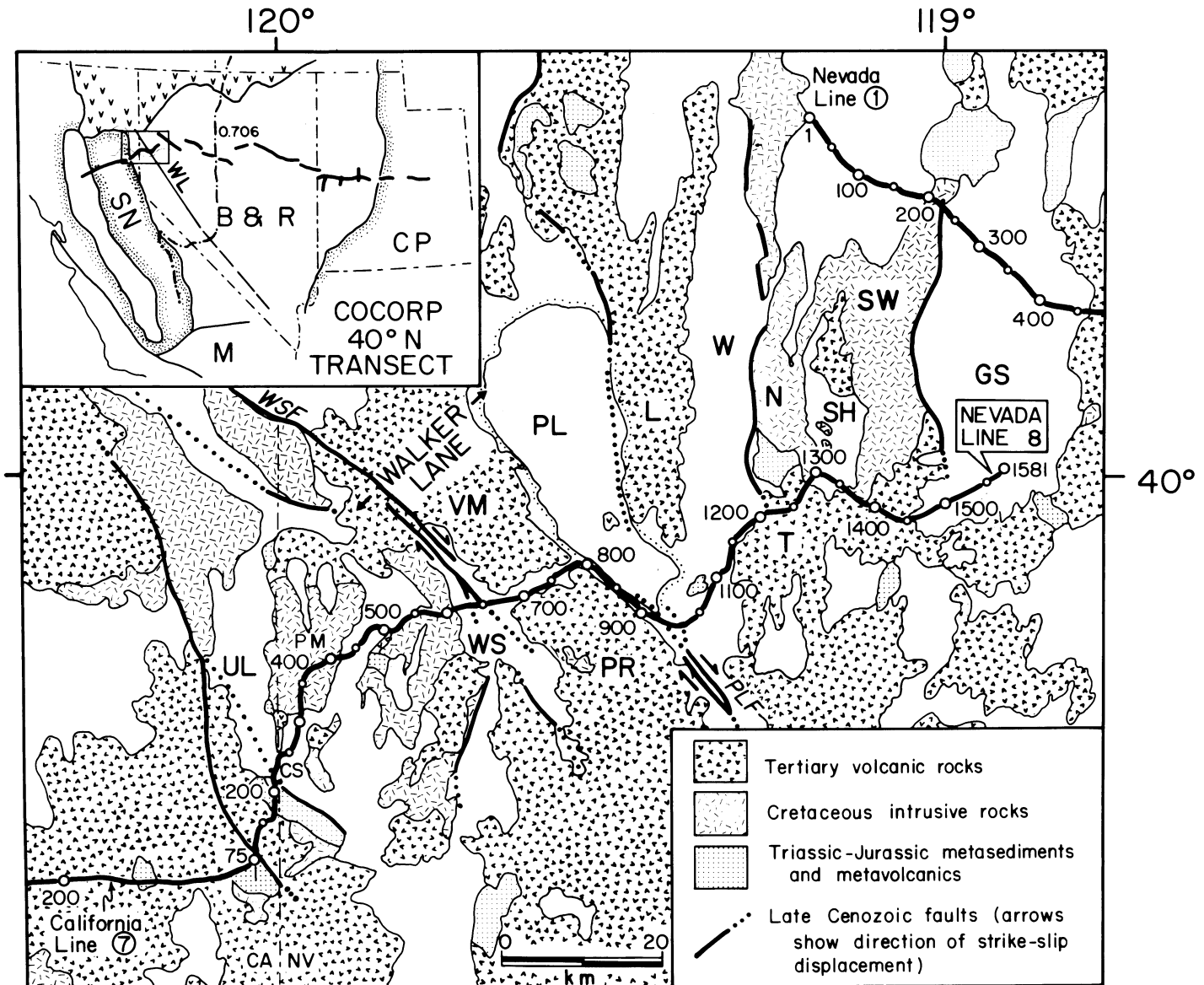


Figure 1. Generalized geologic map of the vicinity of Nevada Line 8, modified from Jennings (1977) and Stewart and Carlson (1978). Inset shows regional physiographic/tectonic provinces (SN, Sierra Nevada; B&R, Basin and Range; CP, Colorado Plateau; M, Mojave; WL, Walker Lane) and 0.706 Sr isotope ratio isopleth modified from Kistler and Peterman (1973). Faults of the Walker Lane are indicated by WSF (Warm Springs fault) and PLF (Pyramid Lake fault). UL, Upper Long Valley; CS, Cold Spring Valley; PM, Peterson Mountain; WS, Warm Springs Valley; VM, Virginia Mts.; PR, Pah Rah Range; PL, Pyramid Lake; L, Lake Range; W, Winnemucca Lake Valley; N, Nightingale Mts.; T, Truckee Range; SH, Sage Hen Valley; SW, Shawave Mts.; GS, Granite Springs Valley.

Pyramid Lake and Warm Springs faults by fault scarps and other geomorphic evidence of recent activity (Bell, 1984; Anderson and Hawkins, 1984). The Walker Lane generally is considered the transition from the Basin and Range province to the Sierra Nevada in this region (Bonham, 1969); southwest of this zone, the structural trends of basins and ranges are less consistent than in the Basin and Range province.

Published interpretations of seismic-refraction surveys indicate different depths to Moho in the region of Nevada Line 8. Priestley and others (1982) reported a depth of about 26–28 km in the eastern part of the line, whereas Prodehl (1979) suggested that the Moho deepens from 32 km to 40 km from the east to west part of the line. Both authors indicated a P_n velocity of 7.8 km/s. Mavko and Thompson (1983) showed both an east-to-west increase in Moho depth from 27 km to 41 km just south of the COCORP line and a south-to-north shallowing of the Moho beneath the Sierra Nevada. COCORP lines to the north and east record a reflection Moho at about 10-s two-way travel-time (Hauge and others, 1987).

DATA ACQUISITION AND PROCESSING

Nevada Line 8 comprises three segments (Fig. 1) trending north to northeast, southeast along the west shore of Pyramid Lake, and east-northeast, respectively. Along strike of the Shawave Mountains and Granite Springs Valley, the east end of Nevada Line 8 overlaps the west end of Nevada Line 1.

Field acquisition parameters for Nevada Line 8 are summarized in Table 1 of Allmendinger and others (1987) and are identical to those of Nevada Lines 1, 2, and 3 as described by Hauge and others (1987), except that four rather than eight sweeps were summed at each vibrating station. Data processing, also summarized in Allmendinger and others (1987), included detailed static corrections, pulse-shaping deconvolution, and detailed velocity analysis. Constant-velocity migrations of line drawings and finite-difference migrations of stacked data using vertically varying velocity functions were performed to assist in the interpretation of COCORP Nevada Line 8. Time to depth conversions are made using the average vertically varying velocity functions obtained from the detailed velocity analysis: 2.8–4.0 km/s for 0–1 s, 5 km/s for 1–2.5 s, 6 km/s for 2.5–5 s, 6.5 km/s for 5–7.5 s, and 6.8 km/s from 7.5 s to the base of the crust. The resolution of the velocity analysis is such that, where good reflectors exist, the uncertainties in velocity functions are generally ± 0.2 km/s for stacking velocities less than about 5

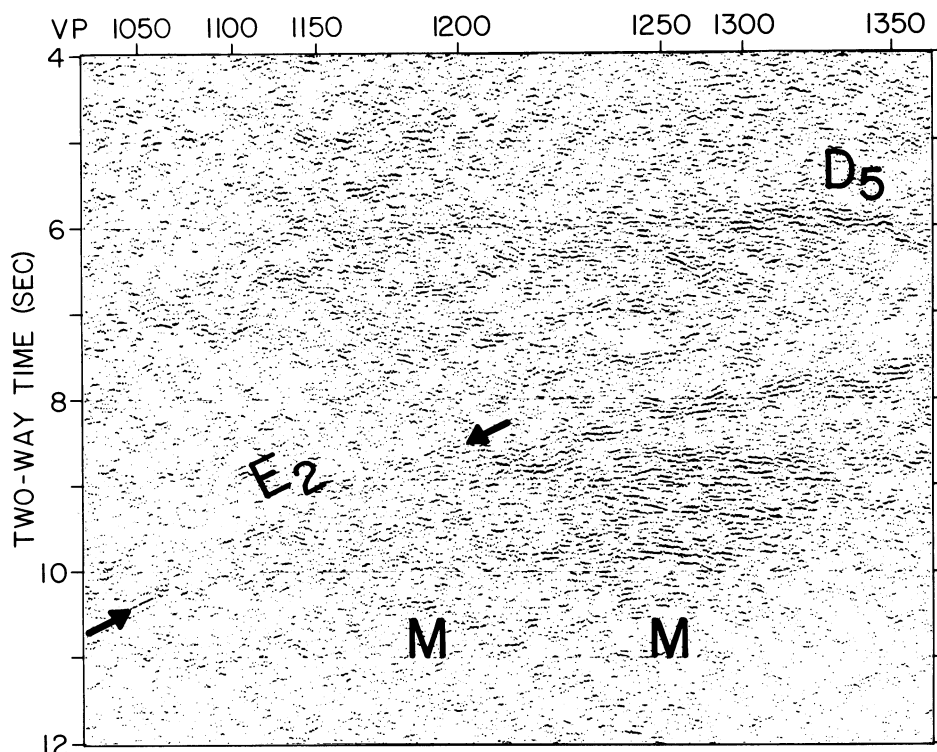


Figure 3. Unmigrated stacked data from 4s to 12s, VPs 1030 to 1360, showing reflective lower crust, Moho reflections, and west-dipping features from eastern part of Nevada Line 8. Letters refer to features discussed in text. Coherency filtering has been applied to stacked data to produce this display. Scale 1:1 @ 6 km/s.

km/s, but above 6 km/s, the uncertainties are as great as 0.5 km/s. Although individual depth calculations may thus be in error by about 5%–10%, the relative changes in depth across the line are well resolved.

COCORP DATA FROM THE BASIN AND RANGE-SIERRA NEVADA TRANSITION

COCORP Nevada Line 8 data from the Basin and Range-Sierra Nevada transition zone in westernmost Nevada include sequences of shallow reflections beneath several basins; relatively few dipping and horizontal reflections in the upper crust except for a group of discontinuous west-dipping reflections between 2 and 7 s west of Pyramid Lake; prominent horizontal to subhorizontal short mid-crustal reflections between 5 and 7 s along much of the line; and locally prominent reflections between 7 and 9.5–11+ s, with a general absence of reflections at greater two-way traveltimes. The most prominent features are the west-dipping, upper- and mid-crustal reflections west of Pyramid Lake, the contrast across the Moho between the reflective crust and the nonreflective upper mantle,

and the mid-crustal reflections at 6–7 s. These features are shown in Figure 2 and discussed in the following paragraphs.

Deep-Crustal Reflections and the Moho

The base of the crust is apparent on the reflection data across most of Nevada Line 8, although generally it is not marked by the prominent horizontal reflections imaged elsewhere in Nevada that Klempner and others (1986) termed the “reflection Moho.” On Nevada Line 8, the Moho is recognized principally by a change in reflective character at the base of the crust, specifically a *lack* of reflections at greater two-way traveltimes. The base of the crustal reflections is relatively clear beneath VPs 1200–1500, where the lower crust is more highly reflective than on other parts of the section (Fig. 3). In this interval, the reflection Moho is imaged between 9.5 and 10.2 s (28–30 km using the time-depth conversion noted above) by short, discontinuous subhorizontal reflections, similar to reflections defining the Moho on other Nevada COCORP data (Klempner and others, 1986). Reflections possibly related to the Moho are imaged at 10.2 s (~30 km) beneath

VP 1100 and at 10.0–10.2 s below VPs 850–920 along Pyramid Lake (Fig. 2a). Discontinuous subhorizontal reflections are imaged to 10.6 s (~32 km) beneath VPs 500–600 (Fig. 2a) and to 10.9 s (~33 km) beneath VPs 320–340 (Fig. 4), and weak discontinuous reflections are imaged as deep as 11.3 s (~34 km) beneath VPs 120–200 and 11.6 s (~35 km) beneath VP 75. These, too, may be related to the Moho, given their similarity in character to reflections interpreted as Moho farther east on Nevada Line 8. Deep crustal reflections that are at least locally similar to the reflection Moho imaged elsewhere in Nevada thus appear to increase in two-way traveltime from 9.5–10.2 s at the east end of the COCORP line to 11.6 s at the west end. Locally, scattered subhorizontal reflections are visible below the Moho in unmigrated sections, as below VPs 1220–1280 (Fig. 2a), but these migrate above the Moho. In general, reflections are absent below 9.5–11.5 s along Nevada Line 8.

The reflection Moho is imaged at 10–10.5 s (29–31 km) on the west end of Nevada Line 1 (Hauge and others, 1987), about 40–70 km north of the east end of Nevada Line 8 (Fig. 1). This implies that the Moho is nearly flat in the north-south direction, with relief of only 1–3 km over the 40–70 km distance between Lines 1 and 8, similar to the limited Moho relief in the east-west direction shown by the COCORP Nevada data east of Line 8 (Allmendinger and others, 1987).

Middle and Lower Crustal Faults

The most continuous and prominent dipping feature imaged on Nevada Line 8 is a set of west-dipping reflections visible from 1.5 s below VP 780 to 7 s below VP 520 (events W_1 and W_2 in Fig. 5; also shown in Fig. 2a). W_1 has an apparent dip of 45° west beneath VPs 750–780 on the seismic section (Fig. 2a) and migrates to a dip of at least 55°SW–65°SW beneath VP 800 (Fig. 2b). It projects upward toward the northwestern extension of the Pyramid Lake fault, and so the W_1 reflections may image the Pyramid Lake fault. The apparent dip of W_2 is 20° to 30° west along the line of the section before migration (Fig. 2a) and 35° to 42° southwest after migration (Fig. 2b). W_2 appears to project beneath the more steeply dipping W_1 feature toward Pyramid Lake or its eastern margin (a west- or southwest-dipping normal fault shown in Fig. 1), but it may steepen upward into W_1 . The details of the intersection between W_1 and W_2 are not well resolved in the seismic section. No reflections that can be clearly associated with W_2 are apparent below 6.5–7.0 s (Figs. 2a and 5). The migrated position of dipping reflections W_2 places them at about

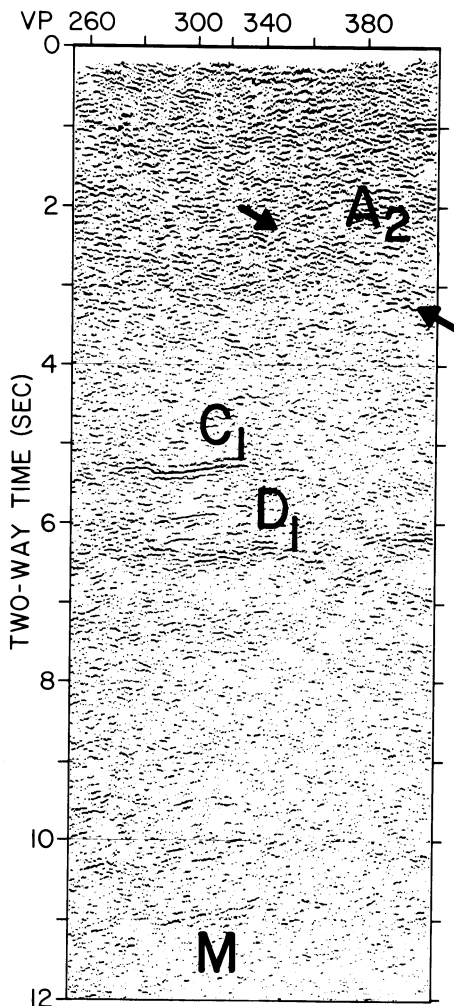


Figure 4. Unmigrated stacked data from 0s to 12 s, VPs 260–400, showing prominent C_1 and D_1 reflections and reflection Moho. Note increase in Moho depth from 9.8 s in east part of line (Fig. 3) to 10.8 s here. Coherency filtering applied to stacked data. Scale 1:1 at 6 km/s.

17 km beneath VP 600, at or above prominent mid-crustal reflections that are described below (Fig. 2b). Migration also indicates that the W_2 reflections are planar (Fig. 2b), rather than curvilinear as shown in unmigrated data (Fig. 2a).

In detail, Nevada Line 8 has a crooked geometry between VPs 500 and 700 (not visible at the scale of Fig. 1) that allows examination of the three-dimensional shape of the W_2 feature. From this geometry, we subdivided the line into five short stacks (average 35 CDPs), determined apparent dips on each segment, and calculated the true migrated attitude of the structure based on interval velocities and two-way traveltimes.

This analysis indicates that the W_2 reflector strikes northwest and dips about 45°SW.

Two groups of discontinuous horizontal and subhorizontal mid-crustal reflections are imaged on Nevada Line 8. The first group includes prominent reflections between 5 and 6 s beneath VPs 285–330 (C_1 in Figs. 2a and 4) and similar features beneath VPs 630–650 (C_2 in Figs. 2a and 5) and 1420–1440 (C_3 in Fig. 2a). Additional prominent subhorizontal reflections between 6 and 8 s are imaged beneath VPs 290–350 (D_1 in Fig. 4), VPs 430–460 (D_2 in Fig. 5), VPs 800–850 (D_3 and D_4), and VPs 1280–1330 (D_5 in Fig. 3). East of about VP 1200 and between VPs 580 and 650, the D reflections form the irregular upper limit of a moderately to highly reflective middle and lower crust (Figs. 2 and 3). Although the D reflections are discontinuous on the seismic sections, they may represent a continuous mid-crustal structure.

A less prominent zone of west-dipping reflections is imaged in the eastern half of the survey, at 9.5–10.5 s below VPs 1030–1130 (E_2 in Figs. 2a and 3) and at 4–7 s below VPs 1300–1500 (E_1 , Fig. 2a). On the unmigrated section, E_2 appears to form the western boundary of a zone of numerous subhorizontal reflections (Fig. 2a). After migration, however, the E_2 reflections are located entirely within the zone (shown diagrammatically in Fig. 2b) and apparently do not define a continuous feature. The dipping E_1 reflections below VPs 1300–1500 image a relatively continuous, west-dipping, mid-crustal structure after migration. We estimated the attitude of this structure from the crooked geometry of the COCORP line, using procedures similar to those described above; it strikes north-northwest and dips 45° west-southwest after migration.

Shallow Basins and Basin-Bounding Faults

Nevada Line 8 traverses several late Cenozoic basins, notably Granite Springs Valley, Pyramid Lake Valley, the southeast margin of Winnemucca Lake Valley, and Warm Springs Valley (Fig. 1). Sequences of reflections to 2 s underlie Pyramid Lake–Winnemucca Lake valleys (B at VPs 850 and 1050 in Fig. 2a) and Warm Springs Valley (Fig. 6). Reflections generally are discontinuous and appear to define asymmetric wedge-shaped basins marked principally by east-dipping and subhorizontal reflections. Some shallow reflections also underlie Granite Springs Valley (B at VP 1500 in Fig. 2a). Smaller basins, including Sage Hen Valley (VPs 1310–1360) and Cold Spring Valley–Upper Long Valley (VPs 240–310) are not evident in the COCORP reflection data.

The reflection packages beneath valleys most likely are from basin-filling sediments and volcanics. The horizontal and subhorizontal reflection fabric may be produced by the expected impedance contrasts between poorly consolidated late Tertiary/Quaternary sediments and late Tertiary volcanics such as those exposed in ranges crossed in the eastern two-thirds of the line (Fig. 1). In addition, discontinuous eastward-dipping reflections at 1.3–2.5 s are imaged beneath VPs 1020–1040, where the line turns eastward to cross Pyramid Lake Valley. These reflections may image a steeply dipping normal fault to a depth of at least 4 km.

Basin-bounding normal faults generally are not well imaged on Nevada Line 8. The wedge of reflections below Pyramid Lake Valley, however, terminates against a set of discontinuous reflections dipping moderately to the southwest between 0.5 and 1.5 s (Fig. 2a, reflections P beneath VPs 1050–1100). These reflections can be traced to a two-way travelttime of 1.8 s below VP 1050 (~2.5 km), and they are interpreted as the image of the basin-bounding normal fault, possibly a southern continuation of normal faults that bound the east margins of Pyramid Lake and Winnemucca Lake Valleys (Fig. 1).

Discontinuous northeast-dipping reflections beneath VPs 275–450, marked A_1 and A_2 in Figure 2a, form two low-angle reflectors on migrated sections. The lower (A_2) reflections (Figs. 2b and 5) project upward to a northeast-dipping normal(?) fault mapped on the southwest margin of Cold Spring Valley and the upper (A_1) structure projects to the normally faulted eastern margin of Peterson Mountain (Fig. 1). Both of these features, therefore, may image northeast-dipping normal faults to depths as great as 5 km.

The COCORP line crosses mapped traces of the Warm Springs strike-slip fault between VPs 630 and 650. First breaks are offset about 100 ms at station 630 and are disrupted at station 650 on source point gathers that include these stations. Prominent subhorizontal reflections from 0.2 s to 0.5 s beneath Warm Springs Valley terminate at VP 635 and VPs 645–650 (Fig. 6), where traces of the Warm Springs fault are mapped at the surface (Bonham, 1969). In addition, some diffractions are visible on stacked sections from 0.2–0.5 s beneath VPs 650–655. Two sets of east-dipping reflections, labeled A_3 and A_4 in Figures 2, 5, and 6, also are imaged beneath Warm Springs Valley. The A_3 reflections, 0.8–1.2 s beneath VPs 623–637 (Fig. 6), project to the surface near VP 615 at the west margin of Warm Springs Valley. The reflections continue uninterrupted beneath VP 635, the surface location of a trace of the Warm Springs fault. Gimlett's (1967) gravity modeling in Warm Springs

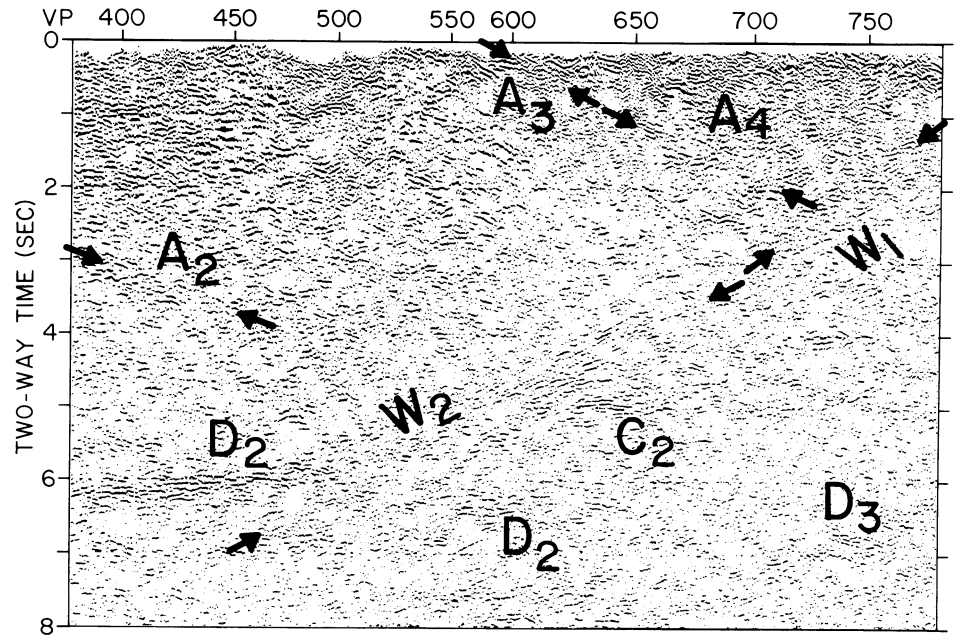


Figure 5. Unmigrated stacked seismic data from 0 s to 8 s, VPs 340 to 780, showing dipping W_2 reflections and their relation to subhorizontal mid-crustal (D) reflections. W_2 reflections migrate above the level of D reflections (compare with Fig. 2b). Coherency filtering applied to stacked data. Scale 1:1 @ 6 km/s.

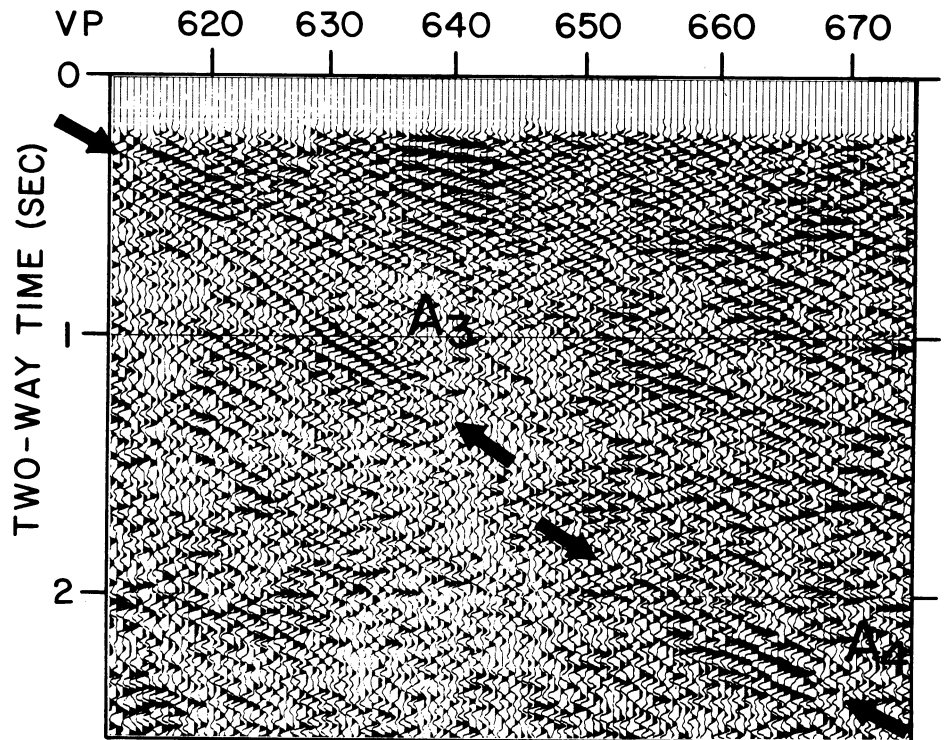


Figure 6. Unmigrated stacked seismic data from 0 s to 2.5 s, VPs 615–685, showing reflections beneath Warm Springs Valley. Note prominent basin reflections beneath VP 640 and their termination beneath VP 645. Lettered features discussed in text. Scale 1:1 @ 4 km/s.

Valley shows a steep east dip for this fault trace, and the reflection data are consistent with this interpretation (that is, the fault must dip steeply eastward if it truncates both the shallow reflections and A_3). The A_4 reflections align with A_3 , but they are not continuous; thus we are uncertain if these two sets of reflections image a continuous structure (as implied in Fig. 2b). Finally, first breaks are disrupted on source-point gathers that include station 1030, where the seismic line crosses a projected trace of the Pyramid Lake strike-slip fault, and the W_1 reflections may image this fault.

Discontinuous southwest-dipping shallow reflections are imaged between 0.5 s and 1.5 s below VPs 850–930 (Fig. 2a, marked B) where the seismic line parallels Pyramid Lake. The reflections may emanate from volcanic units dipping from the Pah Rah Range beneath Pyramid Lake Valley, from alluvial-fan deposits, or from an east-dipping normal fault postulated to bound the southwest margin of Pyramid Lake basin (Speed and Moores, 1980). Other features in the upper few seconds of data include east-dipping reflections at two-way traveltimes of 1–3 s below VPs 450 and 1230 that are not clearly related to surface structures and southwest-dipping reflections at 1–2 s below VP 200.

DISCUSSION

In the vicinity of the COCORP Nevada Line 8, the northern Walker Lane and several northwest-trending faults to the west are considered to be the transition between the Basin and Range and the northern Sierra Nevada (Bonham, 1969), with no prominent escarpment at the boundary. The COCORP data illuminate three aspects of the transition: a moderately dipping reflector (W_2) underlying the northern Walker Lane that appears to terminate at a zone of subhorizontal mid-crustal reflections, a reflection Moho that appears to deepen gradually across the transition zone, and a change from a highly reflective lower crust typical of the Nevada Basin and Range to a less reflective lower crust beneath the Sierra Nevada.

Prominent, west-dipping reflections, marked " W_2 " on Figures 2 and 5, underlie the Walker Lane, including both the Warm Springs fault and the Pyramid Lake fault. As noted previously, the details of the intersection of W_2 with the more steeply dipping W_1 reflections are not well resolved by the seismic data. We cannot, therefore, determine with certainty if the W_1 reflector truncates or displaces W_2 , if W_2 truncates the Pyramid Lake fault, or if W_2

steepens into the Pyramid Lake fault. In any case, the W_1 reflections define a steeply west-dipping fault in the upper 2–3 km that projects to the surface trace of the Pyramid Lake fault. Trenches across the active Pyramid Lake fault expose steep west-dipping and east-dipping fault traces (Anderson and Hawkins, 1984), so a west-dipping fault at depth is consistent with at least some of the surface data.

W_2 apparently is not disrupted or displaced beneath surface traces of the Warm Springs fault, which it underlies by 4–5 s on the stacked section (Fig. 2a), or beneath any portion of the northern Walker Lane. If the Walker Lane consisted entirely of vertical, purely strike-slip faults, the W_2 reflector could show no displacement or disruption on the seismic section (although it is difficult to imagine that 10–30 km of strike-slip fault displacement would not juxtapose different levels of a dipping structure). The northern Walker Lane, however, includes both strike-slip and normal faults (Bonham, 1969), and Mesozoic basement of the Virginia Mountains block is downdropped at least 1,000 m between the Pyramid Lake and Warm Springs faults (Bonham, 1969), so there must be substantial dip-slip displacement across the Warm Springs fault. Furthermore, the Warm Springs fault probably dips northeast 60°–70° [from Gimlett's (1967) gravity modeling], and such a dipping fault would produce an apparent displacement of W_2 , even if all true displacement were strike-slip. If W_2 were displaced 1 km (300 ms at two-way traveltimes of 3–5 s) vertically by Walker Lane faulting, it would be visible on the section. The lack of disruption, the apparent continuity of W_2 from 2–3 km to 20 km depth, its likely projection to surface faults, and its strike parallel to the Walker Lane, lead us to conclude that the dipping reflections image a moderately dipping fault into which the northern Walker Lane faults terminate, or at least the Warm Springs fault does.

W_2 thus accommodates the large amount of strike-slip displacement mapped across the northern Walker Lane and the dip-slip displacement within the Walker Lane. The total late Cenozoic extension across the northern Walker Lane is unknown. There is no evidence of very large extension like the 130% described by Proffett (1977) from the Yerington district 100 km south of Nevada Line 8, and the moderate tilting of Cenozoic volcanics (20°–30° in the Virginia Mountains and Pah Rah Range, according to Bonham, 1969) contrasts with the highly extended near-vertical volcanics at Yerington.

We use the name "Pyramid Lake Valley fault" (PLVF) to describe the W_2 structure and to distinguish it from the Pyramid Lake fault, into which it may or may not project. We interpret the PLVF as the upper to middle crustal expression of a predominantly strike-slip fault that has accommodated as much as 32 km of late Cenozoic right-lateral displacement.

The migrated seismic data indicate that the PLVF itself terminates in a subhorizontal zone of mid-crustal reflections at a depth of ~16 to 19 km below VPs 500–530. These D reflections may represent a mid-crustal detachment level extending westward beneath the Sierra Nevada; similar reflections are imaged at 7.2–7.8 s (20–22 km) beneath VPs 0–100 at the east end of California Line 7 (Fig. 7; Nelson and others, 1986). The westward extension of this postulated detachment is uncertain, given a lack of reflections from it west of VP 100 on California Line 7. Similar D reflections are imaged intermittently to the east end of the line, and so we postulate that all of the D reflections define a continuous crustal feature that is locally reflective.

The origin and evolution of these mid-crustal reflections that apparently act as a detachment west of the northern Walker Lane, and perhaps across most of Nevada Line 8, are more problematical. Possible origins of C and D reflectors include mylonite zones along the detachment or the base of the Sierran granitic rocks (compare with Lynn and others, 1981). The deepening of the D reflections from ~14–16 km on the east end of Nevada Line 8 to 18–23 km at the west end of the line and the east end of California Line 7 (Fig. 7) is consistent with the results of gravity modeling across the Sierra Nevada about 150 km south of the COCORP line that imply a thickness of 20+ km for the Sierran batholith (Oliver, 1977). Furthermore, the D reflections extend beneath the entire inferred extent of the Cretaceous northern Sierran batholith (as shown, for example, by Armstrong and Suppe, 1973) from eastern California across most of western Nevada. The C reflections may be from mafic layering in the basal portions of the batholith (compare with Lynn and others, 1981).

The mid-crustal detachment defined by the D reflections may be inherited from Mesozoic or latest Paleozoic tectonic regimes. The Late Jurassic–Early Cretaceous Fencemaker episode of shortening produced an imbricate series of thrust faults, including some dipping W, within and east of the region crossed by Nevada Line 8 (Oldow, 1984). The southwest-dipping PLVF and E reflections thus may have originated as

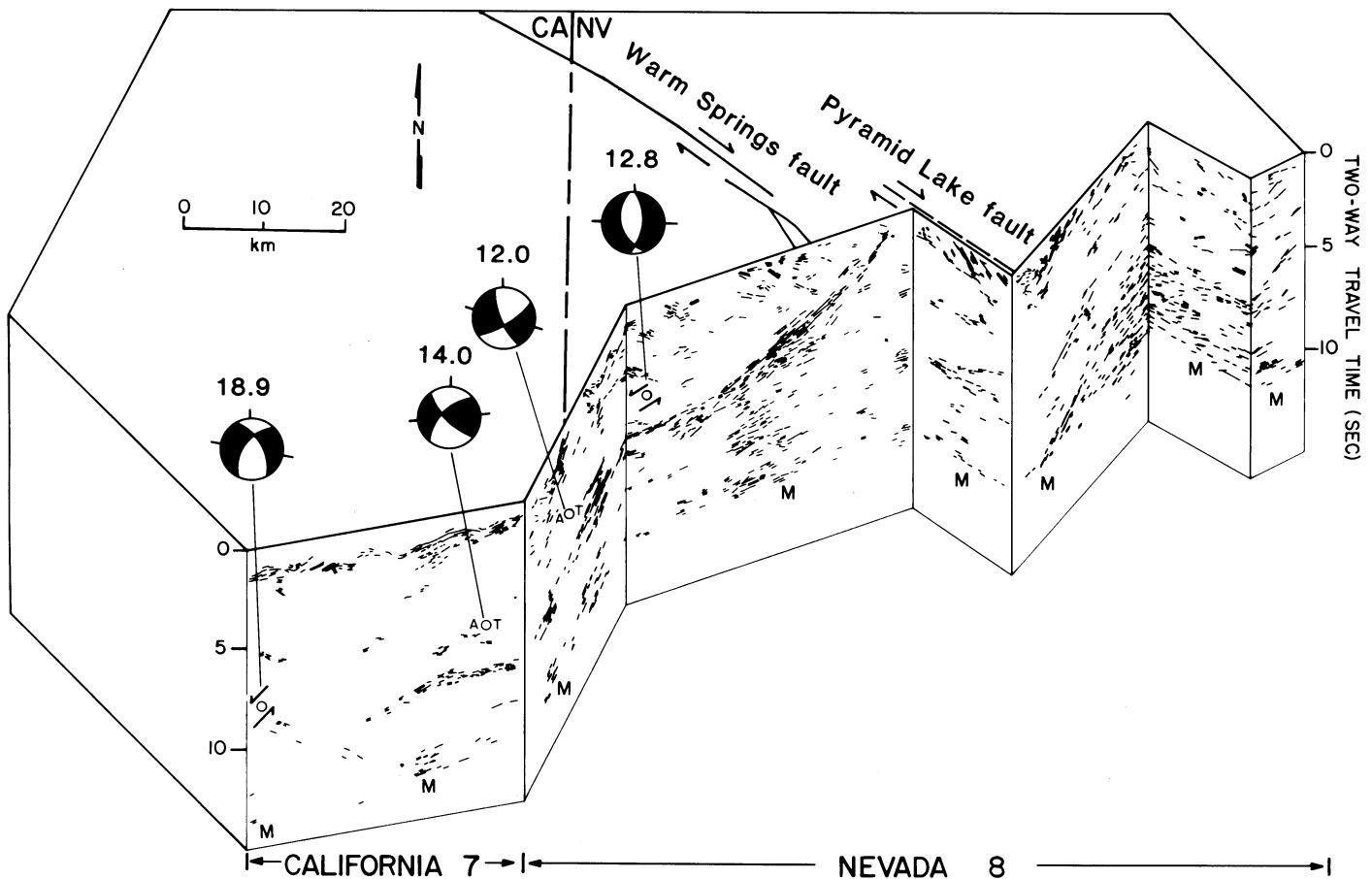


Figure 7. Block diagram showing line drawings of Nevada Line 8 and the eastern end of California Line 7 projected to show the geometries of the crooked lines. California Line 7 data from Nelson and others, 1986. Note westward deepening of reflections M, interpreted as representing the Moho. Note also westward continuation of mid-crustal reflections on California Line 7. Selected focal mechanisms, taken from Vetter and Ryall (1983) and Vetter (1984), are projected onto the seismic sections. Lower-hemisphere projections are shown, and corresponding normal or strike-slip symbols are shown in section. Focal depths are shown in kilometres for each mechanism, and the hypocenters are projected to the approximate two-way traveltimes corresponding to reported hypocentral depths.

Mesozoic thrust faults and may have been reactivated as late Cenozoic normal and strike-slip faults. The coincidence of the northern Walker Lane and the Pine Nut fault of Oldow (1983) further suggests that the PLVF may actually be inherited from an earlier phase of strike-slip faulting.

The observation that a zone of strike-slip faults apparently terminates at a mid-crustal detachment, as concluded from the Nevada Line 8 data, is not unique to the northern Walker Lane. Cheadle and others (1986) showed from COCORP data that the Garlock fault is underlain by a flat reflector at 9 km depth. Webb and Kanamori (1985) summarized data on earthquakes that indicated mid-crustal detachments beneath the Transverse Ranges in Southern Cal-

ifornia. Nicholson and others (1986) suggested that strike-slip faults in this same region are underlain by detachments at perhaps 10 km depth.

In the vicinity of the COCORP Nevada Line 8, available focal mechanisms indicate a coexistence of strike-slip, normal, and normal-oblique faulting. Vetter (1984) recorded strike-slip solutions for earthquakes as deep as 12–14.5 km, and Vetter and Ryall (1983) recorded strike-slip solutions as deep as 17 km. Normal-slip solutions are recorded for events at 12.8 and 17.0 km about 25 km south of the COCORP line in Nevada and at 14.4-km depth about 20 km northwest of the line in California (Vetter and Ryall, 1983). The fault planes generally dip between 40° and 60°. Representative solutions are shown in Figure 7, which illustrates the rela-

tionship between some of the focal mechanisms and the PLVF and other features imaged on COCORP Nevada Line 8 and the east end of California Line 7. These focal mechanisms are consistent with the COCORP data which suggest that both strike-slip and normal faulting may persist to a depth of 16–22 km in the crust beneath westernmost Nevada and easternmost California. The 45° dip obtained for the PLVF is on the lower end of the range of fault-plane dips obtained in these mechanisms.

The apparent westward deepening of the reflection Moho across Nevada Line 8 is further supported by sparse Moho reflections from California Line 7 to the west (Nelson and others, 1986). In the context of the Nevada 8 data, deep reflections from the east end of California 7 at

11.6–11.8 s (35–36 km) beneath VPs 80–130 and 12.6–12.8 s (~39 km) beneath VPs 350–500 (Fig. 7; reflections labeled “M”) probably represent the Moho, implying that the reflection Moho continues to deepen under the Sierra Nevada. No clear evidence of sharp offsets in the Moho is provided by the reflection data. This result is consistent with refraction evidence for a gradual shallowing of the Moho from the northern Sierra Nevada (~42 km, according to Prodehl, 1979) to the Basin and Range (Mavko and Thompson, 1983). We thus recognize a 90- to 125-km-wide transition zone of crustal thinning from the northern Sierra Nevada into the Basin and Range, beginning beneath the Sierra Nevada and continuing to or east of the surface location of the northern Walker Lane.

The lower crust on Nevada Line 8 east of VP 1200 is relatively highly reflective (Fig. 3). A similar but more restricted panel of reflective lower crust is imaged beneath VPs 580–650 (Fig. 2). West of this area, the lower crust is less reflective, although prominent subhorizontal reflections, features termed “C” and “D” in the preceding discussion, are present between 5 and 8 s (13–23 km) in much of the western part of the line, implying that over-all lower reflectivity of the lower crust is not due simply to poor signal penetration. This less-reflective lower crust continues on most of California Line 7 across the northern Sierra Nevada. The transition between these two lower-crustal reflection fabrics may occur principally east of the northern Walker Lane faults beneath Truckee Valley, or the panel of reflective crust beneath the PLVF may mark the transition. In either case, the zone is not bounded by any clearly imaged structure, so the change in reflective character appears to be gradational across the seismic line.

SUMMARY

COCORP data from the northern Walker Lane and across the boundary between the Basin and Range and Sierra Nevada provide images of three main aspects of the transition between these two tectonic provinces. The strike-slip and normal faults of the northern Walker Lane, which dip at high angles at the surface, are underlain by, and presumably terminate at or sole into a moderately west-dipping fault. This fault, which we have named the “Pyramid Lake Valley fault,” has accommodated both strike-slip and normal displacement

in the late Cenozoic. The west-dipping fault itself appears to sole into a mid-crustal reflector that may be a detachment at or near the base of the Sierran batholith. Locally prominent but generally sparse reflections from the deep crust and the lack of reflections from later two-way traveltimes define a reflection Moho that gradually deepens from east to west along the line. The horizontally to subhorizontally layered reflective fabric of the middle and lower crust that characterizes much of the Nevada COCORP data to the east is present in the eastern part of Nevada Line 8 but absent west of the Walker Lane. This predominantly subhorizontal reflection fabric may terminate below the Truckee Range or beneath the northern Walker Lane, but the termination appears to be gradual rather than abrupt.

The features that comprise the transition between Basin and Range and Sierra Nevada crust in the Pyramid Lake region all appear to have been active in the late Cenozoic. Although some may have originated in the late Cenozoic, several of the faults may reactivate older Mesozoic structures.

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