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Crustal structure of eastern Nevada from COCORP deep seismic reflection data

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ABSTRACT

The COCORP deep seismic reflection profiles in eastern Nevada, part of the 40°N traverse of the North American Cordillera, reveal crustal features probably developed or strongly modified during Mesozoic shortening and Cenozoic extension. A west-dipping crustal reflection fabric is interpreted to represent structures of the Mesozoic hinterland which are largely intact, although uplifted and locally cut by Tertiary normal faults. The discordance of the northern Snake Range décollement and the west-dipping zones of reflections below it are consistent with a simple-shear-zone model for the evolution of the décollement. The dipping crustal fabric and a deeply penetrating fault of eastern Nevada contrast with the subhorizontally layered lower crust of central and western Nevada and suggest that a pure-shear model of pervasive, horizontal ductile stretching of the lower crust is not the favored model of Basin-Range extension here.

Subhorizontal reflections and diffractions beneath the Diamond Mountains, which lie in the transition from the generally west-dipping reflection fabric of eastern Nevada to the subhorizontal reflection pattern of the lower crust of central and western Nevada, may represent structures like those exposed in the metamorphic-plutonic complex of the Ruby Mountains to the north, which are largely Mesozoic but were modified during Cenozoic extension.

A zone of subhorizontal Moho reflections which separate the reflective crust from the seismically transparent upper mantle is nowhere demonstrably offset and varies only regionally from 10 to 11 sec two-way traveltime. The present smooth Moho in eastern Nevada locally appears to postdate the Schell Creek fault, a unique crustal-penetrating Basin-Range fault which may be traced into the lower crust along a prominent east-dipping boundary defined by the termination of subhorizontal reflections. Offset at depth along this fault has probably been accommodated mainly by intrusions into and at the base of the footwall; the presently smooth reflection Moho may evolve in part by a process of magma underplating and may be quite young.

The eastward extent of well-developed Moho reflections corresponds generally to a location where important Cenozoic detachments and Basin-Range normal faults of opposite vergence focus extensional displacements deeply into the crust. This relationship may indicate that the prominent Moho represents a basal-crust zone of decoupling for extension and westward translation of much of the Basin-Range crust relative to the Colorado Plateau. Such decoupling may be enhanced by a lubricating zone of underplated magma.

INTRODUCTION

COCORP (Consortium for Continental Reflection Profiling) deep reflection data along a transect at approximately lat 40°N across the northern Basin and Range province provide new constraints and insights into the nature and geometry of Cenozoic extension and the evolution of the Moho (Allmendinger and others, 1983; Klemperer and others, 1986; Hauge and others, 1987; Potter and others, 1987; Knuepfer and others, 1987; Allmendinger and others, 1987a). In this paper (one of a series, including Allmendinger and others, 1987a; Hauge and others, 1987; and Potter and others, 1987), we discuss the part of that transect exploring the crustal structure in the central Basin and Range province of eastern Nevada (Fig. 1), the region of exposed core complexes in the hinterland of the Mesozoic orogen. The frontal part of the late Mesozoic Sevier thrust belt, exposed to the east in Utah, roots and continues in some way beneath eastern Nevada (Armstrong, 1968, 1972), where structures of Mesozoic age include the Confusion Range and Butte synclinoria (Hose, 1977; Hose and Blake, 1976), Jurassic and late Cretaceous granitic intrusions (Hose and Blake, 1976; Lee and others, 1968, 1980), and metamorphic and plutonic rocks of the core complexes (Misch, 1960; Lee and others, 1968, 1980; Coney, 1980; Snoke, 1980; Howard, 1980; Armstrong, 1982; Miller and others, 1983). Late Tertiary extension and normal faulting developed the present Basin and Range physiography (Zoback and others, 1981), but pre-Basin-Range, gently dipping normal faults and detachments are exposed in many ranges (Armstrong, 1972; Snoke, 1980; Howard, 1980; Howard and others, 1979; Gans and Miller, 1983).

Among the remarkable features of the COCORP data from eastern Nevada (Fig. 2), there is a subhorizontal and laterally persistent zone of Moho reflections, this Moho perhaps evolving by magma underplating and intrusion during Cenozoic time. A west-dipping crustal reflection fabric in the east, perhaps of Mesozoic age, gives way westward to a

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Geological Society of America Bulletin, v. 99, p. 833–844, 12 figs., December 1987.

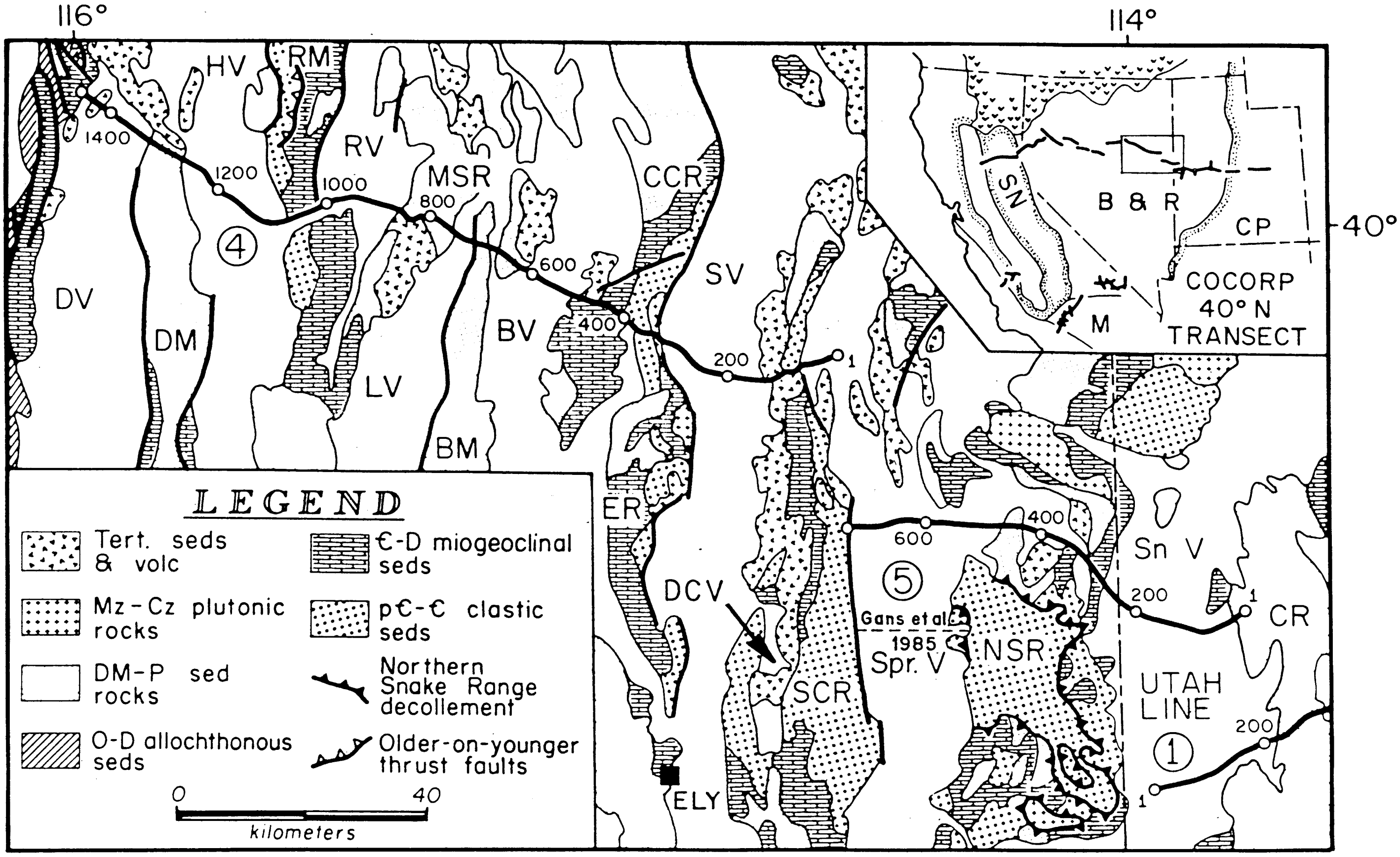

Figure 1. Generalized geology and location map of COCORP lines in eastern Nevada. Heavy east-west lines with numbered circles are COCORP lines with vibration-point numbers; large numbers in circles denote COCORP line numbers (that is, COCORP Nevada lines 4 and 5 in Utah line 1). Other heavy lines denote important faults. The location of the proprietary industry line in Snake Valley discussed by McCarthy (1986) is unknown. Diamond Valley = DV, Diamond Mountains = DM, Ruby Mountains = RM, Long Valley = LV, Maverick Springs Range = MSR, Butte Mountains = BM, Huntington Valley = HV, Ruby Valley = RV, Butte Valley = BV, Cherry Creek Range = CCR, Egan Range = ER, Steptoe Valley = SV, Duck Creek Valley = DCV, Schell Creek Range = SCR, Spring Valley = Spr.V, northern Snake Range = NSR, Snake Valley = Sn V, Confusion Range = CR, Sierra Nevada = SN, Basin and Range = B & R, Colorado Plateau = CP, Mojave = M.

subhorizontal, middle- and lower-crustal reflection fabric, perhaps representing Cenozoic intrusion and ductile extension. An exception to this general pattern is the prominent subhorizontal reflections of the middle and lower crust below the northern Snake Range which define a boundary that may represent the lower-crustal continuation of the Schell Creek and other Basin-Range faults, the formerly offset Moho now smoothed by magma intrusion and underplating.

DATA ACQUISITION AND PROCESSING

The COCORP deep seismic reflection lines 4 and 5 in eastern Nevada (Fig. 1) are 74 and 143 km long, respectively, and were collected using a 100-m station spacing and a 96-channel recording system. The near and far offsets were nominally 0.3 and 9.8 km, respectively. An 8- to 32-Hz vibrator sweep for 32 sec was used. Correlated data of 16 sec (two-way traveltime) was collected, corresponding to a depth >50 km. Vibrating every station (5 vibrators × 8 sweeps/station) resulted in nominal 48-fold CMP data.

Processing of the data included Vibroseis (registered trademark of CONOCO, Inc.) correlation, application of variable elevation statics corrections calculated from shallow refraction arrivals in the COCORP data, deconvolution and frequency-wavenumber filtering before stack, CMP gathering, trace editing, refraction muting, velocity analysis, normal moveout (NMO) correction, and CMP stacking. Iterative velocity analysis, using velocity spectra, moved-out CMP's, and constant velocity stacks at 300 m/sec increments, was carried out approximately every 25–50 CMP's (1.2–2.5 km).

THE EASTERN NEVADA COCORP DATA

Moho Reflections

One of the most remarkable aspects of the COCORP data from eastern Nevada is the laterally persistent zone of prominent, subhorizontal reflections (M in Figs. 2, 3, and 4) at 10 to 11 sec two-way traveltime. These reflections have amplitudes which are commonly visible on shot records without application of gain balancing. These deepest subhorizontal reflections are interpreted as imaging the Moho because they are prominent and laterally extensive and lie at a depth of ~32–35 km (~31–33 km below sea level), comparable with the Moho as determined from limited refraction data (Smith, 1978; Prodehl, 1979). These strong reflections also lie at the boundary between reflections above and an absence of reflections below, perhaps indicating a seismically more transparent upper mantle below a reflective crust. Amplitude decay plots for the data (Fig. 5) reveal

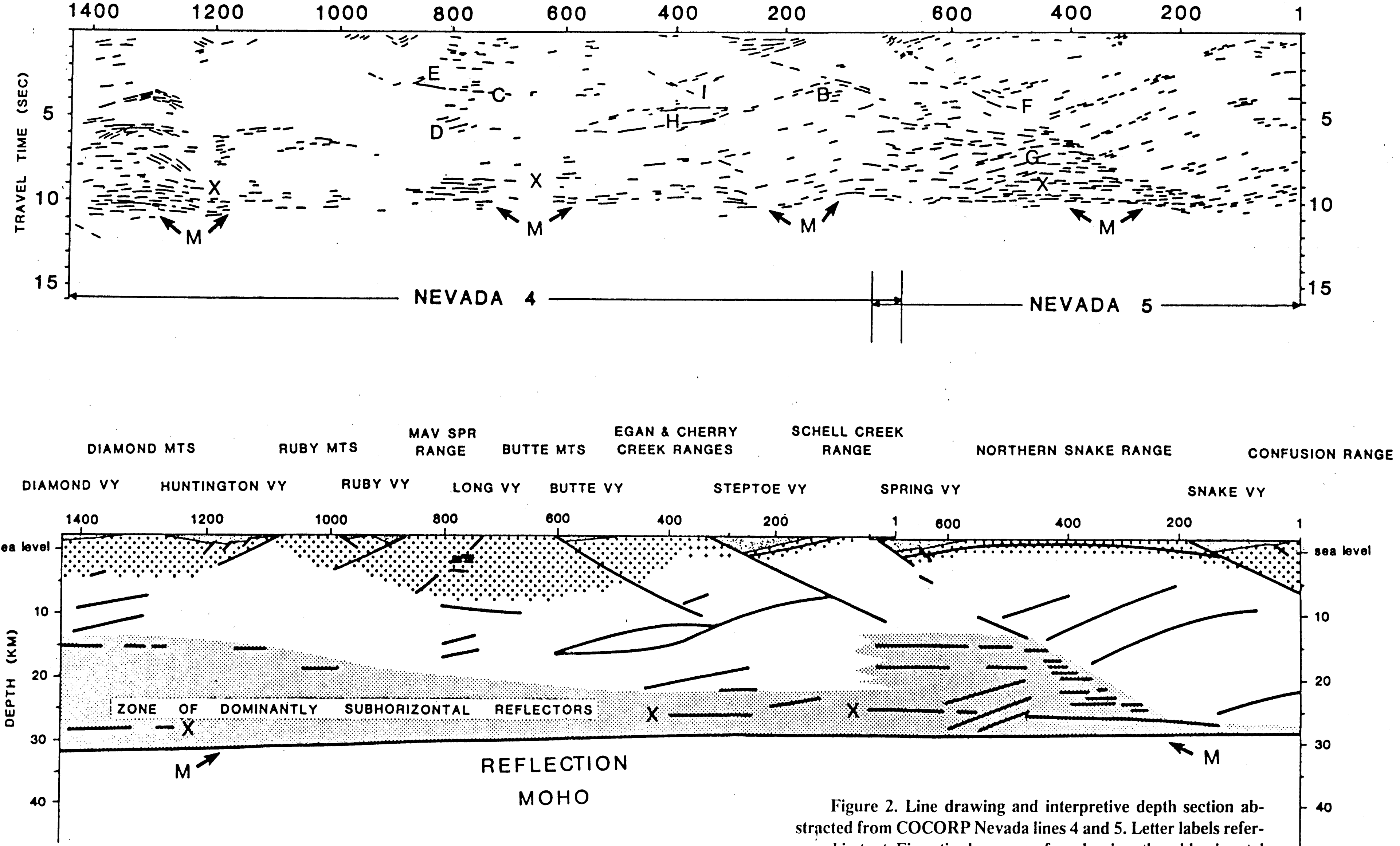

Figure 2. Line drawing and interpretive depth section abstracted from COCORP Nevada lines 4 and 5. Letter labels referenced in text. Fine stipple = zone of predominantly subhorizontal reflections; dot pattern = Phanerozoic sequence.

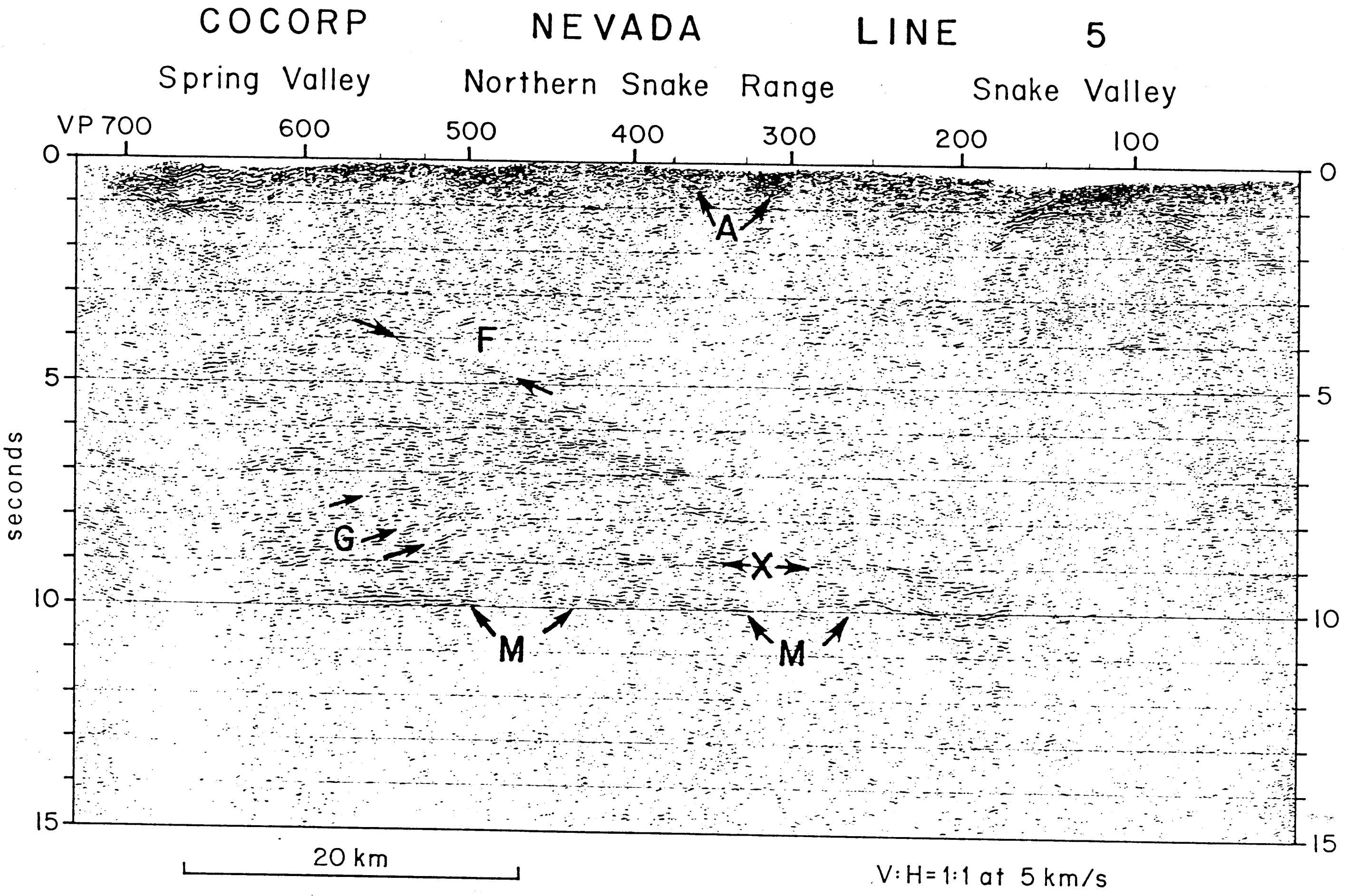

Figure 3. COCORP Nevada line 5. Deconvolved before stack; trace amplitude balanced using 1-sec window. This unmigrated time section has been coherency filtered for photographic enhancement. Letter labels are referenced in text.

that source-generated energy continues to arrive to the end of the 16 sec data, suggesting that this disappearance of reflections at depth does not indicate that a threshold of ambient noise has been reached. Klemperer and others (1986) discussed further the character and nature of the reflection Moho and its relationship to refraction results across Nevada along the 40°N transect.

The reflection Moho lies at 10–11 sec in eastern Nevada (Fig. 2). Most of the variation in two-way traveltime for the Moho reflections is attributable to velocity pull-down below thick sequences of low-velocity basin fill (that is, below Snake, Spring, and Steptoe Valleys in Figs. 2, 3, and 4). At locations of significant velocity pull-down, range stacks and preliminary modeling show that the dip of strong crossing reflections in this zone (that is, below Steptoe and Snake Valleys; Figs. 2, 3, and 4) is probably a consequence of the variety of ray paths through wedge-shaped basin fill having slow velocity. Modeling by Peddy and others (1985) indicates that the complex ray paths through slow-velocity basin fill lead to a smearing of deeper reflections in multifold stacked reflection data. Attenuation of seismic energy in the Tertiary sedimentary and volcanic rocks in the basins probably also contributes to the commonly observed degradation of deeper reflections below shallow basins.

Although local variation in the traveltime to these deepest reflections can be related to the position of sedimentary basins and attributed to velocity pull-down, the traveltime below physiographic ranges in eastern Nevada increases regionally westward from a uniform 10 sec below the Snake Range to ~11 sec below the Diamond Mountains. This regional variation of ~1 sec may indicate a variation in crustal thickness of >3 km along this part of the traverse or it may to some extent represent a regional westward decrease (as much as 10%) in average crustal seismic velocity.

Schell Creek Fault

The most dramatic crustal feature imaged on line 5 (Figs. 2 and 3) beneath the northern Snake Range, other than the prominent Moho reflections, is a crustal-scale, east-dipping boundary defined by the eastward termination of prominent subhorizontal reflections. These reflections contrast markedly with the west-dipping reflection character of the crust in this region (Fig. 2). The gently west-dipping reflection pattern is also observed on local industry data (see Fig. 3 of McCarthy, 1986, especially 6–7 sec below the eastern margin of the northern Snake Range).

The Schell Creek fault bounds a half graben beneath Spring Valley containing ~1.0 sec (1.3 km) of basin fill. Offset along the Schell Creek fault is probably at least 5–6 km where line 5 crosses (E. Miller, 1986, personal commun.) but is thought to reach as much as 10 km a short distance to the south (Fig. 1) (Gans and others, 1985). Gently east-dipping fault-plane reflections can be traced to nearly 15 km depth (F, Figs. 2 and 3). Some of these east-dipping reflections project into the Schell Creek

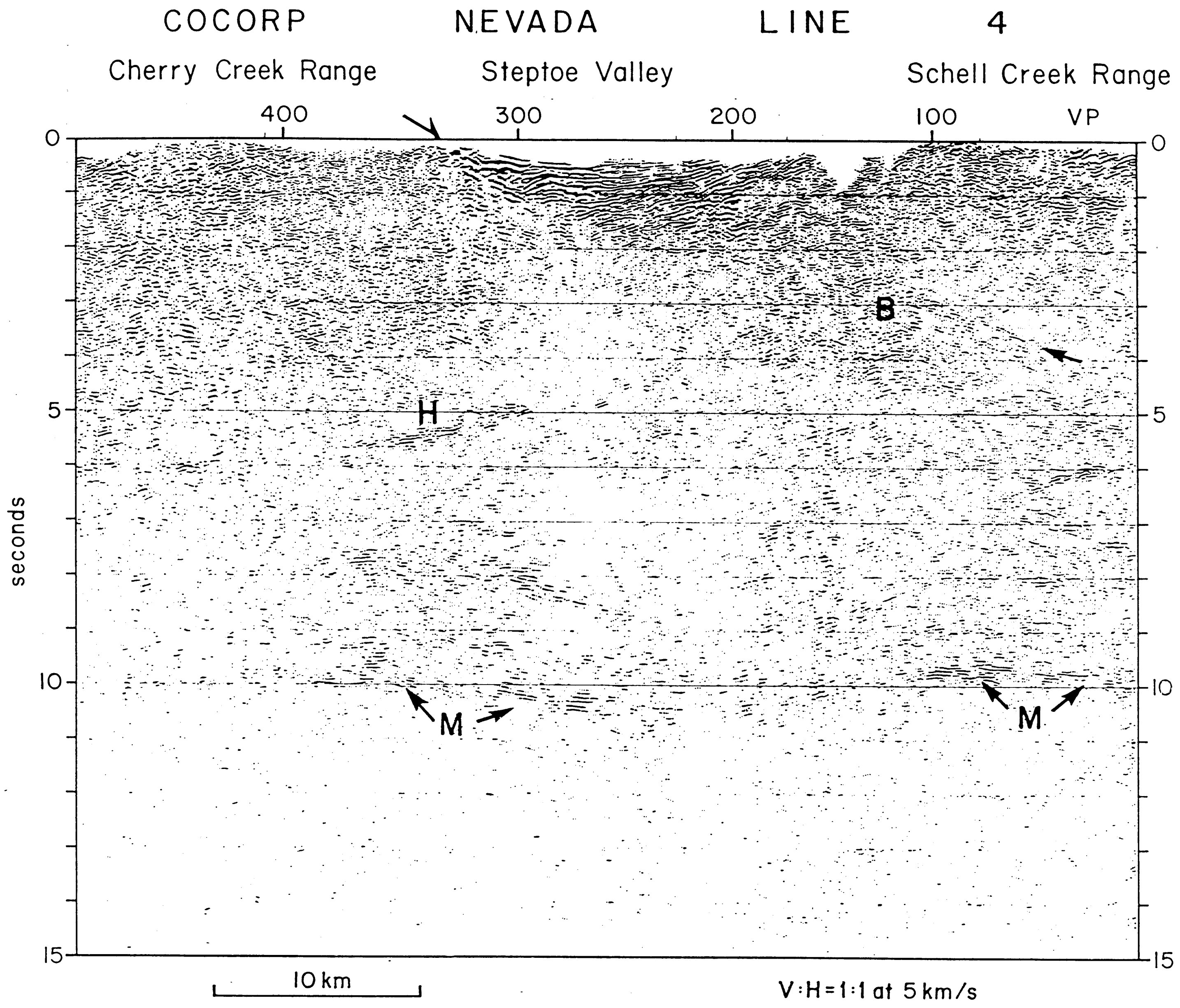

Figure 4. COCORP Nevada line 4 between VP's 1 and 415. Only 12 sec of the 16 sec data are shown. Note the reflection Moho affected by velocity pull-down below Steptoe Valley. Deconvolved before stack; trace amplitude balanced using 1-sec window. This unmigrated section has been coherency filtered for photographic enhancement. Letter labels are referenced in text.

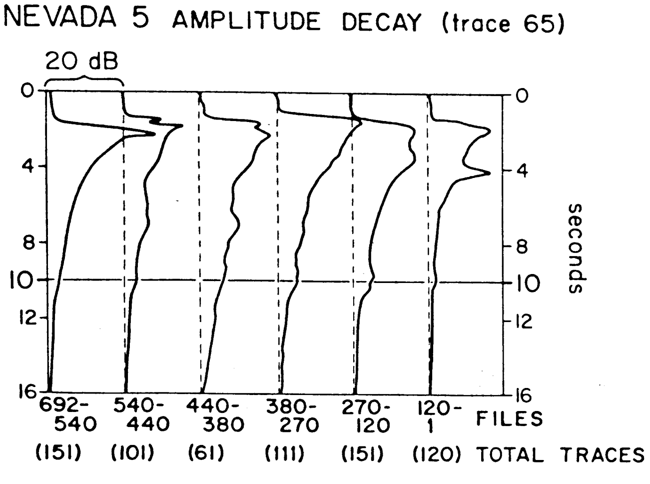

Figure 5. Amplitude decay curves for COCORP Nevada line 5, showing the continued return of source-generated energy at times >10 sec. Note the significant amplitudes of Moho reflections at ~10 sec on many plots. Also note the prominent amplitude anomaly at ~7 sec on the plots for files 540–440 and 440–380. The absolute values of the amplitude of trace 65 from a number of adjacent shot-point gathers (FILES) were combined for each plot shown. Only trace 65 (approximate range of 6,800 m) from each shot-point gather was used to avoid the airwave, but surface waves are locally prominent (that is, 4 sec on curve for files 1–120). Each plot is normalized to its value at 16 sec to emphasize the continued decay of source-generated energy to at least 16 sec without reaching a uniform ambient-noise level.

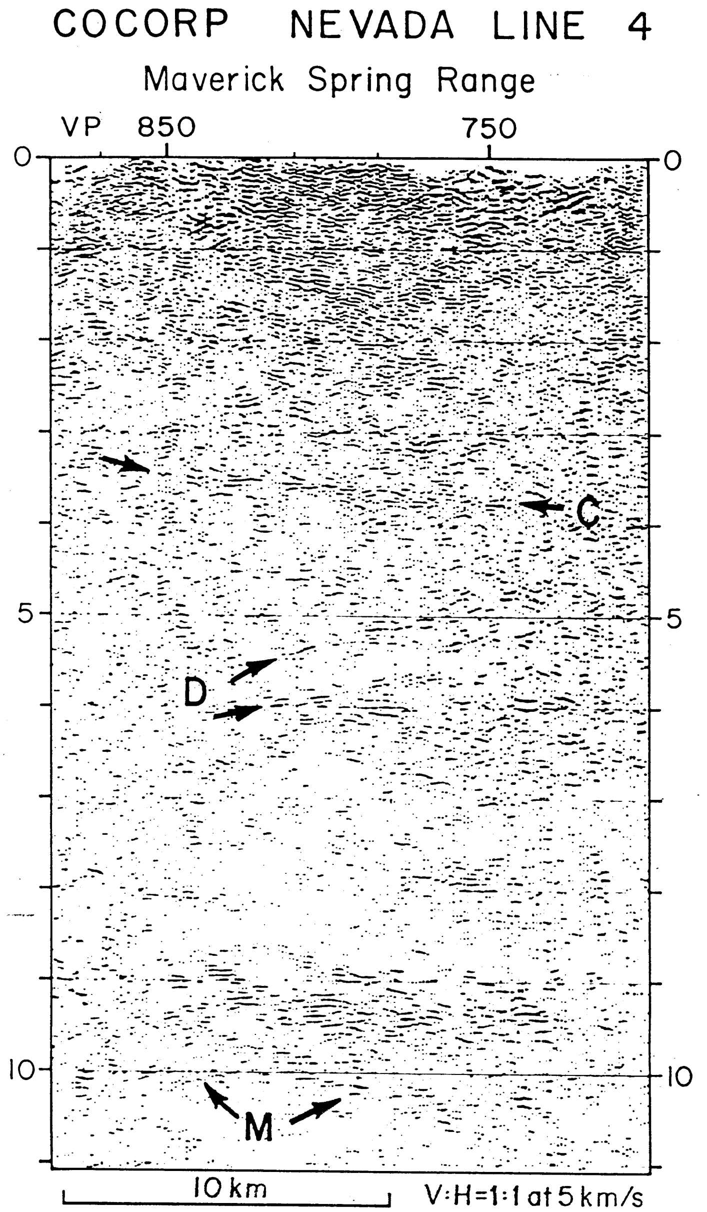

Figure 6. Segment of COCORP Nevada line 4 below the Butte synclinorium and the Maverick Springs Range. Deconvolved before stack; trace amplitude balanced using 1-sec window. This unmigrated section has been coherency filtered for photographic enhancement. Letter labels are referenced in text.

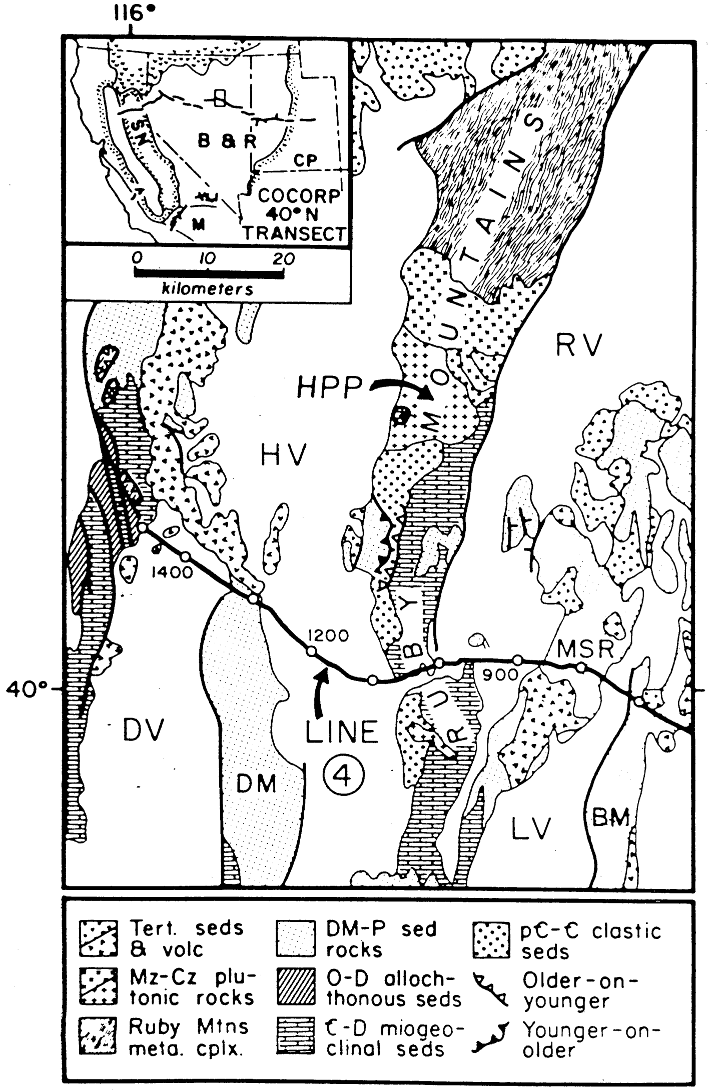

Figure 7. Generalized geology and COCORP line location map of the Ruby Mountains region at the west end of Nevada line 4. Heavy east-west line is COCORP line 4 with vibration-point numbers. Other heavy black lines are faults. This figure is modified from the geologic map of Nevada (Stewart and Carlson, 1978); the extent of the thrust fault in the southern Ruby Mountains, as mapped by Willden and Kistler (1967), differs in detail from the state geologic map. HPP = Harrison Pass pluton of Tertiary age, Diamond Valley = DV, Diamond Mountains = DM, Huntington Valley = HV, Ruby Valley = RV, Maverick Springs Range = MSR, Long Valley = LV, Butte Mountains = BM (other abbreviations as in Fig. 1).

Range and may represent the fault bounding the west side of Duck Creek Valley (Fig. 1). The fault in Duck Creek Valley dies out to the north and is not seen on Nevada line 4. These dipping fault-plane reflections can be traced to ~5 sec near the top of the prominent subhorizontal reflections near their eastern boundary. This alignment suggests that this boundary in some way represents the middle- and lower-crustal continuation of the Schell Creek fault and probably other faults to the west.

Steptoe Valley (Figs. 1 and 4) is underlain by a half graben containing ~2 km of Tertiary and Quaternary basin fill. The prominent basin-bounding fault on the west side of Steptoe Valley, observable even on shot-point gathers, dips ~20° to the east and is traced on the stacked section as a series of discontinuous east-dipping reflections beneath the Schell Creek Range to ~4.5 sec (about 14 km) at the east end of line 4 (Figs. 2 and 4). Simple calculations indicate that there is as much as 10 km of perpendicular throw of the Cambrian-Precambrian contact related to displacement along this and other lesser faults between the Egan and Cherry Creek Ranges to the west and the Schell Creek Range to the east,

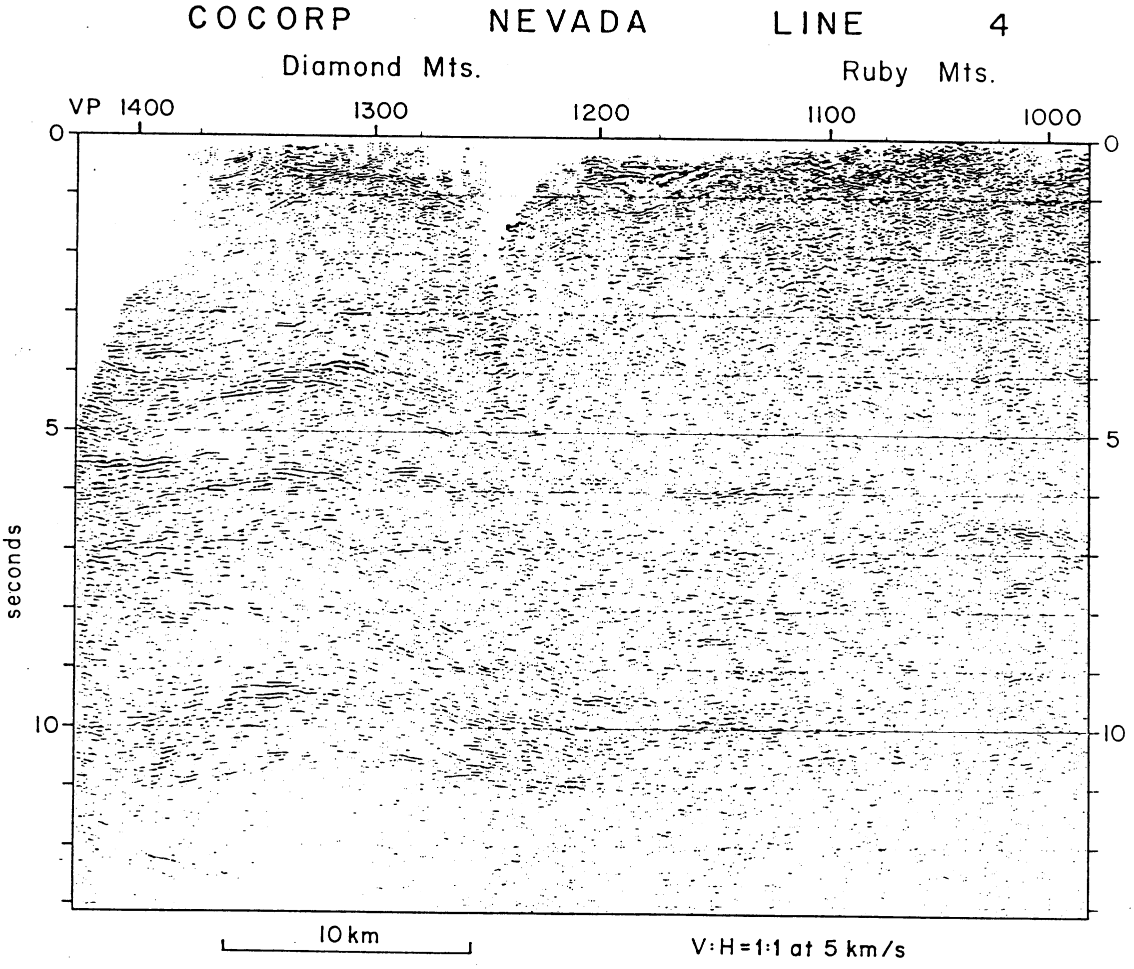

Figure 8. COCORP Nevada line 4, west end. Deconvolved before stack; trace amplitude balanced using 1-sec window. This unmigrated stacked section is coherency filtered for photographic enhancement.

even excluding 8 km of Oligocene offset (Gans and Miller, 1983) along pre-Basin and Range faults in the northern Egan Range. This 10 km of Basin-Range–age offset, mainly along the Steptoe Valley fault, roots into the middle crust beneath and east of the Schell Creek Range in the vicinity of the prominent subhorizontal reflections. Because of the offset between lines 4 and 5, the Steptoe Valley fault cannot be traced with certainty into line 5, but it is interpreted to pass near the top of the prominent subhorizontal reflectors on line 5 and to continue, together with the Schell Creek fault, along the prominent reflection boundary at depth (Figs. 2 and 3). The combined displacement of the Schell Creek fault (5 km or more), the Steptoe Valley fault (10 km or more), and other faults between may continue in the middle and lower crust along a dipping ductile shear zone now outlined by the prominent dipping reflection boundary.

The prominent reflection boundary (Fig. 3) continues downward to the base of the crust, where the present reflection Moho exhibits no clear offset; the apparent relief on the Moho at this location is probably the result of velocity pull-down beneath Snake Valley. No reflections are observed which might suggest a continuation of this inferred fault into the upper mantle, although displacement may instead be accommodated by a detachment at the prominent Moho. The absence of offset or large-scale undulation of the present reflection Moho by such a crustal-scale fault might be explained by subsequent intrusion and underplating of magma which smoothed the irregularity. The prominent subhorizontal reflections which define the boundary may image intrusions in the middle and lower crust largely bounded by the pre-existing Schell Creek fault zone at depth. The amplitude of these reflections, especially those at ~7 sec (Figs. 3 and 5), are anomalously high for usual rock interfaces and, like other amplitude anomalies at mid-crustal depths (deVoogd and others, 1986; Brown and others, 1980), may also suggest the local presence of magma. The eastern terminations of such intrusions may have obscured the ductile shear zone itself, and the absence of diffractions at the termination of these prominent horizontal reflections may indicate an absence of sharp truncation at their eastern termination. These reflections are being studied in more detail to evaluate the likelihood that they represent magma. In this interpretation, the present nature and form of the smooth and subhorizontal Moho, well developed here, postdates major Basin-Range faulting and, as a result, is in places late Cenozoic in age.

Independent evidence for such young intrusions is largely lacking. Very young volcanism is widespread elsewhere in the Basin and Range province (Stewart, 1980), but the Cenozoic volcanic or intrusive rocks in eastern Nevada are predominantly older than 34 m.y., some of the oldest volcanic rocks of Cenozoic age in the Basin and Range province (Stewart, 1980; Gans and Miller, 1983). The absence of young surface volcanism locally is curious if the intrusions are voluminous, although it is not essential that such magma must vent to the surface. Low-temperature geothermal water has been recognized in Steptoe Valley (Muffler, 1979), but there

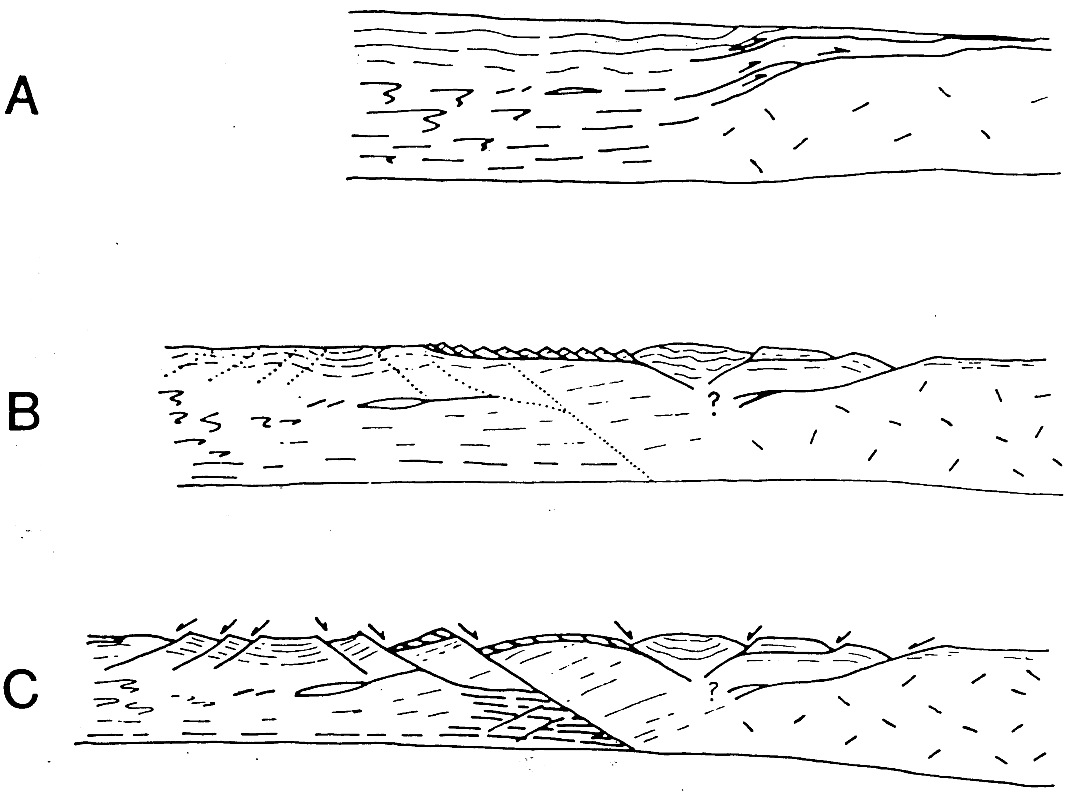

Figure 9. Cartoon suggesting the development of crustal features of eastern Nevada. (A) Mesozoic shortening and crustal thickening; thrust faults pass into a region of ductile deformation at depth in the hinterland. Little-involved Precambrian basement shown by random dash pattern to east. (B) Pre-Basin and Range Cenozoic extension and evolution of northern Snake Range décollement as well as Sevier Desert detachment to east. Dotted lines are future Basin-Range faults. (C) Basin and Range extension, deep faulting, and young magma intrusion and underplating (see also Fig. 10).

is a clear paucity of hot-spring temperature and heat-flow measurements in the vicinity of Spring Valley, northern Snake Range, and elsewhere in eastern Nevada. The present heat-flow data set in this area is too sparse to argue for or against the presence of an important volume of young intrusions at depth. Although such independent evidence is lacking, perhaps future geophysical studies will be able to further evaluate this hypothesis. For example, a unique swarm of micro-earthquakes at an unconstrained depth beneath the northern Snake Range comprises nearly all of the instrumentally recorded earthquakes in the central Basin and Range province (Arabasz and others, 1979; U.S. Geological Survey, earthquake data report, 1952–1983). Is this earthquake swarm perhaps related to the Schell Creek fault or intrusions at depth?

Northern Snake Range Décollement

The northern Snake Range décollement is broadly arched and exposed ~5–10 km south of line 5 between VP's 300 and 550 where it plunges gently northward (Fig. 1). The Snake Range décollement, although originally interpreted as a basal décollement for Mesozoic thrusting, is now widely recognized as accommodating significant extension (Misch, 1960; Lee and others, 1970; Hose and Blake, 1976; Armstrong, 1972; Miller and others, 1983). The northern Snake Range décollement unfortunately is very poorly imaged on line 5. The imaging of deeper reflections apparently indicates that the complexly faulted upper plate rocks (numerous authors, for example, Gans and Miller, 1983) are not entirely responsible for its absence in the data. Locally, west-dipping reflections (A, Fig. 3), apparently representing rotated upper plate strata, lie above horizontal reflections at 0.6 sec (0.8 km), which may represent the northern Snake Range décollement. The northern Snake Range décollement is obscure also in published shallow industry data from Spring Valley ~10–15 km south of line 5 (Fig. 1) (Gans and others, 1985; McCarthy, 1986). To the west, the northern Snake Range décollement dips gently westward below Spring Valley, where it is apparently cut by the Schell Creek fault and is probably exposed in the Schell Creek Range as an approximately bedding-parallel fault in the Upper Cambrian strata (Gans and others, 1985). Related faulting dies out before reaching the Butte Mountains to the west. To the east on COCORP Utah line 1 (Allmendinger and others, 1983) and proprietary industry data (McCarthy, 1986), well-developed east-dipping reflections beneath Snake Valley and the western margin of the Confusion Range are attributed to the northern Snake Range décollement. Although Nevada line 5 crosses Snake Valley only 20 km to the north of Utah line 1, clear reflections from the northern Snake Range décollement or a basin-bounding fault for Snake Valley are lacking on Nevada line 5 (Fig. 3). The relationship shown in Figure 2, indicating that the basin-bounding fault passes to depth along the northern Snake Range décollement rather than offsetting it at depth, is consistent with, although not well constrained by, the presently available data.

The west-dipping crustal reflection fabric is not parallel to the gently arched northern Snake Range décollement (Fig. 2). This discordant relationship suggests that a postulated large magnitude (several hundred percent) of horizontal ductile pure-shear stretching parallel to and beneath the décollement during its evolution (Miller and others, 1983) is unlikely for the crust below the décollement. Instead, this angular relationship suggests that the northern Snake Range décollement and the strongly flattened Cambrian and upper Precambrian strata exposed beneath and parallel to it (Gans and Miller, 1983) more likely represent a simple shear zone and strata strongly strained into parallelism with the zone of simple shear (Davis, 1983; Bartley and Wernicke, 1984; Gaudemer and Tapponnier, 1987). The discordant west-dipping reflections in the crust below the northern Snake Range décollement, which characterize much of the crust in eastern Nevada and western Utah, are interpreted to represent layering developed before displacement along the northern Snake Range décollement. They probably represent Mesozoic-age structures developed at depth in the hinterland during Mesozoic tectonism, although they might alternatively be considered structures developed in part as a result of thermal and ductile processes in the middle and lower crust early in extension which were uplifted and translated along the décollement to their present dipping position (for example, Davis, 1986). During detachment faulting and uplift, this dipping crustal fabric apparently experienced less Cenozoic ductile simple-shear strain, far from the ductile simple-shear zone of the northern Snake Range décollement.

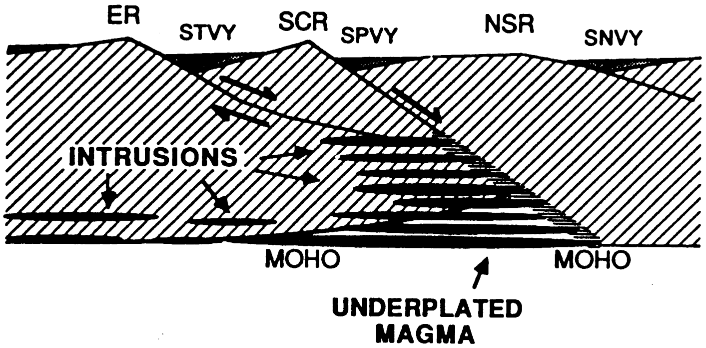

Figure 10. Schematic model of the Schell Creek fault and lower-crustal reflections which may represent footwall underplated magma. See discussion in text. ER = Egan Range, STVY = Steptoe Valley, SCR = Schell Creek Range, SPVY = Spring Valley, NSR = northern Snake Range, SNVY = Snake Valley.

Butte Synclinorium

Below the Butte synclinorium, a series of weak and discontinuous subhorizontal reflections is observed down to 3.5–4.0 sec two-way traveltime (~9–12 km) at VP 800, line 4 (Figs. 2 and 6). These reflections probably arise from the Paleozoic and upper Precambrian strata, correlatives of which are exposed in the Egan, Cherry Creek, and Schell Creek Ranges to the east and the southern Ruby Mountains to the west (Fig. 1). On the basis of local Paleozoic and upper Precambrian stratigraphic thicknesses (Hose and Blake, 1976; Stewart and Poole, 1974), the top of the Cambrian-Precambrian clastic sequence probably lies at a depth of ~10 km (~3.3 sec at 6 km/sec) below the Butte synclinorium in the Butte Mountains and the Maverick Springs Range (Figs. 2 and 6, line 4, VP 780), and the upper Precambrian sequence probably continues at least to 14 km (nearly 4.7 sec at 6 km/sec). A subhorizontal to very gently east-dipping zone of reflections at ~3.7 sec (C, Figs. 2 and 6) may represent thick units of argillite and quartzite or perhaps sills in the upper Precambrian stratigraphic sequence as described by Stewart and Poole (1974). The depth to Precambrian basement is not known in eastern Nevada (Stewart and Poole, 1974), but west-dipping reflections (D, Figs. 2 and 6) at traveltimes >4.7 sec may be from features within the Precambrian basement (such as pre-existing crystalline basement structures or late Precambrian rift-related features). Alternatively, they may represent imbricate or crosscutting features developed subsequently (in Mesozoic or Cenozoic time) within the basement or a much thicker upper Precambrian sedimentary sequence.

To the east beneath the Egan Range, mid-crustal reflections outline a lenticular form (H, Figs. 2 and 4). A zone of west-dipping reflections is traceable eastward from this lenticular feature into the upper crust to where the zone appears to be truncated beneath the Schell Creek Range by the Steptoe Valley fault (B, Figs. 2 and 4). The depth to this feature is comparable to that attained by known thrust detachments to the east in Utah (Armstrong, 1968, 1972; Allmendinger and others, 1983), and so these west-dipping reflections and associated lenticular body are interpreted to represent Mesozoic structures, probably a thrust detachment and minor duplex, truncated and offset by the Steptoe Valley fault. A competing but less favored hypothesis might suggest that these reflections represent a locally anastomosing extensional detachment cut by a younger Basin-Range normal fault.

The COCORP traverse crosses Ruby Valley at its southern end where displacement on the prominent normal fault on the east side of the Ruby Mountains has diminished (Fig. 7). Where the traverse crosses Ruby Valley and to the south along the west side of the Maverick Springs Range, the main Basin and Range fault offsets the exposed upper Paleozoic rocks of the Butte synclinorium. The fault is obscure but might be traced in the seismic data as gently west-dipping reflections (E, Fig. 2). This change in Cenozoic faulting along strike and the physiographic disruption of the Ruby Mountains at the pass where the traverse crosses (Fig. 7) suggest that structural complications by transverse faults, intrusion, or other complex structures may contribute to the local absence of clear reflections in the data beneath the Ruby Mountains and Ruby Valley. The nearly continuous sequence of east-dipping Paleozoic strata exposed in the Maverick Springs Range and the southern Ruby Mountains (Fig. 7) along the traverse suggests that the Ruby Mountains here are the normal-faulted and uplifted western flank of the Butte synclinorium.

Crustal Layering West of the Butte Synclinorium

Below the Diamond Mountains at the west end of line 4 (VP's 1250–1400), there are some west-dipping reflections from the upper crust, but the middle and lower crust appear dominated by subhorizontal reflections and diffractions (Fig. 8). The arched nature of reflections below the Diamond Mountains (Fig. 8) is probably mostly a consequence of velocity pull-down below adjacent basins. Similar strong horizontal middle- and lower-crustal reflections, but without the apparent diffractions, are also prominently developed in COCORP data immediately to the west (Potter and others, 1987) where the COCORP seismic lines cross the Northern Nevada rift (Zoback and Thompson, 1978). The prominent horizontal

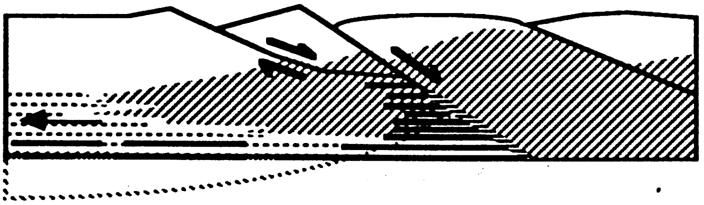

Figure 11. Cartoon schematically showing salient features of the transect in eastern Nevada, emphasizing a possible transition from predominantly lower-crustal extension in the west to deep faulting in the east. Possible intrusions shown as heavy lines; see also Figure 10. Faulted dipping reflection fabric to east passes westward to a subhorizontal middle- and lower-crustal reflection fabric perhaps resulting from horizontal ductile stretching and intrusion.

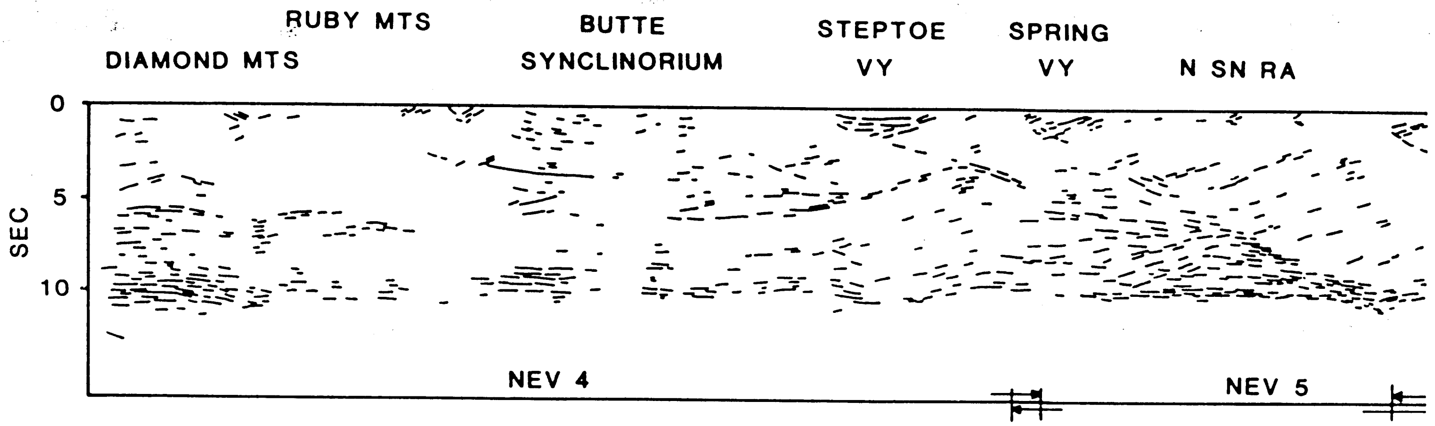

Figure 12. Composite line drawing of the COCORP deep reflection data of eastern Nevada and western Utah along the 40°N transect, abstracted from this paper and Allmendinger and others (1983). (Note overlap in center.)

reflections on line 4 may therefore represent intrusions or layering related to late Cenozoic extension and related magmatism (see Potter and others, 1987). Alternatively, some of the reflections and diffractions from beneath the Diamond Mountains may be from recumbent folds and metamorphic or plutonic structures largely developed during Mesozoic shortening and magmatism equivalent to structures exposed in the core of the Ruby Mountains igneous-metamorphic complex (Snoke, 190; Howard, 1980) to the north (Fig. 7).

Beneath Huntington Valley (Fig. 8) from 0.5 to 1.5 sec are several irregular reflections as well as generally west-dipping zones of reflections. These may represent faulted Tertiary sedimentary and volcanic rocks as well as Paleozoic rocks above gently west-dipping normal faults. Some of these features may be associated with the west-dipping low-angle normal fault (Snoke and Howard, 1984) exposed on the west flank of the Ruby Mountains (Fig. 8). These west-dipping rocks of the upper plate consist of mid-Paleozoic rocks and jasperoid breccia above the deformed rocks of the Oligocene Harrison Pass pluton (Fig. 7) (Sharp, 1942; Howard and others, 1979; Snoke and Howard, 1984). Snoke and others (1982) and Snoke and Howard (1984) described mylonitic rocks from the west flank of the Harrison Pass pluton. A Tertiary low-angle normal fault has been interpreted from industry seismic data by Effimoff and Pinezich (1981) to bound the west margin of the Ruby Mountains farther north. Zones of gently west-dipping reflections at 2–4 sec beneath the Diamond Mountains (Fig. 8) project to the surface in the vicinity of Huntington Valley and the west side of the Ruby Mountains and may represent one or more gently west-dipping normal faults. Alternatively, these gently west-dipping reflections beneath the Diamond Mountains may be related to features of Mesozoic age, such as the minor thrust fault exposed in the southern Ruby Mountains (Sharp, 1942; Willden and Kistler, 1967; Stewart and Carlson, 1978) or subhorizontal Cenozoic-Mesozoic ductile deformation and migmatization as exposed in the Ruby Mountains igneous-metamorphic complex to the north (Snoke, 1980; Howard, 1980; Snoke and Lush, 1984).

The subhorizontal to gently west-dipping reflections at ~0.5 sec beneath the Diamond Mountains and Diamond Valley (Fig. 8) contrast with the folded upper Paleozoic strata exposed in the Diamond Mountains and suggest that the Mesozoic folds developed in the upper Paleozoic strata there lie above a shallow thrust detachment. The normal fault that bounds the east side of the Diamond Valley half graben farther south is suggested by Effimoff and Pinezich (1981) to sole into and reactivate an older detachment, but this normal fault dies out to the north where apparently nonfaulted Tertiary volcanic rocks are exposed along and north of the COCORP line (Fig. 7).

DISCUSSION

In eastern Nevada, west of a major thrust ramp in west-central Utah, Mesozoic thrust faults root deeply into the crust of the orogenic hinterland (Fig. 9A) (Armstrong, 1968, 1972; Allmendinger and others, 1983). The gently west-dipping reflection fabric here resembles that seen elsewhere in deep reflection data sets wherein thrust detachments pass to depth in thrust belts (Cook and others, 1981; Lillie and others, 1983; Ando and others, 1984; Potter and others, 1986) and probably is a common aspect of convergent orogens (Allmendinger and others, 1987b). This dipping crustal fabric in eastern Nevada probably represents Mesozoic deformational, metamorphic, and magmatic structures like those locally seen in the exhumed metamorphic complexes of eastern Nevada (Misch, 1960; Snoke, 1980; Howard, 1980; Lee and others, 1968, 1980; Armstrong, 1982; Miller and others, 1983). Ductile deformation at depth, distributed both in time and space, in the Mesozoic hinterland is consistent with the relatively uniform crustal thickening and low pre-Oligocene structural and topographic relief of eastern Nevada suggested by the regional absence in eastern Nevada of significant angular discordance between Oligocene rocks and upper Paleozoic rocks (Young, 1960, p. 166; Moores and others, 1968; Armstrong, 1972; Gans and Miller, 1983). An abrupt drop in surface slope in the interior of thrust belts is commonly observed where thrust detachments pass into a region of plastic deformation at depth (Davis and others, 1983).

One of the most remarkable aspects of the COCORP data is the subhorizontal reflection Moho separating the reflective crust from the seismically transparent upper mantle. This Moho is equally well developed beneath both the western margin of Precambrian crust and the Paleozoic accreted terranes in central and western Nevada, indicating that it developed into its present form at least during Mesozoic or younger events (Klemperer and others, 1986; Hauge and others, 1987; Potter and others, 1987). Cenozoic extension in central and western Nevada is apparently accommodated by basin-bounding faults which pass into the middle crust where a subhorizontally layered lower crust and prominent reflection Moho may have evolved by a combination of horizontal ductile extension

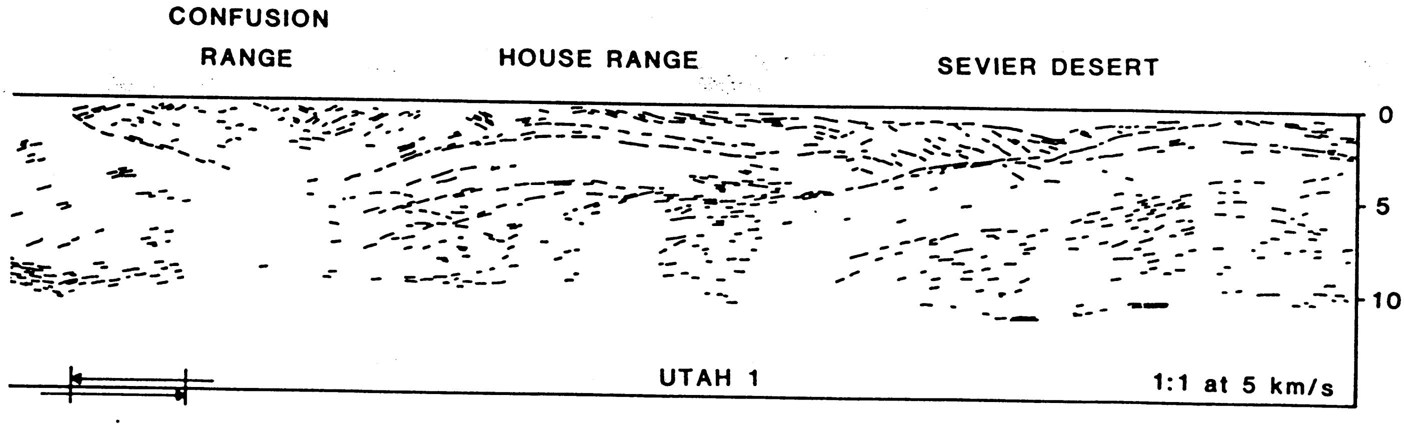

Figure 12. (*Continued*).

and intrusion (Hauge and others, 1987; Potter and others, 1987). In contrast, Basin-Range extension in easternmost Nevada is apparently accomplished by the rotation of fault-bounded blocks, locally on a crustal scale (Figs. 2, 9C, and 10), suggesting that a pure-shear model of pervasive, horizontal ductile stretching of the lower crust is not the favored mechanism of Basin-Range extension there. Instead, the west dip of a pre–Basin-Range crustal fabric probably increased to some degree by such large-scale domino-like rotation (Fig. 9C). Offset at the base of the crust in at least one place in eastern Nevada probably was healed and smoothed by intrusion and underplating of magma (Figs. 9C and 10). This would indicate that the prominent reflection Moho is locally very young and may largely evolve by a process of magma intrusion and underplating.

The transition from the subhorizontal reflection pattern of the lower crust of western Nevada to the generally west-dipping reflection fabric of eastern Nevada is gradual, the subhorizontally layered lower crust narrowing eastward to a thin zone at the base of the crust (Fig. 2). The subhorizontal reflections and diffractions beneath the Diamond Mountains lie in this transition and may represent hybrid structures like those exposed in the metamorphic-plutonic complex of the Ruby Mountains to the north, which are largely Mesozoic but were modified during Cenozoic extension. Also in this transition is the Butte synclinorium, the upper crust of which is largely intact and little extended, indicating that the lower crust there must have preferentially thinned. These patterns and relationships may indicate that along this part of the transect, there is a lateral change in extensional style, from the horizontally stretched and intruded lower crust to the west to the deep faulting to the east (Fig. 11).

One might speculate about the cause of this transition and the unique occurrence along the transect of a feature such as the crustal-scale Schell Creek fault. They may indicate that lateral variation of factors, such as temperature, crustal composition, inherited variation in crustal thickness, strain rate, and the effectiveness of lateral accommodation of strain, may be important in the depth of penetration of Basin and Range faults as ductile shear zones in the lower crust. It has long been recognized that the spacing and length of basins and ranges is relatively uniform, with extension being accommodated along strike by transfer to other basin-bounding faults. In places where regional ductile deformation in the lower crust resembles pure-shear extension, perhaps in western Nevada, upper-crustal extension may be accommodated adequately throughout the region by lateral transfer of strain, and the strain rate may be relatively uniform over time. In places where such vertical and lateral accommodation is not effective, faulting may occur more infrequently at higher strain rates, and faults may penetrate as ductile shear zones deeply into the crust. The Schell Creek fault may be such a place; others may exist, such as the prominent fault on the east side of the Ruby Mountains (Fig. 8) or the east side of the Deep Creek Range in western Utah. This speculation may also have bearing on the near absence of historic seismicity in the central Basin and Range province in eastern Nevada (Smith, 1978) despite widespread late Cenozoic Basin-Range faulting.

A reflection Moho is present but less well developed in western Utah (Allmendinger and others, 1983) than in Nevada (Fig. 12); the eastward extent of well-developed Moho reflections corresponds generally to the place where important Cenozoic detachments and Basin and Range normal faults of opposite vergence focus extensional displacements into the lower crust (Figs. 9B, 9C, and 12) and (in particular the northern Snake Range décollement, the Sevier Desert and House Range detachments, and the Schell Creek fault). This relationship may indicate that the subhorizontal and prominent nature of Moho reflections across Nevada is related to crustal extension and thinning, perhaps acting as a basal-crust detachment for westward translation and extension of the Basin-Range crust relative to the Colorado Plateau. Such decoupling would be enhanced by the development of a lubricating zone of underplated magma.

ACKNOWLEDGMENTS

G. Thompson, M. L. Zoback, and J. Stewart first proposed this transect for a COCORP profile across the Basin and Range province. The comments of reviewers F. Royse, A. Snoke, E. Miller, and an anonymous reviewer are appreciated and have led to an improved manuscript. The field data were collected by crew 6834 of Petty-Ray, a division of Geosource. The data were processed on the MEGASEIS (TM Seiscom Delta) system at Cornell University. This research was supported by National Science Foundation Grants EAR82-12445 and EAR83-13569. S. Burtch was partially supported by a Natural Sciences Council (NSERC) of Canada post-graduate scholarship. This paper is Institute for the Study of the Continents (INSTOC) Contribution to Geology 30.

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MANUSCRIPT RECEIVED BY THE SOCIETY SEPTEMBER 11, 1985
REVISED MANUSCRIPT RECEIVED MAY 4, 1987
MANUSCRIPT ACCEPTED MAY 12, 1987

Printed in U.S.A.