

Overview of the COCORP 40°N Transect, western United States: The fabric of an orogenic belt

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ABSTRACT

The COCORP 40°N Transect of the Cordillera of the western United States crosses tectonic features ranging in age from Proterozoic to Recent and provides an acoustic cross-section of a complex orogen affected by extension, compression, magmatism, and terrane accretion. The key features of the transect, centered on the Basin and Range Province, include (1) asymmetric seismic fabrics in the Basin and Range, including west-dipping reflections in the eastern part of the province and predominantly subhorizontal ones in the west; (2) a pronounced reflection Moho at 30 ± 2 km and locally as deep as 34 km in the Basin and Range with no clear sub-Moho reflections; and (3) complex-dipping reflections and diffractions locally as deep as 48 km in the Colorado Plateau and Sierra Nevada. The eastern part of the transect, shot above known and inferred Precambrian crystalline basement, probably records features related to the entire history of the orogen, locally perhaps as old as 1800 Ma. In this region, major paleotectonic features probably controlled subsequent structural development. In the western half of the transect, however, most reflectors are probably no older than Mesozoic. Within the Basin and Range Province, there appears to be a strong Cenozoic overprint that is characterized by asymmetric half-grabens, low-angle normal faults, and a pervasive subhorizontal system of reflections in the lower crust; no one model of intracontinental extension is universally applicable. Processes that produce or are accompanied by thermal anomalies (magmatism, enhanced ductility, and extension) appear to be essential in developing a highly layered lower crust.

INTRODUCTION

More than a century ago, the King Survey of the 40°N parallel (1867–1872) provided the first systematic reconnaissance traverse of the Cordillera of western North America. The Fortieth parallel was a fortu-

itous choice because a large amount of subsequent research has shown that the transect contains one of the most complete records of Cordilleran evolution in the United States. This latitude was thus chosen as the site of the first deep seismic-reflection profile across the orogen. During 1982–1984, the Consortium for Continental Reflection Profiling (COCORP) surveyed >1,000 km in a transect from the northern Sierra Nevada to the northwest Colorado Plateau, centered on the Basin and Range Province (Fig. 1). Like the King Survey, the COCORP transect is reconnaissance in nature, and the significance of many features on the seismic-reflection profiles may become obvious only with additional study and new concepts. Taken as a whole, however, the COCORP transect provides a fundamentally new look at the structure of the continental crust in this broad and complex orogenic system.

At 40°N latitude, the orogen has been shaped by tectonic events spanning nearly 2 b.y. Just as the Basin and Range morphology masks earlier tectonic features at the surface, the reflections produced by Cenozoic features are interpreted most easily on the seismic sections. Asymmetric half-grabens and their bounding structures can be unambiguously identified on the reflection data. Many of the other features, such as broad regions of generally similar reflection geometries, can be interpreted tentatively by their spatial associations with tectonic provinces exposed at the surface. Finally, we can only guess at the significance of many reflections, which thereby provide the impetus for future research. A general conclusion appears relatively certain. Thermally activated processes, including magmatism, fluid flow, metamorphism, and enhanced ductility, acting in concert with deformation characterized by predominantly horizontal displacements, are probably responsible for many of the most pronounced reflections on the seismic lines, perhaps including even the reflection Moho.

This paper provides a brief review of regional tectonics and an overview of data from the entire transect;¹ it is intended to complement previously published regional descriptions (Allmendinger and others, 1983; Von Tish and others, 1985; Nelson and others, 1985; Klempner and others, 1986) and the accompanying (this issue) reports (Hauge and others, 1987; Potter and others, 1987). The latter papers describe the original

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¹All COCORP data are available for the cost of reproduction by writing to Executive Director, COCORP, Snee Hall, Cornell University, Ithaca, New York 14853.

data and the field and processing parameters used for specific segments of the transect. The emphasis herein is on regional features that transcend the individual segments of the survey.

REGIONAL TECTONICS OF THE CORDILLERA AT 40°N

Five tectonic episodes have shaped the western margin of North America at 40°N latitude: Proterozoic, Eocambrian through Devonian, Mississippian through Jurassic, Cretaceous through Eocene, and Oligocene through Recent. The review of tectonics presented herein serves as background for all of the accompanying papers. A potential problem is that many regional features, particularly geochemical isopleths determined from measurements in Mesozoic and Cenozoic igneous rocks, may not be in their original positions because of thrust faulting and low-angle normal faulting. Spatial correlations between the reflection data and such features are thus at best fuzzy, although the uncertainty in resolution is probably of the same order as the uncertainty in the definition of the seismic fabric domains.

Proterozoic: Crystalline Basement

The Precambrian crystalline basement is not exposed in the vicinity of the 40°N Transect. The nearest outcrops, 100 km to the east in the Uncompahgre Uplift along the Utah-Colorado border and 90 km to the north near Santaquin, Utah (Fig. 2), range in age between 1400 and 1800 Ma (Hedge and others, 1968; Wasserburg and Lanphere, 1965). This basement experienced significant deformation, metamorphism, and intrusion between 1650 and 1750 Ma (King, 1969). Closer to Utah line 4, "granites" have been encountered in boreholes on the San Rafael Swell (Hintze, 1973). On the basis of strontium and neodymium isotopes, Pre-

cambrian crystalline basement of probable Proterozoic age has been inferred to extend as far west as central Nevada (Fig. 2) (Kistler, 1974; Farmer and DePaolo, 1983).

Eocambrian through Devonian: Continental Breakup and Passive Margin

The Proterozoic continent was broken up by a major rifting event at the end of the Precambrian (Stewart, 1972), and for the next 200 m.y., a passive margin characterized the west coast of North America from Alaska to southeastern California (Stewart and Poole, 1974; Armstrong, 1968). The rifting and initial development of the Cordilleran miogeocline is not well dated directly, but backstripping analysis of stratigraphic sequences indicates that it occurred between 625 and 550 Ma (Armin and Mayer, 1983; Bond and Kominz, 1984). On modern passive margins, the hinge-line between shelf and miogeocline deposits roughly coincides with the boundary between rift stage and relatively unthinned crust (Grow, 1981). Along the COCORP transect, the lower Paleozoic hinge-line is in Utah at 112°30'W longitude (Fig. 2) (Armstrong, 1968; Stokes, 1976; Allmendinger and others, 1986); it is likely that significant late Proterozoic-Early Paleozoic extension in the basement occurred only west of that point. The edge of the continent during the passive-margin phase is not directly known; the westernmost miogeoclinal strata and the contour of initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ (Fig. 2) indicate that basement extends as far west as 117°W in central Nevada (Stewart and Poole, 1974; Kistler, 1974; Speed, 1982; Farmer and DePaolo, 1983). The muscovite granite belt of Miller and Bradfish (1980) and the boundary between lead isotopic provinces (Figs. 2 and 3) defined by Zartman (1974) suggest that west of the Nevada-Utah border, a thick sequence of pelitic or quartzofeldspathic

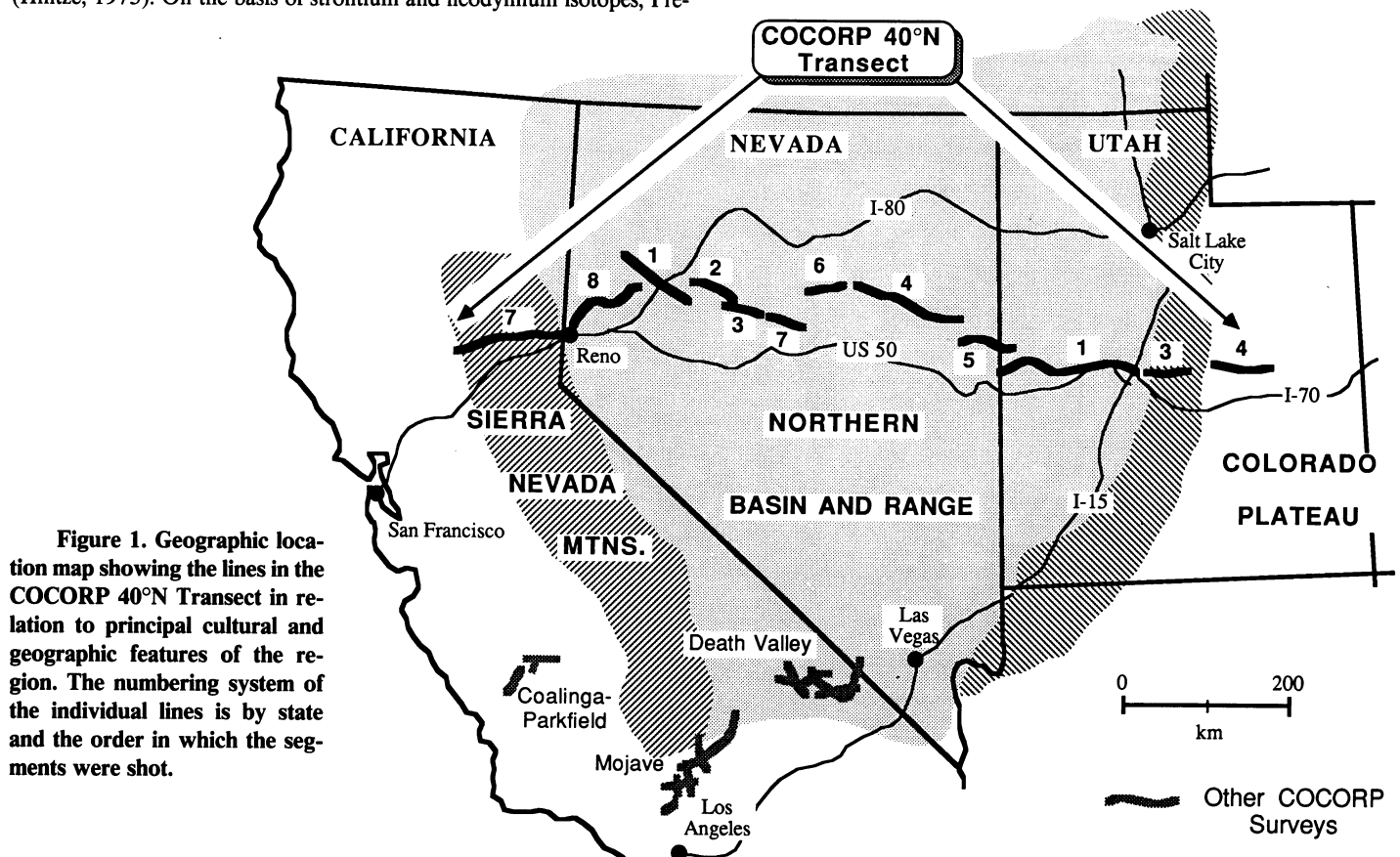


Figure 1. Geographic location map showing the lines in the COCORP 40°N Transect in relation to principal cultural and geographic features of the region. The numbering system of the individual lines is by state and the order in which the segments were shot.

0 200
km

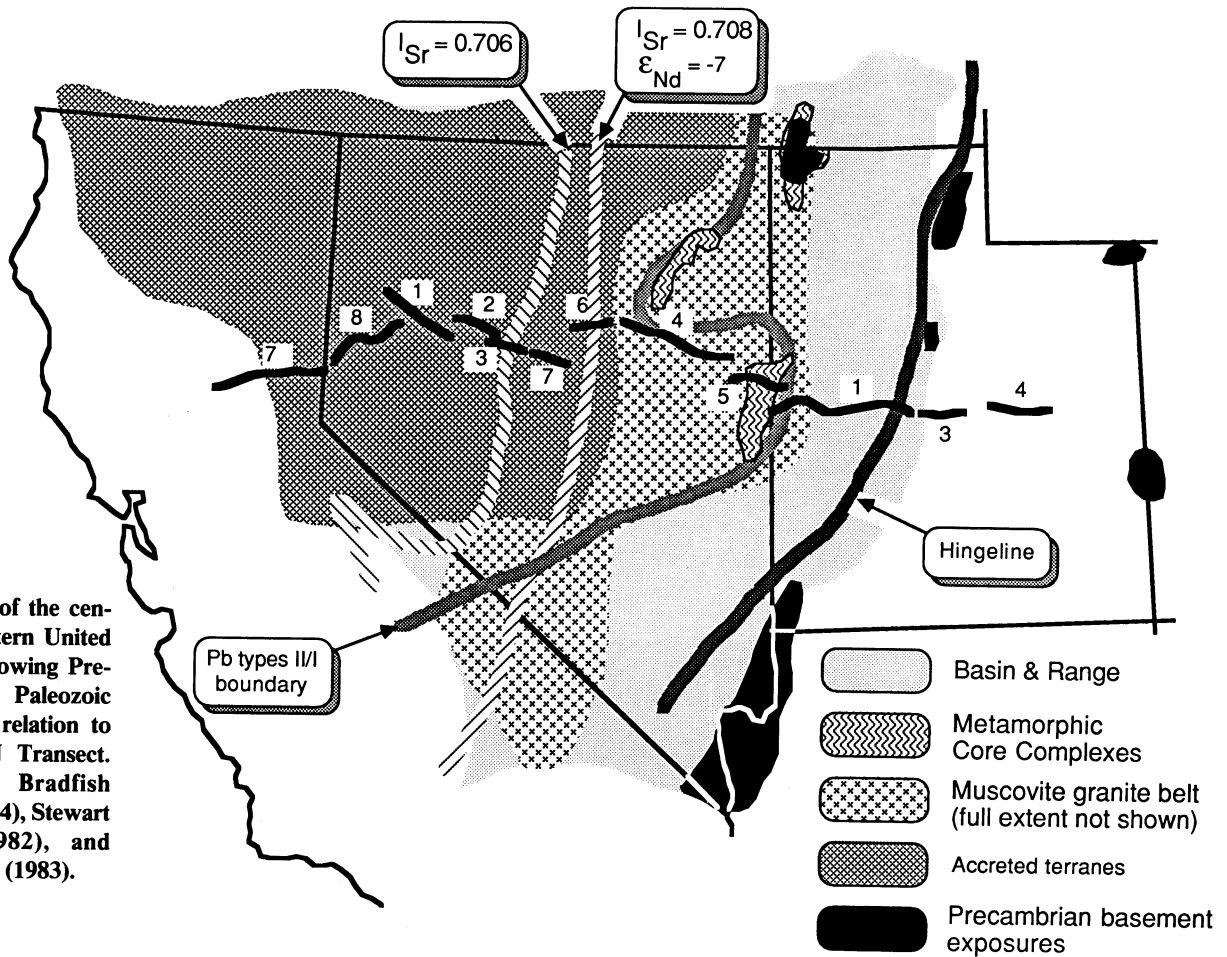


Figure 2. Map of the central part of the western United States Cordillera, showing Precambrian and early Paleozoic tectonic features in relation to the COCORP 40°N Transect. From Miller and Bradfish (1980), Zartman (1974), Stewart (1980), Speed (1982), and Farmer and DePaolo (1983).

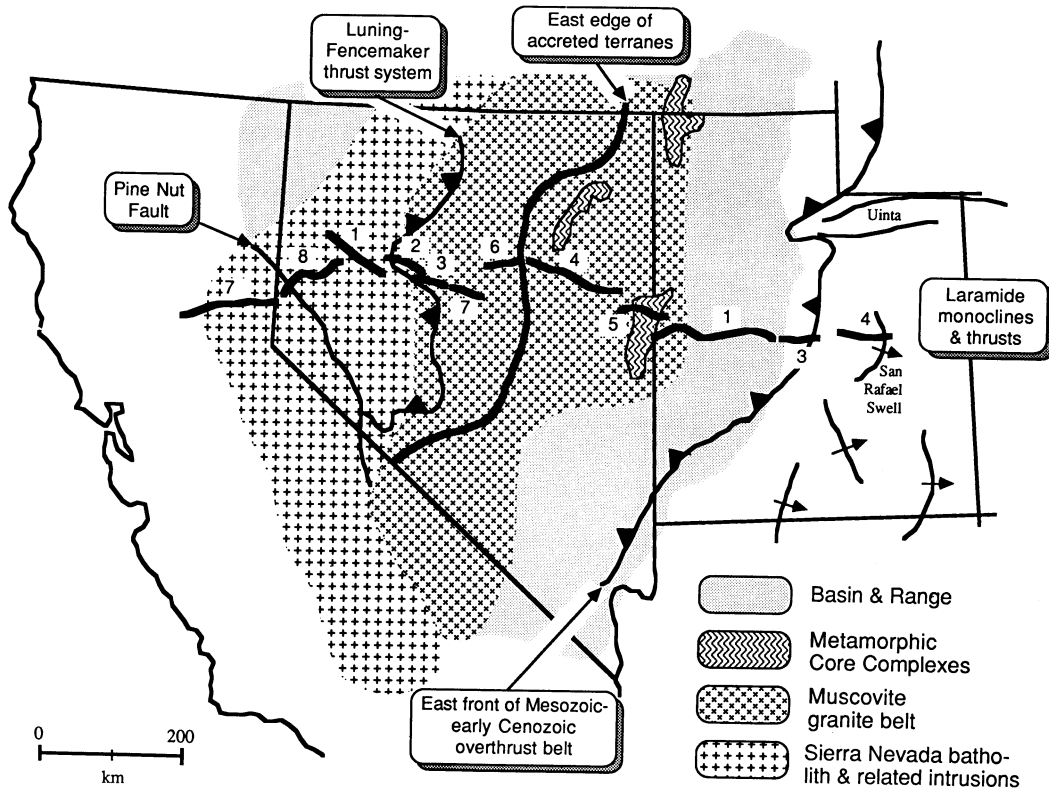


Figure 3. Map of the central part of the western United States Cordillera, showing accreted terranes and Mesozoic tectonic features in relation to the COCORP 40°N Transect. From Stewart (1980), Hintze (1973), Miller and Bradfish (1980), and Armstrong (1968).

strata is probably present and that Precambrian crystalline basement, if present, was markedly thinned and altered by rifting.

Mississippian through Jurassic: Terrane Accretion

In the region of the 40°N Transect, major accretionary events occurred during the Mississippian (the Antler orogeny, Roberts and others, 1958; Speed, 1982), the Permian-Triassic (the Sonoma orogeny, Silberling and Roberts, 1962; Speed, 1979), and the Jurassic (Nevadan orogeny, Schweickert and Cowan, 1975; Schweickert, 1981; Nelson and others, 1985). The easternmost exposure of these terranes along the 40°N Transect is at 116°W between Nevada lines 4 and 6 (Fig. 3). Thrusts associated with the Antler and Sonoma orogenies are known to have a general westward dip, but more controversy surrounds the Nevadan orogeny, which some assume to have a westward vergence (Schweickert and Cowan, 1975) and some an eastward vergence (Moore and Day, 1984), and some do not consider it to be associated with terrane accretion at all (Burchfiel and Davis, 1981).

Cretaceous through Eocene: Andean-Type Margin

After the Nevadan orogeny and subsequent lull in tectonism, the margin of the continent at 40°N assumed a setting similar to that of the modern Andes with eastward subduction beneath the continent (Hamilton, 1969, 1978; Burchfiel and Davis, 1975; Coney, 1978; Dickinson and Snyder, 1978; Jordan and others, 1983). The Sierra Nevada batholith, crossed by COCORP lines 1 and 8 in Nevada (Fig. 3), was emplaced

between ~120 and 80 Ma (Chen and Moore, 1982), and scattered Mesozoic plutons occur as far east as westernmost Utah (Hintze, 1973; Miller and Bradfish, 1980; Stewart, 1980). Shortening of 105–150 km in the thin-skinned Sevier thrust belt in Utah, Idaho, and Wyoming occurred mostly between the mid-Cretaceous and the Eocene (Armstrong and Oriol, 1965; Armstrong, 1968; Roysse and others, 1975; Lawton, 1985). Between the latest Cretaceous and the Eocene, magmatism was mostly absent in the region of the COCORP transect, and the Laramide basement uplifts of the Rocky Mountain foreland were formed, including the San Rafael Swell crossed by Utah line 4 (Fig. 3). COCORP and industry seismic data commonly show that Laramide uplifts are bounded by moderately dipping thrust faults (Smithson and others, 1978; Gries, 1983), but no fault reflection is associated with the San Rafael Swell (Allmendinger and others, 1986).

Oligocene through Recent: Continental Extension

Extensional tectonics has characterized the western United States since at least the mid-Oligocene, during which time, two fundamentally different interactions have occurred along the plate margin to the west (Zoback and others, 1981). The earlier extension, which occurred during eastward subduction and renewed arc volcanism, is characterized by low-angle normal faults and local metamorphism now exposed in the Cenozoic metamorphic core complexes (Fig. 4) (Davis and Coney, 1979; Crittenden and others, 1980; Armstrong, 1982) and may have been the result of gravitational collapse of a tectonically thickened crust (Coney and Harms, 1984). Low-angle normal faults of this time are recognized in much of the

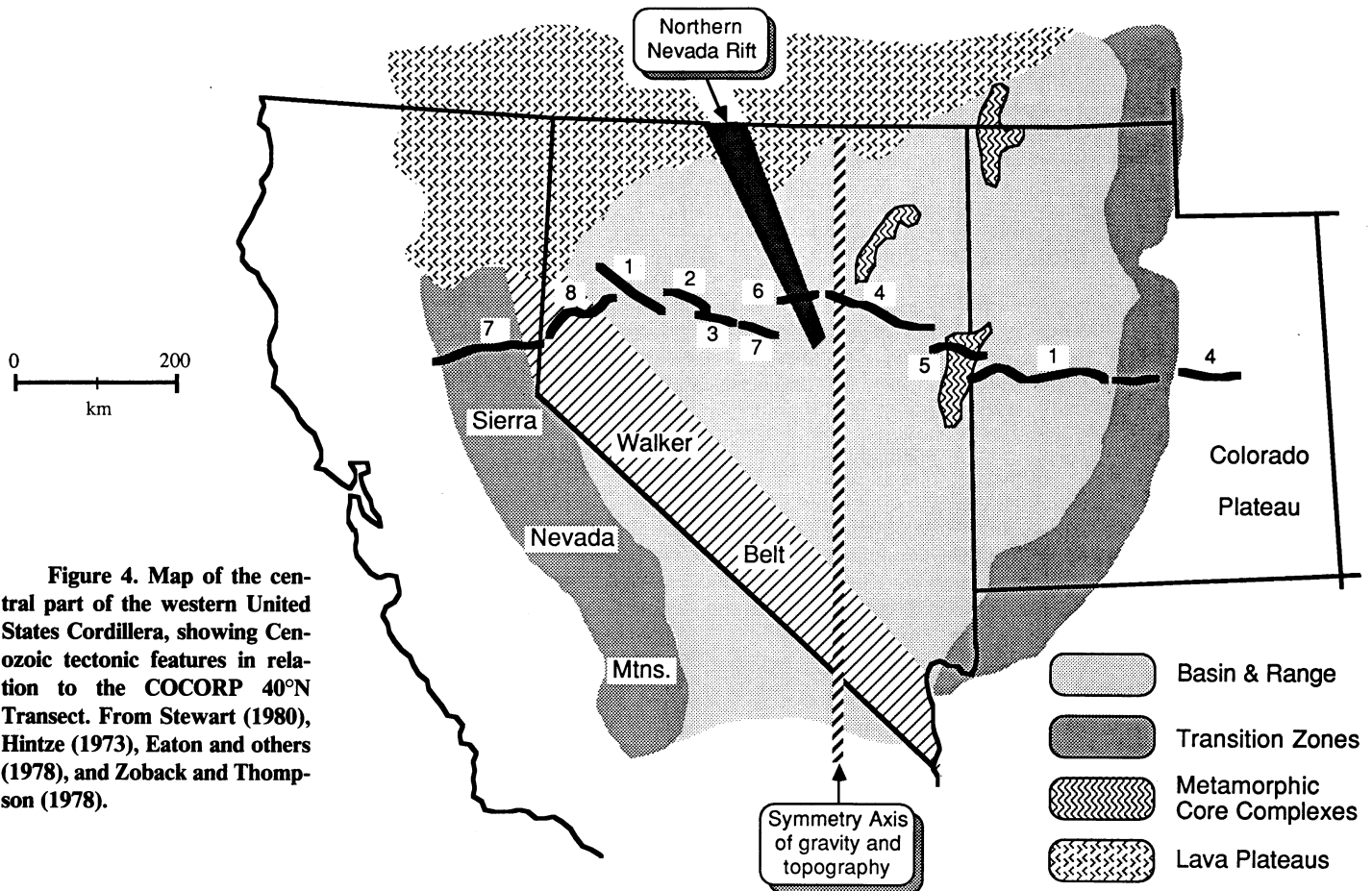


Figure 4. Map of the central part of the western United States Cordillera, showing Cenozoic tectonic features in relation to the COCORP 40°N Transect. From Stewart (1980), Hintze (1973), Eaton and others (1978), and Zoback and Thompson (1978).

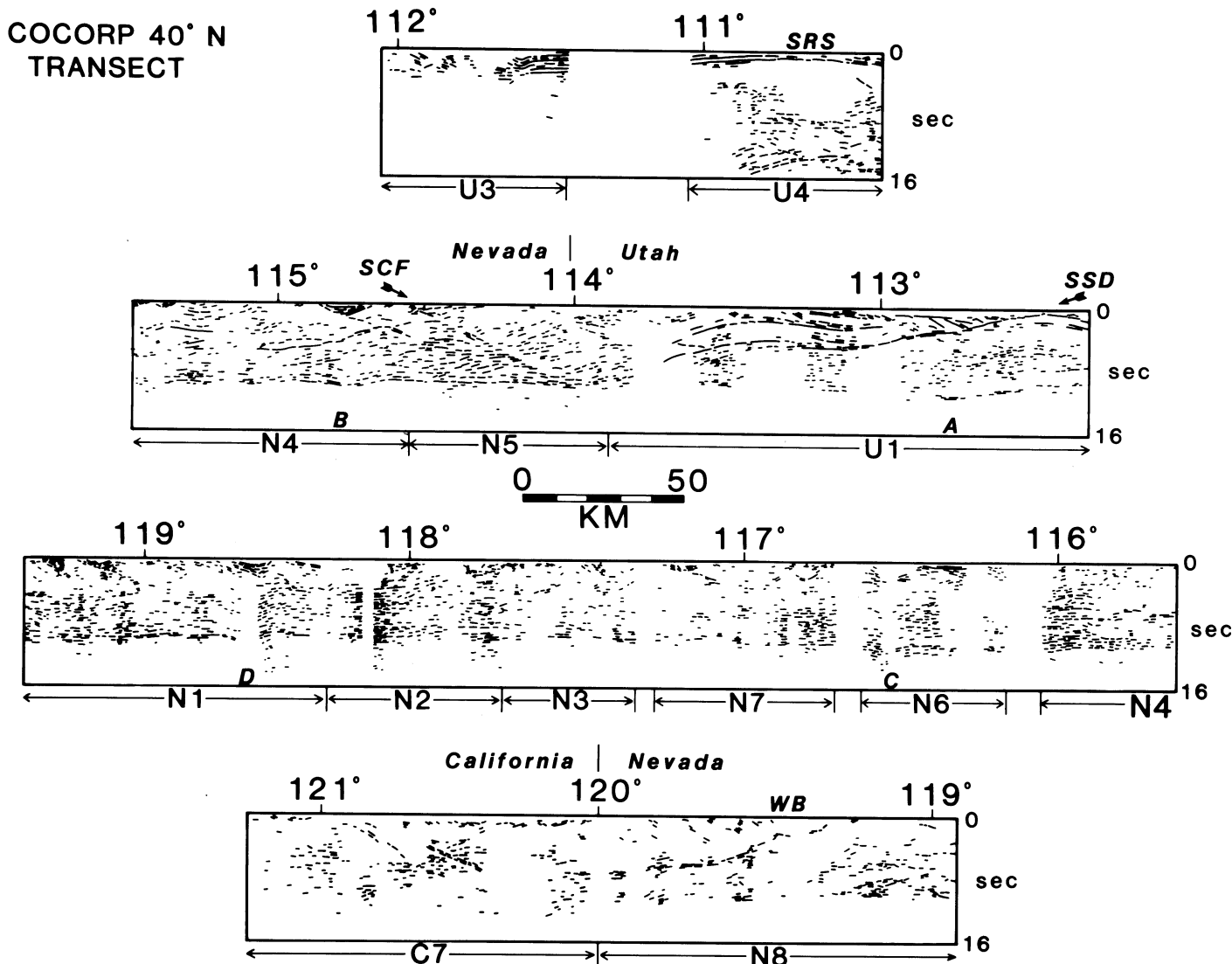


Figure 5. Simplified line drawing of the entire 40°N Transect. Transect is shown in four parts, and vertical boundaries between different line segments have been omitted for legibility. Line drawing constructed from original, unmigrated seismic sections. See data and papers by Hauge and others (1987), Potter and others (1987), Allmendinger and others (1983, in press), Knuepfer and others (in press), and E. C. Hauser and others (unpub. data) for examples of the seismic data and more detailed line drawings.

eastern and southern Basin and Range (Armstrong, 1972) but are seldom described in literature on the central and western parts of the region. A notable exception is Proffett's (1977) elegant analysis of the Yerington district in the Walker Lane of western Nevada. During this earlier phase, extension was oriented east-northeast as indicated by the trend of the northern Nevada Rift (Fig. 4) and other features (Zoback and Thompson, 1978; Zoback and others, 1981).

The typical Basin and Range morphology, characterized by evenly spaced mountain blocks bounded by normal faults having moderate to steep near-surface dips was produced during later, east-southeast extension that began ~10 Ma (Zoback and others, 1981). Stewart (1980) has identified large, regional tilt domains in which mountain blocks and asymmetric half-grabens have a consistent sense of dip. Studies of gravity, topography, and earthquake and refraction seismology show that the present-day Basin and Range has a marked symmetry with thicker crust and higher average elevation in the center of the province (Fig. 4). These data have also been used to infer a regional brittle-ductile transition at 8–15 km depth (Eaton and others, 1978; Smith, 1978; Smith and Bruhn, 1984).

KEY RESULTS OF THE COCORP 40°N TRANSECT

In this section, we present an outline and brief discussion of the major findings of the COCORP 40°N Transect, with references to the individual papers in which the reader may find more detailed analysis. The major points, discussed below, are (1) the spatial variation in reflection "fabric" across the transect, (2) the ages of those fabrics, (3) the nature of the reflection Moho, and (4) the implications for models of extensional tectonics.

Seismic Fabric of the Cordillera at 40°N Latitude

The sheer volume of data in the 40°N Transect ($\sim 7.5 \times 10^9$ individual data samples) requires a very general approach to province-wide synthesis. The seismic-reflection data display regionally coherent patterns or "fabrics" that can be related to the major tectonic features of the Cordillera. Seismic fabric is geometrically similar to its structural or metamorphic counterparts in that all refer to pervasive features of similar

TABLE 1. PROCESSING SEQUENCES, COCORP 40°N TRANSECT

	Utah				Nevada								California
	Line 1	Line 3 43-366	Line 3 378-639	Line 4	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 7
Demultiplex	1	1	1	1	1	1	1	1	1	1	1	1	1
Vibroseis correlation	2	2	2	2	2	2	2	2	2	2	2	2	2
Trace editing		3*			5	5	5		5	3	3		3
F-K filter	3 ^{§§§§}												
CDP gather	5	6	5	4	7	7	7	5	7	5	5	7	4
Datum	1900 m	2450 m	2450 m	1896 m	1180 m	1065 m	1065 m	1800 m	1900 m	1690 m	1650 m	1169-1183 m ^{§§§}	800-2000 m ^{§§§}
Datum velocity	4500 m/s	3500 m/s	3500 m/s	4000 m/s	1500-3600 m/s ^{****}	1670-4410 m/s ^{****}	1700-5000 m/s ^{****}	1904-4639 m/s ^{****}	1421-4357 m/s ^{****}	1200-2750 m/s ^{****}	1556-3600 m/s ^{****}	1400-3950 m/s ^{****}	3000 m/s
Datum statics	4	5	4	5	6	6	6	4	6	6	6	6	5
Velocity analysis [†]	7	7	6	6	9	9	9	6	8	7	7	9	6
Normal moveout	8	8	8	8	10	10	10	7	9	8	8	10	7
Mute	9	9	9	10	11	11	11	8	10	9	9	11	8
Trace equalization	6	10	10	9	8	8	8	9	3	10	10	8	9
Automatic residual statics			7	7									
Stack, 4800%	10		11	11	12	12	12	10	11	11	11	12	11
Filter		12 [§]	12 [§]	12 ^{**}	4 ^{***}	4 ^{†††}	4 ^{†††}					5 ^{††††}	10
Predictive deconvolution		4	3	3	3	3	3	3	4	4	4	4	
Automatic gain control	11 ^{††}	§§	§§	§§	§§	§§	§§	§§	§§	§§	§§	3 ^{††}	

*Extreme highway-cultural noise.
[†]Velocity spectra and constant velocity stacks; picked every 10 to 50 CDP's.
[§]0 to 4 s—12-32 Hz; 6 to 14 s—8-32 Hz interpolated in between.
^{**}0 to 5 s—12-32 Hz; 7 s—8-32 Hz; 12 s—8-28 Hz; 14 s—8-22 Hz.
^{††}1 s AGC window.
^{§§}Trace equalization used 1 s window; AGC not applied.

^{***}0 to 16 s—10-28 Hz bandpass.
^{†††}0 to 16 s—8-32 Hz bandpass.
^{§§§}Line gathered in 3 segments with slightly different datum elevations.
^{****}Varying velocity corrections used along line.
^{††††}0 to 16 s—10-30 Hz bandpass.
^{§§§§}Applied only to VP₁ 1-150; F-K filter tests were run on all lines in the 40°N Transect.

orientations. Seismic fabrics, however, should not be confused with structural or metamorphic fabrics. Patterns of reflections comprise seismic fabrics, and individual reflections can be produced by any of a number of geological features. Furthermore, although every effort has been made to remove artifacts through survey design and processing sequences (Table 1), some constituents of the fabrics described here probably do not correspond to real features in the Earth or are not located directly beneath the survey. The seismic fabrics described below can be discerned on the line drawing of the entire transect (Fig. 5). The original patterns, however, were defined using full-scale seismic-reflection profiles that if laid end to end, would be ~18 m (~60 ft) long.

Three zones of distinct reflection character and orientation can be defined on the 40°N Transect (Figs. 2, 3). These zones are (1) regions in which reflections or diffractions dip in both directions and laterally persistent layering is absent, such as the crust of the Colorado Plateau and the Sierra Nevada; (2) areas of predominantly west-dipping reflections, most notably in the eastern Basin and Range Province; and (3) the subhorizontal layering of the middle and lower crust in the central and western Basin and Range. A fourth zone, the high-amplitude reflections at or near the base of the crust, referred to herein as the "reflection Moho," is discussed separately.

The seismic fabric of Utah line 4 characterizes the first zone (Allmendinger and others, 1986). The reflections there could be produced by dipping intrusive and/or lithologic contacts; Precambrian, late Paleozoic, or Laramide structures; steep metamorphic gradients; zones of hydration; or artifacts such as spatial aliasing or sideswipe. Similar seismic fabrics can be seen on COCORP profiles from the midcontinent (Kansas line 1: Brown and others, 1983; Minnesota: Gibbs and others, 1984) and from the Laramide Province (Wyoming lines 1-6: Smithson and others, 1978; Allmendinger and others, 1982). Although the basement is not directly observable at the surface, it is likely that many of those reflections and diffractions seen on line 4 were produced by Proterozoic features, given the slight deformation of the Colorado Plateau during the entire Phanero-

zoic. Seismic fabric of this nature appears to be fairly typical of old cold cratons.

Within the Basin and Range, the COCORP 40° Transect shows a number of regional variations that one would not predict from the uniform and symmetric morphology of the province. For example, the region of thinnest crust and lowest topography on the east side of the province in western Utah is characterized by the predominantly west-dipping fabric. The corresponding region of thin crust and low topography on the west in the region of the Carson Sink has a well-developed subhorizontal fabric (Figs. 5 and 6). The gravity and topography symmetry axis (Fig. 4) (Eaton and others, 1978) coincides in general with the region of transition from west-dipping to subhorizontal fabric. In short, the seismic fabric domains (Fig. 6) are notably asymmetric and are more suggestive of the pre-10-Ma orogens of the western United States (Allmendinger and others, in press).

Ages of Reflection Fabrics

There is no inherent property of seismic-reflection data that can indicate the age of the reflectors. Despite this limitation, some generalizations about age can be made by considering the spatial distribution of reflections in light of the regional tectonics, described above, as well as by comparing general patterns of reflections with individual reflections that have been drilled or that project to the surface to features of known age. This approach suggests that certain zones of reflections correspond to long-lived features in the crust whereas others can be related only to relatively recent features.

Subhorizontal Fabric. Previous tectonic syntheses suggest that the most fundamental pre-late Mesozoic features of the crust of the western United States are the edge of the Precambrian crust and the boundaries of the accreted terranes (Kistler, 1974; Speed, 1982). On the basis of reflection profiles across passive margins and terrane boundaries (for example, Hutchinson and others, 1986; Nelson and others, 1985), one might assume that the Precambrian and Paleozoic equivalents in the western United

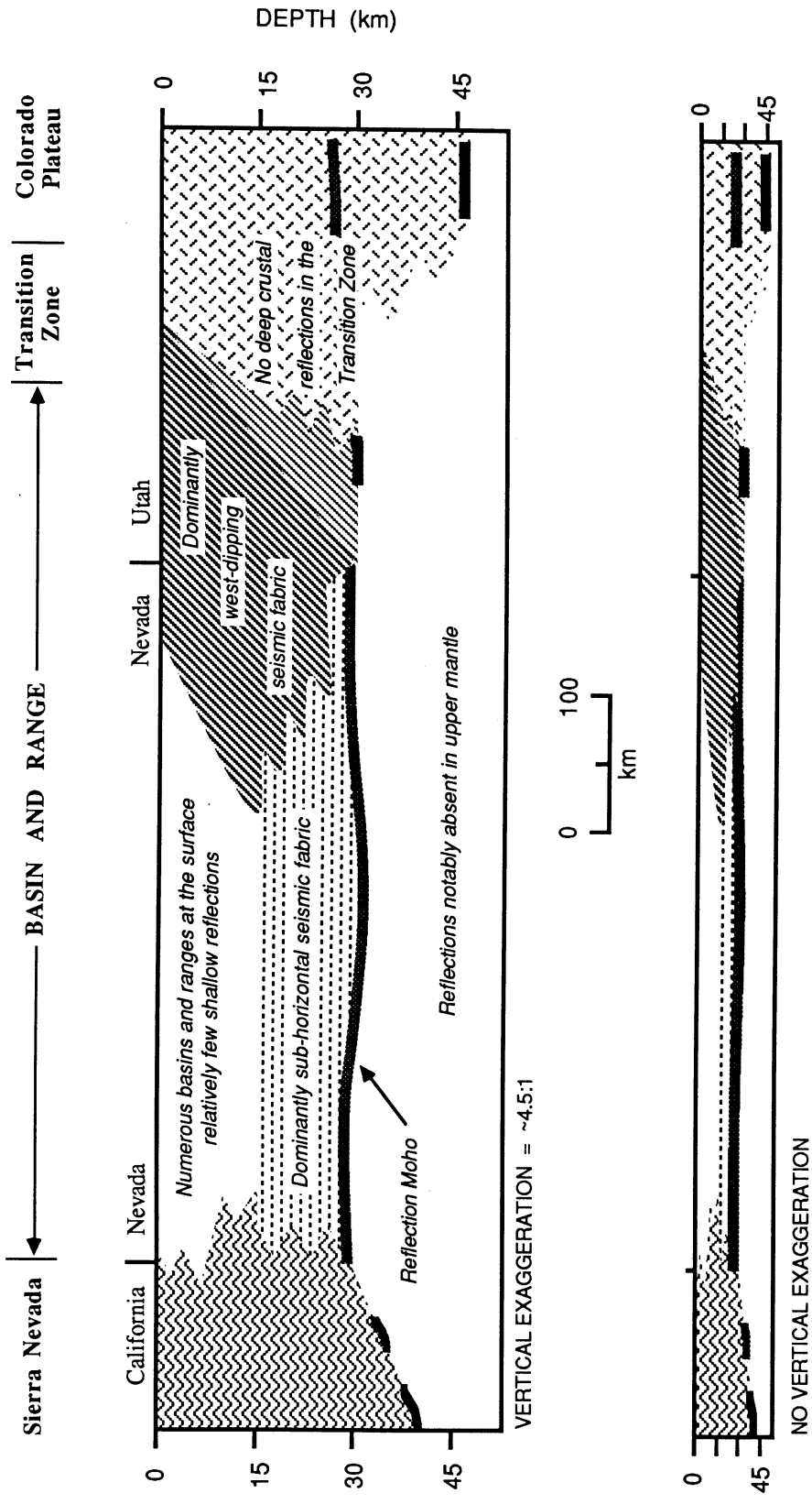


Figure 6. Schematic representation (simplified) of the seismic fabrics seen on the COCORP 40°N Transect. Cross-section is oriented along the transect and is in depth, not time, units. Note that this is not a geologic cross-section but only a mapping of patterns identified in the seismic-reflection data.

States are, or were at one time, reflective as well. At the inferred western edge of Precambrian crystalline basement ($\sim 117^\circ\text{W}$), however, there is no significant structure observed on the 40°N Transect nor is there any regional change in seismic character (Hauge and others, 1987; Potter and others, 1987). Instead, the subhorizontal seismic fabric and pronounced reflection Moho extend across all of central and western Nevada. Two explanations are possible. First, the western edge of Precambrian basement may actually be farther east, perhaps nearer to Zartman's (1974) lead isotope boundary, Farmer and DePaolo's $\epsilon_{\text{Nd}} = -7$ line (Fig. 2), and the gradual change from west-dipping to subhorizontal reflection fabrics (Fig. 6). Alternatively, younger tectonism may have wiped out any seismic signature of the old Paleozoic and Precambrian continental edge.

Also, there appears to be little if any expression of the accreted terranes on the COCORP data as middle and lower crustal subhorizontal layered fabric occurs both east of and within the region of accretion (Figs. 5 and 6) (Hauge and others, 1987). No major crustal-scale faults separating the terranes from the rocks autochthonous to North America appear on the seismic data, although the Roberts Mountains thrust and the Golconda thrust may have been imaged in the shallow section (Hauge and others, 1987; Potter and others, 1987). We thus conclude that the subhorizontal reflection fabric observed in the middle and lower crust of central and western Nevada (Nevada lines 1–3, 6 and 7) was produced by features younger than Jurassic in age.

The subhorizontally layered middle and lower crust of Nevada does correlate spatially with the region where Mesozoic plutons are present at the surface and the region where Mesozoic metamorphism is inferred to have been present over large regions (for example, Snoko and Lush, 1984). Some of the most prominent subhorizontal layering also correlates closely with magmatic features of Cenozoic origin, such as that on Nevada line 6 (Potter and others, 1987) in the vicinity of the mid-Miocene northern Nevada Rift (Zoback and Thompson, 1978). Some of the subhorizontal fabric both along the 40°N Transect (Nevada lines 5, 6 and 7; E. C. Hauser and others, unpub. data; Potter and others, 1987) and elsewhere within the extended regions of the western United States (Rio Grande Rift: Brown and others, 1979; Death Valley: de Voogd and others, 1986) is closely associated with amplitude anomalies, which in the latter areas, have been interpreted as evidence of late Cenozoic mid-crustal magma bodies. We thus conclude that magmatism, metamorphism, and perhaps attendant ductile deformation play key roles in the development of middle and lower crustal horizontal or subhorizontal reflections.

West-Dipping Fabric. The west-dipping fabric correlates spatially with tectonic features of several different ages. The hingeline of the Cordilleran miogeocline, broadly located beneath the Sevier Desert, generally coincides with the eastern edge of the region of pervasively west-dipping seismic fabric that can be seen as far west as east-central Nevada (Allmendinger and others, 1986, in press; E. C. Hauser and others, unpub. data). Although individual rift structures of latest Precambrian age have not been identified on the seismic lines, it is possible that at least some of this west-dipping fabric may be related to the latest Precambrian rifting.

In general, the region of west-dipping seismic fabric in western Utah and eastern Nevada also coincides with the Sevier thrust belt, and in particular, where that thrust belt cuts into basement. A package of westward-steepening splays on Utah line 1 is best interpreted as a Mesozoic thrust duplex in the basement, and other reflections farther east are probably also due to thrusting (Allmendinger and others, 1983, 1986). The west-dipping fabric in eastern Nevada could represent the middle crustal roots of the Sevier thrust belt (E. C. Hauser and others, unpub. data).

Finally, the metamorphic core complexes and well-imaged low-angle normal faults appear only in data from the eastern part of the Basin and

Range, in the region of west-dipping fabric (the Sevier Desert detachment, House Range detachment, northern Snake Range décollement: Allmendinger and others, 1983; the Schell Creek fault: E. C. Hauser and others, unpub. data). Similar-dipping crustal-scale reflections are not present in the data from the central and western Basin and Range. This does not mean that low-angle normal faults do not exist in those regions but only that features having the dimensions of the entire crust were not imaged. An exception is in the northern Walker Lane where Knuepfer and others (in press) described a possible low-angle normal fault that may extend beneath the Sierra Nevada.

Nature of the Reflection Moho

The high-amplitude reflections at the base of the reflective lithosphere are herein referred to as the "reflection Moho" (Klemperer and others, 1986). Although reflection fabrics within the crust show considerable variation, crustal thickness as inferred from the two-way times to the reflection Moho agree in general form with previous refraction estimates of crustal thickness (Klemperer and others, 1986). The Basin and Range crust is 15–20 km thinner than is the Colorado Plateau crust and is 10–15 km thinner than is the Sierra Nevada crust. In addition, the 40°N Transect indicates that the crust in the center of the Basin and Range is thicker than at its margins (Nevada line 6, Potter and others, 1987). Detailed comparison of the reflection and refraction data sets across the 40°N Transect shows that the reflection Moho over most of the survey area lies within the range of published estimates of depth to refraction Moho (Klemperer and others, 1986). In western Nevada (lines 1 and 2) and, to a lesser extent, in western Utah, however, the reflection Moho is apparently as much as 6 to 8 km deeper than is the Moho in some popular refraction models (for example, Smith, 1978); the discrepancy is less in other refraction models using the same data sets (Prodehl, 1979). Whether these differences are real or apparent awaits the results of future refraction experiments. An additional intriguing feature of the reflection Moho beneath Nevada and westernmost Utah, although not apparently beneath most of Utah (including the Sevier Desert), is that typically, it is paralleled by a second reflection group variably as much as 5 km shallower in the crust (Klemperer and others, 1986). These parallel reflections at or near the base of the crust define a zone that is conceivably analogous to rift pillows recognized by refraction experiments across major grabens and rift zones worldwide.

The lateral variability of the reflection Moho and the extent to which it correlates with the present morphological Basin and Range have a bearing both on models of continental extensional deformation and on the origin of the Moho itself. Some of the lateral variability can be attributed to noise variations during the collection of the data, but there are also changes in the character of the deep-crustal reflections between Nevada and Utah (Klemperer and others, 1986). If the variations are real, then the following spatial correlations can be made. (1) The reflection Moho and subhorizontal layering are most poorly developed where the low-angle normal faults are best developed. Nowhere in the survey, however, can normal fault offset of the reflection Moho be documented (E. C. Hauser and others, unpub. data). (2) The Moho is deepest and the subhorizontal layering is very prominent in the vicinity of Northern Nevada rift, which is demonstrably related to Cenozoic extension (Zoback and Thompson, 1978; Potter and others, 1987). (3) The subhorizontal seismic fabric is well developed everywhere west of and locally beneath the core complexes.

The smooth continuity of the reflection Moho beneath much of the Basin and Range, where 10 km of vertical displacements in the upper crust during the late Cenozoic are not uncommon, suggests that the reflection Moho may well occur at a structural discontinuity of probable Cenozoic age, although it may owe its variable character to older features. The origin

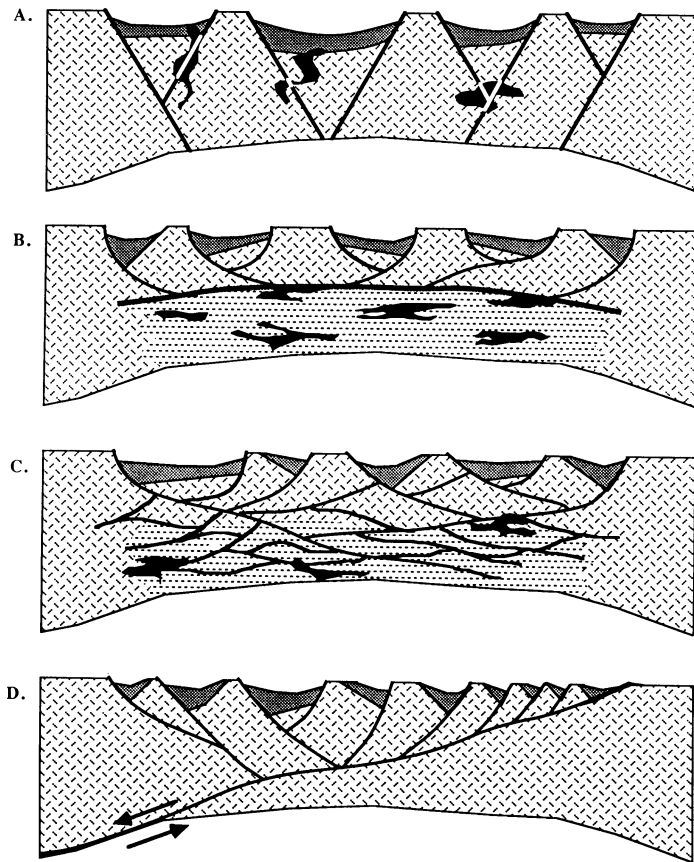


Figure 7. Simplified models of intracontinental extension. (A) Classic horst and graben model, (B) subhorizontal-decoupling-zone model, (C) anastomosing shear-zone or lenses model, and (D) crustal-penetrating shear-zone model.

of the reflections from the base of the crust, however, remains enigmatic, and it is likely that several different features and processes acting in combination are responsible for the reflection character. For example, if the Moho is a compositional boundary, rheological models suggest that there would be a pronounced ductility contrast across it (Smith and Bruhn, 1984), and thus, structural features would also be guided by it.

Models of Extensional Tectonics

The COCORP 40°N Transect provides a province-wide, uniform data base for testing the various models of intracontinental extension that have been proposed in recent years. There are four basic models (Fig. 7): (1) the classic symmetric horst and graben, (2) the subhorizontal decoupling zone (Smith, 1978; Eaton, 1979; Miller and others, 1983; Smith and Bruhn, 1984), (3) the anastomosing shear zones or "lenses" (Hamilton, 1982; Kligfield and others, 1984), and (4) crustal-penetrating shear zone (Wernicke, 1981). No one model of extension is completely supported by the seismic data from the 40°N Transect, but only the model of symmetric horsts and grabens can be largely ruled out. Nearly all of the grabens profiled are asymmetric, having a major bounding fault of low to moderate dip on only one side, an observation also shown by most industry profiles in the region (Hastings, 1979; Vreeland and Berrong, 1979; Effimoff and Pinezich, 1981; Anderson and others, 1983; Robison, 1983; Gans and others, 1985).

The prevalence of low-angle normal faults and the lack of a laterally continuous mid-crustal boundary in the eastern Basin and Range of western Utah and easternmost Nevada indicates that the subhorizontal decoupling model is not directly applicable there. This does not mean, however, that the brittle-ductile transition is extraordinarily deep there but only that individual shear zones cross that transition, which is probably considerably more complex than indicated by simple rheological models. The lack of a simple horizontal mid-crustal boundary could be due to the presence of thicker Precambrian crystalline basement there or to pre-existing control by Mesozoic thrust faults. In the central and western Basin and Range, however, the seismic data suggest a simpler crustal structure with a relatively nonreflective upper crust and much more reflective, laminated lower crust (Figs. 2 and 3). The subhorizontal decoupling model could apply to much of that region (Hauge and others, 1987). The anastomosing shear zones model (Hamilton, 1982) is closely related to the above model on a crustal scale but in detail, it avoids many of the observational problems associated with a simple, abrupt, horizontal brittle-ductile transition. Much of the data from the 40°N Transect are consistent with the lenses model but do not prove it.

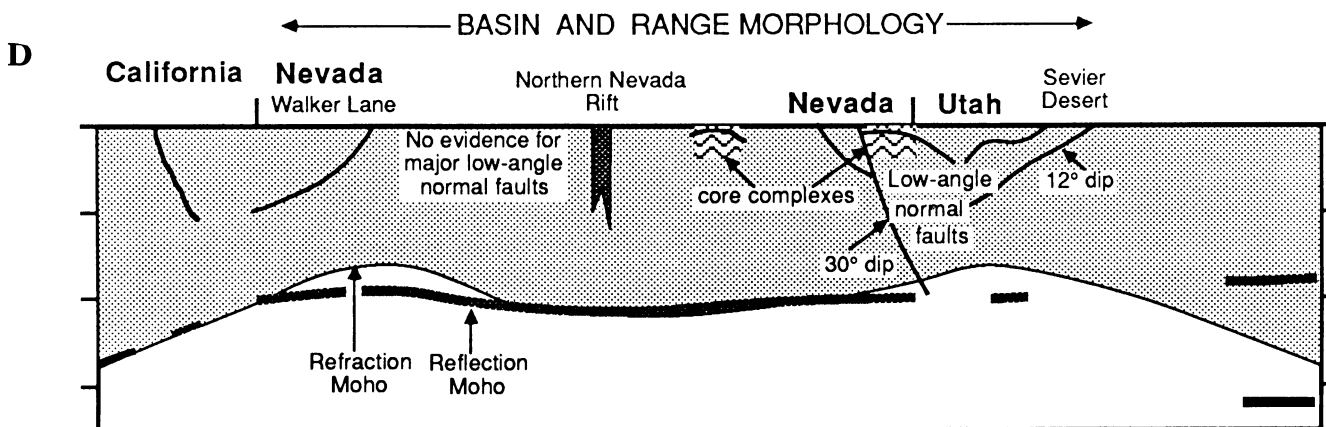
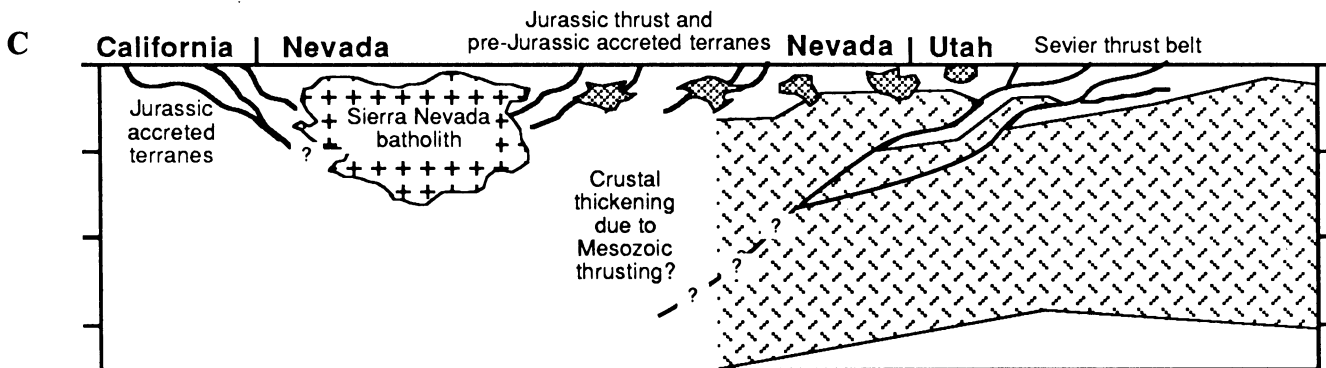
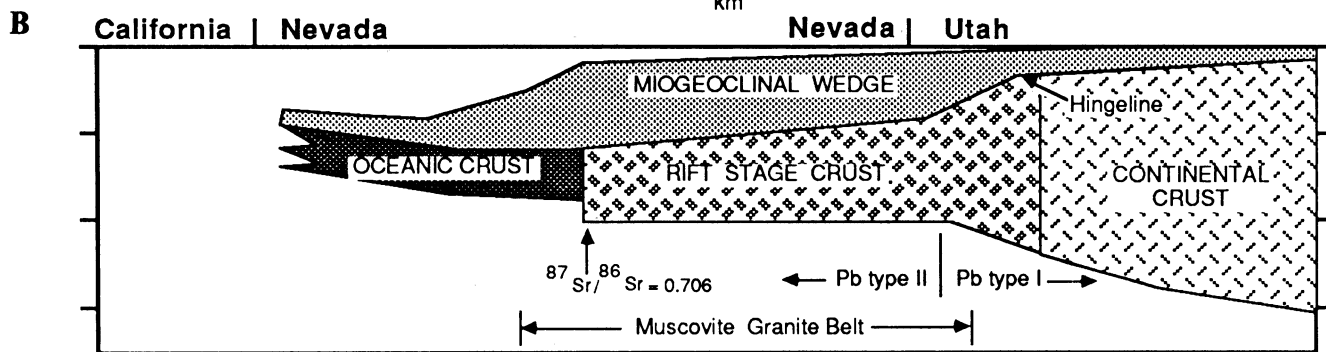
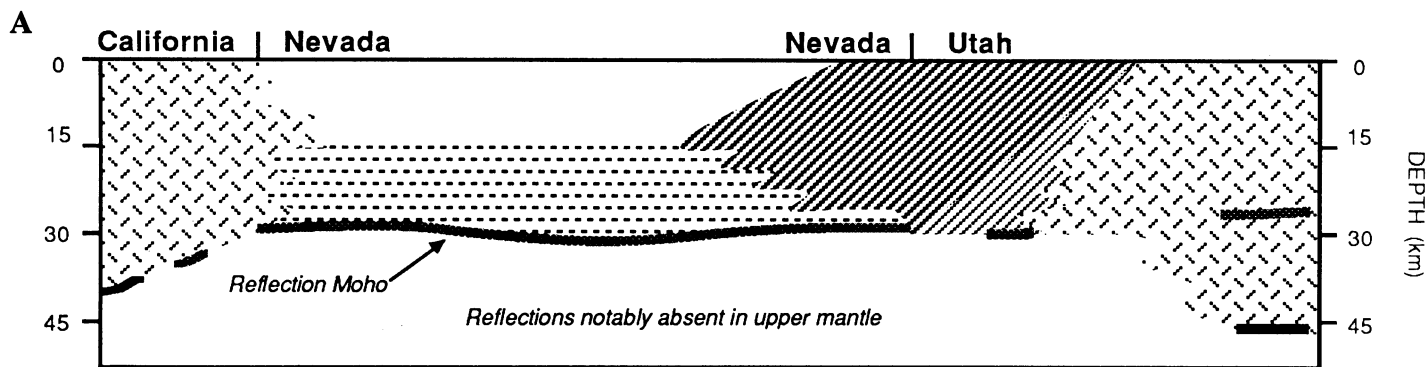
The above crustal-scale, pure shear models contrast sharply with the simple shear model of Wernicke (1981). The low-angle normal faults of the eastern Basin and Range closely resemble Wernicke's model for the upper and middle crust and, in one case (E. C. Hauser and others, unpub. data), for the lower crust as well. Along the transect, however, there are large parts of the Basin and Range where no major low-angle detachment faults are imaged on the COCORP seismic data (Hauge and others, 1987; Potter and others, 1987). More importantly, the reflection Moho, although varying regionally in depth by a small amount and also laterally in character, is nowhere observed to be abruptly truncated and displaced, unlike in some extensional provinces where the Moho may be offset by normal faults (for example, the Outer Isles thrust, Peddy, 1984; Wernicke, 1986). Nowhere, however, does the 40°N Transect provide evidence or support for Wernicke's model on the scale of the entire continental crust or lithosphere. The Moho may possibly be cut and displaced on a short time scale by normal faults but is healed relatively quickly by magmatic processes and ductile flow (E. C. Hauser and others, unpub. data).

SUMMARY

The seismic fabrics of the 40°N Transect are compared to tectonic features of various ages in the cross-sections in Figure 8. The cross-sections

Figure 8. Simplified and idealized cross-sections of tectonic features of different ages along the COCORP 40°N Transect, showing the comparison to the seismic fabrics in the top section. (A) Patterns of seismic fabrics, as in Figure 3. (B) Inferred generalized geometry of the continental margin prior to the initial terrane-accretion event in the Late Devonian. Section is based on the geometries observed on the modern East Coast passive margin (Grow, 1981). (C) Early Tertiary (post-thrusting, pre-extension). The individual structures and the shapes of plutons are largely schematic and are meant to show only general structural style and location. (D) Present configuration of the continental crust. Structures shown in D are known faults derived from surface geology and the seismic-reflection data. Note that because magnitudes of shortening and extension across the entire province are poorly known, none of the sections is plotted on a palinspastic base. Each section has $\sim 4.5\times$ vertical exaggeration; thus, the faults are shown with considerably steeper dip than is actually observed. See text for references and discussion.

Sierra Nevada ← BASIN AND RANGE → Transition Zone | Colorado Plateau



are constructed based on known features in combination with crustal geometries from modern analogs such as the modern passive margin of eastern North America (Grow, 1981). All of the sections shown are plotted on a present-day geographic base, so that the tectonic features are variably distorted from their original geometry. Unfortunately, lack of knowledge of magnitudes of shortening and extension both regionally and locally precludes the use of palinspastically restored base, making spatial correlations more tentative. In addition, spatial correlations do not prove causal relations between features but only provide circumstantial evidence that a relation is possible.

As a number of authors have pointed out (Burchfiel and Davis, 1975; Stokes, 1976; Armstrong, 1968), much Cenozoic and Mesozoic deformation has been localized along the Precambrian-lower Paleozoic hingeline. The COCORP 40°N Transect shows that the crust of that region still bears the imprint, or at least the influence, of that important feature. The west-dipping fabric of the eastern Basin and Range occurs west of the hingeline, in the region of west-dipping Sevier thrusts and west- and east-dipping Cenozoic low-angle normal faults. We suggest that much of the west-dipping fabric is predominantly a structural fabric.

In contrast, the predominantly subhorizontal fabric appears to ignore many of the important structural and tectonic boundaries of pre-Mesozoic age, including the easternmost accreted terranes and the inferred western edge of "rift stage" continental crust. This fabric does correlate with regions of Cenozoic and Mesozoic magmatism, and of inferred metamorphism, and with the deep-crustal, westward projection of major structures in the eastern part of the province (for example, the Sevier Desert detachment, the Sevier thrust belt). The metamorphic core complexes occur in the region of overlap between subhorizontal and west-dipping fabrics, just outboard of the Paleozoic-Precambrian transition from rift stage to little-deformed continental crust. We suggest, thus, that the subhorizontal fabric is related to ductile deformation and magmatism produced in the deep crust during major horizontal displacements of crustal masses. Mesozoic tectonics certainly must have prepared the crust for subsequent extension, but it seems most likely that most of the subhorizontal fabric and the high-amplitude Moho are primarily thermal and structural products of Cenozoic extension. This conclusion is borne out by deep seismic profiles in many other parts of the world where the final tectonic event was accompanied by significant thermal activity; a well-developed subhorizontal fabric in the lower crust and a high-amplitude, layered Moho is commonly observed (Brewer and Smythe, 1984; Brown and others, 1979; Matthews and Cheadle, 1986; Meissner and Wever, 1986).

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