

PHANEROZOIC TECTONICS OF THE BASIN AND RANGE - COLORADO PLATEAU TRANSITION FROM COCORP DATA
AND GEOLOGIC DATA: A REVIEW

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Abstract. The COCORP 40°N transect in Utah and easternmost Nevada crosses the eastern Basin and Range Province and the northwest Colorado Plateau. This part of the Cordillera of western North America has been the site of late Precambrian rifting, Mesozoic and early Cenozoic thrust faulting, and middle and late Cenozoic extension. The COCORP data, in combination with drilling and surface geologic data, suggest that a major change in seismic character and crustal structure occurs at the location of the autochthonous hingeline, which was formed during the Precambrian rifting and subsequent passive margin stage. East of the hingeline, there is little evidence that neither thrust faults nor low-angle normal faults cut deeply into the continental basement. West of the hingeline, a prominent, west-dipping seismic fabric may correspond to Cenozoic and perhaps Mesozoic low-angle structures that cut down to middle and lower crustal levels. The deepest reflections in the Basin and Range (28-30 km) correspond in depth to a prominent mid-crustal horizon (~27 km) in the Colorado Plateau; their relation is uncertain. The Colorado Plateau crust appears to be more than 15 km thicker than the Basin and Range crust. Also, the Colorado Plateau data is dominated by diffractions, where as the Basin and Range has a more persistent west-dipping or layered fabric. These contrasting seismic characters may be typical of cratonic versus orogenic crust, respectively.

Introduction

The eastern half of the COCORP 40°N transect of the western U.S. Cordillera is located on rocks autochthonous to the North American continent and

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spans the eastern Basin and Range in eastern Nevada and western Utah to the northwestern Colorado Plateau (Fig. 1). These Cenozoic morphotectonic provinces are only the youngest manifestations of a series of tectonic events that have modified the western margin of the continent. The region has also been the site of: 1) latest Precambrian rifting to form the Cordilleran miogeocline, 2) the Late Jurassic(?) through Early Tertiary Sevier foreland thrust belt, 3) the Early Tertiary Laramide basement uplifts, and 4) Middle and Late Cenozoic extensional tectonics. The COCORP data and available surface and subsurface data summarized here suggest that the structures and sedimentary basin geometries related to these events are closely interwoven to form the current fabric of the continental crust. Although it is difficult to prove that any particular fault has been reactivated, older structures and basins have clearly influenced the general position and geometry of younger features. The features of the COCORP seismic lines reviewed here are described in detail in Allmendinger et al., [1983], Von Tish et al., [1985], and Sharp [1984]. Industry seismic data bearing on these same topics have also been published by Royse et al., [1975], McDonald [1976], and Smith and Bruhn [1984].

Geology of the Cordilleran Hingezone

The Cordilleran hingeline region (referred to here as the "Hinge Zone" and commonly called the "Wasatch Line" in Utah) is a diffuse boundary that has, for the last 600 Ma, separated the multiply deformed edge of the North American craton from the more stable, less deformed interior of the continent. The hingeline (Fig. 1) is defined as the axis west of which late Precambrian and Paleozoic miogeoclinal strata thicken markedly [Kay, 1951; Stokes, 1976]. This axis was first formed during latest Precambrian rifting of the western margin of North America and the development of a passive continental margin during the early Paleozoic [Stewart, 1972]. The age of the initial rifting event has long been uncertain because the

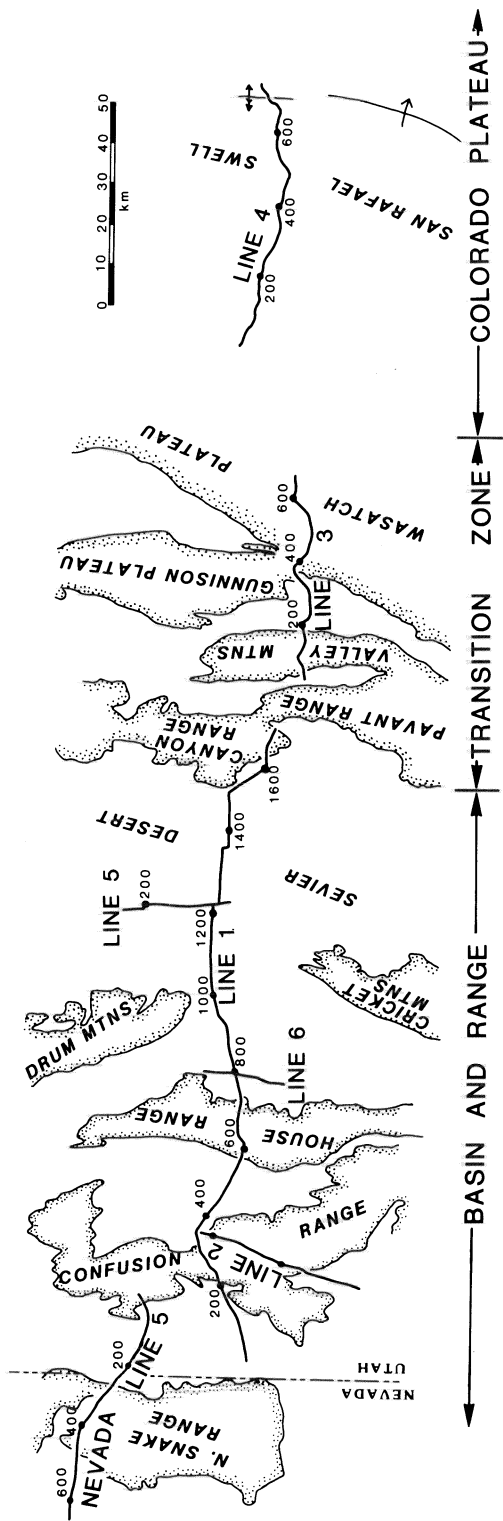


Fig. 1. Map showing geographic locations of COCORP seismic reflection data in central and western Utah. Major geologic provinces annotated at bottom of map. Dashed line shows location of geologic section in Figures 5 and 6.

syn- and early post-rift deposits are poorly dated. However, recent application of back-stripping techniques suggest that rifting occurred in the latest Proterozoic, less than 650 Ma ago [Armin and Mayer, 1983; Bond and Komniz, 1984]. The passive margin persisted, virtually uninterrupted, until the end of the Devonian and the onset of the Antler orogeny [Dickinson, 1977; Speed, 1982]. Thus, the passive margin of western North America existed for about 300 Ma, almost twice as long as its modern counterpart on the east coast of North America. The present width of this ancient passive margin, measured from the hingeline on the east to the westernmost miogeoclinal deposits and the initial $^{87}\text{Sr}/^{86}\text{Sr} = .706$ ratio that define the westernmost North American basement [Speed, 1982], is about 400 km (250 mi) (Fig. 1). Due to superposed younger deformations, the original width is unknown. In comparison, the equivalent part of the modern passive margin on the East Coast is only about 100 km wide [Grow, 1981].

Although middle and late Paleozoic orogenies (probably representing the accretion of allochthonous terranes) occurred in central and western Nevada, the Hinge Zone in central Utah remained undeformed until the Sevier orogeny in the Cretaceous and Early Tertiary [Armstrong, 1968]. At least three major thrust faults of the Sevier belt occur in central Utah (Figs. 1, 2): 1) the structurally highest Canyon Range thrust with a thick sequence of Upper Proterozoic and Paleozoic strata in its hanging wall, 2) the middle Pavant Range thrust that, where exposed, contains Lower Cambrian and younger clastic strata in its upper plate, and 3) the lowest thrust (informally referred to here as the "sub-Pavant thrust") which is nowhere exposed at the surface, but is known from industry drilling and seismic reflection data [Standlee, 1982; Sharp, 1984]. The thrusts are not well dated, but probably range in age from the Cretaceous (Albion) to the Early Tertiary [Speiker, 1946; Lawton, 1983; Villien and Kligfield, in press]. The Mesozoic-Early Tertiary thrust belt extends at least as far east as the west side of the Wasatch Plateau and may extend farther east as a blind thrust fault in the Jurassic section [Standlee, 1982; Villien and Kligfield, in press]. No major thrust faults structurally higher than the Canyon Range thrust have been recognized between the Canyon Range and the Utah-Nevada border, although some small thrust faults occur in the Confusion Range [Armstrong, 1968; Hintze, 1974].

Most recently, the Hinge Zone has been deformed by extensional tectonism that produced the Basin and Range Province. Zoback and others [1981] proposed that this extension took place in two discrete pulses: an earlier phase, beginning in the Oligocene, of low-angle normal faulting and accompanying calc-alkaline volcanism that occurred during the waning phases of subduction beneath the continent; and a later, Miocene and younger phase of higher angle normal faulting and resulted in

UTAH LINE 4

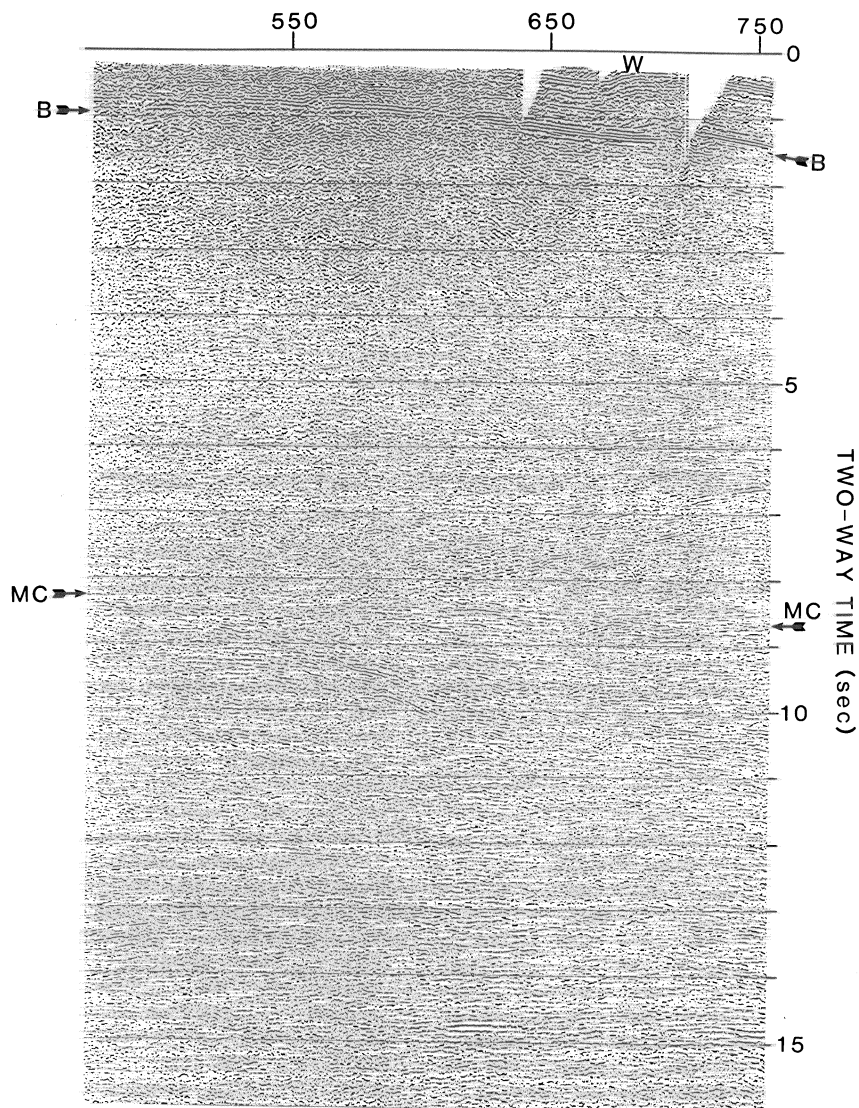


Fig. 2. Seismic reflection data from the eastern part of Utah Line 4. The section shows the entire crust beneath the eastern part of the San Rafael Swell. "W" shows the Woodside anticline. "B" indicates top of basement. "MC" shows the mid crustal horizon discussed in the text. Note dipping and crossing features in the middle and lower crust. Section processed as shown in Table 2. Not migrated. Processed by H. Farmer.

the formation of the present basin-range morphology of the province. Data presented by Von Tish et al., [1985] and reviewed here indicate episodic deformation but only one style of extension, dominated by low-angle normal faulting that probably began in the Late Oligocene and is at least as young as 1 m.y.b.p. Low-angle normal faults in eastern Nevada and west-central Utah have been

described by Armstrong [1972], McDonald [1976], Allmendinger et al., [1983], and Smith and Bruhn [1984].

COCORP Data

The processing and acquisition parameters for the COCORP Utah lines, upon which this review is

TABLE 1: Data Acquisition Parameters, COCORP Utah Lines

| | Line 1 | Line 3 | Line 4 |
|------------------------|---------------|--------|--------|
| Energy Source | Vibroseis | * | * |
| No. of Vibrators | 5 (4 minimum) | | |
| Vibrator Spacing | 12.6 m | 30.5 m | 30.5 m |
| Vibrator Move-up | 12.6 m | | |
| No. of Sweeps/VP | 8 | | |
| Sweep Frequencies | 8-32 Hz | | |
| Sweep Length | 32 sec | | |
| Geophones/Channel | 24 | | |
| Geophone Frequency | 7.5 Hz | | |
| Channel Spacing | 100.6 m | | |
| Source Spacing | 100.6 m | | |
| No. of Channels | 96 | | |
| Recording Filter | 31.25 Hz | | |
| Sample Rate | .008 sec | | |
| Field Record Length | 52 sec | | |
| Correlated Rec. Length | 20 sec | | |

*All parameters the same as Line 1, except as shown.

based, are summarized in Tables 1 and 2. A detailed discussion is beyond the scope of this review. Here we touch briefly on a few of the main points of the data, particularly as they relate to the Phanerozoic tectonics of the region. Excerpts of the original profiles and line drawings of all of the data are shown in Figures 2, 3, and 4.

Colorado Plateau

COCORP Utah Line 4 on the Colorado Plateau (Figs. 2, 4; Tables 1, 2) imaged cratonal-type continental crust that was relatively little deformed during the Phanerozoic. Because the line is directly adjacent to the orogenically modified edge of North America, it provides an excellent basis for comparison of "cratonic" or "pericratonic" vs. "orogenic" crust. Four characteristic features of the continental crust of the northwest Colorado Plateau shown on Line 4 are: 1) The shallow geometry of the Laramide San Rafael Swell, 2) a prominent lower-middle crustal horizon, 3) deep events interpreted to lie at the base of the reflective lithosphere, and 4) the general seismic fabric of the crust.

The San Rafael Swell appears on Line 4 as a broad, nearly symmetrical arch of reflectors associated with Paleozoic and Mesozoic strata that overly the Precambrian basement (Fig. 2). This arch has a half wavelength of about 50 km and a vertical structural relief of about 1.5 km. No events in the basement show a direct relation to the swell structure; the nature of Laramide basement deformation is thus enigmatic. Unless the sedimentary rocks responsible for the arched reflections are completely detached from the basement, the upper part of the crust must also be arched. There is little evidence for a west-

dipping thrust or reverse fault in the basement beneath the Swell (Fig. 2). This could be due to 1) lack of a basement fault, 2) a fault too steep to be imaged, or 3) insufficient impedance contrast, perhaps due to the fact that displacements are probably dying out at the north end of the Swell where it was crossed by the COCORP line. A small, antithetic east-dipping reverse fault in the basement on the east side of the Swell produced the Woodside anticline (Fig. 2).

At ~8.5 s (27-29 km), a prominent horizontal zone of reflections occurs somewhat discontinuously across most of the section (Figs. 2,4). This band of reflections is at about the same time as a velocity discontinuity or gradient in the lower-middle crust of the Plateau identified by Roller [1965], and Prodehl [1979]. Unlike the Swell above it, the reflections are horizontal, not arched, suggesting that corresponding reflectors may be either younger than the Early Tertiary Swell or that the upper crust is detached at or above it. As noted below, the 8.5 s event is at about the same depth in the crust as the deepest reflections in the eastern Basin and Range Province to the west.

The deepest reflections on Line 4 are at about 14.8 s (~47 km); the crooked line geometry on the eastern side of the profile where these events occur suggests that they are directly beneath the line and not a result of sideswipe. These reflections are considerably deeper than what Roller [1965] and Prodehl [1979] interpreted to be Moho from refraction data, the mid-point of which was located 200 km south of the COCORP line. The velocity structure at this depth in the crust is not known in detail; however, the reflections are probably more than 15 km deeper than any reflections observed on the COCORP transect in the Basin and Range.

TABLE 2: Processing Sequence, COCORP Utah Lines

| | Line 1 | Line 3 | | Line 4 |
|----------------------------|----------|----------|----------|----------|
| | | 43-366 | 378-639 | |
| Demultiplex | 1 | 1 | 1 | 1 |
| Vibroseis Correlation | 2 | 2 | 2 | 2 |
| Trace Editing | | 3 (a) | | |
| F-K Filter | 3 | | | |
| CDP Gather | 5 | 6 | 5 | 4 |
| Datum | 1900 m | 2450 m | 2450 m | 1896 m |
| Datum Velocity | 4500 m/s | 3500 m/s | 3500 m/s | 4000 m/s |
| Datum Statics | 4 | 5 | 4 | 5 |
| Velocity Analysis (b) | 7 | 7 | 6 | 6 |
| Normal Moveout | 8 | 8 | 8 | 8 |
| Mute | 9 | 9 | 9 | 10 |
| Trace Equalization | 6 | 10 | 10 | 9 |
| Automatic Residual Statics | | | 7 | 7 |
| Stack, 4800% | 10 | 11 | 11 | 11 |
| Filter | | 12 (c) | 12 (c) | 12 (d) |
| Predictive Deconvolution | | 4 | 3 | 3 |
| Automatic Gain Control | 11 (e) | (f) | (f) | (f) |

Notes

- a) extreme highway-cultural noise
 b) velocity spectra and constant velocity stacks; picked every 10 to 50 CDPs
 c) 0 to 4 s -- 12-32 Hz; 6 to 14 s -- 8-32 Hz interpolated in between
 d) 0 to 5 s -- 12-32 Hz; 7 s -- 8-32 Hz; 12 s -- 8-28 Hz; 14 s -- 8-22 Hz
 e) 1 s AGC window
 f) trace equalization used 1 s window; AGC not applied

Aside from the three features discussed above, the general character of the Colorado Plateau crust is one of numerous dipping, curving, and crossing events. Many of these features are reasonably interpreted as diffractions, although some may be dipping reflections or reflections from out of the plane of the section. These events occur both above and below the 8.5 s reflection (Fig. 2).

Wasatch Plateau and Transition Zone

COCORP Utah Line 3 (Fig. 1) crosses the Wasatch Plateau, Sevier Valley, and the Valley Mountains. Good shallow data were obtained from beneath the Wasatch Plateau (Fig. 3), but farther west and deeper than about 4 s the data provide little insight into crustal structure. The data show that the Mesozoic-early Cenozoic thrust faults and accompanying structural duplication occur at least as far east as the west side of the Wasatch Plateau (Fig. 3); blind thrusts in the Jurassic section could extend farther east [Standlee, 1982; Villien and Kligfield, in press]. The COCORP seismic data also suggest that the normal faults on the Plateau do not cut into basement, but may instead sole into and reactivate a blind thrust in the Jurassic section (Fig. 3). This conclusion is somewhat tenuous given the resolution of the seismic data and the small displacements on most of the normal faults.

A normal fault does offset the basement by 1.4-1.8 km beneath the prominent syncline on the west side of the Wasatch Plateau (Fig. 3). This normal fault does not cut above the Jurassic section; the syncline of Cretaceous rocks above it is unbroken. Thus, two interpretations of the fault are possible. First, it may be a Jurassic normal fault that controlled evaporite deposition in the Arapien basin directly to the west (i.e., the "Ancient Ephraim fault" of Moulton, 1975). Second, the fault could be Cenozoic in age, representing the location where the shallow normal faults of the Wasatch Plateau depart from their detachment horizon in the Jurassic section and cut down-section into the crust. Directly west of this normal fault the basement surface occurs at about 3.5 s (~9 km) depth (Fig. 3); farther west the top of the basement is only poorly imaged, if at all, on Line 3. Drilling results from the Placid WXC No. 1 well on the west side of the Valley Mountains, however, indicate that basement may be at approximately 9 km there as well, assuming no major thrusts and a normal stratigraphic section below total depth of the borehole.

Eastern Basin and Range

COCORP Utah Line 1 (Fig. 4) from the eastern Basin and Range showed remarkable overlapping lateral continuity of gently dipping structures across more than 120 km perpendicular to strike.

UTAH LINE 3

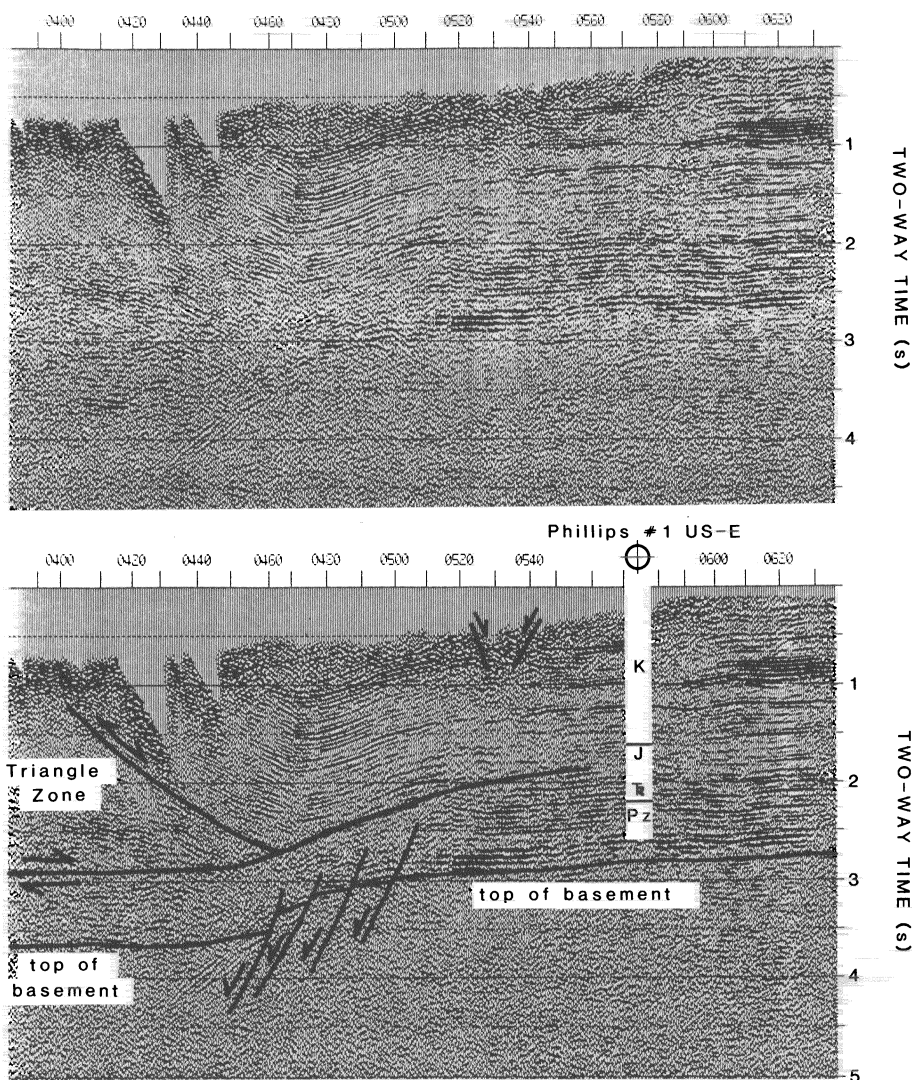


Fig. 3. Seismic reflection data from the eastern part of Utah Line 3; both interpreted (bottom) and uninterpreted (top) sections shown. Tops of units shown in Phillips #1 US-E well converted to time using the well sonic logs. Small graben interpreted in the bottom section is the Water Hollow fault zone. The Wasatch monocline is within the mute zone at the top of the section. Section processed as shown in Table 2. Not migrated. Processed by H. Farmer.

The Sevier Desert detachment is a low-angle normal fault that underlies the Cenozoic Sevier Desert basin. Normal faults within the basin that cut volcanic and sedimentary rocks at least as young as 4 m.y., but do not significantly offset (by more than about 300 m [Peddy and Brown, this volume] the detachment. The basinal geometries and ages in combination with palinspastically restored sections (discussed below) show that the long term rate of extensional displacement on the detachment is between 0.7 and 1.9 mm/yr [Von Tish

et al., 1985]. These rates are the same order of magnitude as those determined for foreland fold-thrust belts (~1.5 mm/yr for the Idaho-Wyoming thrust belt [Allmendinger and Jordan, 1981]) and both have rates that are, on the average, one to two orders of magnitude slower than plate convergence rates. Hiatuses are recorded in the basin sediments [Von Tish et al., 1985; Lindsey et al., 1981], but there is no resolvable change in the rates of extension.

One of the major remaining problems posed by

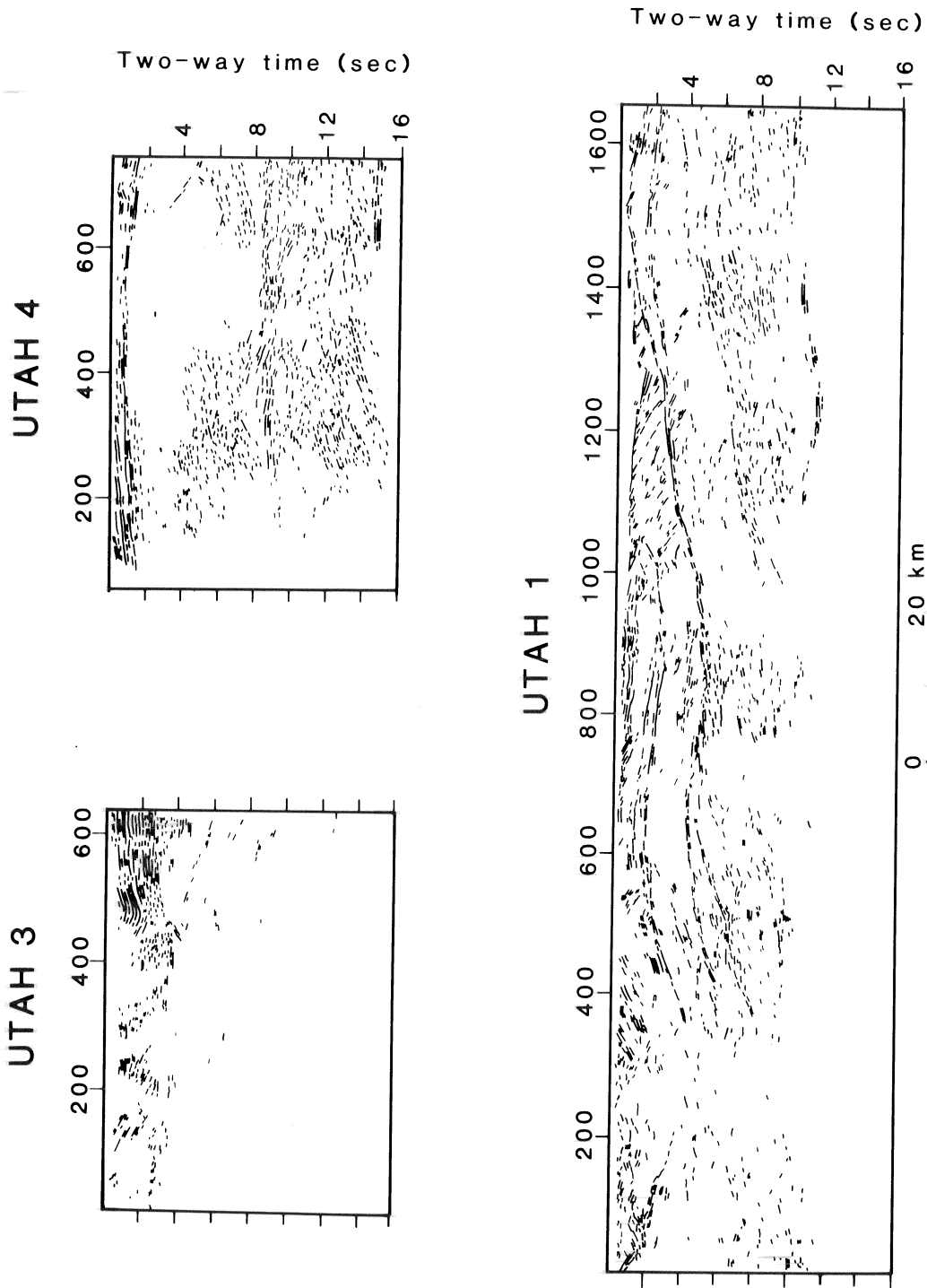


Fig. 4. Composite line drawings of Utah Lines 1, 3, and 4. Line drawing of Line 1 from Allmendinger et al. [1983]. Approximately 1:1 at a velocity of 5 km/s.

BALANCED & RESTORED SECTIONS -- WEST-CENTRAL UTAH
 SEVIER DESERT DETACHMENT AS A NEW CENOZOIC NORMAL FAULT

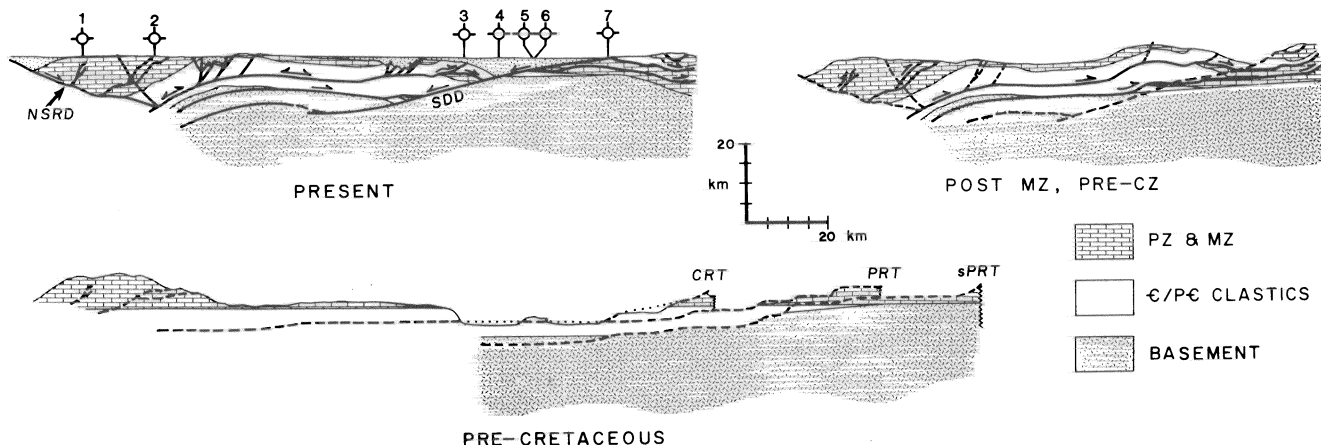


Fig. 5. Geologic section and palinspastic restoration constructed assuming the Sevier Desert detachment is a new Cenozoic normal fault. Section simplified from Sharp [1984]. The restoration indicates about 28 km extension on the Sevier Desert detachment and 35 km overall. About 110 km of Mesozoic-early Cenozoic thrust shortening are interpreted. Wells shown are: 1) Tiger Oil #1 USA Bishop Springs; 2) Cities Services #1 State-AB; 3) Cominco-American #2 Bear River; 4) Gulf-Gronning #1; 5) Argonaut Energy #1 Federal; 6) Arco Oil and Gas Pavant Butte #1; 7) Placid Oil Henley #1.

COCORP Line 1 and also by recent field studies is whether or not low-angle normal faults are reactivated thrust faults or new Cenozoic faults. To test these alternatives, balanced cross-sections were constructed [Sharp, 1984; R. Allmendinger, unpublished data, 1984] following standard techniques outlined by Dahlstrom [1970]. These cross-sections used the constant bed length technique and were constrained by the COCORP data, 10 industry boreholes in the region, and surface geology. Of six alternative sections constructed, two end members are presented here (Figs. 5, 6). The sections proved ambiguous regarding the question of reactivation, but both show that the geometry of the miogeocline may have exerted a fundamental control of the subsequent geometry of both compressional and extensional structures.

In the fully restored state, both end-member sections show a sharp westward increase in thickness of upper Proterozoic and Lower Cambrian clastic strata (Figs. 5,6). These rocks, the initial syn- and early post-rift deposits in the Cordilleran miogeocline, thicken from less than 1 km to more than 5 km in a lateral distance of only 20-30 km. Such gradients generally occur in fault-bounded sedimentary basins, and given the tectonic setting of these deposits, those faults were undoubtedly normal faults. The hingeline occurs at this gradient of rapid thickness change and corresponds to the point west of which the North American craton was significantly thinned

during the late Proterozoic rifting that formed the Cordilleran passive margin and miogeocline. The autochthonous position of the hingeline lies directly beneath the Sevier Desert basin.

Despite the differences in initial assumptions, the two cross-sections both show that trajectories of the basal Mesozoic-early Cenozoic thrust fault track along the contact between basement and upper Proterozoic strata where the gradient of thickening was steepest; this is the region where Precambrian normal faults were most likely to be present (Figs. 5,6). Though it cannot be shown that the younger thrust faults reactivated the Precambrian normal faults, the structures and basin geometries of the Proterozoic rifted margin controlled the geometry of the compressional structures. More importantly, surface geology, drilling, and seismic data all indicate that both thrust faults and low-angle normal faults of Mesozoic and Cenozoic age cut deeply into the crust only west of the hingeline.

Summary--The Transition from Cratonic to Orogenic Province

COCORP Lines 1, 3, and 4 in Utah and Line 5 in Nevada, in combination with surface and subsurface data, enable us to construct a simplified structural cross-section of the crust from the north-western Colorado Plateau and eastern Basin and Range (Fig. 7). This cross-section illustrates

BALANCED & RESTORED SECTIONS -- WEST-CENTRAL UTAH
SEVIER DESERT DETACHMENT AS A REACTIVATED THRUST

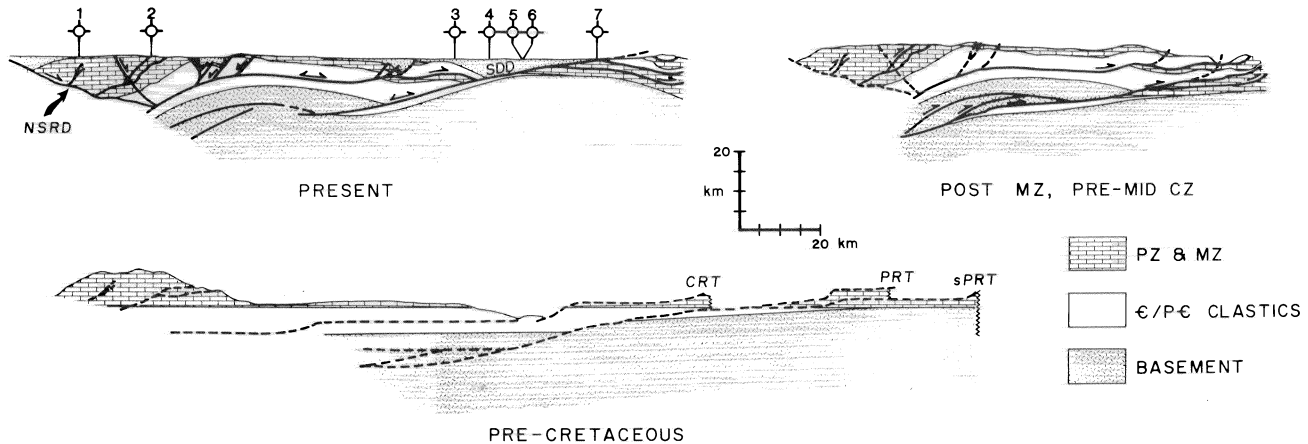


Fig. 6. Geologic section and palinspastic restoration constructed assuming the Cenozoic Sevier Desert detachment reactivates the Pavant Range thrust. The section, simplified from R. Allmendinger [unpublished data], indicates about 40 km of Cenozoic offset on the Sevier Desert detachment and 45 km of extension overall. Section has about 110 km of thrust shortening. Location and wells same as in Figure 5.

the changes in crustal structural geometry that occur across the transition from a province that has largely (although not completely) maintained its cratonic character to a province that has been deformed at times throughout the Phanerozoic by both compressional and extensional tectonism. A number of key features are highlighted by the cross-section:

1. In the transition zone between the Basin and Range and Colorado Plateau, most of the faulting occurred above the sediment-basement interface. Basement in this zone is gently warped or arched, probably because of loading or unloading due to thrust faulting or low-angle normal faulting (respectively) that occurred in the overlying sedimentary column [see Jordan, 1981; Spencer, 1984]. A notable exception to this conclusion is the normal fault that offsets the basement surface beneath the western edge of the Wasatch Plateau. The origin of this normal fault remains ambiguous.

2. Significant faulting of the basement by thrusts of the Mesozoic-early Cenozoic Cordilleran fold-thrust belt and by younger low angle normal faults in the Basin and Range Province occurred mostly west of the autochthonous position of the late Proterozoic-early Paleozoic Hingeline. Thus, the late Proterozoic rifting event controlled the general character and location of subsequent low-angle thrusting and extension. The Laramide basement thrust faults that occur well east of the Hingeline in Wyoming, Colorado, and eastern Utah are tectonically very different than the Cordilleran fold-thrust belt.

3. The seismic data identify a reflective

horizon at 27-30 km depth in both the Basin and Range and the Colorado Plateau, although it cannot be traced continuously between the two provinces. In both provinces, this horizon could be interpreted either as a structural decoupling zone for Mesozoic-Cenozoic structures, or as a younger feature of unknown origin, superimposed on or truncating those structures. In the Basin and Range, the 30 km horizon marks the boundary between reflective and nonreflective lithosphere. In the Colorado Plateau, however, the horizon appears to occur within a zone of otherwise similar seismic fabric above and below it, and the base of the reflective lithosphere is 15-20 km deeper.

4. The general character of the crust in the Colorado Plateau is one that appears dominated by numerous diffractions and reflections that dip in both directions and may be partly out of the plane. In contrast, the eastern Basin and Range crust has a west-dipping or horizontal fabric, although there are also some east-dipping features that are probably related to Cenozoic structures. We interpret this difference in character to represent a dominantly "cratonic" fabric in the Plateau versus a dominantly orogenic fabric in the Basin and Range. The orogenic fabric in the Basin and Range crust is due to Cenozoic, Mesozoic, and perhaps even late Proterozoic extension and compression. The cratonic fabric of the Plateau is related to structural, lithologic or perhaps metamorphic features dominantly of middle Proterozoic or older age. The 27-30 km horizon in the Colorado Plateau appears to be superimposed on and younger than this cratonic fabric. In the Basin

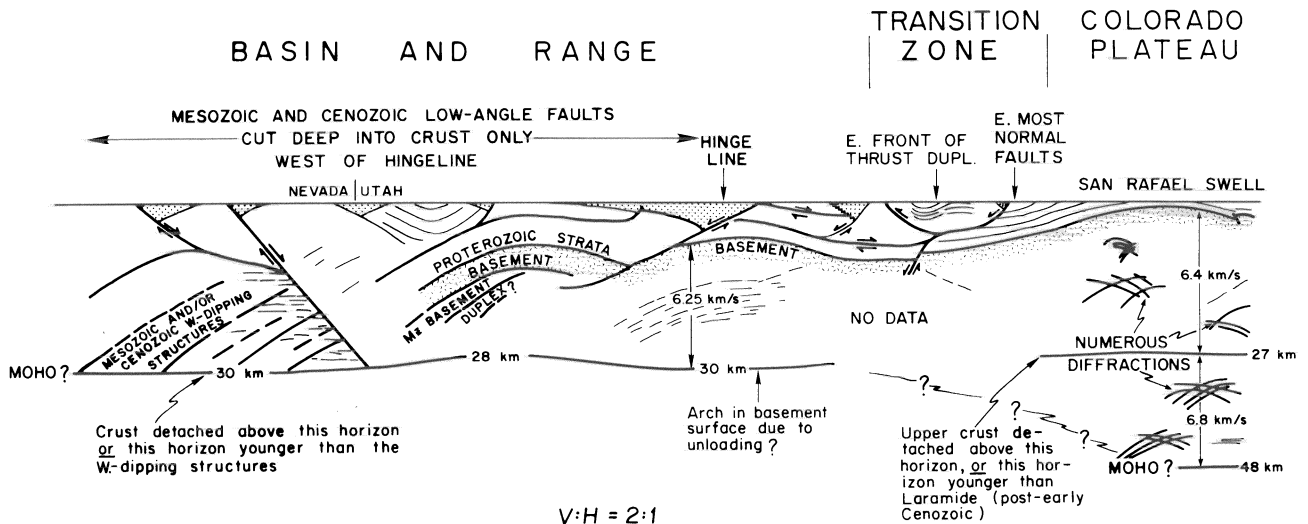


Fig. 7. Simplified and idealized crustal scale structural cross-section from the northwest Colorado Plateau to easternmost Nevada. Velocities beneath San Rafael Swell from Roller [1965] and Prodehl [1979]. Velocity beneath hingeline from Liu et al., [this volume]. Easternmost Nevada from Hauser et al., [unpublished data]. Section has 2:1 vertical exaggeration.

and Range, however, the 27-30 km horizon appears to be spatially and perhaps genetically related to the orogenic fabric; it is probably related to the Cenozoic tectonics of the region and may also be related to the Mesozoic tectonics.

5. The reflective lithosphere is 15-20 km thicker in the Colorado Plateau than in the Basin and Range. When this difference in thickness developed and by what processes is unknown. This is, perhaps, one of the great remaining mysteries of the region.

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