

COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part 2: Precambrian basement structure and its influence on Laramide deformation

R. W. ALLMENDINGER

J. A. BREWER*

L. D. BROWN

S. KAUFMAN

J. E. OLIVER

R. S. HOUSTON

Department of Geological Sciences, Cornell University, Ithaca, New York 14853

Department of Geology, University of Wyoming, Laramie, Wyoming 82071

ABSTRACT

The influence of Precambrian basement structures on subsequent deformation is of considerable relevance to studies of continental evolution. COCORP deep seismic-reflection profiles were recently recorded in southeastern Wyoming, where several major, but temporally separated, tectonic elements of the western United States are superimposed. Of these, a fundamental boundary between Archean and Proterozoic basements and the eastern front of Laramide deformation were the principal targets of the reflection survey. The former may represent an ancient Proterozoic plate boundary; the latter is a prominent physiographic feature that signifies crustal deformation far within the North American craton, more than 1,500 km from the nearest coeval plate margin.

The major crustal feature controlling a lateral, north-south variation in Laramide tectonic style appears to be the Archean-Proterozoic crustal boundary, known in the nearby Medicine Bow Mountains as the Mullen Creek-Nash Fork shear zone. COCORP data in the Laramie Mountains and the Laramie Basin suggest that this shear zone dips $\sim 55^\circ$ to the southeast. Northwest of the shear zone, the seismic basement is also characterized by southeast-dipping events, suggesting that the early Proterozoic tectonics that produced the shear zone were distributed over a wide

region. Complex reflections down to 15-km depth or more under the Laramie Basin may correspond to structures or erosional truncations in metasediments overlying the Archean basement complex. Deep crustal events (between 35 and 40 km) north of the shear zone are short and discontinuous, in contrast with flat, laterally continuous reflections south of the shear zone at about 48-km depth which are interpreted as the crust-mantle transition. Thus, COCORP data and published results of regional refraction and gravity surveys suggest that the crust is significantly thinner in the Archean basement terrane northwest of the shear zone than it is in the Proterozoic province to the southeast. Differences in crustal thickness may be partly responsible for the difference between Laramide structures in Wyoming and Colorado, and a thin crust may also have facilitated Laramide deformation farther east in the Black Hills, located north of the shear zone.

INTRODUCTION

Thick-skinned Laramide structures extend to the eastern edge of Phanerozoic deformation in the Cordillera of western North America and occur from New Mexico to southern Montana. A significant change in orientations of Laramide uplifts constitutes one of the differences between the Wyoming and Colorado parts of the province. The Front Range in Colorado forms the linear, eastern morphologic boundary of the province (the "Front"), although structures vary along its extent. In this southern part, Laramide trends are

dominantly north-northwesterly, commonly paralleling Ancestral Rockies structures, and basins are generally narrower than their northern counterparts. In most of Wyoming, there is no distinct Rocky Mountain Front; instead, the Black Hills lie isolated to the east, at the western edge of the Great Plains. In this northern part of the province, Laramide structural trends vary between west and west-northwest, and large basement uplifts are separated by broad basins.

This north-south variation in structural style has been attributed to the interaction of the Colorado Plateau with the rest of the North American craton (Sales, 1968; Hamilton, 1981). However, the change also coincides sharply with the Archean-Proterozoic crustal boundary (Houston, 1971). These observations raise the question: What was the role of Precambrian basement structures in the development of the Laramide province more than 1,500 km from the nearest coeval plate margin?

For investigation of deep crustal structures, the seismic-reflection method offers the highest resolution of structural details. In late summer and early fall of 1979, the Consortium for Continental Reflection Profiling (COCORP) conducted a survey across the Laramie Mountains of southeastern Wyoming (Fig. 1). The Laramie Mountains present a unique opportunity to study the structure of the Front at the transition between the northern and southern parts of the province. The COCORP profiles also cross the boundary between Archean and Proterozoic crystalline basement, which to the southwest is expressed as the Mullen Creek-Nash-Fork shear zone

*Present address: Department of Earth Sciences, Bullard Labs, Cambridge University, Madingley Rise, Madingley Road, Cambridge, CB3 0E2 England.

This shear zone forms the northern boundary of the Colorado Lineament of Warner (1978). Logistical problems at the time of the survey prevented a planned continuation of the profiles southwestward over the exposed shear zone in the Medicine Bow Mountains. The seismic sections presented here cross the buried extension of the shear zone in the Laramie Mountains and provide a preliminary look at the subsurface structure of the Archean-Proterozoic boundary.

Part I of this study, appearing as a companion paper (Brewer and others, 1982), describes the Laramide structure of the northern Rocky Mountain Front in southeastern Wyoming. The western edge of the southern Laramie Mountains is bounded by a set of en echelon thrust faults of variable, but generally shallow westerly dip. The frontal fault apparently steepens and dies out just north of the COCORP profiles. To the north, faulting steps eastward along the range, and a mapped basement arch, bounded to the east by a thrust (Newhouse and Hagner, 1957), is apparent in down-plunge projection on the seismic section. Although fault-plane reflections are not as pronounced as those seen on the COCORP

profiles across the Wind River Mountains (Smithson and others, 1978, 1979; Brewer and others, 1980), the thrust interpretation is supported by truncations of upper-plate basement events (or coherent lineups on the seismic section); by the apparent extension of basal, upper Paleozoic sediments under the mountains; and by west-dipping reflections farther west under the mountains. The less pronounced and more discontinuous nature of the fault-plane reflections may result from smaller displacement on the Laramie thrust system, which may have produced a juxtaposition of more nearly similar basement rock types and/or less significant mylonite development. The principal frontal fault system in the Laramie Mountains appears to die out northward as it approaches the projected Mullen Creek-Nash Fork shear zone, although the detailed relations between the two structures have not been resolved on the seismic sections.

The over-all structure of the Rocky Mountain Front in the Laramie Range seems best understood when viewed in terms of its interactions with the Archean-Proterozoic boundary. In this paper, we dis-

cuss COCORP results which suggest significant differences in crustal structure on either side of the boundary, including a possible change in crustal thickness by ~10 km across the shear zone. The seismic sections, geologic mapping, and sparse geophysical data in the Wyoming province and to the south along the Rocky Mountain Front suggest that the northeast-trending crustal boundary and subsidiary shear zones to the south (Tweto and Sims, 1963; Warner, 1978) coincide with and may have influenced the north-south lateral variation in structure of the Rocky Mountain Front and the Laramide province in general. Thinner crust in the northern part of the province may have favored the greater variation in structural trends through pre-existing crustal weaknesses. Furthermore, the propagation of Laramide deformation farther east on the north side of the boundary to produce the Black Hills dome may be related to crustal thinning, inherent differences in Archean crust, or both. Ancestral Rockies deformation clearly influenced the Laramide evolution of the Front in Colorado (Tweto, 1975), and early-middle Paleozoic kimberlite diatremes (McCallum and oth-

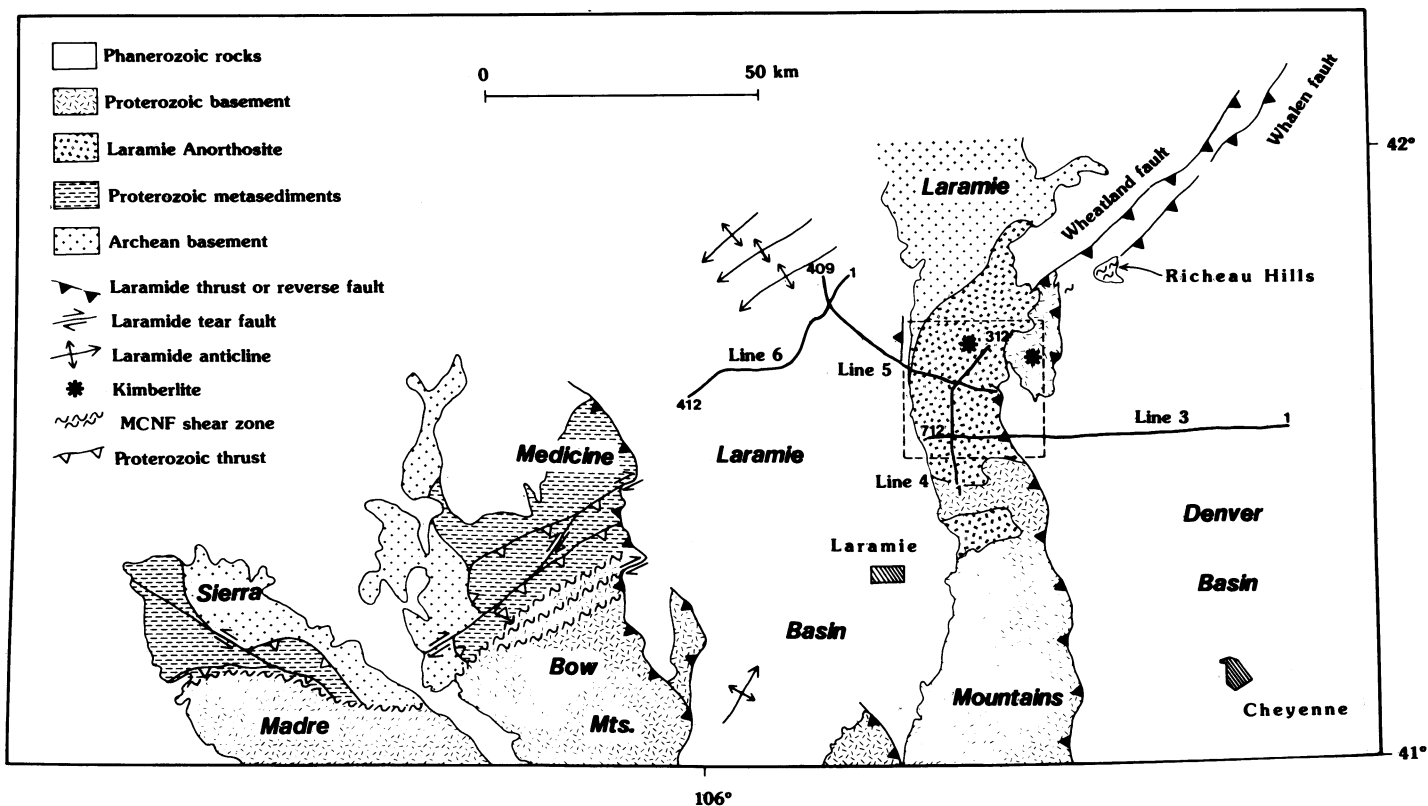


Figure 1. Generalized tectonic map of southeastern Wyoming. Location of COCORP profiles in Denver Basin, Laramie Mountains, and Laramie Basin shown. Area of Figure 2 outlined. From Drouillard (1963), Graff and others (1981), Karlstrom and others (1981), Newhouse and Hagner (1957).

ers, 1975) along the axis of the Front may indicate another form of structural control on the linear morphology of the Front. However, Ancestral Rockies structures or diatremes have not yet been recognized on the seismic sections, even though both are known in the vicinity of the survey.

PRECAMBRIAN TECTONIC SETTING

The most fundamental basement feature in the Wyoming-Colorado region is the boundary between Archean and Proterozoic crust. Named the "Cheyenne belt" in southeastern Wyoming (Houston and others, 1979), this boundary trends northeastward, with older rocks to the northwest and younger rocks to the southeast (Fig. 1). The variation in lithologies across the major shear zone and the observation that Archean crust is nowhere exposed to the south have led Hills and others (1975), Camfield and Gough (1977), Warner (1978), and Houston and others (1979) to suggest that this feature is a major Proterozoic plate boundary.

The boundary between the two provinces in the Medicine Bow Mountains is formed by the Mullen Creek-Nash Fork (MCNF) shear zone (Houston and McCallum, 1961; Houston and others, 1968). The shear zone is at least 0.2 km wide, strikes northeastward, and, at the surface, dips 60° to 80° to the southeast (McCallum, 1974; Houston and others, 1968, 1979). The minimum strike separation is 7 km (Houston and others, 1975) and some Laramide reactivation is probable.

In the Laramie Mountains, Proterozoic shear zones with the same trend as the MCNF zone are present but have significantly less apparent displacement (Newhouse and Hagner, 1957). The Laramie anorthosite was probably intruded along the shear zone and postdated most of its movement (Hills and Armstrong, 1974). The northeast projection of the MCNF shear zone is supported by recent mapping in the Richeau Hills east of the Laramie Range (Fig. 1) that shows a 1.4-km-wide shear zone between undated metamorphic rocks to the south and Archean metasediments to the north (Graff and others, 1980). Thus, although the anorthosite obscures the structural boundary between basement provinces in the Laramie Mountains, the shear zone probably is present beneath the anorthosite and may be imaged on the seismic sections.

The Archean basement complex in the Medicine Bow and Laramie Range consists of a highly deformed and metamorphosed gneiss terrane (at least 2,500 m.y. old) that includes granite, granite gneiss, and migmatite. In the Medicine Bow Mountains, lower Proterozoic (1,700 to 2,500 m.y. old) metasedimentary rocks including quartzite, marble, and metavolcanics unconformably overlie the Archean terrane and contrast with somewhat younger Proterozoic basement to the south of the MCNF shear zone. The Proterozoic metamorphic suite in the southern Medicine Bow Mountains consists of strongly metamorphosed plagioclase and hornblende gneiss and associated metasedimentary and mafic metavolcanic rocks (Houston and others, 1968; Houston, 1971; Hills and others, 1968). In the southern Laramie Mountains, only scattered outcrops of the Proterozoic metamorphic complex are present; the Sherman Granite batholith (1,410 m.y. old; Peterman and Hedge, 1968) and Laramie anorthosite (1,420 to 1,510 m.y. old; Hills and Armstrong, 1974) have intruded the region south of the Archean-Proterozoic boundary. K-Ar dates on muscovite suggest a metamorphic event in both the Archean and the Proterozoic terranes between 1,400 and 1,600 m.y. ago (Hills and Armstrong, 1974). However, the earlier histories of the two terranes are dissimilar, indicating that they were not connected prior to that time.

East of the Laramie Mountains, north-east-trending Mesozoic and Cenozoic faults parallel the Cheyenne belt and are generally on strike with the projection of the MCNF shear zone. These trends occur at the southern end of the North American Central Plains conductive anomaly (Camfield and Gough, 1977), which can be traced northward around the east side of the Black Hills and into the Churchill Province of Canada.

The MCNF shear zone forms the northern edge of the Colorado Lineament as defined by Warner (1978). He interprets this broad band of northeast-trending Precambrian shear zones as a Proterozoic wrench fault system that may extend to the terranes of Minnesota. Alternatively, the shear zone may represent a suture produced during a Proterozoic continental collision, and some combination of these two schemes is also possible (Houston and others, 1979).

COCORP RESULTS

The locations of the COCORP deep seismic profiles in the Laramide Mountains

survey are shown in Figures 1 and 2 (for a complete line location map, see Fig. 3 in Brewer and others, 1982). Two-way travel-times are used throughout this paper; to convert these to approximate depths, multiply one-half the time by a velocity of 6 km/s for the basement rocks. All of the profiles were recorded to 20 s, equivalent to about 60-km depth. A general review of COCORP surveying and processing methods may be found in Brewer and Oliver (1980) and Schilt and others (1979).

Five main aspects of the Laramie seismic sections shed light on Precambrian basement structure and its influence on Laramide deformation. These are (1) shallow Precambrian structure; (2) south-dipping events on line 4; (3) contrasts in seismic character, apparent truncations, and diffractions on line 5; (4) seismic "fabric" of the basement of lines 5 and 6; and (5) events near the base of the crust on all profiles.

Shallow Precambrian Structure

All of the COCORP profiles in the Laramie Range display remarkable detail in the Precambrian basement, in some cases down to 17 s (50 km). The nature of at least some of this deformation can be better understood by focusing on events on the profiles recorded in the mountains, where Precambrian structures and contacts at the surface can be traced to depth.

On the western part of line 3 between 0 and 1.5 s (5 km), two events are particularly important (Fig. 3). The shallower of the two (event A) has an apparent west dip of 25° (migrated) and projects to the surface near VP 620. Surface mapping (Fig. 2) suggests that a major, asymmetric, east-verging antiform in the anorthosite-noritic anorthosite terrane has a brecciated fault zone in its hinge that coincides with the surface projection of event A (Newhouse and Hagner, 1957). This same event also lines up with a small offset in event B (Fig. 3). The coincidence with the brecciated antiformal axis and the offset in B suggest that A is a small thrust, probably formed during Laramide deformation. Event A is parallel to the frontal fault system (Fig. 3; Brewer and others, 1982) and both have approximately the same westward dip as the Precambrian compositional foliation mapped at the surface (Fig. 2). More subtle, subparallel, west-dipping events below and east of event A may correspond to Precambrian foliation or additional minor thrusts.

Crosscutting the predominantly west-

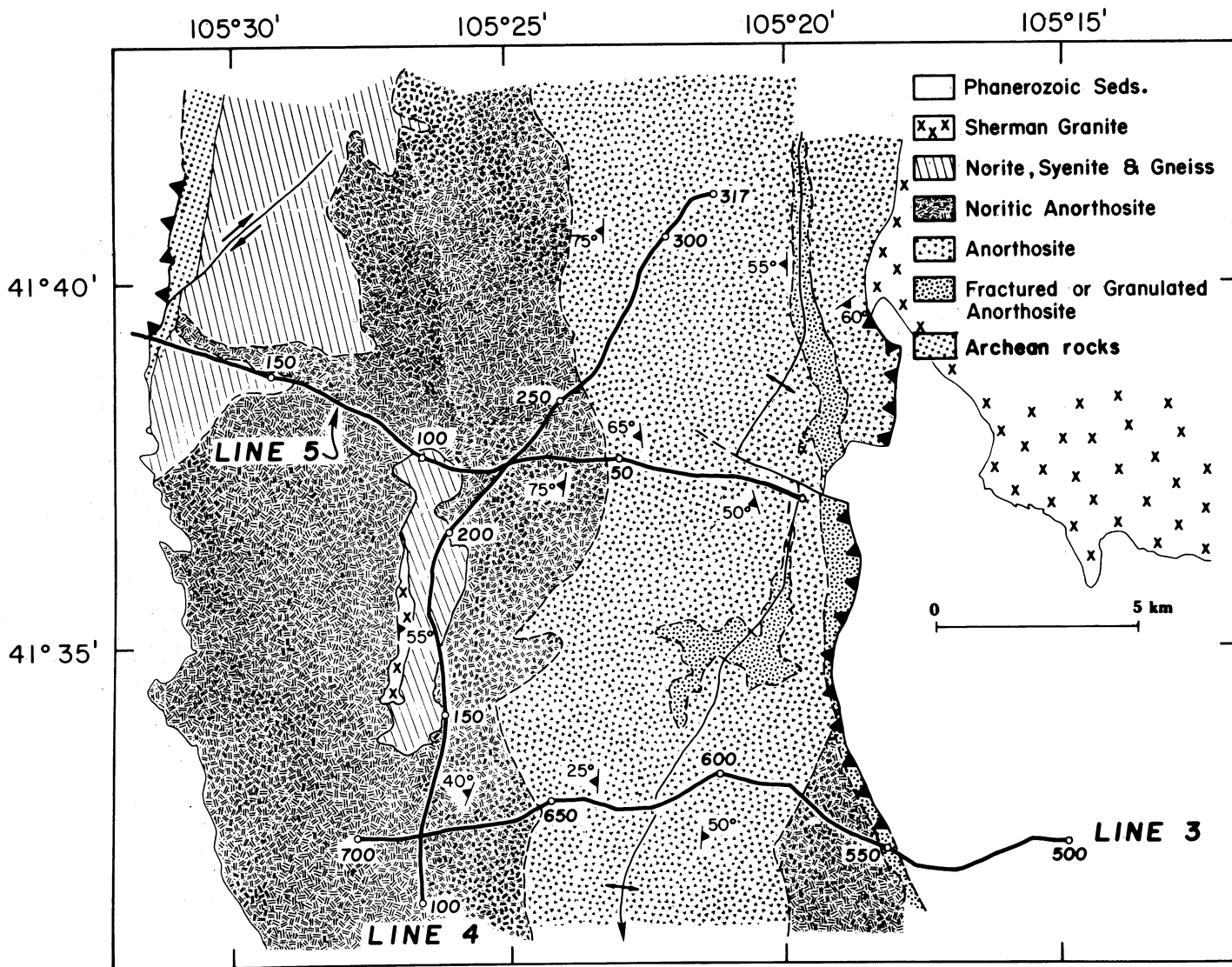


Figure 2. Map of COCORP line locations in the Laramie Mountains. Precambrian geology generalized from Newhouse and Hagner (1957). Selected attitudes of compositional foliation in Precambrian units shown with short barbed lines. Mapped thrust faults shown with sawteeth. For more complete location map of all lines, see Figure 3 of Brewer and others (1982).

dipping seismic basement is event B, which has an apparent eastward dip of 10° and is most pronounced between VPs 695 and 665, although it may extend as far east as VP 640 (Fig. 3). This event is most prominent under VP 680, at ~ 1.2 s (about 4 km deep, assuming an anorthosite velocity of 6.6 km/s; Press, 1966). The depth of event B is very close to the base of the anorthosite body as inferred from gravity (Hodge and others, 1973) and shallow seismic-reflection data (Smithson and others, 1977). Alternatively, event B might be caused by dikes or sills of Sherman Granite, as the eastward dip, crosscutting older structures, is consistent with, although shallower than, mapped dike-like bodies of the granite and norite that dip eastward and crosscut the foliation in the anorthosite (Fig. 2; Newhouse and Hagner, 1957). A combination of these two

alternatives, which we prefer, is that the base of the anorthosite is a gently east-dipping intrusive contact with the younger Sherman Granite that has truncated the older Precambrian foliation. Event B (labeled "base of the anorthosite" in Fig. 4) can also be seen on line 4, where it shallows slightly northward.

Although Precambrian compositional foliation at the surface dips more steeply westward (50° to 65°) on the eastern part of line 5 (Fig. 2), events with these dips can be imaged by processing the seismic data using stacking velocities of ~ 10 km/s.¹ A stack of

¹Note that stacking velocity here is determined by the geometry of the dipping reflector and is considerably higher than realistic average rock velocities. See Dobrin (1976, p. 207–210) for a discussion of stacking velocities of dipping beds.

line 5, using that velocity (shown in Fig. 9 of Brewer and others, 1982), shows an event of that dip which projects to the surface at the contact between anorthosite and noritic anorthosite (VP 55, Fig. 2). As on the west end of line 3, the event on line 5 parallels the interpreted frontal fault event that is located deeper in the crust and to the east.

In general, both lines 3 and 5 show a striking correlation between the westward dip of the Precambrian compositional foliation and that of Laramide thrust and reverse faults bounding the east side of the Laramie Mountains. Thus, the data suggest that Precambrian foliation controls the near-surface orientation of Laramide structures. On the basis of these data and the extent of brittle deformation in the anorthosite, the north-trending antiform in the Laramie Range (Fig. 2) might be inter-

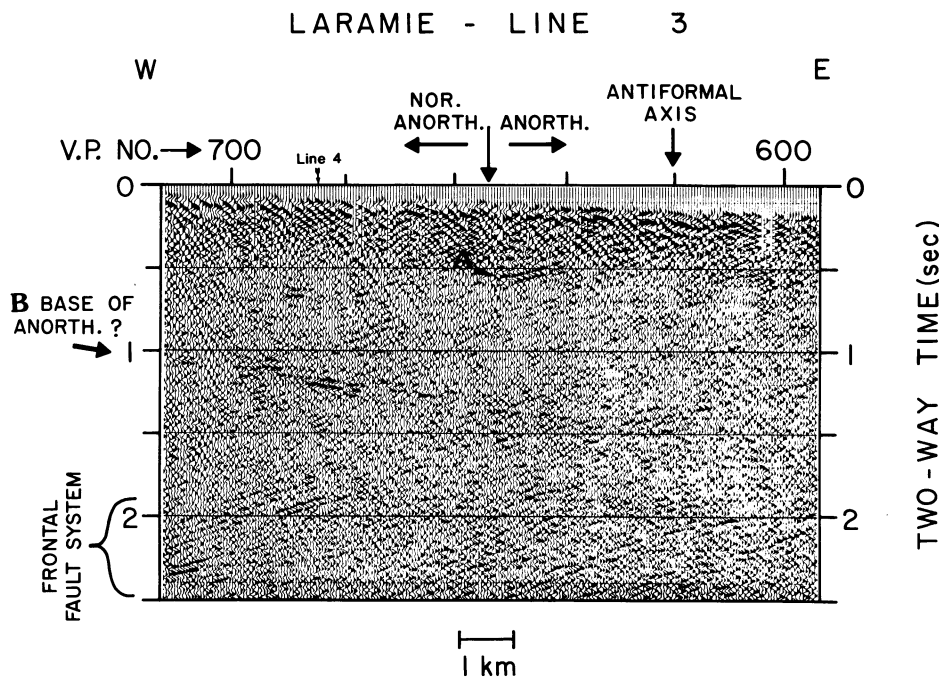


Figure 3. Detail of COCORP Wyoming line 3 near the west end. Seismic section shows minor thrust fault (A) in core of antiformal structure and interpreted base of the anorthosite (B), as well as the general west-dipping fabric of the crust beneath the Laramie Mountains. Note the parallelism of Precambrian and probable Laramide structures (that is, the frontal fault and event A).

preted as structure formed by differential rotation of different parts of the anorthosite during Laramide thrusting.

SOUTH-DIPPING EVENTS ON LINE 4

Line 4 runs generally north-south along the axis of the mountains, completely within the outcrop area of the Laramie anorthosite and related units. The most

prominent feature on the line is a band of complex and locally diffuse reflections with an apparent southward dip (approximately 34° unmigrated; Fig. 5). Although individual events are relatively short and discontinuous, the entire band can be traced from a time of 1.3 s (4 km) near VP 260 to at least 4.0 s (12 km) under VP 140, and possibly as deep as 6.0 s (18 km) beneath VP 90. North of VP 260, the band of events appears to flatten somewhat. The base of the anortho-

site, discussed above, is much shallower than these reflections at the south end of line 4 and even on the north end appears to be confined completely to the zone above this band of events; no other reflections sharply crosscut it. Most deeper basement events on line 4 either parallel the south-dipping band or are apparently horizontal.

If this feature is extended to the surface north of the end of line 4, it aligns well with both the projected MCNF-Richeau Hills shear zone and the southeast-dipping Wheatland fault, a Laramide structure (Fig. 1). We cannot, on the basis of line 4 alone, unequivocally state which of these two structures produced the band of reflections. However, surface geology suggests that displacement on the Wheatland fault must have died out almost completely by the point at which its projection crosses line 5 and the west side of the Laramie Mountains (Newhouse and Hagner, 1957; Graff and others, 1980). This observation, combined with the fact that the over-all seismic grain of Archean crust is southeast-dipping (see below), leads us to conclude that the Proterozoic shear zone is primarily responsible for the band of reflections on line 4. Certainly, though, the coincidence of the Wheatland, Whalen, and related faults with the shear zone (Fig. 1) is excellent evidence for reactivation of Precambrian crustal structures during Laramide deformation.

Events on Line 5

Line 4 provides only an apparent dip on the shear zone reflections. Where line 5 crosses line 4, the south-dipping band described above occurs between 1.6 and 2 s (4.8 to 6 km). Within this time range on line 5 (note that the datum is slightly different on Figs. 5 and 6), an event with an apparent east dip occurs (Fig. 6), which would intersect the ground surface at VP 170, were it not for the anorthosite. VP 170 also lies along the projected shear zone, and thus we can determine the true dip of the shear zone from the two apparent dips (by three-dimensional hand migration) as ~55° to the southeast. This orientation is somewhat shallower than, but consistent with, the near-vertical to steeply southeast-dipping attitude of the exposed shear zone in the Medicine Bow Mountains (Houston and others, 1968). The dip is also very close to that shown by Drouillard (1963) in his cross section of the Whalen fault, a Laramide reverse fault that parallels the Wheatland fault.

One of the most striking features of line 5 is the difference in seismic character be-

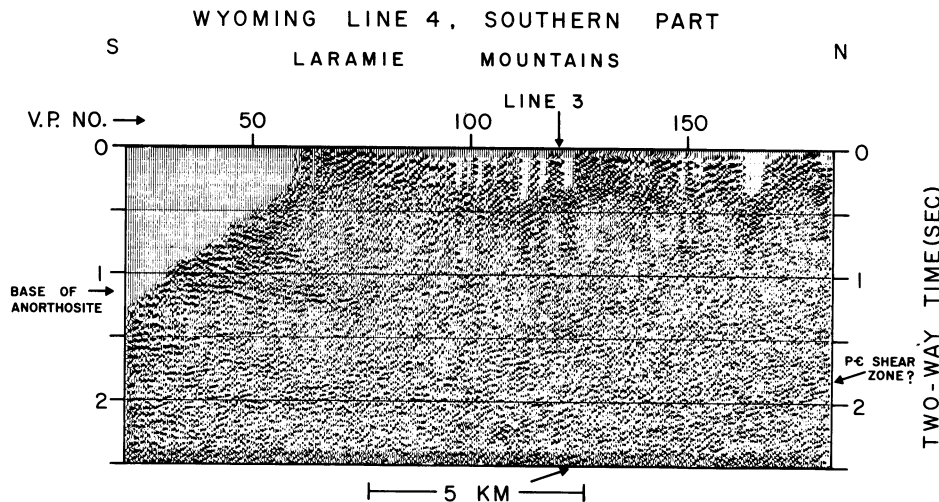


Figure 4. Detail of COCORP Wyoming line 4 at the south end. The interpreted base of the anorthosite event on this line shallows gently northward, as do subtler events that may correlate with the frontal thrust system.

LINE 4 - WYOMING

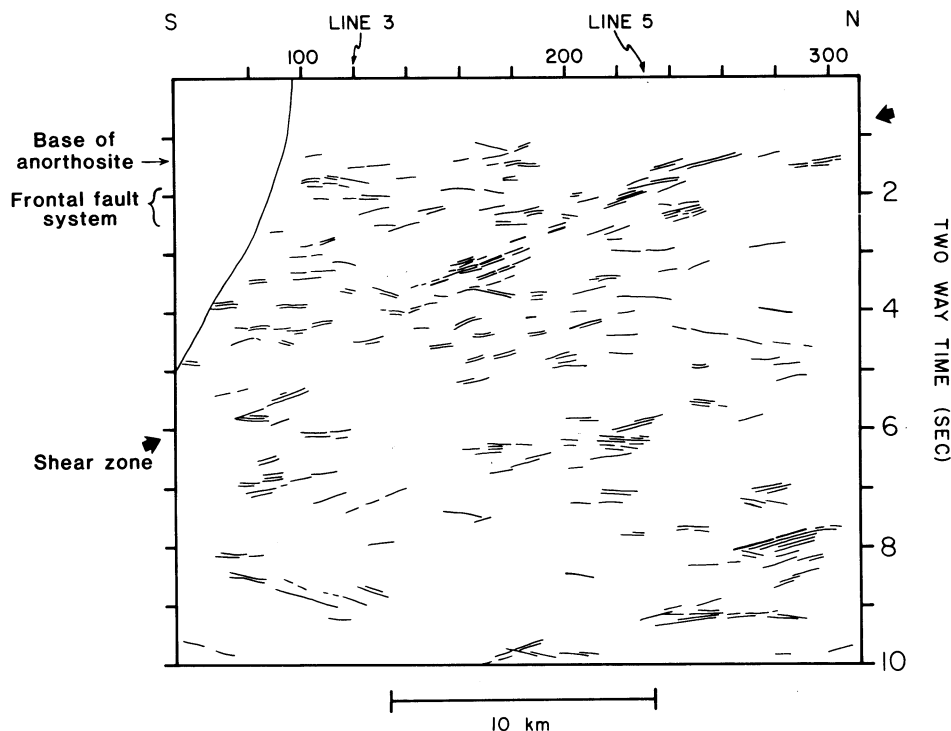


Figure 5. Line drawing of the top 10 s of line 4. Note the prominent band of events with an apparent south dip (that is, to the left). This band may correspond to the northeast extension of the MCNF shear zone.

WYOMING LINE 5, EAST END

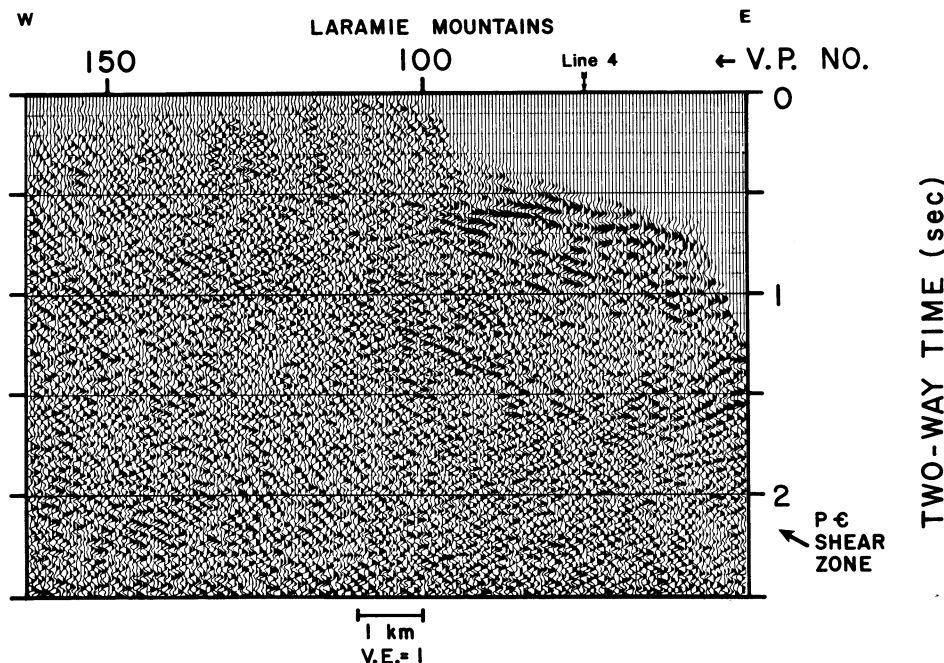


Figure 6. Detail of COCORP Wyoming line 5 at the southeast end. The southeast-dipping shear zone event can be seen between VPs 70 and 100 and may extend as far northwest as VP 140 (at 0.8 s, about 2.5 km). Events with westerly or northwesterly dip at southeast end (right side) of line 1.5 s (4.5 km) may correspond to the frontal thrust (see Brewer and others, 1982).

tween basement under the Laramie Mountains and that under the basin to the west (Fig. 7). This contrast is probably related to near-surface attenuation of seismic waves and surface coupling effects rather than to basement structure. Seismic traces recorded by geophones planted in the sedimentary section have a notably lower frequency content than those recorded by geophones in the Precambrian rocks in the mountains. The change in character noted on line 5 between stations 185 and 233 coincides with the transition in the survey from all geophones planted in basin sediments to all in high-velocity Precambrian rocks. A similar but less pronounced change in frequencies can be noted on line 3 at the transition between the Denver Basin and mountains.

Thus, the apparent truncation of a very pronounced basement event at 4.3 sec (13 km) is probably, for the most part, an artifact of the survey rather than a representation of a real structure in the basement (Fig. 7). Close inspection of the 4.3-s event on line 5 (Fig. 7) shows that it continues southeastward beyond VP 200, although with modified character, probably due to survey considerations noted above. The event may be offset from 4.3 s to 4.5 s under VP 190 (an approximate vertical throw of 600 m) and can be traced eastward at least to VP 150 and possibly to VP 100. The offset on the event may be due to the reverse fault bounding the east side of the anorthosite body east of station 1 on line 5 (Brewer and others, 1982) or to a minor, northeast-trending strike-slip fault (Fig. 2) that may have been reactivated during Laramide deformation. This latter possibility is suggested by diffractions between 2 and 4 sec on line 5 (not shown).

The 4.3-sec event (Fig. 7) is only part of a complex set of reflections that constitute the most prominent basement events in the entire Laramie Range survey. Of particular importance is that the flat part of the 4.3-s event appears to truncate dipping reflections below it, in a relationship suggestive of an erosional truncation. After simple manual and computer migrations, the dipping events shift to the right but still do not cut across the horizontal event. Basement events on line 6 between 2.3 and 6 s (10 to 18 km) exhibit somewhat similar seismic character; other events are probably multiples (Fig. 8). All of these events are in crust on the northwest side of the shear zone.

Interpretation of these reflections is difficult. North of the MCNF shear zone in the Medicine Bow Mountains (Fig. 1), 15 km of Proterozoic quartzite and related rocks

constitute one of the thickest known sections of Precambrian metasedimentary rocks in North America (Houston and others, 1979). It is tempting to relate the 4.3-sec event (at approximately 13-km depth) to those Proterozoic metasediments. However, fragmentary field evidence suggests that Proterozoic metasediments are completely lacking north of the shear zone in the Richeau Hills and probably in the Laramie Mountains as well (Graff and others, 1980). Thus, the most we can say about the 4.3-s event and others of similar character is that they may represent complex tectonic or sedimentary structures in rocks associated with the Archean terrane.

SEISMIC FABRIC OF THE BASEMENT ON LINES 5 AND 6

At the northwest end of line 5 and the northeast end of line 6, most of the basement is characterized by dipping reflections (Fig. 9). Because these can be correlated between the two sections, a true dip and dip direction can be determined. Although somewhat variable, the dip is generally southeasterly and ranges between 30° and 55° (determined by manual migration). Less pronounced events in the deep part of line 5 between VPs 100 and 350 exhibit the same apparent dip direction. In general, both lines 5 and 6 display numerous basement reflections in the upper 5 or 6 sec. The dominant structural grain of the basement appears to be dipping southeasterly, paralleling the shear zone reflections. Since the dips are the same direction as the overlying sediments, some of these events may be multiples, although few can be explained by simple multiple paths. The strongest evidence that at least some of these southeast-dipping events correspond to real basement structure is the observation that the shear zone as well as deeper events to the north on line 4 (Fig. 5), entirely within the Laramie Mountains, have nearly identical dip and dip directions to the southeast.

Structures north of, but related to, the shear zone in the Medicine Bow Mountains are characterized by southeast-dipping imbricate thrust faults and overturned folds (Fig. 1; Houston, 1971; Karlstrom and others, 1981). We interpret the seismic fabric north of the shear zone on lines 4, 5, and 6 as either the roots of these structures in the Archean basement terrane, or perhaps as a set of parallel shear zones of which the MCNF is just one prominent member. Interestingly, Laramide folds in the Laramie Basin just north of line 5 trend to the north-

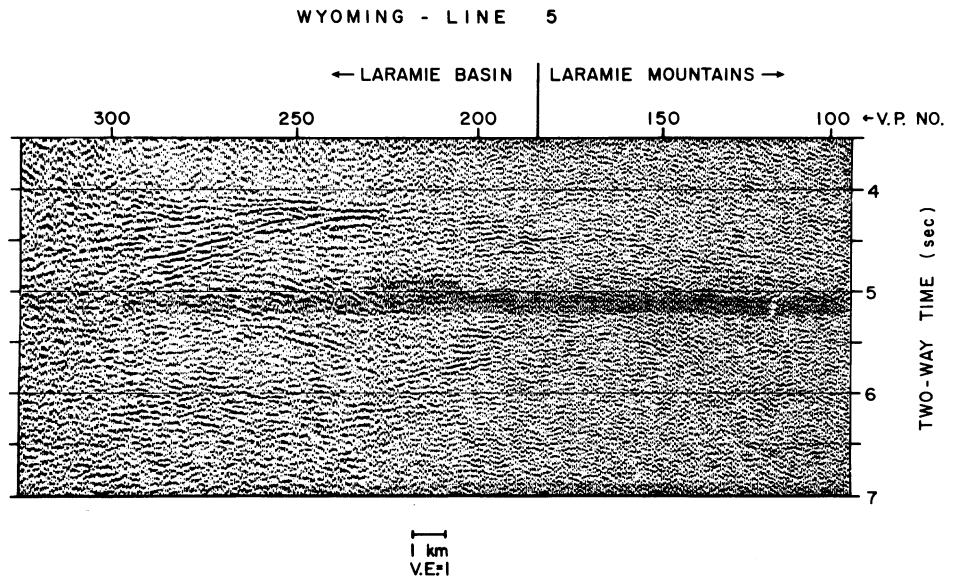


Figure 7. Detail of middle part of COCORP Wyoming line 5 between 3.5 and 7.0 s (10 and 20 km) showing strong but complex and enigmatic basement reflections that may correspond to deformed rocks associated with the Archean terrane. Note change in seismic character (corresponding to change in frequencies) between VPs 185 and 235, which is the zone of transition between all geophones in mountains and all geophones in Laramie Basin. The prominent band of events between 4 and 5 s (12 and 15 km) extends under the mountains to at least VP 100.

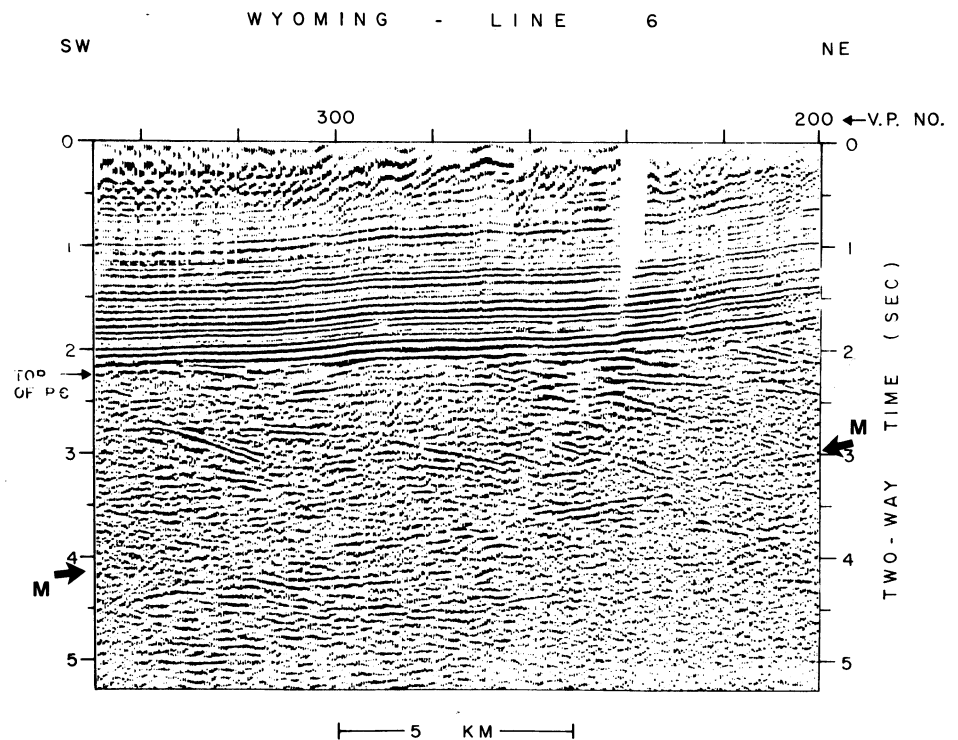


Figure 8. Detail of middle part of COCORP Wyoming line 6 between 0 and 5.5 s (0 and 16 km) displaying shallow, complex basement structure. Note the similar seismic character shown in Figure 7. This section has not been deconvolved and some events (particularly those paralleling the base of the sedimentary section, labeled "M") may be multiples. However, the events with apparent dip to the northeast cannot result from a simple multiple path.

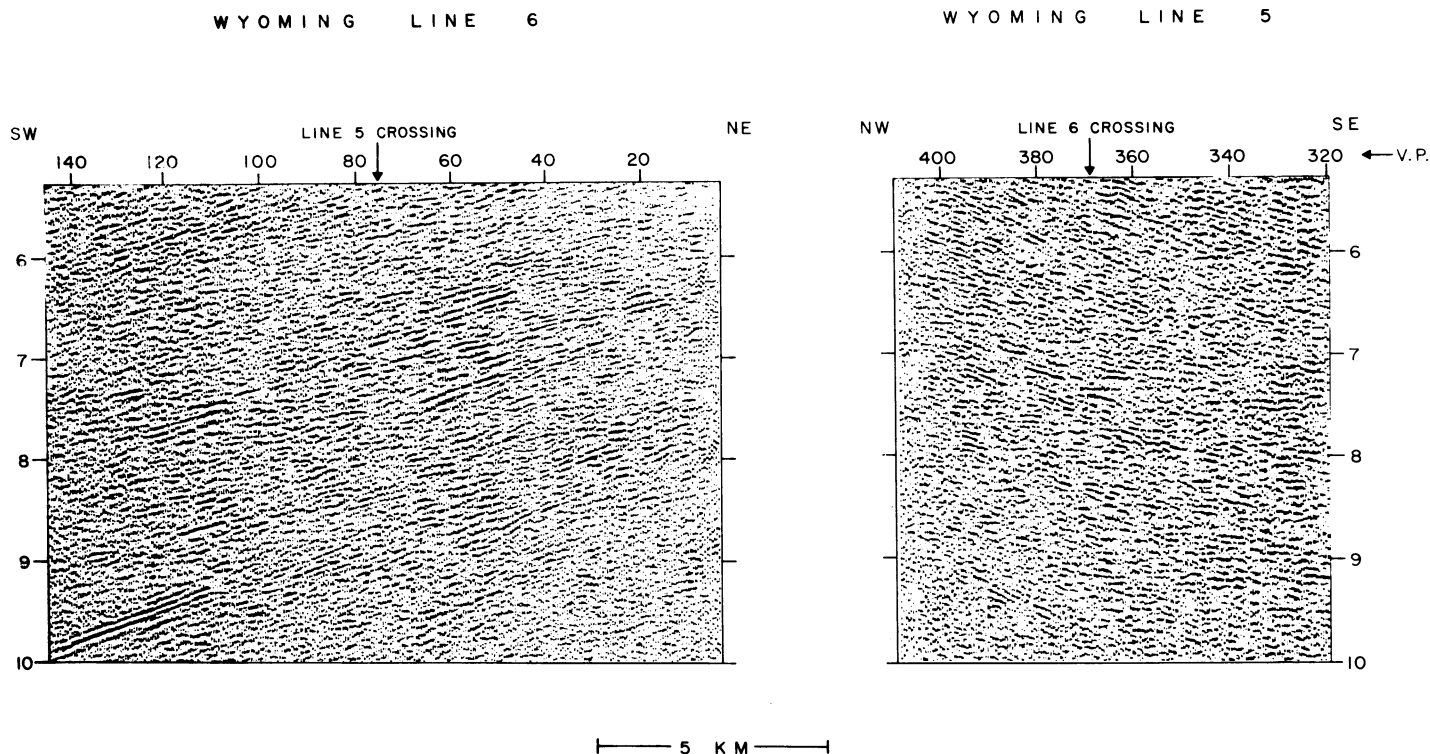


Figure 9. Detail of corresponding dipping events on the northwest end of line 5 and northeast end of line 6, between 5.5 and 10 s (16- and 30-km depth). These lines show that the basement north of the shear zone has a fabric with a true dip to the southeast, although some events may be multiples.

east (Fig. 1) and may be a further suggestion of reactivation of Precambrian structures during the early Tertiary.

Events near the Base of the Crust

On line 3, a relatively continuous band of events occurs at 17 s (48 km) under the Denver Basin and rises gradually westward (with gaps in poor data areas) to 15.5 to 16.0 s (also about 48 km) where sedimentary cover is thinner. This band, consisting of 2 to 4 cycles in general, is particularly well developed beneath VPs 340 and 500 near its western limit of resolution (Fig. 10). Auto-correlation tests and velocity analysis showing negligible move-out characteristic of deep basement events strongly suggest that this feature is not a multiple. Thus, the layer is relatively flat (the time difference is due to velocity pull-up under the thinner sedimentary cover) and lies at about 48-km depth. This depth is nearly identical to that of the Moho indicated by refraction lines in northeastern Colorado (Jackson and others, 1963) and slightly less than the crustal thickness observed under the Colorado Front Range west of Denver (52 km; Prodehl and Pakiser, 1980). We conclude that this band of events may represent the transition from crust to mantle under the Denver Basin and south of the Cheyenne belt.

Continuous deep crustal events are not readily apparent on the western one-third of line 3, nor on any of the other lines in the Laramie survey. On line 4, the deepest events, occurring between 11.0 and 12.5 sec, are discontinuous and some have unmi-

grated apparent dips as high as 15°. These times correspond approximately to depths between 36 and 38 km. The deepest crustal events on lines 5 and 6 are similar in character to those on line 4 and occur between 12.0 and 13.5 sec (about 37 to 40 km). The dip-

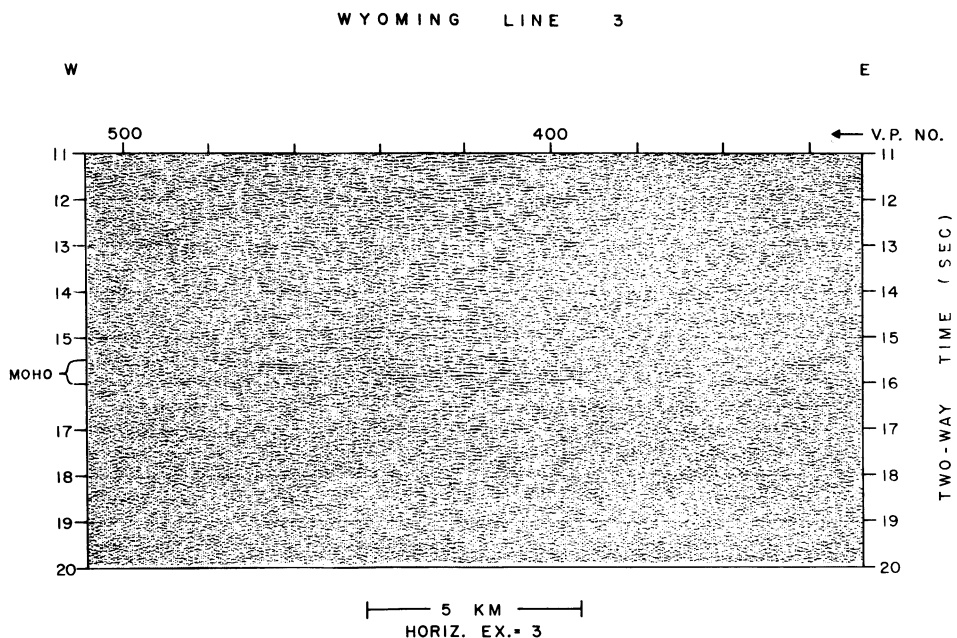


Figure 10. Detail of probable Moho reflections on line 3 at 15.5 to 16 s (46.5- to 48-km depth). The resolution of the reflection deteriorates in poor data area at east/right side of section. See text for discussion.

ping events may be unmigrated reflections or diffractions from features shallower in the crust or out of the plane of the section; and, some of those located under the Laramie Basin may be multiples from the sedimentary section. However, discontinuous horizontal events under the mountains probably are not multiples and will not migrate to a shallower level in the crust. These reflections occur near the same depth as the local Moho defined by unreversed refraction surveys (37 to 39 km; Prodehl and Pakiser, 1980).

These data suggest that the crust may be as much as 10 km thinner north of the shear zone than it is to the south. Gravity data collected by Smithson (Houston and others, 1979), although apparently not exhibiting a distinct gradient across the surface trace of the shear zone, indicate more negative anomalies (and therefore thicker and/or less dense crust) south of the shear zone. A definitive test of this hypothesis would be refraction or wide-angle reflection surveys east of the mountains and south of the shear zone. Furthermore, the COCORP surveys

in the Laramide Mountains and Wind River Mountains of Wyoming (Smithson and others, 1978, 1979) indicate that high-resolution reflection techniques in the Wyoming part of the Laramide province do not show a simple, laterally continuous crust-mantle transition. Immediately east and west of the bounding uplifts (that is, under the Denver Basin and Green River Basin), individual events can be correlated with the Moho. At present, we are unable to determine whether lack of coherent events correlating with the Moho in this province is a product or a cause of Laramide or older deformation, or a function of the surveying techniques.

Summary: Precambrian Basement Structure of the Laramie Area

The COCORP seismic sections resolve considerable detail within the Precambrian basement of the Laramie Mountains and surrounding basins. The shallow structures beneath the mountains appear to be controlled by the west-dipping compositional foliation in the Laramie Anorthosite and related rocks. The frontal thrust system of the Laramide deformation parallels this Precambrian foliation. However, the base of the anorthosite interpreted to be the intrusive contact of a body of Sherman Granite dips gently southeastward and rises from 4-km depth on line 3 to 1.5 km or less under the middle of line 4.

The boundary between the Archean Proterozoic basement provinces (the Cheyenne belt) probably appears on line 4 as a complex band of short, discontinuous events with a southward dip component. Events on line 5 in the same time interval suggest that the Precambrian boundary and Laramide structures controlled by it dip to the southeast at 55° (migrated). Where exposed at the surface, the shear zone dips more steeply, but in the same southeasterly direction (Houston and others, 1968). The seismic fabric of the Archean basement north of the shear zone also dips to the southeast and probably represents a family of subsidiary shear zones or imbricate thrust faults. These and similar structures may control the orientation of northeast-trending, Laramide folds in the Laramie Basin. If the accretion and suturing model of Houston and others (1979) is correct, then the COCORP Laramie data show a more steeply dipping fault and less apparent overthrusting than noted in the COCORP Southern Appalachian traverse (Cook and others, 1979). These differences may be due to fundamental differences between Phan-

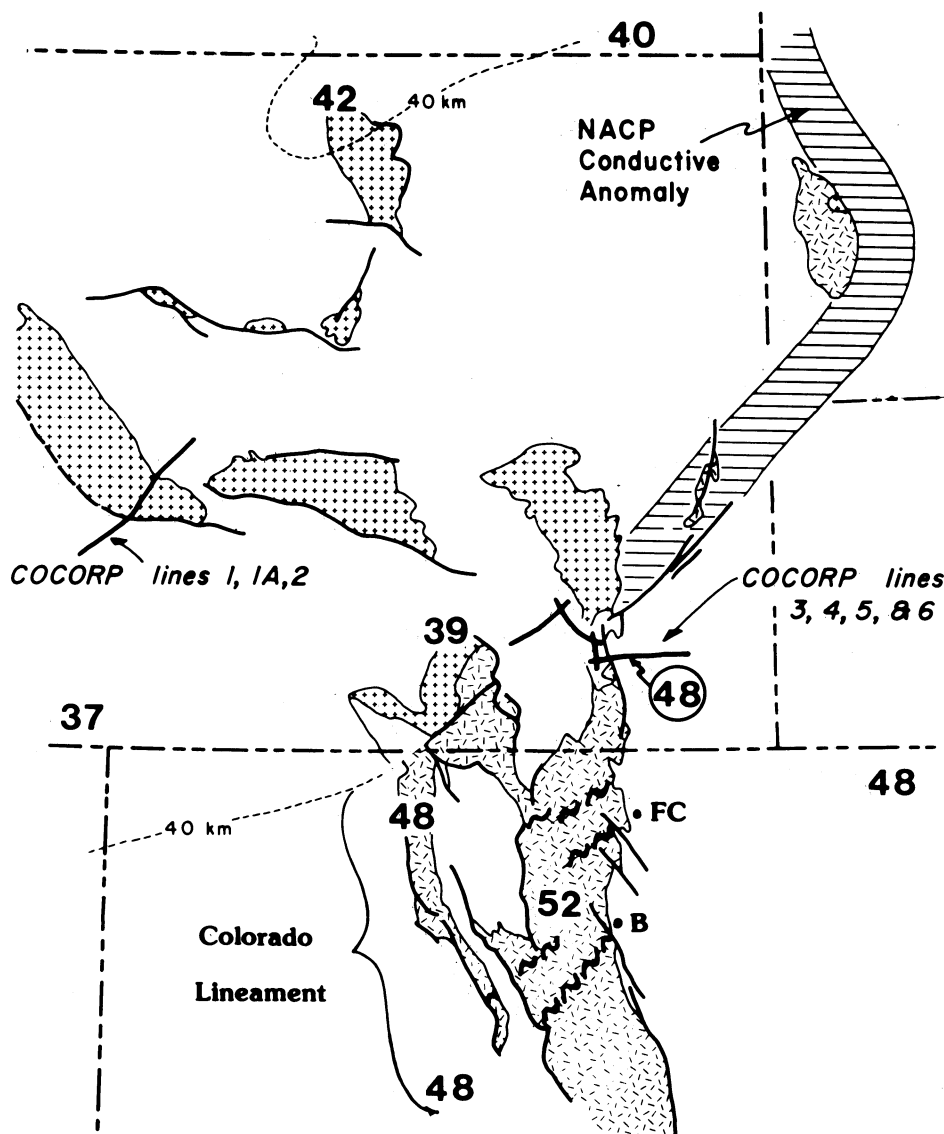


Figure 11. Generalized map summarizing crustal thickness data for the Laramide province in Colorado, Wyoming, and South Dakota. Bold, plain numbers show thicknesses determined by seismic-refraction surveys (Jackson and others, 1963; Warren and Healy, 1973; Prodehl and Pakiser, 1980). Bold circled number shows thickness inferred from COCORP data. The 40-km crustal thickness contour modified after Warren and Healy (1973). Position of the North American Central Plains (NACP) conductive anomaly from Camfield and Gough (1977). Dashed pattern shows outcrop of Proterozoic rocks; pluses show outcrop of Archean rocks. Locations of COCORP lines in the Wind River (1, 1A, and 2) and Laramie (3, 4, 5 and 6) Ranges are shown.

erozoic and Proterozoic collisional tectonics, strike-slip motion on the Cheyenne belt (Warner, 1978), or both.

COCORP profiling and published seismic refraction and gravity data suggest that the crust may be 10 km thinner in the Archean terrane north of the shear zone than it is to the south. Although the data set is small, COCORP profiles in the Laramie and Wind River Mountains indicate that the crust-mantle transition is not well resolved by deep seismic-reflection techniques in the Wyoming part of the Laramide province, but immediately outside on both the east (Denver Basin) and west (Green River Basin), prominent possible Moho reflectors are seen.

REGIONAL SIGNIFICANCE OF THE ARCHEAN- PROTEROZOIC BOUNDARY

Although the Rocky Mountain Front in Colorado and southern Wyoming is a morphologically discrete entity, structural geometry along it varies significantly (Fig. 11). South of Boulder, Colorado, the Golden fault and related structures dip westward and probably have a reverse sense of displacement, placing Proterozoic crystalline rocks at depth over sediments in the Denver Basin. North of Boulder, the structure of the Front is characterized by small, north-northwest-trending, en echelon reverse or thrust faults which dip to the northeast and involve basement. In this interval, west-dipping thrusts bounding the Front are not observed at the surface. Finally, north of the Colorado-Wyoming state line, the Front is again bounded by a west-dipping thrust, as discussed in Brewer and others (1982). The changes in frontal structure along trend tend to correlate with major shear zones in the Colorado Lineament (Tweto and Sims, 1963; Warner, 1978), indicating Precambrian structural control of Laramide deformation. The largest feature in the Colorado Lineament is the MCNF shear zone, which may form or be part of the Archean-Proterozoic boundary.

Although we do not see a discrete offset of the crust-mantle transition across the shear zone, COCORP and other geophysical data suggest significant northward thinning of the crust in the vicinity. More regional data (Fig. 11), although sparse, indicate that throughout the central Rocky Mountains, the crust may be thinner within the Archean basement than in the Proterozoic basement (Warren and Healy, 1973;

Prodehl, 1979; Prodehl and Pakiser, 1980). A possible northeastern extension of the Proterozoic shear zone is indicated by the North American Central Plains (NACP) conductive anomaly. Camfield and Gough (1977) have mapped this electrical conductivity layer from Canada southward, skirting the eastern edge of the Black Hills, and at its southern end, coinciding with the northeast projection of the Mullen Creek-Nash Fork shear zone. Although most of the basement in the Black Hills is Proterozoic, pieces of Archean crust remain (Petersman, 1981). There are no seismic refraction data there, but scattered surveys to the northwest in Wyoming and Montana suggest that the crust is 40 km thick and thickens northward (Fig. 11).

Data bearing on crustal thickness in central Wyoming are lacking, and thus well-constrained models are impossible. However, it is interesting to speculate that the entire Wyoming part of the Laramide province, including the Black Hills, may be part of a lobe of relatively thinner Archean crust; south and east of this lobe, the crust may thicken irregularly by as much as 10 km across the Archean-Proterozoic boundary and shear zone.

The implications of such a model of crustal thickness changes, if correct, for the tectonics of the Rocky Mountains region since the Proterozoic are intriguing. The most obvious of these is the over-all difference between Laramide uplifts in Wyoming, which have a wide range of orientations, and those in Colorado, which trend dominantly north-northwest. Sales (1968) attributed the difference to a major, left-lateral shear couple superposed on the region. By contrast, Houston (1971) postulated that the differences might in some way be due to the MCNF shear zone. Our data show important differences between the seismic fabrics of Archean and Proterozoic basement. In the Archean terrane north of the shear zone, the orientation of Laramide structures appears to be strongly controlled by Precambrian structures, whereas to the south both Precambrian and Paleozoic structures, which exhibit significantly different trends than to the north, have strongly influenced Laramide deformation. The marked increase in diversity of Laramide structural trends in Wyoming correlates closely with the region of possibly thinner Archean crust. Thus, although we cannot determine the relative importance, some combination of thinner crust and greater crustal heterogeneity the Archean of Wyoming may

account for the increase diversity in Laramide structures, including the Black Hills. The importance of Precambrian structure, stressed in this paper, does not discount any of a number of large-scale tectonic schemes for Laramide deformation (Sales, 1968; Dickinson and Snyder, 1978; Brewer and others, 1980; Hamilton, 1981). However, the influence of the pre-existing architecture of the continental crust must be considered in attempting to understand any subsequent deformation.

ACKNOWLEDGMENTS

The field data for the Laramie survey were collected by crew 6834 of Petty-Ray Geophysical, a division of Geosource, Inc. Processing of the data was done both by Geosource and on the Megaseis computer system at Cornell University. We would like to thank the COCORP site selection and technical advisory committees and personnel at Cornell for advice and assistance. D. L. Blackstone, M. McCallum, O. Tweto, and L. A. Warner provided very helpful reviews of the manuscript. The cooperation of federal and state officials and local landowners is much appreciated. This research was supported by the National Science Foundation under Grants EAR-78-23672 and EAR-78-23673 to Cornell University and Grant EAR-80-26580 to the University of Wyoming.

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MANUSCRIPT RECEIVED BY THE SOCIETY

AUGUST 10, 1981

REVISED MANUSCRIPT RECEIVED

DECEMBER 16, 1981

MANUSCRIPT ACCEPTED JANUARY 19, 1982

CORNELL CONTRIBUTION NO. 693