

COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part 1: Laramide structure

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ABSTRACT

COCORP deep seismic-reflection profiles have been recorded showing significant crustal deformation of the North American craton; profiles were made across the Laramie Mountains, the Wyoming section of the Front separating the southern Rocky Mountains from the Great Plains, and eastern margin, in Wyoming and Colorado. These mountains are underlain by a series of westerly dipping seismic reflectors traceable as deep as 10 to 12 km, arranged en echelon with various dips (20° to 50°), which in some cases can be traced to the surface position of faults flanking the Laramie Mountains. Although other interpretations are possible, the reflectors are thought to be thrust faults, whose distribution and orientation suggest that the mountains were uplifted by horizontal crustal shortening during the Laramide orogeny. These inferred thrusts apparently do not generate such pronounced fault-zone reflections as those seen on COCORP lines recorded across the Wind River Mountains in Wyoming, probably because fault displacements were much smaller. Differential movements along the thrusts may explain variations in the character of the Rocky Mountain Front in the region of the COCORP lines. On the basis of morphological continuity, the Front in Colorado may also have been uplifted by crustal shortening with variations of structural style caused by adjustments to Precambrian and Ancestral Rockies structures. COCORP data have now been recorded across two mountain ranges lying on the eastern and western margins of the region of Laramide base-

ment uplifts in Wyoming. Both ranges (Laramie and Wind River) apparently are underlain by moderately dipping thrust faults. Probably, crustal shortening by lateral compression was the dominant cause of

the Laramide basement uplifts. These mountain-building compressional stresses were transmitted to the interior of the continent, 1,000 to 1,500 km from an active plate margin.

INTRODUCTION

The Rocky Mountain Front forms the distinctive boundary between the Great Plains and the southern Rocky Mountains of Colorado and Wyoming (Fenneman, 1931; Tweto, 1975) and represents the east-

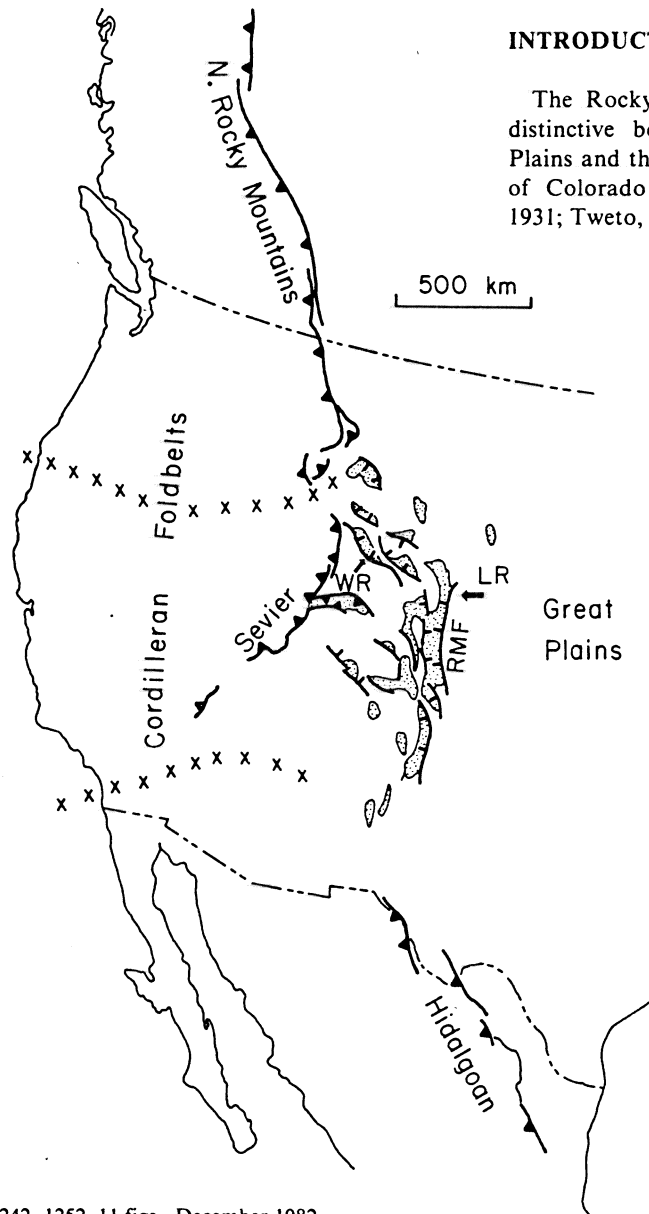


Figure 1. Distribution of Laramide basement uplifts in the North American craton (shaded areas). Faults flanking uplifts are usually reverse and are indicated by ticked lines. Eastern limits of Late Cretaceous-early Tertiary fold-thrust belts marked by barbed lines. Crosses indicate the three main segments of Late Cretaceous-early Tertiary deformation (after Armstrong, 1974). Arrows indicate positions of COCORP traverses; WR = Wind River survey, LR = Laramie survey; RMF = Rocky Mountain Front.

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ernmost extent, with the exception of the Black Hills of South Dakota, of Laramide crustal disruption in the Cordilleran Foreland (Fig. 1). The crustal disruption consists of massive basement uplifts, and there has been much debate about the relative importance of lateral versus vertical movements of the crust during their formation (Matthews, 1976; Stearns, 1978). The uplifts are characterized by large basement relief (>12 km in some cases; Love, 1960), flanking reverse faults of various orientations, and diverse structural trends. This deformation occurred in a region 1,000 to 1,500 km from the North American plate margin (Burchfiel and Davis, 1975) and is not easily explained in terms of plate-margin processes. In an effort to resolve the debate over uplift origin, the Consortium for Continental Reflection Profiling (COCORP) in 1976 and 1977 carried out a deep seismic survey across the Wind River Mountains in Wyoming, the largest of the basement uplifts (Fig. 2). The results showed that these mountains are underlain by a moderately dipping thrust fault, traceable to lower crustal depths, and thus must have formed by horizontal shortening of the Earth's crust (Smithson and others, 1979; Lynn, 1979; Brewer and others, 1980). In order to test whether this structural style applied to other basement uplifts and to study the nature of the transition between the Rocky Mountains and the Great Plains to the east, COCORP profiles were recorded across the Laramie Mountains¹ in 1979 (Fig. 2). Vertical and horizontal movements have been variously suggested for different parts of the Front by Boos and Boos (1957), Osterwald (1961), Harms (1965), Prucha and others (1966), LeMasurier (1970), Matthews and Work (1978), and others. The COCORP profiles show that, in at least part of their length, the Laramie Mountains are underlain by a series of westerly dipping, en echelon reflectors. These reflectors are interpreted as thrust faults, although they could represent lithologic features in the basement. If they are thrust faults, they are of much smaller magnitude than the Wind River fault, but, like that fault, they suggest uplift primarily by lateral shortening of the Earth's crust.

On a broader scale, the thrust faults that are inferred from the COCORP profiles

crossing both the western (Wind River) and eastern (Laramie) margins of the region of basement uplifts suggest that crustal compression was probably the dominant tectonic regime during the Laramide orogeny, at least in southern Wyoming. The extrapolation of the Laramie survey results on the basis of morphological continuity of the range along strike to the south also suggests that crustal shortening was the primary cause of uplift along the Front Range in Colorado. If that is correct, this shortening was apparently expressed in some areas by near-surface vertical movements (Matthews

and Work, 1978), and pre-Laramide features may have influenced structural style (Tweto, 1975).

This paper describes and discusses those results of the COCORP survey across the Laramide Mountains that bear on the problem of Laramide deformation. A companion paper (Allmendinger and others, 1982) discusses the implications of these data for Precambrian geology and its relationship to Laramide tectonics; for, in addition to these inferred thrust faults in the upper crust, many deeper seismic events east and west of the front were recorded. The crust in this

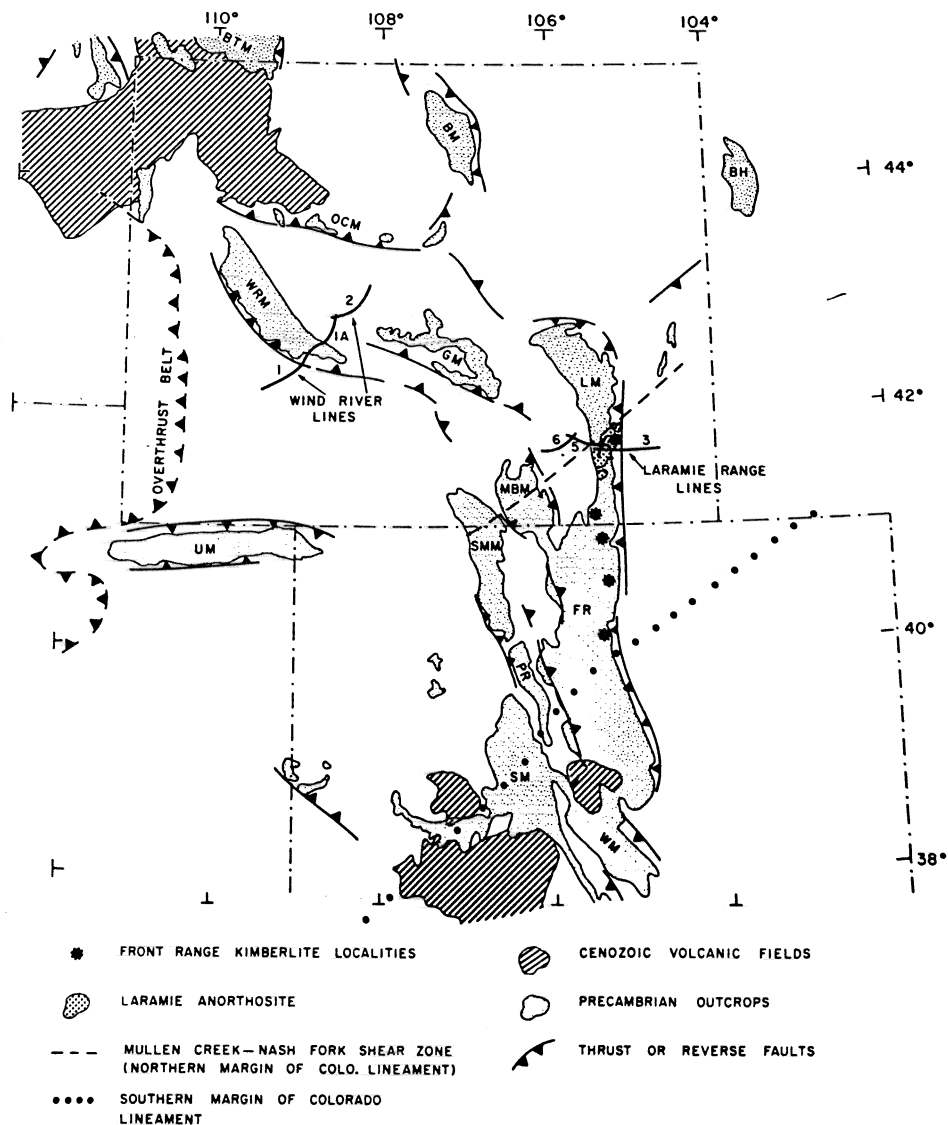


Figure 2. Major geological features of Wyoming and Colorado in the vicinity of the COCORP lines. Base map is after Rocky Mountain Association of Geologists Geological Atlas. Mountain ranges are: BTM, Beartooth Mountains; BM, Bighorn Mountains; OCM, Owl Creek Mountains; WRM, Wind River Mountains; GM, Granite Mountains; BH, Black Hills; LM, Laramie Mountains; MBM, Medicine Bow Mountains; SMM, Sierra Madre Mountains; FR, Front Range; PR, Park Range; SM, Sawatch Mountains; WM, Wet Mountains; VM, Vista Mountains.

¹Although the site crosses the Front in an area where it is topographically subdued, it was chosen from logistical considerations and because of the possibility of studying preferred changes in basement structures.

area has been affected by both Precambrian and late Paleozoic (Ancestral Rockies) deformation, so that many of the reflections on the COCORP data may be due to pre-Laramide structures. However, reflections can be distinguished if they can be traced or extrapolated to the surface to match known features there. An event at ~48-km depth may indicate a horizontal and relatively continuous Moho under the Great Plains, whereas within the Rocky Mountains, events which may be from the deep crust are at shallower depths and laterally more discontinuous. This apparent change in depth and character of the crust-mantle transition may coincide with an Archean-Proterozoic crustal boundary, the Mullen Creek-Nash Fork shear zone, which from the COCORP data appears to dip at about 55° to the southeast. These reflection data and published refraction and gravity surveys suggest that the Archean crust north of the shear zone may be as much as 10 km thinner than the Proterozoic crust to the south. This crustal thinning may have been responsible for the differences in Laramide structure between Wyoming and Colorado (Allmendinger and others, 1982).

GEOLOGICAL AND GEOPHYSICAL SETTING OF THE LARAMIE MOUNTAINS

Late Cretaceous-early Tertiary deformation occurred along the length of western North America in three main segments: (1) Alaska-northern Montana; (2) Wyoming and Colorado; (3) Arizona-Mexico (see Fig. 1; see also Armstrong, 1974). The northern and southern segments are mainly thin-skinned fold-thrust belts, structurally similar to the Late Jurassic-Late Cretaceous-early Tertiary Sevier belt (Armstrong, 1968). In contrast, the central portion consists of uplifts of Precambrian basement bounded by reverse faults ("thick-skinned deformation"). The uplifts lie east of the Sevier belt and extend farther east into the craton than either of the northern and southern segments (Fig. 1). Deformation occurred mainly from Late Cretaceous to early Eocene times (Love, 1960), during this period, magmatic activity in the central portion was less pronounced than in the northern and southern segments (Snyder and others, 1976).

Structures in the North American Cordil-

era are probably related to active Mesozoic-early Tertiary subduction and are possibly analogous with structures in the central Andes caused by Tertiary-Holocene subduction along the west coast of South America (Sales, 1968; Hamilton, 1969; Jordan and others, 1983). Armstrong (1974) and Burchfiel and Davis (1975) suggest that change from thin- to thick-skinned deformation might be related to ductility controls (reflected in the distribution of magmatic activity), possibly caused by changes in dip of Benioff zones such as are found under the Andes of South America (Barazangi and Isacks, 1976; Burchfiel and Davis, 1976). Coney (1976), Cross and Pilger (1978), Dickinson and Snyder (1978), and Brewer and others (1980) specifically relate the Laramide basement uplifts to a shallowly dipping subduction zone during the early Cenozoic.

The Laramie Mountains (Fig. 1) are bordered structurally by the Denver Basin on the east and the Laramie Basin on the west. The mountains form the Wyoming section of the Rocky Mountain Front, the impressive morphological boundary between the basement uplifts of the southern Rocky

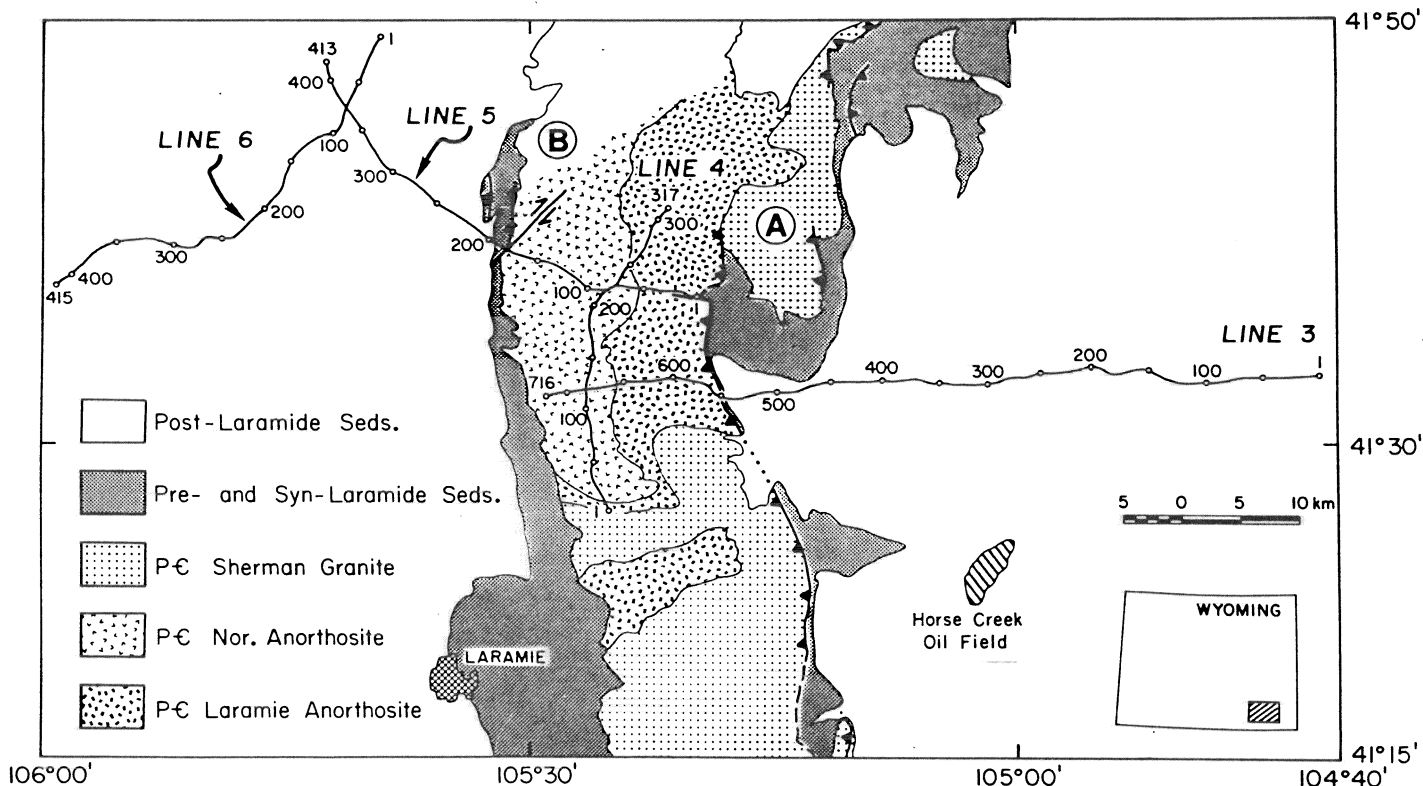


Figure 3. Location of COCORP lines in the Laramie Mountains. Base map after Newhouse and Hagner (1957). Numbers along the lines indicate Vibration Points (VPs). Letter "A" marks the eastern salient in the Laramie Mountain front; letter "B" marks minor Laramide reverse faults on the west flank of the mountains. Note reverse fault that projects to VP 210 on line 5.

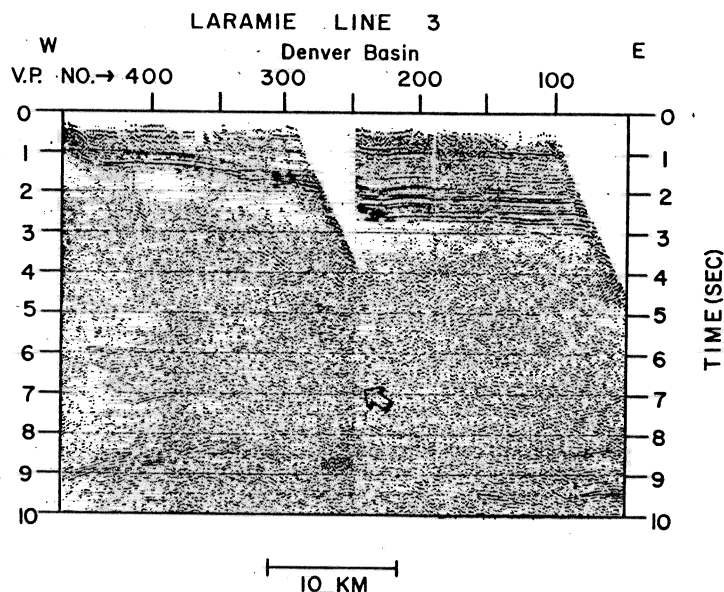


Figure 4. Eastern half of COCORP line 3 in Denver Basin. Vertical scale is two-way traveltime in seconds; to convert two-way traveltime in crystalline basement to approximate depth in kilometres, multiply by 3. Arrow marks position of easterly dipping events in basement under Denver Basin, possibly reflections from thrusts conjugate to those under Laramie Mountains.

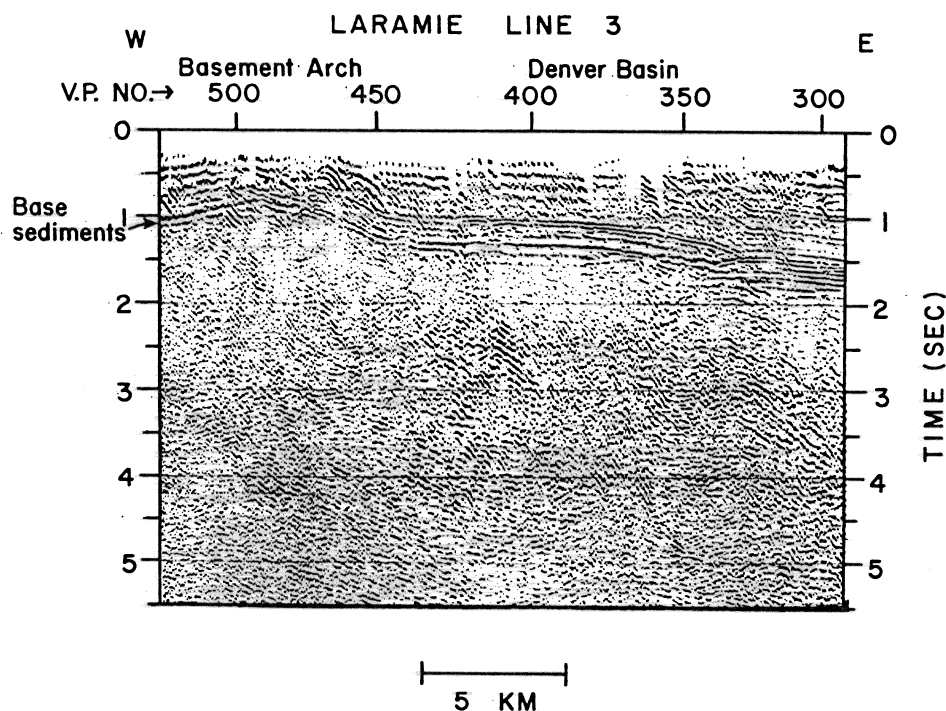


Figure 5. Wyoming line 3 showing basement arch under VPs 450-525 and flexure in sediments under VP 335.

Mountains (which rise to more than 4,200 m in height) and the gently sloping Great Plains to the east. In Colorado and Wyoming, the Front is remarkably linear, with an approximately north-south trend (Fig. 2). In Colorado, structural character of the boundary between the uplifted basement and the sedimentary rocks of the Denver Basin changes along the length of the Front, from folds to faults of variable dips and orientations (Boos and Boos, 1957). This

variation may reflect influence of Ancestral Rockies structures and inherited Precambrian fabrics (Boos and Boos, 1957; Mallory, 1972; Tweto, 1975; Allmendinger and others, 1982). The Front Range in Colorado was first uplifted in the latest Cretaceous (Tweto, 1975), while the Laramie Mountains to the north rose in the late Paleocene (probably during deposition of the Hanna Formation; Blackstone, 1975). In the vicinity of the COCORP lines, Newhouse and

Hagner (1957) mapped a reverse fault on the eastern side of the Laramie Mountains along which this uplift occurred. Fault dips and also dips of associated Laramide fractures in the Precambrian rocks are typically fairly high angle where they are exposed at the surface (S. B. Smithson, 1980, personal commun.).

A major Proterozoic boundary is well exposed southwest of the Laramie Mountains in the Medicine Bow Mountains (Houston and others, 1968), and its inferred extension through the Laramie Mountains to the northeast is crossed by the COCORP lines. Granitic rocks of age >2.5 b.y. lie north of the boundary, and rocks of age <1.7 b.y. lie south (Hills and Armstrong, 1974; Hills and Houston, 1977). The shear zone is largely obscured in the Laramie Mountains by an anorthosite body about 1.4 b.y. old (Hills and Armstrong, 1974), which is crossed by the COCORP lines. Aspects of the COCORP data relating to the Precambrian geology are discussed in Allmendinger and others (1982).

LARAMIDE STRUCTURES REVEALED BY COCORP DATA

Line Locations

Four lines, totaling 186 km in length and numbered 3 through 6, were recorded in the Laramie Mountains area by COCORP. Wyoming lines 1 and 2 are in the Wind River Mountains and are part of the earlier survey (Smithson and others, 1979). Wyoming line 3 runs west from the Denver Basin, crossing the frontal fault of the Laramie Mountains and ending in Precambrian outcrop on the west side. Line 4, running northward along the crest of the mountains, connects line 3 with line 5, the latter trending northwest off the dip slope of the mountains and across the Laramie Basin. Line 6 continues the traverse southwest through

the Laramie Basin, approaching the eastern edge of the Medicine Bow Mountains (Fig. 3). The COCORP profiles consist of 24-fold common depth point data collected using the VIBROSEIS² technique and a 96-channel recording system. Sweep lengths and recording times were adjusted to produce a 20 s record. Seismic-reflection profiling techniques are fully described by Dobrin (1976, p. 107), and a description of COCORP data acquisition and processing techniques may be found in Schilt and others (1979). Examples of the seismic data from Wyoming lines 3 and 5 are shown in Figures 4 through 9. Dip magnitudes quoted in this paper are those obtained from migration in the plane of the profile unless otherwise stated.

Sedimentary Rocks of the Denver Basin

Phanerozoic sediments of the Denver Basin (Martin, 1965) are essentially flat-lying between the eastern end of line 3 (where their thickness is 2.4 s or ~4.6 km) and Vibration Point (VP) 450 farther west (Fig. 4). Between VP 450 and the frontal fault of the Laramie Mountains (Newhouse and Hagner, 1957) at VP 550, these sediments are folded into a gentle anticline cored by basement rock (Fig. 5). At the mountain front, their thickness is about 1.0 s or about 1.7 km (Fig. 6).

The base of the sedimentary rocks in the Denver Basin has a distinctive reflection character that can be traced west of the mountain front, underlying Precambrian rocks exposed at the eastern margin of the Laramie Mountains (see A in Fig. 6). This distinctive horizon suggests Precambrian basement has overthrust the younger sediments by more than 3 km. However, shop-point gathers (field data) and common-depth-point stacks (Dobrin, 1976) incorporating variable ranges of receivers from the source show that its low-frequency character is recorded by receivers lying east of the mountain front, in the Denver Basin. The horizon is much less distinct on data recorded by receivers lying within the Precambrian of the Laramie Range, suggesting that the low-frequency character is due to attenuation of seismic energy propagating through Denver Basin sediments. This suggestion is supported by the notably lower frequency content of the seismic data east of the mountain front (Fig. 6) with respect to the data to the west.

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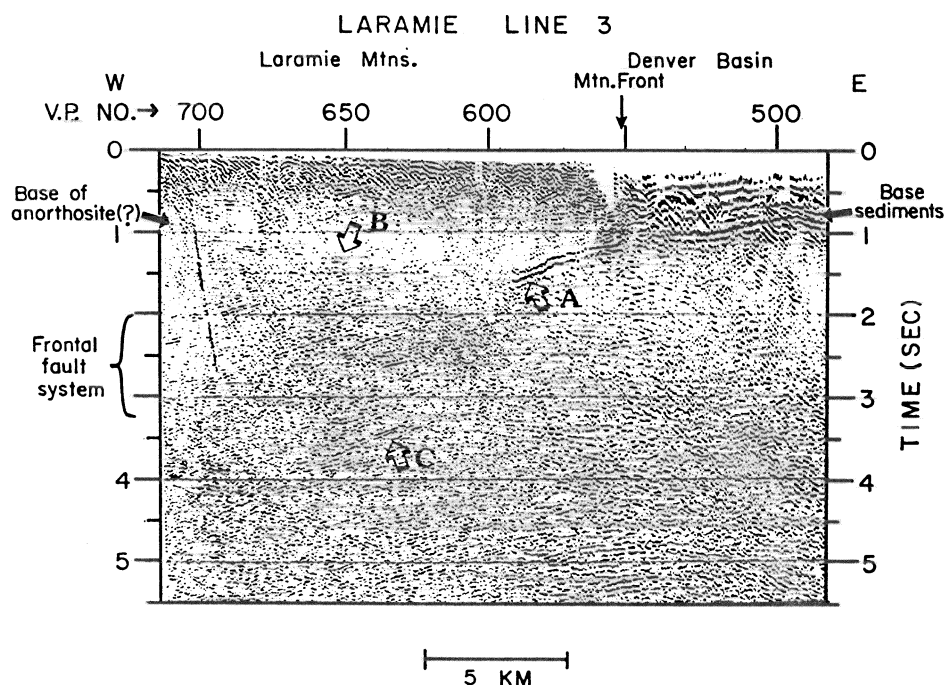


Figure 6. Wyoming line 3 showing transition from Denver Basin to Laramie Mountains. Letter "A" marks inferred basal sediments that can be traced as far as 3 km west of the mountain front, under the overhang of Precambrian rock. The term "Frontal Fault System" marks position of reflectors that can be traced to the surface in the vicinity of the mountain front and are probably thrust faults. Letter "B" marks inferred truncation of base of anorthosite by the Frontal Fault system. Event "C" has hyperbolic curvature and is possibly a diffraction.

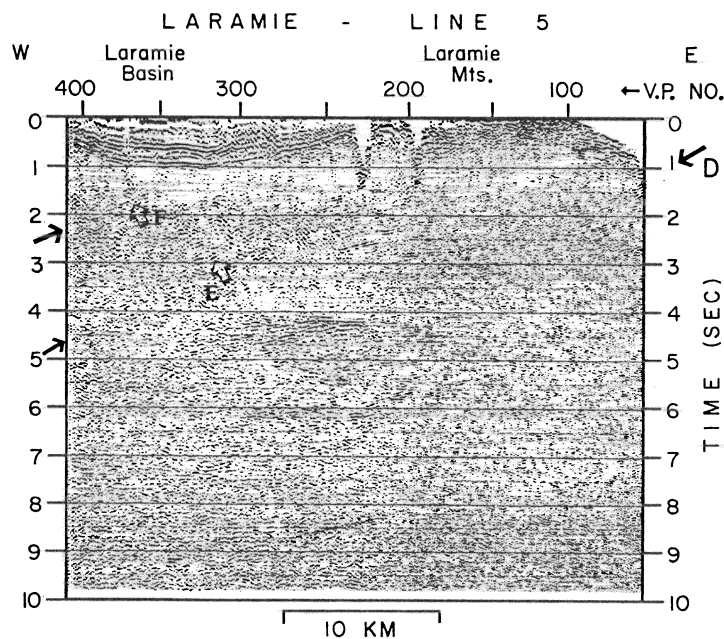


Figure 7. Wyoming line 5. Event "D" at right margin is 50° dipping frontal fault of the Laramie Mountains and events "E" and "F" mark two other possible thrusts under Laramie Basin. Strong reflector at 4.0–5.0 s under VPs 230–300 may be from Proterozoic sedimentary horizons (see Allmendinger and others, 1982).

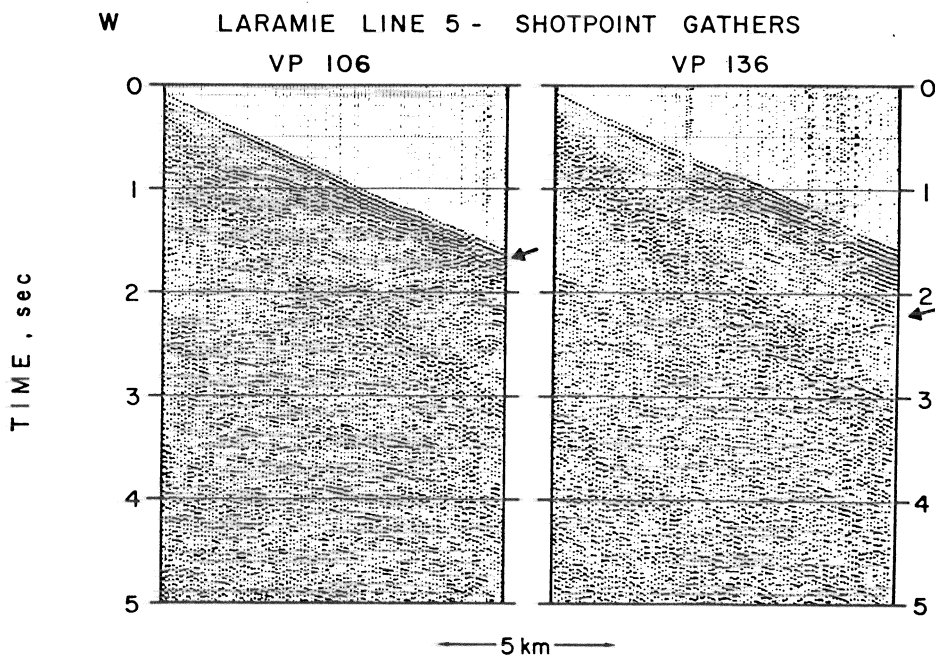


Figure 8. Selected shot-point gathers showing reverse-moveout events (marked by arrows) that are interpreted as reflections from an approximately 50° dipping frontal fault.

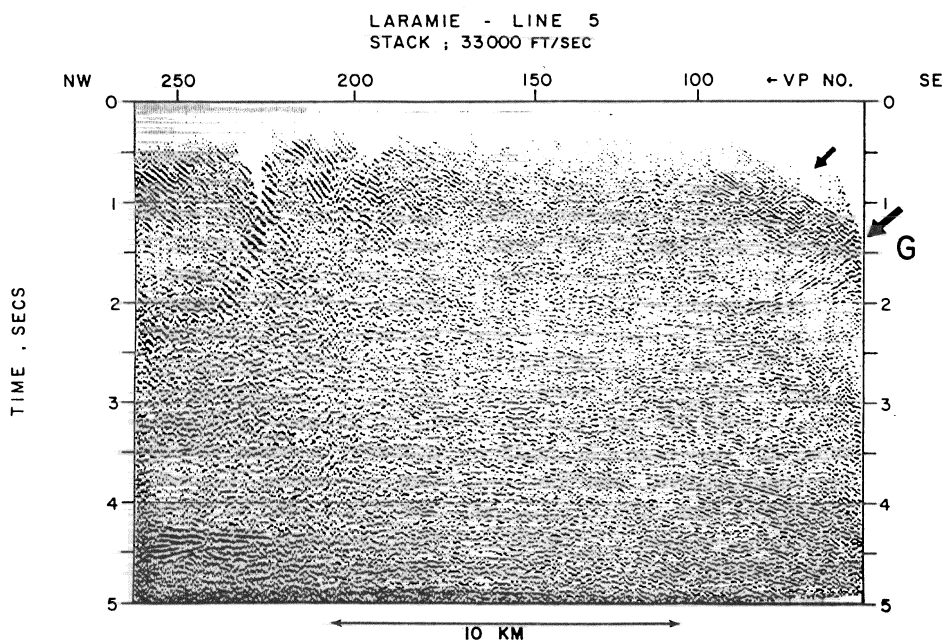


Figure 9. Wyoming line 5 constant velocity stack (33,000 ft/s or about 10 km/s). Event "G" is 50° dipping frontal fault, optimally imaged at this velocity. Smaller arrow represents dipping event that can be extrapolated to boundary between Laramie Anorthosite and Laramie noritic anorthosite in Laramie Mountains (VP 60 of line 5, Fig. 4; see also Allmendinger and others, 1982). The prominent "grain" in the near-surface that dips to the southeast is an artifact produced by the processing of this particular section.

An alternative interpretation of the distinct horizon (see A in Fig. 6) is that it is caused by seismic energy, generated by sources within the Laramie Mountains, that is reflected off sedimentary rocks which lie

only east of VP 550. This would imply little or no overthrusting of the mountain front. These alternatives could be distinguished by seismic profiling experiments designed to image near-surface structures with a higher

resolution than is possible using COCORP techniques. If the overthrust hypothesis is correct, then the overridden sedimentary layers dip at about 20° W to the vicinity of VP590, where event A lies more than 4 km deep (Fig. 6), implying that the front in this area is apparently underlain not by a steeply dipping fault but by a thrust, or series of thrusts, dipping approximately 20° W to 25° W.

Within the Denver Basin, east of VP 450 (the basement arch, Fig. 5), sedimentary rocks lie at three structural levels, shallowing westward. The deepest part of the basin lies east of VP 240 (at about 2.4 s or 4.6-km depth), and it thins farther west, to VP 290, where it lies at about 1.6 s or 2.9-km depth (Fig. 4). The cause of the thinning is not clear because of a gap in the data, and there is no clear indication of any fault attitudes. Offsets of Pennsylvanian horizons suggest that the flexure is a Laramide feature, although paleogeographical maps of Martin (1965) and Mallory (1967, 1972) indicate that the eastern edge of the Pennsylvanian Pathfinder uplift lay farther east, close to the present mountain front. Possibly, Laramide features were influenced by Pennsylvanian structures in this area. Thinning occurs again 6 km farther west due to uplift west of VP 335 (Figs. 4, 5). Simple migration of the structure under VP 335 indicates that the lower sedimentary rocks are offset along a reverse fault dipping 40° W to 50° W, while the overlying rocks are sharply flexured. Presumably, a basement fault underlies this Laramide structure, although again there is no clear evidence on the seismic data for its attitude.

Structure Under the Eastern Margin of the Laramide Mountains

Evidence for upper crustal shortening during the formation of the Laramie Mountains comes from bands of westerly dipping events recorded from the basement, some of which can be traced or projected to known faults or basement arches (Fig. 6). One such band of events can be traced westward, from the surface expression of the mountain front (at VP 550), and from the underlying sedimentary wedge, to depths of 6 to 9 km at the western end of line 3 (Fig. 6). These events may be a system of thrust faults (dipping 20° W to 25° W) along which the Laramie Mountains were uplifted by horizontal shortening, but other possibilities, such as lithological features in the basement, cannot be ruled out. A gently easterly dipping

event, seen in the overthrust plate at 1 to 1.5 s (3 to 4) km depth (Fig. 6), which may be the base of the Laramie Anorthosite (Allmendinger and others, 1982), appears to be truncated at its eastern margin under VP 640 (B in Fig. 6). This truncation may be caused by thrusting, although the offset portion is not obvious in the footwall.

Other westerly dipping events occur from 3 to 5 s (9 to 15 km) under the mountains. Some of these events may project into the core of the basement arch east of the mountain front (Figs. 5, 6), although they are poorly developed in the upper 1.5 s of the stacked section, probably due to the complexities of the near-surface geology in the region of the Laramie Mountain front. The basement arch is the downplunge expression of an easterly salient in the mountain front north of line 3 (A in Fig. 4), the Iron Mountain anticline (Drouillard, 1963). The contact between the eastern margin of the salient and the sedimentary rocks of the Denver Basin is a westerly dipping reverse fault (Newhouse and Hagner, 1957). The west-dipping events under the mountains that may project into the basement arch on line 3 are possibly the downplunge expression of the westerly dipping reverse fault. This interpretation suggests that the easterly salient of the mountain front arose from greater movement on these inferred thrusts to the north of line 3 and from subsequent breaching of the basement arch by erosion.

An alternative interpretation of the fault system bounding the Laramie Mountains is suggested by events with gentle curvature that occur under VPs 600 to 650, between 2.0 and 4.0 s (Fig. 6). One of these, C in Figure 6, suggests a diffraction originating from a point under VP 590, although simple migration experiments do not seem to collapse this event completely, nor does it appear to have the signature expected from a diffraction on reversed shot-point gathers. A diffraction might arise from a frontal fault that steepens to a near-vertical attitude under the region of VP 590. Although this interpretation cannot be ruled out, we prefer to interpret the moderately westerly dipping events that can be traced to the frontal fault of the Laramie Mountains as thrusts. Event C might have been caused by large folds or other structures in the basement (Smithson and others, 1977).

Events with an easterly apparent dip also occur in the basement under the Denver Basin (Fig. 4), but they cannot be traced to the surface or extrapolated to match known structures and hence positively identified.

Possibilities include pre-Laramide structures, sets of easterly dipping incipient thrusts conjugate to the inferred westerly dipping thrusts, or reflections from features out of the plane of the seismic section.

Structure Under the Western Margin of the Laramie Mountains and the Laramie Basin

Sedimentary strata of Pennsylvanian and younger ages in the Laramie Basin dip gently off the western edge of the mountains, west of about VP 210, line 5, and reach a thickness of about 1.0 s (about 1.7 km; Fig. 7). The northwestern end of the line terminates on a basement arch in the middle of the basin. Structure contours in the Laramie Basin trend generally north-south in the region of line 5. The intersection of lines 5 and 6 lies near the northern margin of the basin, delineated by the northeasterly trending Como-McGill anticlinal complex.

Line 5 also exhibits westerly dipping events that can be extrapolated or traced to the surface positions of faults or arches in the basement. Examples include events D, E, and F (Fig. 7), which dip at generally higher angles than westerly dipping events on line 3. Some of the westerly dipping events on line 5 show up well on shot-point gathers (the unstacked field data) because they have "reverse moveout" (that is, the event dips in the opposite direction to that of "normal moveout"; Sheriff, 1980, p. 144) due to their dip direction and relative position of sources and receivers.

A set of poorly defined westerly dipping events (D in Fig. 7) can be traced from 1.3 to 1.5 s under VP 48 possibly to as deep as 3.5 to 4.0 s under VP 200 with an apparent dip of about 50°. They cannot be traced to the surface and positively identified, because the stacked data do not extend far enough eastward, but they may be reflections from the frontal fault of the Laramie Range. The extreme eastern end of line 5 (VP 1) lies close to the northern extension of the frontal fault crossed by line 3, which in this area is marked by a thick band of fractured anorthosite (Fig. 2 of Allmendinger and others, 1982), and the shot-point gathers contain reverse-moveout events (Fig. 8) that can be approximately modeled as a surface dipping westerly at about 50° from this fractured region. The approximate theoretical stacking velocity for an event dipping 50° in rocks of these velocities (6.0 to 6.4 km/s) is about 9.3 to 10 km/s (Everett, 1974), and a constant velocity

stack at 10 km/s (Fig. 9) enhances these westerly dipping events (Levin, 1971). Stacking both above and below this velocity degrades continuity. Thus, the reverse-moveout events on the shot-point gathers are interpreted as the frontal fault of the Laramie Mountains, which dips about 50° W in the region of line 5. Alternatively, the reverse-moveout events could be side reflections or reflected refractions. However, there are no obvious surficial features that could cause side reflections, and their apparent velocity is higher than the refraction velocity of the anorthosite (up to 6.4 km/s). Because the anorthosite is intruded by Sherman Granite (Hills and Armstrong, 1974), of probably lower velocity, refraction along a layer at depth with velocity higher than 6.4 km/s is unlikely.

If the fault-zone interpretation of the reverse-moveout events is correct, the dip of the frontal fault of the Laramie Mountains appears to vary, steepening northward from 20° W to 25° W on line 3 to about 50° W on line 5. It dies out to the north of line 5 (Fig. 3). This variability of dip may be due to structural control by the Precambrian shear zone just to the north (Allmendinger and others, 1982).

Another westerly dipping event, E (Fig. 7), can be traced from about 4.0 s under VP 370 possibly to the surface in the region of VP 210, where it may be rooted in a small basement arch on the west side of the Laramie Mountains. Event E may correspond to a small reverse fault mapped by Love and others (1955) which cuts and repeats Pennsylvanian and Permian sedimentary rocks and is covered by Quaternary alluvial deposits to the south along line 5 (B in Fig. 3). Interpretation of E is complicated by the proximity of events with hyperbolic curvature seen between 1.5 and 3.0 s under VP 200 (Fig. 7), and an alternative possibility for E is a diffraction tail, although simple migration experiments do not cause E to collapse to a point. If the reverse fault interpretation is correct, E is significant for two reasons: first, although the offset along the reverse fault near VP 210 is small, the subsurface expression of the fault apparently can be traced deep into the crust (to about 10 to 12 km); second, although the fault dips steeply near the surface, the dip decreases at the 10-km depth (to about 35° to 40°), and its geometry suggests crustal shortening.

On the northwestern end of line 5, there is another westerly dipping basement event (see F in Fig. 7) (also with reverse moveout

on shot-point gathers), traceable from the base of the sedimentary section under VP 320 to 2.0 to 2.5 s at the western end of the line. Its average apparent dip is about 30° to 40° northwesterly. Although sedimentary bedding is not truncated, there is a small flexure under VP 350 conceivably caused by thrusting along this feature.

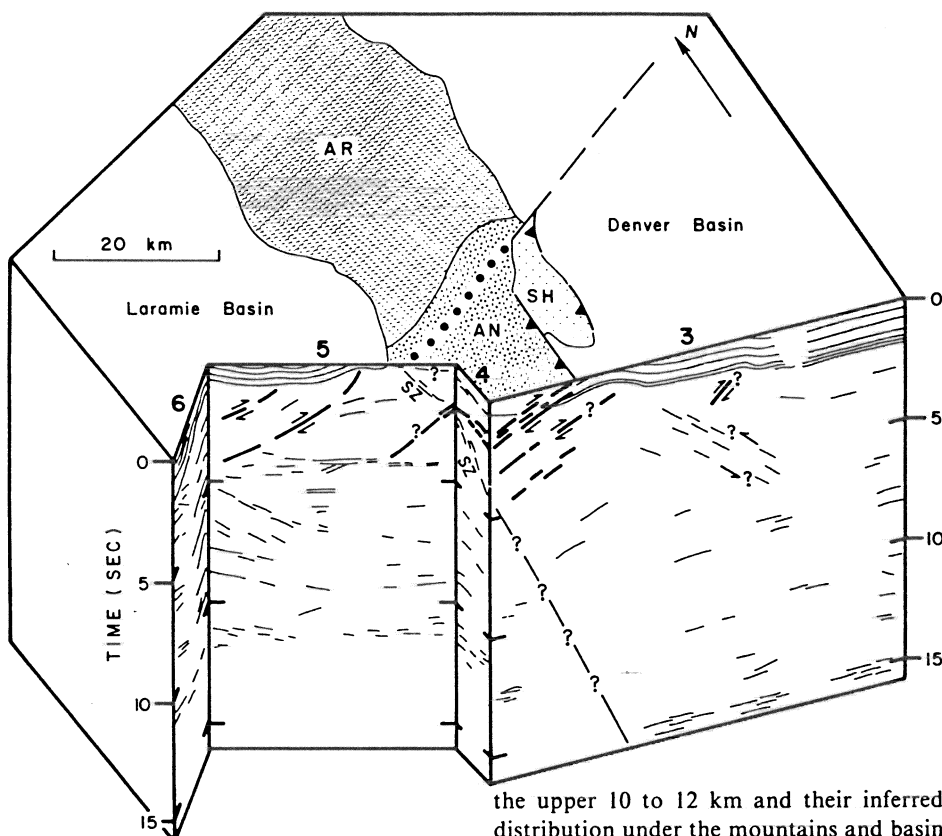
Character of the Thrust Fault System Along Strike (Line 4)

Line 4 contains several diffuse bands of events with generally southerly dip (Figs. 4 and 5 of Allmendinger and others, 1982). Some of these events may be related to the base of the anorthosite and to the Precambrian shear zone (Allmendinger and others, 1982). The Laramide frontal fault system may be represented by a diffuse band of reflections seen on lines 4 and 5, where it corresponds to the interpreted 50° frontal fault seen at the eastern end of line 5.

IMPLICATIONS FOR LARAMIDE TECTONICS

As discussed above, the westerly dipping reflectors which can be traced or extrapolated to the surface position of mapped thrusts or anticlinal features could be a series of westerly dipping, en echelon thrusts underlying the Laramie Mountains (Fig. 10), although alternative interpretations of some of these westerly dipping events would indicate different fault attitudes (for example, lower diagram of Fig. 11). None of these reflections have the striking seismic character of the Wind River thrust, perhaps because of the small relative movements on the Laramie frontal thrusts (possibly on the order of >3 km) with respect to the Wind River thrust (on the order of 20 km; Smithson and others, 1979). Furthermore, some of the interpreted thrusts give rise to coherent reflections (such as F of Fig. 7), even though Laramide movements on these were apparently small and other Laramide features (such as the flexures under the Denver Basin) are not underlain by faults that are seismically distinguishable. The cause(s) of fault-zone reflections are imperfectly understood (Jones, 1981), and it is possible that they are related to the extent of reactivation of Precambrian or late Paleozoic structures by Laramide movements. Different relative movements probably occurred on the different thrusts under the Laramie Mountains. Under line 3, major movements occurred along the frontal thrust exposed

Figure 10. Summary block diagram showing major interpreted features of the Laramie Mountains COCORP lines and their relationship to surface geology. Westerly dipping seismic events interpreted as thrust faults marked by heavy lines; SZ = inferred position of Mullen Creek–Nash Fork shear zone. Inferred base of Laramie Anorthosite is indicated in upper second of section under Laramie Mountains. Easterly dipping events under the middle of line 3 are possibly conjugate shears. Deepest events may be Moho reflections (note change in depth east and west of the Mullen Creek–Nash Fork shear zone). AN = anorthosite; SH = Sherman Granite; AR = Archean basement.



there, while north of line 3 major movements probably occurred along a thrust fault lying at greater depth, causing the easterly salient in the mountain front (B, Fig. 3) which projects downplunge under line 3 as the basement arch under VP 450. Apparently, only minor movements occurred along event E (line 5, Fig. 7), sufficient to form a small reverse fault at the surface on the west side of the Laramie Mountains.

The inferred thrust faults underneath both the Laramie Mountains and Laramie Basin (Figs. 10, 11) imply shortening in at least the upper crust during their formation. It is not clear from the COCORP data what happens to the thrusts below 10 to 12 km. They may maintain their moderate dip to greater depths, steepen, flatten, or die out into wide zones of ductile flow. If the thrusts steepen at depth, vertical movements in the lower crust may be implied. However, the moderate dip of the thrusts in

the upper 10 to 12 km and their inferred distribution under the mountains and basin indicate that horizontal compression was the dominant mode of deformation in the upper crust.

Since the Laramie Mountains trend south into the Front Range in Colorado, it is tempting to speculate whether lateral shortening might have been an important factor in the Laramide uplift of much of that range. However, structures are variable along the front and may reflect adjustments to Precambrian and late Paleozoic (Ancestral Rockies) structures, and post-Laramide vertical movements have modified the present front in some areas (Tweto, 1975). Structures along the eastern foothills of the Front Range vary from high-angle reverse or thrust faults to simple monoclines (Boos and Boos, 1957; Anderman and Ackman, 1963), although kinematically they all suggest horizontal shortening. For instance, LeMasurier (1970) describes a high-angle reverse fault (dipping easterly) associated

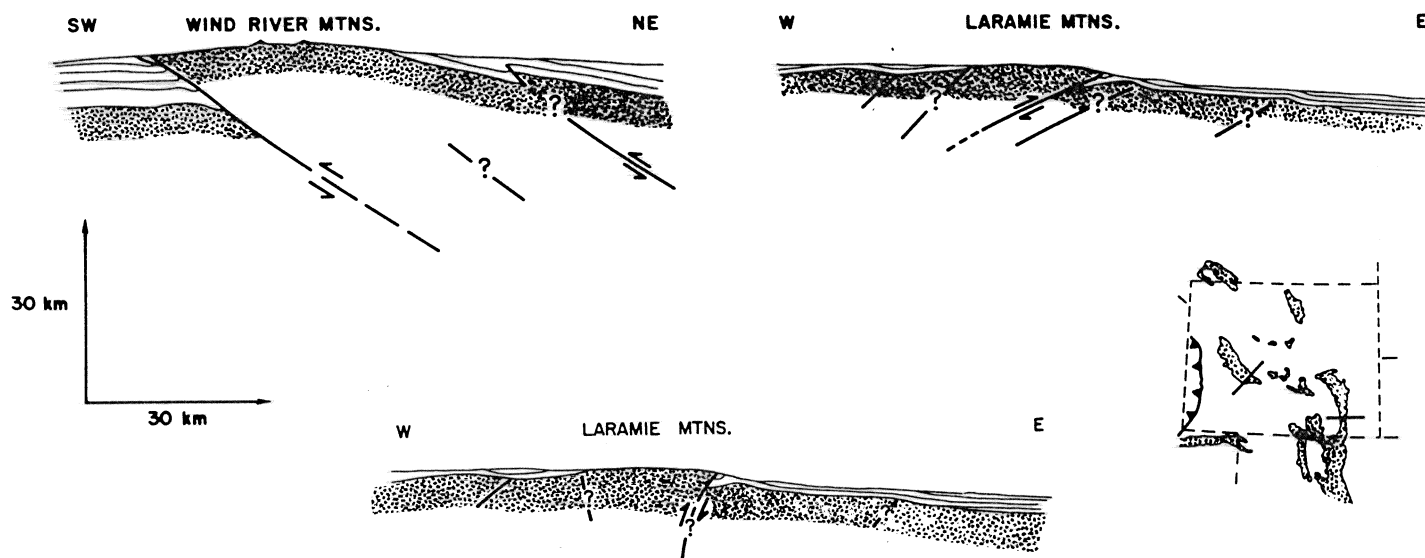


Figure 11. Summary cross section of possible interpretation of Laramide structures under the Wind River and Laramie Mountains from COCORP data. Note that the dip of the frontal fault of the Laramie Mountains in the upper cross section changes along strike (20° to 50°) and that uplifting occurred on different dipping faults along strike. Possible alternative interpretation of faults flanking Laramie Mountains, if alternative interpretations of westerly dipping events (discussed in text) are chosen, is shown in lower cross section.

with Laramide folding of basement and sedimentary cover in the Milner Mountain anticline, along the eastern margin of the Colorado Front Range about 150 km south of the area of the COCORP profiles. This structure appears to be very similar (except for dip direction of the fault) to the basement arch east of the mountain front seen on the COCORP data and may be underlain at depth by moderately dipping thrust. (The Milner Mountain anticline has also been interpreted by Matthews and Work, 1978, as a drape fold over faulted brittle basement.) The westerly dipping Golden fault flanks the Front Range farther south (Boos and Boos, 1957). The dip at depth of this thrust is unknown; it may be moderate, another indication of formation by lateral crustal shortening. The only published seismic data known to the authors from the eastern part of the Front Range is that of Davis and Young (1977), who concluded that steep reverse faults flanked the mountains north of Golden, Colorado. Their data are difficult to interpret, however, because the lines are too short, barely crossing into the exposed Precambrian, and recorded only to 2.5 sec, making it difficult to accurately determine basement structures in this area.

DISCUSSION AND CONCLUSIONS

The data recorded by COCORP profiles crossing two Laramide basement uplifts, the

Wind River and Laramie Mountains, suggest that crustal shortening was the major cause of their formation. In the Wind River, where there is little evidence for Ancestral Rockies or Precambrian structural control, a major thrust fault is traceable to lower crustal depths, with other minor thrusts also identified in the basement (Smithson and others, 1979; Lynn, 1979; McCleod, 1981). In the Laramie Mountains, where both Precambrian and Ancestral Rockies structural controls may be important, Laramide uplift may also have occurred along thrust faults, although the seismic evidence is not so compelling as for the Wind River survey (Fig. 11). These data thus support suggestions (Blackstone, 1963, 1980) that regional, deep-seated lateral stresses were the ultimate cause of the Laramide basement uplifts, with patterns of Precambrian deformation causing the diversity of trends.

Much emphasis has also been placed on evidence for vertical tectonics (Prucha and others, 1965; Stearns, 1971, 1975, 1978; Couples, 1977, 1978; Matthews and Work, 1978) acting at least in the upper 6 km of basement (Stearns, 1978, p. 15). Basement faulting has been modeled by Couples (1977) and Stearns (1978), among others, assuming that uplift is caused primarily by vertical loads. Such solutions predict reverse faults flanking uplifts that are convex downward and dive steeply into the basement, typically depending on how much horizontal loading is applied (Fig. 9, 11, and

13 of Couples and Stearns, 1978). In contrast, the COCORP profiles in the Wind River Mountains show that the flanking fault has a moderate dip to lower crustal depths, with little evidence for steepening. As discussed above, the COCORP profiles in the Laramie Mountains do not well constrain fault attitudes in the middle or lower crust and therefore do not rule out significant vertical loading at depth. However, if moderately dipping thrust faults do occur under the Laramie Basin and the west side of the Laramie Mountains, these are not predicted by basement faulting models of Couples (1977). Note that possible alternative fault attitudes (for example, lower diagram of Fig. 11) might be explained by such models. Couples and Stearns (1978) suggest that while horizontal loading may have been important in the southwest part of the Laramide foreland, it was negligible in the northeast. An alternative possibility is that fundamental horizontal crustal compression throughout the Wyoming region was augmented by a minor component of vertical uplift in the north in the areas described by Stearns (1971, 1975). This lateral compression was probably oriented in an approximately northeast-southwest direction because the dominant trend of Laramide uplifts (for example, the Wind River) is approximately northwest-southeast (Prucha and others, 1965; see also our Fig. 2 above). Variation of structures and trends probably reflects either pre-existing inho-

mogeneities in the basement (Blackstone, 1963; Allmendinger and others, 1982) and/or inhomogeneities in the local stress field, superimposed on the fundamental stress field, caused by crustal movements along faults. Sales (1968) considers that the diversity of structures arose from a large, left-lateral shear couple applied to the Wyoming area during the Laramide and shows that clay model experiments can reproduce structural trends similar to those in Wyoming. If the Laramide basement uplifts are linked to a shallowly dipping Benioff zone (Burchfiel and Davis, 1975; Coney, 1976; Cross and Pilger, 1978; Dickinson and Snyder, 1978; Brewer and others, 1980), possibly mechanical coupling along the Benioff zone may have set up such a shear system promoting the structural diversity of the basement uplifts.

In summary, COCORP reflection profiles across the Laramie Mountains, Wyoming (the northern part of the central Rocky Mountain Front) suggest uplift along a set of westerly dipping thrust faults. These inferred thrust faults occur en echelon under the Laramie Mountains and Laramie Basin, and in some cases can be traced to 10-12-km depth (Figs. 10, 11). Their distribution and orientation indicate crustal shortening and compression during Laramide time. These studies suggest that crustal shortening may have been the fundamental cause of uplift for much of the front in Colorado and Wyoming. Precambrian and Pennsylvanian (Ancestral Rockies) trends probably influenced parts of the front and details of deformation. Despite the anomalous position and style of deformation of the basement uplifts with respect to the rest of the Late Cretaceous-early Tertiary orogenic belt (Fig. 1), the COCORP data suggest that they fundamentally are caused by crustal shortening due to lateral compression. In Wyoming and Colorado, compression was of sufficient magnitude to cause crustal fracturing and thick-skinned deformation as far as 1,500 km from the active plate margin.

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