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Thrusts, back-thrusts, and detachment of Rocky Mountain foreland arches

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ABSTRACT

The basement geometry of the central Rocky Mountains provides a critical test for Laramide tectonic models. On a large scale, Laramide structural highs are better described as anastomosing, connected arches than as individual "uplifts." Thrust and reverse faults on the margins of Laramide arches dip both under and away from the ranges. Structural modeling shows that faults dipping toward the basins are commonly backthrusts off master thrusts which underlie and bring up the arches. These master thrusts alternate between emergent thrusts with major basement overhangs and blind thrusts below imbricate back thrusts.

The northwest-trending average orientations of Laramide faults, folds, and arches suggest northeast-southwest–directed slip over the entire province. The continuity of Laramide arches suggests direct linkages between underlying northeast- and southwest-directed master thrusts. Basement rotations and geophysical evidence for a continuous crust-mantle interface in Wyoming indicate that these master faults are listric, and merge in a subhorizontal detachment in the lower crust. Southwest-directed faults like the Wind River thrust are probably backthrusts off the northeast-directed detachment. West- and north-trending sections of basement arches probably form by oblique slip on lateral ramps connecting the northwest-trending arch culminations.

The minimal penetrative strain and the variety of fault styles at the surface in the Laramide foreland indicate that horizontal compression on a mid-crustal stress guide drives Laramide crustal shortening and detachment. Unlike shortening in the coeval Cordilleran thrust belt, Laramide shortening parallels the plate convergence vector and may reflect increased interaction between the North American and Farallon plates during low-angle oblique subduction.

INTRODUCTION

What caused the Laramide basement-cored structures of the central Rocky Mountains? The current lack of consensus on tectonic models for the Laramide orogeny is truly puzzling considering the volume of data on individual Laramide structures. Structural interpretations of the past decade invoked horizontal compression, suggesting that basement-cored structures of the Laramide foreland are just a variant of the Cordilleran thrust belt. However, differences in structural geometry and strain between Laramide and Cordilleran thrust-belt structures (Schmidt and Perry, 1988) suggest that their underlying mechanisms of horizontal shortening may be fundamentally different. A better understanding of the mechanisms responsible for Laramide structures should provide insights into basement-involved foreland deformation throughout the world (Rodgers, 1987).

In this hypothesis-level chapter the large-scale basement geometries of the Laramide foreland are examined using principles of structural balance to explain the connections between Laramide structures. Two major hypotheses are presented. First, the anastomosing nature of Laramide arches (Figs. 1A and 2B) suggests that the master thrusts underlying the arches merge into a

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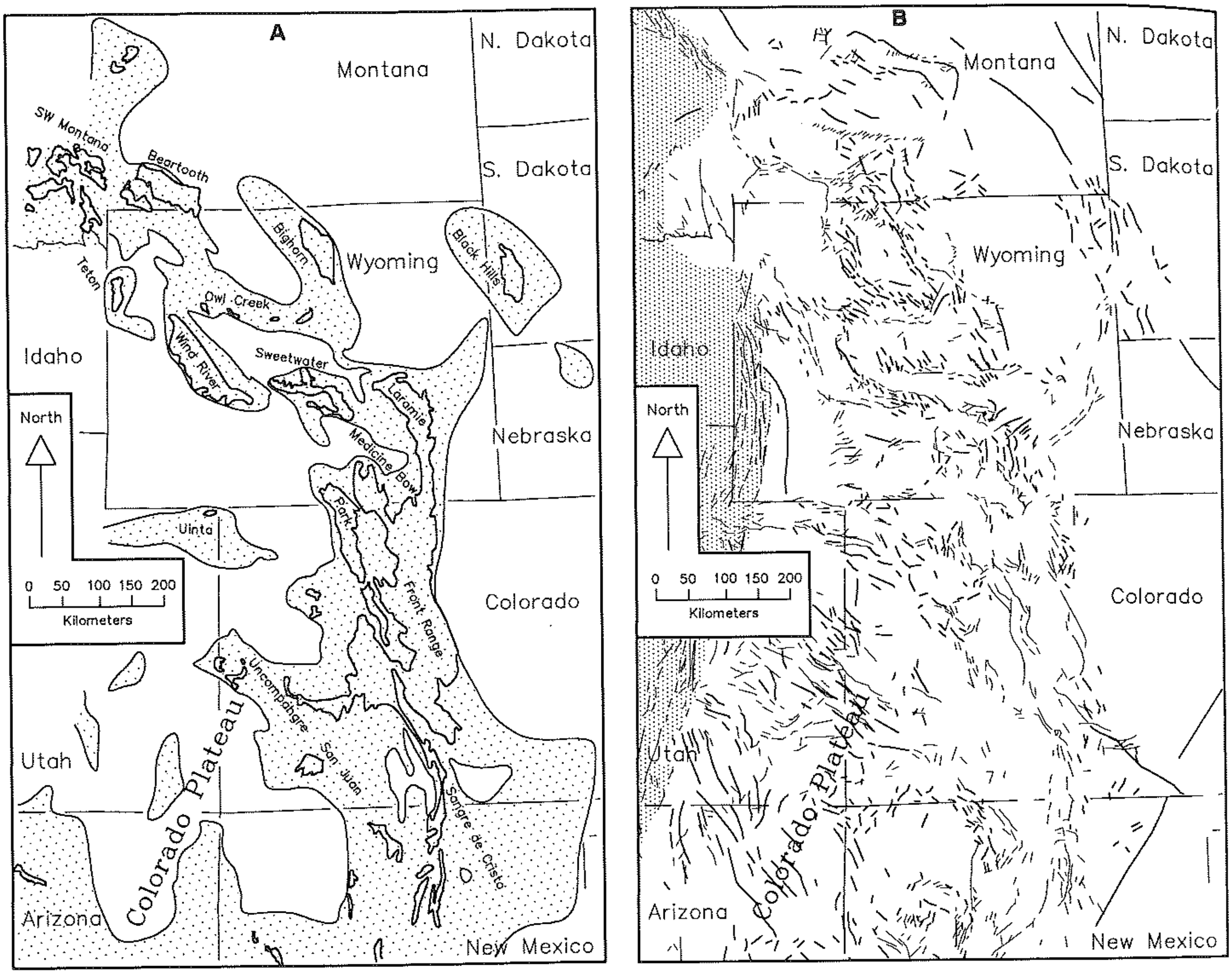


Figure 1. Geologic (A) and structure (B) maps of the Rocky Mountain foreland (after MacLachlan and others, 1972). Exposed Precambrian crystalline rocks are outlined by thick lines and Precambrian rocks above sea level are stippled in the geologic map. The structure map shows faults in fine lines and folds in thicker lines and the Cordilleran thrust belt in the stippled area.

northeast-directed detachment within the lower crust. Second, the differences between the structural orientations (Figs. 1B and 2A) and penetrative strains of the coeval Laramide foreland orogen and Cordilleran thrust belt may result from differing stress guides (zones of stress transmission) in the lithosphere. I hope that these two hypotheses of Laramide crustal detachment and multiple Cordilleran stress guides will stimulate future inquiries into the origin of Laramide tectonics.

PREVIOUS TECTONIC HYPOTHESES

Tectonic hypotheses for the Laramide orogeny of the central Rocky Mountains were delayed by the lack of an immediately proximal plate margin and the popularity of erroneous vertical uplift models during the 1970s. Dickinson and Snyder (1978) noticed the coincidence of the eastern migration of arc volcanism and the initiation of Laramide deformation in the western United

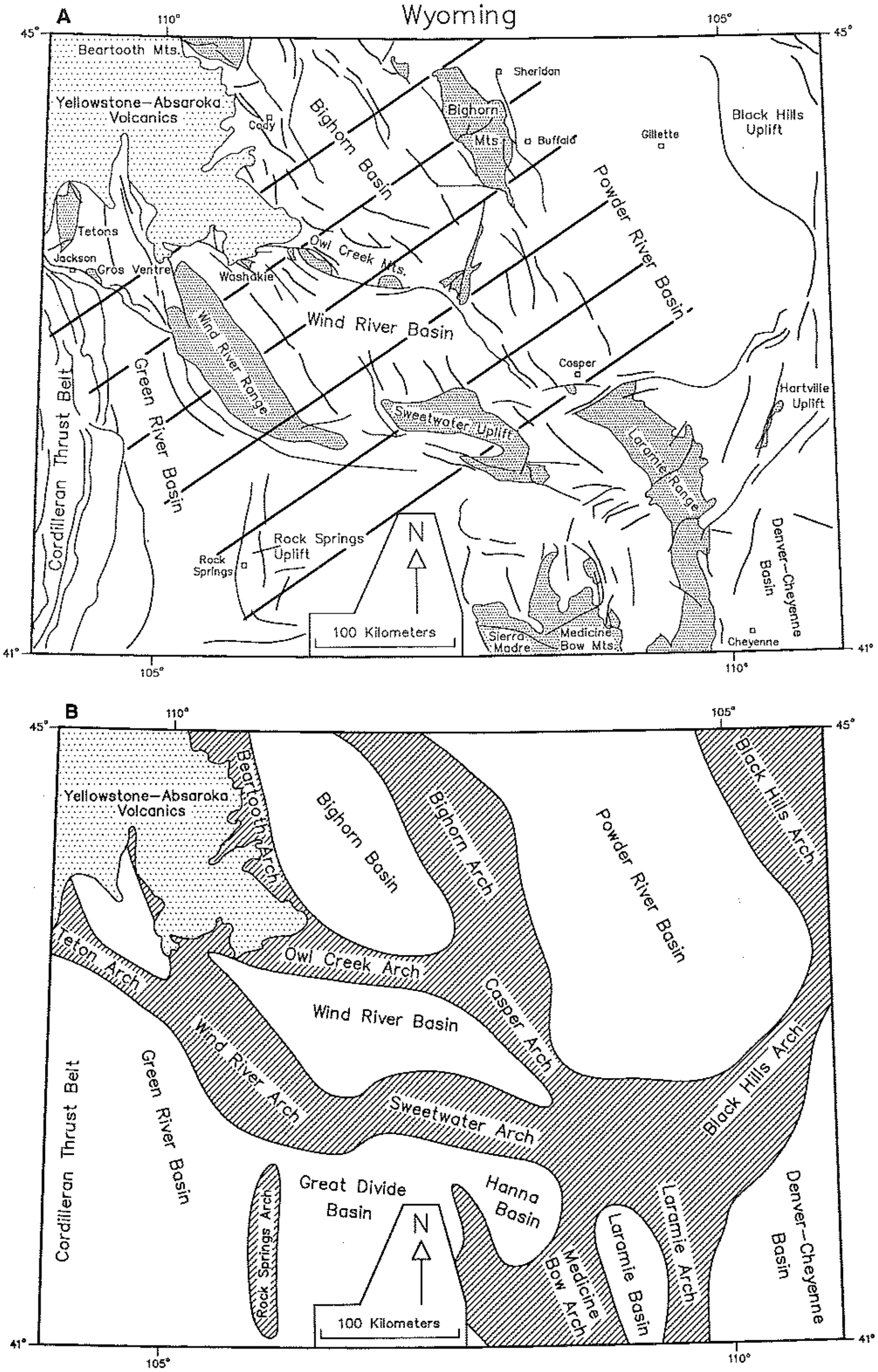


Figure 2. A: Structure map of Wyoming (after Blackstone, 1990a) with faults in finer lines and folds in thicker lines. Thick, broken straight lines show the cross-section lines for Figure 12. B: Arches and basins in Wyoming illustrating the connections between Rocky Mountain foreland culminations.

States. They suggested that progressively shallowing angles of Farallon plate subduction could be responsible for both features. A connection between low-angle subduction and foreland basement deformation was confirmed by the occurrence of analogous structures in the Andean Cordillera, where volcanic gaps underlie low-angle Benioff zones (Jordan and others, 1983; Jordan and Allmendinger, 1986).

Two-dimensional tectonic models

The causal link between low-angle subduction and foreland basement deformation is not clear. Bird (1984, 1988) hypothesized that shear between the subducting oceanic lithosphere and the lower continental crust could result in shortening far out into the continental foreland. His finite-element models of subcrustal traction predict eastward transport of lower crust and the stripping of the mantle lithosphere from beneath Laramide structures. Neither prediction is supported by recent studies of the crust and lithosphere under the Rocky Mountain region (Prodehl and Lipman, 1989; Hurich and Smithson, 1982; Hall and Chase, 1989). Changes in crustal thickness under the Rocky Mountain region are better correlated with Precambrian crustal provinces than with Laramide structures (Prodehl and Lipman, 1989). In addition, the strontium and lead isotope characteristics of late Cenozoic basalts indicate clearly the presence of Precambrian mantle lithosphere under the Colorado Plateau, Rio Grande rift, and Snake River–Yellowstone area (Leeman, 1982).

Other authors have suggested that the upper crust was detached and pushed eastward by Farallon–North American plate convergence. Lowell (1983), Brown (1988), Kulik and Schmidt (1988), Verrall (1989), and Oldow and others (1989) proposed hanging-wall shortening above a subhorizontal detachment in the lower crust. In contrast to the dominance of thrusting in these models, Fletcher (1984) explained the eastward-increasing spacing between ranges as a consequence of multilayer buckling. This model is not necessarily incompatible with detachment models if initial buckling determined the location of subsequent thrust ramps in the upper crust (Schmidt and others, 1985).

These two-dimensional models of Laramide tectonism do not address directly either the highly variable strike of Rocky Mountain structures or their strong discordance with the structural grain of the adjacent thrust belt (Fig. 2A). For example, the detachment models suggest that Cordilleran thrust belt and Laramide structures should parallel each other, yet their structures are commonly oblique to each other (Figs. 1B and 2). Whereas the size of individual Laramide structures increases and their spacing decreases toward the Wyoming-Idaho-Utah thrust belt, the belts do not merge together continuously, but rather form a complex overlap zone (Schmidt and Perry, 1988). Because both thrust-belt and Laramide structures were active during Late Cretaceous to Eocene time (Hunter, 1988; Perry and others, 1988), differences in their structural trends and styles cannot be solely a function of timing. Kulik and Schmidt (1988) argued that this coincidence in time and space indicates a shared mechanism of horizontal compression, with variations in crustal heterogeneity causing the differences in structural style. This hypothesis does not, however, address differences in the attitude of Laramide and Cordilleran structures.

Three-dimensional tectonic models

The variable structural orientations in the Laramide foreland have prompted several authors to propose a component of strike-slip faulting in the central Rockies. Wise (1963), in his "outrageous hypothesis," and Sales (1968), who simulated Laramide deformation using plaster analog models, proposed that many foreland structural geometries can be explained by transpressive "megashear." Subsequent documentation of the oblique subduction of the Farallon plate during the Laramide orogeny (Engebretson and others, 1985) and the substantial horizontal shortening associated with recent transpression on the San Andreas system lend credibility to the megashear concept.

The style of proposed strike-slip structures has been controversial. High-angle strike-slip faults were used by Stone (1969) to explain east-west Laramide ranges in the context of northeast-southwest shortening. Gries (1983a), however, documented extensive well and seismic evidence for low-angle thrust faulting in the east-west–striking Uinta, northern Laramie, and Owl Creek ranges. Thrusting is also indicated by basin loading adjacent to east-west ranges (e.g., Wind River Basin south of the Owl Creek Mountains).

Another apparent anomaly in the Laramide foreland is the minimally deformed, rotated Colorado Plateau. Bryan and Gordon (1990) used paleomagnetic poles to show a 5.0° clockwise rotation of the Colorado Plateau since the Jurassic. Both the possibility of a 10° rotation and the null hypothesis of no rotation were rejected at a 99.99% confidence level. Hamilton (1981, 1988) and Scheevel (1983) explained the arcuate array of faults and ranges bounding the Colorado Plateau by suggesting that the plateau acted as a rotating, miniplate indentor converging on the North American craton. Why the Colorado Plateau acted so rigidly is puzzling. The increased crustal thickness of the Colorado Plateau relative to crust in Wyoming suggests that the lower crust under the plateau is probably hotter and weaker, not stronger, than the lower crust under Wyoming (Prodehl and Lipman, 1989; Ord and Hobbs, 1989).

Chapin and Cather (1983) documented a distinct group of narrow, north-trending Eocene basins of probable strike-slip origin along the eastern margin of the Colorado Plateau. They suggested that the Laramide deformation occurred in separate stages characterized by distinctly different structural styles. Gries (1983b) agreed and proposed that changes in shortening directions resulted from the progressive rotation of the principal stress orientation from east-west in the Late Cretaceous to north-south in the Eocene. In her model, north-trending ranges formed first, followed by northwest-trending ranges, and finally by west-trending ranges. However, recent studies of synorogenic sedimentation by Cross (1986), Dickinson and others (1988), and Perry and others (1991) have provided little conclusive support for a correlation between range orientation and the initiation of Laramide deformation.

All of these models make specific predictions about the geometry of deformation in the Rocky Mountain foreland. Detachment models integrating Laramide and Cordilleran structures into a single "orogenic float" (Oldow and others, 1989) predict a common slip direction for these structures. Multiple-deformation models suggest that the Laramide foreland can be viewed as an interference pattern of different age structures. In this chapter I test these models using Laramide structural geometries and structural modeling based on restorability criteria.

ANASTOMOSING LARAMIDE ARCHES, NOT UPLIFTS

The term "uplift" is commonly used to describe Laramide structural highs in the Rocky Mountain foreland. Unfortunately, "uplift" places primary emphasis on the vertical rise of Laramide structures, whereas their horizontal translation is clearly of larger magnitude (Hurich and Smithson, 1982; Blackstone 1983, 1986, 1990b, 1991; Gries, 1983a, 1983b; Brewer and others, 1982; Kulik and Schmidt, 1988; Stone, 1985a, this volume; Williams and others, 1990). In addition, the concept of isolated "uplifts" describes only poorly the actual structural geometry of Laramide structures. Examination of Figure 1A and the more detailed basement structure contour map of Blackstone (1990a, this volume) shows that basement highs are not isolated block uplifts as envisioned by those of the vertical uplift school. Instead, basement highs form an anastomosing pattern of arches (Scholten, 1967; Schmidt and others, 1985), with culminations exposing Precambrian rocks in today's ranges (Fig. 2B). Saddles between arch culminations are still quite high, only infrequently bringing the basement unconformity below sea level. The arches are connected in an anastomosing web that bifurcates and merges, defining the isolated, elliptical foreland basins of the Rocky Mountains.

The system of interconnected arches spans the entire Laramide orogen. For example, the Front Range arch of Colorado can be followed north to the Wyoming border, where it bifurcates into the Laramie and Medicine Bow arch culminations (Fig. 2B). The Laramie arch increases in width as the Black Hills and Sweetwater–Wind River arches branch off. The remainder of the Laramie arch continues north and then west to merge with the Casper arch. This arch bifurcates at the Owl Creek Mountains, with one basement ridge heading north to the Bighorn Mountains and one heading west to the Washakie Mountains. At the Washakie Mountains, the Owl Creek arch splits again, with one arm heading north to the Beartooth Mountains and one continuing west to merge with the Wind River arch near the Teton Range. The Wind River–Teton arch can be projected across the Snake River Plain to the Madison and Gallatin ranges of southwest Montana. Thus, if you were able to walk the top of these basement arches, you would find a continuous path on basement ridges to nearly all major Laramide culminations.

The anastomosing nature of the arches is difficult to explain by the progressive interference of north-south, northwest-southeast, and east-west fold trends. Many arch intersections, like the bifurcation of the Casper, Bighorn, and Owl Creek arches, show triple junction–like geometries, not intersecting four-arm interference patterns. If arch intersections formed to due the superposition of separate structural trends of different ages, then these intersections should also be arch culminations. But most arch intersections do not correspond with arch culminations. The arch culminations in the Front, Wind River, Beartooth, Black Hills, and Bighorn ranges all occur in the middle of arches, far removed from their intersections.

MASTER THRUSTS AND BACK THRUSTS

The continuity of Laramide arches implies connected deformation consistent with principles of three-dimensional balancing. One possible mechanism allowing connected deformation is shown in microcosm by the Oregon Basin–Line Creek–Beartooth thrust system on the western side of the Bighorn basin near Cody, Wyoming (Fig. 3; Blackstone, 1986). At Oregon Basin south of Cody (Stone, 1985a), and along the eastern Beartooth front north of Cody (Bonini and Kinard, 1983; Williams and others, 1990), subthrust wells penetrated the west-dipping fault sytem whose load depresses the western side of the Bighorn and Crazy Mountains basins. Deep drilling by Texas, Inc. (Sheets #1), nearer to Cody also penetrated a smaller basement overhang east of the classic Rattlesnake Mountain structure.

Fanshawe (1939) and Gries (1985, personal commun.) suggested that the Rattlesnake Mountain structure may just be a back-thrust off the Line Creek fault. Because the surface exposures of Precambrian basement at Rattlesnake Mountain show no evidence of penetrative deformation (Pierce, 1966; Erslev, 1990), this hypothesis was tested using two-dimensional block balancing algorithms (Erslev, 1986) to extrapolate the fault and fold geometries to depth (Fig. 4). Briefly, this involves calculating the fault slip and curvature indicated by surface-fold geometries so that when folded strata are restored to horizontal, the basement blocks restore to a nearly continuous mosaic bounded by a horizontal basement unconformity. The Rattlesnake Mountain fault must be listric, because the hanging-wall strata dip 14° NE and the footwall strata are nearly horizontal (Brittenham and Taldewald, 1985).

Extrapolation of the Rattlesnake Mountain fault shows that this fault probably curves around into tangency with the basin-bounding Line Creek fault, which was penetrated by the Texaco, Inc., Sheets #1 well. This back-thrust geometry can explain why thrust slip varies so dramatically along the Oregon Basin–Line Creek–Beartooth thrust system. The Line Creek thrust does not offset the sedimentary strata as much as the Oregon basin thrust to the south and the Beartooth thrust to the north because the Rattlesnake Mountain fault disperses much of its slip as back-thrusting. The greater uplift in the Beartooth Mountains to the north probably results from both decreased back thrusting and

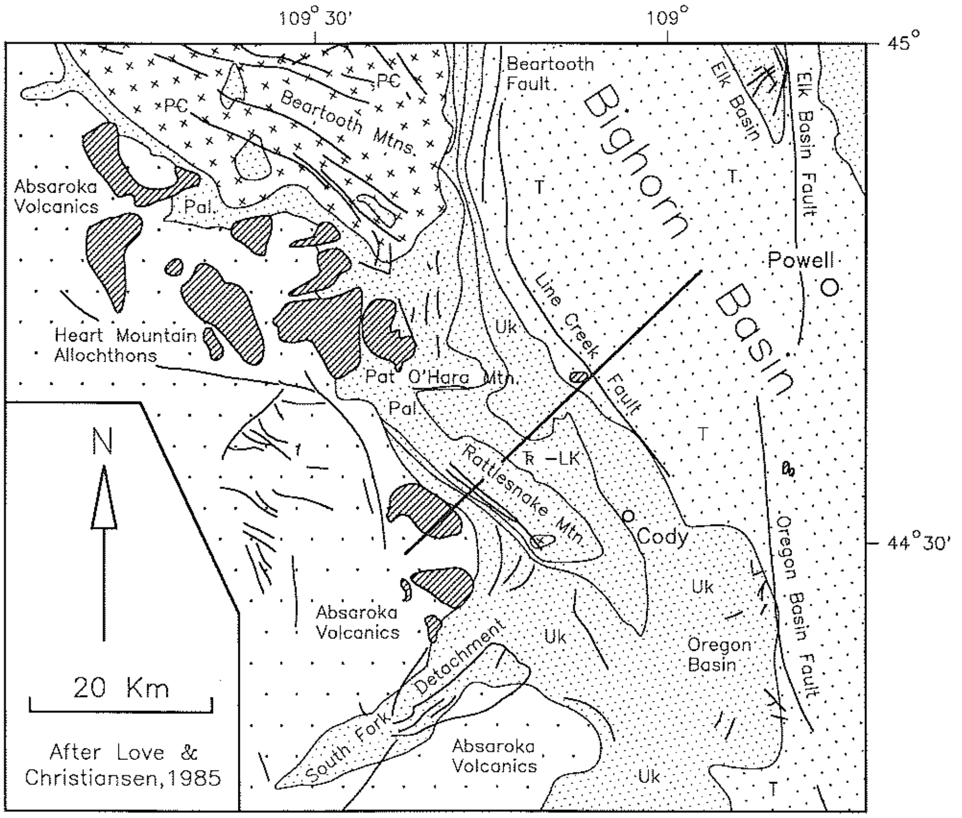
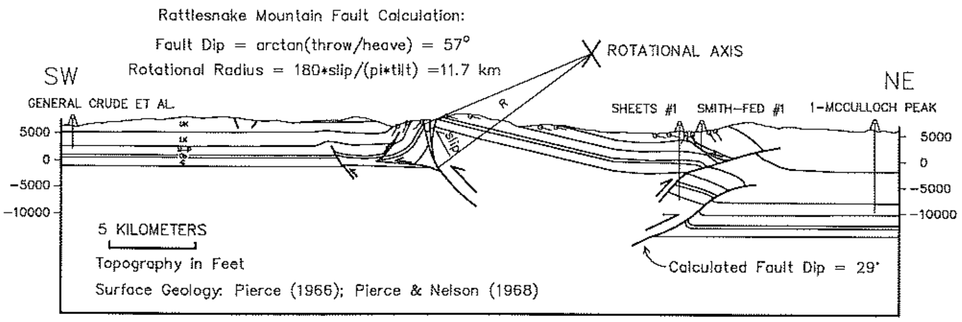


Figure 3. Simplified geologic map (after Love and Christiansen, 1985) of the southern Beartooth arch and western Bighorn basin.



Restorable Interpretation

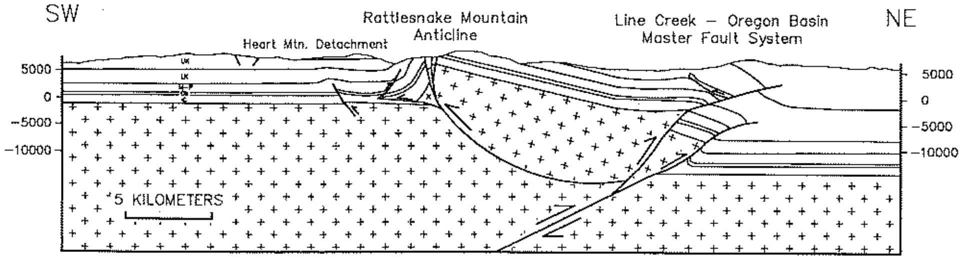


Figure 4. Cross section through Rattlesnake Mountain (Erslev, 1990; cross-section line in Fig. 3) through wells General Crude et al. (SW¼, SE¼, sec. 11, T.52N, R.105W) and Sheets #1 (SW¼, SW¼, sec. 21, T.54N, R.102W). The top diagram shows the data and method (Erslev, 1986) used to calculate the restorable geometry. Note that the Rattlesnake Mountain fault extrapolates right into the Line Creek– Beartooth thrust system, making this fault a back-thrust off the major thrust system which brought up the arch to the west.

the coalescence of slip from the Line Creek and Elk basin thrusts into a single thrust displacement.

A similar distribution of slip between forward and back-thrusts occurs in the northwestern plunge of the Beartooth arch near Livingston, Montana. In this area, slip on the Beartooth thrust decreases as the Mission Creek, Livingston, Suce Creek, and Hogback back thrusts develop in the hanging wall (Robbins and Erslev, 1986). Thus, the northeastern margin of the Beartooth arch can be modeled as the combination of forward and backward thrusting off a southeasterly dipping master thrust that transfers slip to back-thrusts on both flanks.

An analogous back-thrust geometry can be used to explain the changes in structural style along the east side of the Front and Laramie ranges, which define a continuous basement arch from central Colorado through southeastern Wyoming (Figs. 1A and 5). Despite the continuity of the basement high, exposed faults and basin geometries change radically along the eastern margin of the arch. Major west-dipping thrusts in the southern Laramie Range (Brewer and others, 1982) and central Front Range from Boulder to Colorado Springs (Jacobs, 1983) bring Precambrian crystalline rocks over Phanerozoic sedimentary strata. Thrust loading depresses the Denver-Cheyenne basin to its lowest points adjacent to these thrusted margins.

The intervening section of the Front Range–Laramie Range arch in northern Colorado shows a completely different structural style (Braddock and others, 1970; Erslev and others, 1988; Erslev and Rogers, this volume). The axis of the Denver-Cheyenne basin is much farther to the east in this area, forming a shallow, symmetric basin quite different from the asymmetrical, more clearly thrust-loaded basin to the south (Fig. 5). Along the eastern margin of the range, exposed basement-cored anticlines are underlain by thrust and reverse faults that dip northeast. These faults bring the basin side of the fault up and the range side down, the direct opposite of the regional pattern of uplift.

A restorable section through the northeastern flank of the Front Range (Fig. 6) can resolve the geometry of individual domains but cannot account for either the uplift of the range or the basinward tilt of the hogbacks. The similarity of these hogback geometries with the basinward dips at Rattlesnake Mountain suggests the existence of a west-dipping master thrust underlying the northeast-dipping faults in the northeastern Front Range (Fig. 7). This interpretation suggests that most of the surface faults are back-thrusts. Unlike the situation at Rattlesnake Mountain, however, the only direct evidence of a west-dipping thrust cutting the basement unconformity in this area is a set of small, east-vergent anticlines forming the Pierce–Black Hollow–New Windsor oil field complex immediately west of the basin axis (Stone, 1985b). At Fort Collins (Fig. 5), well and outcrop data clearly show that the basement unconformity is not broken by a major west-dipping thrust at the base of the hogbacks (Erslev and others, 1988).

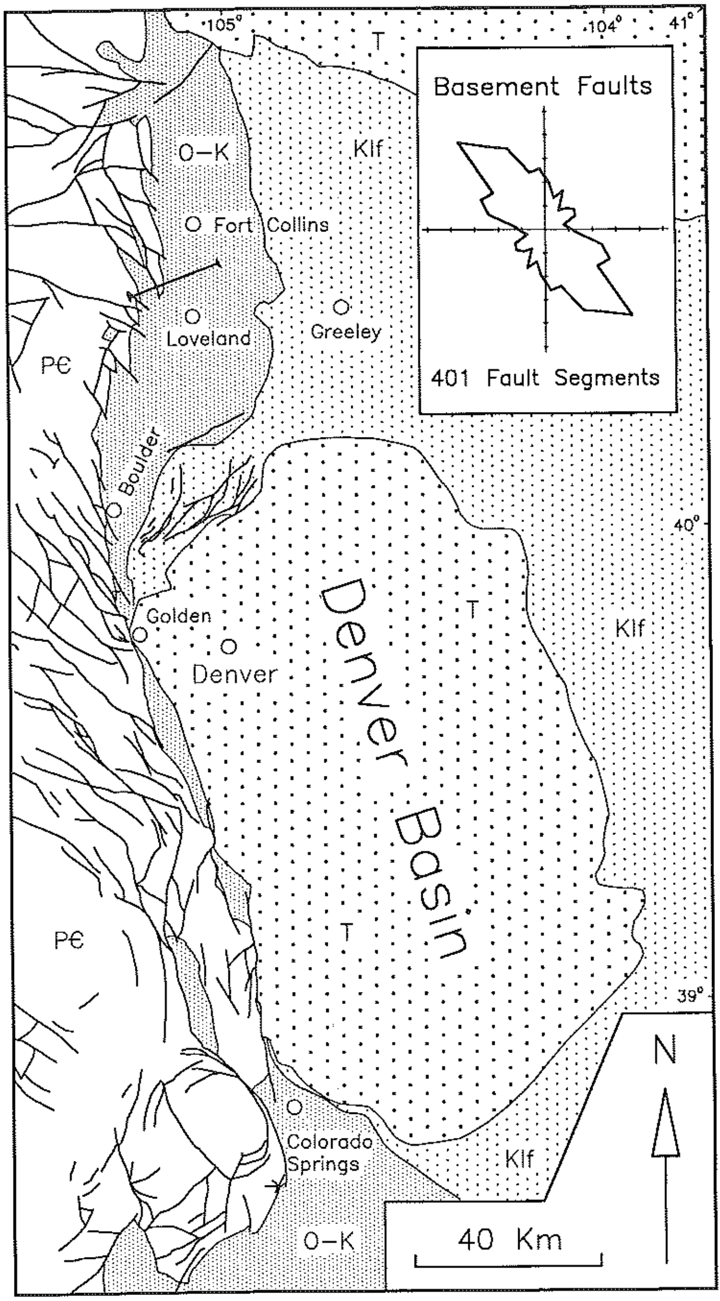


Figure 5. Geologic map of the northeastern Front Range and the adjacent Denver basin (after Tweto, 1979) and a rose diagram showing the distribution of basement-involved fault strikes.

Similar situations in thin-skinned thrust belts are commonly interpreted as buried or blind thrusts (Morley, 1986; Dunne and Ferrill, 1988). For the northeastern Front Range, a blind thrust interpretation (Fig. 7) allows the basement unconformity to be restored to the horizontal while providing structural continuity with the west-dipping Laramie and Golden thrusts systems to the north and south. The east-directed slip on the Golden-Laramie thrust system was dissipated by the back-thrusts in the northeastern Front Range. Back-thrusts on the western side of the range at North Park and South Park also decrease the slip on the master

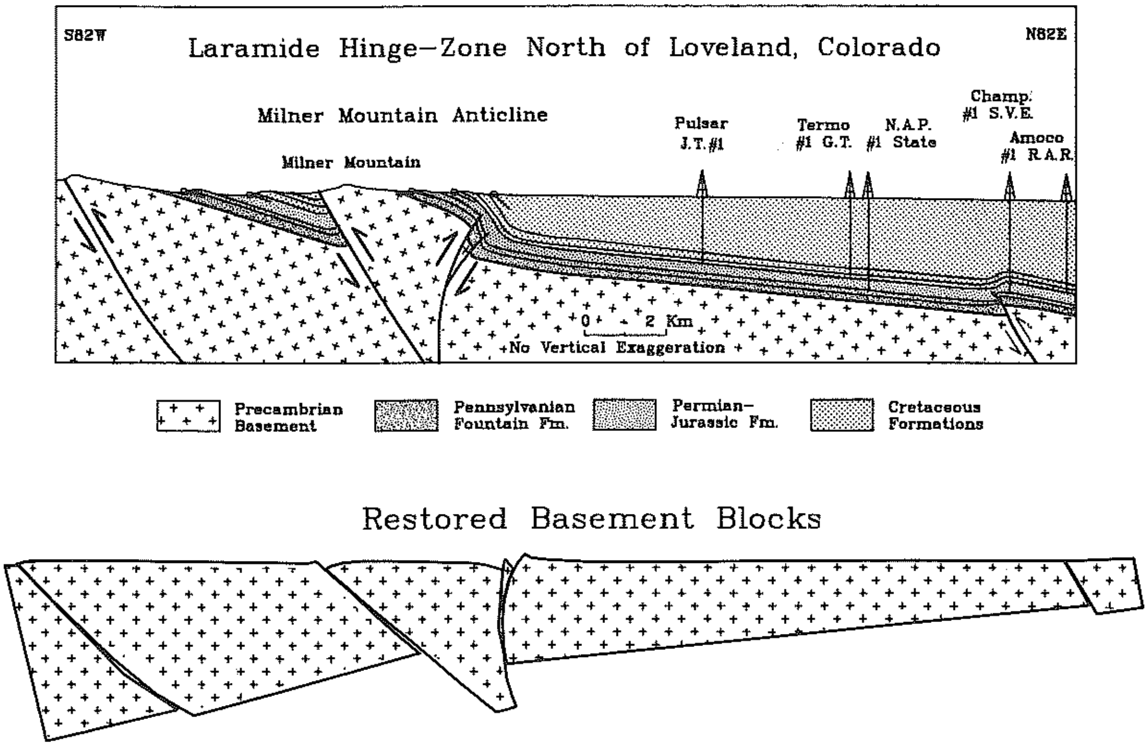


Figure 6. Restorable cross section through the northeastern Front Range between Fort Collins and Loveland (cross-section line in Fig. 5). Note that most faults bring the basin side up and the range side down, in direct contradiction to regional elevation changes.

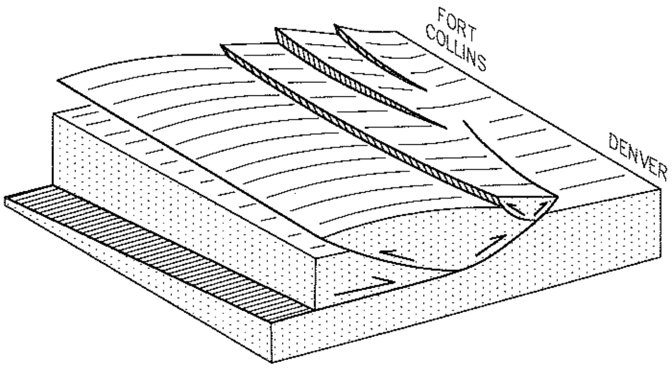


Figure 7. Schematic cartoon of the basement surface showing the Front Range arch as a northeast-directed thrust block with both forward and back thrusting on its eastern margin.

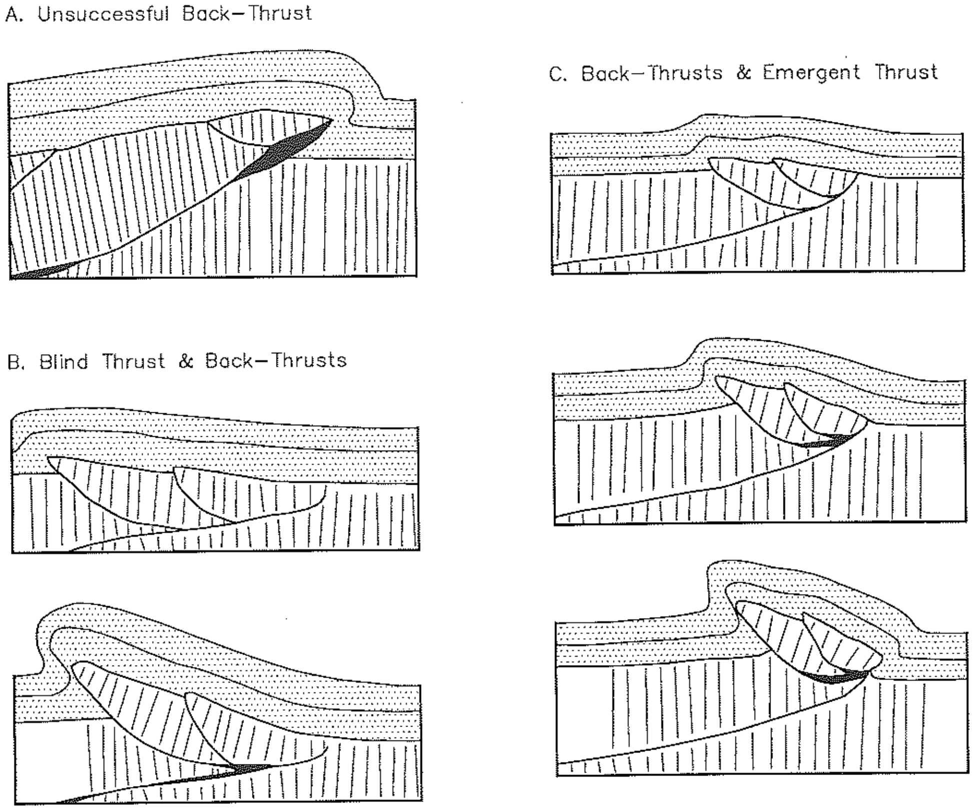
thrust, with the Front Range arch forming a wedge-shaped pop-up from a low-angle detachment in the lower crust (Kluth and Nelson, 1988).

The reason for the transition from emergent, east-directed thrusting in the central Front Range and blind thrusting in the northeastern Front Range is not clear. The zone of transition occurs at the intersection of the Colorado mineral belt with the eastern margin of the Front Range at Boulder, Colorado. The heat associated with these Laramide intrusions may have caused detachment at higher levels in the crust south of Boulder. Increasing depth of detachment to the north may have caused the thrust system to go blind. Alternatively, reactivation of a preexisting weakness in the western margin of the northern Front Range may have reduced the forward slip in the eastern margin of the range. This would account for the decreased depth of this segment of the Denver basin and the corresponding increased depth of the North Park basin on the northwestern margin of the Front Range.

Analog modeling of back-thrusting

The kinematics of back-thrusting above a blind master thrust were explored using analog modeling in collaboration with Donald Stone. We used previous modeling techniques (Stone, 1985a) that generated relatively realistic analogs of Laramide structures. Oil-based clay simulated basement and a more ductile mixture of flour, salt, and water simulated the sedimentary cover. In these experiments, master thrusts and back-thrusts were precut tangentially above a listric master thrust (Fig. 8). As shown in Figure 8A, precutting and lubricating the back-thrusts does not guarantee that they will slip.

The geometry of the master thrust near the "basement-cover" interface determined whether back-thrusting occurred.



A. Unsuccessful Back–Thrust

B. Blind Thrust & Back–Thrusts

C. Back–Thrusts & Emergent Thrust

Figure 8. Analog models of back-thrust development off master thrusts sketched from photographs. Oil-based clay simulated basement (with precut, lubricated faults and vertical striations) and a salt plus flour mixture simulated more ductile cover strata. A: Precut back thrust off a concave-downward (upthrust) did not slip. The resulting void (in black) would cause range collapse (Sales, 1983) at larger (e.g., Laramide) scales. B: When the master fault was not precut to the top of the clay block, the master fault was blind and its slip was taken up by back thrusting and basement rotations (cf. Figs. 6 and 7). C: When the fault was abruptly listric at the top of the clay block, back thrusting was followed by emergent forward thrusting (cf. Fig. 4).

Initial models with planar or concave-downward master thrusts had no slip on the precut back-thrusts. The void that developed in the concave-downward geometry (Fig. 8A) would result in hanging-wall collapse similar to that proposed by Sales (1983).

Back-thrusts only developed when the master fault met resistance to forward faulting. If the master fault was not cut all the way through the block of oil-based clay, this fault remained blind and slip was transferred to back-thrusts (Fig. 8B). Progressive slip caused progressively greater back-thrusting and hanging-wall rotations similar to the geometry proposed for the northeastern Front Range (cf. Figs. 8B and 7).

If the master fault was precut with an abruptly listric tip, back-thrusting was followed by emergent forward thrusting on the master thrust (Fig. 8C). The first increments of slip on the master thrust were transferred to the back-thrusts, rotating the blocks toward the basin. Finally, after substantial deformation at the tip of the master thrust, it broke through, forming a geometry analogous to that hypothesized for Rattlesnake Mountain (cf. Figs. 8C and 4). These experiments suggest that if a master thrust meets resistance to forward propagation, it may develop antithetic back-thrusts to dissipate its slip.

LARAMIDE SLIP ORIENTATIONS

Another puzzling aspect of both the northeastern Front Range and the Rattlesnake Mountain areas is the obliquity between the northwest-trending, right-stepping faults and their accompanying folds and the north-south trend of the regional arch axis in these areas. A symmetric rose diagram of basement-involved fault strikes (inset in Fig. 5) from the eastern Front Range shows the preponderance of northwest-striking faults despite the generally north-south trend of the arch. If the slip direction is assumed to be perpendicular to both fault strike and arch trend, then these structures give contradictory slips. The fault orientations suggest northeast-southwest dip slip, whereas the arch boundaries suggest east-west slip, perpendicular to the fault ramp that uplifts the arch. Thus, either or both features must have developed by oblique slip.

Some Laramide faults must have oblique slip because they are commonly quite variable in strike. For example, the Wind River thrust has a strike variation of at least 60°, the maximum uplift being adjacent to the northwest-striking parts of the fault (Blackstone, 1991). Dip slip on all sections of this fault would cause divergent flow in the hanging wall, shattering the continuity of the range. However, the continuity of the hanging wall, as seen by the linear basement-cover contact on the northeast side of the range (Fig. 2A), is one of the most remarkable things about the Wind River culmination.

The sinuous nature of the arch axes also suggests uplift oblique to the regional slip. Other sections of the Front and Beartooth arches do strike more northwesterly, showing that slip cannot be perpendicular to arch axes everywhere. The northwest-trending arch segments typically show the greatest differences in range height relative to basin depth.

Limited slip information from slickenline analysis suggests that the smaller fault and fold orientations may give a better estimation of the regional slip. Slickensides in northwest-trending structures at Rattlesnake Mountain (Erslev, 1990), the Teton Range (Rogers, 1989), and the northeastern Front Range (Erslev and others, 1988) all give fault-perpendicular slip, although the sense of slip varies widely with structural location in individual structures. At Rattlesnake Mountain, slickenlines on both normal faults near the basement unconformity in the hanging wall and thrust faults in the Tensleep Formation are oriented perpendicular to the fold axis, indicating plane strain where the fold axis is neither shortened nor elongated.

Near the Wyoming border along the northeastern margin of the Front Range, several northeast-striking faults and folds extend out into the Denver basin (Fig. 5). The faults are steeper (commonly approaching vertical) than nearby northwest-striking reverse faults. Slickenlines on the steep faults are subhorizontal, indicating a significant strike-slip component in the northeast-southwest direction. An analogous discordance between northwest-trending structures and overall arch orientation occurs on the west-trending Granite and western Owl Creek arches (Paylor and Yin, this volume; Blackstone, 1990b). Here, however, the northwest-trending structures are left stepping instead of right stepping. Experimental simulations of transpression above basement reverse faults give similar obliquities between minor structures and arches during oblique slip (Cobbold and others, 1991). This indicates that the geometry of Laramide faulting and folding may be partially independent of arch orientation.

Unlike the oblique faults in the western Owl Creek arch, fault strikes in the central Owl Creek Mountains generally parallel the west-trending arch axis. However, the average slickenline rake (angle between the slickenline and the fault strike on the fault plane) of more than 1000 minor faults is 41°, indicating nearly equal amounts of strike slip and dip slip on these faults (Molzer and Erslev, 1991). Similar minor faults with more strike-slip than dip-slip motion parallel the axis of the west-trending Casper Mountain structure. Minor structures along the west-striking Tensleep fault in the Bighorn basin (Allison, 1983) also indicate the predominance of northeast-southwest shortening during the Laramide.

Obliquity of Laramide fault, fold, and arch orientations

The average orientations and variability of Laramide structures in Wyoming were analyzed to test the generality of the above observations. Structures in Wyoming were studied in detail because of the minimal influence of previous Ancestral Rocky Mountain deformation and subsequent Basin and Range and Rio Grande extension, as well as the availability of structure maps encompassing both Laramide and Cordilleran thrust-belt structures. Fault traces, fold axes, and arch trends from Blackstone (1989, 1990a) were digitized as line segments (uncorrected for earth curvature) and imported into a computer spreadsheet to analyze the degree of preferred orientation. Symmetric rose diagrams of structural strikes and trends show the general northwest-trending orientation of foreland structures (Fig. 9).

Average fault and fold orientations (Table 1) were calculated by determining the vector mean of the doubled fault strikes and fold trends and then halving this number. This prevents the canceling of orientations nearly 180° apart (Krumbein, 1939; Davis, 1986). For example, similar strike lines oriented N01E (1°) and S01E (179°) will largely cancel each other in a conventional vector mean. If these angles are doubled, however, they will reinforce the vector mean because their orientations, when doubled in 360° format and converted back to quadrant format, are N02E and N02W. The mean resultant length (the length of the resultant orientation vector divided by the sum of the line lengths; Davis, 1986) was used to define the dispersion of the line data. The mean resultant length will be 1.0 for perfectly clustered orientations with only one orientation and 0.0 for random lines.

In contrast to the north-south strike of thrust-belt faults in Wyoming (Fig. 9A), Laramide fault and fold orientations define a distinctly different northwest-southeast structural grain (Fig. 9, B, C, D, and E). The average vector-mean orientation of Laramide faults (Fig. 9B, Table 1) is N42W, with a low mean resultant length (0.23), indicating considerable dispersion. Some of the variation in fault strikes is due to high-angle faults at the crest of several arch culminations (see the Rock Springs, Laramie, Medicine Bow, and Bighorn arches, Fig. 2A), faults that are nearly perpendicular to the arch axis. These faults may relieve axial stretching at the arch crests. If these faults are removed from the data set, the remaining faults, mostly reverse and thrust faults (Fig. 9C, Table 1), give a vector-mean orientation of N41W. Still, the mean resultant length for these Laramide thrust and reverse faults (0.42) is much smaller than the mean resultant length (0.77) for faults from the Wyoming thrust belt. Laramide reactivation of pre-existing faults (Hansen, 1986; Stone, 1986; Huntoon, this volume) and mafic dikes (Erslev and Rogers, this volume; Schmidt and others, this volume) in the Precambrian basement probably caused some of this variability in fault strikes.

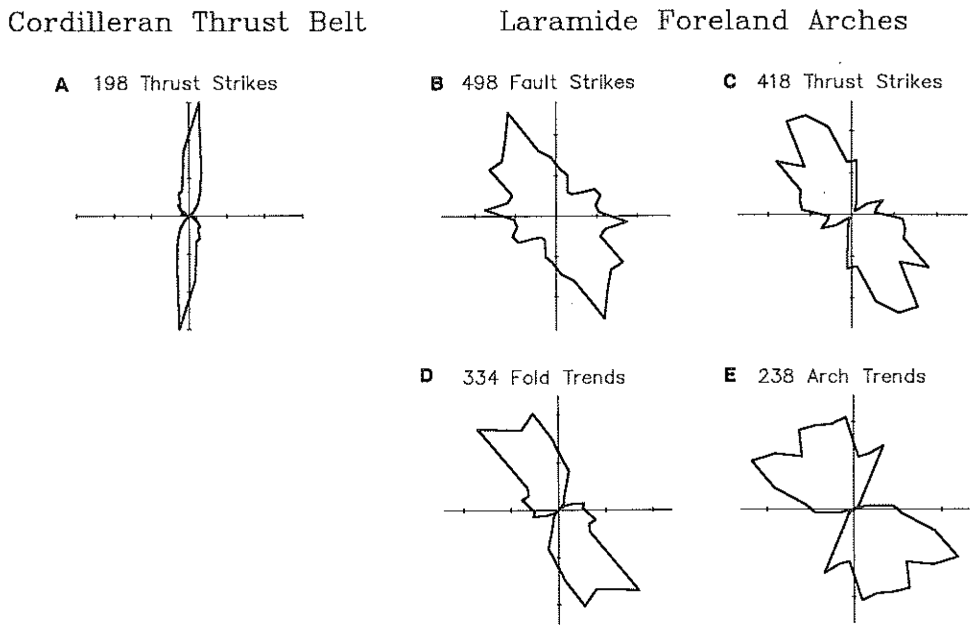


Figure 9. Symmetric rose diagrams showing the distribution of Cordilleran thrust belt fault strikes (A), Laramide foreland fault strikes (B), Laramide reverse and thrust fault strikes (C), Laramide fold axis trends (D), and Laramide arch trends (E). Fault and fold trends were digitized from structure maps of Wyoming (Blackstone, 1989, 1990a) and plotted in 10° intervals. Axes have tick marks for every 20 orientations.

TABLE 1. ORIENTATION OF ROCKY MOUNTAIN STRUCTURES

Data set	Structure type	Number	Vector mean	Mean resultant length\ (R)
N.E. Front Range, CO	Basement fault strikes	399	N39W	0.35
Wyoming foreland	Basement fault strikes	498	N42W	0.23
	Thrust and reverse strikes	417	N40W	0.42
	Fold axis trends	334	N31W	0.45
	Arch axis trends	237	N36W	0.40
Wyoming thrust belt	Thrust strikes	197	N0W	0.77
Wyoming foreland thrust and reverse faults sorted by adjacent arch trends				
Adjacent to west-trending arches	Fault strikes	139	N64W	0.53
	Arch trends		N82W	
Adjacent to northwest trending arches	Fault strikes	139	N44W	0.57
	Arch trends		N45W	
Adjacent to north-trending arches	Fault strikes	139	N16W	0.63
	Arch trends		N7W	
Fold axis trends sorted by adjacent arch trends				
Adjacent to west-trending arches	Fold trends	111	N47W	0.48
	Arch trends		N75W	
Adjacent to northwest-trending arches	Fold trends	111	N35W	0.64
	Arch trends		N36W	
Adjacent to north-trending arches	Fold trends	112	N11W	0.55
	Arch trends		N10E	

Laramide fold axes (Fig. 9D, Table 1) from Blackstone (1989) give similar mean vector (N31W) and mean resultant vector (0.45) values. The slightly lower dispersion for the fold axes suggests that there may be more oblique-slip faults than folds oriented obliquely to the regional shortening direction. The orientations and variability of Laramide arches are equivalent to those of adjacent faults and folds; the average vector mean is N36W and the mean resultant length is 0.40 (Fig. 9E, Table 1). These orientations are consistent with northeast-southwest compression and shortening. The lack of fold and arch orientations paralleling the N60E direction suggests that this was the Laramide shortening direction in Wyoming. This conclusion is consistent with a similar analysis of Laramide shortening vectors by Kanter and others (1981).

If the Laramide foreland was characterized by northeast-southwest compression, then we might expect a consistent obliquity of Laramide faults and folds in north-south and east-west ranges. To further test this hypothesis, fault and fold orientations from Figure 9 (C and D) were paired with the orientation of the nearest arch. A simple computer program selected the arch-segment orientation closest to the mid-point of each fault and fold segment. These orientations are plotted against each other in Figure 10, which shows that fault strikes and fold trends are positively correlated with the trends of the adjacent arches. But the slope of an average line does not appear to be one, suggesting that, on average, there is less than a one-to-one correspondence between arch trend and the average orientation of adjacent faults and folds.

These fault and fold data were subdivided into thirds by the orientation of the adjacent arches to test for any consistent obliquity between these structures and their adjacent arches. Histograms of structure orientations (Fig. 11) and their mean resultant vectors (Table 1) show that the third of the fault and fold orientations adjacent to northwest-trending arches are generally better clustered than those adjacent to west- and north-trending arches. In addition, the vector-mean orientations for the faults and folds adjacent to northwest-trending arches are within 1° of the vector mean of the arches. In contrast, the vector-mean orientations of faults and folds adjacent to north- and west-trending arches are all significantly more northwesterly than the vector means of the arches themselves. Because both north- and west-trending arches are dominated by northwest-trending faults and folds, the asymmetries shown by the north-trending Front Range and west-trending Owl Creek Mountains are confirmed. This consistent obliquity supports the hypothesis that north- and west-trending arches developed oblique to northeast-southwest shortening and compression directions.

HYPOTHESIS 1: NORTHEASTERLY LARAMIDE DETACHMENT

All the above observations suggest northeast-southwest shortening and compression in Laramide structures of the central Rocky Mountains. Specifically, these patterns suggest a significant strike-slip component of motion on arches oblique to the average northwest-southeast trend. But the high-angle strike-slip faults used to explain west-trending ranges by Wise (1963), Sales (1968), and Stone (1969) are difficult to reconcile with the evidence for low-angle thrusting (Gries, 1983a) and thrust loading of adjacent basins. In addition, there is no seismic or gravity evidence for high-angle faults cutting the crust-mantle boundary in the central part of the province (Hurich and Smithson, 1982; Hall and Chase, 1989).

Oblique slip, however, need not be accomplished on high-angle faults. Low-angle lateral ramps are an equally important path for oblique slip in thin-skinned thrust belts (Dahlstrom, 1970). If the west- and north-trending arch segments are underlain by lateral ramps, then these ramps can merge with normal ramps in a zone of lower crustal detachment. A common detachment in the lower crust would explain the continuity of the Laramide basement arches. The pop-up models for the structural geometries of the Uinta (Bruhn and others, 1986) and Front

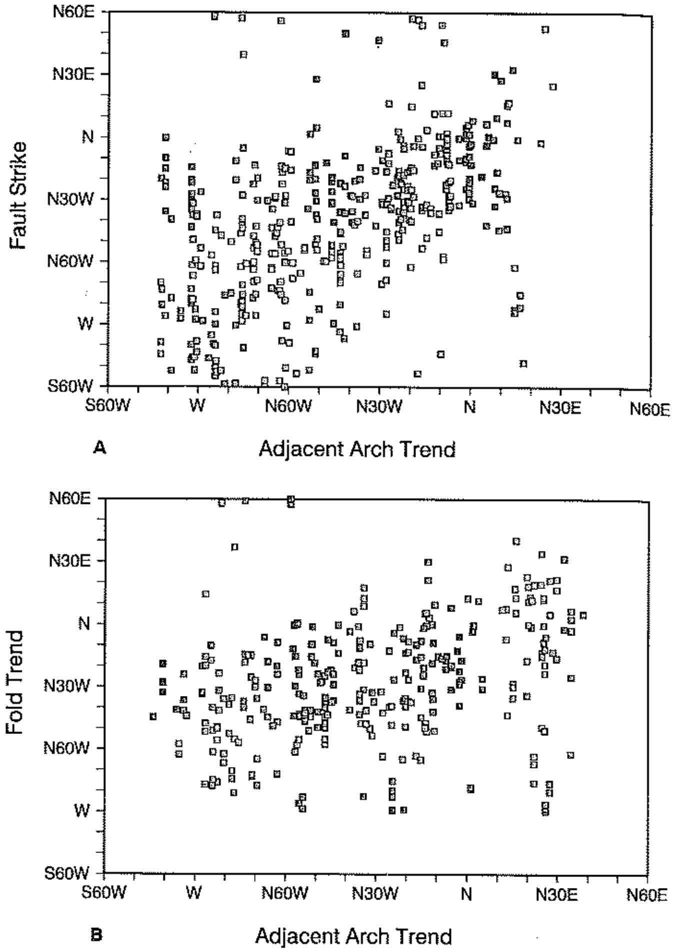


Figure 10. Fault strikes (A) and fold trends (B) from Figure 9, C and D, plotted versus the trend of the arch nearest to the structure.

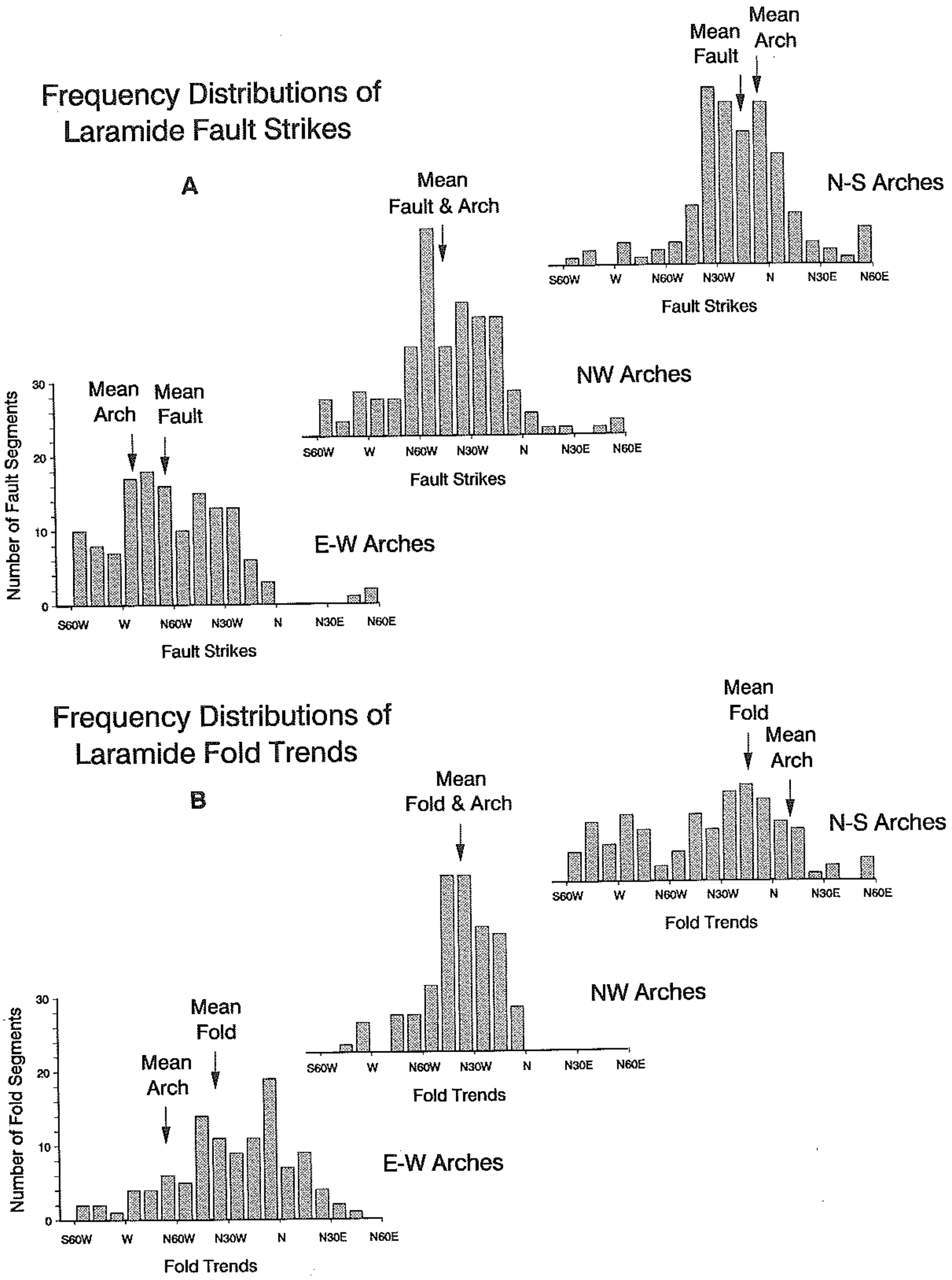


Figure 11. Frequency distributions and vector mean orientations of fault strikes (A) and fold trends (B) sorted into three groups based on the orientation of the adjacent arches. Note the close correspondence of arch, fault, and fold vector mean orientations and the tighter clustering of those orientations for structures adjacent to northwest-trending arches. Structures adjacent to more north- and west-trending arches are oriented in a more northwesterly direction than the arches themselves and commonly show poorer clustering. This asymmetry shows differences in structural style controlled by arch orientation.

Range (Kluth and Nelson, 1988) arches are consistent with an underlying detachment in the lower crust.

Schematic cross sections (Fig. 12) of the basement surface defined by Blackstone (1990a, this volume) in central Wyoming show how a linked, northeast-directed thrust system could be responsible for the complexly anastomosing pattern of Laramide arches. The deep thrust geometries are hypothetical and are based on detachment in the lower crust above a 40 km depth.

The interplay of forward and backward thrusting is clearly shown in the Bighorn Mountain arch, where the only emergent northeast-directed thrusts are exposed at the arch culmination. The plunging ends of the Bighorn arch are dominated by back-thrusts that, like in the northeastern Front Range, brought the basin side up and the range side down. On a larger scale, the Wind River and Owl Creek arches are interpreted to have formed above back-thrusts off the detachment in the lower crust. Individually, these structures could be modeled as forward thrusts. But this would require the faults to root in the stable craton to the east, far away from an active plate margin and in an area of decreasing Laramide deformation.

Arch culminations appear to coincide with the concentration of slip on a single northwest-striking fault, with areas of distributed faulting forming broader, more symmetric saddles on the arches. These geometries are closely analogous to fault-propagation-fold and detachment-fold geometries forming above low-angle detachments in thin-skinned thrust belts (Jamison, 1987). Variations between these end-member geometries can explain the changes between the asymmetrical culmination of the Wind River arch and its continuation along trend in the more symmetrical Sweetwater arch.

Slip on individual arches appears to be inversely proportional to the cumulative slip on other structures in the same cross section. For example, increased slip on the Beartooth arch in the northernmost section in Figure 12 corresponds to decreased slip on the Wind River and Bighorn thrust systems. The Bighorn arch reaches its highest culmination only when the Owl Creek and Black Hills arches are minimized. The apparent decreases in thrust displacement and overall uplift in the southernmost cross section in Figure 12 through the northern Laramie Mountains are readily understood on a more regional scale. Part of the missing slip was probably transferred to the northeast through the section to the Black Hills arch. The remainder of the slip was probably intercepted by the Uinta arch in northwestern Colorado and dissipated by the uplift of that arch. The distribution of a relatively constant, northeast-directed slip between arches could be responsible for the en echelon arch highs in the central Rocky Mountains. To the north and south, Laramide slip probably decreases and may change in orientation as Rocky Mountain foreland deformation decreases in these directions.

Lithologic controls on arch geometry

The controls on the location of the arches and their culminations are probably in the lower crust and thus hidden from view. Changes in geothermal gradient due to Laramide magmatism could cause undulations in the brittle-ductile transition, which might deflect thrusts upward, forming ramps (Schmidt, 1987). Alternatively, increased competence in the lower crust could cause sticking points that might force thrusts upward. For example, deformation in a detachment cutting from quartz-rich metasedimentary rocks to feldspathic plutonic rocks could change from ductile shear to brittle cataclasis.

To evaluate the possibility that variations in basement lithologies could nucleate Laramide arches, the exposed Precambrian rocks were studied to see if there is a preferential distribution of individual lithologies in certain parts of the ranges. This analysis assumes a positive correlation between surface and lower crustal lithologies. The Precambrian rock types in 13 ranges were lumped as either metasedimentary, granitic, or gneissic lithologies. Each range's exposures of Precambrian rocks was divided along the axis of the range into 10 segments of equal width and the proportion of the three rock types in each segment was estimated. These estimates were summed over all the ranges, giving the average distribution of rock types shown in Figure 13.

The increased abundance of feldspathic granitic rocks in the center of the ranges suggests that the feldspathic roots of these plutons might have caused sticking points in a lower crustal detachment. These sticking points may have played a role in nucleating the Laramide arches. The upward deflection of the detachment could initiate a master thrust, which could then propagate into the upper crust and form an arch culmination.

DIFFERENCES BETWEEN LARAMIDE AND CORDILLERAN STRAIN AND STRESS

Stress orientations

The differences in structural orientations between the Rocky Mountain foreland orogen and the Cordilleran thrust belt suggest that there was a strong contrast in the orientation of shortening and stress. The Cordilleran thrust belt describes a large arc with the eastern limit of imbricate thrusting starting in southeastern Nevada, continuing to the north-northeast to Wyoming, and then north-northwest to northwestern Montana (Fig. 1B). One might expect the section of the thrust belt in Wyoming to contain structural trends paralleling those in the Laramide arches. Instead, the rose diagram of Wyoming thrust-belt fault strikes in Figure 9A and their vector-mean orientation (N0W, Table 1) show a tight grouping around a north-south strike.

If dip slip dominated on these faults, then the resulting east-directed motion would be oblique to the northeast-directed motion of the Laramide basement arches. Application of the bow and arrow rule of Elliott (1976) to the entire thrust belt also suggests slip perpendicular to the north-south section of the thrust front in Wyoming. Accordingly, Royse and others (1975) and Lamerson (1982) assumed east-directed motion in their balanced cross sections of the Cordilleran thrust belt in Wyoming. East-directed motion was confined by paleomagnetic (Eldredge and

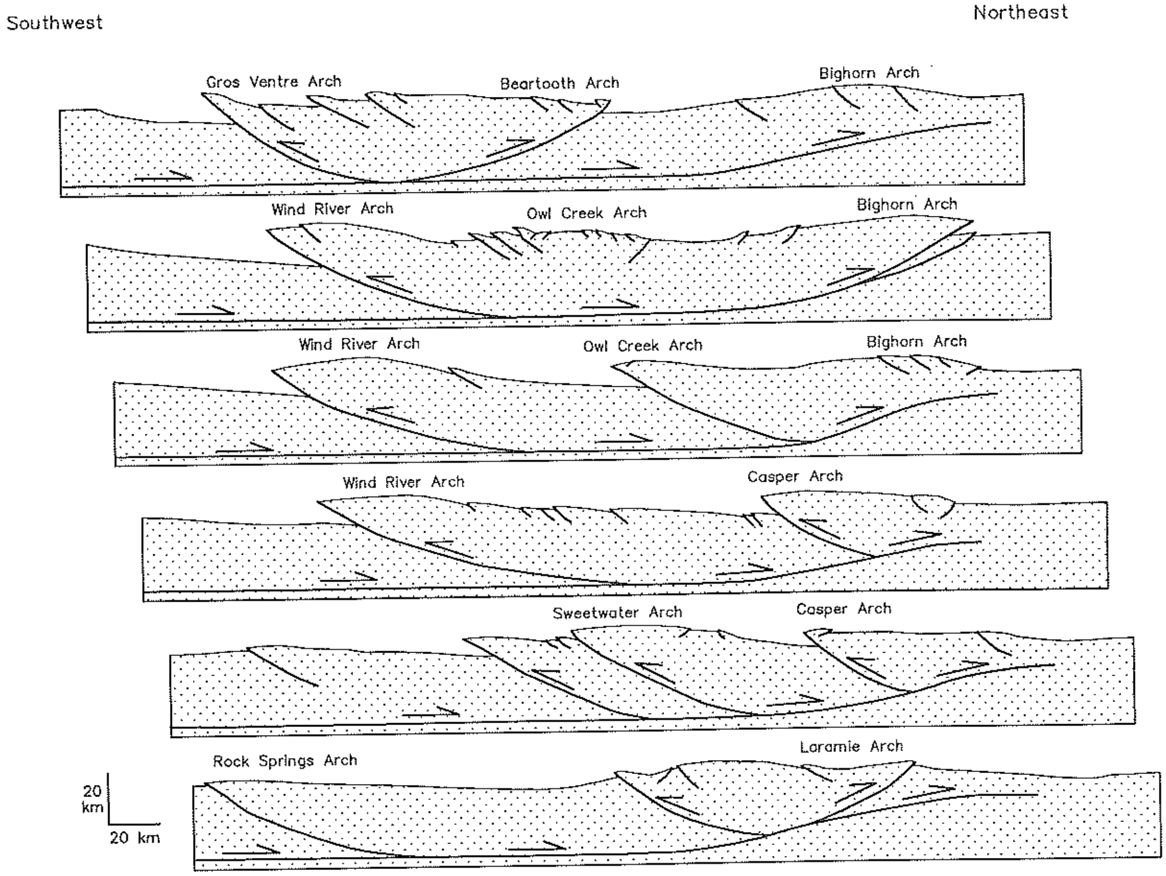


Figure 12. True-scale cross sections of the Precambrian basement surface in Wyoming (after Blackstone, 1990a) on lines shown in Figure 2A. These sections assume delamination in the lower crust and a uniform crust-mantle interface at 40 km below sea level. All fault geometries in the lower crust are schematic yet restorable in concept.

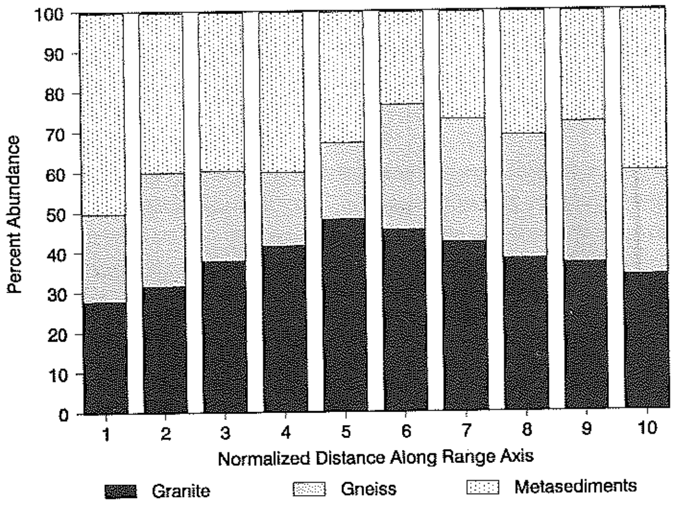


Figure 13. Lithologic profiles through 13 basement-cored uplifts using geologic maps in Houston and others (1993).

Van der Voo, 1988), joint, and calcite-twin (Craddock and others, 1988) data from the northern Wyoming thrust belt. In this area, only the leading thrust sheets rotated toward a northeasterly slip direction due to interference with the Cache Creek fault of the Teton arch (Craddock and others, 1988).

Penetrative strain and stress

The overall shortening of thrust belts is commonly several times larger than that of adjacent basement-involved foreland provinces. In the thin-skinned Wyoming-Idaho-Utah thrust belt, Royse and others (1975) calculated ~50% shortening, whereas adjacent cross sections through the Laramide foreland indicate between 10% and 15% shortening (Kanter and others, 1981; Brown, 1988; Stone, this volume).

Another major difference between thrust belt and Laramide structures is the prevalence of penetrative strain. Penetrative strain occurs at all scales in thin-skinned thrust belts (e.g., Mitra and others, 1988). Both spaced and penetrative pressure-solution cleavages are common in thrust belts, attesting to the distributed character of thrust-belt deformation. The occurrence of crushed pebbles in clast-supported conglomerates suggests high deviatoric stress in the sedimentary rocks of thrust belts.

In contrast, there are few reported examples of deformation cleavage or shattered conglomerates in Laramide structures. It is possible that temperatures and fluid fluxes in sedimentary rocks of the Laramide foreland were not sufficient to cause solution cleavage. However, cleavage does occur near Laramide structures in the northern Tobacco Root Mountains of southwest Montana (Schmidt and others, 1988), where it is associated with encroaching thin-skinned thrust sheets, not basement-cored structures. This indicates comparatively low levels of deviatoric stress in the sedimentary rocks of Laramide structures.

Center-to-center strain analysis of Paleozoic oolitic limestones and quartz arenites (Erslev and Rogers, this volume; Erslev and Ge, 1990) has revealed no measurable tectonic strains, even from highly tilted strata adjacent to major faults. It is clear that the sedimentary strata of Laramide structures did not undergo the penetrative stress and resulting strain characteristic of thin-skinned thrust belts.

Stress and strain variabilty

The diversity of Laramide fault orientations also points to minimal regional stress fields at the level of the sedimentary strata. As shown earlier, Laramide fault strikes in Wyoming are much more variable (mean resultant length of 0.23) than coeval faults of the Cordilleran thrust belt (mean resultant length of 0.77). Local topographic slopes caused southeast-directed gravity detachments in the Denver (Wattenburg area; Kittleson, 1990) and Bighorn basins (South Fork fault; Blackstone, 1986; Clarey, 1990). At Rattlesnake Mountain, the fact that reverse and normal faults merge together as fault splays requires minimal deviatoric stresses so that the requirements of strain compatibility can override the regional stress. The reverse-fault orientations documented by Erslev and Rogers (this volume) do not provide optimal planes for either maximizing the shear stress or minimizing the normal stress. Basement block rotations, however, generally indicate that these faults shallow with depth, suggesting that they are better oriented for optimal fault slip at deeper levels in the crust.

Differences in the magnitude of deformation could be explained by differences in the rocks themselves, one of the strongest contrasts between thin-skinned thrust belts and thick-skinned foreland orogens. Thin-skinned thrust-belt research demonstrates clearly the importance of elevated fluid pressures for thrust-sheet motion (Davis and others, 1984), yet most Rocky Mountain basement underwent Precambrian amphibolite or granulite facies dehydration and thus lacked an internal source of fluids. Ingress of water into dry basement rocks would form hydrous alteration products, making the basement act as a sponge as it absorbed free water, decreasing fluid pressures and thus increasing the rock strength. Whereas differences in rock strength can explain differences in the amount of shortening, they cannot explain differences in shortening and stress orientations.

HYPOTHESIS 2: MULTIPLE CORDILLERAN STRESS GUIDES

Because both provinces responded to lateral compression, one important difference between them may be the location of their zones of stress transmission or, in other words, their stress guides. In thin-skinned thrust belts, layer anisotropy, fluid pressure, and rock composition weaken the strata. Elliott (1976), Chapple (1978), and Davis and others (1984) showed that forward progress of thin-skinned thrust sheets requires that the entire mass of sedimentary strata transmit the stress. In the Wyoming thrust belt, the entire sedimentary sequence probably made a wedge-shaped stress guide, and pressure-solution cleavage and penetrative deformation acted to distribute the stress equally through the strata.

The lack of regional penetrative strain in the sedimentary strata of the Laramide foreland suggests that the stress guide responsible for Laramide deformation must reside in the basement rocks below (Fig. 14). Models of crustal strength under cratonic heat-flow conditions (Carter and Tsenn, 1987; Ord and Hobbs, 1989) show clearly that the middle crust is the strongest layer in the continental crust, and is a clear candidate for the Laramide stress guide. These models also predict maximum lithospheric weakness in the lower crust above the strong mantle lithosphere. The resulting concepts of intracrustal delamination and detachment were used by Burchfiel and others (1989) to link compressional uplifts in the Tibetan Plateau and by Ribeiro and others (1990) and Banks and Warburton (1991) to explain the basement-cored structures of the Iberian peninsula.

Sources of Cordilleran and Laramide stress

The differences in stress orientations between the Cordilleran thrust belt and the central Laramide foreland suggest different contributions to their stress fields. The range of possible plate-convergence vectors between the North American and Farallon plates (N25E to N59E, according to Engebretson and others, 1985) is within the range of shortening directions indicated by Laramide structures in Wyoming. If low-angle subduction either increased the area of contact between converging plates or cooled the lower lithosphere of the North American plate (Dumitru and others, 1991), it may have enhanced coupling between the plates, increasing the loading of the lower North American lithosphere. This hypothesis can explain the occurrence of thick-skinned, Laramide-style thrusting in areas of low-angle subduction in the Andes (Jordan and Allmendinger, 1986) without calling on distributed shear from below (e.g., Bird, 1988).

It is important, however, to realize that structures analogous to those in Laramide and Sierra Pampeanas (Argentina) forelands also occur in areas adjacent to continental collisions (Rodgers, 1987; Burchfiel and others, 1989; Ribeiro and others, 1990). This suggests that low-angle subduction is just one way to produce the stress loads in the lower continental lithosphere required by basement-involved foreland structures.

The orientation of Cordilleran thrust-belt faults more closely

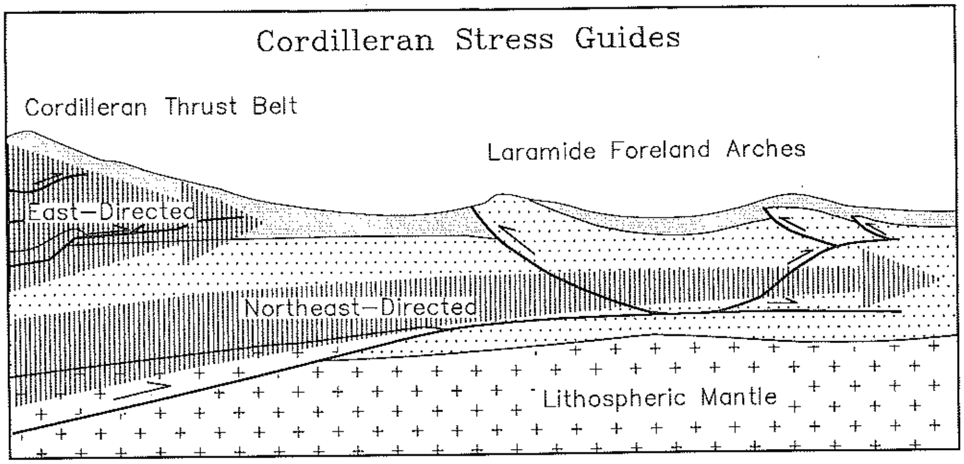


Figure 14. Schematic cartoon showing multiple stress guides and multilevel detachment during Cordilleran-Laramide lateral compression.

parallels the orientation of the actual plate margin than the plate-convergence vector. The eastward motion in the thrust belt in Wyoming may be a function of the orientation of a wedge-shaped stress guide. This wedge geometry is probably controlled by the orientation of the topographic welt paralleling the plate margin and the dip of the miogeoclinal prism. A topographic contribution to the orogenic wedge is consistent with the calculations of Elliott (1976) and Davis and others (1984) that indicate that the body force provided by a topographic slope is necessary for thrusting in a thin-skinned thrust belt. Because the Laramide structures of the Rocky Mountain foreland did not create a uniform slope and the cratonic sedimentary rocks do not wedge in a specific direction, their motion may have been determined purely by the plate-convergence vector. The effects of topographic slope in the Laramide foreland may be limited to local body forces contributing to down-slope sliding on gravity detachments and gravitational spreading of individual ranges. The parallelism of the thick-skinned Sierra Pampeanas and thin-skinned pre-Cordillera thrust belts in Argentina may be simply because Andean low-angle subduction in this area is not oblique.

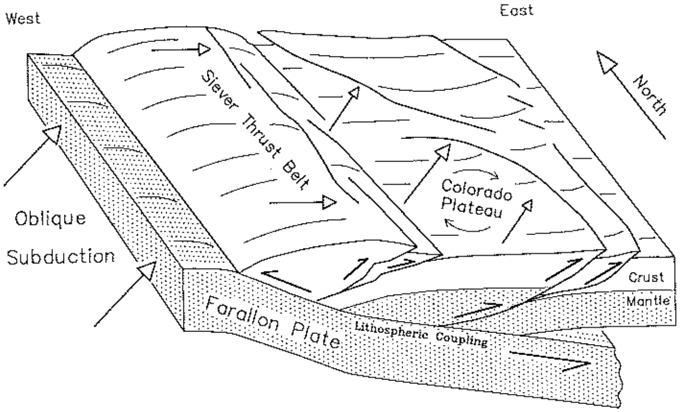


Figure 15. Schematic block diagram showing the development of Laramide structures by crustal detachment during lithospheric coupling in a low-angle subduction west of the Rockies. Note that variable slip on the detachment could explain the rotation of the Colorado Plateau.

Geophysicists have found no evidence for Laramide faults cutting the crust-mantle boundary in Wyoming (Prodehl and Lipman, 1989), yet this may not be the case elsewhere in the Rocky Mountains. Cross (1986) and Hamilton (1988) suggested that the rigidity of the Colorado Plateau may have resulted from underpinning by strong subducted lithosphere. Alternatively, the rigidity of the Colorado Plateau could also be explained if this crust was pinned to strong North American upper mantle during the Laramide. The stiffening of the Colorado Plateau by an underlying plate of strong mantle lithosphere would provide a good explanation for the plateau's decreased deformation. Both possibilities suggest that the thrust slip on the bordering Front Range passes into the mantle along the eastern margin of the Colorado Plateau (Figs. 14 and 15). The clockwise rotation of the Colorado Plateau (Bryan and Gordon, 1990) could have resulted from northward-increasing slip on a master detachment underlying the plateau, which is suggested by the increase in the amount and breadth of Laramide deformation in Wyoming.

The eastern margin of the Colorado Plateau is complicated by subsequent extension on the Rio Grande rift system west of the Front Range. Laramide thrusting of mantle over crust along the margins of the Colorado Plateau could have created a gravitationally unstable overhang of dense mantle rocks over less-dense crustal rocks. Whereas this is admittedly extremely speculative, subsequent back sliding on these Laramide faults could have initiated crustal extension in the Rio Grande rift.

CONCLUSIONS

Laramide fault, fold, and arch orientations are highly variable and strongly oblique to coeval structures in the Cordilleran thrust belt. The arch geometries range between asymmetrical fault-propagation folds off thrust ramps propagating up from the lower crust, and more symmetric detachment folds above a master detachment in the lower crust. The anastomosing, continuous web of Laramide basement arches indicates connected deformation, necessitating oblique slip on north-south- and east-west-trending arches. Oblique slip is also indicated by slickenside orientations and the asymmetry of faults and folds relative to arch crests.

Northeast-dipping back-thrusts in the Front Range, Beartooth Mountains, and Bighorn Mountains probably sole into southwest-dipping master faults that uplift the ranges. The larger, southwest-directed Wind River and Owl Creek arches probably formed above back thrusts off a detachment in the lower crust that linked all Laramide foreland arches. Detachment within a zone of delamination in the lower crust is consistent with the continuity of the anastomosing arch system and the apparent transfer of slip between the en echelon arch culminations. Models of northeast-progressing thrusting in the Laramide foreland (Brown, 1988; Perry and others, 1991) are consistent with propagation of the detachment to the northeast, with ranges popping up in areas of favorable thermal gradients, pre-existing weaknesses, and lithologic contrasts. North- and west-trending arches probably formed by oblique slip on lateral ramps connecting northwest-trending frontal ramps underlying arch culminations.

Differences in rock types, stress guide, and proximity to the plate margin can account for many of the differences between Laramide and Cordilleran thrust-belt structures. The lack of penetrative strains and the variability of surface-fault orientations in basement-cored structures indicate that the Laramide stress guide was located in the middle crust above a lower crustal detachment. In Wyoming, northeast-directed Laramide slip may have more closely paralleled plate convergence than east-directed thrust-belt slip, which was also controlled by gravitational spreading of the Cordilleran crustal welt. To the north, the Cordilleran and Laramide stress guides may have combined to form the closely-spaced arches of southwest Montana before merging into the Canadian thrust belt. Decreasing deformation to the south may have rotated the Colorado Plateau, the anomalous rigidity of which can be explained by pinning the plateau to strong North American mantle lithosphere during the Laramide orogeny. Foreland basement-cored deformation may result from more effective coupling of converging lithospheres during low-angle subduction and continental collision.

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