Laramide Structures in Basement and Cover of the Beartooth Uplift Near Red Lodge, Montana[1]

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ABSTRACT

Ramp mechanisms associated with decoupling of a 6–7-km-thick basement slab may have been responsible for progressively more and more horizontal components of thrusting of the northeast corner of the Beartooth uplift near Red Lodge, Montana. As part of a nearly right-angle corner of the uplift, two apparent tear faults bound a 7-km-long block of Laramide mountain-front structures. New roadcuts and a deep well through basement refine geometry of range overthrusting and show that these apparent tear faults are really pivoting normal faults that cut frontal thrust structures on either side of an uplifted corner flap. A ship's prow analogy of late-stage horizontal thrust motion is proposed with the "bow wave" causing uplift and rotation of the corner flap. Volumetric adjustments associated with late-stage stuffing of basin material beneath frontal thrusts plus deeper duplexing of basement beneath the uplift helped define final details of range geometry, a mechanism probably applicable elsewhere in the middle Rocky Mountains.

These mechanisms of basement deformation at the northeast corner contrast with those of the western Beartooth uplift where strong, dense rocks associated with the Precambrian mafic Stillwater Complex precluded detachment of a basement slab and created a different style of structural underthrusting and frontal rotation. Eastward escape tectonics around the Stillwater obstacle caused later stages of the Beartooth uplift to change thrust direction from north-northeast to east, helping form the Red Lodge corner and to create the east-directed thrusts that separate the uplift from the adjacent Bighorn basin.

INTRODUCTION

Debates on mechanisms of Laramide uplift have occupied several generations of geologists during the middle of the 20th century [see summaries by Snoke (1993) and by Schmidt et al. (1993)]. These arguments about dominance of horizontal vs. vertical motion have largely subsided, the general consensus now being in favor of the horizontal school as a result of drill data (Berg, 1962; Gries, 1983), seismic data (Smithson et al., 1978), balanced section models (Erslev, 1993), present-day analogs in the Andes (Allmendinger, 1986; Jordan and Allmendinger, 1986), and better understanding of orogenic scale decollement mechanics (Cook and Varsek, 1994).

The Beartooth uplift of Montana and Wyoming (Figure 1) is a 60×125 km Precambrian crystalline mass that was once covered by 3–4 km of mostly marine Phanerozoic sedimentary rocks (Foose et al., 1961). During the Laramide orogeny, the area achieved approximately 8 km of structural relief (Blackstone, 1986) (Figure 2) largely during the Paleocene (Dutcher et al., 1986; DeCelles et al., 1991). Fission track dates record sudden cooling by exhumation at 52 Ma (Omar et al., 1994). Along the edges of the uplift, many parts of the Phanerozoic sequence were thrust and folded and are now eroded to spectacular limestone palisades. The eroded top of the uplift now stands with peaks of Precambrian basement at 3–4 km elevation.

The northeast corner of the uplift (Figure 3) is formed by a right-angle change in strike of range front structures. A variation of this figure has been published previously in Foose et al. (1961), as was a variation of Figure 13 in Wise (1983). Both figures have been updated here to show the frontal thrusts along the margin of the Bighorn basin and the newly recognized corner structures. At the very corner of

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The Yellowstone Bighorn Research Association field camp at Red Lodge served as a base for work on this project on and off over the last 40 years. Members of that association, as well as Alan and Helen Weaver of Red Lodge, were of great assistance. Much of the work in the 1970s and 1980s was done at the University of Massachusetts at Amherst. Final manuscript preparation was as a research associate at Franklin and Marshall College. Grateful acknowledgment is given for the sharpening and refining of ideas and data by a host of friends, associates, colleagues, and former students, all of whom managed to overcome their natural shyness to highlight many inherent problems. John Bartley, Edward Beutner, Peter DeCelles, Richard Hoppin, Neil Mancktelow, and Walter Snyder provided helpful reviews; however, none of the above should be held culpable for the final product.

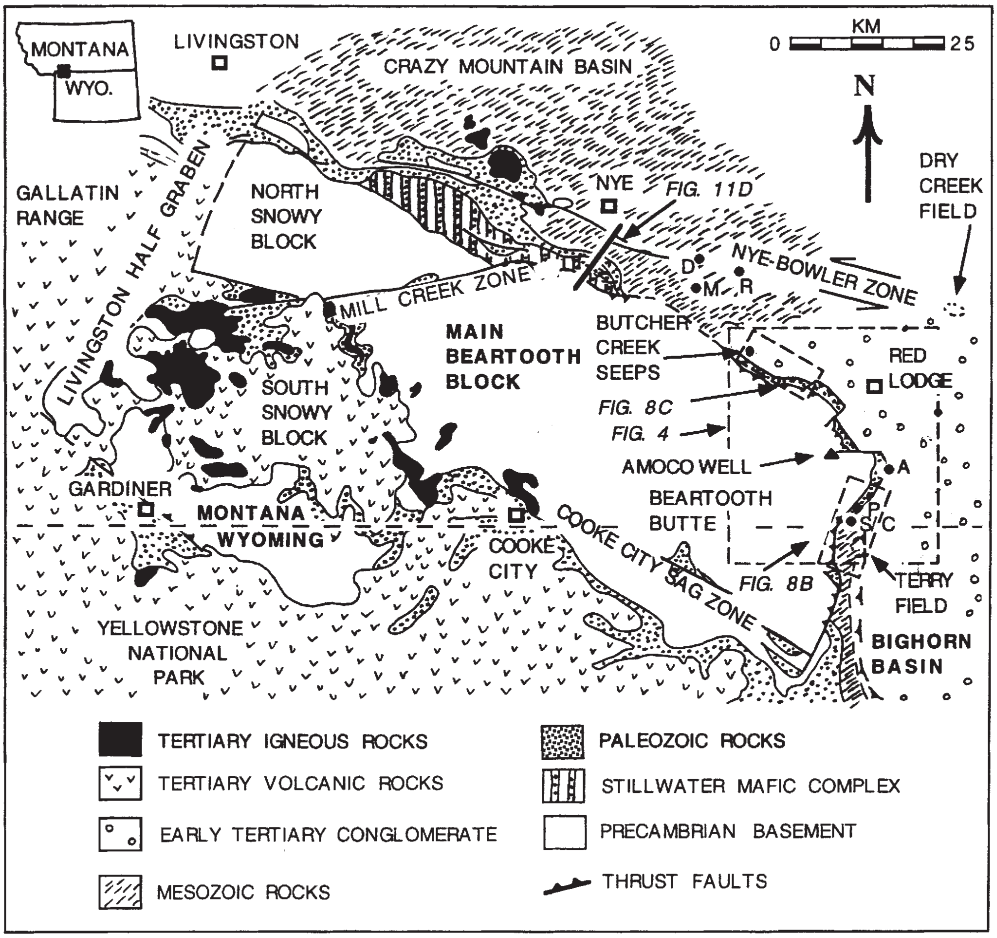


Figure 1—Tectonic features of the greater Beartooth uplift. A = Amoco Burlington Northern well 1, D = Dean dome, M = Mackay dome, P = Phillips Ruby A well, R = Roscoe dome, S/C = Shell/Carter Line Ditch well.

the block, frontal thrust zones and upturned Paleozoic cover units are cut by two large apparent tear faults, the Maurice on the southeast and the Willow Creek on the northwest (Figure 4). These faults bound a corner block in which a 7 km along-strike block of frontal thrust structures is more thoroughly broken and overturned than its offset continuations on either side of the corner (Figure 5).

Over the years this area with its prominent apparent tear faults and location on the major northeast route to Yellowstone (Figure 1) has been prominent in development of ideas about tectonic mechanisms of the middle Rocky Mountains. Innumerable field trips, conferences, industry training courses, etc. have passed through it. Currently, many university field trips provide students with brief looks at this area, and several geology field camps conduct student mapping exercises in it every summer. At one time or another, perhaps a quarter of American geologists have looked at these structures and many have mapped some of them in considerable detail. Despite this attention, to the best of my knowledge, the tear fault nature of the corner structures has never been questioned in print; however, new data suggest that some of the traditional interpretations have been wrong and that refinements of current tectonic models may be in order for this and perhaps for other basement-cored uplifts.

HYDROCARBON ASPECTS

Hydrocarbon exploration interest has a long history in the Red Lodge area. Active oil seeps and tar sands have been known at Butcher Creek, about 18 km west-northwest of Red Lodge (Figure 1) at least since the days of the early fur trappers. The first well drilled for oil in Montana was near these seeps in 1890 by T. S. Cruse and associates (Calvert, 1917). In an unpublished map, J. Fanshaw of Billings (1985) described the seeps as yielding brown-colored Phosphoria-type oil in overturned Greybull sandstone. Brief periods of production

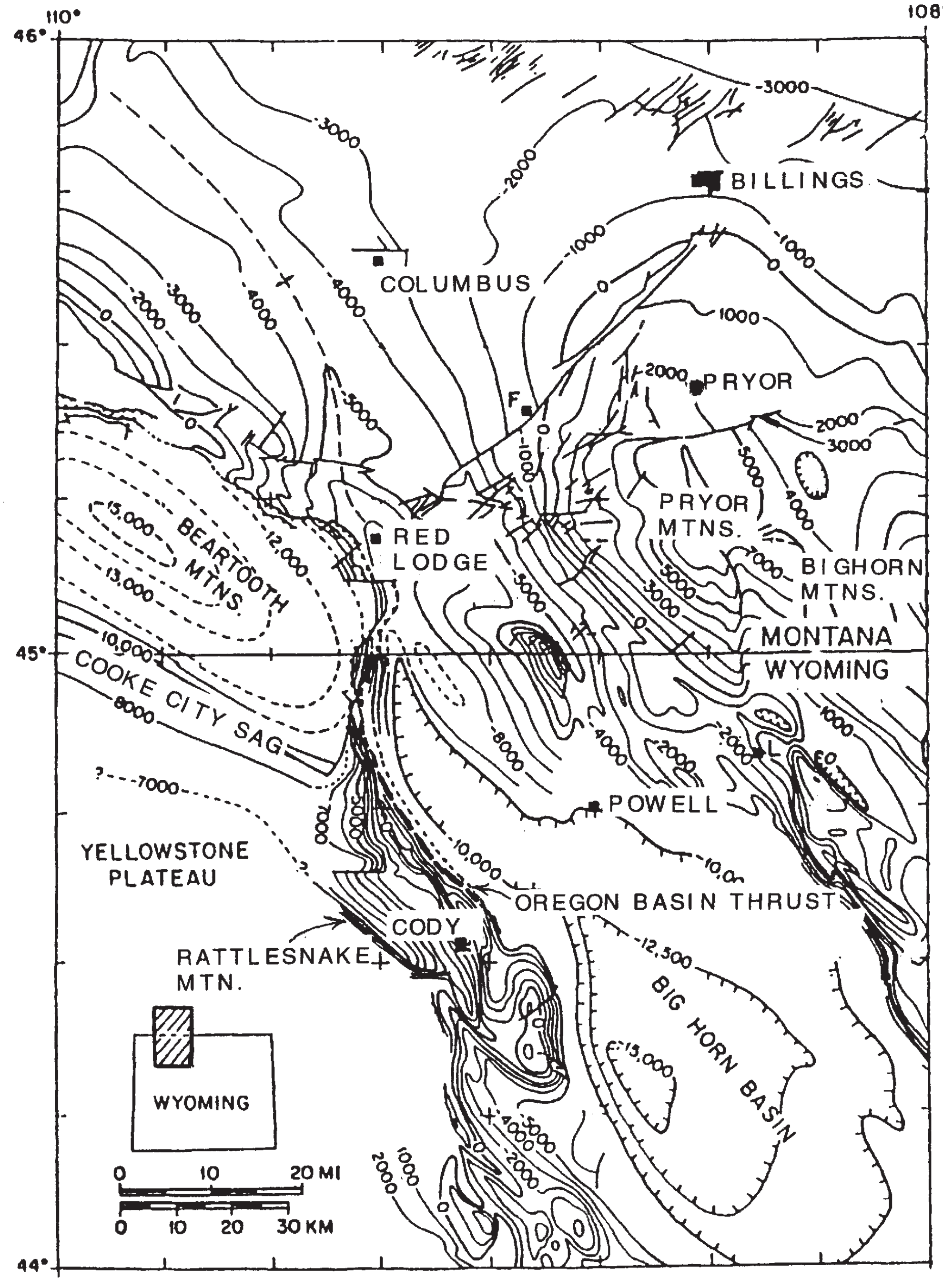


Figure 2—Restored structural contours (in feet) on the base of the Madison Limestone for the Beartooth-Bighorn region (modified from Wise and Obi, 1992). Note the Red Lodge corner and the disruption of the axis of the Bighorn basin by the north-south front of the Beartooth Mountains. The Oregon basin thrust continues the mountain front to the south and southeast as the west edge of the Bighorn basin.

from the nearby Mackay and Dean domes in the 1950s and 1960s and from the Roscoe and Dry Creek domes along the Nye-Bowler left-lateral shear zone (Figure 1) continue to encourage further exploration.

South of Red Lodge on the other side of the corner, the small Terry oil field (Figure 1) lies along the Beartooth frontal zone just south of the Wyoming state line. A number of oil wells also located on that figure have tested this same frontal upturned and overthrust zone. The Amoco Burlington Northern 1 well reached 14,841 ft (4526.5 m) in the Mowry; the Phillips Ruby A well reached 11,759 ft (3586.4 m) in the Cretaceous Fussion, while its sidetrack well penetrated Madison at 8200 ft (2501 m) within an overturned section dipping at 75° beneath the

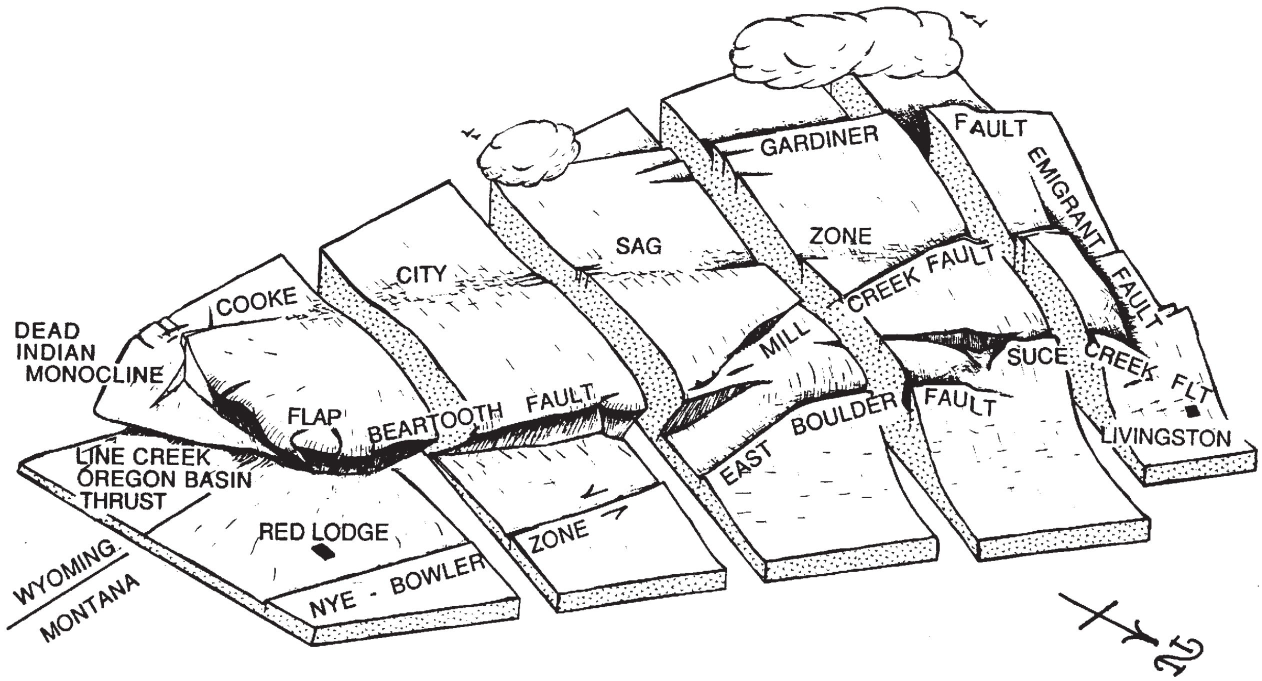


Figure 3—Configuration of the restored sub-Cambrian basement surface of the greater Beartooth uplift. View is from the northeast [eastern end revised and updated from Foose et al. (1961)].

frontal thrusts; and the Shell/Carter Line Ditch well reached 10,518 ft (3207.9 m) in the Cloverly.

With so much hydrocarbon activity on either side of the Red Lodge corner as well as Blackstone's (1986) projection of the axis of the hydrocarbon-rich Bighorn basin into and under this corner of the Beartooth uplift (see Figure 2), Amoco's deep test well through the basement thrust (Figure 1) was a logical exploration target. Even though that well produced some hydrocarbon shows, its chief value to date has been as a source of structural information (Tables 1 and 2). The following discussion makes use of data from that well plus some new and old exposures to suggest a structural evolution in which the axis of the Bighorn basin does not pass beneath the corner area. The proposed kinematic sequence may also help explain some of the complexities encountered in the deeper exploration of these mountain-front structures.

NEW ROADCUT EXPOSURES

Opening of a ski road to Grizzly Peak, 6 km west of Red Lodge, provided new exposures of Beartooth frontal structures, as located on Figure 4. The southeastern or lower 2 km of roadcuts consist of poor exposures of the Paleocene Fort Union Formation (Dutcher et al., 1986; De Celles et al., 1991). These units, located just below the frontal thrust, are predominantly flat-lying, relatively undeformed arkosic sandstones and granite pebble conglomerates shed from and later deformed and overthrust by range-bounding structures of the rising Beartooth uplift.

The key roadcut (Figure 6) is a 150-m-long oblique slice through the Beartooth frontal thrust zone (see Figure 4 for location). The cut exposes a 25-m-thick stack of imbricated and overturned Paleozoic carbonates. In a swale just southeast of the cut, the master fault at the base of the stack can be located to within a few meters. This fault is probably parallel to a number of 30° southwest-dipping disturbed and shattered zones exposed in the cut. These are subparallel to poorly defined and probably overturned bedding in the intervening slices of mostly Paleozoic carbonates, a relationship somewhat similar to the thrust zone encountered in the Amoco deep well as described in a following section.

The most significant imbricate zone in the outcrop is a partly covered, highly weathered slice of Paleocene Fort Union Formation (Figure 6A) sandwiched between the Paleozoic carbonates. This 3–4-m-thick, deeply weathered, clay-rich zone includes thoroughly decomposed remnants of 1–5 cm clasts, mostly granitic boulders now reduced to 1 cm mica fragments in the soil cover. Most surviving clasts are angular, but a few quartz and chert pebbles have well-rounded shapes. The lithology is

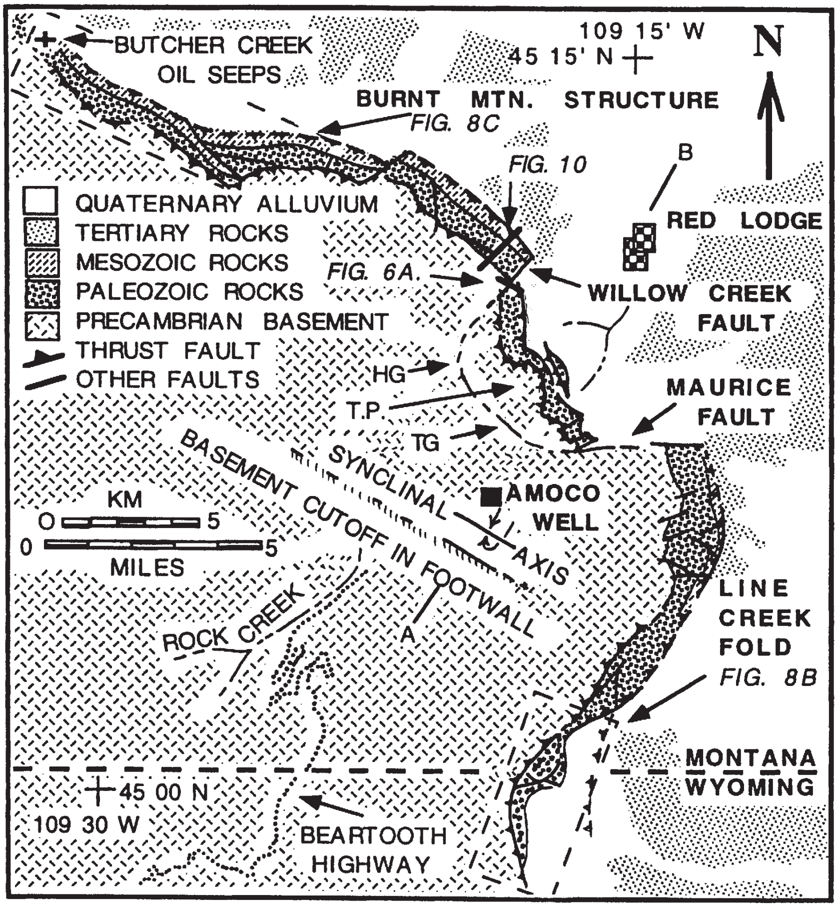


Figure 4—Structural features associated with the Red Lodge corner of the Beartooth uplift [mountain front data after Foose et al. (1961)]. T.P. = Towne Point, TG = Towne Gulch, HG = Hayward Gulch.

interpreted as a mixture of original sedimentary clasts later reworked to fault breccia and fault gouge. At road level this zone also includes a more intact slice of poorly sorted, well-bedded, brown-weathering lithic-rich sandstone, a lithology unknown in local Paleozoic stratigraphy but common in the Fort Union formation.

A series of minor crosscutting faults appears in the northwest end of the roadcut before it passes northwestward into a small gully and a 100-m-wide zone of disintegrated basement gruss. This disturbed zone is part of the N40°E-trending Willow Creek fault zone (Figure 4) defined by 1500 m of apparent dextral displacement of the frontal thrusts. The highly imbricated Paleozoic carbonate units in the roadcut contrast sharply across the fault with their former continuation of steeply dipping, but largely unbroken, representatives of the same formations. The marked contrast in structural style argues strongly against simple, purely strike-slip motion on the fault.

Paleozoic carbonate units in the roadcut record a sequential brittle fracture history starting with early thrusting followed by crosscutting en echelon normal faulting and a final development of a joint set parallel with and adjacent to the Willow Creek fault zone. The most prominent early crosscutting structure is a 5 m nearly vertical fault surface with oblique slickenlines. Abundant calcite overgrowths in pressure shadows behind its asperities record unequivocal left-lateral motion (Figure 6C). This distinctive surface with displacement sense opposite that of the master Willow Creek zone and a strike 20° clockwise from it, is interpreted as an early conjugate shear associated with inception of the fault zone. This mineralized surface contrasts with all other observed fault surfaces in the cut. These are smaller, nearly unmineralized, and strike east-west on average. Most fault dips are north and all slickenlines are dip-slip (Figure 6B, C). Where motion sense is determinable, displacements are normal. These faults are interpreted as a set of en echelon transtensional right-lateral features, younger than the large mineralized surface. The final brittle feature in the cut is a prominent joint set superimposed on the faults. This joint set, most

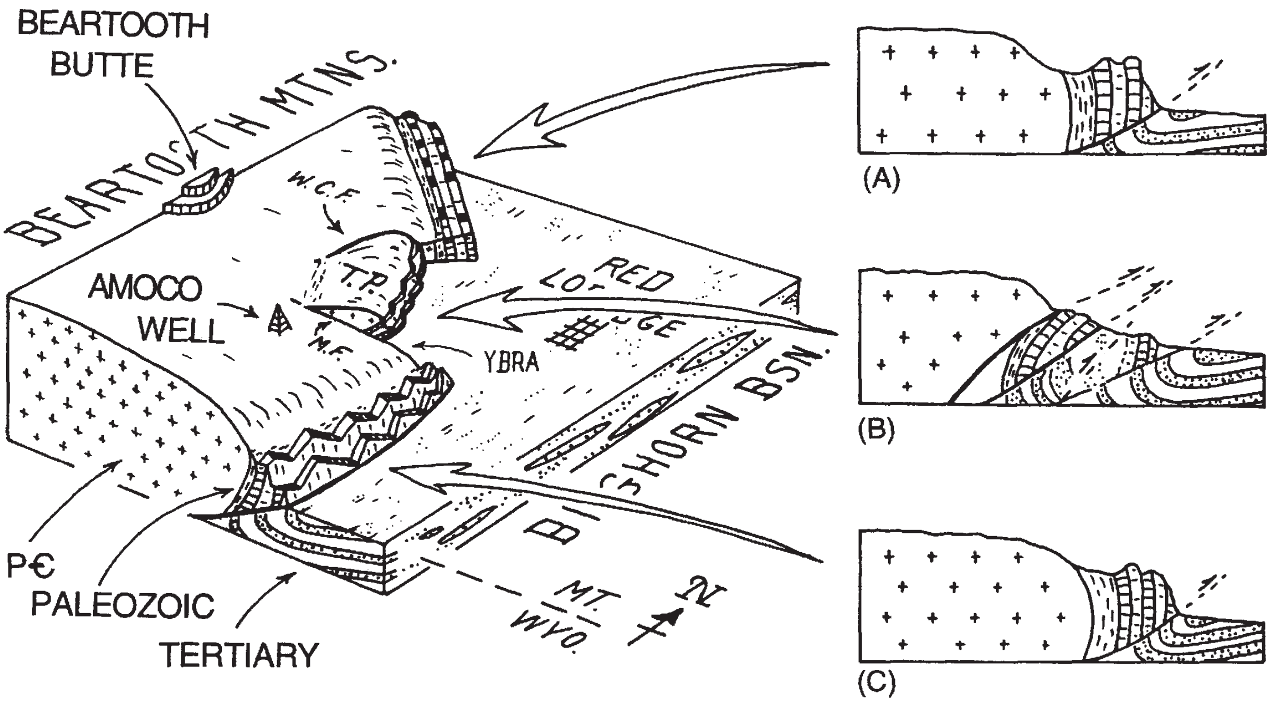


Figure 5—Block diagram of structures at the Red Lodge corner. W.C.F. = Willow Creek fault, M.F. = Maurice fault, T.P. = Towne Point. Note the contrast of complex overturning and thrusting in the uplifted and rotated corner block with respect to more simple mountain-front structures on either side.

Table 1. Data on Piney Dell Amoco 1 Well*

	Main Well		Sidetrack Well	
	Meters	Feet	Meters	Feet
Surface	0	0	0	0
Basement into fault zone	2537.7	8326	2509.1	8232
Base of "shattered granite"	2558.2	8393	2531.4	8305
Top of Bighorn	2558.2	8393	2531	8305
Permian–Pennsylvanian	2538.4	8328	–	–
Chugwater	2591.7	8503	2568.5	8427
Gypsum Springs	2615.5	8581	2660.3	8728
Sundance	2643.2	8672	2699	8855
Morrison, etc., into Cody	2699.4	8840	2756.9	9045
Core of syncline in Cody	3101.3	10,175	3296.4	10,815
Frontier (and younger)	3671.6	12,046	–	–
Lakota	4199.2	13,777	3610.9	11,847
Morrison	–	–	3627.1	11,900
Top of Madison	–	–	4059.6	13,319
Madison at total depth	–	–	4228.2	13,872

*The well is located along the Beartooth Highway south of Red Lodge, opposite Piney Dell Restaurant and resort. It was drilled in basement 1.4 mi (2.25 km) behind the frontal limestone palisades from 1986 to 1988. The well was spudded in at elevation 1902 m (6240 ft) with an intended target beneath the Beartooth thrust in the Frontier Formation about 686 m (2250 ft map distance) to the southwest. A sidetrack well was started at drill depth of 1919 m (6295 ft) still in basement. It was abandoned in the Madison Formation at 4698 m (15,413 ft) drill distance (vertical depth = 4228 m; 13872 ft) with bore inclination of 48.6°. Total departure was 1587 m (5208 ft) in a S46°W direction. The data are for vertical depths in the well at which tops of units were penetrated.

Table 2. Some Details of Drilled Thickness Through the Beartooth Thrust Zone in the Amoco 1 Sidetrack Well

	Drilled Thickness	
	Meters	Feet
Surface	0	0
Precambrian Basement	2509.1	8232
"Shattered Granite"	21.3	70
Bighorn Dolomite	7.3	24
Pennsylvanian–Permian	29.9	98
Chugwater	91.7	301
Overturned Jurassic, etc.	–	–

strongly developed next to and parallel with the Willow Creek fault zone (Figure 6D), is interpreted as a final phase of extensional strain normal to the zone.

NEW WELL

New data on the deeper structure of the corner appeared in Amoco 1 well drilled in 1986–1988 at Piney Dell along the Beartooth Highway, 2.3 km southwest of the frontal palisades (Figures 4, 5, 7). Some details of the well are given in the figure captions for Figures 4, 5, and 7 and in Tables 1 and 2. The well penetrated vertically about 2500 m of basement before passing through the Beartooth thrust at 0.6 km below sea level. The fault dip is probably in the 10–15° range based on dipmeter readings on carbonate slices in its immediate footwall. The fault zone consisted of 21 m of "shattered granite" above 37 m of severely faulted Ordovician Bighorn Dolomite and Pennsylvanian–Permian units (Table 2). The next 500 m of drilling penetrated an overturned and attenuated section of Mesozoic units before intersection with a nearly recumbent synclinal axial surface in the Cretaceous Cody Shale at vertical depths of 3101 and 3296 m in the main well and its sidetrack, respectively. Beneath the fold's axial surface, a right-side-up, relatively unfaulted stratigraphy dipped moderately to the northeast to terminate in the Mississippian Madison Limestone at a total depth of 4.228 km or 2.3 km below sea level.

Dipmeter data indicate that the major syncline is nearly recumbent and its strike is approximately parallel to the west-northwest–trending part of the Beartooth front. In the overturned limb of the fold, dipmeter readings are relatively flat (6–22° to the southeast, southwest, and northwest), whereas below the synclinal hinge dips are uniformly to the northeast at angles of 30–55°. Calculated orientations of lines joining corresponding intersections in the two borings trend N30°E with plunges equal to or even slightly greater than those reported from the dipmeter measurements. These relationships suggest that the N30°E line plunges almost directly down the dip of beds in the right-side-up limb. Accordingly, the trend of the major recumbent synclinal axis should be approximately N60°W or parallel with the trend of the greater Beartooth uplift (Figure 1). The S60°E projection of this fold hinge, in order to merge with the eastern Beartooth frontal structures, must either terminate abruptly or turn very sharply just southeast of the well (Figure 4). The N60°W fold trend indicates that a right section through the well should be drawn north-northeast across the Maurice fault and through the complicated frontal thrust zone. This cross section (Figure 7) shows that the faulted cutoff edge of basement in the footwall lies approximately 2.5 km map distance south-southwest of the drill site or about 7 km behind the present frontal palisades (Figures 4, 7).

CORNER FLAP

An upward-pivoting corner flap (Figure 5) may best explain the new data, starting with the problem of the tear faults. Although hampered by poor exposure, lateral projection of the traces of the Willow Creek and Maurice faults into basement (Figures 4, 5) yields no sign of gulches or lineaments to mark selective erosion along a fracture zone. For these faults, large apparent strike-slip displacements of frontal structures seem to vanish along strike into basement. The westernmost indication of the Maurice fault is repetition of five nearly vertical, 100-m-long, en echelon slices of Cambrian limestone, features too small to appear on Figure 4. The map pattern of these en echelon slices suggests indropping of a series of minor fault blocks along a zone of left-lateral transtensional strain, a mirror image of the Willow Creek roadcut exposure with its evidence of increasingly prominent extension in a zone of right-lateral transtension (Figure 6).

Rather than supporting the traditional interpretation of these structures as a pair of tear faults, all the data are more appropriate to a pair of pivoting normal fault zones bounding a rising corner flap undergoing increasing intensity of northwest-southeast extensional strain. The rear edge of such a flap should be a hinge zone connecting the two pivot points of the bounding faults. Towne Point (Figures 4, 7) is an isolated mountain of basement lying between the two fault zones. It is separated from the higher Beartooth uplift to the southwest by an erosional saddle connecting the heads of Towne and Hayward gulches (Figure 4). These features are ideal candidates for origin by localized erosion along a fractured basement hinge zone at the rear of the proposed flap.

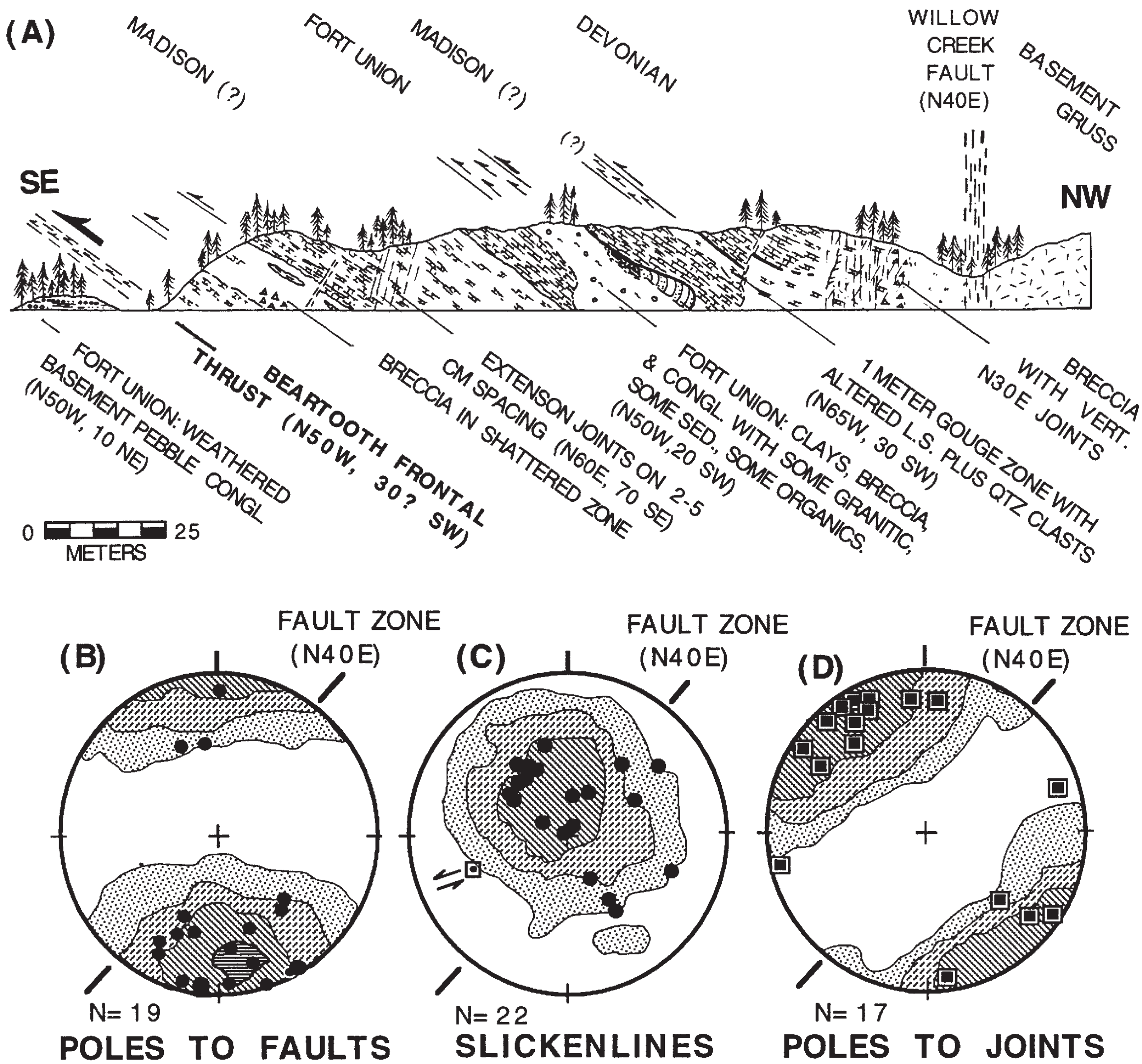


Figure 6—Grizzly Peak Ski Area roadcut (location on Figure 4). (A) Sketch of the outcrop showing the frontal thrust of the Beartooth uplift at left, imbricate portions of the thrust zone at center, and jointing and minor faults associated with the Willow Creek fault zone at the right. (B–D) Equal-area Kamb plots of roadcut structures. Contour interval is 2 sigma. Note the en echelon trend of structures in B and C and the parallel trend in D with respect to the strike of the master N40°E Willow Creek fault zone as indicated by the heavy line. Slickenline orientation of the only observed strike-slip fault is indicated separately by the square on (C). All other observed motion sense indicators were of normal displacement.

Structures about 15 km on either side of the corner provide broader evidence of larger scale late-stage strain. At Line Creek, 15 km south of the corner (Figures 4, 8B), the frontal palisades are deformed into a large vertically plunging fold indicating late-stage dextral motion of the uplift with respect to the basin (Wise, 1983). This frontal structure is quite different from nearby prethrust fold structures that are truncated and preserved in the hanging wall of the Beartooth thrust (Wise 1983). Instead, this structure represents folding and dextral slip faulting of vertically dipping Paleozoic units previously upended as part of the frontal thrust zone (Figure 8B). A similar, but mirror, image

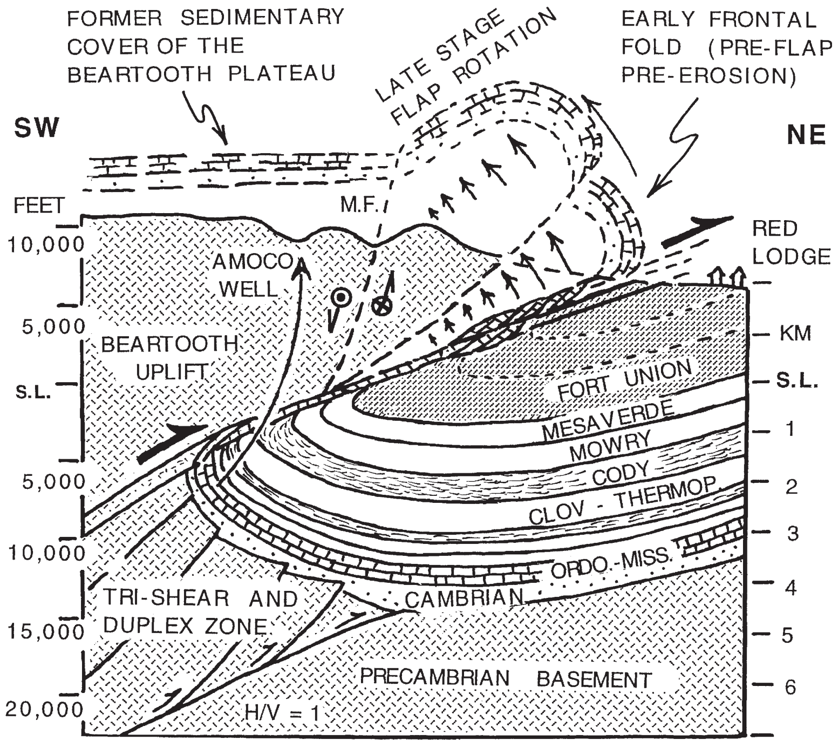


Figure 7—Cross section (line A-B on Figure 4) of the Red Lodge corner including the Amoco 1 well. Frontal fold/thrust structures predating flap rotation are solid. Subsequent flap rotation is indicated by the arrows and by the dashed pattern on carbonate units. Note that the line of section cuts obliquely across the Maurice fault zone (M.F.).

feature occurs with sinistral shear at Burnt Mountain, 15 km northwest of the corner (Figures 4, 8C) (Foose et al., 1961).

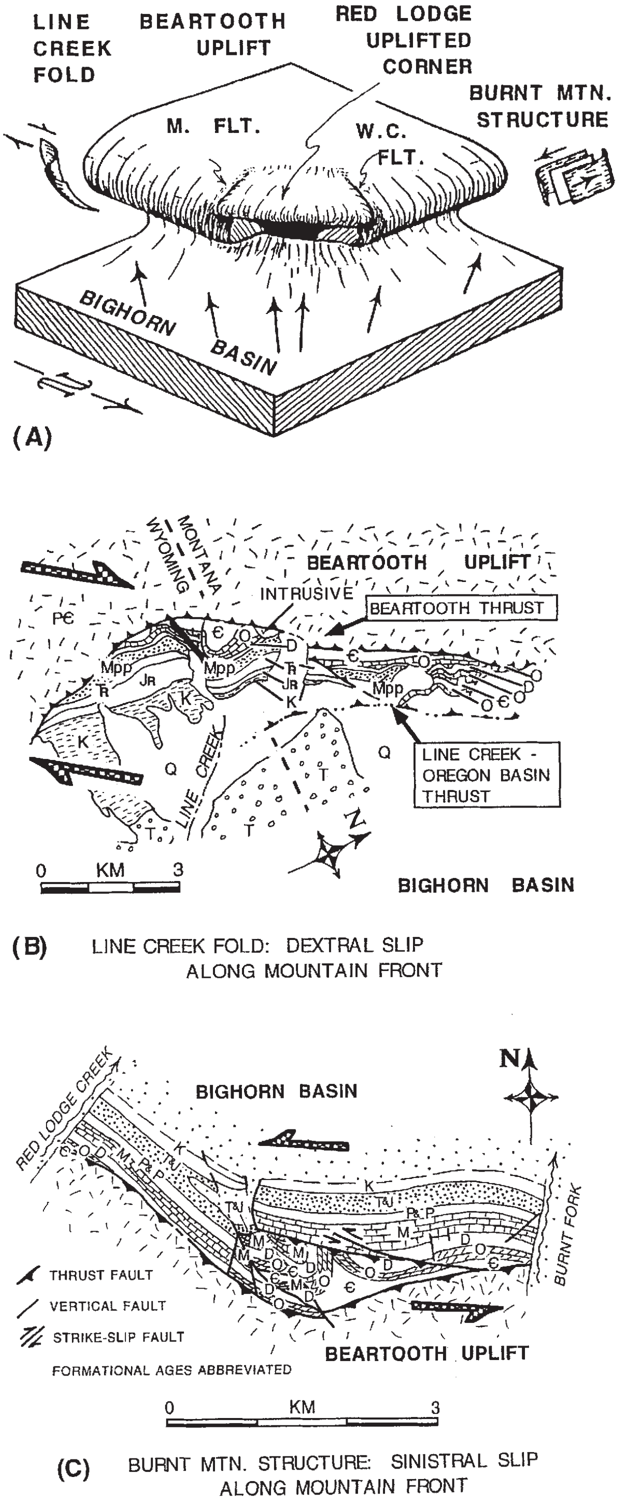
The combination of all of these corner structures might be likened to the blunt prow of a ship of basement sliding past and through the "water" of basin fill and upended Paleozoic frontal structures. Frictional drag on either side created appropriate late-stage dextral or sinistral features in the nascent frontal palisades at Line Creek and Burnt Mountain. This drag created strong along-strike extensile stresses at the corner to initiate bounding faults of the flap. As corner stretching continued and more and more basin material was forced beneath the advancing "prow," a bow wave formed and began to rotate the fault-isolated corner flap. Ultimately, the flap rotated by about 20° and subsequent erosion moved its leading edge back to the present line of exposed thrusts.

BASEMENT SLAB RAMPING AND EARLY FOLDING

Detachment and ramp formation of a thick slab of the upper basement can explain the kinematic development sequence of these corner structures. Cook and Varsek (1994) and Erslev (1993) among others discuss variations of such models. General evidence for the existence of such slabs of the upper basement includes the dominance of earthquake activity in the upper 10–15 km of continental crust (Scholz, 1988) and experimental data (Hirth and Tullis, 1994) suggesting that the onset of partially ductile behavior of quartz-rich rocks begins at 10–15 km depth. Examples of far greater basement decollement and transport occur in Appalachian Blue Ridge and eastern Alpine structures. The model proposed here (Figure 9) assumes for reasons discussed in following paragraphs that during Laramide deformation a zone of potential detachment existed about 10 km below the surface. Considering the 3–4 km cover of sedimentary units at that time, the proposed slab of upper basement was 6–7 km thick.

Laramide effects on any shallow basement slab clearly would not have been independent of deeper crustal and lithospheric deformation. Whether tectonic stresses merely end-loaded the lithosphere or stressed it by sublithospheric mantle drag (Dickinson and Snyder, 1978), as indicated by the arrows in Figure 9A, the total shortening of the entire lithospheric column had to be approximately the same as that of the uppermost slab. Even though Figure 9 focuses on the shallow basement slab, these deeper structures must have provided the primary driving forces, as well as the limitation on total amounts of shortening. The ramp and triangle zone of Figure

Figure 8—(A) Block diagram showing structures associated with late-stage dominantly horizontal thrust displacement. Features are analogous to a blunt ship's prow raising a bow wave. (B) Structure of vertical and upended formations in the Line Creek fold produced by late-stage dextral slip along the mountain front. (C) Burnt Mountain structure showing late-stage sinistral shear of upended mountain-front sedimentary formations. Map data after Foose et al. (1961). Ages of rock units are abbreviated.



9C and D are merely symbolic of these processes. Any changing stress or strain within the evolving shallow slab would have had relatively little control on the overall tectonic process.

Early stages of slab formation (Figure 9A) required a relatively flat detachment fault to develop in the vicinity of the brittle-ductile transition (Figure 9A), as well as significant regional shortening for duplex formation to begin. In the proposed model, this shortening produced many of the minor, second-order oil-producing structures of the region, as well as thrust faults uplifted onto the ranges. The fault system associated with Beartooth Butte (Figure 1) would be an example of the latter. These features are not included on Figure 9B–D in order to show the slab more clearly.

Eventually, the leading edge of the slab ramped upward to break the sub-Cambrian surface at a relatively steep angle (Figure 9B). Duplex development at the base of the slab began to cause broad uplifting of the future range and probably helped pop-up minor fault blocks. The geometry was probably somewhat like the present Black Hills (Lisenbee and DeWitt, 1993).

Splaying faults in the upper 1 km or so of the leading edge allowed a crude fold to form in the basement surface, the tri-shear model of Erslev (1993) or the balanced basement-cored folds of Cook (1988). Innumerable smaller faults helped refine geometry of that crude fold/fault block by triboplastic (beanbag) shape readjustment of the basement slices, a process described by Wise and Obi (1992) for an area on the front of the western Bighorn Mountains. The 1–2 km estimate of the radius of curvature of the basement surface in this brow fold is based on local geometry of the corner and a few remnants of flat-lying Cambrian clastics on the crest of the uplift adjacent to very steep dips of the same units in adjacent mountain-front structures. A similar radius of curvature for the basement surface on a frontal fold is exposed on the west edge of the Bighorn Mountains (Wise and Obi, 1992). These observations are the basis for suggesting that the early splaying faults at the ramp lip were limited to approximately 1–2 km of the upper surface of basement.

Proof of the magnitude of folding and frontal rotation of the basement surface appears in an old mine adit (Figure 10) on the Willow Creek valley

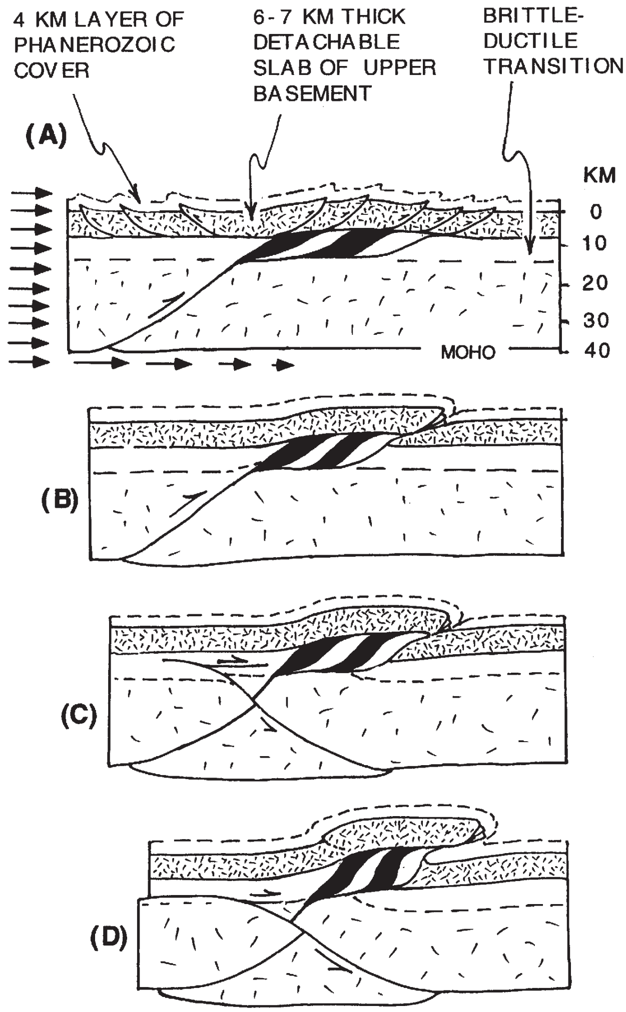


Figure 9—Kinematic model based on detaching slab of upper basement with related ramp and duplex structures. To concentrate on slab geometry, shallow structures are shown only in the top panel. (A) Early-stage shortening, possibly regional in nature, produces many second-order thrusts in a basement slab and causes forced folding of sedimentary formations across them. The lower boundary of the 6–7-km-thick slab was defined by the top of the brittle-ductile transition zone. Duplexes begin to form in the transition zone, possibly at the top of a deeper ramp. (B) Additional duplex pile-up begins the broader uplift process. Splaying minor faults at the top of the basement ramp create a brow fold with about 1–2 km of curvature. The 3–4-km-thick cover of sedimentary formations is force folded across this basement geometry. (C) Continued thrusting and duplex development raises the slab to clear much of the opposing basement ramp and begin stronger components of horizontal motion. The upper parts of the brow fold begin to ride passively on the thrust lip while sedimentary formations in the steeper limbs of the fold are progressively attenuated into thrust-parallel shear zones and an overturned limb on the footwall syncline. Other shortening processes may come into play in the deeper basement, such as a backthrust and triangle zone. (D) Continued shortening piles up duplexes beneath the uplift while the advancing lip plows forward into and over the footwall sedimentary formations.

floor 200 m due north of the main roadcut of Figure 6. This mine exposure and the nearby basement roadcuts about to be described would lie just northwest of the Willow Creek fault beyond the corner flap (Figure 5A). The mine adit exposes the vertical unconformity of Cambrian Flathead Quartzite resting on basement with no evidence of faulting along the contact. Clearly, basement just below the unconformity in the adit suffered a 90° rotation during Laramide deformation.

Additional evidence of basement rotation mechanisms appears in several roadcuts lying 200–500 m northwest of the roadcut described in Figure 6. Basement lithology in the roadcuts is a poorly to moderately foliated, medium- to coarse-grained granitic gneiss with some amphibolite and schist units. The mass is highly fractured with abundant chlorite and other signs of retrogressive metamorphism. Dominant foliation dips gently to moderately to the southwest (stereonet, Figure 10). Parallel to this foliation are numerous zones of crushed granitic fault horses, disrupted slices of amphibolite, and fine-grained gouge, all signs of pervasive low-temperature cataclasis. Plotted points for orientations of two of the zones coincide with the foliation plot on the stereonet. No reliable slickenline indicators of motion sense or direction were observed. These geometric relationships, coupled with the unconformity in the nearby mine adit, suggest that prior to Laramide deformation, basement foliation at this location was steeply dipping and had a strike subparallel to the future mountain front. Early stages of minor fault block deformation rotated foliation toward potential thrust fault orientation. Eventually, the partially rotated foliation reached a dip where it could operate as a pervasive anisotropy for thrusting. Ultimately, internal rotation by each fault slice overriding the one beneath it completed the 90° external rotation of the basement surface and its overlying Cambrian unconformity.

LATER STAGE BASEMENT-RELATED STRUCTURES

Once the initial ramp and brow fold had formed, a thickening mass of evolving duplexes and horse slices at the base of the slab continued the uplifting process and lowered the effective angle of inclination of the footwall ramp (Figure 9C). At this stage,

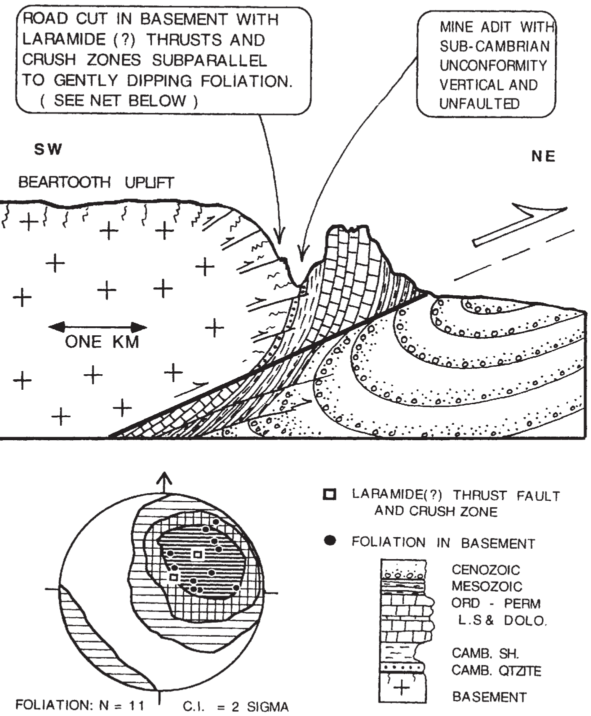


Figure 10—Relationships among Laramide thrust faulting, basement rotation, and Precambrian foliation along the Beartooth mountain front just northwest of the Willow Creek fault zone (location on Figure 4).

the anticlinal part of the 1–2-km-radius early brow fold in basement and its covering sedimentary formations became relatively passive elements, merely riding the advancing lip of the thrust. Sedimentary units in the vertical to slightly overturned limbs of the fold were caught beneath the advancing thrust to undergo thinning, stretching, and faulting, eventually forming the overturned and thrust limb of the footwall syncline now exposed in the main roadcut and penetrated in the Amoco well.

Once the basement slab had been raised clear of its opposing basement footwall via the complex mass of duplexes beneath it, nearly horizontal displacement could occur across footwall sedimentary formations (Figure 9D). The vertical rise or structural relief at this stage should have been somewhat in excess of the thickness of the slab. This model and the 8 km structural relief at the corner are the basis for suggesting that the basement slab had a thickness on the order of 6–7 km.

Volumetric maladjustment of sedimentary rocks in the underplate of the Red Lodge corner produced the flap structure. For linear mountain fronts in both this and other ranges of the middle Rocky Mountains, the same process probably produced additional flattening in dip of the overthrust lip. Deeper beneath the uplift, volumetric effects of basement duplexing may have caused additional late-stage uplift with further basinward rotation of the overriding sheet and even further flattening of dip of the overall thrust slab.

LARAMIDE STRUCTURE AND THE STILLWATER COMPLEX

The effects of differing basement lithology in controlling Laramide structures are well documented by Chase et al. (1993). Among the finest examples of such control is the western Beartooth frontal zone underlain by the Precambrian Stillwater Complex (Figure 1). The main mass of the Stillwater Complex, a 7–8-km-thick mafic lopolith, lies beneath the plains north of the Beartooth uplift (Bonini, 1982). Along the south edge of the complex, igneous layering had an original dip of about 30° northward toward the lopolith's center. The 30° dip difference between this older layering and the unconformably overlying Cambrian sedimentary units is still evident despite major Laramide mountain-front rotation. At present, the Stillwater igneous layering in this part of the mountain front (Figure 11D) is approximately vertical, whereas faulted remnants of Cambrian quartzite retain dips on the order of 60° to the north. The Cambrian remnants have two anomalous features: (1) all are preserved in fault blocks downthrown on the side toward the uplift and (2) despite the steep dip of individual Cambrian beds, the elevation distribution of the preserved remnants shows that the average basement surface slopes gently toward the adjacent plains at only about 15° (Figure 11D).

A sequence of structural mechanisms to account for these seemingly anomalous fault and dip relationships is suggested in Figure 11 A–C. The Stillwater Complex was a poor candidate for inclusion in any Laramide range uplift. Even though initial trends of the Beartooth front might logically have passed through the complex (Figure 12A), the Stillwater rocks were too heavy and too strong to become a major part of the uplift. The absence of quartz virtually precluded detachment of a shallow slab within the complex. At best, only the south edge of the body could be rotated and uplifted into the range. Early small faults formed as underthrusts beneath the complex, possibly using the north-dipping igneous layering. With progressive shortening and continued motion on the faults, the edge of the complex was internally rotated to produce the presently observed dips, whereas the gross uplift of the Beartooth Range produced only an overall 15° external rotation. Ultimately, the resistance forced the evolving Beartooth uplift to shift its dominant frontal thrust zone to the opposite or south side at Gardiner (Figure 1) (Foose et al., 1961).

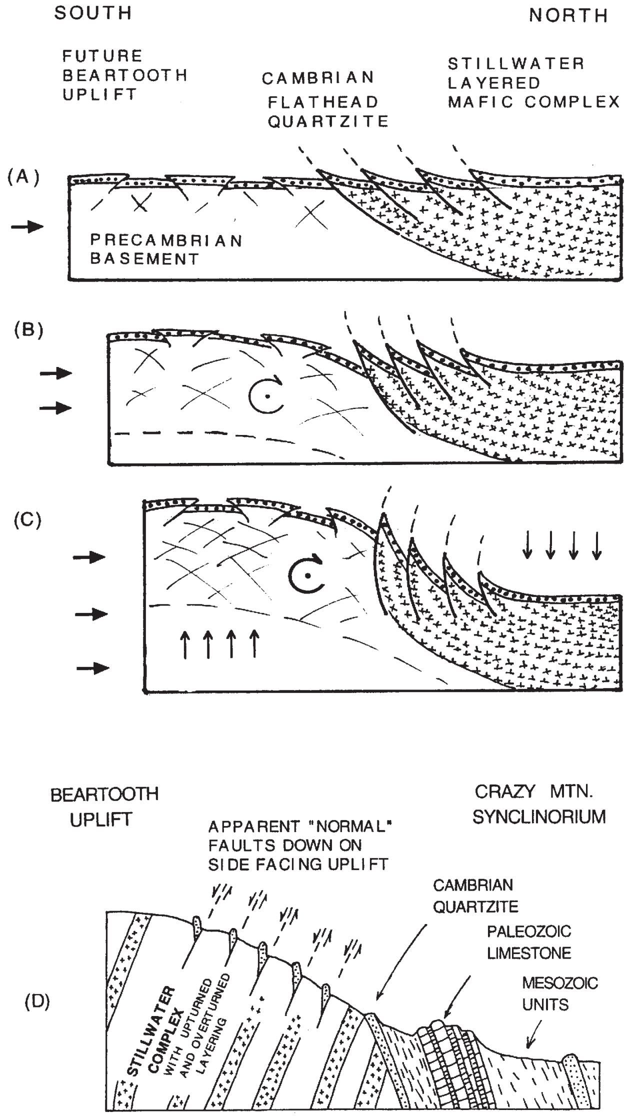


Figure 11—Mountain-front rotational mechanisms involving strength and density contrasts associated with the Stillwater Complex. (A) Early-stage Laramide configuration with the main mass of the strong dense complex lying generally north of the future uplift. The south edge of the lopolithic complex lies with 30° angular unconformity beneath horizontal Cambrian quartzites. Underthrusting may be partially controlled by dip of layering in the complex. (B) Continued underthrusting, rotation, and uplift. The frontal zone is forced to be at the south edge of the main Stillwater body. (C) Continued rotation of early elements as underthrusting progresses until present geometry is reached. (D) Presently exposed structural features. Layering in the complex is approximately vertical to mildly overturned. Remnants of Cambrian quartzite in small fault blocks have very steep dips, but the average sloping surface connecting these preserved fragments dips gently toward the basin. Each fault block is downthrown on the side toward the uplift.

As north-northeast compression continued, the fixed Stillwater Complex prevented any significant northward advance of that part of the mountain front (Figure 12A). Only the south edge of the Stillwater lopolith could be incorporated into the western Beartooth frontal structures (Figure 1). The North Snowy block (Figure 1) was forced to rise, but remained essentially in place while the main Beartooth block escaped eastward via the left-lateral transpressional Mill Creek zone (Figure 1) (Foose et al., 1961) and possibly along the Nye-Bowler regional shear zone.

These eastward components of motion forced the east end of the rising Beartooth uplift to separate from and thrust eastward over the Bighorn basin, isolating the Cooke City sag (Figures 1, 2) from its former role as the axis of the Bighorn basin. Definition of an eastern end to the Beartooth uplift caused frontal structures to turn abruptly to north-south strike and create the Red Lodge corner. The change in motion direction is recorded at the southeast corner of the uplift by early north-north-east–south-southwest–directed conjugate shears and minor thrusts that are then truncated by east-west–directed compressional features, such as the Dead Indian monocline and Line Creek-Oregon basin thrust (Figure 13) (Wise, 1983).

SUMMARY AND CONCLUSIONS

The unique structure of the Red Lodge corner of the Beartooth uplift allows some separation of early and late styles of Laramide deformation. These structures require kinematic evolution from early deformation involving strong vertical components of motion, at least at shallow levels, to increasingly horizontal components in the final tectonic stages.

These new exposures and the deep well bring into question some long-held structural views. The two corner fault zones, almost universally interpreted as tear faults, show minor structures more appropriate to pivoting normal faults. Differential vertical displacement across one of these, the Willow Creek fault zone, allows comparison of side-by-side exposure of differing levels of an overturned frontal fold and thrust zone, and the nearby Amoco well provides details of the deeper thrust and near-recumbent synclinal nature of the same frontal zone.

This kinematic sequence of basement-driven structures may be modeled by some form of detaching slab and associated ramp and duplex structures within the upper basement. Deeper

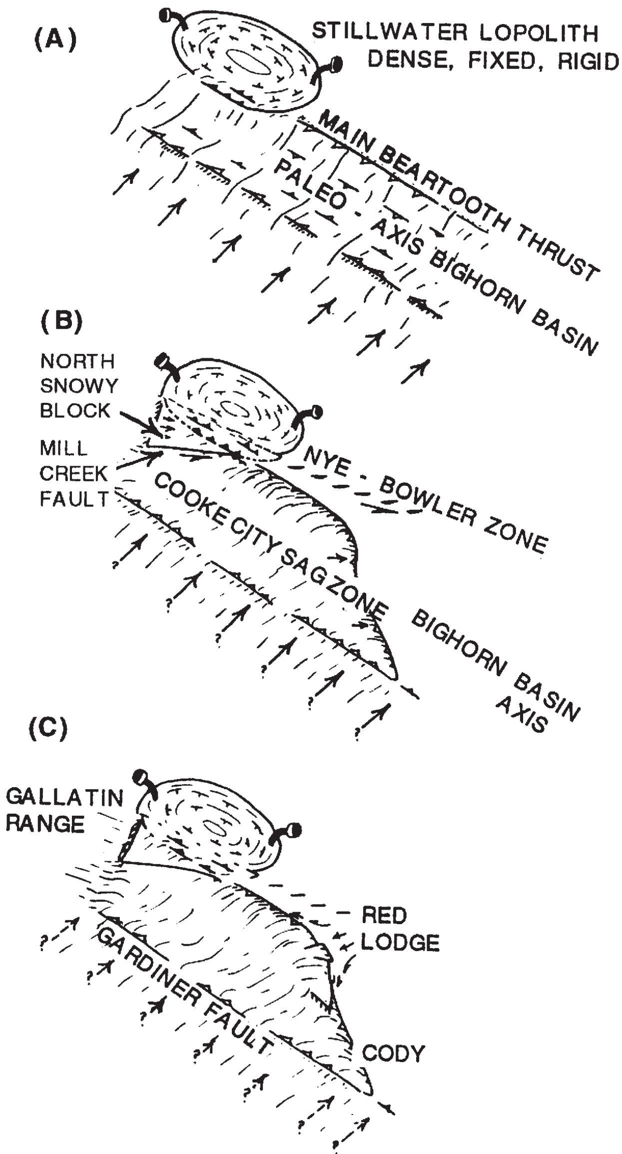


Figure 12—Eastward escape tectonics of the greater Beartooth uplift. (A) Initial deformation against the fixed Stillwater basement obstruction (here "nailed" in place). (B) Strength and density contrasts of the Stillwater Complex forced later stages of the evolving Beartooth uplift to begin eastward escape via the Mill Creek strike-slip fault, possibly influenced by the Nye-Bowler strike-slip zone. North of the Mill Creek fault, the North Snowy block (Figure 1) was left behind. (C) The eastward components of escape motion produced eastward thrusting of the east end of the uplift, created the Red Lodge corner and its flap geometry, separated the former axis of the Bighorn basin to produce the Cooke City sag zone, and pop-up a southeast corner block (Figure 13) using sag zone and frontal structures.

crustal and mantle structures clearly controlled the magnitude and rates of crustal shortening of this shallow slab. The detachment level at 6–7 km beneath the basement surface, based on corner geometry, was probably related to the brittle-ductile transition. The leading edge of the evolving ramp splayed to produce a crude fold structure as it exited the basement surface. This fold was softened in part by minor faulting and triboplastic mechanisms that rotated the basement surface through about 90° on a 1–2 km radius and formed a brow fold on the lip of the early thrust. This structure with its sedimentary covering formations and its shattered basement is well exposed in roadcuts, a mine adit, and frontal palisades just northwest of the Willow Creek fault zone. In later tectonic stages, the brow fold was largely abandoned to ride as a passenger on the advancing lip of the basement thrust sheet. Development of duplexes within and beneath the basement sheet raised it as the core of the Beartooth uplift and allowed the sheet to pass more easily into later phases of dominantly horizontal motion.

These structures contrast sharply with those of the western Beartooth front where the massive Precambrian Stillwater Complex precluded similar basement detachment and uplift. Instead, the rising uplift could only underthrust and uplift the edge of that complex. Resistance of the complex forced the Beartooth uplift to make the south or Gardiner side its major frontal thrust zone. Eastward escape tectonics around the Stillwater obstacle via the Mill Creek transpressional zone caused separation and eastward thrusting of that end of the Beartooth uplift with respect to the adjacent Bighorn basin. The separation allowed the former axis of the basin to become part of the uplift, the present Cooke City sag zone (Figures 1, 2).

These tectonic views suggest that hydrocarbon exploration based on projection of the axis of the Bighorn basin under the Red Lodge corner of the Beartooth uplift may be misguided. Instead, the deep structure of that corner resulted from the dominantly north-northeast thrust motions of the uplift, which were further complicated by eastward escape tectonics and late-stage corner flap development.

This type of basement slab kinematic model in which shallow-level structural elements show increasingly large components of horizontal motion as a function of time and growing structural relief may be a partial explanation for the old debate of vertical vs. horizontal tectonics. Similar to the famous blind men and the elephant, that debate was merely a question of which stage and which magnitude of structural relief was being used as the tectonic model for any particular part of the middle Rocky Mountains.

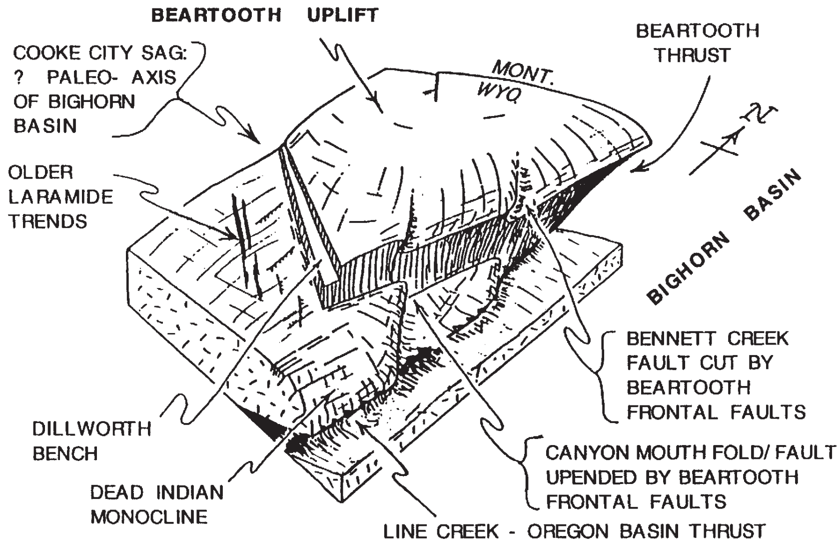


Figure 13—Superimposed structural trends shown on the restored basement surface of the southeast end of the Beartooth uplift. The block represents the Deep Lake 15° Quadrangle as viewed from the southeast. Late-stage north-south–trending frontal thrust and tilt structures associated with the Beartooth and Line Creek–Oregon basin thrusts cut older northwest-southeast–trending Laramide structures related to the Cooke City sag zone and the paleoaxis of the Bighorn basin. The pop-up corner as defined by intersecting faults of the Cooke City and Beartooth frontal zone was raised by volumetric adjustments from sedimentary rocks forced beneath the frontal thrusts; revised from Wise (1983).

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