THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

FORELAND COMPRESSIONAL TECTONICS: SOUTHERN BIGHORN BASIN AND ADJACENT AREAS, WYOMING

by

D.L. BLACKSTONE, JR.

Report of Investigations No. 34
1986

LARAMIE, WYOMING

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Cover photograph - *View to the northwest along the crestal area of Black Mountain anticline, Hot Springs County, Wyoming. The anticline trends N70°W through the common corner of Ts.42 and 43N., Rs.90 and 91W. The photo shows the steep southwest dip in the Mowry Shale on the southwest flank of the fold that reverse to gentle northeast dip on the eastern hillslope in the upper right of photo. Frontier Formation caps the high eastern ridge. (University of Wyoming Archives photo.)*

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Abstract

Sedimentary rocks in the Bighorn Basin (Figure 1) have been deformed into faulted folds ranging in size from intermontane basins (Bighorn Basin) to those with an amplitude of 500 to 5,000 feet. Essentially all folds result from movement on reverse faults at the interface between the sedimentary cover and the crystalline Precambrian basement. Faults steepen as they propagate upward through the sedimentary cover. Large wedge-shaped crustal segments result from reverse in dip of controlling faults, with resultant change in asymmetry of folds.

The geologic structures in this tectonic province are considered to be the result of a pervasive horizontal stress field during the Laramide orogenic episode.

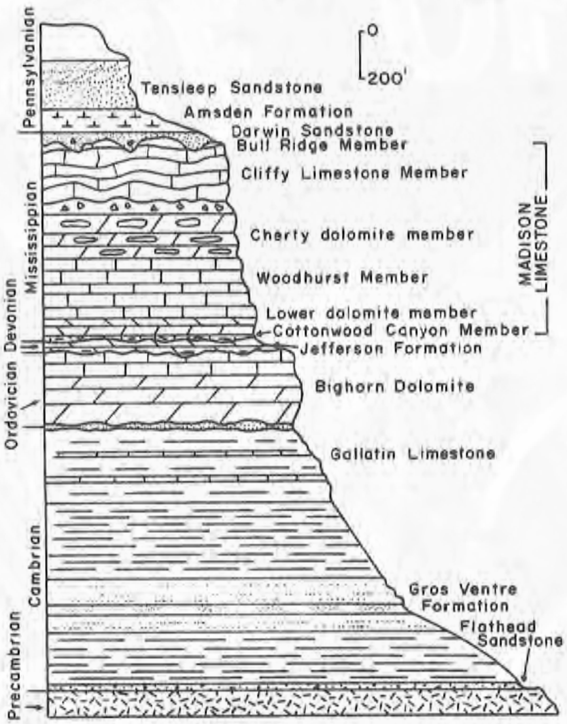


Figure 1. The Paleozoic stratigraphic section in the southern Bighorn Basin, Wyoming.

Regional tectonic framework

The Bighorn Basin is a large intermontane basin in the Rocky Mountain foreland, extending from Montana southeastward to the Bridger-Owl Creek uplift in central Wyoming (Figure 2). Within the outcrop of Upper Cretaceous rocks, the basin covers approximately 10,000 square miles and is 200 miles long and about 50 miles wide. It is bounded on the north by the Montana lineament (Lewis and Clark line); on the east by the Pryor Mountains-Bighorn uplift; and on the south by the southern extension of the Bighorn Mountains and the Bridger-Owl Creek uplift. The western margin is concealed beneath the Absaroka volcanic field, and flanks of the buried Washakie Range (Love, 1939). In the north, the basin is constricted between the east face of the Beartooth Mountains (Bonini and Kinard, 1983) and the west flank of the Pryor Mountains and is modified by the Nye-Bowler lineament with trends transverse to the basin axis.

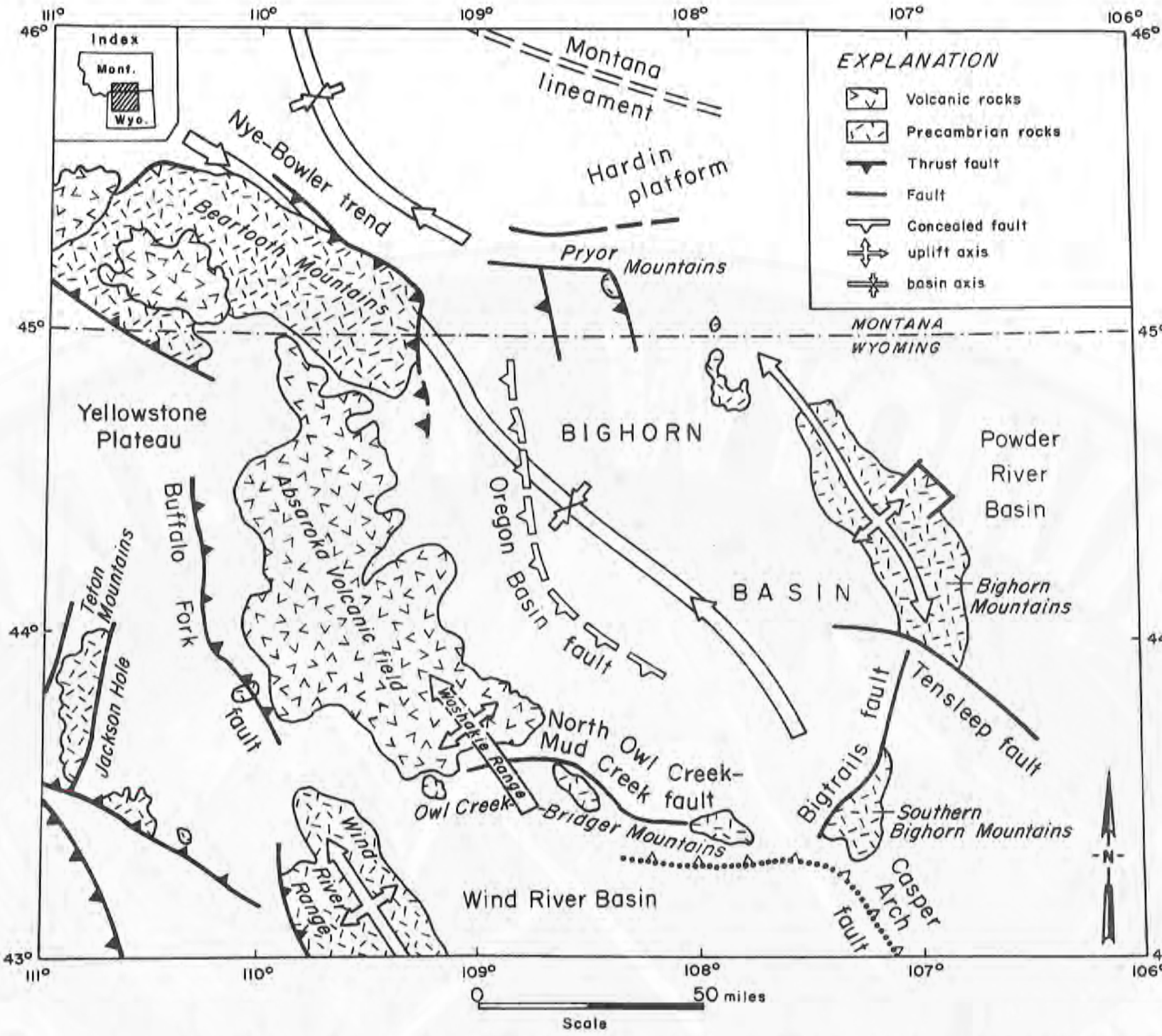


Figure 2. Tectonic index map, Bighorn Basin and adjacent areas, Wyoming and Montana.

The south end of the Washakie Range consists of several folds (cored by Precambrian basement) that plunge to the northwest (Figure 3). A major east-dipping fault, the Buffalo Fork thrust (Love, 1956), bounds the west margin of the uplifted area, and has a displacement of at least 12,000 feet.

The Bridger-Owl Creek uplift extends from the southern extension of the Bighorn Mountains westward to the exposed part of the Washakie Range, and is segmented by northwest-trending faults and folds (Figure 3). The overall more or less east-west trend of the uplift is controlled by a major reverse fault (known as the Casper Arch fault) on the south margin of the ranges (Gard, 1969; Wise, 1963). The regional transverse orientation of the uplift indicates that the controlling movement was later than the northwest folding and faulting.

The Absaroka volcanic field and the adjacent volcanic rocks of the Yellowstone Plateau conceal the structure of the underlying sedimentary sequence.

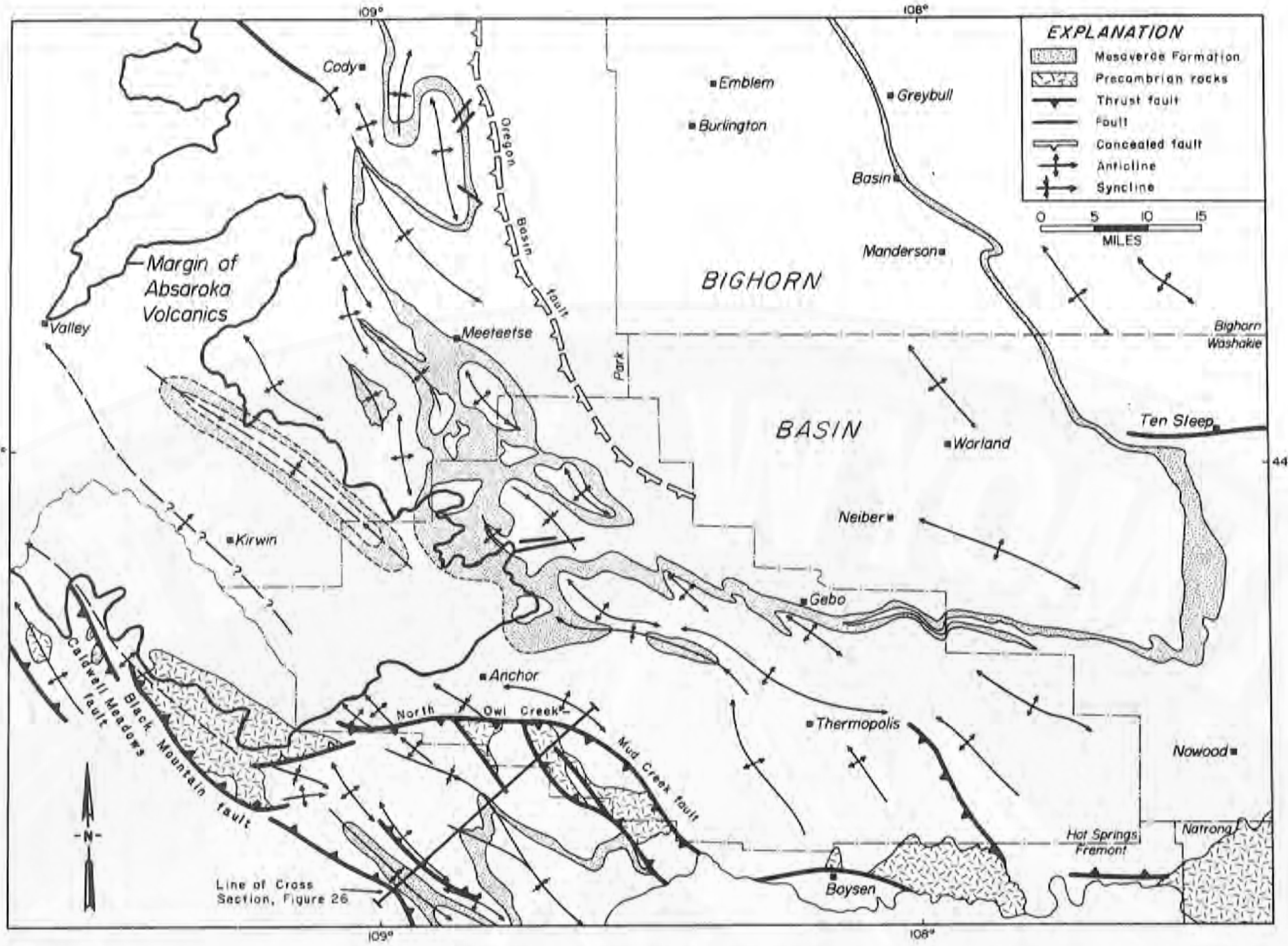


Figure 3. Tectonic map of the southern Bighorn Basin and adjacent areas, Wyoming.

However, the writer believes that a syncline containing Cretaceous Mesaverde Formation lies just west of the margin of the Absaroka volcanic field (Figure 3). Geologic mapping in the eastern part of the Absaroka volcanic field by Rohrer (1964), Wilson (1982), Bown (1982) and Sundell (1982) reveals extensive areas of large-scale slides in this sequence of rocks. Detached masses, which range from small areas of a few hundred square feet to others covering square miles, have had no effect on the underlying older rocks.

Specific structural elements

The general structure of the Bighorn Basin was originally described as a large, fairly simple, major syncline with marginal folds (Fisher, 1906). Detailed mapping, drilling and extensive seismic work reveal far more complex structural patterns. This paper describes structural patterns in the southern part of the basin. The southeast basin margin is a major fault - the Bigtrails (or Deep Creek) fault (Figure 2) - that trends N15°E; relative movement was down to the west, and Precambrian basement is exposed in the hanging wall. Major displacement indicates that the fault dips to the west at a high angle, but also has associated antithetic eastward-dipping faults. Mapping along this fault is not adequate to fully evaluate the nature of the displacement.

North of the Bigtrails fault, the Tensleep fault (Figure 2) trends transverse to the axis of the Bighorn Mountains uplift. The Tensleep fault was originally treated as a normal fault, down to the south (Wilson, 1938). Detailed study (Hoppin, 1965) shows that the fault location is controlled by anisotropy in the Precambrian basement. P.W. Huntoon (personal communication, 1985) reports that the Tensleep is a reverse fault with the north side up, perhaps modified by later normal faulting. The extension of the fault west of Ten Sleep townsite (Figure 3) shows two periods of movement, the later of reverse-fault character (Allison, 1983). The fault, or its effects, do not continue down plunge for any considerable distance into the basin (Figure 3).

A major fault, concealed beneath Eocene Willwood Formation, can be traced along the west side of the basin using drilling information and seismic profiling (Figure 3). The fault was penetrated in the Hunt No. 1 Loch Katrine test (sec. 2, T.51N., R.100W.) on the northeast flank of Oregon Basin anticline. It dips approximately 30° west and may have numerous splays. Displacement decreases to the southeast, and the fault probably does not reach as far south as Gebo anticline (Sheet 1, back pocket). The name Oregon Basin - Beartooth fault was used by Scheevel (1983) for this fault. The writer believes the Oregon Basin fault is a separate fault, and does not connect with the Beartooth fault.

Northwest-tending belt of major folding

Major folds on the west and southwest side of the Bighorn Basin are outlined by rims of Cretaceous Mesaverde Formation (Figure 3). The belt of folding lies west and southwest of the pre-Willwood Oregon Basin thrust fault described above. In general, individual folds trend northwest and are asymmetric to the west.

The possible relationship of the belt of major folds and the major deep fault in the basement will be discussed later.

Northwest Wind River Basin

Folds on the northwest flank of the Wind River Basin are shown outlined by the Mesaverde Formation (Figure 3). Precambrian basement is exposed in the core of large faulted folds between the Mesaverde outcrops on the west flank of Hamilton Dome and the folds at Maverick Springs and Little Dome (Murphy and others, 1956) (Sheet 1, back pocket).

The major fault bounding the Precambrian exposures is on the north and northeast flanks. The fault dips to the southwest, and is up on the south side. It has been referred to as the North Owl Creek fault (Masursky, 1952) and as the Mud Creek fault (Flanagan, 1955).

Faults of opposite dip, but similar strike, exist on the southwestern flank of the exposed Washakie Range. The thrust fault exposed at Black Mountain (Love, 1939) was penetrated by the Shell Oil Company #1 Gov't at Goose Lake in sec. 9, T.42N., R.106W. The compound band of Precambrian exposures appears as a major, wedge-shaped uplift plunging to the northwest, and possibly continuing farther to the northwest as the ultimate west margin of the Bighorn Basin.

The dominant northwest trend of the large-scale features agrees with the major northwest regional structural grain of the Wind River Range and the east-dipping thrust faults on the west side of the Absaroka volcanic field.

Folds

Review of interpretations

The geometry of folds in the Rocky Mountain foreland has been a fruitful field of study as well as a source of major geological controversy. Geologic thought relative to fold geometry has developed as a function of depth of drilling and industry's willingness to drill prospects with unorthodox geological interpretations; seismic investigations; and various authors' interpretive concepts.

Thom (1923) proposed that the geometry of foreland folds in central Montana was governed by faulting in the basement, and that the faults dipped toward the steep limb and had the characteristics of normal faults. Later Thom (1937) used the descriptive term "drape" to describe the behavior of the sedimentary cover over basement fractures in foreland structures. Wilson (1934), mapping at Five Springs Creek, Big Horn County, Wyoming, advanced the concept that the basement could be flexed. Blackstone (1940) proposed that the blocks making up the Pryor Mountains were underlain by reverse faults that dipped beneath the block and would attain lower dip by shearing out the corner of the footwall. Berg (1962) proposed a fold-thrust model. At a much later date, Stearns (1971) proposed a very controversial model for foreland folds using Rattlesnake Mountain west of Cody as the type example. Vertical motion on normal faults was the essence of this model. Stone (1984) presented an excellent review of terminology of deformation in the foreland. Brown (1983) suggested that there can be several satisfactory models, but noted that any model should account for crustal shortening and have a reasonable balance of bed length and volume.

Fold geometry

The structural pattern of the southern Bighorn Basin is presented on Sheet 1, using contours depicting the top of the Pennsylvanian Tensleep Sandstone. Principal facts concerning known folds appear in Table 1. Regional cross sections (Sheet 2, back pocket) were designed to accompany Sheet 1 and provide an overview of the structural style. Table 2 provides an explanation of formation symbols used on the cross sections.

Cross sections of representative folds were constructed where drilling provided adequate subsurface control of fold geometry (Figures 4 through 24, p. 8 through 19). The relationship of the Precambrian basement to the overlying sedimentary column was carefully considered in each case, and reflection seismic data was used where available.

Folds in the southern Bighorn Basin are examples of the structural styles that exist, and all can be fitted to a single tectonic episode, and a single regional stress field. Depth of exposure in these folds ranges from Precambrian crystalline basement to Late Cretaceous rocks.

The visible geometry of folds in the southern Bighorn Basin depends upon the level of erosion. Folds high on the basin flanks may have Precambrian crystalline basement exposed in the core, but farther out in the basin several folds are eroded to the Triassic Chugwater Formation red beds, or to the Lower Cretaceous Mowry Shale and the Cloverly Formation. Many of the large folds on the southwest and west flanks of the basin are expressed at the surface in Cretaceous Cody Shale and Mesaverde Formation.

Table 1. Characteristics of folds in the southern and western Bighorn Basin, Wyoming.

Name of fold	County	Township and Range	Formation at Surface	Trend of Axis	Direction of Asymmetry	Oldest Unit Drilled	Production
Black Mountain	Hot Springs, Washakie	42-43N, 90-91W	Frontier, Mowry	N60W	SW	Cambrian	Yes
Bruce area	Washakie	43N, 89-90W	Cody	N55W	SW	Tensleep	No
Bud Kimball	Washakie	44-45N, 88W	Sundance	N40W	NE	Tensleep	No
Chabot	Washakie	42-43N, 88W	Gallatin	N45-N20W	SW	Madison	No
Corley-Zimmerman Butte	Washakie, Hot Springs	43-44N, 92-93W	Cody	N60W	SW	Madison	No
Embar	Hot Springs	8N-2E	Tensleep	N60W	NE	Precambrian	No
Enos Creek	Hot Springs	46N,100W	Mesaverde	N30E-N50W	SW	Madison	Yes
Ferguson Ranch	Park	50N,102W	Mowry	N-S	W	Madison	Yes
Four Bear	Park	48N,103W	Mowry	N45W	SW	Cambrian	Yes
Gebo	Hot Springs	44N,95W	Cody	N65W	SW	Precambrian	Yes
Golden Eagle	Hot Springs	45N,96-97W	Fort Union	N45W	SW	Madison	Yes
Gooseberry	Park	46-47N, 100W	Cody	N10W	SW	Tensleep	Yes
Grass Creek	Hot Springs	45N,98W	Cody	N10-N70W	SW	Precambrian	Yes
Half Moon	Park	51-52N,102W	Mowry	N-S-N40W	SW	Tensleep	Yes
Hamilton Dome	Hot Springs	44N,97-98W	Mowry	N65W	SW	Precambrian	Yes
King Dome	Hot Springs	44N,96-97W	Phosphoria	N65W	SW	Tensleep	Yes
Kirby Creek	Hot Springs	43N,92W	Cody	N60W	SW	Madison	Yes
Lake Creek-Lake Creek West	Hot Springs	43N,91-92W	Mowry	N55W	SW	Madison	No
Little Buffalo Basin	Park, Hot Springs	47N,100W	Cody	N10W	SW	Tensleep	Yes
Little Sand Draw	Hot Springs	44N,96W	Cody	N30W	SW	Cambrian	Yes
Lucerne	Hot Springs	43N,94W	Cody	N60W	SW	Tensleep	No
Lysite Mountain	Hot Springs	41-42N,90W	Tertiary	N40W	?	Madison	No
Mahogany Butte	Washakie	43N,89W	Mowry	N35W	NE	Tensleep	No
Meeteetse	Park	49N,99W	Fort Union	N-S	SW	Frontier	Yes
Murphy Dome	Washakie, Hot Springs	43-44N,91-92W	Cody	N60W	SW	Cambrian	Yes
Neiber	Washakie	45N,91-92-93W	Fort Union	N75W	SW	Madison	Yes
North Sunshine	Park	47N,101W	Thermopolis	N-S	SW	Precambrian	Yes
Norwood	Washakie	48N,89-90W	Chugwater	N30W	NE	Tensleep	No
Oregon Basin	Park	50-52N,100W	Cody	N-S	E	Precambrian	No
Pitchfork	Park	48N,102W	Mowry	N-S-N30W	SW	Precambrian	Yes
Rawhide	Park	48-49N,101W	Cody	N50W	SW	Madison	Yes
Red Canyon	Hot Springs	42-43N,96W	Phosphoria	N10W	W	Cambrian	No
Red Springs	Hot Springs	43N,93W	Chugwater	E-W	S	Madison	Yes
Rose Dome	Hot Springs	43-44N,96W	Phosphoria	N50W	SW	Precambrian	No
Sand Creek	Washakie	46N,91W	Willwood	N-S	?	Madison	Yes
Sheep Point	Park	47N,102W	Frontier	N50W	SW	Amsden	No
Skelton Dome	Hot Springs	45N,100W	Mesaverde	N-S	E	Madison	Yes
South Fork	Washakie	46N,91-92W	Willwood	N50W	?	Madison	No
South Sunshine	Park	46N,101W	Morrison	N30W	NE	Tensleep	Yes
Spring Creek	Park	49N,102W	Mowry	N40W	SW	Cambrian	Yes
Tensleep	Washakie	46N,89W	Frontier	N30W	NE	Tensleep	No
Thermopolis	Hot Springs	43N,95W	Chugwater	N65W	S	Madison	No
Wagonhound	Hot Springs	44N,98W	Cody	N55W	SW	Madison	Yes
Warm Springs East and West	Hot Springs	43N,93-94W	Chugwater	N85E	S	Madison	Yes
Waugh	Hot Springs	44N,96-97W	Cody	N50W	SW	Madison	Yes
Water Creek	Washakie, Hot Springs	43-44N,90-91W	Cody	N60W	?	Madison	Yes
Willow Creek	Park	48N,103-104W	Cody	N40W	SW	Madison	Yes
West Bud Kimball	Washakie	45N,89W	Mesaverde	N50W	SW	Tensleep	No
Wildhorse Butte	Hot Springs	42-43N,93W	Chugwater	N45W	NE	Madison	No
Zimmerman Butte	Washakie, Hot Springs	43-44N,92-93W	Cody	N60W	SW	Madison	No

Changes in geometry with depth

The detailed cross sections show that almost universally, Precambrian basement is involved in the deformation. (Some cases are indeterminate because of lack of subsurface data.) Basement faults propagate upward into the overlying sediments with varying degrees of structural complexity, including secondary splays, some back thrusting and out-of-the-syncline thrusts.

Variation in tectonic style as seen in cross sections

In this report, the construction of geologic cross sections is based on data at three levels: (1) careful mapping and measurements of the attitude of strata exposed at the surface; (2) stratigraphic control established from a variety of logs obtained from drilled wells; and (3) reflection seismic profiles that show good resolution at the

Table 2. Key to formation symbols used on cross sections.

Eocene	Tw	Willwood Formation
	Tu	Tertiary, undivided
Paleocene	Tfu	Fort Union Formation
Cretaceous	Kl	Lance Formation
	Kme	Meeteetse Formation
	Kmv	Mesaverde Formation
	Kc	Cody Shale
	Kf	Frontier Formation
	Kmd	Muddy Sandstone
	Kcv	Cloverly Formation
Jurassic	Jm	Morrison Formation
	Js	Sundance Formation
	Jgs	Gypsum Spring Formation
Triassic	TR c	Chugwater Formation
	TR d	Dinwoody Formation
	TR u	Triassic, undivided
Permian	Pp	Phosphoria Formation
Pennsylvanian	ℙts	Tensleep Sandstone
Mississippian	Mm	Madison Limestone
	DM	Devonian and Mississippian
Devonian	Dd	Darby (?) Formation
	Du	Devonian, undivided
	DOꞒ	Devonian, Ordovician and Cambrian
Ordovician	Obh	Bighorn Dolomite
Cambrian	Ꞓ	Gallatin Formation, Gros Ventre Formation and Flathead Formation
	Pz	Paleozoic, undivided
Precambrian	pꞒ	Crystalline basement

basement-Paleozoic interface. Unfortunately, all sources of data are not available for each site, some data are proprietary, and some data have been misinterpreted by previous workers.

Several published tectonic models of the southern Bighorn Basin are available for comparison and each will fit some cases. Brown (1984) provided an analysis of a fold in the northern Bighorn Basin that has exposed Precambrian basement. Berg (1976) carefully documented the structure of Hamilton Dome, where faulting at depth is replaced by drastic stratigraphic thinning in the higher Cretaceous units. From seismic data, Lowell (1983), Stone (1984), Gries (1983) and Clements (1977) demonstrated footwall relationships of faulted anticlines involving the Precambrian basement. Petersen (1983) suggested detachment faulting as a mechanism for certain anticlinal features.

No one type of deformation is universal in this province. In each case, a general style is modified by space problems, rock heterogeneity and the relative age of events.

Specific examples of fold geometry

Data concerning wells shown on cross sections (Figures 4 through 24) are placed above the wells in this form:

operator
well name
location
elevation, total depth

Cross sections are located on Sheet 1. Fold geometries depicted do not agree, in all cases, with previously published interpretations.

Black Mountain anticline (Figure 4). T.42 and 43N., R.90 and 91W. Trends N°60W. Sharp surface reversal, steep limb on the southwest. The fold is ruptured by a steep, northeast-dipping reverse fault. Drilling penetrated Cambrian rocks in the hanging wall-block. The basement fault carries upward to the surface with one southwest-dipping back thrust. Displacement at the basement level is approximately 1,200 feet.

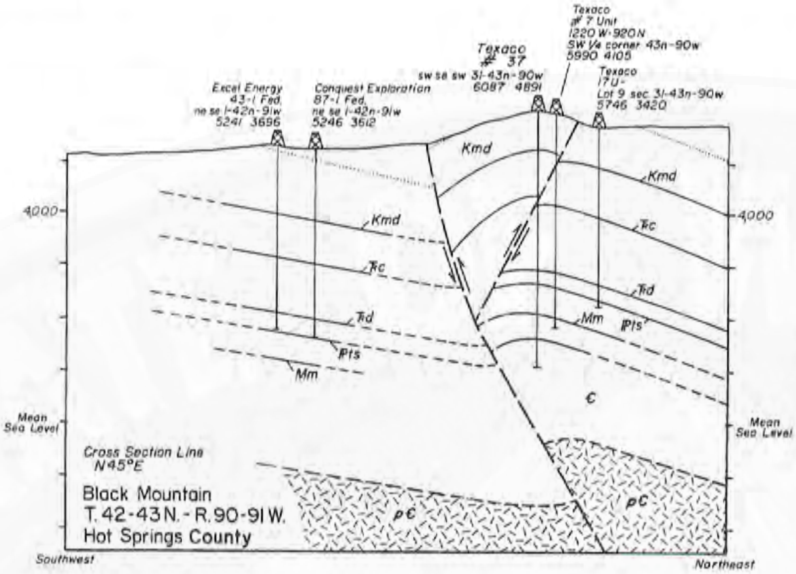
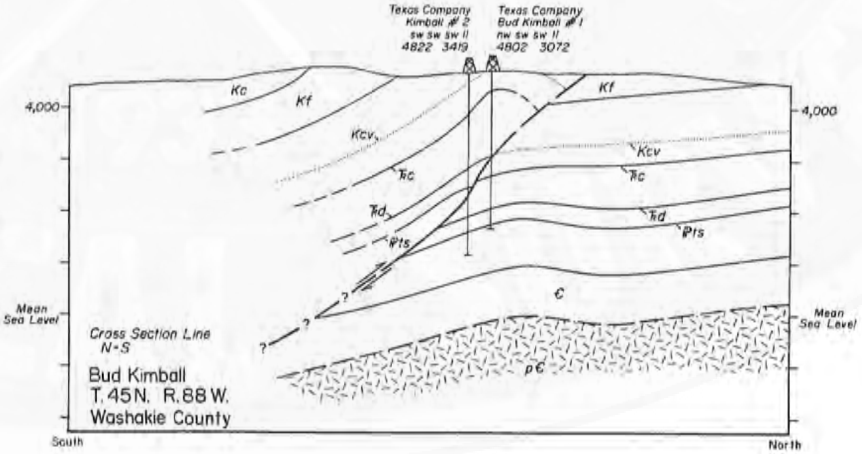


Figure 4. Structural cross section through the Black Mountain Field, Bighorn Basin, Wyoming.

Bud Kimball anticline (Figure 5). T.45N., R.88W. Folds trend N50°W; asymmetric to the northeast. Major thrust dips 50° to the west. Triassic Chugwater Formation is duplicated. Fold may be a detachment structure with the detachment plane located in the Cambrian shales.

Figure 5. Structural cross section through the Bud Kimball anticline. Bighorn Basin, Wyoming.



Chabot anticline (Figure 6). T.42 and 43N., R.87 and 88W. Trends N50°W; asymmetric to the southwest with Cambrian strata exposed in the core in sec. 35, T.43N., R.88W. on Nowood Creek.

The fold is sharply asymmetric to the southwest in the area where Cambrian is exposed. To maintain bed length balance, a fault in the basement is postulated. Drilling on the fold, down plunge, reveals a back thrust dipping to the southwest, but the major underlying and controlling fault must dip to the northeast to account for the observed stratigraphic relationships. Some adjustment of space at the surface probably is accommodated in the Cambrian shale section (1,200+ feet thick).

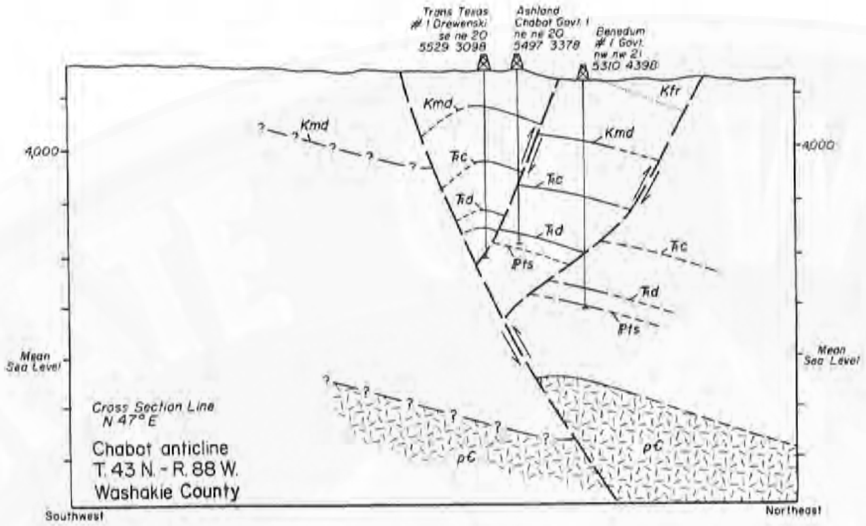
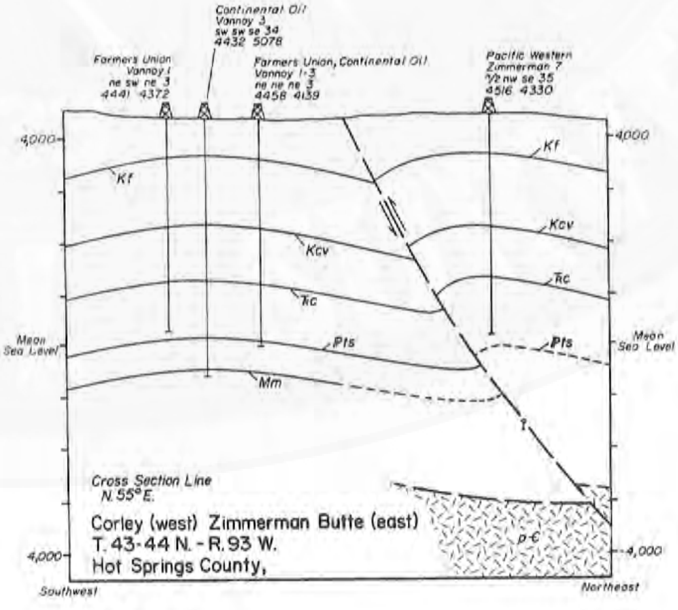


Figure 6. Structural cross section through the Chabot anticline, Bighorn Basin, Wyoming.

Corley-Zimmerman Butte anticline (Figure 7). T.43 and 44N., R.92 and 93W. Paired folds trending N60°W; Corley to the southwest. Cody shale is exposed at the surface. Drilled to the Mississippian Madison Limestone. Zimmerman Butte appears to be controlled by a northeast-dipping reverse fault. Faulting at Corley is indeterminate.

Figure 7. Structural cross section through the Corley-Zimmerman Butte folds, Bighorn Basin, Wyoming.



Four Bear-Willow Creek anticline (Figure 8). T.48N., R.103 and 104W. Folds trend N40°-45°W; separated by northeast-dipping reverse faults. Four Bear was drilled to the Cambrian and then into 1,000 feet of dacite intruded into the Cambrian shale section. Closure is in part due to the intrusive body. Southwest limb of Willow Creek has low dip and faulting is indeterminate.

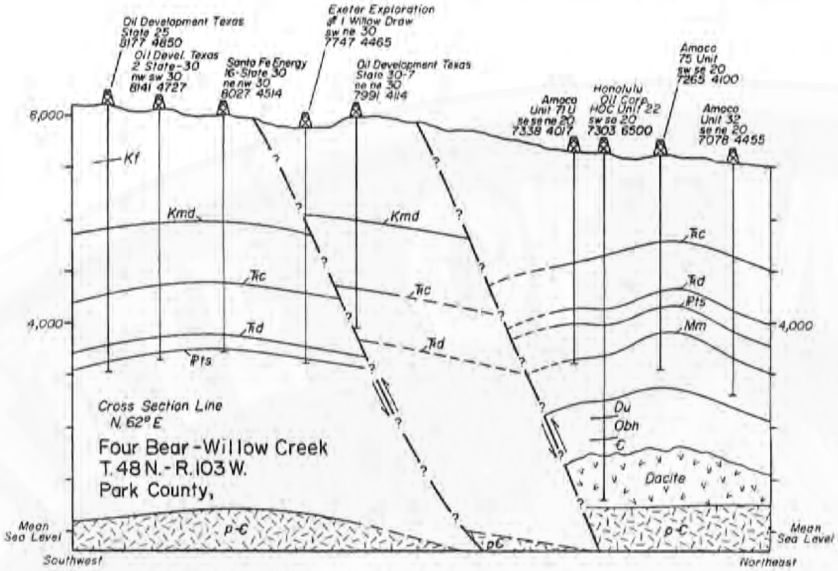


Figure 8. Structural cross section through the Four-Bear-Willow Creek Field, Bighorn Basin, Wyoming.

Gebo anticline (Figure 9). T.44N., R.95W. Trends N60°W; Cody Shale is exposed at the surface in the anticline core. The fold is asymmetric to the southwest, but rather broad and smooth at the surface, with dips ranging from 15° to 20°. The structure is complex at depth, as shown by the records from Continental Oil Company Gebo Unit #65, SE sec. 23, T.44N., R.95W., which reached Precambrian basement and passed through at least three reverse faults. The fold illustrates a problem in the region -- where does the major fault intersect the surface? In this case the fault must surface in the poorly exposed Cretaceous Cody shale (over 2,500 feet thick). Seismic profiles confirm the northeast dip of the fault plane. Displacement on the basement is approximately 2,500 feet.

Grass Creek anticline (Figure 10). T.46N., R.98 and 99W. Arcuate in trend; varying from N20°W at the north end to N60°S at the south end. The structure was drilled to Precambrian basement, and the producing area is well defined by over 500 wells. Offset of the basement is constrained by an essentially flat-lying sedimentary section and adequate well control to the west. The upward propagation of the basement fracture is constrained very closely by two wells - Stanolind Oil and Gas, Lucky Buck No. 5, NE NW SE sec. 30, T.46N., R.98W.; and Lucky Buck No. 6, NW NW NE sec. 30, T.46N., R.98W. The omission of beds in Lucky Buck No. 6 (at 1,400 feet) duplicates the thinning found in the Hamilton Dome cross section (Figure 11) (Berg, 1976). Postulated subsurface faulting resembles Stone's (1984, Figure 7b) interpretation of the seismic profile of a typical Bighorn Basin anticline. Offset is approximately 4,500 feet.

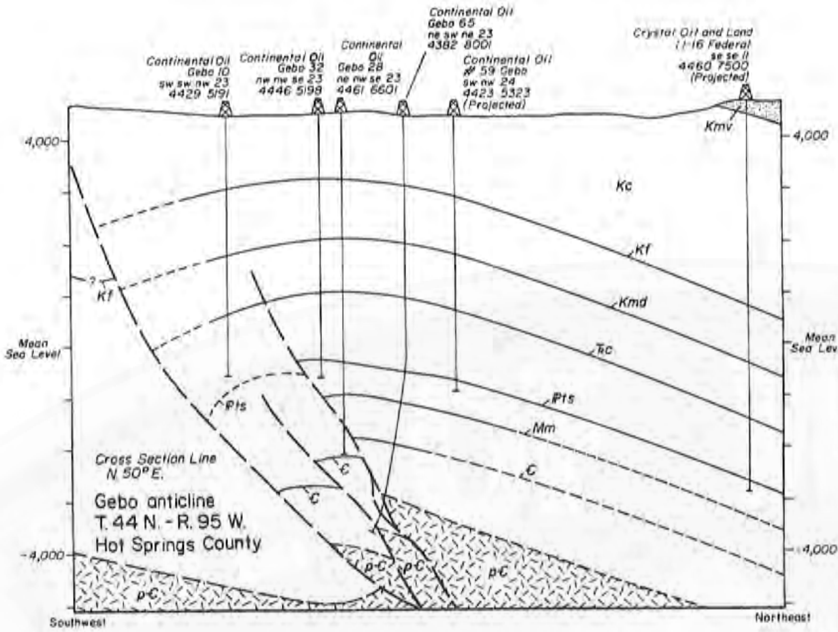
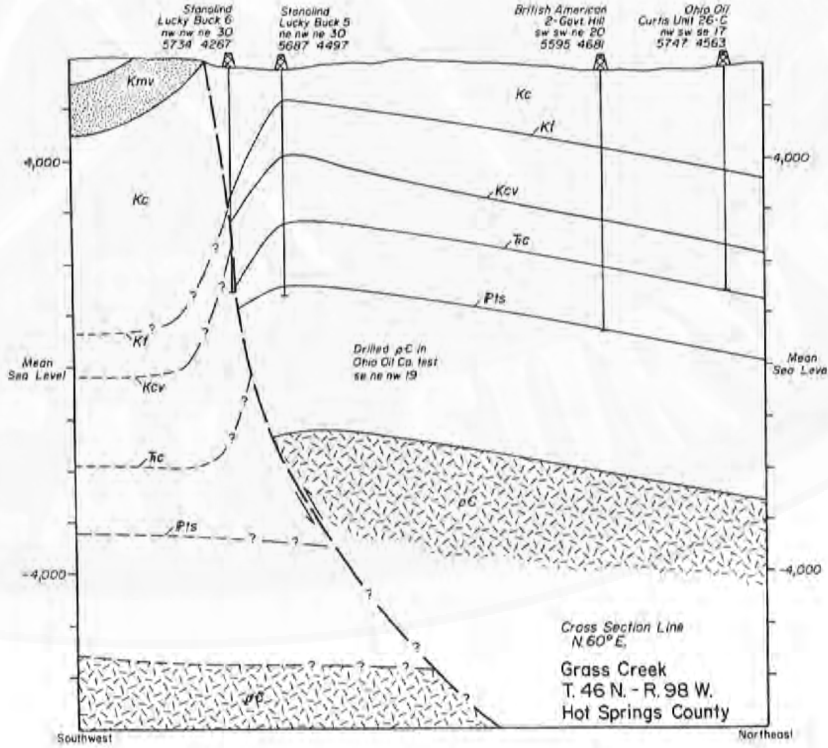


Figure 9. Structural cross section through the Gebo anticline, Bighorn Basin, Wyoming.

Figure 10. Structural cross section through the Grass Creek Field, Bighorn Basin, Wyoming.



Hamilton Dome (Figure 11). T.44N., R.97 and 98W. Fold trends N70°W. Berg (1976) gives an excellent review of this fold, documenting the modification of basement faulting as it propagates upward. The displacement at the level of the basement, which is about 6,000 feet, is accommodated at a higher level by drastic reduction of thickness in the Mesozoic strata, with no positive evidence of the fault emerging at the surface. The fault at the basement level dips to the northeast beneath the fold.

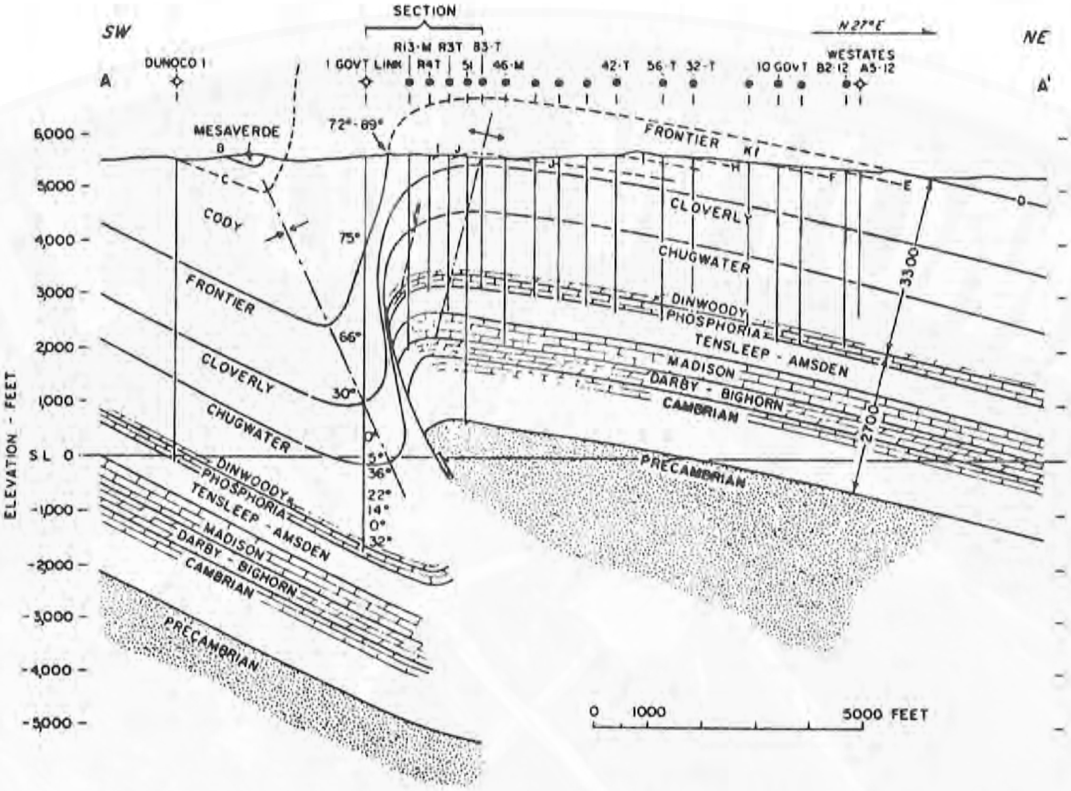


Figure 11. Structural cross section through the Hamilton Dome, Bighorn Basin, Wyoming (from Berg, 1976, Figure 3).

King Dome (Figure 12). T.44N., R.96 and 97W. The surface fold as exposed in the Cretaceous shales is broad and smooth with low dips. No faults were recognized in drilled wells. The space problem on the steep south limb of the fold is acute; outside the line of section, Cretaceous Frontier Formation is in contact with the lower boundary of the Cretaceous Mesaverde Formation, leaving no room for 3,000 feet of Upper Cretaceous Cody Shale. The north-dipping reverse fault accounts for approximately 2,500 feet of stratigraphic separation. The surface fault is projected to the level of the basement on the basis of the comparable situation at both Warm Springs and Rose Dome, where drilling penetrated the basement.

Little Buffalo Basin anticline (Figure 13). T.47N., R.100W. Major fold is arcuate in plan view, ranging from N30°W to N55°W. Cody shale is exposed at the surface. Drilled to the Precambrian basement. Vertical separation at the top of the basement is approximately 3,000 feet. Thinning in the Cretaceous section is probably similar to that at Hamilton Dome. The major fault dips to the northeast.

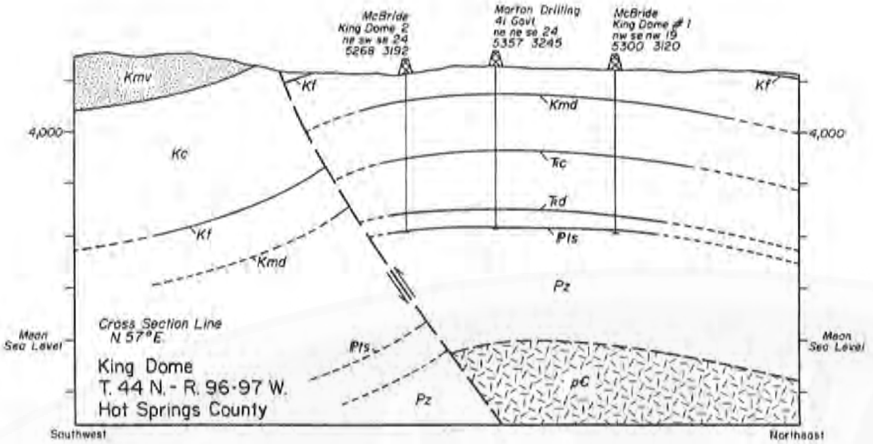


Figure 12. Structural cross section through the King Dome, Bighorn Basin, Wyoming.

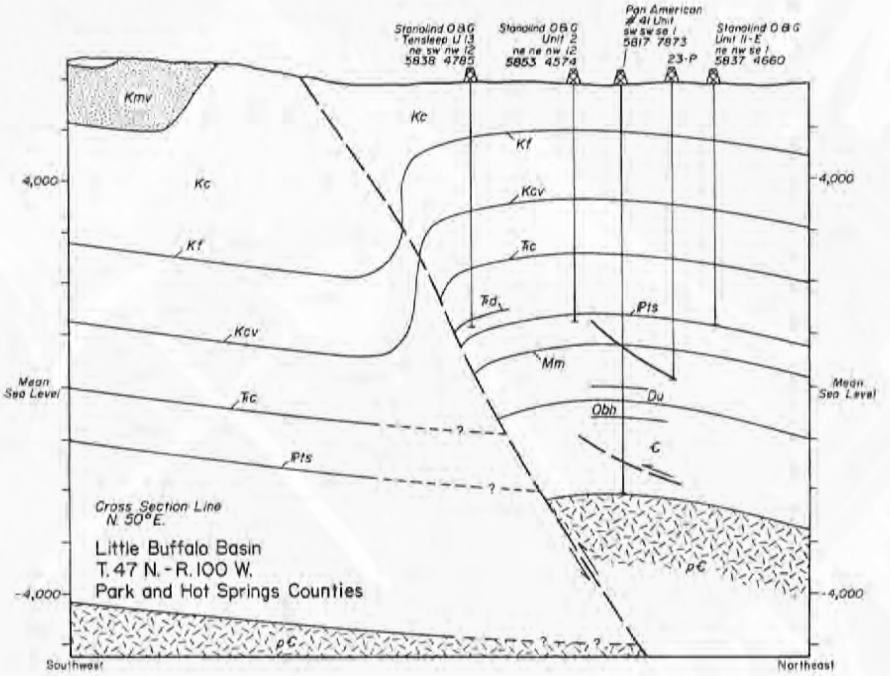


Figure 13. Structural cross section through the Little Buffalo Basin anticline, Bighorn Basin, Wyoming.

Little Sand Draw anticline (Figure 14). T.49N., R.96W. Fold trends N50°W. Cody shale is exposed at the surface. Drilled to the Cambrian Gallatin Formation. Fold is of low relief at the surface and is located well out in the basin. Precambrian basement is probably faulted, but evidence is inconclusive; this may be a case of an antiform in the basement. The size of the fold at the surface (9,000 feet above the basement) demands that the fold tighten with depth if concentric folding continues to depth.

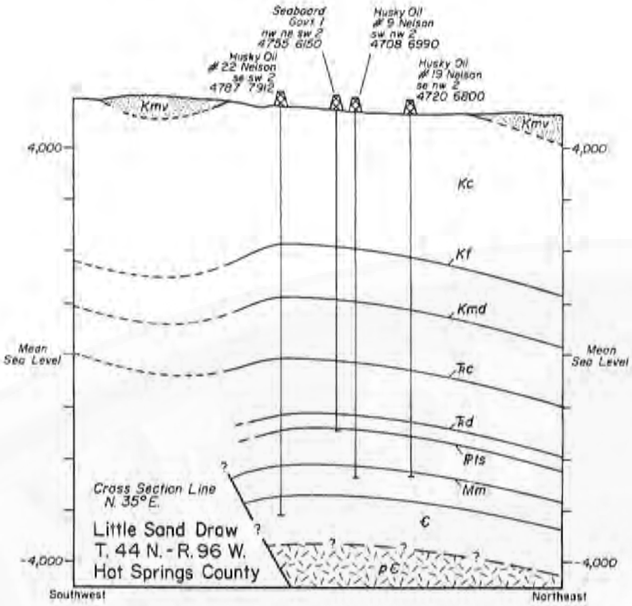


Figure 14. Structural cross section through the Little Sand Draw Field, Bighorn Basin, Wyoming.

Murphy Dome (Figure 15). T.43 and 44N., R.91 and 92W. Fold trends N60°W. Cody shale is exposed at the surface. Fold drilled to Cambrian strata. Stratigraphic constraints on the steep southwest limb require either faulting or bending of the basement. A northeast-dipping reverse fault is the writer's preferred interpretation.

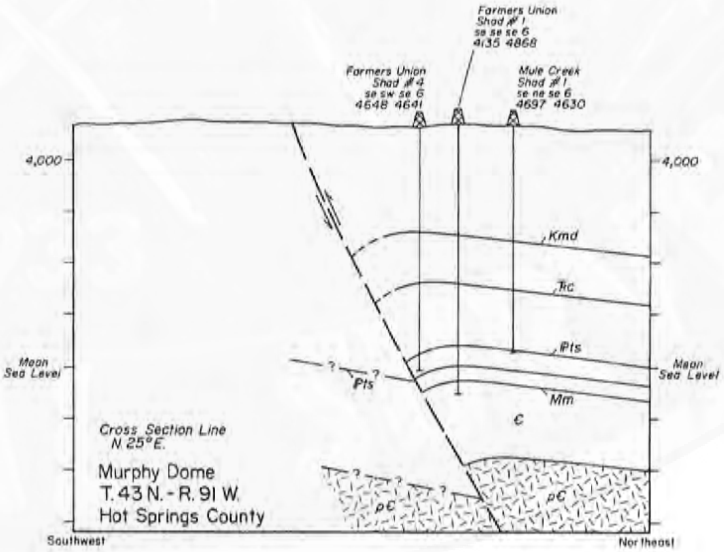


Figure 15. Structural cross section through the Murphy Dome, Bighorn Basin, Wyoming.

North Sunshine anticline (Figure 16). T.47N., R.101W. Fold trends N10°W. Surface fold is asymmetric to the east with steep (60° to 70°) dips in the Frontier Formation and 30°+ dips in the same formation on the west limb. Drilling penetrated the Precambrian basement after passing through a northeast-dipping reverse fault that duplicates the Mississippian and Devonian section. Wells on the east flank constrain the position of the Precambrian basement in the hanging-wall block. The major fault controlling the fold dips to the northeast, and the surface trace must lie well to the west of the fold in the belt of poorly exposed Cody Shale. The surface expression of the fold is the result of shallow thrusting.

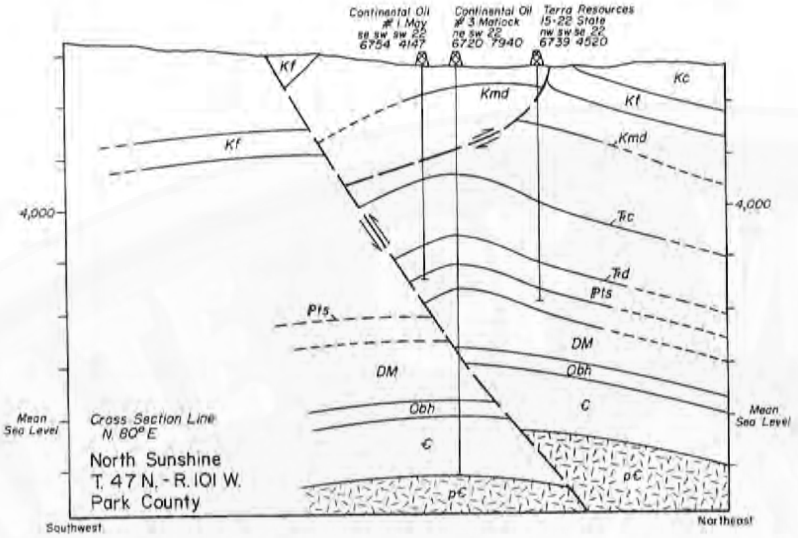


Figure 16. Structural cross section through the North Sunshine Field, Bighorn Basin, Wyoming.

Pitchfork anticline (Figure 17). T.43 and 44N., R.102W. Fold has an arcuate trend ranging from north - south to N30°W (south end). Mowry Shale is exposed in the core. Drilled to the Precambrian basement. Pitchfork anticline is an excellent example of a faulted fold broken by two northeast-dipping reverse faults (dip 45° or less). Vertical separation at the top of the Precambrian is approximately 3,500 feet. A seismic profile indicates persistent, 5° to 10° eastward dip of sediments in the footwall. The writer's interpretation does not agree with the detachment concept of Peterson (1983).

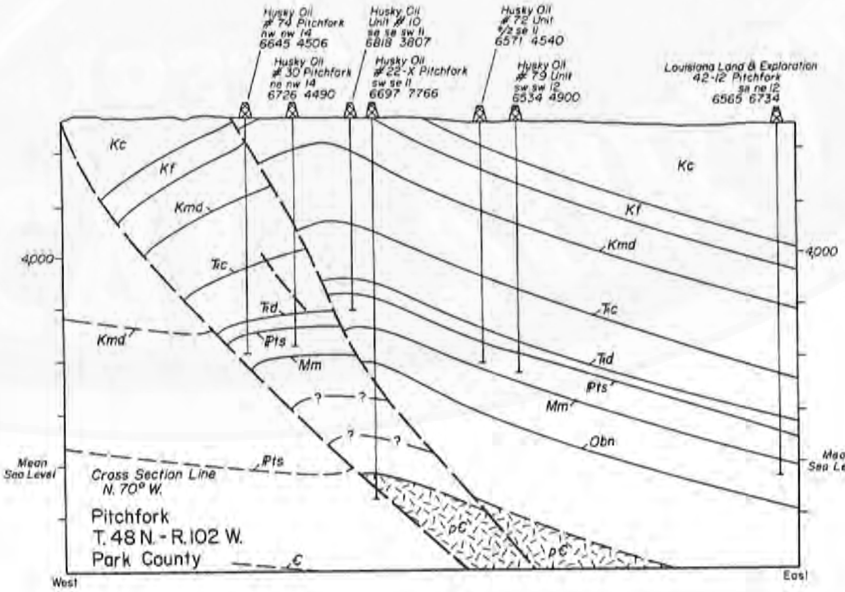


Figure 17. Structural cross section through the Pitchfork Field, Bighorn Basin, Wyoming.

Rawhide anticline (Figure 18). T.48N., R.101W. Fold trends N50°W. Cody shale is exposed at the surface. Drilled to the Mississippian Madison Limestone. Stratigraphic constraints on the southwest limb of the fold indicate a vertical separation on top of the Precambrian basement of 2,000 feet. Fault dips to the northeast. Strata in the footwall (lower level) probably do not bend upward and drag into the fault plane, but continue at low dip beneath it.

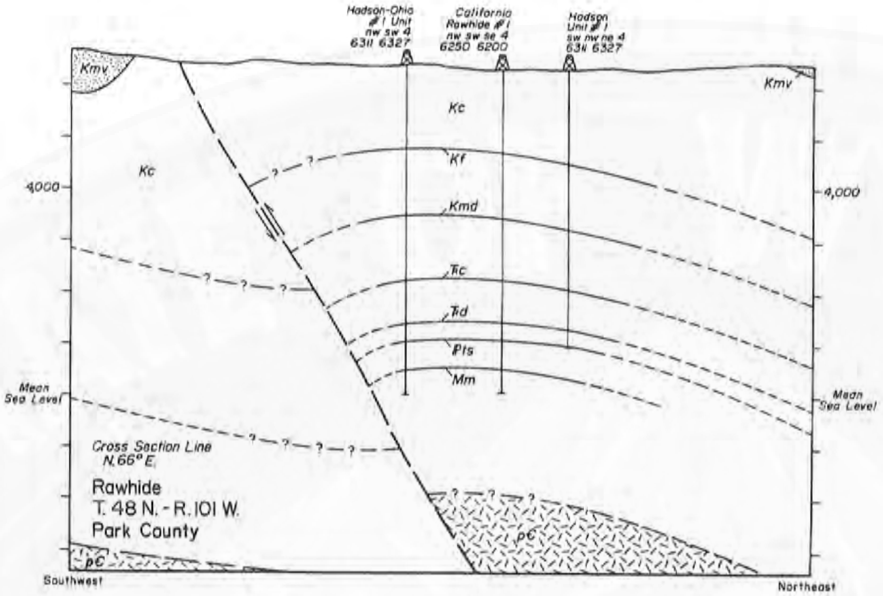


Figure 18. Structural cross section through the Rawhide anticline, Bighorn Basin, Wyoming.

Slick Creek anticline (Figure 19). T.47N., R.92W. The producing area is primarily a stratigraphically controlled accumulation. Several maps indicate that the east-west-trending Tensleep fault extends across this area and westward into the Bighorn Basin. The north-south oriented cross section across the critical area reveals no faulting; any expression of the Tensleep fault in this area must be very subtle.

South Sunshine anticline (Figure 20). T.46N., R.101W. Fold trends N30°W. Jurassic Morrison Formation is exposed at the surface. Surface fold is sharply asymmetric to the northeast. Drilled to the Pennsylvanian Tensleep Formation. Well data indicates that the fold is controlled by a major reverse fault that dips to the southwest. The asymmetry of the surface fold is due to crowding at higher levels.

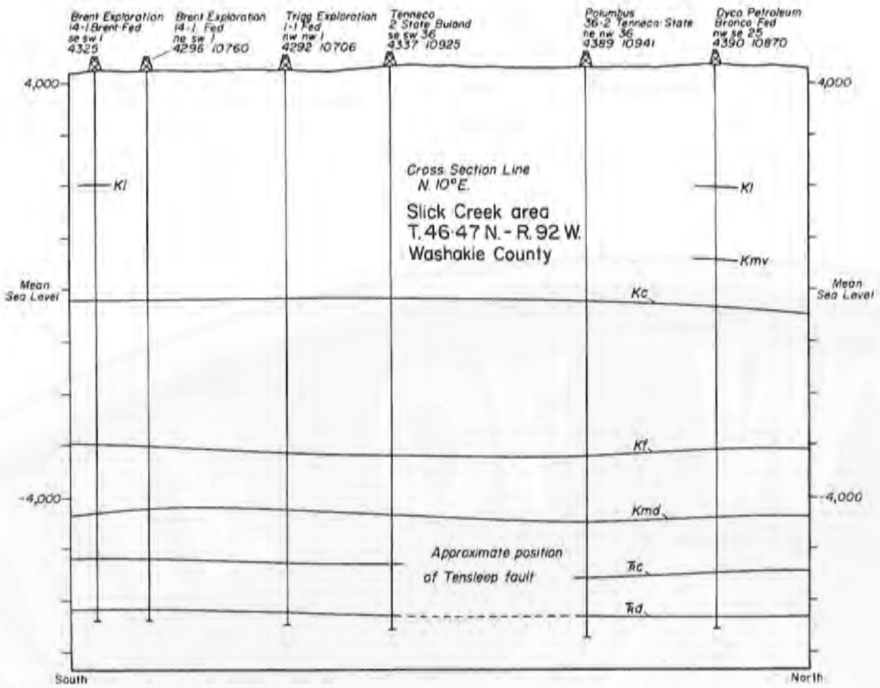


Figure 19. Structural cross section through the Slick Creek Field, Bighorn Basin, Wyoming.

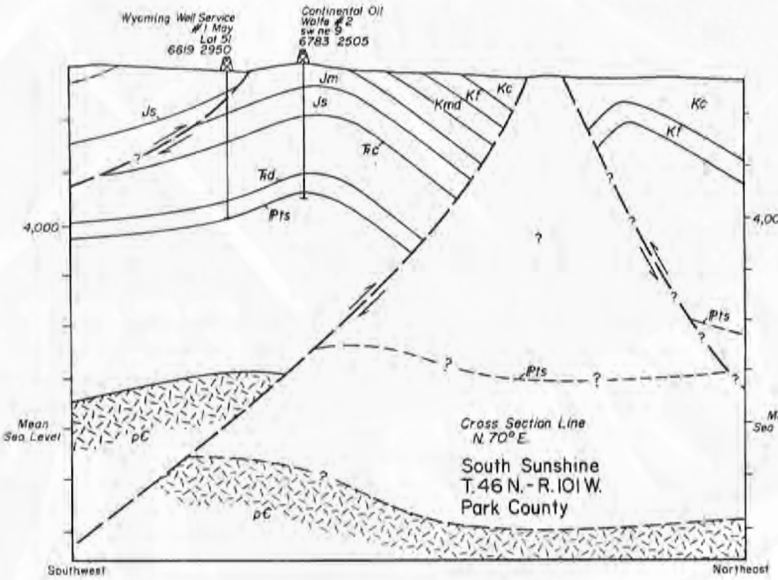


Figure 20. Structural cross section through the South Sunshine Field, Bighorn Basin, Wyoming.

Spring Creek anticline (Figure 21). T.47N., R.102W. Fold trends N45°W. Mowry Shale is exposed at the surface in a sharp fold, asymmetric to the southwest. Drilled to the Cambrian after passing through two reverse faults that repeat the Madison Limestone three times. Major fold is controlled by northeast-dipping reverse faults. Vertical separation of basement is approximately 4,000 feet.

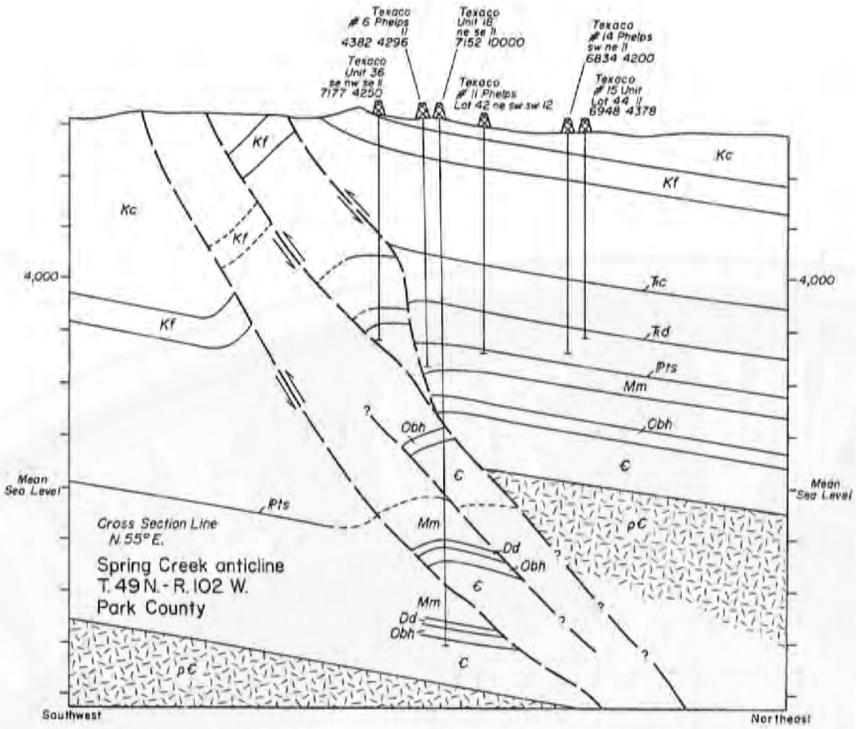


Figure 21. Structural cross section through the Spring Creek Field, Bighorn Basin, Wyoming.

Thermopolis anticline (Figure 22). T.43 and 44N., R.93 through 97W. Fold trends east-west in eastern section, changing to N55°-60°W in the western section, and is asymmetric to the south or southwest. Tested to the Precambrian basement at two sites (Warm Springs and Rose Dome).

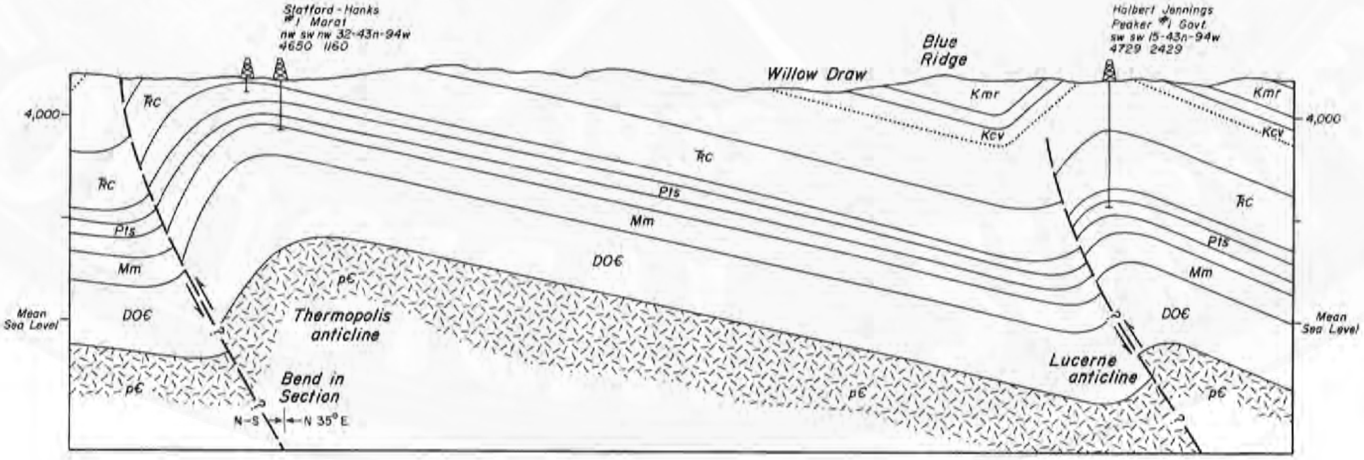


Figure 22. Structural cross section through the Thermopolis anticline, Bighorn Basin, Wyoming.

Warm Springs anticline (Figure 23). T.42 and 43N., R.93 and 94W. Surface fold trends east-west. Triassic Chugwater is exposed at the surface in the anticline core. Basement offset is approximately 1,000 feet.

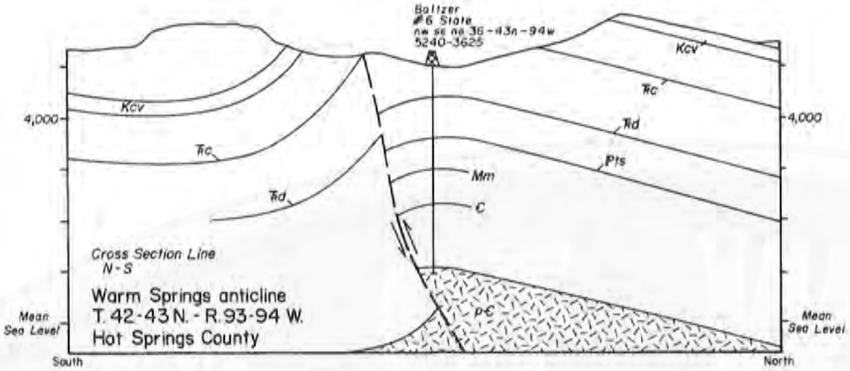


Figure 23. Structural cross section through the Warm Springs anticline, Bighorn Basin, Wyoming.

Waugh Dome (Figure 24). Trends T.44N., R.96 and 97W., 100 feet of closure. Cody Shale is exposed at the surface. Basement offset indeterminate. Drilled to Precambrian.

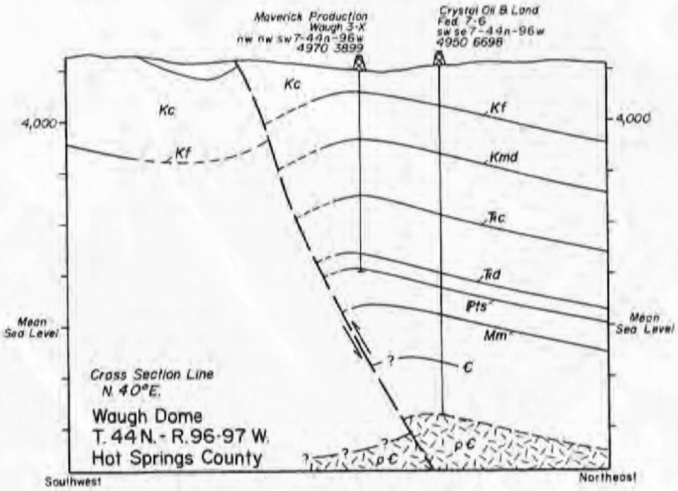


Figure 24. Structural cross section through the Waugh Dome, Bighorn Basin, Wyoming.

Groups of folds with common characteristics

The preceding section described examples of both large and small anticlines in the southern Bighorn Basin where the underlying Precambrian basement is known or presumed to be faulted. The persistence of that characteristic over a large area leads to the conclusion that the structures must have a common origin under reasonably uniform conditions of deformation. The regional cross sections (Sheet 2, back pocket) illustrate the similarity of structural geometry.

The examples described above lie within groups of folds that have similar characteristics. A summary of the general structural pattern of these groups of folds follows.

Washakie-Owl Creek-Bridger Mountains

The elevated region at the south end of the Bighorn Basin includes the southeastern part of the Washakie Range (Love, 1939), the Owl Creek Mountains west of Wind River Canyon and the Bridger Mountains east of the canyon (Darton, 1906). Despite the essentially east-west trend of the topographically high region, the internal structural geology consists predominantly of northwest-trending folds bounded by reverse faults (Figure 3). Folds plunge to the northwest into the Bighorn Basin. A major segment of the southern Washakie Range exposes Precambrian basement in a wedge bounded on the southwest by the Black Mountain and Caldwell Meadows faults and on the northeast by the North Owl Creek - Mud Creek fault.

A series of plunging folds occurs farther to the east. The first of these is associated with the North Owl Creek - Mud Creek thrust fault. Even farther east is the Red Creek anticline and syncline pair. East of Wind River Canyon are the Wildhorse anticline (Peterson, 1983) and several folds adjacent to the Lysite Mountain area.

Southeast corner of the Bighorn Basin

In the southeastern corner of the basin, narrow, elongate, acute folds such as Murphy Dome, Black Mountain, Lake Creek and Corley-Zimmerman Butte trend N50°-60°W. These folds appear to have relatively small offsets of the Precambrian basement on the faults that underlie them.

Western margin of the Bighorn Basin

The most spectacular group of folds occurs on the west side of the basin and extends from Cody, Wyoming, southwestward to near Thermopolis, Wyoming (Figure 3). The Upper Cretaceous Cody Shale is exposed in the cores of many of the folds, which are outlined by prominent rims developed on the Cretaceous Mesaverde Formation. The intervening synclines contain rocks of the Cretaceous Meeteetse and Lance Formations and the Paleocene Fort Union Formation. All of these are locally overlain unconformably by the Eocene Willwood Formation.

Data from surface sections and wells demonstrate that the sedimentary section in the southern Bighorn Basin was approximately 12,000 feet thick before the Laramide deformational episode. The Paleocene Fort Union Formation is unconformable upon the Lance Formation, documenting the time of first major deformation.

Structural analysis and interpretation

Concepts of origin

The southern Bighorn Basin lies within the Rocky Mountain foreland province, an area characterized by large, compound anticlinal uplifts cored by Precambrian basement. Observable faulting is an integral part of the pattern. Structural depressions of comparable size with internal folding lie between the uplifts and contain deposits derived from the adjacent rising highlands.

The origin of the observed structural features has been discussed under two major concepts:

(1) Movement of the crystalline basement has been largely vertical, accomplished on high-angle normal faults. Individual blocks have been rotated to create the observed dips (Stearns, 1971; 1978).

(2) The features evolved within a stress field that was oriented in an essentially horizontal direction. The basement

can be both flexed and faulted. Reverse faults dipping beneath the elevated block are the norm, and crustal shortening occurs on the reverse faults.

The writer has defended the latter concept (for example, Blackstone, 1963), and will attempt to demonstrate the existence of this tectonic style in the southern Bighorn Basin.

Major regional thrust faults

Major thrust faults on the margins of several foreland uplifts adjacent to the southern Bighorn Basin are well documented by surface geology, seismic reflection studies and drilling. The displacements on these low-angle thrust faults (measured in miles) cannot be explained by a geometry that allows only high-angle normal faults and block rotation. Such low-angle faults developed within a fairly restricted time range - Maestrichtian to early Eocene (Gries, 1983). The dominant stress field must have been fairly uniform, and was directed in a nearly horizontal orientation. Crustal shortening on the reverse faults was the mechanism for relief from existing stress.

The best-documented occurrence of this type of crustal behavior in the Rocky Mountain foreland is the Wind River Range of Wyoming, bounded by the low-angle (30°), east-dipping Wind River thrust. Interpretations of deep seismic profiles obtained by the Consortium for Continental Reflection Profiling (COCORP) leave little doubt that the controlling thrust faults extend to a depth of at least 15.5 miles (25 kilometers) (Smithson and others, 1979). The thrust is similar to the Oregon Basin fault, Owl Creek fault and Casper Arch fault. Other examples of low-angle thrust faults that bound foreland structures are listed in Table 3.

Table 3. Probable overhang of major thrust faults.

Name and location	Probable overhang	Source of data
Beartooth Mountains (northeast and east sides)	7.5 miles	Bonini and Kinard (1983)
Heart Mountain anticline	1 mile	Lowell (1983)
Oregon Basin thrust	5+ miles	Unpublished data, drilling
North Owl Creek - Mud Creek fault	2+ miles	Darton (1906), Lowell (1983)
Black Mountain and Caldwell Meadows thrusts (Washakie Range)	8 miles	Love (1939) Gries (1981), Clements (1977), drilling
Owl Creek Mountain thrust	10-12 miles	Fanshawe (1939), Wise (1963), Gard (1969)
Southwest flank of Casper Arch	6-7 miles	Sprague (1983), drilling
Piney Creek thrust (east flank of Bighorn Mountains)	3+ miles	Hudson (1969), Blackstone (1981), drilling

Possible influence of Precambrian structure on later events

Blackstone (1973), in an attempt to evaluate Earth Resources Technology System (ERTS) imagery, studied the relationship of linear photo features in the exposed core of the Bighorn Mountains to the orientation of folding in the Bighorn Basin. Hoppin (1974) performed a similar and somewhat more detailed analysis. Figure 25A is a rose diagram plot of 51 well-defined linear features in the Precambrian core of the range. Sixty-three percent of the linears trend northeast and only 27 percent trend northwest.

Figure 25B depicts trends of fold axes in Bighorn Basin sedimentary rocks (83 cases). Eighty-seven percent of the fold axes trend northwest, and only 14 percent trend northeast. Either the orientation of basement features changes drastically or the dominantly northeast orientation is not reflected in the overlying sediments.

Cross sections through representative folds (Figures 4 through 24) indicate that Precambrian basement is involved in deformation of the southern Bighorn Basin. The dominant fold trend is N40°-50°W. The orientation of the principal axis of stress to generate those folds, and the orientation of underlying and controlling faults in the basement, would be in a direction S40°-50°W. An exception to this anticipated orientation is the essentially east-west-trending western part of the North Owl Creek - Mud Creek fault.

Photolinears / Bighorn Mountains
1 division = 2%
52 cases
A

Fold axes / Bighorn Basin
1 inch = 40 divisions
83 cases
B

Figure 25. Rose diagrams showing photolinears (A) and fold axes (B), southern Bighorn Basin, Wyoming.

Younger east-west-trending structures

Although the dominant trend of the thrust-fold structures in the southern Bighorn Basin is northwest (Figures 3 and 25), a few folds such as the King Dome - Thermopolis - Warm Springs complex trend essentially east-west, paralleling the mountains to the south.

The major structural and topographic divide between the Wind River Basin and the southern Bighorn Basin is the structural complex including the southern Washakie Range, the Owl Creek Mountains and the Bridger Range. The overall trend of these features is approximately N75°W and is controlled by a major thrust (or thrusts) that dips north beneath the elevated blocks (Fanshawe, 1939; Gard, 1969; Wise, 1963).

The strong variance in structural grain between the Bighorn Basin structures and the Owl Creek Mountains complex is evidence that the region has undergone two episodes of deformation. The structures with a northwest trend developed in Late Cretaceous and Paleocene time. These were transected by younger structures that developed from a regimen of nearly north-south compression during early and middle Eocene time (Gries, 1983).

New interpretations

Data derived from deep tests and extensive seismic profiles require changes in previous structural interpretations for the southern Bighorn Basin. Discussion of these changes follows.

Oregon Basin fault

A major west-dipping thrust fault along the west side of the basin (Figures 2, 3, and Sheet 1) lies east of the segment containing the large petroleum-producing anticlines such as Oregon Basin, Little Buffalo Basin, Grass Creek and Hamilton Dome. This fault is clearly documented in the Hunt Oil Company Loch Katrine well in sec. 2, T.51N., R.100W. The well passed through the fault zone at about 14,000 feet and bottomed in Devonian Three Forks Formation at 23,860 feet. Vertical separation on this fault from the crest of the Oregon Basin fold to completion depth is about 20,000 feet.

A geologic interpretation of a reflection seismic traverse in an east-west direction through the Hunt Oil Company Loch Katrine well was presented by Stone (1984). The seismic traverse provides positive evidence of the fault dip.

Seismic profiles in the vicinity of Grass Creek are equally definitive as a series of deep tests drilled east of the fault (Sheet 1). The deepest well - American Quasar, Sellars Draw unit 1, sec. 21, T.48N., R.98W. - bottomed at 23,081 feet in Permian Phosphoria Formation. The well is located in the footwall of the fault, and vertical separation, based on data from folds in the west, is approximately 18,000 feet. The Oregon Basin fault does not reach the surface, but is unconformably overlain by Eocene Willwood Formation.

The northern extent of the Oregon Basin fault is undetermined. One interpretation indicates that the fault changes trend to the northwest and passes east of the Shoshone-Heart Mountain fold zone (Lowell, 1983), continuing north to join the low-angle thrusting along the east flank of the Beartooth Mountains (Thom, 1952; Scheevel, 1983). A second interpretation extends the fault from Oregon Basin north to join faulting along the east flank of the Elk Basin Field (Rea and Barlow, 1975). Because of the vertical separations involved, the writer believes the second interpretation is more plausible. The southeast extension or termination of the fault is not well established. The data suggest it may extend almost to the Neiber anticline.

The relationship has not been definitely established between the folds that are asymmetric to the southwest and the Oregon Basin fault, which has a sense of tectonic transport to the northeast (as do the faults on the east-central segment of the Bighorn Mountains).

If the Oregon Basin fault continues at depth to the west at an angle of approximately 30° ± 10°, the large folds southwest of the subcrop trace must lie in the hanging wall of the major thrust fault. No deep reflection seismic profiles were available to define the possible depth to which this fault extends. The major folds such as Little Buffalo, Grass Creek, Hamilton and Meeteetse (Figures 10, 11 and 13) are asymmetric to the southwest, and the Precambrian basement is displaced to the southwest on east-dipping reverse faults. The east-dipping faults that define the individual folds are interpreted to terminate at the fault plane of the Oregon Basin fault. The individual faults are in the hanging wall of the Oregon Basin fault, and are back-limb thrusts that allow displacement to the southwest under compressive stress. Earlier interpretations considered the folds to have developed out of the basin or syncline by movement individually rooted in the Precambrian basement (Hewett and Lupton, 1917).

A generalized cross section by Peterson (1983) illustrates part of the problem, but the Oregon Basin fault is not recognized. Figure 26 illustrates the wedge relationship across the buried Oregon Basin fault and the North Owl Creek - Mud Creek fault.

Faults on the southwest margin of the Washakie Mountains

A discontinuous series of thrust faults exists along the southwest flank of the Washakie Range, including the Black Mountain and Caldwell Meadows thrust (Figure 3). The Buffalo Fork thrust (Figure 2) (Love, 1956) lies to the northwest and continues into Yellowstone National Park. This series of faults dips to the northeast and may be considered the western margin of a rather wide crustal wedge, bounded on the east by the Oregon Basin fault. Unfortunately, structural details between the two faults are largely concealed by the Absaroka volcanic field.

A smaller, but similar wedge relationship, involving the Precambrian basement, lies between the Black Mountain - Caldwell Meadows fault system and the western extent of the North Owl Creek - Mud Creek thrust. Faults on the margin dip under the elevated block (Figure 3), and the block appears to have been elevated under the compressive stress field.

The relationship of the folds in the vicinity of Golden Eagle - Gebo - King Dome and Warm Springs Fields to the Oregon Basin fault is not clear. In these structures, the Precambrian basement is offset on northeast-dipping reverse faults, and the tectonic transport direction is to the southwest. No evidence of a southwest-dipping master fault similar to the Oregon Basin fault has been observed, and no marked offset of the two regions along a northeast-trending zone is evident.

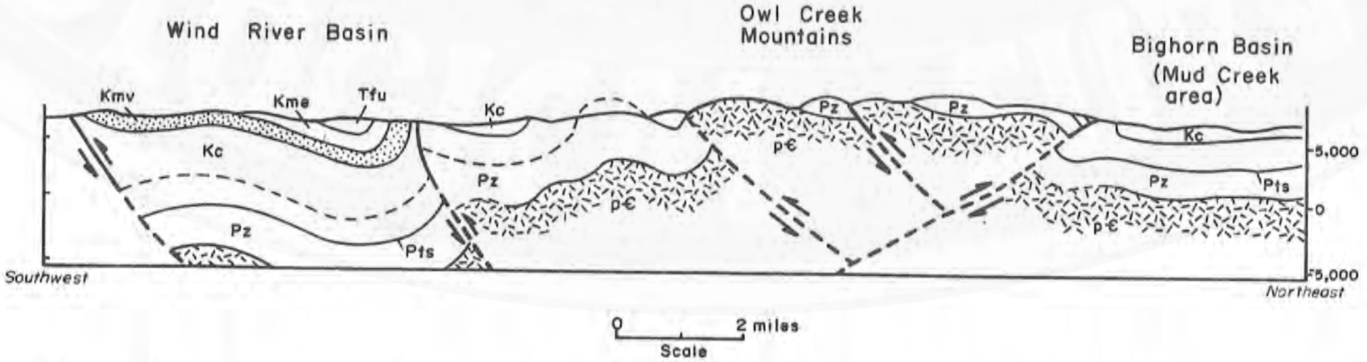


Figure 26. Structural cross section through the western Owl Creek Mountains from the Wind River Basin to the Bighorn Basin, Wyoming. Elevations are in feet above sea level. Cross section location is shown on Sheet 1 (back pocket) and Figure 3. (See Table 2 for formation abbreviations.)

Crustal behavior

The distinctive character of the Rocky Mountain foreland province was recognized almost as soon as mapping began in the region. The geometry of the major and minor uplifts became the focus of investigations that have been pursued up to the present day. Thom (1923) originally related the folding in the sedimentary cover to faulting in the basement complex. Many investigators provided new interpretations of the geometry, as the technology of gravity measurements, drilling and seismic reflection surveys developed. Brown (1983) updated ideas concerning the geometry of such structures. Investigation of the geometry of the thrust fold (Stone, 1983) paralleled an attempt to solve the problem of "first cause" and the potential source of the energy required for the deformation.

Thom (1952) suggested a hierarchy of structural elements, and an evolutionary sequence of events, but the proposal did not receive a great deal of attention. He also theorized that the uplifts in the Yellowstone - Bighorn area were controlled by downward-wedging plutonic rock masses that responded to compressive stress as units. This type of anisotropy in the basement has been proven to be invalid (Wise, 1983). The controversy concerning the relative role of horizontal versus vertical stress as the controlling factor in the deformation emerged at about this time (Stearns, 1971). The writer favored the horizontal stress field concept, basing the conclusion on the pattern of deformation seen throughout the foreland province.

Data concerning the behavior of rocks based on laboratory tests and theoretical grounds also developed at a rapid rate. Among these investigators, Stearns (1971) and his graduate students turned their attention to features in the Rocky Mountain foreland in an attempt to relate their laboratory models to field occurrences. Perhaps the most-discussed case was that of Rattlesnake Mountain near Cody, Wyoming, which Stearns presented many times as a typical Rocky Mountain foreland faulted fold. Current interpretations by Brown (1983) and Stone (1983) are distinctly different. Thom (1952) suggested that the Rattlesnake Mountain structure lay above a deeper-seated fault and therefore was not typical.

Throughout the evolution of interpretations, all investigators have recognized that they were dealing with a region of sub-cratonic proportions overlain by shelf-type sedimentary strata of remarkable regional consistency. The thickness of the sediment cover, prior to the Laramide deformation episode, was 10,000 to 12,000 feet over extensive areas. If the Moho lies at about 28 miles depth, the sedimentary veneer is about eight percent of the rocks that were subjected to deformation. One regional stratigraphic variation has affected the geometry and response in different localities; the presence or absence of a thick section of Cambrian shales found in Montana and northern Wyoming markedly affects the internal structure of many foreland thrust-folds. Fanshawe (1939) developed the idea of yield units in the sedimentary column, their effect on the geometry of folds and the effect of the Cambrian shale section.

A development of the last decade that has sharply focused the vertical vs. horizontal argument has been the data gathered from wells drilled through the overhang of major thrusts along the margin of some of the major uplifts. Gries (1981) has fully documented the case histories.

The majority of folds seen in the Rocky Mountain foreland province are dependent upon a fracture (fault) in the top of the crystalline Precambrian basement. Detachment structures (Lowell, 1983; Peterson, 1983) are secondary or incidental to primary movement at the level of the basement-sedimentary rock interface. Since the deformation of the basement at that level is of primary importance, "first causes" must deal with the basement behavior. Sheevel (1983) proposed that the first cause for the observed folds is faulting at the upper surface of the Precambrian basement, generated under a regime of horizontal compression. He noted that there are structures with amplitudes of 42,000 feet and those of lesser scale (5,000 feet).

Scheevel's (1983, Figure 6) cross sections, demonstrating the development of potential faults, all dipping in one direction and propagating downward with increasing crustal shortening, leave an unfortunate impression. Earlier, Scheevel (1983, Figure 2) presented an illustration of shear-fault trajectories in conjugate sets inclined 30° to the initial horizontal surface. There is no *a priori* reason why only one set of the shear-fault trajectories will become dominant as shown by Scheevel (1983, Figure 6). Further, the final attitude of the fault planes will change during the development of large-magnitude deformational features such as the Bighorn Basin. At such amplitudes, the original sedimentary - basement rock interface may be inclined as much as 8° to 10°, as shown on the north flank of the Owl Creek Mountains. This regional tilting will be reflected in individual faults, depending upon which trajectory in the conjugate pair became the plane of release of stress by fault slippage.

The consistent relationship of basement faults to folds in the overlying sedimentary cover is well documented in the southern Bighorn Basin. All faults that are well documented by drilling and seismic profiles are reverse in character and allow for crustal shortening. No examples of normal faults were found. Crustal shortening is not possible under the regimen of extensional tectonics. Since crustal shortening *does exist* in this region, a compressional regimen must have existed during the Laramide deformation episode. The writer's conclusion is that the foreland deformation described in this review is clearly due to compression.

Summary

The major observations derived from this review are listed below:

1. Folds in the sedimentary rocks are generated by faults in the Precambrian basement and are asymmetric.
2. Reversal of asymmetry of folds is not uncommon.
3. Reversal of asymmetry creates wedge-shaped crustal segments on several scales.
4. Faults of low angle (30°+) in the basement steepen upward to a ramp or sled-runner form as they propagate through the sedimentary column.
5. Drastic thinning of the sedimentary section may occur on the steep limbs of large folds. Mesozoic shale sections are particularly susceptible.
6. Detachment structures occur locally, but are controlled by primary movement of faults at the basement level.

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The writer is solely responsible for all conclusions.

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