GEOLOGICAL SURVEY OF WYOMING

FORELAND COMPRESSIONAL TECTONICS: SOUTHERN BIGHORN BASIN, WYOMING

by

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OPEN FILE REPORT 85-3

Prepared through the auspices of the Wyoming Water Research Center, University of Wyoming for the U.S. Department of the Interior, Geological Survey (Research Project Technical Completion Report USGS G-879, Project No. 02).

The research on which this report is based was financed in part by the U.S. Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

1985

Laramie, Wyoming

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ABSTRACT

Movement of ground water in aquifers of Paleozoic age in the southern Bighorn Basin, Wyoming, is influenced by anisotropy which is the result of deformation of the sedimentary rocks. The sedimentary rocks prior to the Laramide orogeny were approximately 12,000 feet thick of which approximately 2,200 feet are of Paleozoic age (Figure 1). The sediments 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 in dip as they propagate upward through the sedimentary cover. Wedge shaped crustal segments of large size 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 generally pervasive horizontal stress field during the Laramide orogenic episode.

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. Within the outcrop of Upper Cretaceous rocks, the basin covers approximately 10,000 square miles and is 200 miles long and about 50 miles in width; is roughly bounded on the north by the Lewis and Clark line (Montana limeament); on the east by the Pryor Mountains-Bighorn uplift; and on the south by the south extension of the Bighorn Mountains and the Bridger-Owl Creek uplift. The western margin is concealed beneath the Absaroka volcanic field, and flanks the buried Washakie Range (Love, 1939). The basin is constricted in the area between the eastern face of the Beartooth Mountains (Bonini and Kinard, 1983) and the west flank of the Pryor Mountains and modified by the Nye-Bowler lineament with trends transverse to the basin axis. The major outline is portrayed on Figure 2.

The south end of the Washakie Range consists of several folds (cored by Precambrian basement) which plunge to the northwest (Figure 3). A major fault, the Buffalo Fork thrust (Love, 1956), bounds the west margin of the uplifted area, dips to the east, 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. The overall more or less east-west trend of the uplift is controlled by major reverse faulting (known as the Owl Creek thrust) on the south margin of the ranges (Gard, 1969; Wise, 1963). The regional transverse orientation of the uplift indicates that the controlling movement is 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, however, the writer believes that a syncline containing Cretaceous Mesaverde Formation lies just west of the margin of the Absaroka volcanic field (Figure 3).

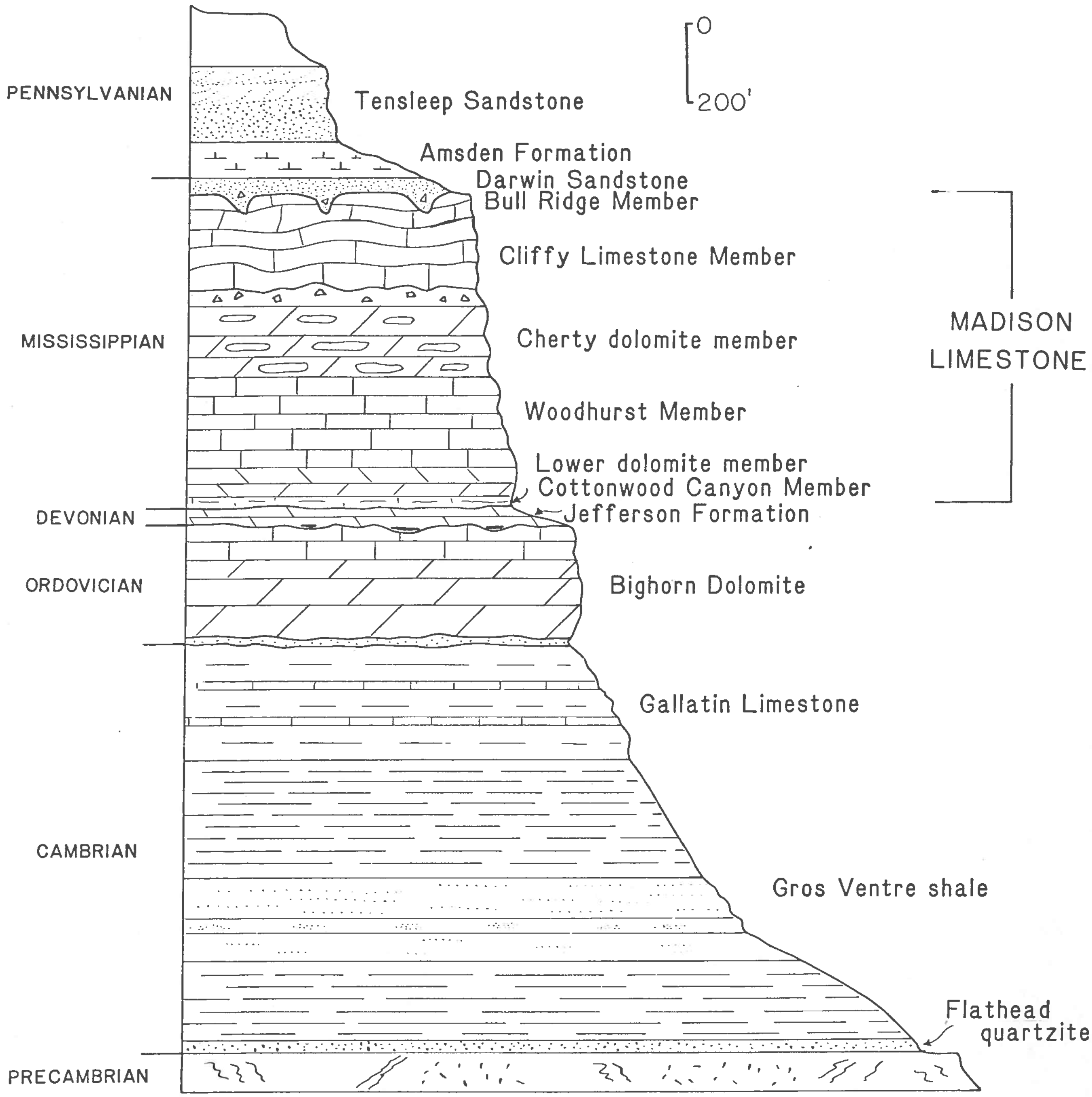

Figure 1. The Paleozoic stratigraphic section in the southern Bighorn Basin, Wyoming.

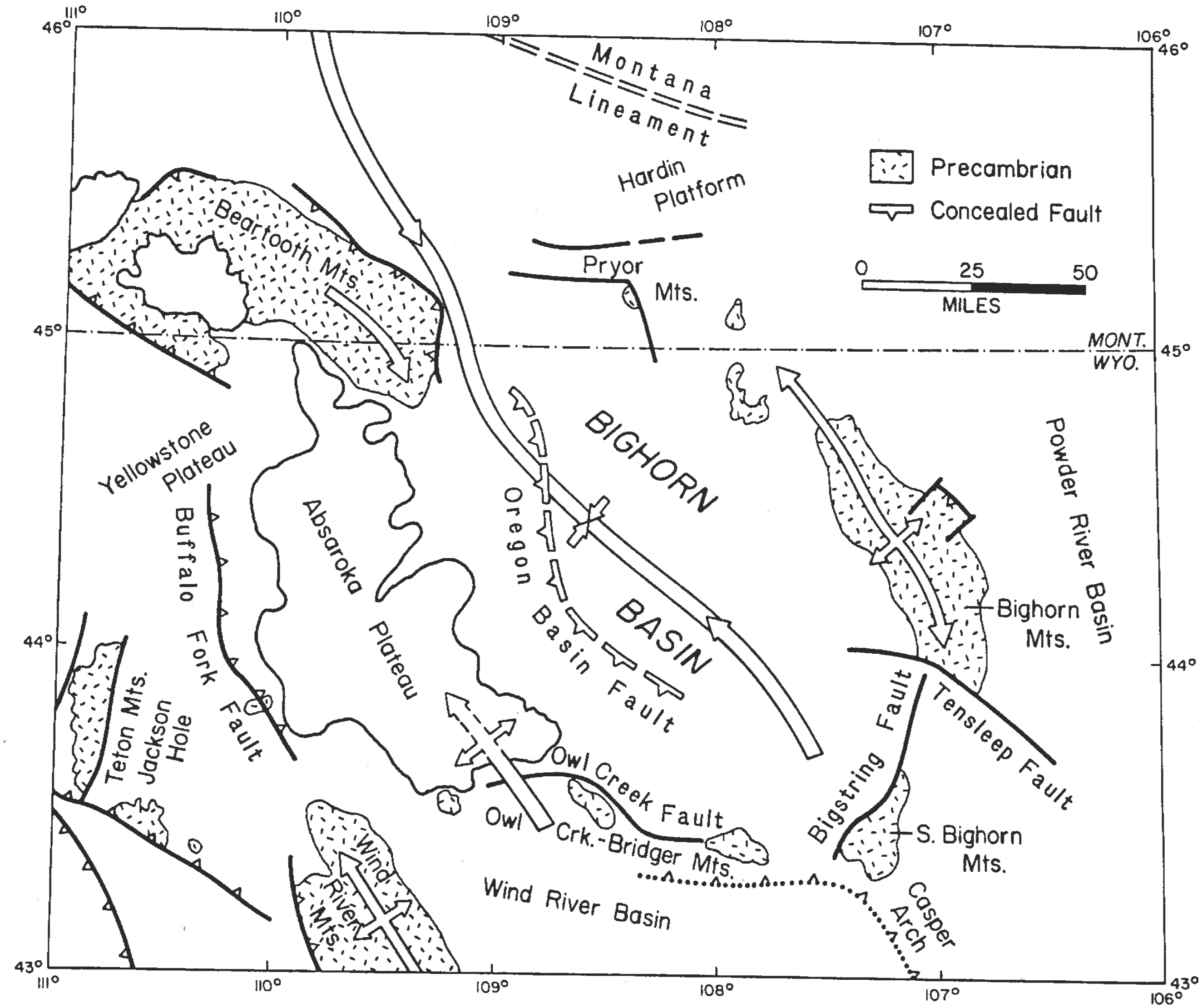

Figure 2. Tectonic index map, Bighorn Basin, Wyoming.

Geologic mapping in the eastern part of the Absaroka volcanic field by Rohrer (1964), Wilson (1982), Bown (1982), and Sundell (1982) has shown that there are 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. Detailed mapping, drilling, and extensive seismic work reveal far more complex structural patterns. The southeast basin margin is a major fault - the Bigtrails or Deep Creek fault - trending N15°E, down to the west, with Precambrian basement exposed in the hanging wall. Major movement 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.

The Tensleep fault which trends transverse to the major axis of the Bighorn Mountains uplift was originally treated as a normal fault, down to the south. Detailed study (Hoppin, 1965) shows that the fault location is controlled by an anisotropy in the Precambrian basement. Huntoon (personal communication) reports that the Tensleep fault is reverse in character with the north side up, perhaps modified by some 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 by using data from drilling 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, dips approximately 30° west, and may have numerous splays. The fault decreases in displacement to the southeast, and probably does not reach as far south as Gebo anticline. The name Oregon Basin - Beartooth fault was used by Scheevel (1983) for this fault.

Northwest-trending belt of major folding

Major folds on the west and southwest side of the Bighorn Basin are outlined by rims of Cretaceous Mesaverde Formation shown by a stippled pattern on Figure 3 to accentuate extent and size. The belt of folding lies to the west and southwest of the pre-Willwood Oregon Basin thrust fault described above, and in general, individual folds trend to the 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).

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

Faults of opposite dip but similar

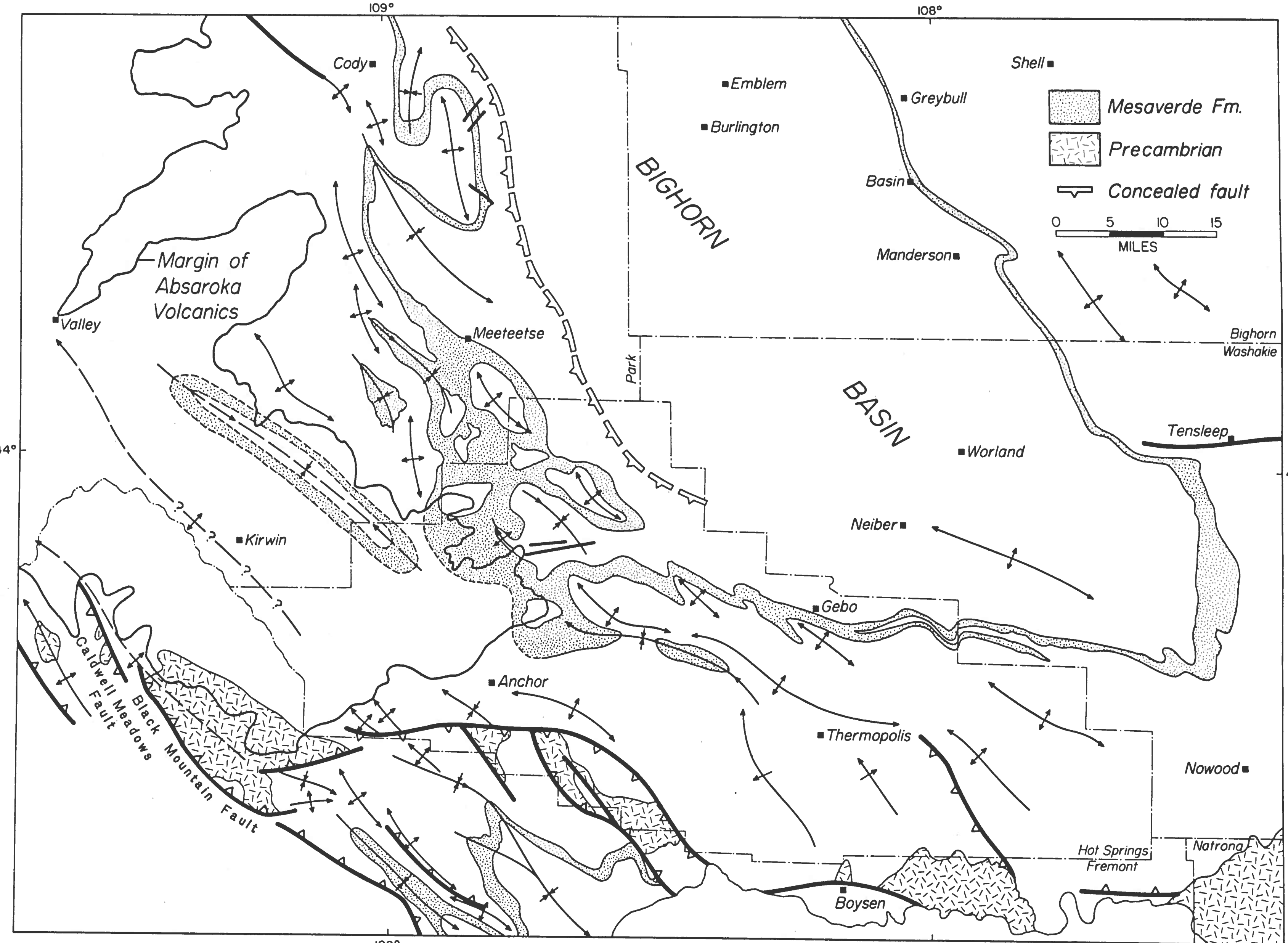

Figure 3. Tectonic map of the southern Bighorn Basin, Wyoming.

strike exist on the 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 all the large scale features agrees with the northwest major regional structural grain of the Wind River Mountains and the east-dipping thrust faults on the west side of the Absaroka volcanic field.

REVIEW OF INTERPRETATIONS

The geometry of folds in the Rocky Mountain foreland has been a fruitful field of study as well as the source of major geological controversy. The development of geologic thought relative to fold geometry is, in part, a function of depth of drilling, the willingness to drill prospects with unorthodox geological interpretation, intensive seismic investigations, and occasional human errors in interpretation of data.

The initial concept of the nature of foreland folds was that of Thom (1923) who proposed that the geometry of 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) by 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 which dipped beneath the block and which would attain lower dip by shearing out the corner of the footwall. Berg (1962) proposed the 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) presents an excellent review of terminology of deformation in the foreland.

Brown (1983) has suggested that there can be several satisfactory models, but that all account for crustal shortening and have a reasonable balance of bed length and volume.

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. Folds in this area range from those in which the crystalline basement is exposed up plunge in the structure, to those in which only nonmarine Late Cretaceous rocks are exposed.

FOLD GEOMETRY

The structural pattern of the southern Bighorn Basin is presented on Figure 4 by structural contours depicting the top of the Pennsylvanian Tensleep Sandstone. Principal facts concerning known folds appear in Table 1. Regional cross sections designed to accompany Figure 4 and provide an overview of the structural style appear as Figures 5-12. (Table 2 provides an explanation of formation symbols used on the cross sections).

Cross sections of representative folds were constructed where drilling provided

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	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	Dry
Bud Kimball	Washakie	44-45N, 88W	Sundance	N40W	NE	Tensleep	Dry
Chabot	Washakie	42-43N, 88W	Gallatin	N45W-N20W	SW	Madison	Dry
Corley-Zimmerman Butte	Washakie, Hot Springs	43-44N, 92-93W	Cody	N60W	SW	Madison	Dry
Embar	Hot Springs	8N-2E	Tensleep	N60W	NE	Precambrian	Dry
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	N10W-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	Dry
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	Dry
Lysite Mountain	Hot Springs	41-42N,90W	Tertiary	N40W	?	Madison	Dry
Mahogany Butte	Washakie	43N-89W	Mowry	N35W	NE	Tensleep	Dry
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	Dry
Oregon Basin	Park	50-52N,100W	Cody	N-S	E	Precambrian	Dry
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	Dry
Red Springs	Hot Springs	43N-93W	Chugwater	E-W	S	Madison	Yes
Rose Dome	Hot Springs	43-44N,96W	Phosphoria	N50W	SW	Precambrian	Dry
Sand Creek	Washakie	46N-91W	Willwood	N-S	?	Madison	Yes
Sheep Point	Park	47N-102W	Frontier	N50W	SW	Amsden	Dry
Skelton Dome	Hot Springs	45N-100W	Mesaverde	N-S	E	Madison	Yes
South Fork	Washakie	46N,91-92W	Willwood	N50W	?	Madison	Dry
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	Dry
Thermopolis	Hot Springs	43N-95W	Chugwater	N65W	S	Madison	Dry
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	Dry
Wildhorse Butte	Hot Springs	42-43N,93W	Chugwater	N45W	NE	Madison	Dry
Zimmerman Butte	Washakie, Hot Springs	43-44N,92-93W	Cody	N60W	SW	Madison	Dry

adequate subsurface control of fold geometry. The question of 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 to the writer. Typical examples of fold geometry follow and do not agree in all cases with previously published interpretations.

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 level of 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 the Cretaceous Cody Shale and Mesaverde Formation.

Changes in geometry with depth

The detailed cross sections show that almost universally (some cases are inde-

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

Eocene	Tw	Willwood Formation
Cretaceous	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	Trc	Chugwater Formation
	Trd	Dinwoody Formation
Permian	Pp	Phosphoria Formation
Pennsylvanian	Pts	Tensleep Sandstone
Mississippian	Mm	Madison Limestone
Mississippian-Devonian	MD	Madison Limestone, Darby Formation, Jefferson Limestone
Devonian	D	Darby (?) Formation
Ordovician	Obh	Bighorn Dolomite
Cambrian	Ꞓ	Gallatin, Gros Ventre, and Flathead Formations
Precambrian	pꞒ	Crystalline basement

terminate because of lack of subsurface data) the Precambrian basement is involved in the deformation. The basement is faulted, and the fault has propagated upward into the overlying sediments with varying degrees of structural complexity. The complexity consists of 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) attitude of strata exposed and critically mapped at the surface; (2) stratigraphic control established from a variety of logs obtained from drilled wells; and (3) reflection seismic profiles of good resolution at the basement interface. Unfortunately all sources of data are not available for the same site; some data are proprietary; and some data have been misinterpreted.

Several published models are available for comparison when dealing with the southern Bighorn Basin, each of which will fit some cases. Brown (1984) provides an analysis of a fold with exposed Precambrian basement in the northern Bighorn Basin. Berg (1976) has carefully documented the situation at Hamilton Dome wherein 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) have demonstrated footwall relationships of faulted anticlines involving the Precambrian basement. Advocates of Petersen (1983) suggest detachment faulting as a mechanism for certain anticlinal features.

It is obvious that no one type or style of deformation pattern is universal in this province. All that can be expected is a general style modified by space problems, rock heterogeneity, and the relative age of events.

SPECIFIC EXAMPLES OF FOLD GEOMETRY

The described geometry is repeated in other folds, and appears on the regional cross sections. Data on most folds are given in Table 1.

Black Mountain anticline (Figure 13)

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 has 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.

Bud Kimball anticline (Figure 14)

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

Chabot anticline (Figure 15)

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 essential. 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 allow for the stratigraphic relationships. Some adjustment of space at the surface probably is accommodated in the Cambrian shale section (1,200 feet plus in thickness).

Corley-Zimmerman Butte anticline (Figure 16)

T.43 and 44N., R.92 and 93W. Paired folds trending N60°W; Corley to the southwest. Cody shale at the surface; drilled to the Mississippian Madison Limestone. Zimmerman Butte appears to be controlled by a northeast-dipping reverse fault. Corley indeterminate as to faulting.

Four Bear-Willow Creek anticline (Figure 17)

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

Gebo anticline (Figure 18)

T.44N., R.95W. Trends N60°W; Cody Shale exposed in core at surface. The fold is asymmetric to the southwest, but rather broad and smooth at the surface with dips in the 15° to 20° range. The structure is complex at depth as shown by the records from Continental Oil Company Gebo Unit #28, SE sec. 23, T.44N., R.95W., which reached Precambrian basement and passed through at least three reverse faults. The fold illustrates the 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 in thickness). Seismic profiles confirm the northeast dip of the fault plane. Displacement on the basement is approximately 2,500 feet.

Grass Creek anticline (Figure 19)

T.46N., R.98 and 99W. Arcuate in trend; varying from N20°W at north end to N60°S at the south end. The structure is 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 (1,400 feet) duplicates the thinning found in the Hamilton Dome cross section (Berg, 1976). Subsurface faulting is very similar to the seismic profile of a typical Bighorn Basin anticline as presented by Stone (Figure 7B, 1984), and offset is approximately 4,500 feet.

Hamilton Dome (Figure 20)

T.44N., R.97 and 98W. Fold trends N70°W. Berg (1976) gives an excellent review of this fold, documenting the situation wherein basement faulting is modified in its upward propagation. 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.

King Dome (Figure 21)

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 encountered in drilled wells. The space problem on the steep south limb of the fold is acute. 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 marine Cody Shale. The north-dipping reverse fault allows 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 the basement was penetrated by drill.

Little Buffalo Basin anticline (Figure 22)

T.47N., R.100W. Major fold arcuate in plan view ranging from N30°W to N55°W. Cody shale 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. Major fault dips to the northeast.

Little Sand Draw anticline (Figure 23)

T.49N., R.96W. Fold trends N50°W. Cody shale at the surface; drilled to the Cambrian Gallatin Formation. Fold of low relief at surface and located well out in the basin. Precambrian basement probably faulted, but evidence inconclusive. 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.

Murphy Dome (Figure 24)

T.43 and 44N., R.91 and 92W. Fold trends N60°W. Cody shale at the surface. Fold drilled to the Mississippian Madison Limestone. 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.

North Sunshine anticline (Figure 25)

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 which duplicates the Mississippian Madison Limestone. 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 poorly exposed Cody Shale outcrop belt. The surface expression of the fold is the result of shallow thrusting.

Pitchfork anticline (Figure 26)

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. 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. Seismic profile indicates persistent eastward dip of the sediments in the footwall at 5° to 10° beneath the Precambrian in the hanging wall. The writer's interpretation does not agree with the detachment concept of Petersen (1983).

Rawhide anticline (Figure 27)

T.48N., R.101W. Fold trends N50°W. Cody shale 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 the fault plane.

Slick Creek anticline (Figure 28)

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, therefore, the writer concludes that any expression of the Tensleep fault in this area must be very subtle.

South Sunshine anticline (Figure 29)

T.46N., R.101W. Fold trends N30°W. Jurassic Morrison Formation exposed at 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 which dips to the southwest. The asymmetry of the surface fold is due to crowding at higher levels.

Spring Creek anticline (Figure 30)

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, repeating the Madison Limestone three times. Major fold is controlled by northeast-dipping reverse faults. Vertical separation of basement is approximately 4,000 feet.

Thermopolis anticline (Figure 31)

T.43 and 44N., R.93 through 97W. Trends east-west in eastern section and changes to N55°-60°W in the western section. All folds asymmetric to south or southwest. Tested to the Precambrian basement at two sites.

Warm Springs anticline (Figure 32)

T.42 and 43N., R.93 and 94W. Surface fold trends east-west; Triassic Chugwater exposed in core. Basement offset is approximately 1,000 feet.

Waugh Dome (Figure 33)

T.44N., R.96 and 97W.

The preceding section described examples of both large and small anticlines in the southern Bighorn Basin wherein the underlying Precambrian basement is faulted. The persistence of this characteristic over a large area leads to the conclusion that the structures must have a common origin and originated under reasonably uniform conditions of deformation. The regional cross sections illustrate the similarity of structural geometry.

GROUPS OF FOLDS WITH COMMON CHARACTERISTICS

The examples described above lie within groups of folds which have similar characteristics. The general structural pattern of these groups of folds is summarized in the following sections.

Washakie-Owl Creek-Bridger Mountains

The elevated region at the south end of the Bighorn Basin collectively consists of the southeastern part of the Washakie Range (Love, 1939), the Owl Creek Mountains west of the 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 in the southern Washakie Range has the Precambrian basement exposed in a wedge bounded on the southwest by the Black Mountain and Caldwell Meadows faults and on the northeast by the North Owl Creek or Mud Creek fault.

Farther to the east is a series of plunging folds. The first of these is associated with the Mud Creek thrust fault. Even farther to the east is the Red Creek anticline and syncline pair. East of the 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, there are narrow elongate acute folds such as Murphy Dome, Black Mountain, Lake Creek, and Corley-Zimmerman Butte, which trend N50°-60°W. These folds appear to have relatively small offsets of the Precambrian basement on the faults which underlie them.

Western margin of the Bighorn Basin

The most spectacular group of folds is that on the west side of the basin extending from Cody, Wyoming, southwestward to near Thermopolis, Wyoming. The Upper Cretaceous Cody Shale is exposed in the core 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 prior to the Laramide deformational episode the sedimentary section in the southern Bighorn Basin was approximately 12,000 feet in thickness.* The Paleocene Fort Union Formation is unconformable upon the Lance Formation documenting the time of first major deformation.

STRUCTURAL ANALYSIS

Concepts relative to origin

The southern Bighorn Basin lies within the Rocky Mountain foreland province, an area characterized by large, compound anticlinal uplifts cored by the 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. One concept is that the movement of the crystalline basement has largely been vertical, the movement accomplished on high angle "normal" faults, and that the individual blocks have been rotated to create the observed dips (Stearns, 1971, 1978). A second concept is that the features evolved within a stress field that was oriented in an essentially horizontal direction, that the basement can be both flexed and faulted, that reverse faults dipping beneath the elevated block are the norm, and that crustal shortening occurs on the reverse faults.

The writer has defended the latter concept, 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 margin of several foreland uplifts adjacent to the area under consideration are well documented by surface geology, seismic reflection studies, and drilling. Specific examples follow.

The displacements on these low angle thrust faults (measured in miles) cannot be explained by a geometry which 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 upon the reverse faults was the mechanism for relief from existing stress.

The best documented occurrence of this type of crustal behavior in the Rocky

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Hewett (1926) reports a variation in thickness for the total section from 11,500 feet to 22,350 feet in the western Bighorn Basin. Thickness in numerous wells is approximately 9,000 feet from the top of the marine Cretaceous Cody Shale to the Precambrian basement. A section encountered in the American Quasar Sellars Draw Unit, sec. 21, T.48N., R.98W. from surface to the Permian Phosphoria Formation was 23,081 feet. Moore (1961) indicates 8,000 feet of Paleocene Fort Union Formation at this site, leaving approximately 3,500 feet of Eocene Willwood Formation.

Mountain foreland is the Wind River Range of Wyoming, bounded by the low angle (30°) east-dipping Wind River thrust. Deep seismic profiles obtained in the COCORP Program 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 similarity of this feature to some of the examples listed earlier is self evident.

Possible influence of Precambrian structure on later events

Blackstone (1973) in an attempt to evaluate 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) did a similar and somewhat more detailed analysis. Figure 34 is a rose diagram plot of 51 well defined linear features in the Precambrian core of the range. Sixty-three percent of the linears have a northeast trend, and only 27 percent have a northwest trend.

An analysis of trends of axes of folds in the sedimentary rocks of the Bighorn Basin (83 cases) is shown on Figure 34. Eighty-seven percent of the fold axes trend northwest, and only 14 percent trend northeast. Either the orientation of basement features changes drastically or if the same orientation persists in the deeper parts of the basin, the features are not reflected in the overlying sediments.

Construction of cross sections through representative folds indicates that the Precambrian basement is involved in the deformation. The predominant trend of the folds is N40°-50°W. The orientation of the principal axis of stress to generate folds and the underlying and controlling faults in the basement of such an orientation would be in a direction S40°-50°W.

Exceptions to this anticipated orientation are the essentially east-west-trending western part of the Mud Creek fault and the North Owl Creek thrust.

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 exists along the west side of the basin (Figures 2, 3, and 4) and lies east of 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 in sec. 2, T.51N., R.100W. (T.D. 23,860 feet). The well passed through the fault zone at about 14,000 feet and bottomed in Devonian Three Forks Formation. The vertical separation on the hanging wall of this fault from the crest of the Oregon Basin fold to completion depth is about 20,000 feet.

Seismic profiles in the vicinity of Grass Creek are equally definitive as a series of deep tests drilled east of the fault (Figure 4). The deepest test - 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 on the order of 18,000 feet. The Oregon Basin fault does not reach the surface, but is unconformably overlain by the Eocene Willwood Formation.

The northern extent of the Oregon Basin fault is doubtful. One interpretation indicates that the fault changes trend to the northwest and passes east of the Shoshone-Heart Mountain fold zone

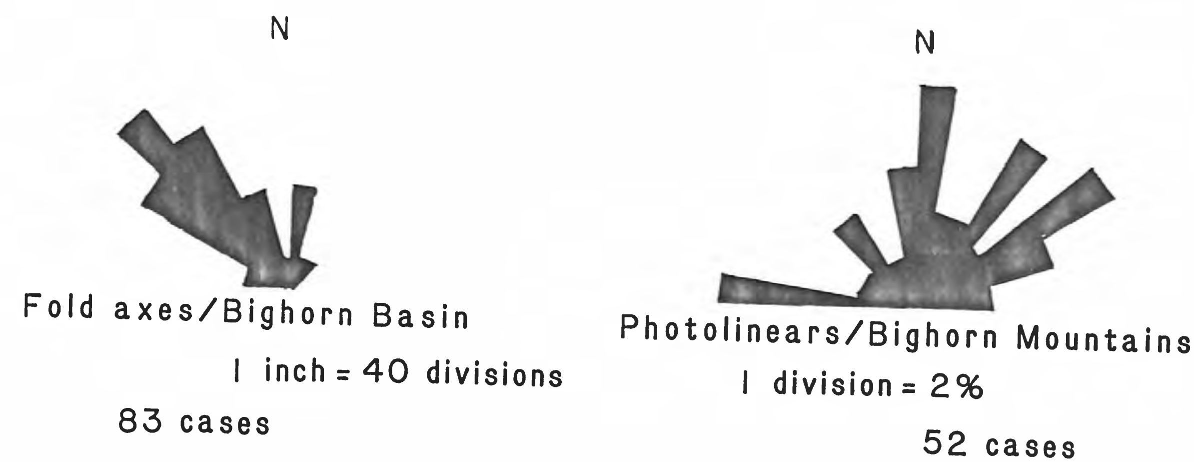

Figure 34. Rose diagram showing photolinears and fold axes, southern Bighorn Basin, Wyoming.

(Lowell, 1983), thence continues north to join the low angle thrusting along the east flank of the Beartooth Mountains (Thom, 1952; Scheevel, 1983). A second interpretation would extend the fault from Oregon Basin north to join faulting along the east flank of the Elk Basin Field (Rea and Barlow, 1975).

The writer believes the first interpretation to be more plausible on the basis of the vertical separations involved.

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 of 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), to the folds which are asymmetric to the southwest has not been definitely established.

If the Oregon Basin fault continues at depth to the west at an angle of approximately 30° $\pm$ 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 19, 20, and 22) are asymmetric to the southwest, and the Precambrian basement is displaced to the southwest on east-dipping reverse faults. The east-dipping faults which define the individual folds are interpreted to terminate at the fault plane of the Oregon Basin fault. The individual faults are in the fault plane of the Oregon Basin fault. The individual faults are in the nature of 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.

A generalized cross section by Petersen (1983) illustrates part of the problem, but the Oregon Basin fault is not recognized. A somewhat less extensive section (Figure 35) 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 somewhat discontinuous series of thrust faults exist along the southwest flank of the Washakie Range, including the Black Mountain and Caldwell Meadows thrusts. The Buffalo Fork thrust (Love, 1956) lies to the northwest and continues into Yellowstone National Park. This series of faults dips to the northeast and may be considered as the western margin of a rather wide crustal wedge, bounded on the east by the Oregon Basin fault. Unfortunately, details between the two faults are for a large part 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 "popped" up 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.

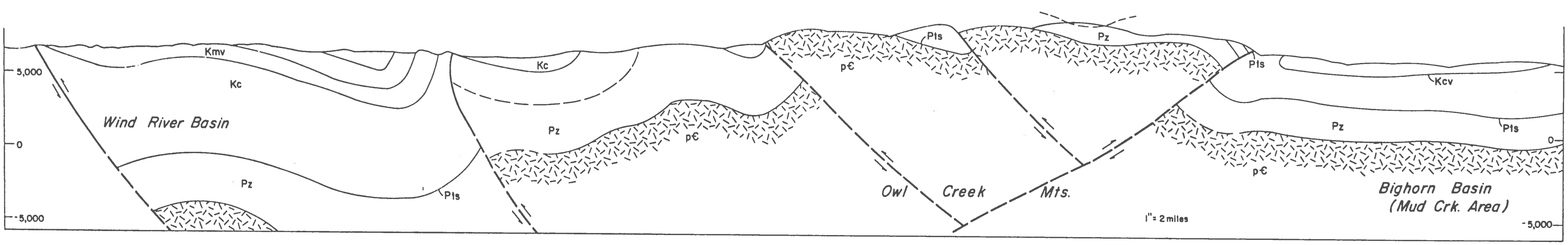

Figure 35. Structural cross section through the western Owl Creek Mountain, Bighorn Basin, Wyoming.

YOUNGER EAST-WEST-TRENDING STRUCTURES

The dominant trend of the "thrust-fold" structures in the southern Bighorn Basin is northwest (Figure 3). A few folds such as the King Dome - Thermopolis - Warm Springs complex trend essentially east-west, parallel to 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 controlled by a major thrust or thrusts which dip to the 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 Mountain 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 which developed from a regimen of nearly north-south compression during early and middle Eocene time (Gries, 1983).

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) began a train of thought relating the folding in the sedimentary cover to faulting in the basement complex. Many investigators (see references) provided new interpretations of the geometry as technology of gravity measurements, drilling, and seismic reflection surveys developed. Brown (1983) brought up-to-date ideas concerning the geometry of such structures. Paralleling the investigation of the geometry of the "thrust-fold" (Stone, 1983) concept has been 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. Among his ideas was one suggesting that the uplifts in the Yellowstone - Bighorn area were controlled by downward-wedging plutonic rock masses which responded to compressive stress as units. This type of anisotropy in the basement has been proven to be invalid. The controversy concerning the relative role of horizontal versus vertical stress as the controlling factor in the deformation emerged at about this time. 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. A listing of the investigators would be superfluous. Among them, 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 less than 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 covers, 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 which are subjected to deformation. One regional stratigraphic variation has affected the geometry and response in different locales. 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, and their effect on the geometry of folds.

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

There has been no denial that 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) exist but are secondary or incidental to primary movement at the level of the basement sedimentary interface. Since the deformation of the basement at that level is of primary importance, "first causes" must deal with the basement behavior. Scheevel (1983) presented a very logical model for the development of the foreland "thrust-folds" and points out the existence of features on at least two scales. He notes that there are structures with amplitudes of 42,000 feet and those of lesser scale (5,000 feet). The model proposes 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.

Scheevel's (1983, Figure 6) cross sections, demonstrating the development of potential faults all dipping in one direction and their propagation downward with increasing crustal shortening, leave an

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
Mud Creek - North Owl 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

unfortunate impression. Earlier, Scheevel (1983, Figure 2) presents 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 in Scheevel's Figure 6. Further, the final attitude of the fault planes will change by the development of large magnitude deformational features such as the Bighorn Basin. At such amplitudes, the original sedimentary - basement 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, dependent 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 area under consideration. 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 review of the structural geology in the southern Bighorn Basin of Wyoming has established the anisotropy which affects the movement of fluids in the Paleozoic aquifers.

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. Faults of low angle (30°+) in the basement steepen upward to a ramp or sled-runner form as they propagate upward through the sedimentary column.
4. Drastic thinning of the sedimentary section may occur on the steep limb of large folds. Mesozoic shale sections are particularly susceptible.
5. Reversal of asymmetry creates wedge shaped crustal segments on several scales.
6. Detachment structures occur locally, but are controlled by primary movement of faults at the basement level.
7. The displacement on faults creates anisotropy sufficient to completely disrupt the continuity of the Paleozoic aquifers at many localities.

ACKNOWLEDGMENTS

The writer gratefully acknowledges the support of the Department of Geology and Geophysics of the University of Wyoming for office space, library facilities, secretarial help, and drafting. The Geological Survey of Wyoming and the Wyoming Oil and Gas Conservation Commission have supplied maps, well logs, advice, and drafting service. Numerous companies engaged in both exploration and production of hydrocarbons in this area have provided data which has aided greatly in the research. Previous mapping, particularly by personnel of the U.S. Geological Survey, provided invaluable aid. Discussion with colleagues and friends provided the criticism that is necessary to test ideas. I am particularly indebted to Peter Huntoon, Henry Heasler, Robert Houston, Don Stone, Kent Sundell, William H. Wilson, Bayard Rea, J.R. Fanshawe, Robert Berg, and James Lowell for such discussions.

The writer is solely responsible for the conclusions reached.

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APPENDIX A
STRATIGRAPHIC COLUMN

Era	Period/Epoch	Formations
Cenozoic	Eocene	Willwood Formation (Absaroka volcanics are volcanic equivalents)
	Paleocene	Fort Union Formation
Mesozoic	Cretaceous	Lance Formation Meeteetse Formation Mesaverde Formation Cody Shale Frontier Formation Mowry Shale Greybull (Muddy) Sandstone Cloverly Formation
	Jurassic	Morrison Formation Sundance Formation Gypsum Spring Formation
	Triassic	Chugwater Formation Dinwoody Formation
Paleozoic	Permian	Phosphoria Formation
	Pennsylvanian	Tensleep Sandstone
	Pennsylvanian-Mississippian	Amsden Formation
	Mississippian	Darwin Sandstone Madison Limestone
	Devonian	Three Forks - Jefferson Formation (?)
	Ordovician	Bighorn Dolomite
	Cambrian	Gallatin Formation Gros Ventre shale Flathead quartzite
	Precambrian	Gneiss, schist, and granite

FIGURE 4. STRUCTURE CONTOUR MAP OF THE TOP OF THE PENNSYLVANIAN TENSLEEP SANDSTONE, SOUTHERN BIGHORN BASIN, WYOMING

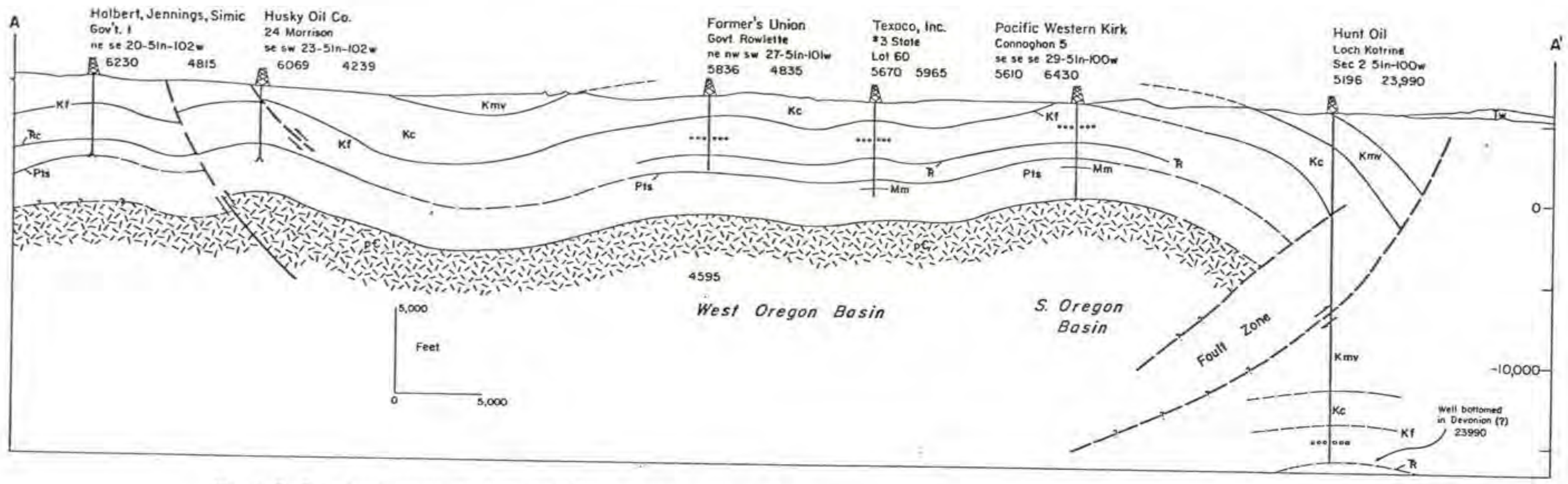

Figure 5. Structural cross section A-A' to accompany Figure 4.

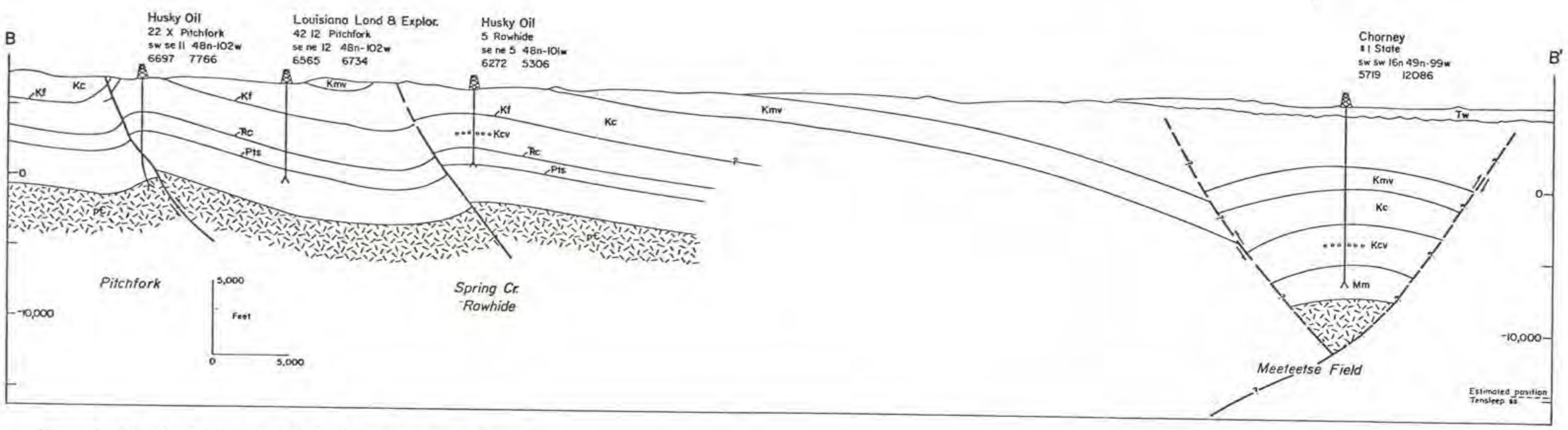

Figure 6. Structural cross section B-B' to accompany Figure 4.

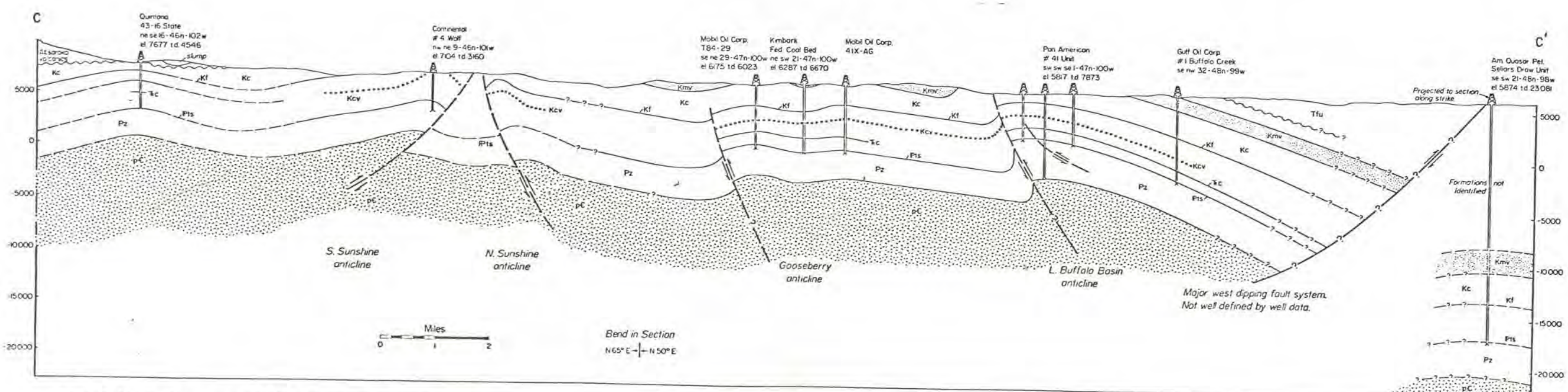

Figure 7. Structural cross section C-C' to accompany Figure 4.

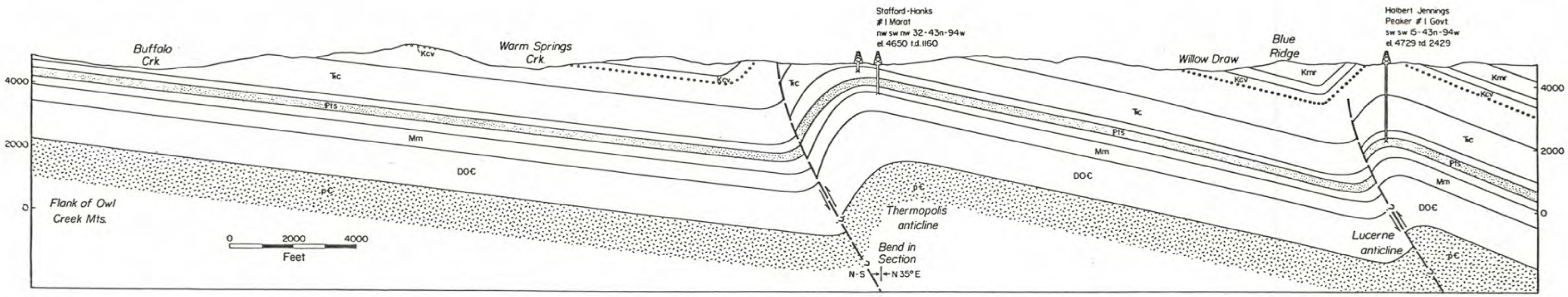

Figure 31. Structural cross section through the Thermopolis anticline, Bighorn Basin, Wyoming.

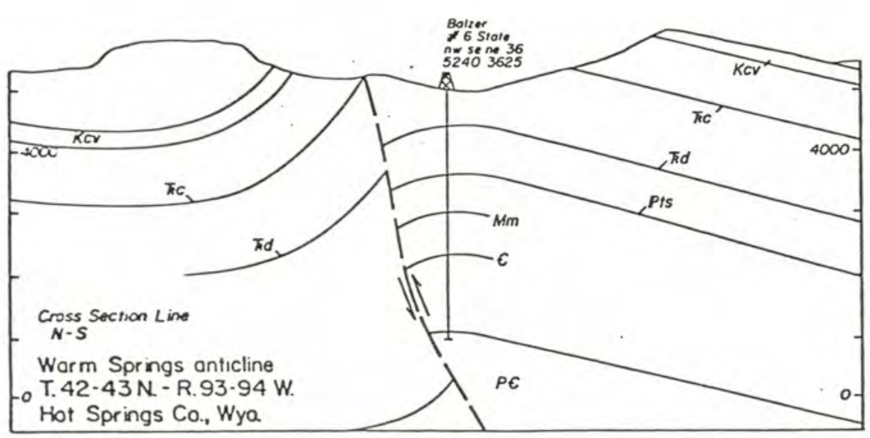

Figure 32. Structural cross section through the Warm springs anticline, Bighorn Basin, Wyoming.

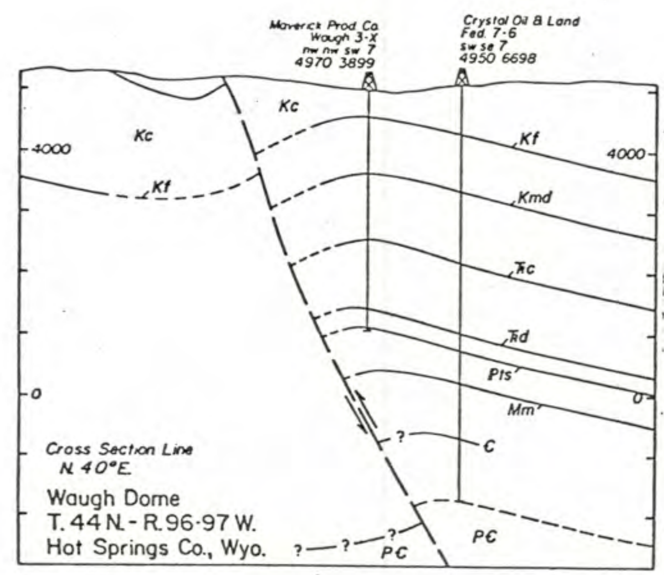

Figure 33. Structural cross section through the Waugh Dome, Bighorn Basin, Wyoming.

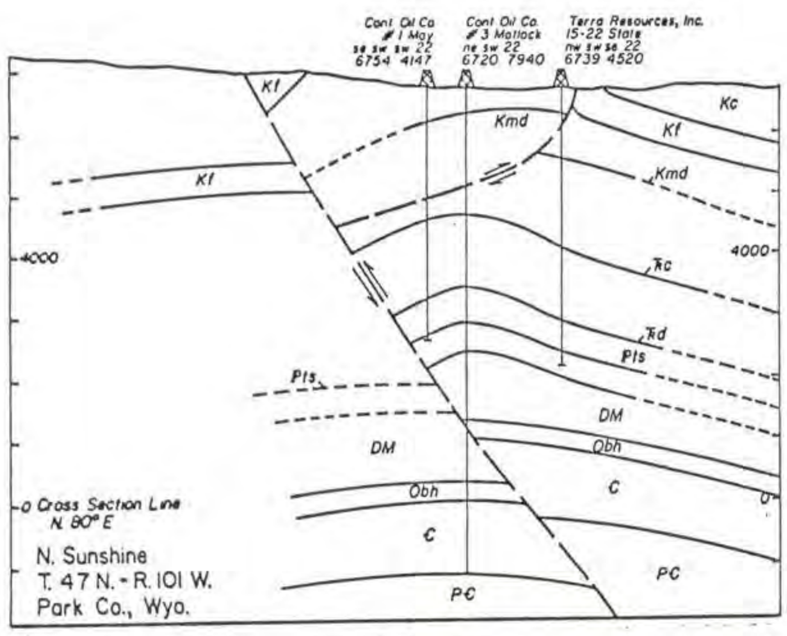

Figure 25. Structural cross section through the North Sunshine Field Bighorn Basin, Wyoming.

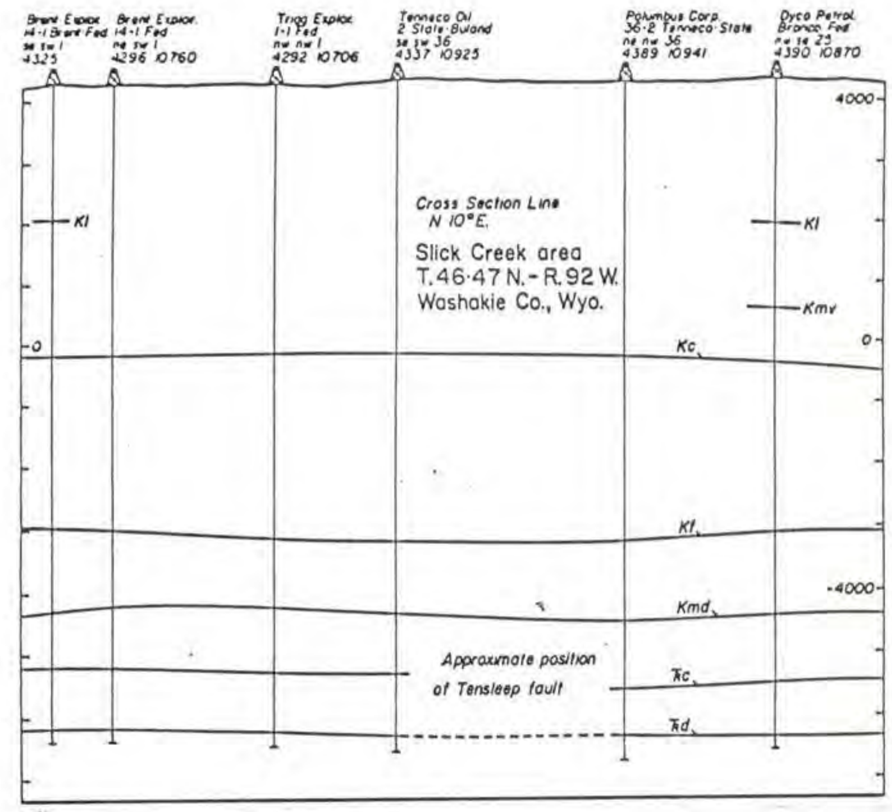

Figure 28. Structural cross section through the Slick Creek Field, Bighorn Basin, Wyoming.

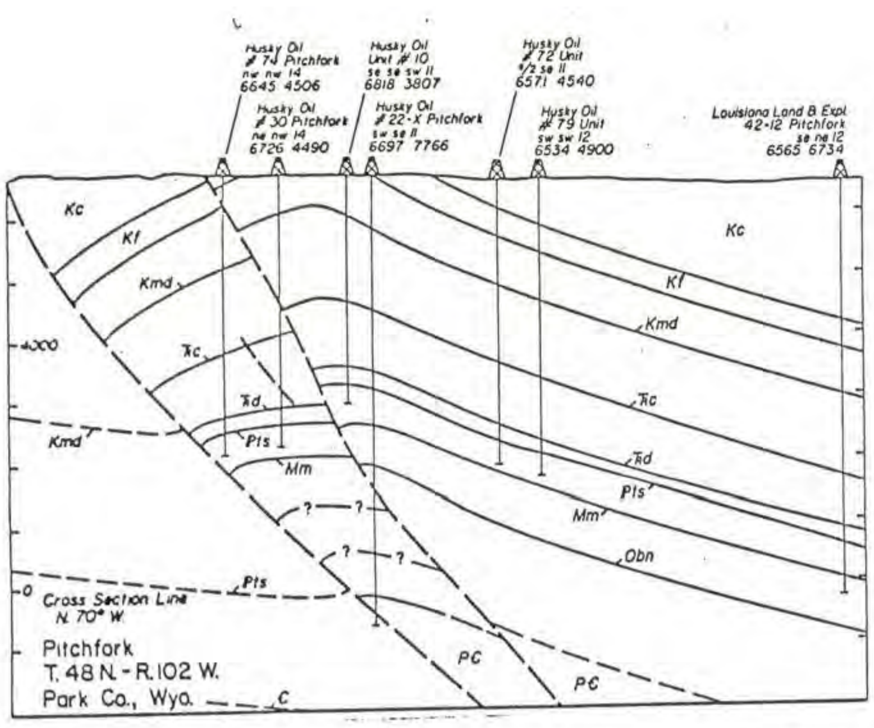

Figure 26. Structural cross section through the Pitchfork Field, Bighorn Basin, Wyoming.

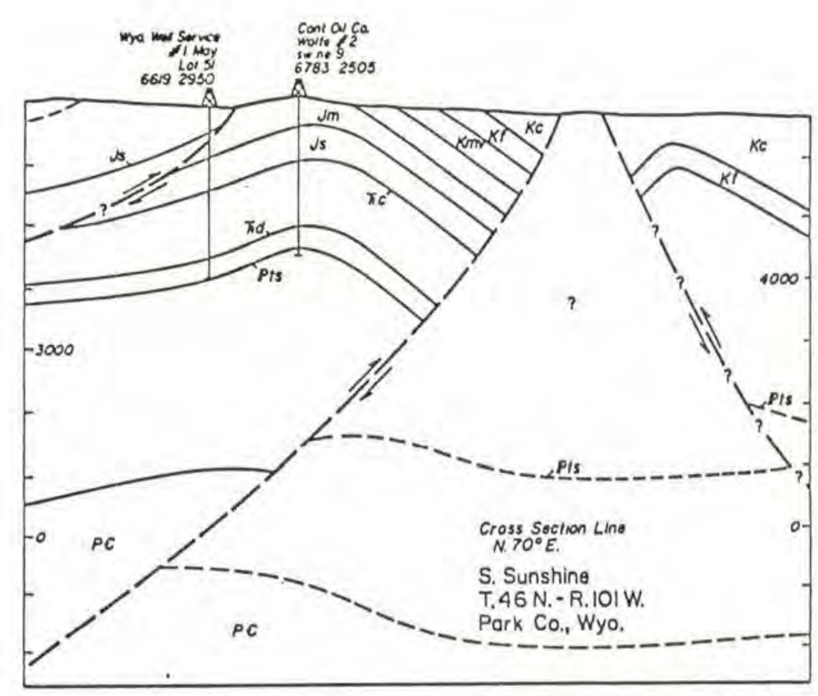

Figure 29. Structural cross section through the South Sunshine Field, Bighorn Basin, Wyoming.

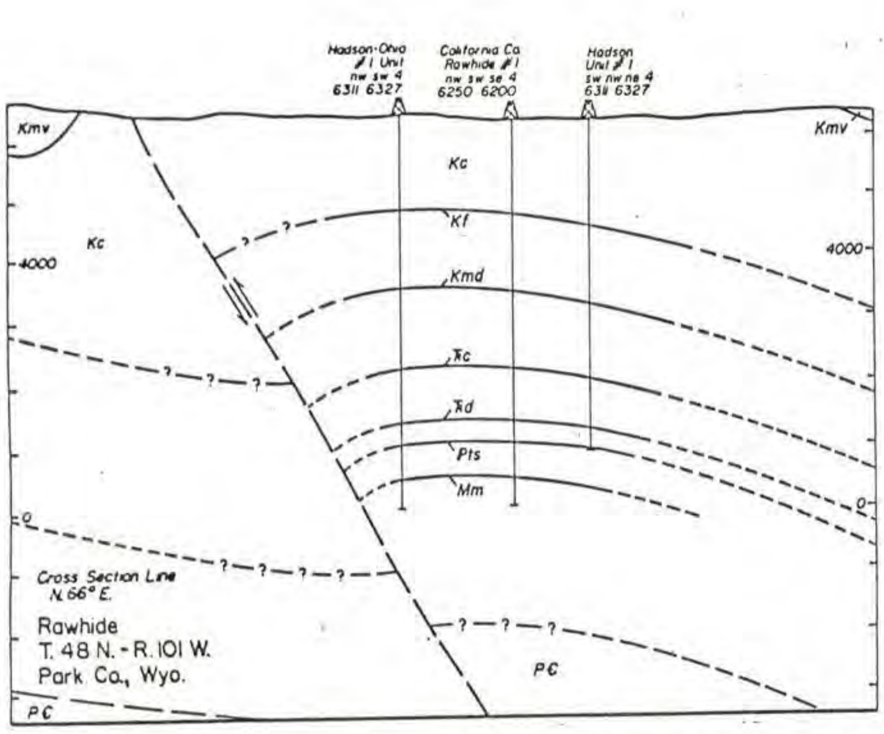

Figure 27. Structural cross section through the Rawhide anticline, Bighorn Basin, Wyoming.

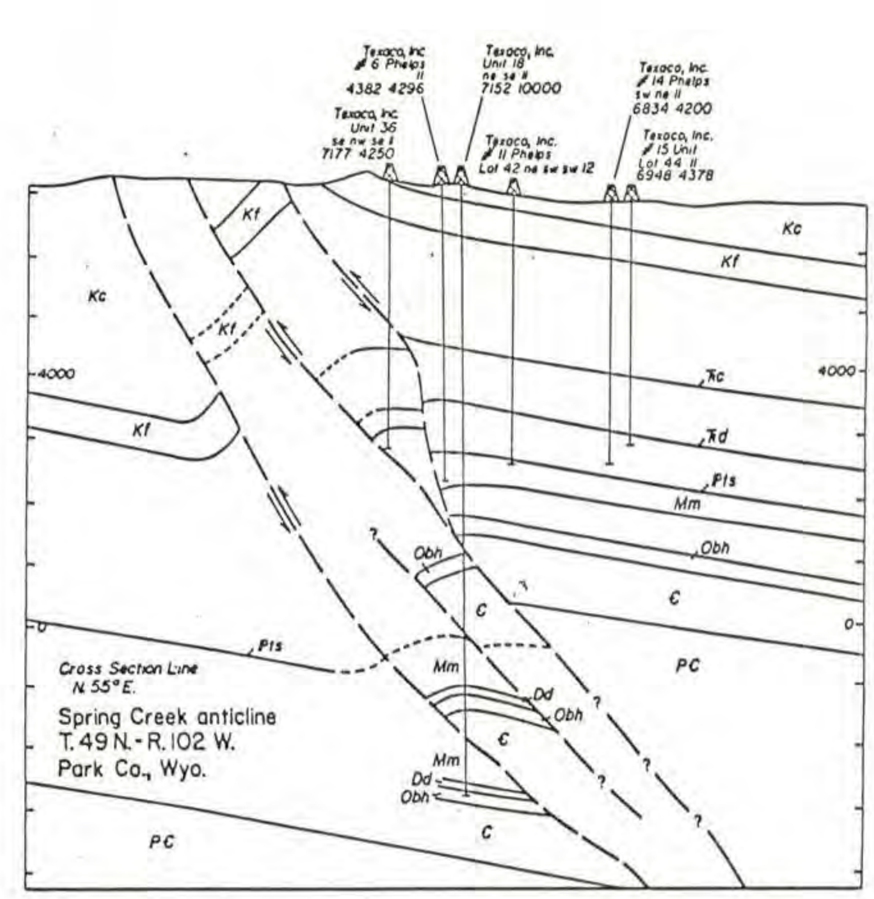

Figure 30. Structural cross section through the Spring Creek Field, Bighorn Basin, Wyoming.

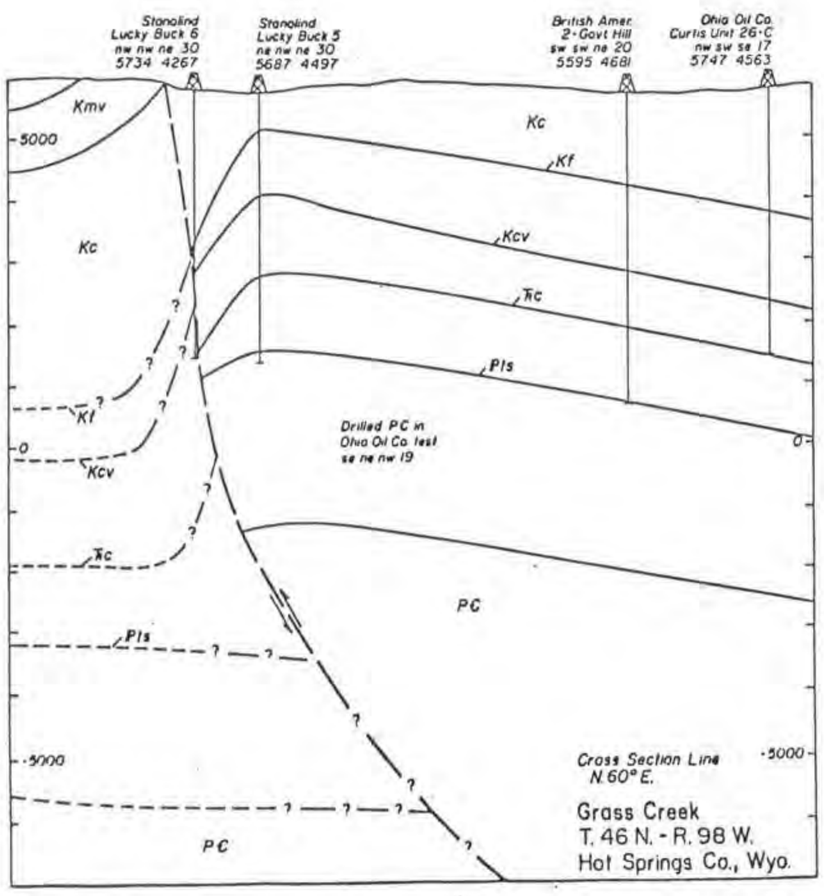

Figure 19. Structural cross section through the Grass Creek Field, Bighorn Basin, Wyoming.

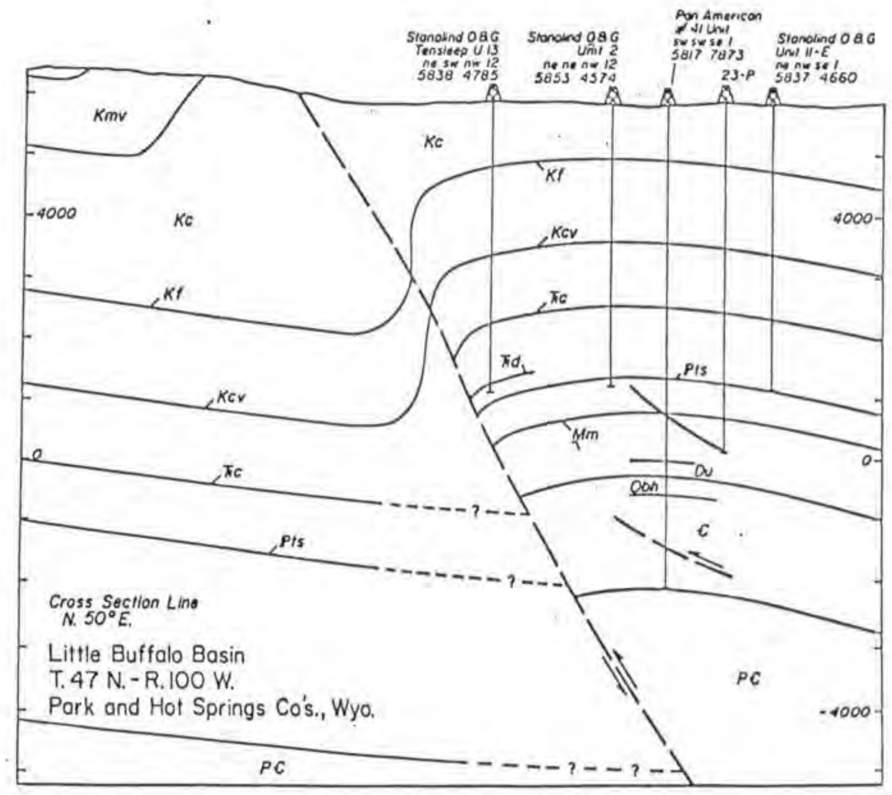

Figure 22. Structural cross section through the Little Buffalo Basin, Bighorn Basin, Wyoming.

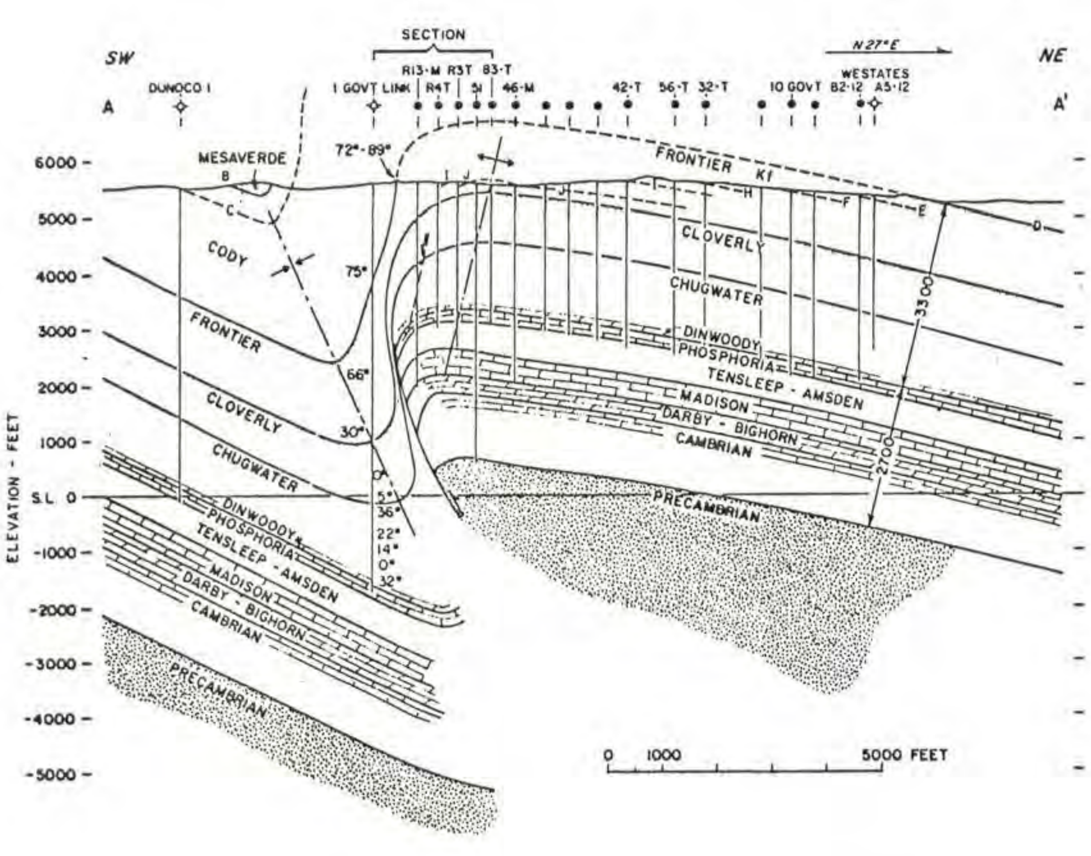

Figure 20. Structural cross section through the Hamilton Dome, Bighorn Basin, Wyoming (from Berg, 1976, Figure 3).

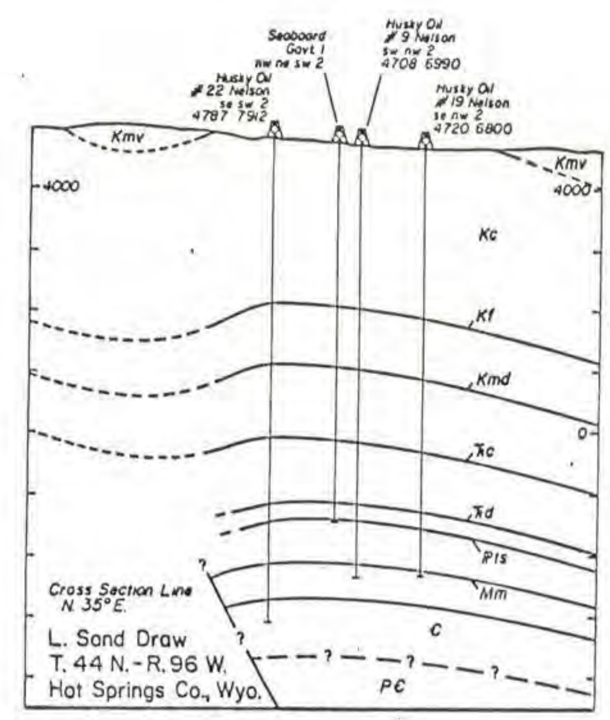

Figure 23. Structural cross section through the Little Sand Draw Field, Bighorn Basin, Wyoming.

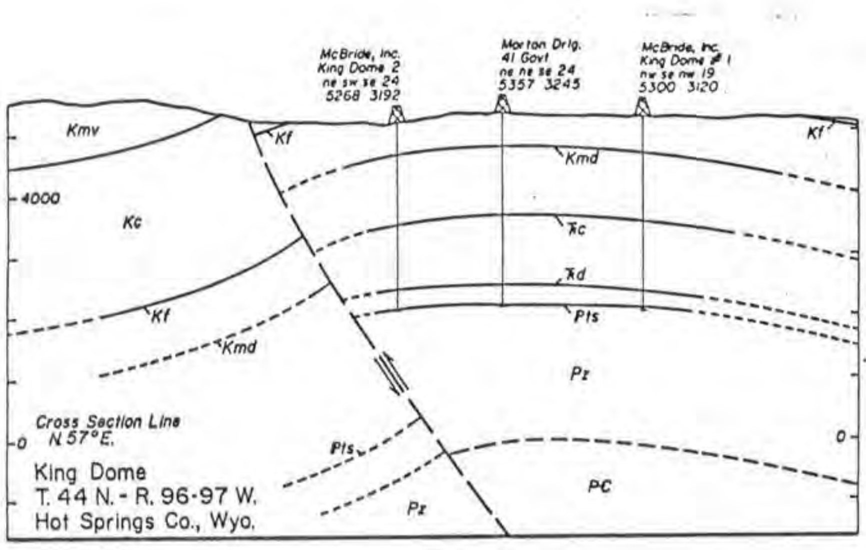

Figure 21. Structural cross section through the King Dome, Bighorn Basin, Wyoming.

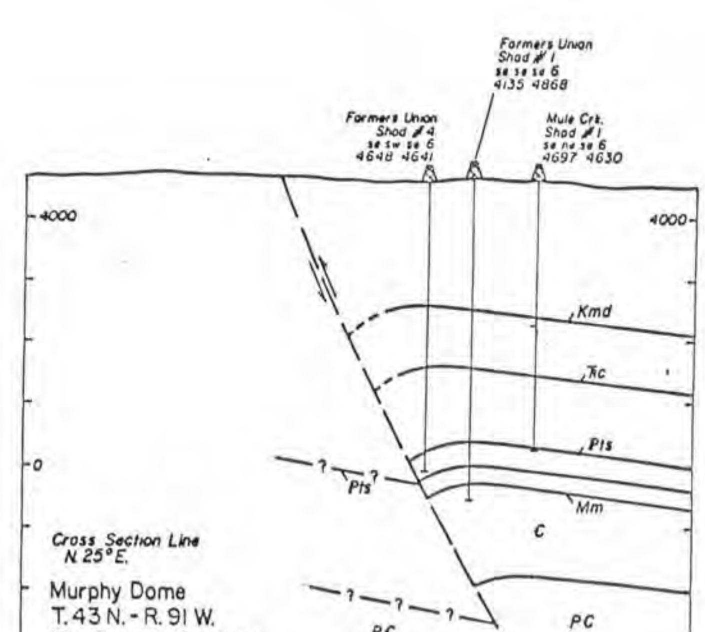

Figure 24. Structural cross section through the Murphy Dome, Bighorn Basin, Wyoming.

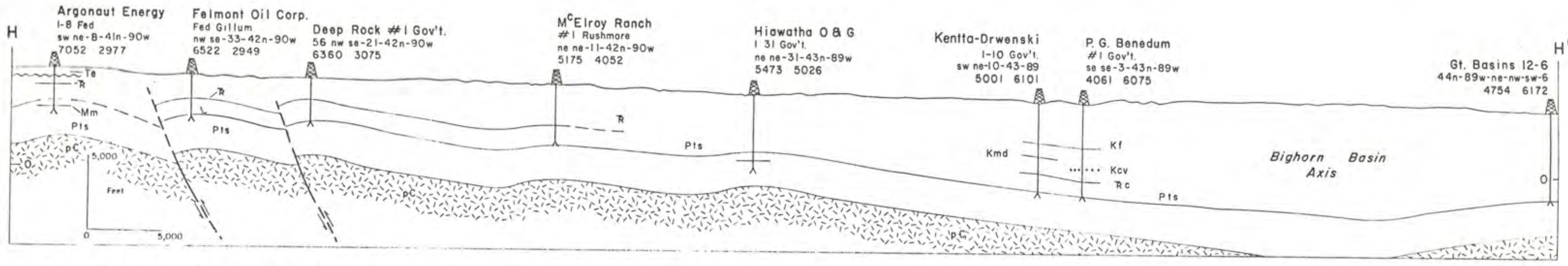

Figure 12. Structural cross section H-H' to accompany Figure 4.

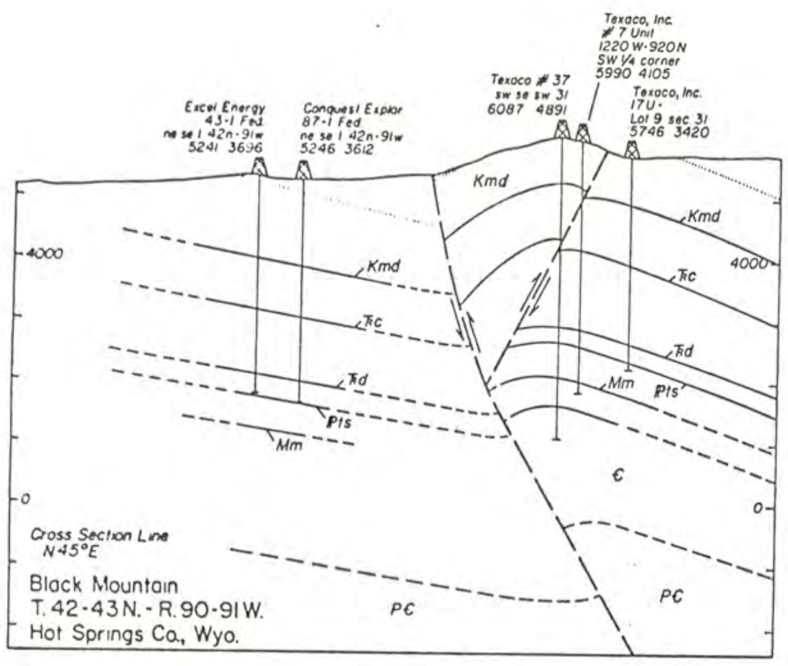

Figure 13. Structural cross section through the Black Mountain Field, Bighorn Basin, Wyoming.

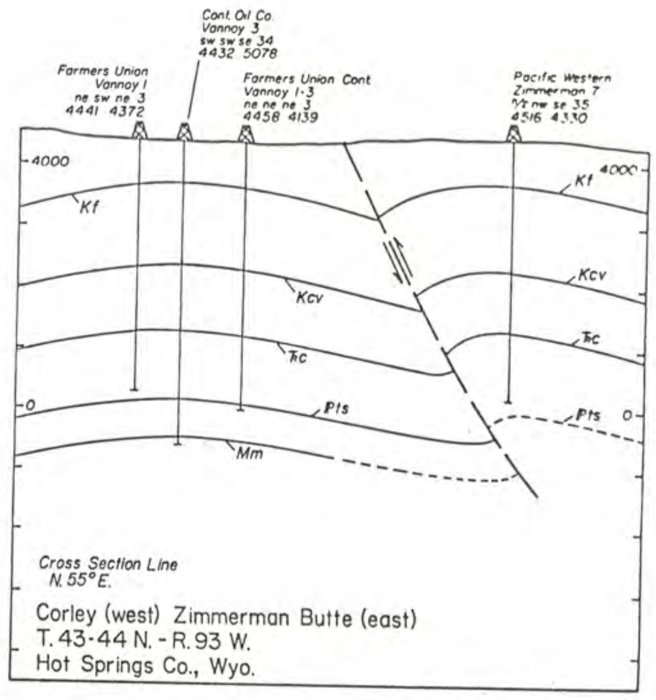

Figure 16. Structural cross section through the Corley-Zimmerman Butte folds, Bighorn Basin, Wyoming.

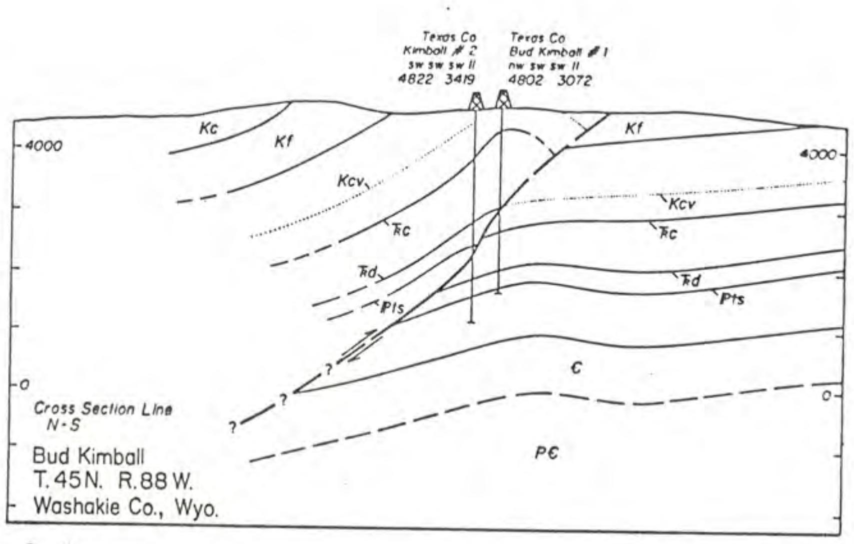

Figure 14. Structural cross section through the Bud Kimball anticline. Bighorn Basin, Wyoming.

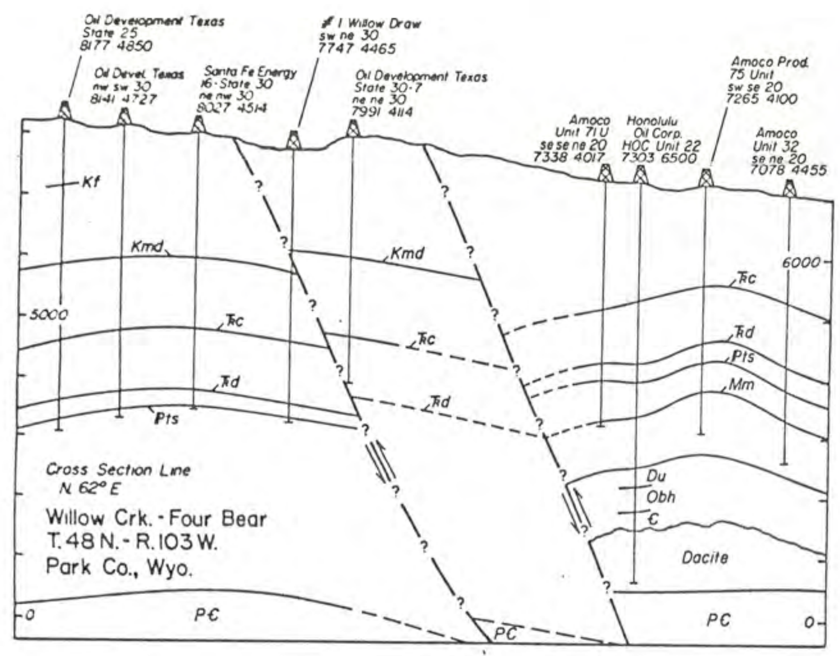

Figure 17. Structural cross section through the Willow Creek-Four Bear Field, Bighorn Basin, Wyoming.

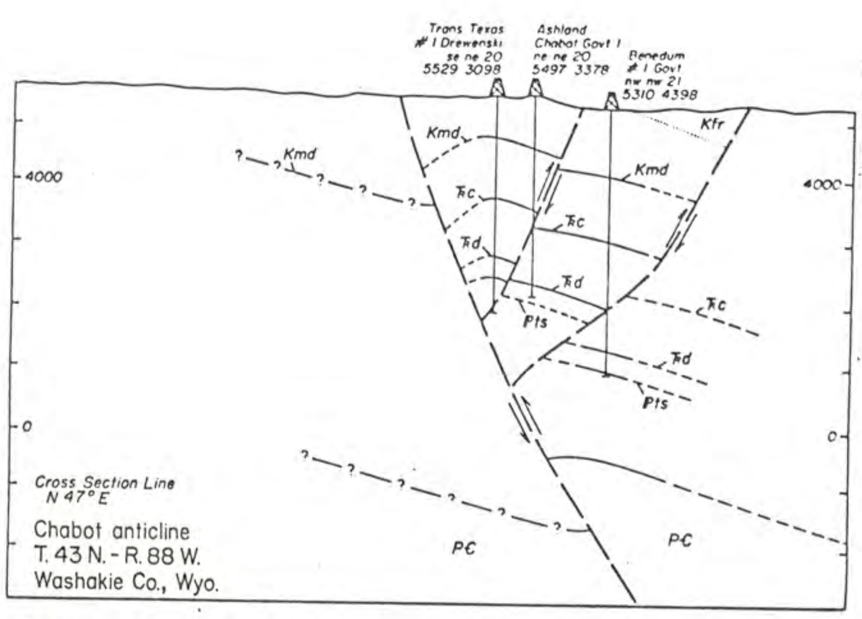

Figure 15. Structural cross section through the Chabot anticline, Bighorn Basin, Wyoming.

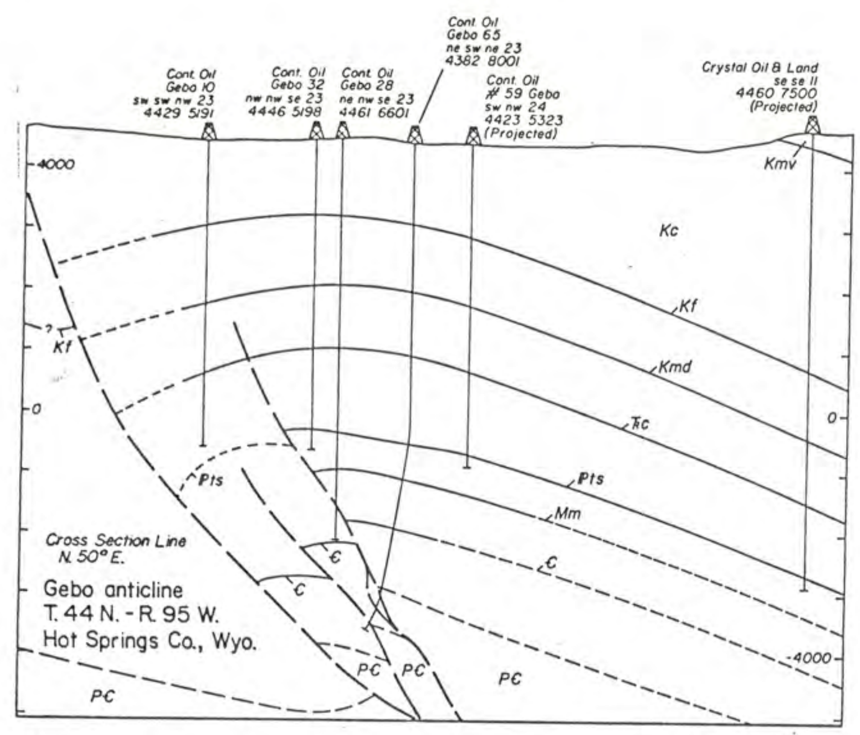

Figure 18. Structural cross section through the Gebo anticline, Bighorn Basin, Wyoming.

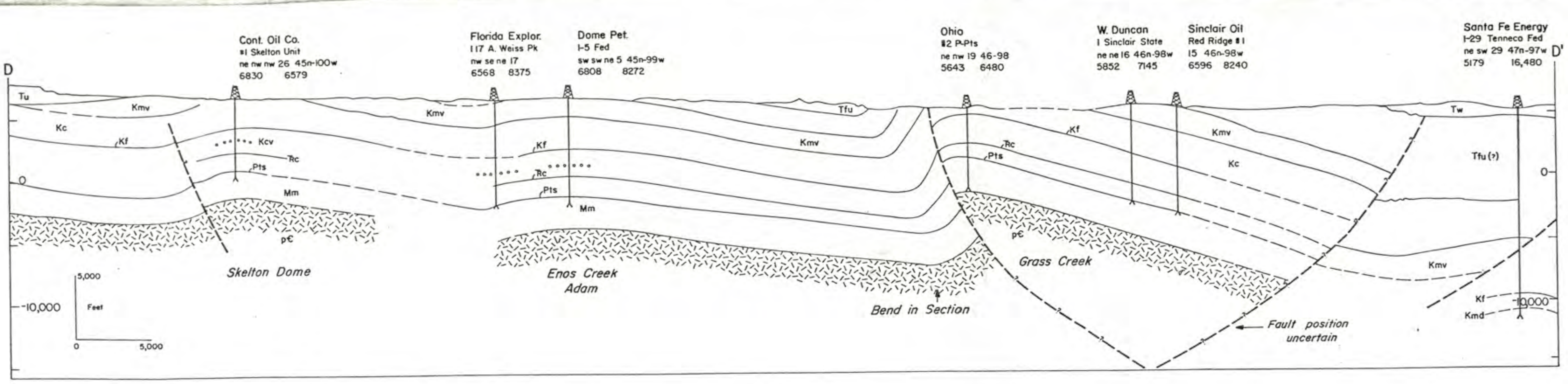

Figure 8. Structural cross section D-D' to accompany Figure 4.

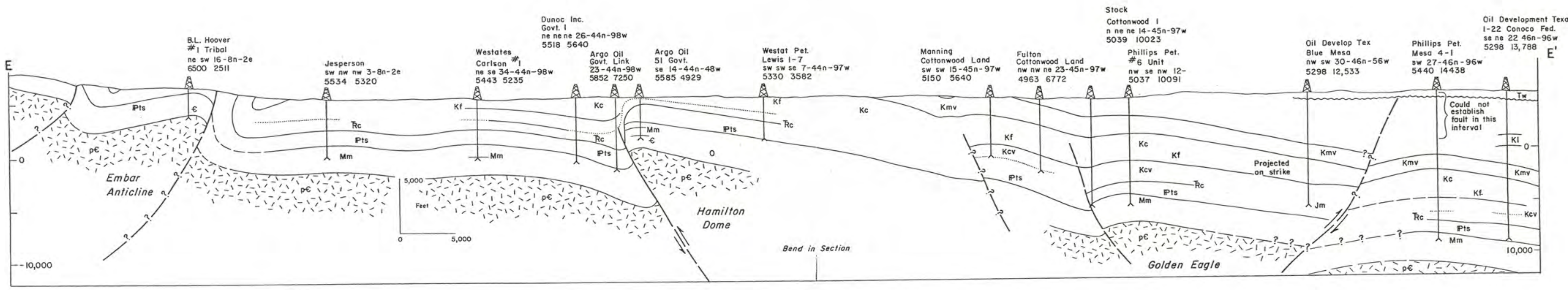

Figure 9. Structural cross section E-E' to accompany Figure 4.

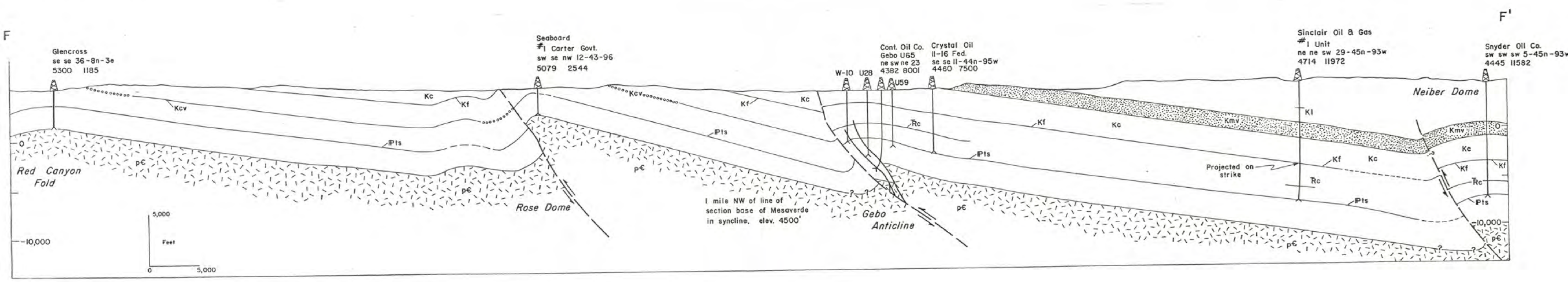

Figure 10. Structural cross section F-F' to accompany Figure 4.

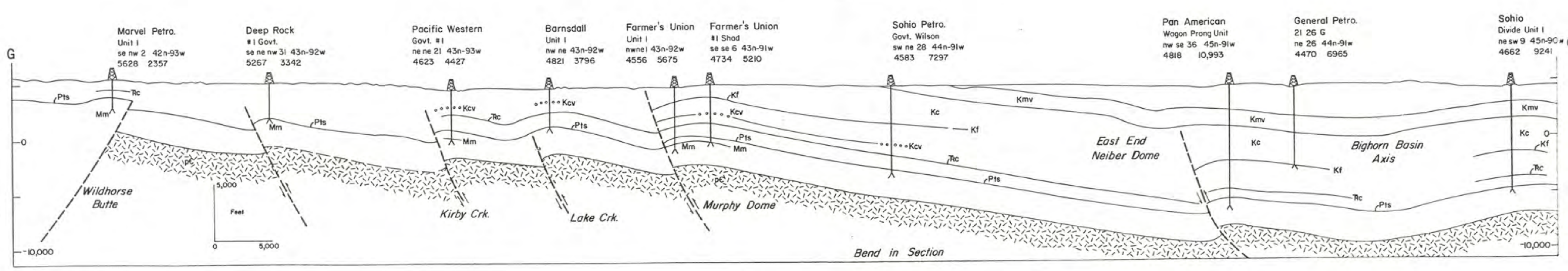

Figure 11. Structural cross section G-G' to accompany Figure 4.