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TECTONIC STRUCTURES RESPONSIBLE FOR ANISOTROPIC TRANSMISSIVITIES IN THE PALEOZOIC AQUIFERS SOUTHERN BIGHORN BASIN, WYOMING

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HYDROGEOLOGIC OVERVIEW

Peter Huntoon

Active ground water circulation as we understand it today did not begin through the major Paleozoic aquifers in the Bighorn Basin until after the Laramide orogeny. The reason for this is that the Bighorn Basin did not exist until after this tectonic event. Let us first define the principal Paleozoic aquifers, and next consider briefly the tectonic events which produced the basin framework with which we are concerned. It will become evident that the tectonic structures - faults and folds - imprinted zones of enhanced fracture permeability in various locations, whereas in other locations the structures produced barriers to flow. Obviously, the first step in characterizing ground water circulation in the Bighorn Basin is that of defining the geologic framework in which the water circulates. A primary component in this task is to locate the tectonic structures, and deduce their local impact on circulation. This step is the goal of this report.

DEFINITION OF THE PALEOZOIC AQUIFERS

The principal aquifers in the Paleozoic section in the southern part of the Bighorn Basin are defined on Table I. Of particular interest is the carbonate sequence that when saturated comprises the Madison aquifer.

The rocks comprising the Paleozoic aquifers were deposited in a widespread shelf environment in which the basement was gradually subsiding. The result was a layered succession of various lithologies that had remarkable lateral continuity. Regional deposition continued into upper Cretaceous time, culminating with a sedimentary succession that was approximately 12,000 feet thick in the Bighorn Basin. The Paleozoic rocks of interest to this investigation occupied the lower quarter of this pile. Most of the overburden consisted of shales which have proven to be exceptionally effective regional confining layers.

The Madison aquifer in unfractured regions includes from the bottom up, the Bighorn, Jefferson, and Madison limestones (Table I). These units are vertically interconnected by joints and in some locations by solution enlarged fractures. The upper and lower surfaces of the aquifer are confining shales which are demonstrably effective because they localize springs throughout the basin. Additional evidence that the Madison aquifer is confined both from the overlying Tensleep and underlying Flathead aquifers are the substantial head differences which develop between the aquifers. Data obtained from drill stem tests support this conclusion. In contrast, tests within different intervals in the Madison aquifer yield similar heads.

On a regional scale, the definition for the Madison aquifer shown on Table 1 is valid only for the unfaulted parts of the basin. As the Madision aquifer is traced from the outcrop areas into the Bighorn Basin, the vertical character of the flow system becomes complex due to the presence of anticlines. The fracturing associated with the anticlines has propogated upward through the Paleozoic section and in places into the Mesozoic rocks, thus destroying the hydraulic integrity of the confining layers listed on Table I. Using head data and fluid chemistry, Stone (1967) has demonstrated that water and petroleum circulate vertically to overlying units along these anticlines through zones of fracture enhanced permeability.

BIGHORN BASIN CIRCULATION SYSTEM

The Laramide orogeny produced the major mountain and basin elements that now comprise the Wyoming foreland geographic province, and also coincided with a major episode of regional uplift that has continued to the present. The magnitude of deformation can be appreciated when one considers that there is six miles of vertical displacement between the reconstructed position of the rocks comprising the Madison aquifer along the crest of the Bighorn Range and identical rocks in the center of the Bighorn Basin. As the mountains gained elevation, they shed considerable volumes of eroding sediments into the deepening basins therby adding thousands of feet of additional confining layers onto the Mesozoic pile already in place. Gradually through Cenozoic time both the mountains and basins have been elevated thousands of feet. Even so, the present base of the Paleozoic section in the Bighorn Basin remains as much as two miles below sea level.

The hydrologic significance of the Laramide deformation is three fold. (1) The uplift of the region was accompanied by extensive erosion which in places stripped as much as 12,000 feet of Paleozoic and Mesozoic rocks from the sedimentary pile and in turn exposed the upturned edges of the Paleozoic aquifers along the mountain flanks. (2) The deformation imprinted a structural fabric on the Paleozoic aquifers that locally enhanced permeabilities. (3) The combination of great structural relief and differential depths of erosion along the flanks and interiors of the basins provided for development of steep hydraulic gradients within the Paleozoic aquifers.

In a simplistic view, circulation of water through the Paleozoic aquifers has been from the upturned exposed sediments along the flanks of the range toward springs localized along fault zones (Thermopolis Hot Springs) or to erosionally dissected parts of the aquifers (Sheep Mountain Anticline Springs) in the basin interiors. Basin permeability characteristics have changed during Cenozoic time. Permeabilities in the aquifer in the recharge areas have been enhanced through the processes of dissolution of cements and matrix from the rocks. Conversely the permeabilities of the same rocks in the basins have tended to decrease through cementation, compaction, and recrystallization. The result has been the development of large permeability contrasts between the basin margins and the basin interiors during late Cenozoic time.

Petroleum has accumulated in combination stratigraphic-structural-hydrodynamic traps. The cap rocks for the oil traps in the section also serve as the upper confining units for the various Paleozoic aquifers, thus part of the ground water that discharges from the principal springs in the interior parts of the Bighorn Basin has actually flowed under existing oil accumulations. This circulation partially accounts for the poor water qualities associated with the waters. The depths that the water reached between the recharge areas and springs allowed for geothermal heating of the water as well. The nature of the Bighorn Basin ground water circulation system is one and the same as the fluid system of great concern to the petroleum geologist!

GRADIENTS AND ANISOTROPIC TRANSMISSIVITIES

Potentiometric data for the Bighorn Basin is derived from data gathered in producing oil fields and supplemented by drill stem tests in exploration wells and spring elevations. Regional potentiometric maps reveal two startling facts. (1) The gradients in the interior and northwestern parts of the basin are virtually flat. (2) Gradients in the southern and eastern parts of the basin are unusually flat in directions parallel to the strikes of the numerous northwest trending anticlines that dominate the tectonic fabric of that part of the basin. Among the many possible explanations, two hypotheses have gained credence for explaining these phenomena.

The minescule gradients associated with the central and northwestern parts of the basin, despite proximity to recharge areas, result from fault severing of the Paleozoic aquifers along the major Oregon Basin thrust fault. The fault isolates the basin interior from the recharge areas to the south and west, thus minimizing circulation.

The gentle slope of the potentiometric surface associated with the northwestern strikes of the anticlines in the southern part of the basin reveals extreme anisotropy in transmissivities wherein the maximum principal transmissivity tensors are oriented roughly parallel to the strikes of the axes of the anticlines. Two facts explain this occurrence. The anticlines are fault controlled, and commonly the magnitudes of displacements across the faults are sufficient to displace the Paleozoic aquifers against impermeable rocks, therby preventing flow perpendicular to the strikes of the anticlines. Secondly the extensional fractures associated with folding of the anticlines have produced fracture permeability favoring flow parallel to the axes.

CONTRIBUTION PROVIDED BY THIS STUDY

A provocative analysis of ground water circulation through the Bighorn Basin requires careful consideration of the effect of major and minor tectonic structures. Such an analysis reveals directly those parts of the basin in which recharge areas are severed from the basin interior by large displacement thrust faults, and those parts of the basin which contain anticlines that favor ground water flow parallel to the fold axes. The report that follows documents the tectonic framework. It comprises the first, and single most important step, in characterizing fluid flow - both water and petroleum - in the Bighorn Basin. Original insights that have emerged from this research include documentation of the extent of the Oregon Basin thrust fault which effectively divides ground water circulation in the Bighorn Basin into two parts, (1) a northern stagnate system in the footwall block and (2) a southern active system in the hanging wall block. Numerous anticlines in the hanging wall block provide permeable conduits for ground water circulating from the Absaroka, Owl Creek, and Bighorn mountain recharge areas toward the thermal springs at Thermopolis. These same anticlines provide the structural traps for major petroleum reserves in the basin.

Delineation of the structural framework of the ground water system as provided here allows us to qualitatively characterize permeability distributions within the various structural domains in the basin, identify discontinuities within the potentiometric surfaces in the basin, better predict the directions of ground water flow between recharge areas and springs, and deduce regions that should sustain head declines as a result of petroleum fluid production.

FORELAND COMPRESSIONAL TECTONICS: SOUTHERN BIGHORN BASIN, WYOMING

D.L. Blackstone, Jr.

ABSTRACT

Movement of groundwater 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 (3657 m) thick of which approximately 2200 feet (670 m) 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 ranging from 500 to 5000 feet (150 - 1500 m.) 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 propogate 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.

NOTE

The explanation for formation symbols used on the cross sections that accompany this report appears on Table III.

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 Lewis and Clark line (Montana lineament); on the east by the Pryor Mountain - 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 which 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 (Fig. 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 ft.

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 on the south margin of the ranges known as the Owl Creek Thrust (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 (Fig. 3). 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 range from small areas of a few hundred square feet to others covering square miles but have 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 N 15° 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 Mountain 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 Tensleep townsite (Fig. 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 (Fig. 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 (Fig. 3). The fault was penetrated in the Hunt No. 1 Loch Katrine test sec. 2, T. 51 N., R. 100 W., 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 stippled pattern on Figure 3 to accenuate 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 (Fig. 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 N. Owl Creek and as the Mud Creek fault.

Faults of opposite dip but similar 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 Co. #1 Gov't at Goose Lake in sec. 9, T. 42 N., R. 106 W..

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 fault. 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 (1971) Stearns 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 non-marine 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 II. Regional cross sections designed to accompany Figure 4 and provide an overview of the structural style appear here as Figures 5-12 .

Cross sections of representative folds were constructed where drilling provides 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 indeterminate 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 secondarys plays, some back thrusting, and out of the syncline thrusts.

Variation in Tectonic Style as Seen in Cross Sections.

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 basement interface. Unfortunately all sources of data are not available for the same site; are proprietary; or 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 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. Lowell (1983), Stone (1984), Gries (1983) and Clements (1977) have demonstrated from seismic data footwall relationships of faulted anticlines involving the Precambrian basement. Petersen (1983) advocates suggest detachment faulting as a mechanism for certain anticlinal features.

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

SPECIFIC EXAMPLES OF FOLD GEOMETRY

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

Black Mountain anticline (Fig. 13)

T.'s 42 & 43 N., R.'s 90 & 91 W. Trends N. 60° W. Sharp surface reversal, steep limb on the southwest. The fold is ruptured by a steep, northeast dipping reverse fault. Cambrian rocks have been penetrated by drill 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 approximataely 1200 feet.

Bud Kimball anticline (Fig. 14)

T. 45 N. - R. 88 W. Fold trends N. 50° 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 (Fig. 15)

T.'s 42 & 43 N., R.'s 87 & 88 W. Trends N. 50° W.; asymmetric to the southwest with Cambrian strata exposed in the core in sec. 35, T. 43 N., R. 88 W. on Nowood Creek.

The fold is sharply asymmetric to the southwest in area of Cambrian exposures. To maintain bed length balance a fault in the basement is essential. Down plunge drilling on the fold 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 accomodated in the Cambrian shale section (1200 feet plus in thickness).

Corley-Zimmerman Butte anticline (Fig. 16)

T.'s 43-44 N., R.'s 92-93 W. Paired folds trending N. 60° W, Corley to the southwest. Cody shale at 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 (Fig. 17)

T. 48 N., R.'s 103-104 W. Folds trend N. 40° to 45° W. Folds separated by northeast dipping reverse faults. Four Bear drilled to the Cambrian and then into 1000 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 (Fig. 18)

T. 44 N., R. 95 W. Trends N. 60° 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 Co., Gebo Unit #28, se sec. 23, T. 44 N., R. 95 W. 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 2500 feet in thickness). Seismic profiles confirm the northeast dip of the fault plane. Displacement on the basement is approximately 2500 feet.

Grass Creek anticline (Fig. 19)

T. 46 N., R.'s 98 & 99 W. Arcuate in trend; varying from N. 20° W. at north to N. 60° S. at the south end. The structure drilled to Precambrian basement, and the producing area is well defined by over 500 wells. Offset of the basement is constrained by 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 ne 30 T. 46 N., R. 98 W. and Lucky Buck No. 6 nw nw ne 30 T. 46 N., R. 98 W. The omission of beds in Lucky Buck No. 6 (1400 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 (Fig. 7B, 1984) and offset is approximately 4500 feet.

Hamilton Dome (Fig. 20)

T. 44 N., R.'s 97-98 W. Fold trends N. 70° W. Berg (1976) gives an excellent review of this fold documenting the situation wherein basement faulting is modified in the upward propagation. The displacement at the level of the basement is about 6000 feet, but is accomodated 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 (Fig. 21)

The surface fold as exposed in the Cretaceous shales is broad, smooth with low dips. No faults were encounterd 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 Maseverde Formation, leaving no room for 3000 feet of Upper Cretaceous marine Cody Shale. The north dipping reverse fault allows for approximately 2500 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 (Fig. 22)

T. 47 N., R. 100 W. Major fold arcuate in plan view ranging from N. 30° W. to N. 55° W. Cody shale at the surface. Drilled to the Precambrian basement. Vertical separation at top of the basement approximately 3000 feet. Thinning in the Cretaceous section probably similar to that at Hamilton Dome. Major fault dips to the northeast.

Little Sand Draw anticline (Fig. 23)

T. 49 N., R. 96 W. Fold trends N. 50° 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 9000 feet above the basement demands that the fold tighten with depth if concentric folding continues to depth.

Murphy Dome (Fig. 24)

T. 43-44 N., R.'s 91-92 W. Fold trends N. 60° 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 (Fig. 25)

T. 47 N., R. 101 W. Fold trends N. 10° Surface fold is asymmetric to the east with steep (60°-70°) dips in the Frontier Formation and 30°+ dips in the same formation on the west limb. Drilled to 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 (Fig. 26)

T. 43-44 N., R. 102 W. Fold has arcuate trend ranging from N - S to N. 30° W. (south end). Mowry shale exposed in 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 approximately 3500 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 (Fig. 27)

T. 48 N., R. 101 W. Fold trends N. 50° 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 2000 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 (Fig. 28)

T. 47 N., R. 92 W. 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 (Fig. 29)

T. 46 N., R. 101 W. Fold trends N. 30° W. Jurassic Morrison Formation exposed at surface. Surface fold 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 (Fig. 30)

T. 47 N., R. 102 W. Fold trends N. 45° W. Mowry Shale exposed at the surface in sharp fold asymmetric to the southwest. Drilled to the Cambrian passing through two reverse faults repeating the Madison limestone three times. Major fold is controlled by northeast dipping reverse faults. Vertical separation of basement approximately 4000 feet.

Thermopolis anticline (Fig. 31)

T.'s 43 & 44 N., R.'s 93 through 97 W. Trends east-west in eastern section and changes to N. 55° to 60° W. in the western section. All folds asymmetric to south or southwest. Tested to the Precambrian basement at two sites.

Warm Springs anticline (Fig. 32)

T's 42 and 43 N., R.'s 93 and 94 W. Surface fold trends E.W. Triassic Chugwater exposed in core. Basement offset approximately 1000 feet.

Waugh Dome (Fig. 33)

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

The preceding section describes 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 Range 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 (Fig. 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 No. 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. Farther to the east is the Red Creek anticlino and syncline pair. East of the canyon the Wildhorse anticline (Peterson, 1983) are several folds adjacent to the Lysite Mountain area.

Southeast Corner of Bighorn Basin

In the southeastern corner of the basin there are narrow elongate acute folds such as Murphy Dome, Black Mountain, Lake Creek, Corley-Zimmerman Butte which trend N 50^{o} - 60^{o} W.. These folds appear to have relatively small offsets of the Precambrian basement on the faults which underlie them.

Western Margin 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.

NOTE

Hewett (1926) reports a variation in thickness for the total section from 11,500 ft. to 22,350 ft. in the western Bighorn basin. Thickness in numerous wells is approximately 9,000 ft. 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. 48 N., R. 98 W. from surface to the Permian Phosphoria Formation was 23,081 feet . Moore (1961) indicates 8000 ft. of Paleocene Fort Union Formation at this site, leaving approximately 3500 ft. of Eocene Willwood Formation.

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.

Name and Location	Probable Overhang	Source of Data
Beartooth Mts. NE 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 - N. Owl Creek Black Mt. and Caldwell Meadows thrusts (Washakie Range	2 miles + 8 miles	Darton (1906), Powell Love (1939), Gries (1981), Clements (1977) Drilling
Owl Creek Mt. thrust	10-12 miles	Fanshawe (1939), Wise (1963), Gard (1969)
Southwest flank Casper Arch	6-7 miles	Sprague (1983) Drilling
Piney Creek thrust - east flank Bighorn Mts.	3+ miles	Hudson (1969), Blackstone (1981) Drilling

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 Mountain foreland is the Wind River Range of Wyoming, bounded by the low angle (30^{o}) 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 25 km. (Smithson and others, 1979). The similarity of this feature to some of the examples listed 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 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 77% 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% 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 N 40° to 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 S 40° - 50° W.

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

NEW INTERPRETATION

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 western side of the basin (Figs. 2, 3, and 4) and 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 Co. Loch Katrine in sec. 2, T. 51 N., R. 100 W., T.D. 23,860. 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.

Seismic profiles in the vicinity of Grass Creek are equally definitive as a series of deep tests drilled east of the fault (Fig. 4). The deepest test - American Quasar Sellars Draw unit 1, sec. 21, T. 48 N., R. 98 W., bottomed at 23,081 in Permian Phosphoria Formation. The well is located in the footwall of the fault and vertical separation based on data from folds to the west is in 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 (Lowell, 1983) thence continues north to join the low angle thrusting along the east flank of the Beartooth Mountains. (Thom, 1952, Scheevell, 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 $30^{\circ} \pm 10^{\circ}$ 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 (Figs. 19,20,22) 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 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 (Fig. 35) illustrates the wedge relationship across the buried Oregon basin fault and the North Owl Creek - Mud Creek fault.

Faults on Southwest Margin of Washakie Mountains

A somewhat discontinuous series of thrust faults exists 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 N. Owl Creek - Mud Creek thrust. Faults on the margin dip under the elevated block (Fig. 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 to Warm Springs field 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.

YOUNGER EAST-WEST TRENDING STRUCTURES

The dominant trend of the "thrust-fold" structures in the southern Bighorn basin is northwest (Fig. 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 N. 75° W. 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 hiearchy 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 investigations have recognized that they were dealing with a region of sub-cratonic proportions overlain by sedimentary strata of shelf type of remarkable regional consistency. The thickness of the sediment covers prior to the Laramide deformational episode was 10,000 to 12,000 feet over extensive areas. If the Moho lies at about 28 miles (45 kilometers) depth the sedimentary veneer is about 8% 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 focussed 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, 1982; 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 foreland "thrust-folds" and points out the existence of features on at least two scales. He notes that there are structures with amplitudes of 13,000 meters (42,000 feet) and those of lesser scale 1,500 meters (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, Fig. 6) cross sections demonstrating the development of potential faults all dipping in one direction and their propagation downward with increasing crustal shortening leave an unfortunate impression. Earlier, (Scheevel 1983, Fig. 2) presents an illustration of shear-fault trajectories in conjugate sets inclined 30° to the initial horizontal surface.

There is no <u>a priori</u> reason why only one set of the shear-fault trajectories will become dominant as shown in Scheevel's Fig. 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 maybe inclined as much as 8° - 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 a regimen of extensional tectonics. Since crustal shortening does exist in this region a compressional regimen must have existed during the Laramide deformational 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 effects 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^{o} +) in the basement steepen upward to a ramp of 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.

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Table I. Definition of the principal aquifers in unfaulted parts of the Bighorn Basin, Wyoming.

Age	Unit	Lithology	Hydrologic Character
Mesozoic	Various Units	thick shales	confining layers
Permian	Phosphoria Fm.	shale, gypsum	TENSLEEP-PHOSPHORIA AQUIFER
Pennsylvanian	Tensleep Ss.	sandstone	TENSLEEP-PHOSPHORIA AQUIFER
Pennsylvanian	Amsden Fm.	shale, siltstone, limestone	confining layer
Mississippian	Madison Ls.	limestone	MADISON AQUIFER
Devonian	Jefferson Ls.	limestone	MADISON AQUIFER
Ordovician	Bighorn Dol.	dolomite	MADISON AQUIFER
Cambrian	undivided Gellatin and Gros Ventre Fms.	shale, minor limestone	confining layer
Cambrian	Flathead Ss.	sandstone	FLATHEAD AQUIFER
Precambrian	Basement rocks	metamorphic rocks	confining layer

DATA SHEET-Folds in southern and Western Bighorn Basin, Wyoming

Name of Fold	County	T. & R.	Formation at Surface	Trend of Axis	Direction of Asymmetry	Oldest Unit	Production
Black Mountain	Hot Springs Washakie	42-43N, 90-91W	Frontier Mowry	N60 W	SW	Cambrian	P
Bruce Area	Washakie	43N, 89-90W	Cody	N55 W	SW	Tensleep	D
Bud Kimball	Washakie	44-45N, 88W	Sundance	N40 W	NE	Teensleep	D
Chabot	Washakie	42-43N, 88W	Gallatin	N45 W-N20 W	SW	Madison	D
Corley-Zimmerman Butte	Washakie Hot Springs	43-44N, 92-93W	Cody	N60 W	SW	Madison	D
Embar	Hot Springs	8N-2E	Tensleep	N60 W	NE	Precambrian	D
Enos Creek	Hot Springs	46N-100W	Mesaverde	N30 E-N50 W	SW	Madison	P
Ferguson Ranch	Park	50N-102W	Mowry	N-S	W	Madison	P
Four Bear	Park	48N-103W	Mowry	N45W	SW	Cambrian	P
Gebo	Hot Springs	44N-95W	Cody	N65W	SW	Precambrian	P
Golden Eagle	Hot Springs	45N-96-97W	Ft. Union	N45W	SW	Madison	P
Gooseberry	Park	46-47N,-100W	Cody	N10W	SW	Tensleep	P
Grass Creek	Hot Springs	45N-98W	Cody	N10W-N70W	SW	Precambrian	P
Half Moon	Park	51-52N-102W	Mowry	N-S-N40W	SW	Tensleep	P
Hamilton dome	Hot Springs	44N-97-98W	Mowry	N65W	SW	Precambrian	P
King dome	Hot Springs	44N-96-97W	Phosphoria	N65W	SW	Tensleep	P
Kirby Creek	Hot Springs	43N-92W	Cody	N60W	SW	Madison	P
Lake Creek-Lake Creek West	Hot Springs	43N-91-92W	Mowry	N55W	SW	Madison	D
Little Buffalo basin	Park Hot Springs	47N-100W	Cody	N10W	SW	Tensleep	P
Little Sand Draw	Hot Springs	44N- 96W	Cody	N30W	SW	Cambrian	P
Lucerne	Hot Springs	43N-94W	Cody	N60W	SW	Tensleep	D
Lysite Mountain	Hot Springs	41-42N-90W	Tertiary	N40W	?	Madison	D
Mahogany Butte	Washakie	43N-89		N35W	NE	Mowry	D
Meeteetse	Park	49N-99W	Ft. Union	N-S	SW	Frontier	P
Murphy dome	Washakie Hot Springs	43-44N-91-92W	Cody	N60W	SW	Cambrian	P
Neiber	Washakie	45N-91-92-93W	Ft. Union	N75W	SW	Madison	P
North Sunshine	Park	47N-101W	Thermopolis	N-S	SW	Precambrian	P
Norwood	Washakie	48N-89-90W	Chugwater	N30W	NE	Tensleep	D
Oregon basin	Park	50-52N-100W	Cody	N-S	E	Precambrian	D
Pitchfork	Park	48N-102W	Mowry	N-S-N30W	SW	Precambrian	P
Rawhide	Park	48-49N-101W	Cody	N50W	SW	Madison	P
Red Canyon	Hot Springs	42-43N-96W	Phosphoria	N10W	W	Cambrian	D
Red Springs	Hot Springs	43N-93W	Chugwater	E-W	S	Madison	P
Rose dome	Hot Springs	43-44N-96W	Phosphoria	N50W	SW	Precambrian	D
Sand Creek	Washakie	46N-91W	Willwood	N-S	?	Madison	P
Sheep Point	Park	47N-102W	Frontier	N50W	SW	Amsden	D
Skeleton dome	Hot Springs	45N-100W	Mesaverde	N-S	E	Madison	P
South Fork			Willowood	N50W	?	Madison	D
South Sunshine	Park	46N-101W	Morrison	N30W	NE	Tensleep	P
Spring Creek	Park	49N-102W	Mowry	N40W	SW	Cambrian	P
Tensleep	Washakie	46N-89W	Frontier	N30W	NE	Tensleep	D
Thermopolis	Hot Springs	43N-95W	Chugwater	N65W	S	Madison	D
Wagonhound	Hot Springs	44N-98W	Cody	N55W	SW	Madison	P
Warm Springs E & W	Hot Springs	43N-93-94W	Chugwater	N85E	S	Madison	P
Waugh	Hot Springs		44N-96-97W	N50W	SW	Madison	P
Water Creek	Washakie Hot Springs	43-44N	Cody	N60W	?	Madison	P
Willow Creek	Park	48N-103-104W	Cody	N40W	SW	Madison	P
W. Bud Kimball	Washakie	45N-89W	Mesaverde	N50W	SW	Tensleep	D
Wildhorse Butte	Hot Springs	42-43N-93W	Chugwater	N45W	NE	Madison	D
Zimmerman Butte	Washakie Hot Springs	43-44N-92-93W	Cody	N60W	SW	Madison	D

TABLE III. Key to symbols used on cross sections.

Eocene	Tw	Willwood Formation
	Kmv	Mesaverde Formation
	Kc	Cody Shale
	Kf	Frontier Formation
Cretaceous	Kmd	Muddy Sandstone
	Kcv	Cloverly Formation
	Jm	Morrison Formation
Jurassic	Js	Sundance Formation
	Jgs	Gypsum Spring Formation
	Trc	Chugwater Formation
Triassic	Trd	Dinwoody Formation
Permian	Pp	Phosphoria Formation
Pennsylvanian	Pts	Tensleep Sandstone
Mississippian	Mm	Madison Limestone
Miss. - Devonian	MD	Madison Limestone, Darby Formation, Jefferson Limestone
Devonian	D	Darby (?) Formation
Ordovician	Obh	Bighorn Dolomite
Cambrian	C	Gellatin, Grosventre and Flathead Formations
Precambrian	PC	Crystalline basement

APPENDIX A
STRATIGRAPHIC COLUMN

Cenozoic	Eocene	Willwood Formation (volcanic equivalents Absaroka volcanics)
	Paleocene	Fort Union Formation
		Lance Formation
		Meeteetse Formation
		Mesaverde Formation
	Cretaceous	Cody Shale
Mesozoic		Frontier Formation
		Mowry Shale
		Graybull (Muddy) Sandstone
		Cloverly Formation
		Morrison Formation
	Jurassic	Sundance Formation
		Gypsum Spring Formation
	Triassic	Chugwater Formation
		Dinwoody Formation
	Permain	Phosphoria Formation
	Pennsylvanian	Tensleep Formation
	Penn. - Miss.	Amsden Formation
Paleozoic		Darwin Sandstone
	Mississippian	Madison Limestone
	Devonian	Three Forks - Jefferson (?)
	Ordovician	Bighorn Dolomite
		Gallatin Formation
	Cambrian	Gros Ventre Shales
		Flathead Quartzite
	Precambrian	Gneiss, schist and granite

NOTE: The Paleozoic aquifers are shown graphically on Plate II.

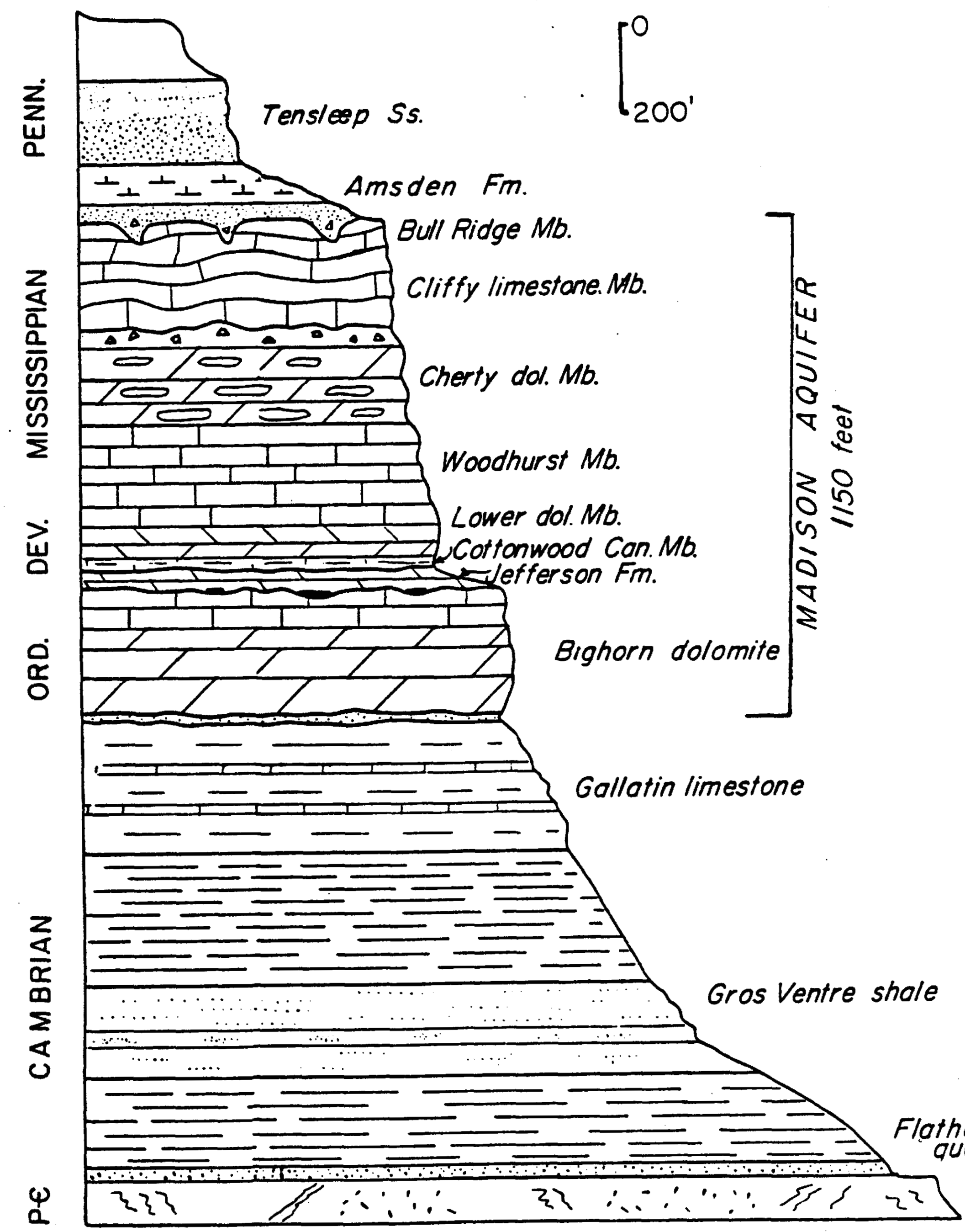


Figure 1. The Paleozoic stratigraphic section in the southern Bighorn Basin, Wyoming.

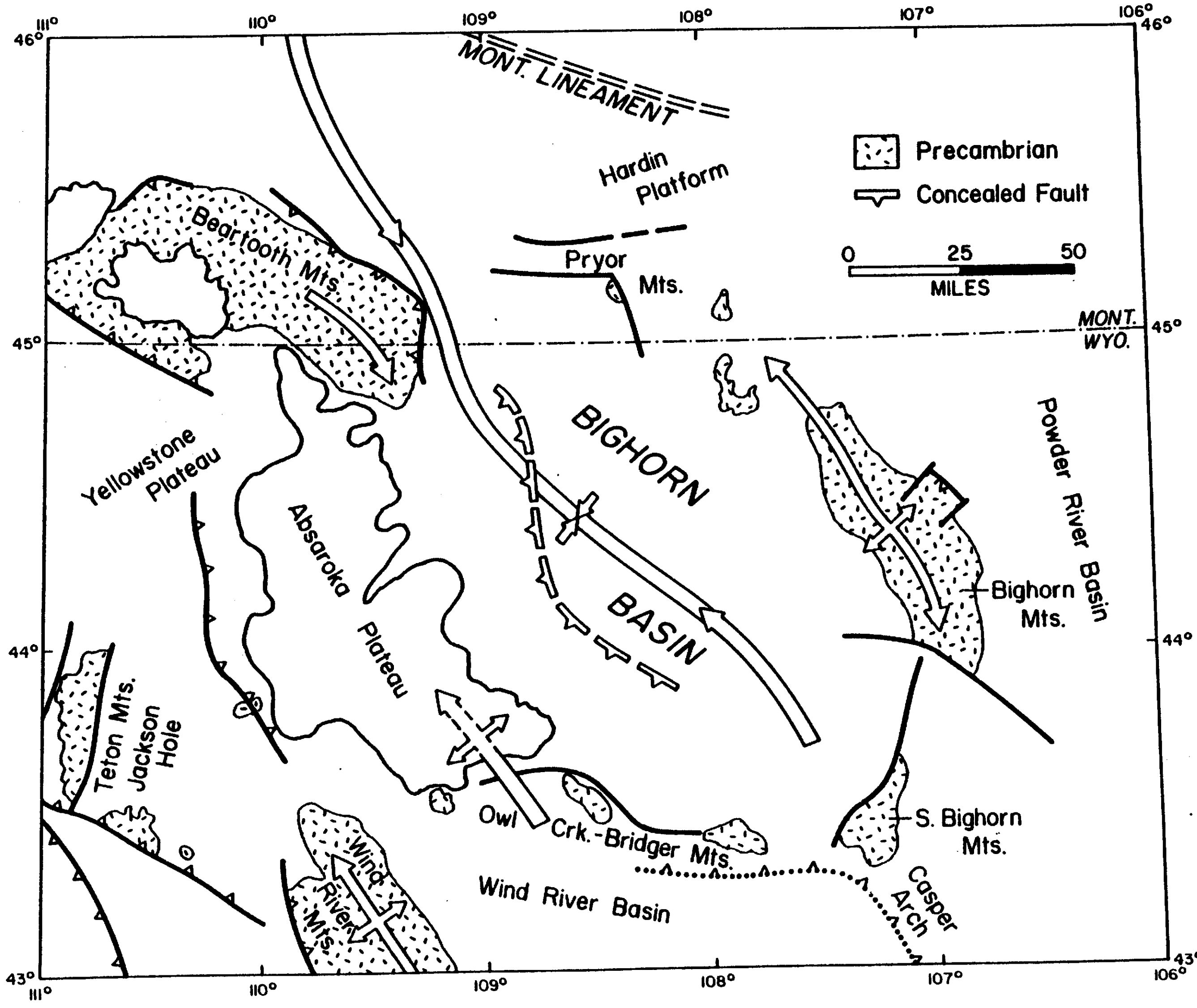


Figure 2. Tectonic index map, Bighorn Basin, Wyoming.

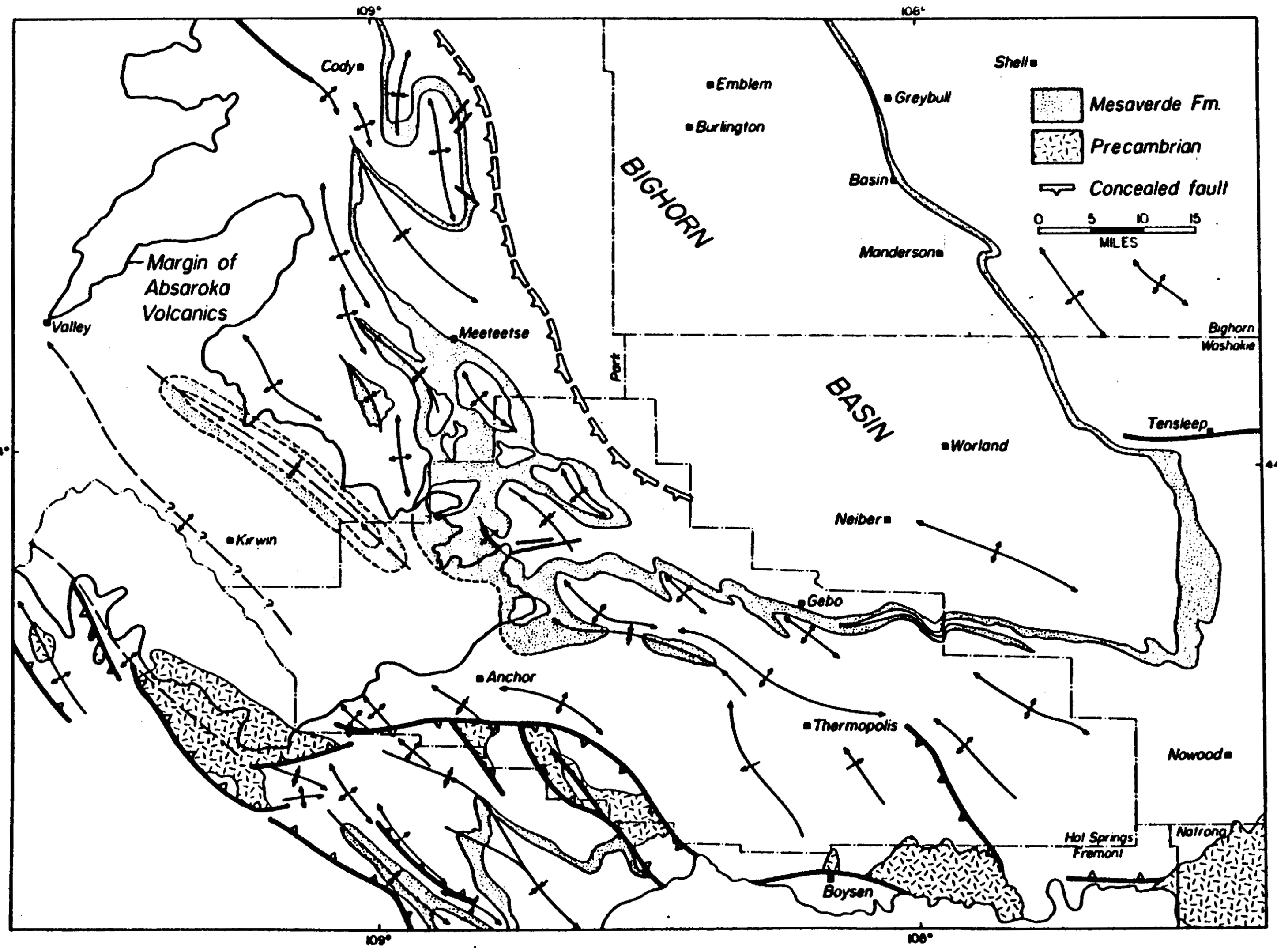


Figure 3. Tectonic map of the southern Bighorn Basin, Wyoming.

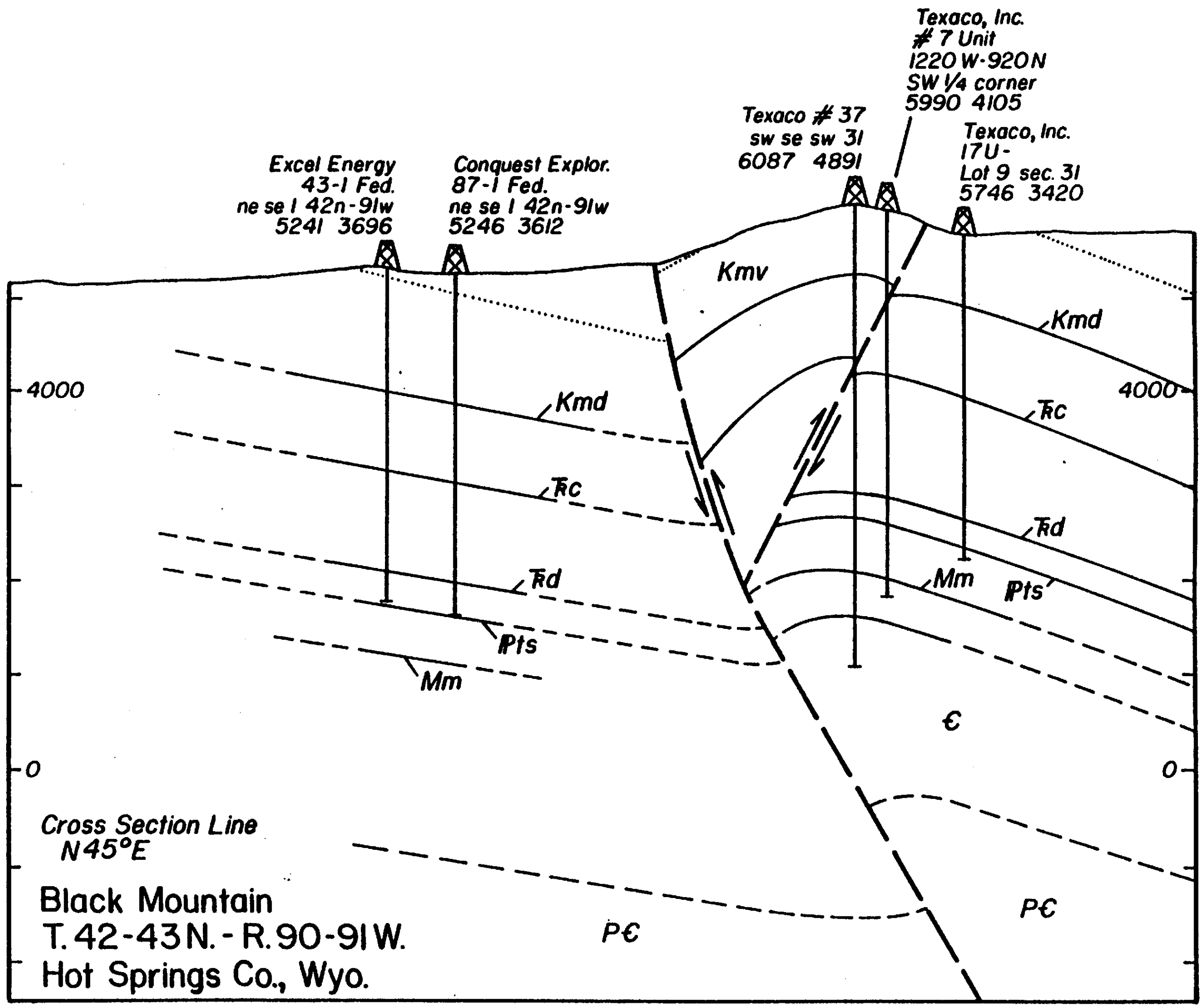


Figure 13. Structural cross section through the Black Mountain field, Bighorn Basin, Wyoming.

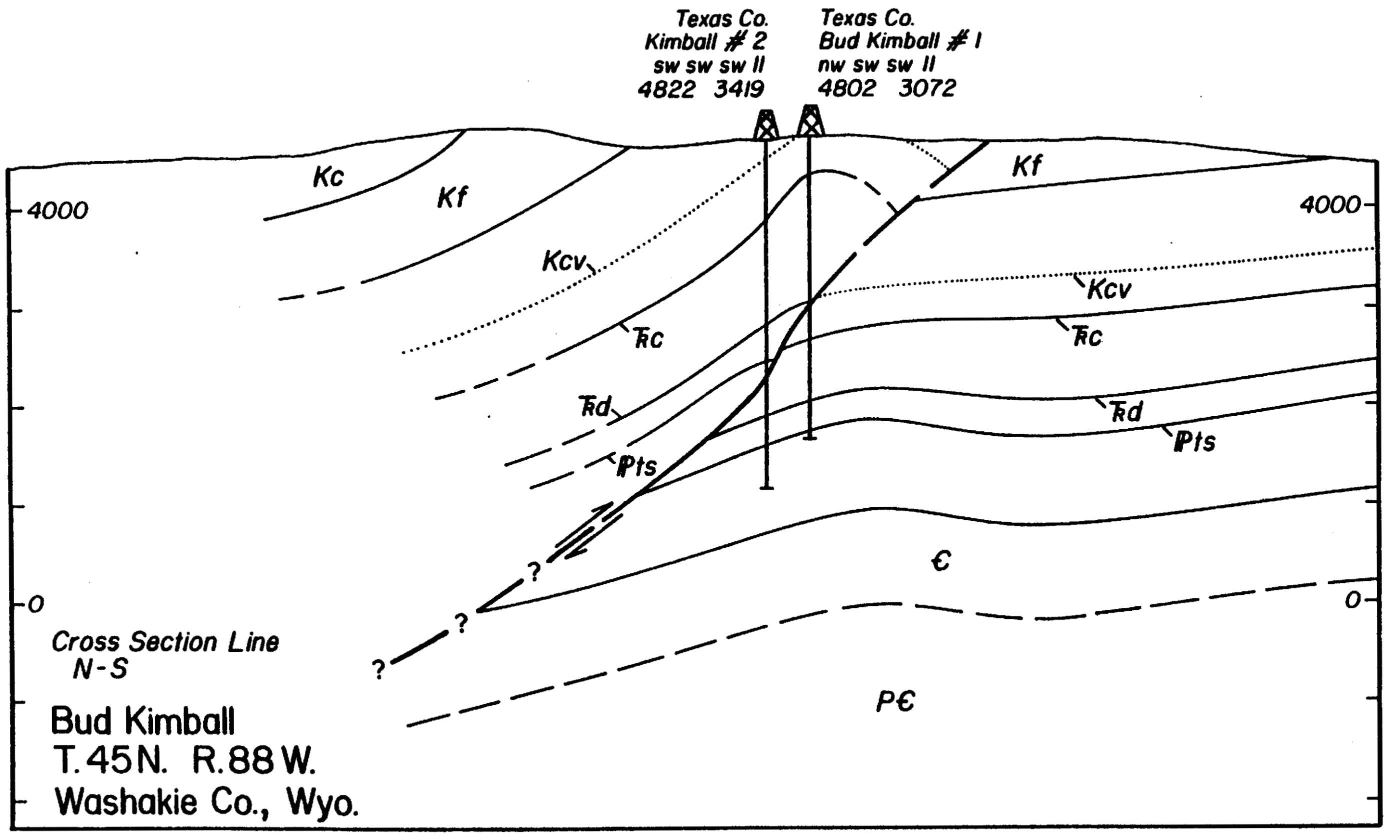


Figure 14. Structural cross section through the Bud Kimball anticline, Bighorn Basin, Wyoming.

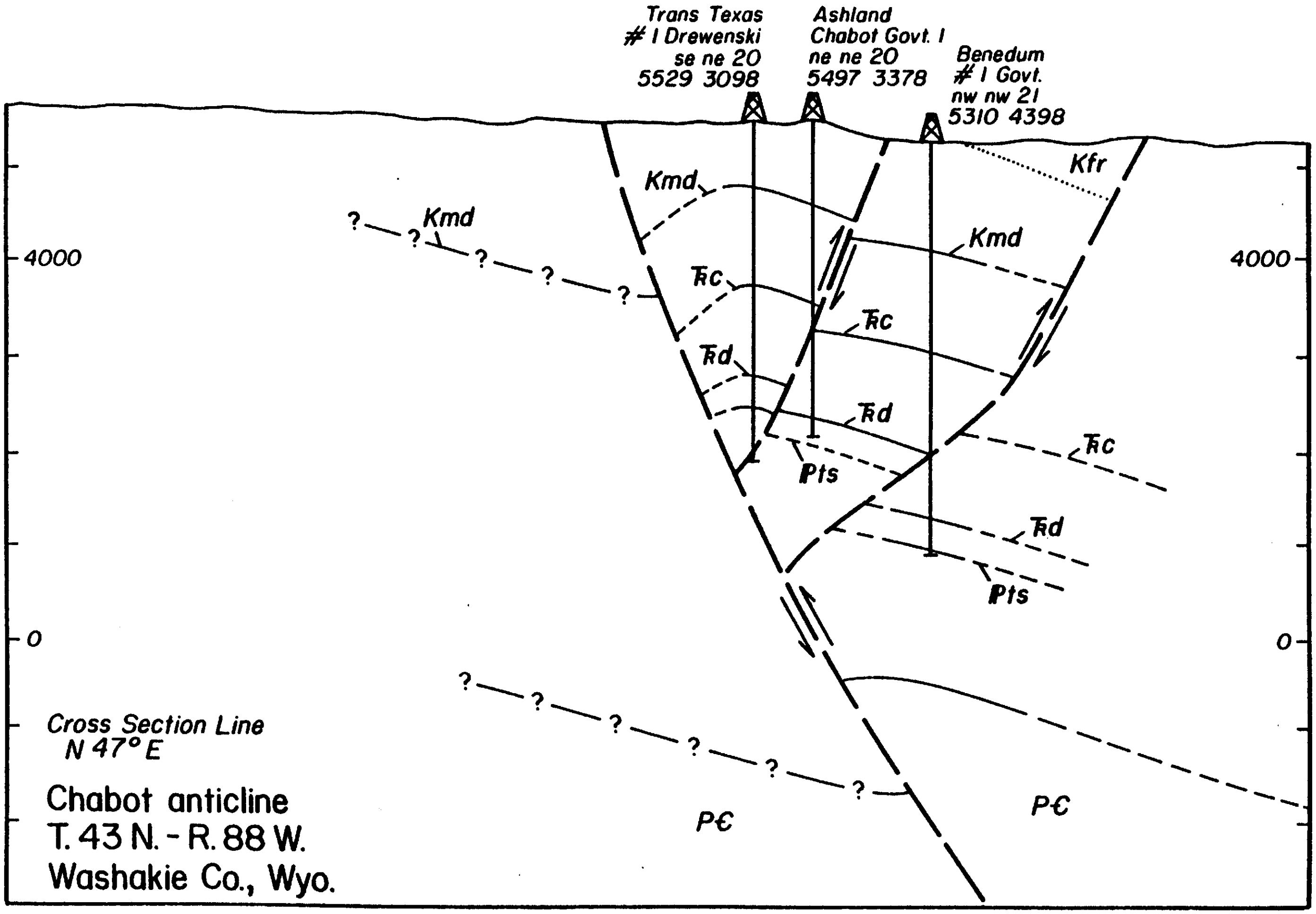


Figure 15. Structural cross section through the Chabot anticline, Bighorn Basin, Wyoming.

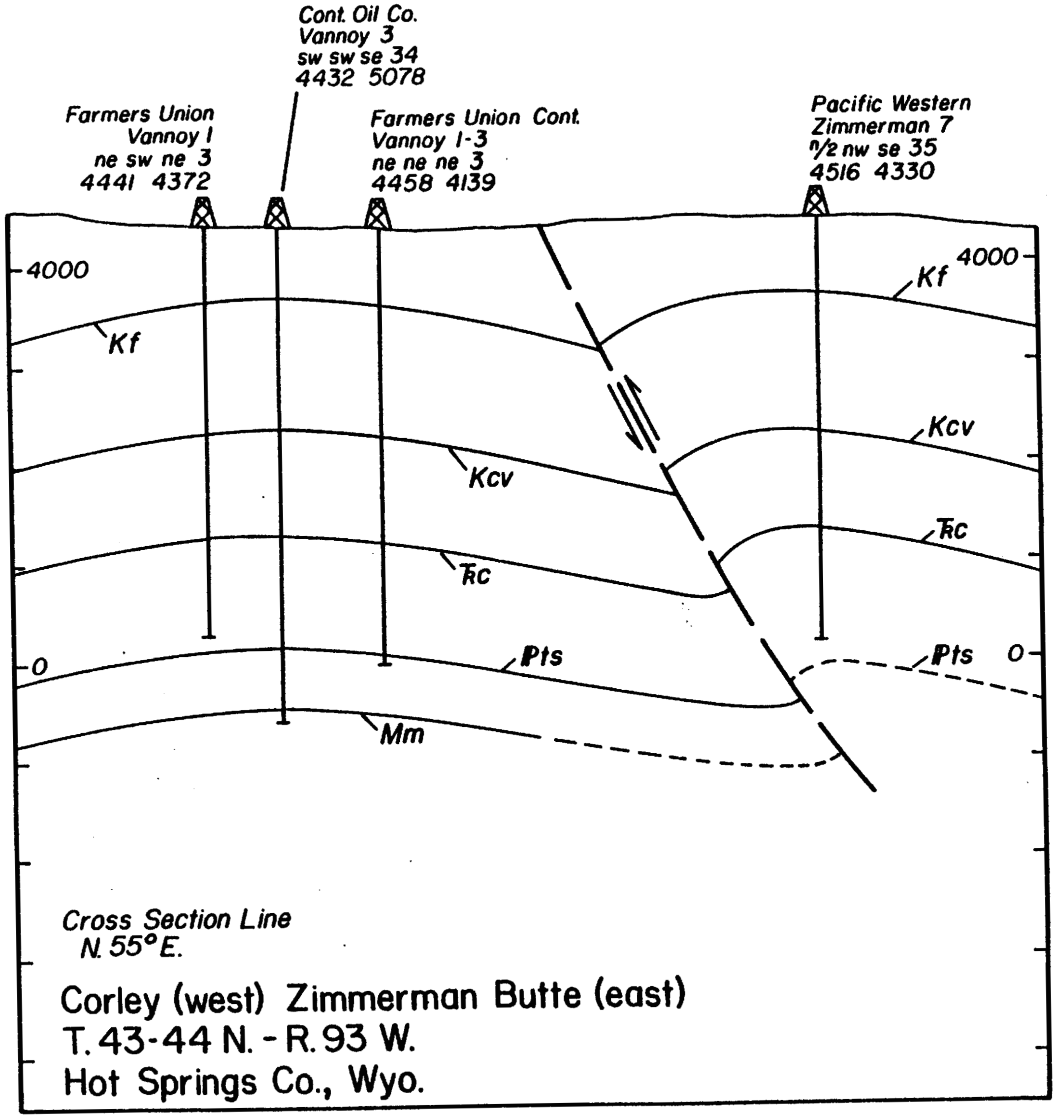


Figure 16. Structural cross section through the Corley-Zimmerman Butte folds, Bighorn Basin, Wyoming.

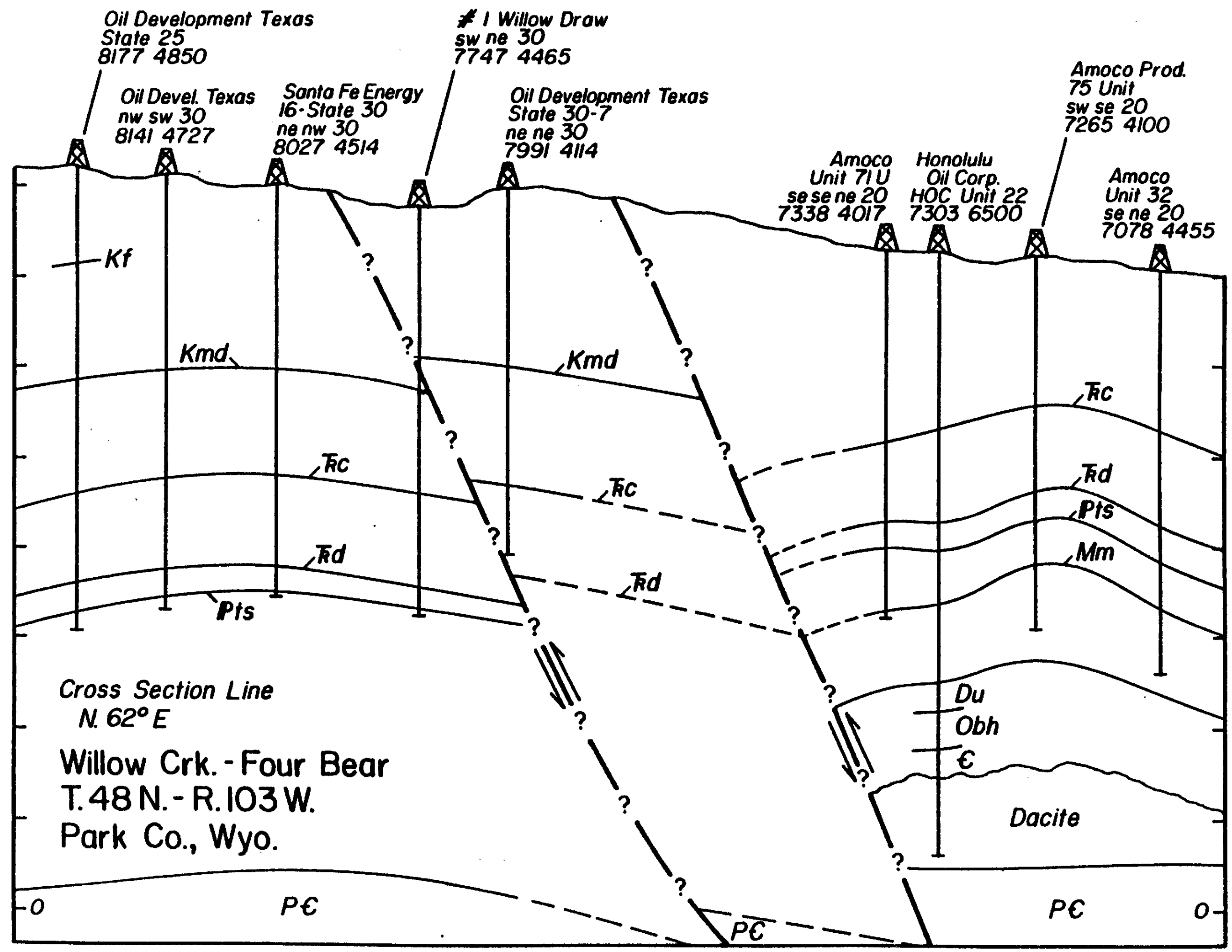


Figure 17. Structural cross section through the Willow Creek-Four Bear field, Bighorn Basin, Wyoming.

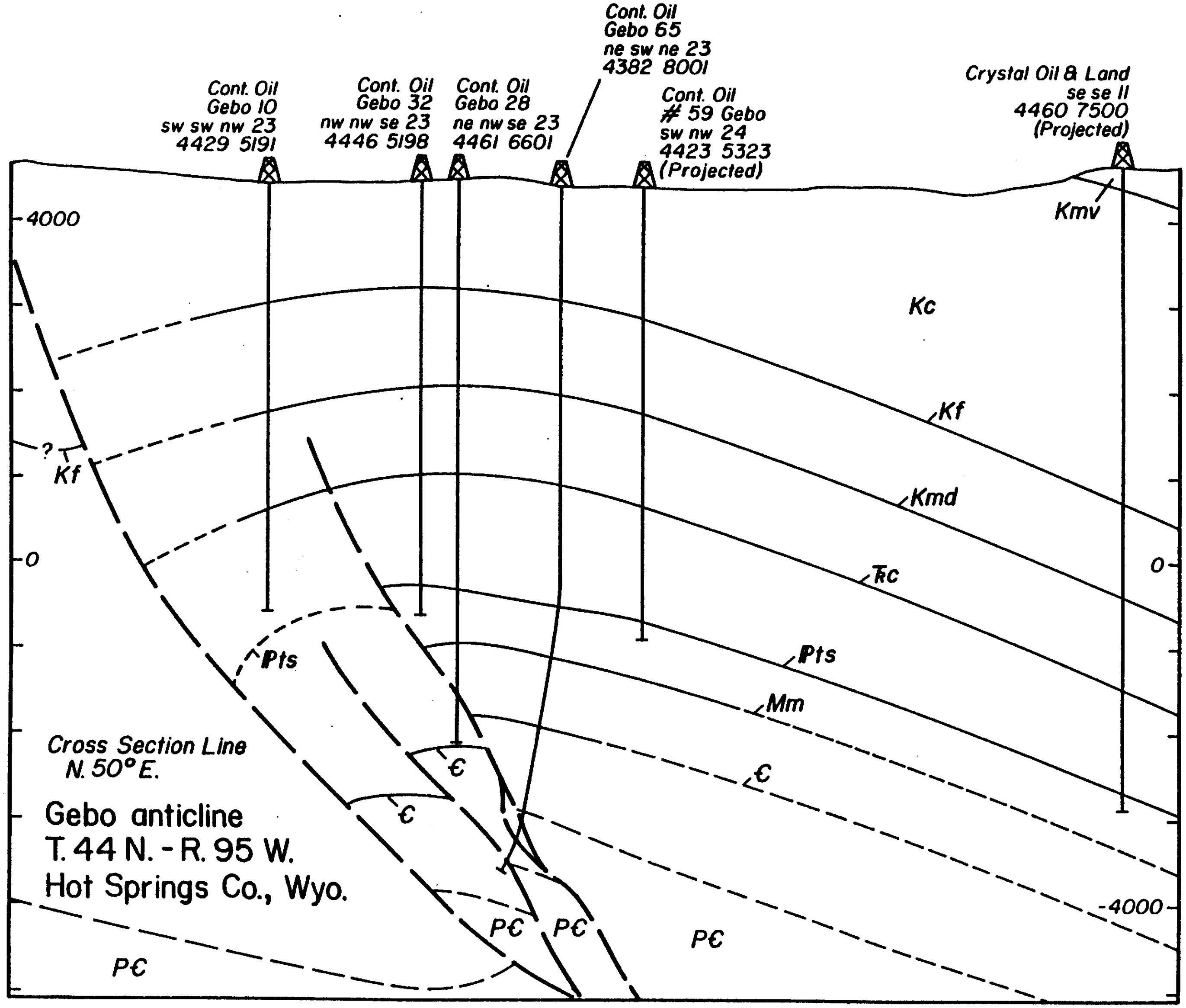


Figure 18. Structural cross section through the Gebo anticline , Bighorn Basin, Wyoming.

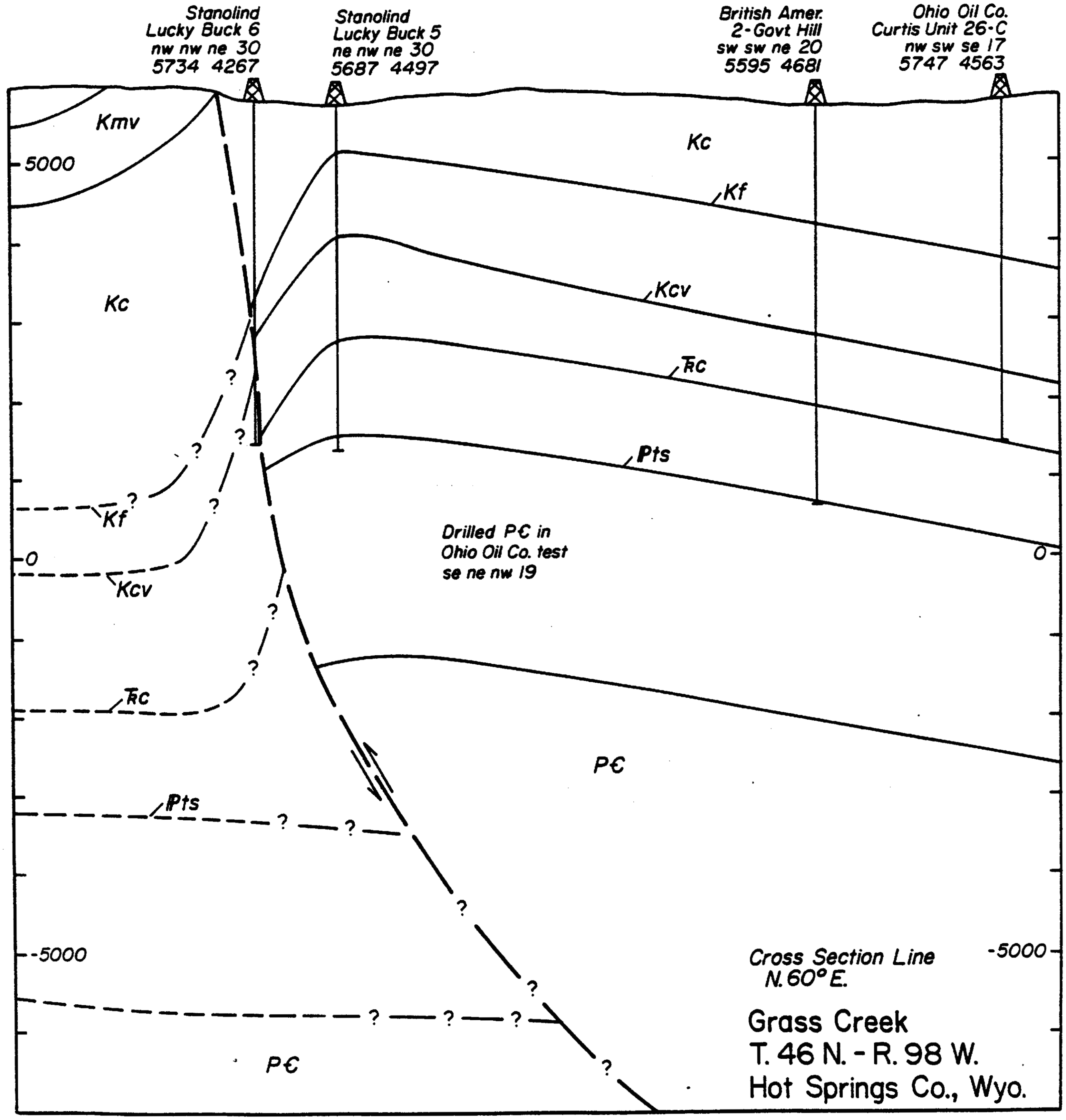


Figure 19. Structural cross section through the Grass Creek field, Bighorn Basin, Wyoming.

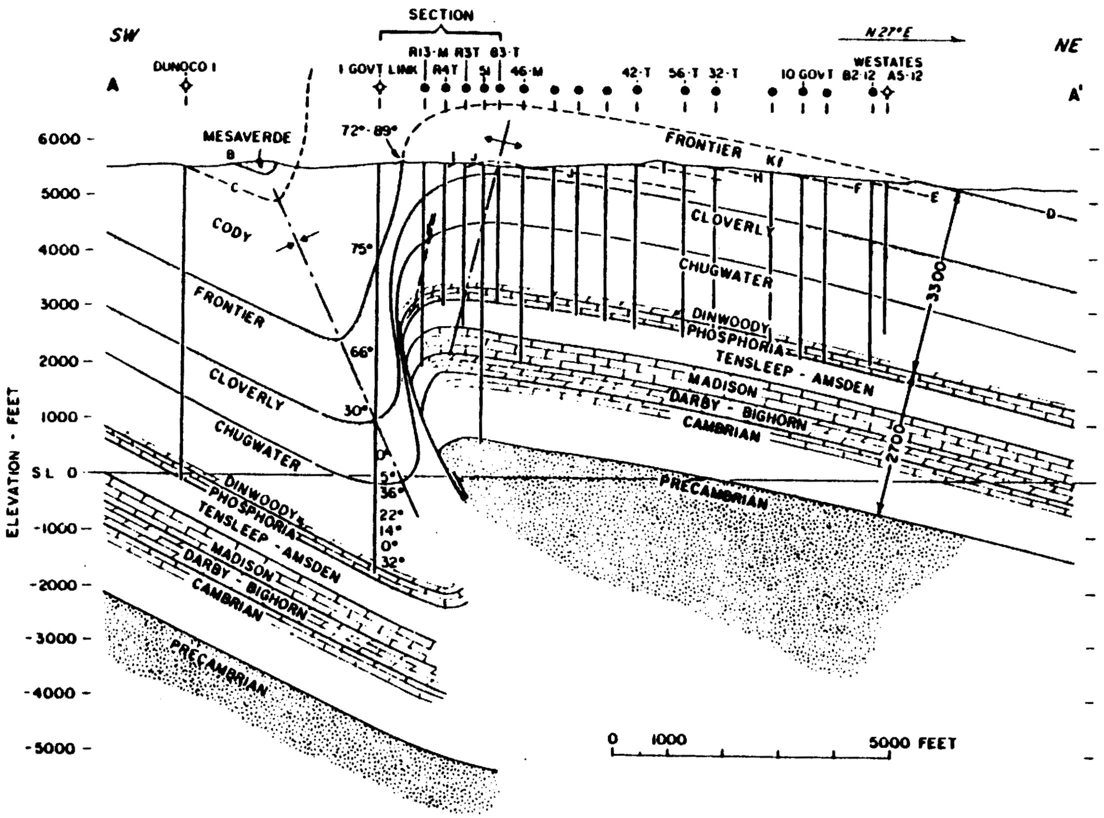


Figure 20. Structural cross section through the Hamilton Dome, Bighorn Basin, Wyoming (From Berg, 1976, Fig. 3).

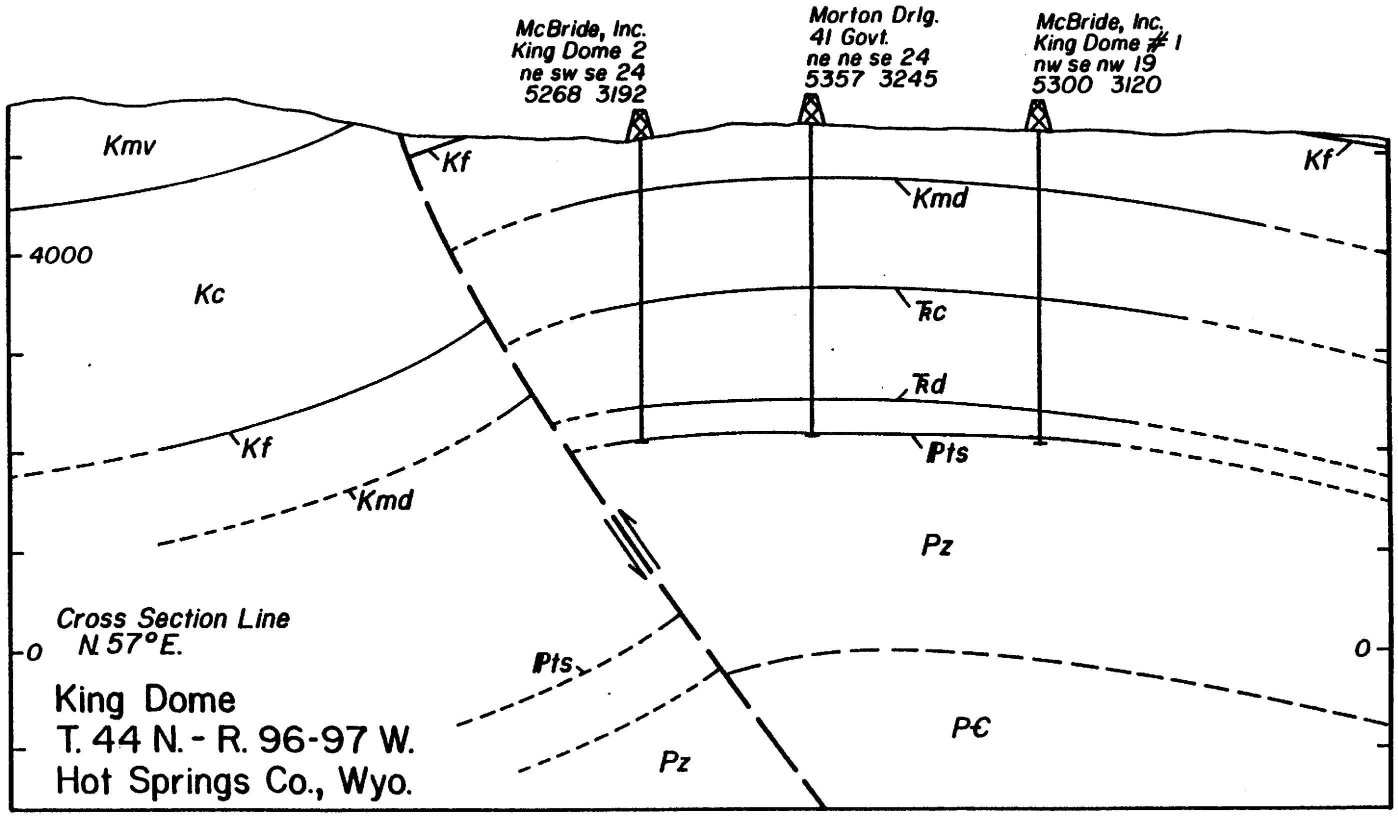


Figure 21. Structural cross section through the King Dome, Bighorn Basin, Wyoming.

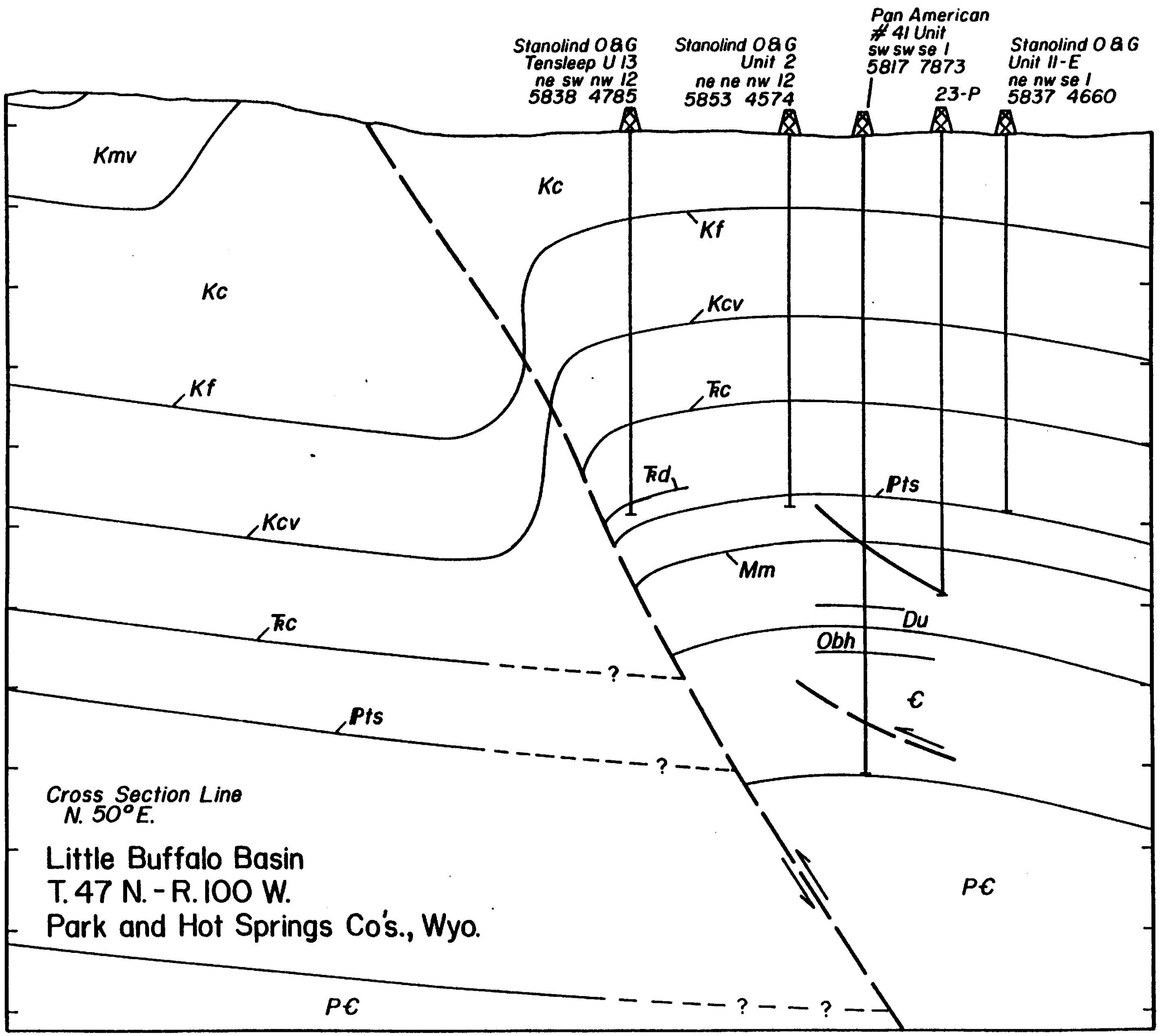


Figure 22. Structural cross section through the Little Buffalo Basin, Bighorn Basin, Wyoming.

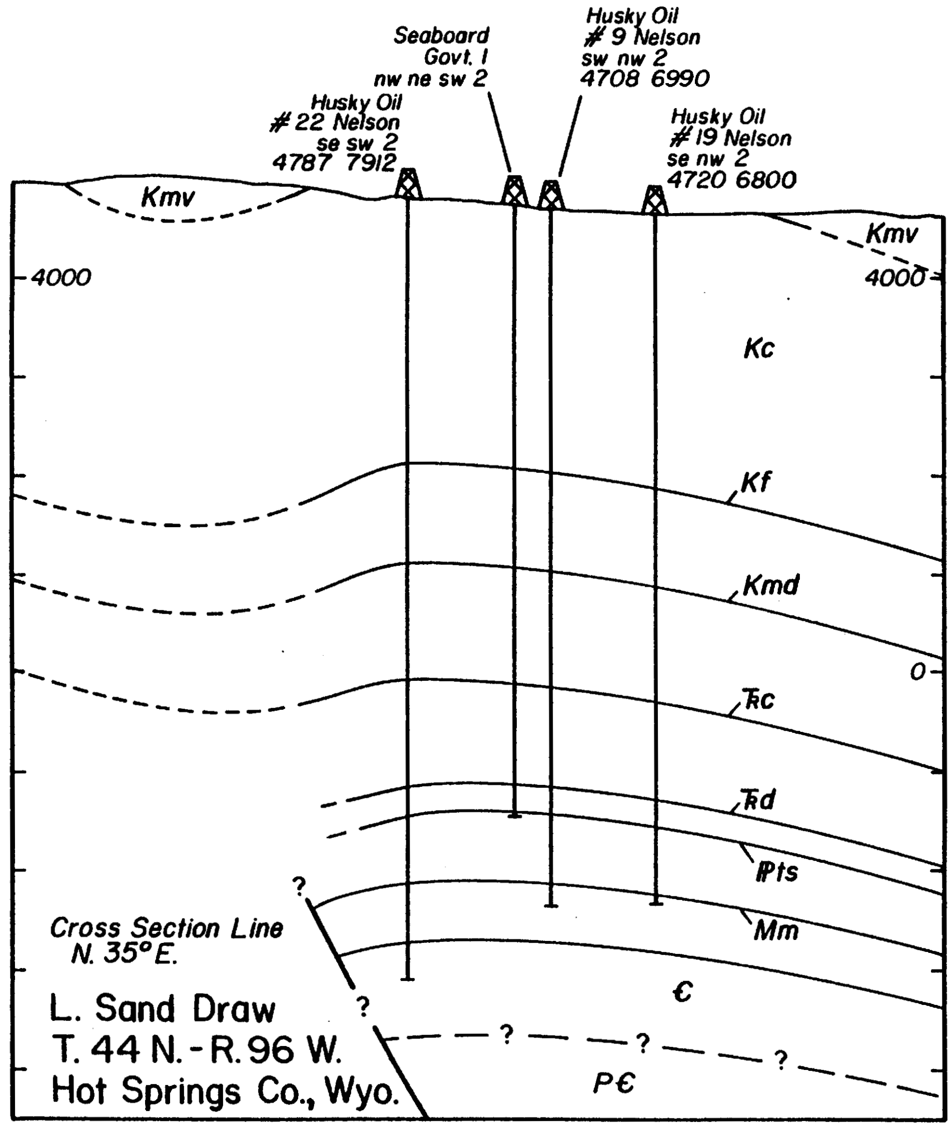


Figure 23. Structural cross section through the Little Sand Draw field, Bighorn Basin, Wyoming.

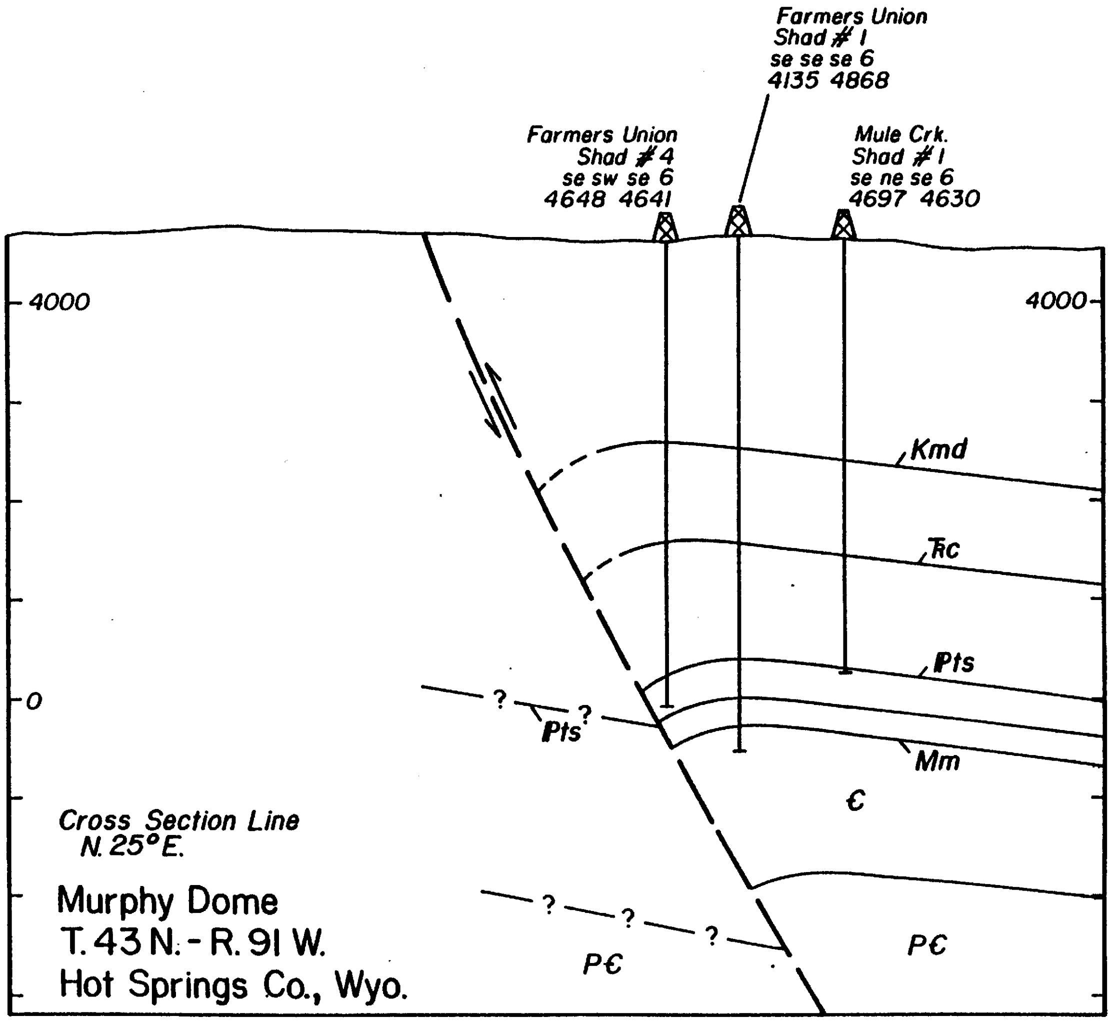
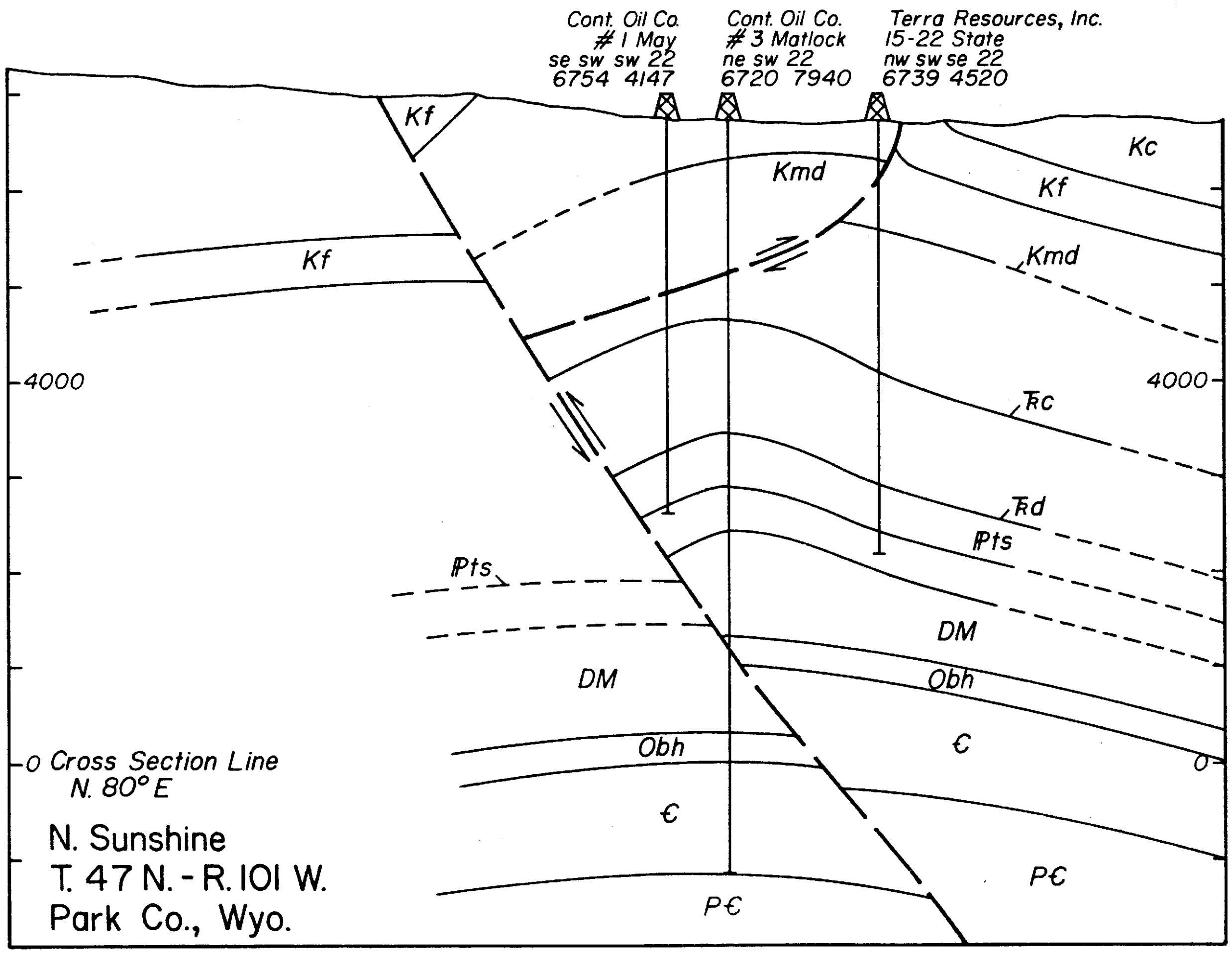


Figure 24. Structural cross section through the Murphy Dome, Bighorn Basin, Wyoming.

Fig. 25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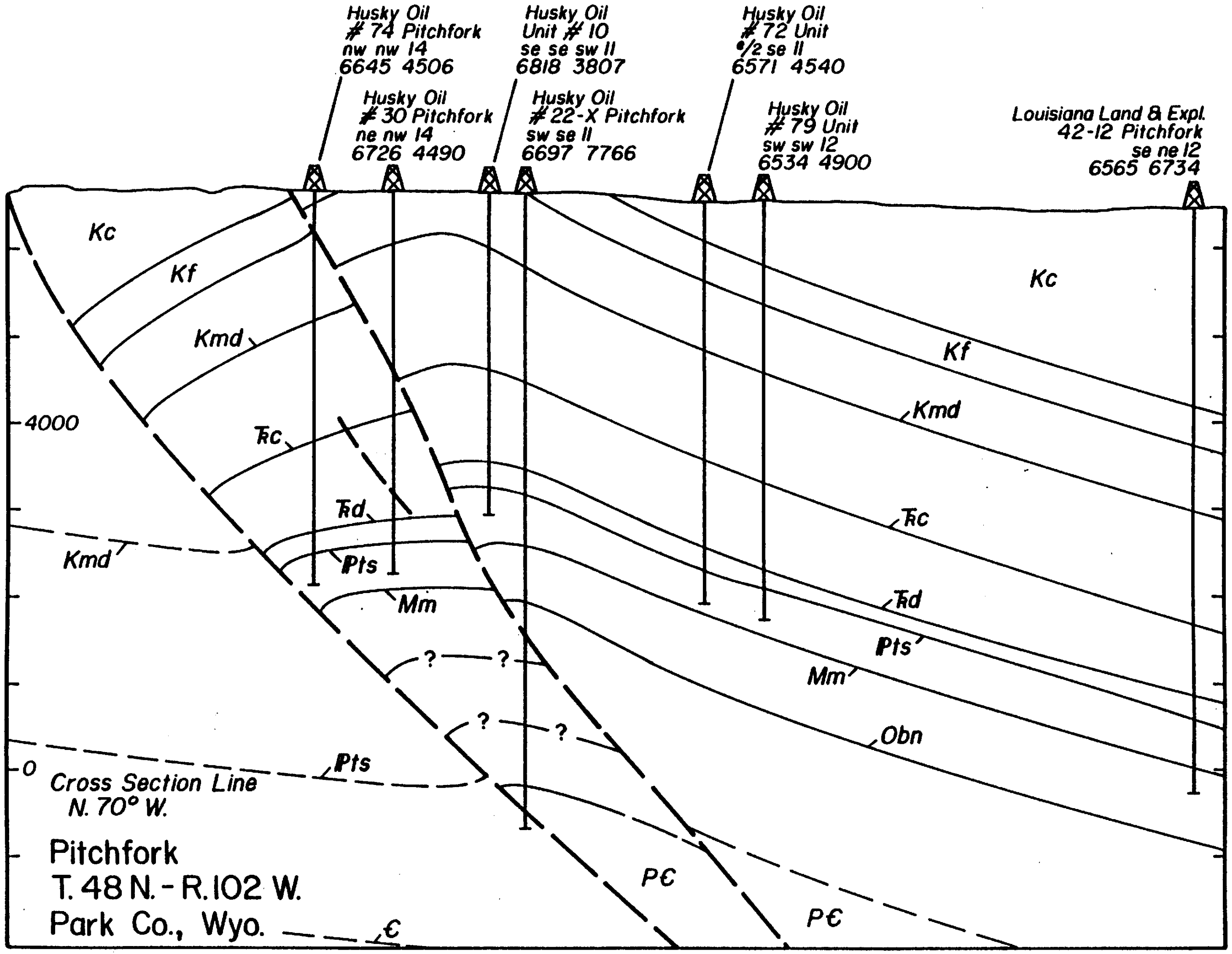

Figure 26. Structural cross section through the Pitchfork field, Bighorn Basin, Wyoming.

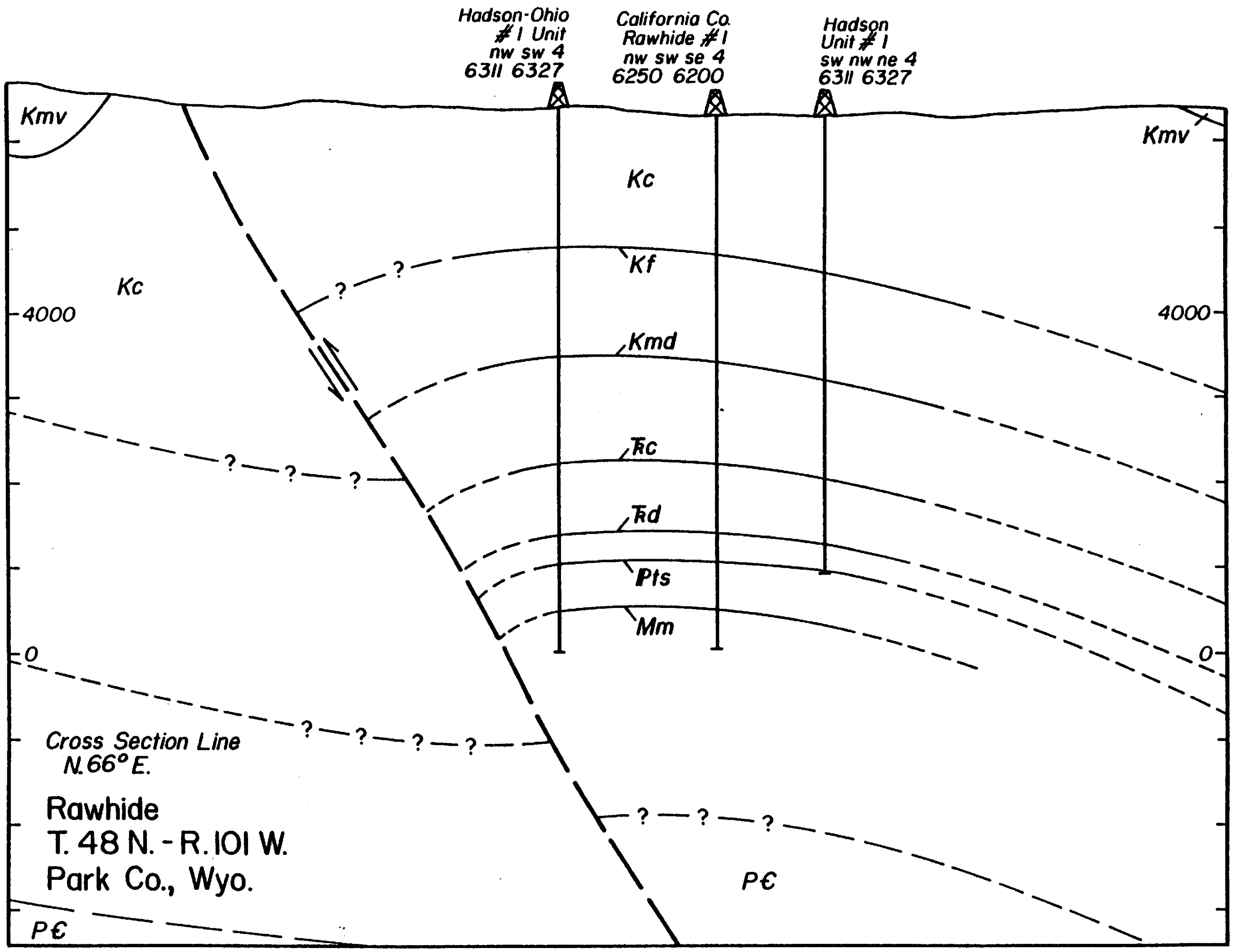

Figure 27. Structural cross section through the Rawhide anticline, Bighorn Basin, Wyoming.

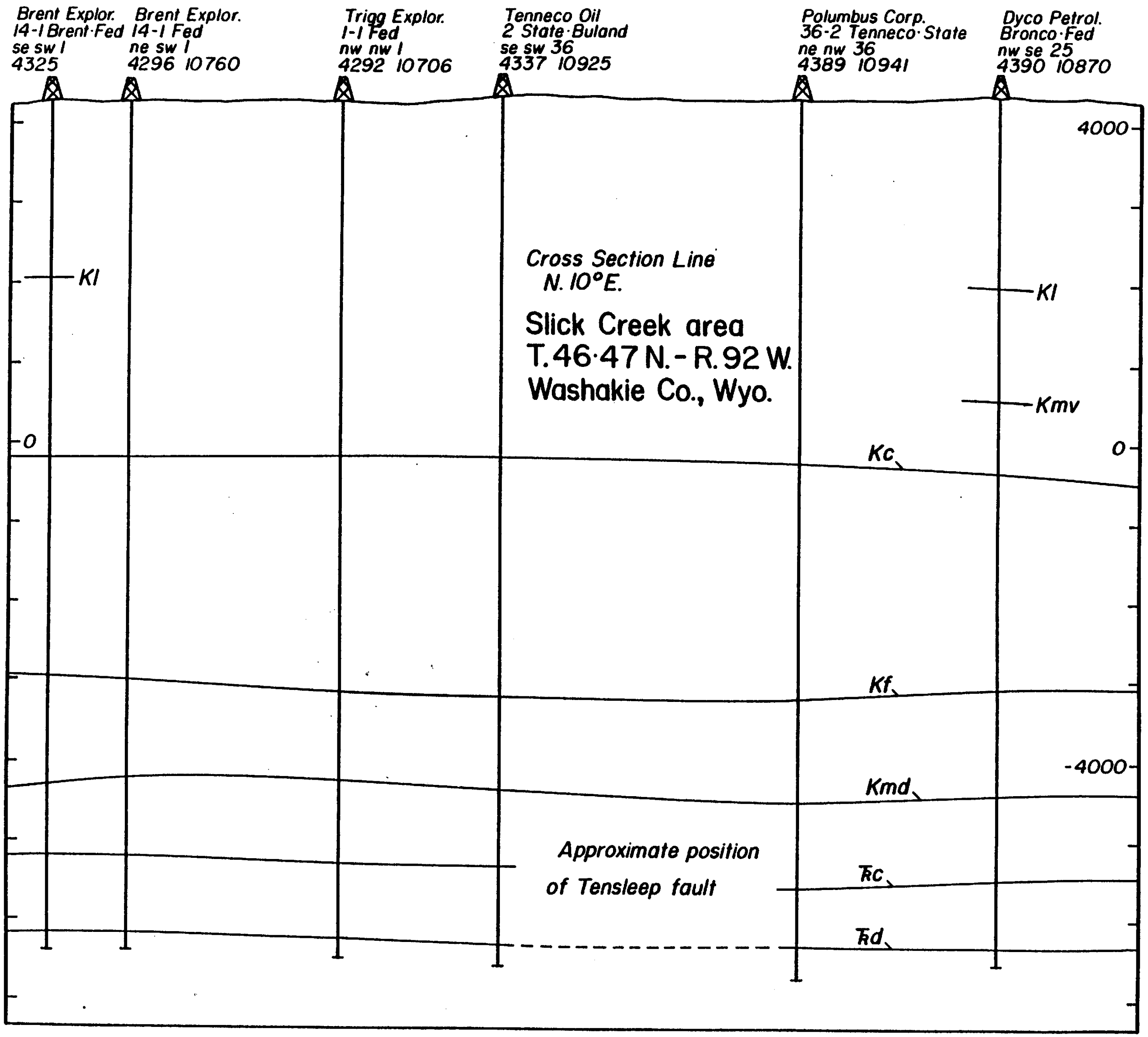

Figure 28. Structural cross section through the Slick Creek field, Bighorn Basin, Wyoming.

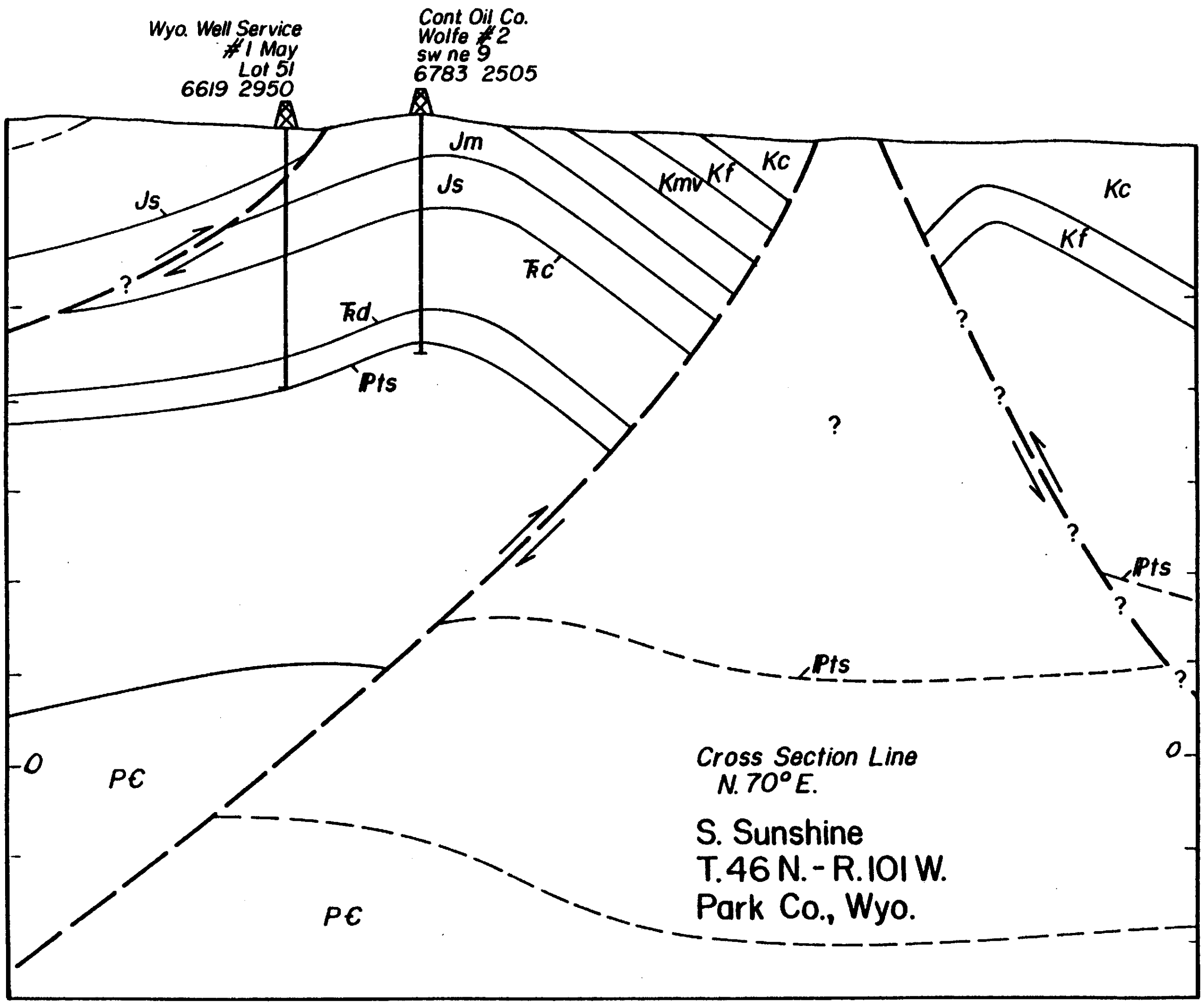

Figure 29. Structural cross section through the South Sunshine field, Bighorn Basin, Wyoming.

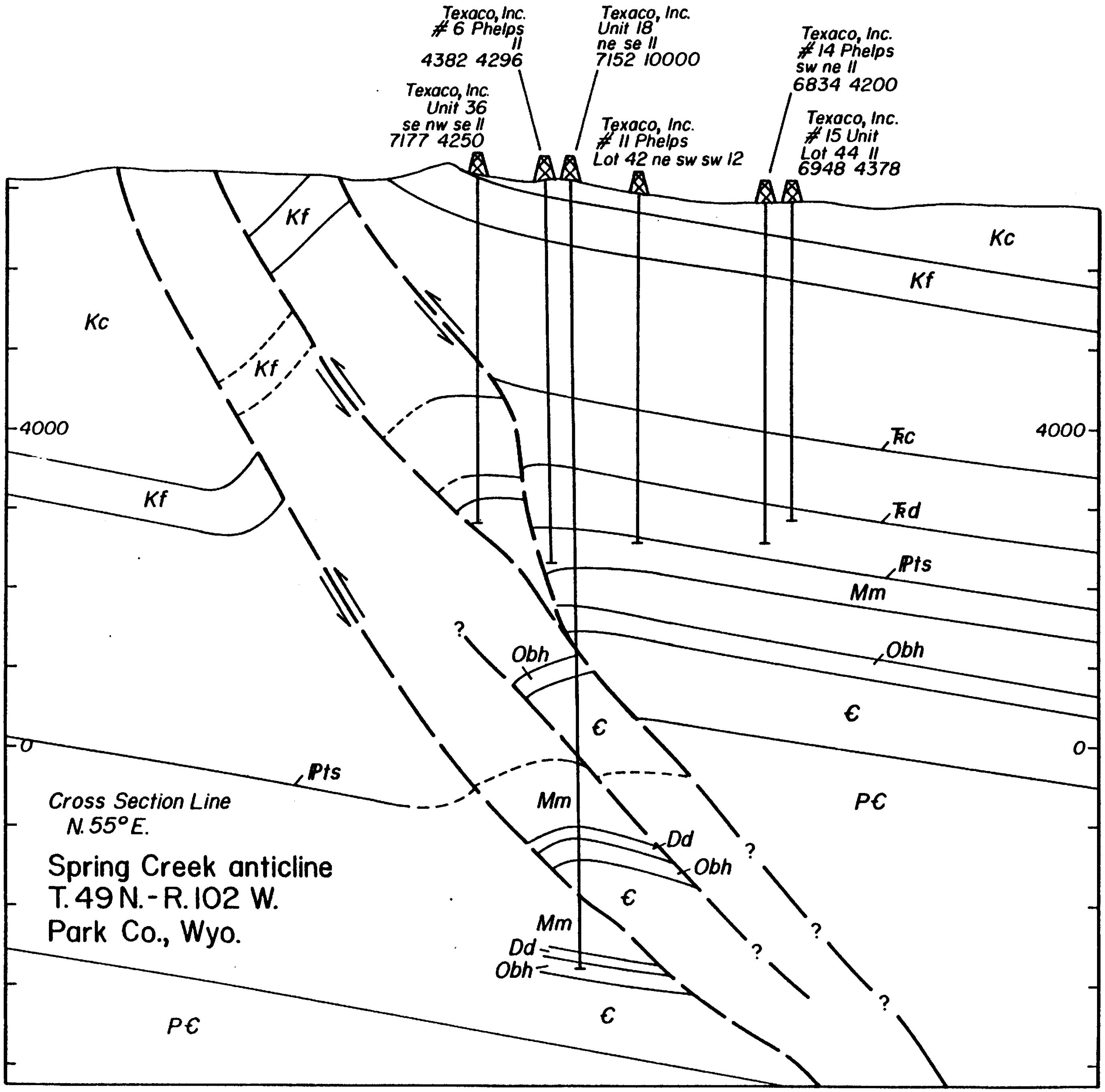

Figure 30. Structural cross section through the Spring Creek field, Bighorn Basin, Wyoming.

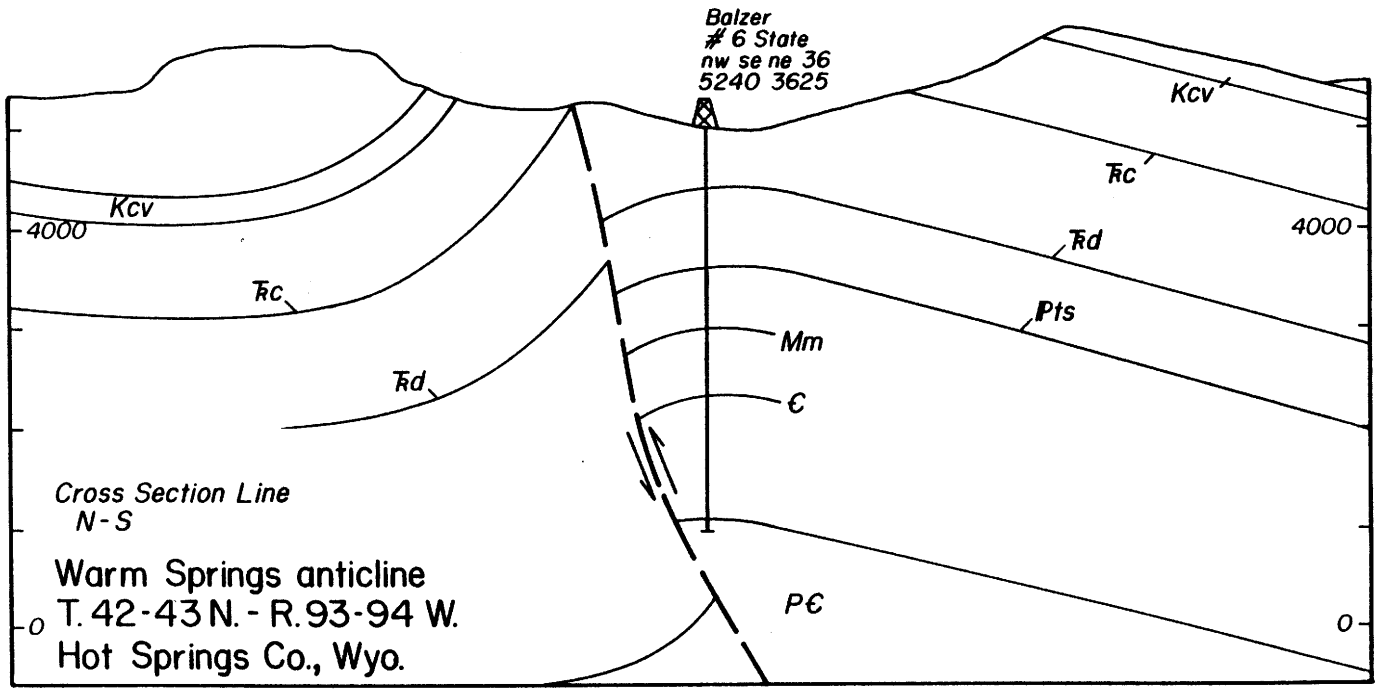

Figure 32. Structural cross section through the Warm Springs anticline, Bighorn Basin, Wyoming.

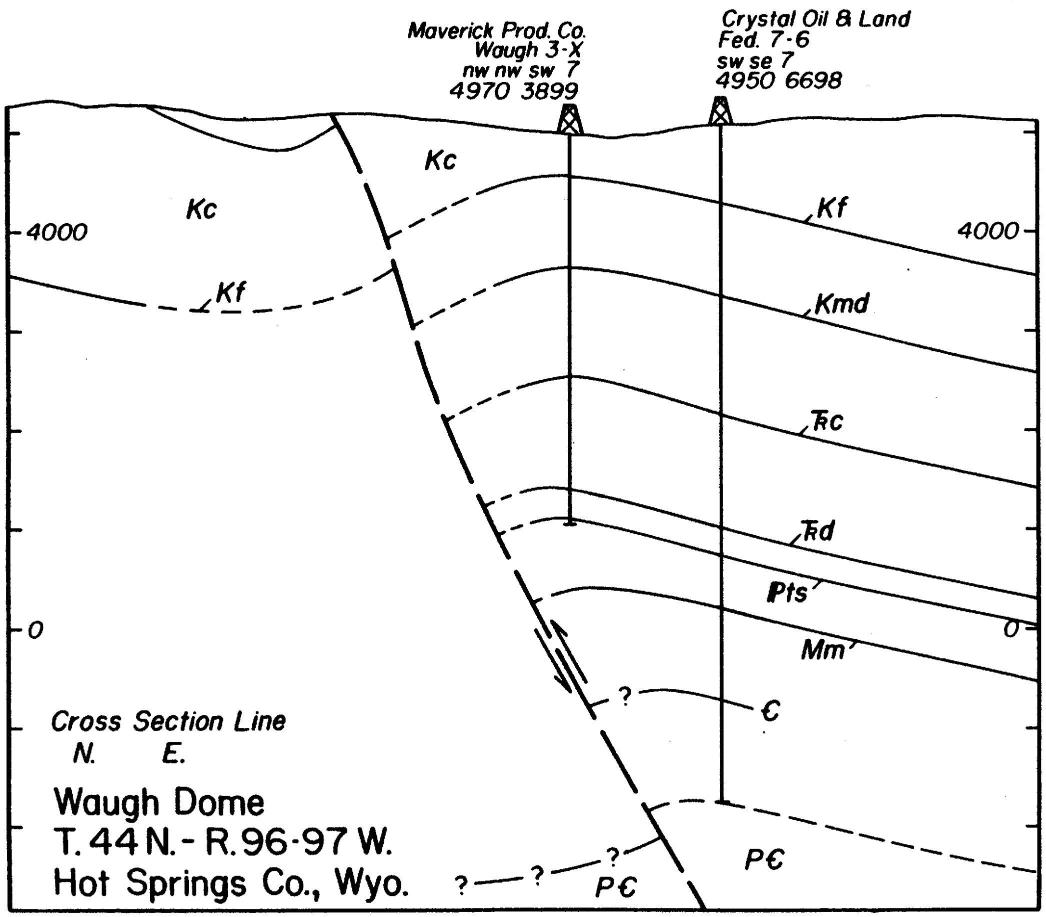

Figure 33. Structural cross section through the Waugh Dome, Bighorn Basin, Wyoming.

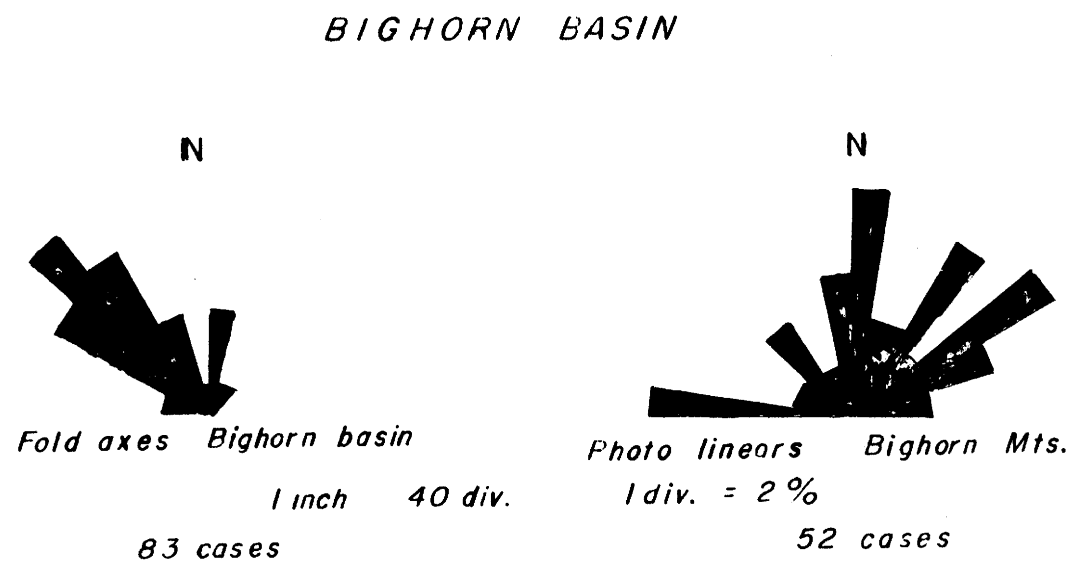

Figure 34. Rose diagram showing photolinears and fold axes, southern Bighorn Basin, Wyoming.