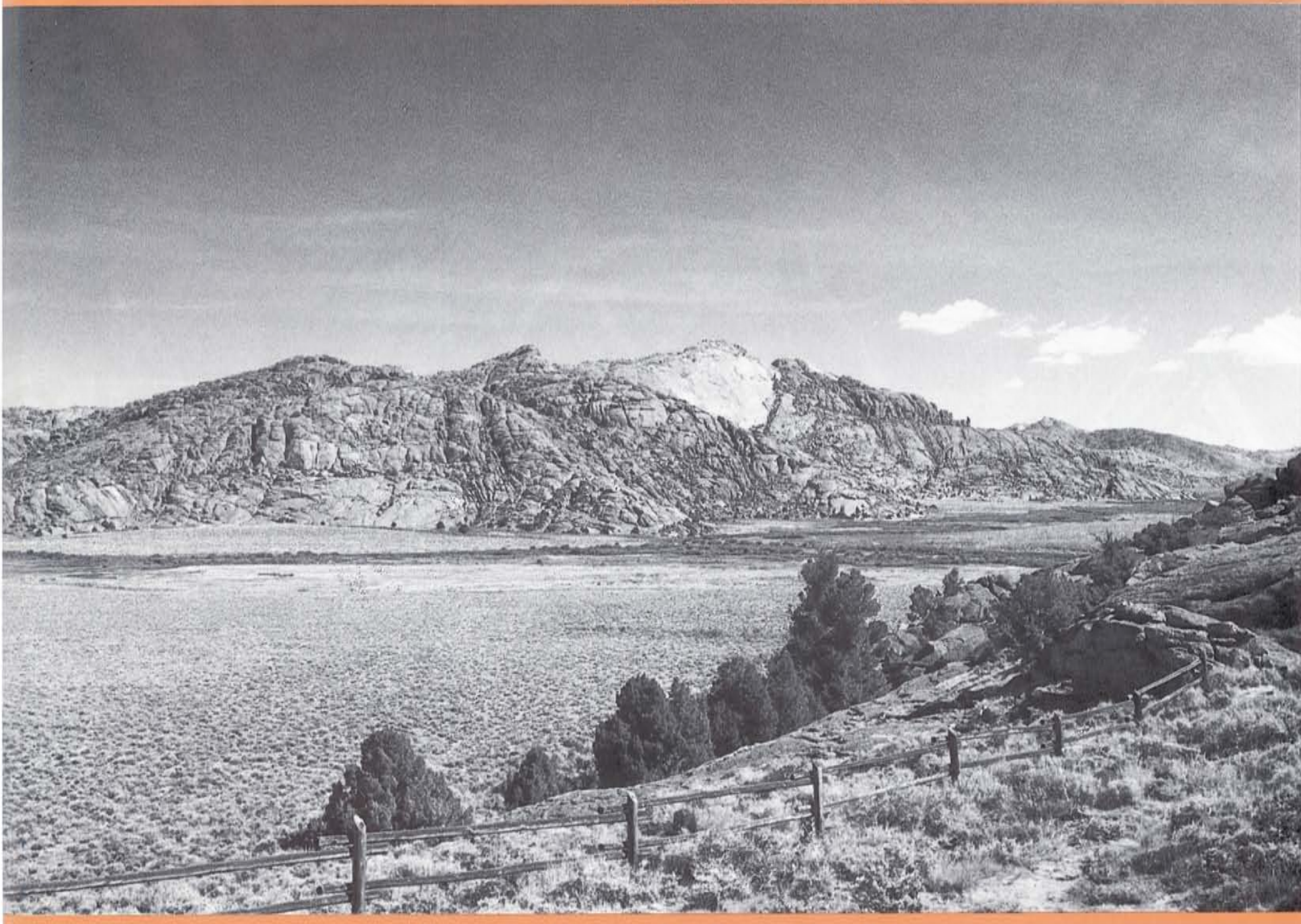
THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

TECTONIC RELATIONSHIPS OF THE SOUTHEASTERN WIND RIVER RANGE, SOUTHWESTERN SWEETWATER UPLIFT, AND RAWLINS UPLIFT, WYOMING

by

D.L. Blackstone, Jr.



Report of Investigations No. 47
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Front cover: View northwest across the Sweetwater River toward Split Rock in the Granite Mountains. The mountain is composed of Archean granite approximately 2.6 billion years old. The river flows across Miocene Split Rock Formation that unconformably overlies the Precambrian granite. The view is from the Sweetwater Crossing historical site on Wyoming Highway 287, approximately 7.5 miles northwest of Muddy Gap. The Oregon Trail followed the Sweetwater River valley in this area.

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Abstract

The southern Wind River Range is bounded on the southwest flank by the Wind River thrust fault. Subsidiary structures are present along the southeast plunging arch. The Sweetwater Crossing anticline lies on the northeast flank of the southern Wind River Range and is bounded on the south flank by the northeast dipping Mormon Trail fault. The Sweetwater uplift, east of the southern Wind River Range, has a structural pattern similar to that of the Wind River Range and is bounded on the southwest by the northeast dipping Emigrant Trail thrust fault. A complex series of folds lies in the area between the Wind River thrust fault and the Emigrant Trail thrust fault. Several of the folds host producing oil fields.

The geologic structures resulted from a horizontally directed compressive stress field that shortened the Precambrian crystalline basement during the Laramide tectonic event. As much as 20 miles (32 km) of lateral tectonic transport and crustal shortening is documented. Little evidence exists for strike-slip movement on wrench faults. A period of post-Miocene extensional tectonics reactivated earlier thrust faults in the hanging walls of the major thrust faults, creating normal faults such as the Continental fault and the South Granite Mountains fault.

Regional tectonic framework

The Wind River Range is the largest single discrete structural entity in Wyoming, extending from the Buffalo Fork River (Bengston, 1956) almost to the Rawlins uplift (Barlow, 1953), a distance of about 175 miles (280 km) (**Figure 1**). The range is bounded on the south and west by an east dipping, low-angle reverse fault (Smithson and others, 1979). The Wind River Range is the eastern boundary of the Green River Basin and the northern boundary of the Great Divide Basin. The other large structural element in this area is the Sweetwater uplift (Granite Mountains), bounded on the southern flank by the Emigrant Trail thrust fault. The region lying between the Wind River Range and the Sweetwater uplift and extending southeast to the Hanna Basin exhibits a series of folds and complex geology (Blackstone, 1990; and **Plate 1**).

Review of interpretations of the development of geologic structures

Previous investigators of this area have proposed several, sometimes conflicting, interpretations of the development of the existing geologic structures:

(1) *Deformation was attained by essentially vertical displacement of the Precambrian basement on high-angle faults*. This viewpoint was developed particularly by Prucha and others (1965) and Stearns (1978). Prucha and others (1965) proposed that vertical faults at depth in the basement complex flattened near the surface and allowed the basement to override sediments and sedimentary rocks in the footwall. Stearns (1978) advanced the idea that faults in the basement were high angle (70°) with normal-fault movement.

(2) *Deformation was the product of horizontal compression and resulted in crustal shortening and reverse faults.* Lovering (1929, 1932) indicated that thrusting was a major element of the deformation in the area, thereby implying horizontal compression. The same view was suggest by Fath (1922) and Fath and Moulton (1924). Branson and Branson (1940) viewed the Wind River Range as a large simple anticline, thereby suggesting crustal shortening. Blackstone (1940) and Berg (1962) presented evidence that the foreland structures were the result of horizontal compression. Barlow (1953) and Bell (1955) also supported that view. Love (1970) and Gries (1883) presented data in support of the horizontal compression view.

(3) *Deformation was controlled by a widespread system of wrench faults with large strike-slip movement.* This viewpoint was advanced by Sales (1968) and Stone (1971). Bell (1956) interpreted some structures in the southern Wind River Range to be associated with wrench-fault tectonics.

(4) *In a later stage of deformation, extensional tectonics with large-scale normal-fault movement resulted in*

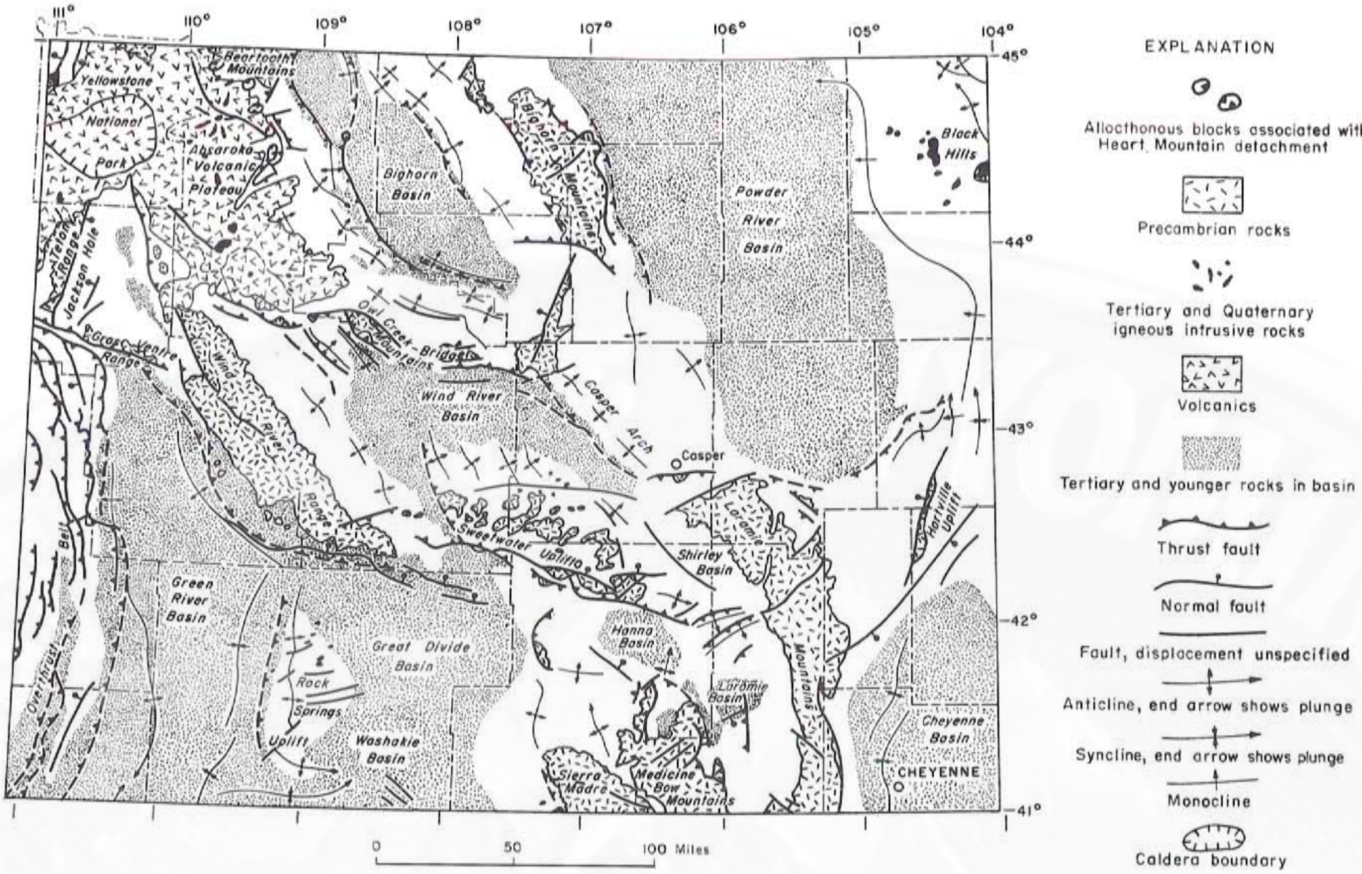


Figure 1. Major structural elements in Wyoming.

"collapse of mountains". This concept was presented by Nace (1939), Love (1970), and Sales (1971). Love viewed the normal faults as affecting the basement rocks and causing large-scale subsidence of mountain ranges ("collapse of mountains").

This study presents data to test the concepts outlined above, and also to review the influence of structures on the accumulation of oil and gas.

Stratigraphy

The timing of Laramide deformation was established on the basis of the stratigraphic record (Bell, 1956; Love, 1970). The basic pre-Tertiary stratigraphy of the area is presented in **Table 1A** The stratigraphy of rocks older than Late Cretaceous is relatively consistent across the area from west to east. Late Cretaceous and early Cenozoic rocks vary considerably in thickness from place to place, with the maximum total thickness in the Hanna Basin. Love (1970) discussed the Cenozoic rocks of the Granite Mountains (Sweetwater uplift of this report) in detail and the reader is referred to that source. Steidtmann and others (1983, 1989) reviewed the Cenozoic history of the southwestern corner of the Wind River Range with detailed stratigraphy.

Table 1A. Generalized pre-Tertiary stratigraphy of the region covered in Plate 1.

Geologic age	Formation name	Lithology	Thickness in feet West	East
CRETACEOUS	Lance Formation	Sandstone - white, gray buff; shale/claystone; coals	0?	1,700-2,500
	Fox Hills Sandstone	Sandstone - buff to light gray, fine- to medium-grained	0-150	0
	Lewis Shale	Shale - dark gray, soft; interbedded with thin sandstone beds		
	Mesaverde Formation	Sandstone - gray and brown, fine- to medium-grained; some thin carbonaceous layers and coals	1,000	1,200
	Cody Shale	Shale - gray, limy in lower part; thin persistent shales in upper part	4,000+	4,500-5,000
	Frontier Formation	Sandstone - gray and brown, more abundant in upper part; bentonite and tuff beds in lower part	800-900	700-900
	Mowry Shale	Shale - black, weathering to silver gray, hard, siliceous, abundant fish scales	250-300	450-500
	Thermopolis Shale	Muddy Sandstone Member: sandstone - gray to brown, medium-grained; black shale partings Lower Member: shale - black, soft, sandy near base	40-75 140	25-50 150
CRETACEOUS AND JURASSIC	Cloverly and Morrison	Upper part: sandstone and thin conglomerate; variegated claystones Lower part: sandstone - gray, silty; interbedded dull claystones	350-400	300-350
JURASSIC	Sundance Formation	Upper part: sandstone - pale green and brown, abundant glauconite; sandy glauconitic limestones Lower part: sandstone - gray, very fine-grained; thin, fossiliferous limestones	115-150 75-100	115-140 180-200
	Gypsum Spring Formation	Anhydrite (gypsum on outcrop) at base; red siltstones and red shales above	0-150	0
JURASSIC AND TRIASSIC	Nugget Sandstone	Sandstone - salmon red, medium-grained, crossbedded, rounded quartz grains	400-525	?
TRIASSIC	Chugwater Formation	Popo Agie Member: siltstone and claystone - purple, red, ocher Crow Mountain Member: sandstone - salmon-red, crossbedded Alcova Limestone Member: limestone - purple gray, thinly bedded Red Peak Member: siltstone and shale - brick red, soft	235- 50-100 2-10 800-900	0- 50-100 10-25 700-800
	Dinwoody Formation	Siltstone - brown, dolomitic, hard	50-100	50-100
PERMIAN	Phosphoria Formation	Dolomite - tan, petroliferous, thin sandstones; bedded chert	275-325	300
PENNSYLVANIAN	Tensleep Sandstone	Sandstone - white to gray, fine-grained, crossbedded; thin dolomite beds	250-300	300-350
PENNSYLVANIAN AND MISSISSIPPIAN	Amsden Formation	Shales - red and green; thin, dense, white dolomite Darwin Sandstone Member: sandstone - red and gray	260-300 0-50	250-300 0-50
MISSISSIPPIAN	Madison Limestone	Limestone - white to blue-gray, in part dolomitic, hard, cherty	400-500	200-300
DEVONIAN	Darby (?) Formation	Dolomite - thin, brown, petroliferous, if present	?	?
ORDOVICIAN	Bighorn Dolomite	Dolomite - gray to tan, hard, siliceous, massive; chert beds locally	0-50	0
CAMBRIAN	Undifferentiated	Limestone - brown to gray, glauconitic in upper part; green shales in middle part; red and brown sandstone in lower part	900-1,000	200-300
PRECAMBRIAN ARCHEAN		Gneisses, schists, and iron formation; granitic intrusion		

Table 1B. Stratigraphic names and abbreviations used in cross sections (Plate 2 and Figure 4). Presentation style of well data and well data abbreviations are also shown.

Stratigraphic names with abbreviations used in cross sections:

Tertiary

Tu = Tertiary, undivided
Tbs = Battle Springs Formation
Tw = Wasatch Formation
Tfu = Fort Union Formation

Cretaceous

Kla = Lance Formation
Kfh = Fox Hills Sandstone
Kle = Lewis Shale
Ka = Aspen Shale
Krs = Rock Springs Sandstone Member
Kbs = Baxter Shale
Kme = Meeteetse Formation
Kmv = Mesaverde Formation
Kc = Cody Shale
Kss = Shannon Sandstone
Ks = Steele Shale
Kn = Niobrara Formation
Kf = Frontier Formation
Kmr = Mowry Shale
Kmd = Muddy Sandstone Member, Thermopolis Shale
Kcv = Cloverly Formation
Kd = Dakota Sandstone

Jurassic

Jm = Morrison Formation
Js = Sundance Formation

Jurassic-Triassic

JTRn = Nugget Formation

Triassic

TRc = Chugwater Group or Formation

Permian

Pp = Phosphoria Formation

Pennsylvanian

Pts = Tensleep Sandstone

Mississippian

Mm = Madison Limestone

Cambrian

Ꞓ = Cambrian sedimentary rocks

Precambrian

PꞒ = Precambrian igneous and metamorphic rocks

Well data presentation:

Company name
Well name
Location (section-township-range)
Surface elevation   Total depth

Well data abbreviations:

Am.	=	American	Explor.	=	Exploration	Mt.	=	Mountain
Assoc.	=	Association	Fed.	=	Federal	O. & R.	=	Oil and Refining
Co.	=	Company	Gen.	=	General	Pac.	=	Pacific
Corp.	=	Corporation	Gov't.	=	Government	Petrol.	=	Petroleum
et al.	=	and others	Inc.	=	Incorporated	Prod.	=	Production

Structural geology

The principal geologic structures in south-central Wyoming are the southeastern part of the Wind River Range, the Sweetwater Crossing anticline, the Sweetwater uplift, and the Rawlins uplift (**Plate 1**). These features are large, fault-bounded, asymmetrical uplifts cored by segments of the Precambrian basement. Deformation occurred in the Late Cretaceous and Paleocene. Details of the geology of these structural elements follows.

Wind River Range

The modern topographic Wind River Range is underlain by a large, doubly plunging, asymmetrical anticline cored by Archean crystalline rocks. The major part of the fold trends N30°W. The western boundary of the Precambrian core of the range was established by surface mapping (Richmond, 1945; Baker, 1946; Love, 1950; Skinner, 1956; and Mitra and Frost, 1981). Further definition of the range core was derived from geophysical data (Coffin, 1946; Berg and Romberg, 1966a and b; and Smithson and others, 1979). Wells drilled during oil and gas exploration further delimited the bounding fault (Baker, 1946; Skinner, 1956; and Berg, 1983).

Wind River thrust fault

The southeastern segment of the Wind River thrust fault presented here (**Plate 1**) strikes generally N70°W and dips 25° to 30°NE (see **Plate 2A-D**). The COCORP reflection seismic line (Brewer and others, 1980) reveals a fault plane dip of 30°NE, essentially the same as shown in the current cross sections.

Horizontal displacement on the Wind River thrust fault in the central segment of the Wind River Range was interpreted by Royse and others (1975) to be 20 miles (32 km). Berg and others (1966a) interpreted the displacement to be 8.5 miles (13.6 km). Smithson and others (1979) interpreted the horizontal displacement to be 11 miles (18 km) in the southern part of the range. The writer interprets the horizontal displacement in the area of this report to be approximately 12 miles (19 km) (see **Plate 2A-D**). All these values are minima because erosion has stripped all sediments from the toe of the overthrust block, eliminating a reference surface to compare to the footwall cutoff.

Maximum vertical separation on the Wind River thrust fault occurs north of the study area between the Green River Basin near Pinedale, where the top of the Precambrian basement is at an elevation of 35,000 feet (10,670 m) below sea level, and the adjacent Wind River Range, where the same reference plane (top of the Precambrian) is elevated at least as high as the summit of Gannet Peak (13,804 feet/4,208 m above sea level). Vertical separation is therefore at least 48,804 feet (14,878 m). Vertical separation decreases to the southeast, reaching zero at the fault termination in T26N, R92W.

The COCORP seismic reflection traverse (Brewer and others, 1980) showed that the Wind River thrust fault extends to a depth of approximately 18 miles (30 km). The reflection data also indicates that the Wind River thrust fault extends through the upper crust with a dip of 30° to 38°, flattening above the Moho discontinuity. The crust behaved as a brittle material and failed by shearing. The data indicate a single major shear zone with no later movement.

Southeastern Wind River Range and associated structures

The southeastern end of the Wind River Range is a broad southeast plunging anticline. Precambrian basement is at an elevation of 12,490 feet (3,903 m) above mean sea level at Atlantic Peak (**Figure 2**) and crops out at least as far east as T28N, R97W. Beyond the last surface outcrop, the top of the basement slopes southeastward to an elevation of 12,000 feet (3,658 m) below sea level. The southwest flank of the anticline is bounded by the northeast dipping Wind River thrust fault, the trace of which is concealed by Cenozoic sediments.

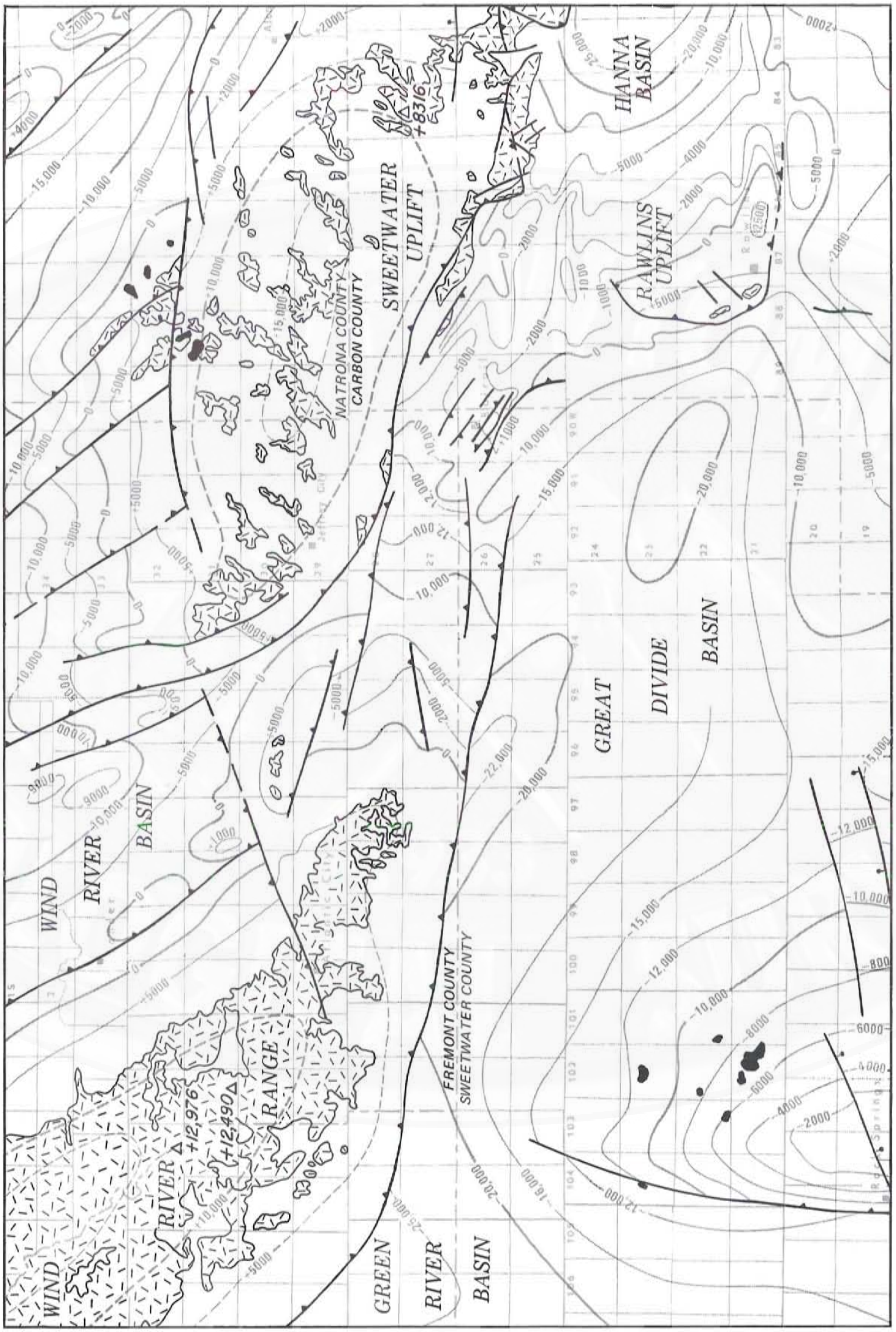
Four small structures are located on the major anticline: (1) Bison Basin fault and anticline (**Plate 2H**), (2) east Antelope anticline (**Plate 2J**), (3) Barren Butte graben, and (4) Flat Top fault (**Plate 2H** and **I**).

Bison Basin fault and anticline

The anticline, in T27N, R95W, lies in the footwall of the Bison Basin high-angle reverse fault. The controlling fault strikes N80°W and dips 70°NW (Bell, 1955) as shown on **Plate 2H** and **I**. Oil production is from the Frontier Formation. Deepest well penetration was to the Pennsylvanian Tensleep Sandstone.

East Antelope anticline

The structure, in T27N, R93W (**Plate 2J**), has been tested to the Pennsylvanian Tensleep Sandstone with


WIND RIVER BASIN
WIND RIVER RANGE
+12,976
+12,490
GREEN RIVER BASIN
FREMONT COUNTY
SWEETWATER COUNTY
GREAT DIVIDE BASIN
NATRONA COUNTY
CARBON COUNTY
SWEETWATER UPLIFT
+8316
RAWLINS UPLIFT
HANNA BASIN

SCALE 1:1,000,000

10 0 10 20 30 40 MILES

10 0 10 20 30 40 50 KILOMETERS

N

EXPLANATION

LITHOLOGIC UNITS

Precambrian rock outcrop.

Tertiary igneous intrusive rocks.

FAULTS (shown where they intersect Precambrian rocks at the surface or in the subsurface).

Thrust fault, sawteeth on upthrown side; dashed where inferred.

Normal fault, ball and bar on downthrown side; dashed where inferred.

High-angle fault, bars on upthrown side; dashed where inferred.

Fault, movement unspecified; dashed where inferred.

CONTOURS

-10,000 / +6000 — Elevation contour on top of Precambrian basement, in feet above (+) or below (-) mean sea level. Contour interval varies; heavy contour lines at 10,000-foot intervals.

3000 — Contour in footwall of thrust.

20,000 — Contour restored to pre-erosion elevation.

DATA POINTS

+12,490 △ — Elevations of Precambrian rocks in some of the highest mountain peaks (in feet).

Figure 2. Precambrian outcrop and structural configuration of part of central Wyoming, including the southern Wind River Range, Sweetwater uplift, and Rawlins uplift (from Blackstone, 1990).

no hydrocarbon production. Subsurface control is limited, but it is possible that the fold is controlled by a reverse fault of small displacement in the basement rocks.

Barren Butte graben

Barren Butte graben (also Bare Ring Butte of Love, 1970) trends approximately east-west. Subsurface control is so sparse that it is impossible to define the extent of the faults shown at the surface as bounding the graben. Displacement on these faults must be small, probably less than 500 feet. Three tests drilled on the north side of the graben failed to discover producible hydrocarbons. One of these reached the Pennsylvanian Tensleep Sandstone at a depth of 16,819 feet.

Flat Top fault

The Flat Top normal fault was named and described by Bell (1955) at a locality near a butte of the same name. The fault trends approximately N70°W, passes through Ts26 and 27N, Rs94, 95 and 96W, and dips to the south with the south side down. Bell (1955) reported the fault to have *several thousand feet of separation.* Love (1970) repeated this idea and stated:

> *This is a major fault, not only because of its enormous displacement in some localities, but because it represents several episodes of movement.*

Wells drilled subsequent to the work of these two investigators provided new data relative to movement along the fault. The fault was penetrated by General American Oil Company's No. 6 Olsen Springs test in sec. 6, T26N, R95W. In this test, the Cody Shale in the hanging wall is in fault contact with the Frontier Formation in the footwall with a vertical separation of approximately 3,000 feet (900 m).

The writer's interpretation is shown on **Plate 1** and **Plate 2H** and I. The cross section indicates that the Flat Top normal fault lies in the hanging wall of the Wind River thrust fault and is not the usual listric normal fault associated with thrust faults in this area. The specific mechanics and spatial relationships of this fault remain unresolved.

Sweetwater Crossing anticline

The Sweetwater Crossing anticline lies on the northeast flank of the southern Wind River Range, in Ts29 and 30N, Rs95 and 96W (**Plate 1**). It was named the Sweetwater Crossing anticline by Bell (1955) because it lies athwart the Sweetwater River on the historic Oregon Trail.

The anticline is cored at the surface by Precambrian basement, is asymmetrical to the southwest, and trends N70°W. It is the southernmost of a line of northwest trending, southwest verging folds extending from the Winkelman dome, in T2N, R1W (W.R.M.), to Sheep Mountain anticline, in Ts30 and 31N, Rs97 and 98W, as shown on the *Geologic map of Wyoming* (Love and Christiansen, 1985), and lying parallel to the northeast flank of the Wind River Range.

The anticline is bounded on the south by the Mormon Trail thrust fault system (Bell, 1955). The attitude of the fault is shown on **Plate 2G, I, J, and K.** The northeast flank of the Sweetwater Crossing anticline dips to the northeast and is overridden by the Emigrant Trail thrust plate.

Sweetwater Crossing anticline is separated from Sheep Mountain anticline by Spring Creek fault (**Plate 1**) (Gooldy, 1947), which trends N70°E and dips 60°S. The fault extends from T31N, R95W into the core of the Wind River Range near South Pass City, T29N, R100W (Hausel, 1986). Gooldy (1947) interpreted the fault as a low-angle, north dipping thrust fault. Subsequent drilling and surface mapping demonstrated this interpretation to be in error. The northeast part of the Sweetwater Crossing anticline is thrust northward over the Pennsylvanian Tensleep Sandstone exposed in the core of the Sheep Mountain anticline in the footwall of the Spring Creek thrust fault.

Sweetwater uplift (Granite Mountains)

The Sweetwater uplift (or arch) (**Plate 1**) is a major structure in central Wyoming. The appropriate name for this feature has been the subject of discussion (see Love, 1970), but the writer prefers the name Sweetwater uplift as more descriptive of the structural character and reserves the name Granite Mountains for the topographically high bare knobs of Precambrian granite in the core of the uplift.

The Sweetwater uplift is an asymmetrical, doubly plunging anticline cored by Archean basement. The uplift trends N70°W and is bounded on the west and southwest by the northeast dipping Emigrant Trail thrust fault that places Precambrian basement rocks in contact with sedimentary strata as young as the Eocene Wasatch-Battle Springs Formation (Love, 1970). The northern flank of the uplift is less well defined (Rich, 1962) and includes a series of northwest trending folds that plunge to the northwest into the Wind River Basin away from the uplift (Love and Christiansen, 1985). Near the northeast corner of the uplift, in Ts31 and 32N, Rs84 and 85W, exploratory drilling demonstrated that the boundary is a south dipping, high-angle reverse fault.

At an early stage of its development, the Sweetwater uplift was wedge-shaped in cross section, bounded on the north by a high-angle, south dipping reverse fault. The sedimentary cover was stripped from the hanging wall so that adjacent northwest plunging folds terminate against the bounding fault. The North Granite Mountains normal fault system (Love, 1970) is overprinted upon earlier structure, concealing the primary fault pattern.

Emigrant Trail thrust fault

The Emigrant Trail thrust, which bounds the Sweetwater uplift on the west and southwest, was initially named the *Immigrant* Trail thrust (Anonymous, 1951; Berg, 1962). The fault extends from T34N, R95W in a S25°E direction, then changes direction in T28N, R92W to S70°E. The eastern part of the fault system was originally termed the Seminoe thrust fault (Lovering, 1929, 1932). Later, Bayley (1968) and Blackstone (1983) referred to the fault as the Bradley Peak thrust fault. The dip of the fault plane is approximately 30°NE but may have a lower dip in some sections.

Separations on the fault are difficult to establish because most of the sedimentary cover has been stripped from the hanging wall, eliminating a reference plane for comparison with strata in the footwall (**Plate 2-J** and **K**). Near Crooks Gap, Paleozoic rocks are present on the toe of the hanging wall of the Emigrant Trail thrust fault and provide a datum to establish the amount of slip and vertical separation on that part of the fault. The lateral displacement (and overhang of the Precambrian) is approximately 7 miles (11 km). In the vicinity of Bradley Peak, in T25N, R85W, the horizontal displacement is approximately 1.3 miles (2 km) (Blackstone, 1983).

The amount of vertical separation on the fault varies. The sea-level elevation of the Precambrian basement in the footwall of the Emigrant Trail thrust fault ranges from 0 to -12,000 feet (-1,524 m) (**Plate 1**). The highest elevation of exposed Precambrian basement in the Granite Mountains (Pyramid Peak) is 8,316 feet (2,535 m), indicating vertical separation of at least 13,000 feet (3,963 m). Restoration of the original position of the Precambrian-Cambrian interface (Blackstone, 1990) indicates that the higher parts of the Sweetwater uplift may have been as much as 15,000 feet above sea level and the vertical separation is in excess of 24,000 feet (6,907 m).

The segment of the Emigrant Trail thrust fault between Three Forks Junction (Muddy Gap) (S 1/2 T28N, R89W) and Sand Creek Pass (NW T26N, R86W) has not been clearly defined. The Ferris Mountains lie south of this segment as a high prominent ridge characterized by steeply south dipping Paleozoic and Mesozoic rocks exposed in striking hogbacks (Heisey, 1951) (**Plate 2O**).

Immediately west of Three Forks Junction (T28N, R99W, **Plate 1**), the entire stratigraphic section from the Cambrian to the Upper Cretaceous strikes N60° to 65°W and dips steeply to the southwest or is overturned and overridden by the Precambrian basement. East of Three Forks Junction, the Cambrian-Precambrian interface crops out throughout the Ferris Mountains in the footwall of the thrust fault. Near Sand Creek Pass (T26N, R86W) the Cambrian-Precambrian interface passes eastward beneath Precambrian in the hanging wall (Lovering, 1929; Blackstone, 1965; Bayley, 1968). Between the two localities, the trace of the Emigrant Trail thrust fault must lie in the Precambrian terrane north of the Ferris Mountains, concealed by Late Cenozoic deposits. The relationship of the Ferris Mountains to the Emigrant Trail thrust fault is shown on **Plate 2-O** and **2-P**. Berg (1962) described the panel of overturned strata lying in the footwall beneath the fault plane (as encountered in the Carter Oil Co. No. 1 Scarlett Ranch tests in sec. 32, T30N, R93W), but such a panel of overturned strata is not a consistent feature of the fault throughout its extent.

Subsidiary structures

Jeffrey City triangle

The writer proposes the name Jeffrey City triangle for an area of complex faulting and folding located in T28N, Rs92 and 93W, about 4 miles south of Jeffrey City (**Plate 1 and Figure 3**). The area is between the surface traces of the Emigrant Trail thrust fault and the Mormon Trail thrust fault. Anticlines situated here include North and South Happy Springs, Crooks Gap, Spring Creek, Jade Ridge, the Kirk-Golden Goose fold complex, and Sheep Creek (**Figure 3** and accompanying cross sections, **Figure 4**).

North Happy Springs anticline

The fold, in T28N, R93W, trends essentially east-west and lies in the footwall of a high-angle reverse

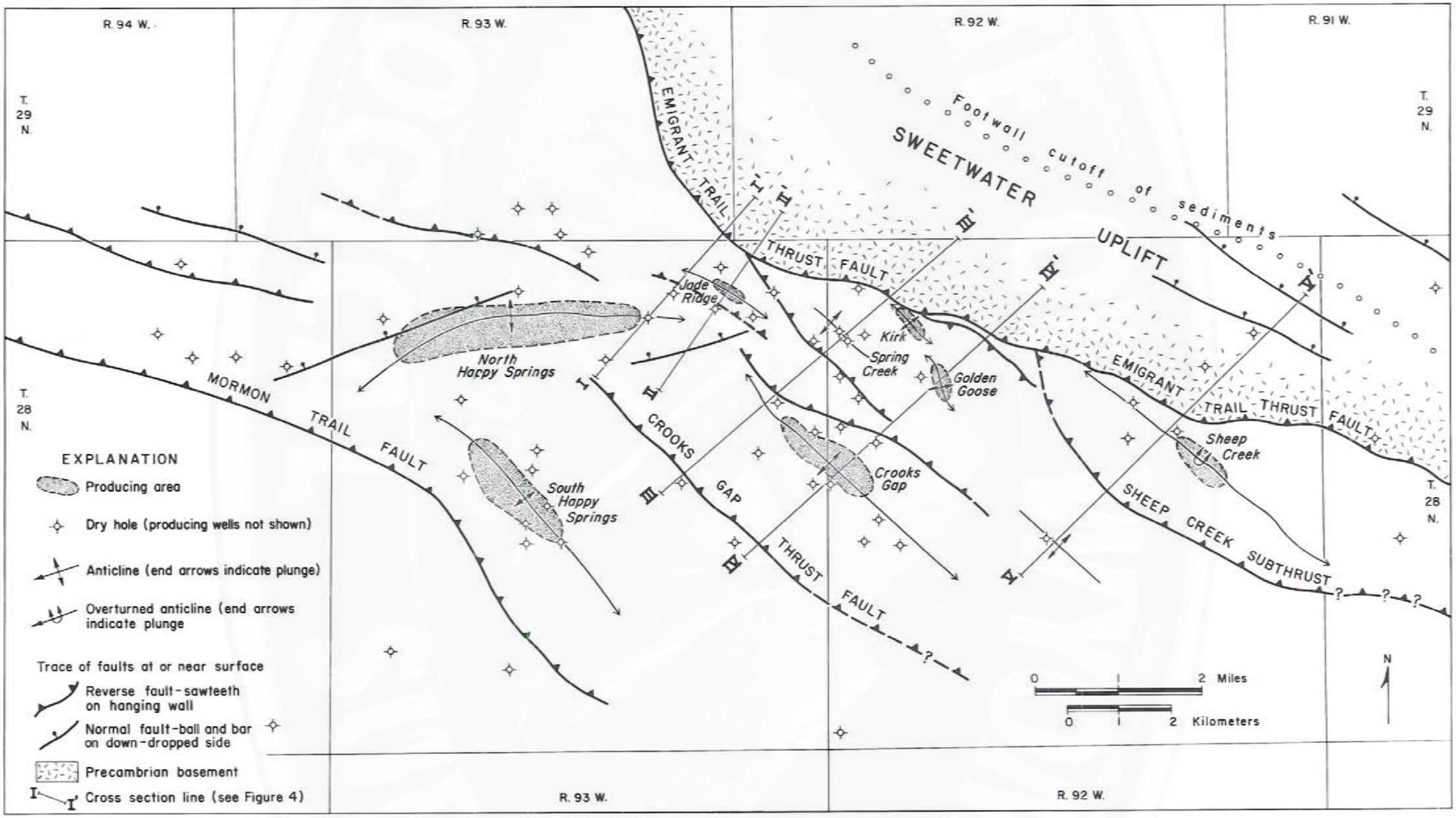


Figure 3. Geologic structure map of the Jeffrey City triangle area, Fremont County, Wyoming, with oil-producing areas and dry holes. Locations of cross sections I through V (Figure 4) are also shown.

fault, here called the North Happy Springs fault. The fault dips approximately 65°N (**Figure 4I**) and has a vertical separation of approximately 500 feet (150 m). The basic structure at the basement level is relatively straightforward, but the fault is concealed by Cenozoic deposits and is further complicated by the South Granite Mountains fault system (Love, 1970).

South Happy Springs anticline

The fold, in T28N, R93W, trends N30°W, plunges northwest and southeast, and is bounded on the southwest flank by the Mormon Trail reverse fault. The Mormon Trail fault dips 50°NE, is subparallel to the Emigrant Trail thrust fault, and has a vertical separation of approximately 4,000 feet (1,219 m).

Jade Ridge anticline

The Jade Ridge fold centers in secs. 1 and 2, T28N, R93W, trends N58°W, and is bounded on the southwest by a north dipping reverse fault (**Figure 3**). The bounding fault may be the southeast extension of the North Happy Springs fault. The fold is further constrained by a northeast dipping normal fault penetrated by two wells (**Figure 4II**). The apparent dip of the fault is 62°NE, with a vertical separation of approximately 800 feet (243 m).

Crooks Gap anticline

The anticline is a major fold trending N55°W in T28N, Rs92 and 93W. The fold is asymmetric to the southwest and lies in the hanging wall of a high-angle reverse fault (**Plate 1** and **Figures 4III** and **4V**) associated with the North Happy Springs fault. The fold is well defined by extensive drilling, with several wells reaching the Pennsylvanian Tensleep Sandstone.

Spring Creek anticline

The crest of the Spring Creek anticline lies in SW sec. 6, T28N, R92W. The fold trends N40°W (**Figures 3 and 4III**) and is very tight and complicated by several high-angle reverse faults. The fold lies in the footwall of the Emigrant Trail thrust fault and is bounded on the steep flank by two reverse faults that dip approximately 68°NE. The fold appears to be part of a wedge-shaped block bounded on the northeast flank by a north dipping reverse fault.

Kirk-Golden Goose fold complex

The fold complex, in secs. 5, 6, 7, and 8, T28N, R92W, trends N40°W and lies immediately in front of the surface trace of the Emigrant Trail thrust fault. The fold is bounded on the southwest by a reverse fault (**Figures 3 and 4III and IV**). The back limb dips to the northeast beneath the Emigrant Trail fault. The northeast extent of this fold is unknown.

Sheep Creek anticline

Sheep Creek anticline was described by Berg (1962), Hoots and Lavington (1979), Riva (1959), and Sales (1983). The southwest limb of the fold trends N50°W and is overturned, with dips from 60° to 75°NE, essentially parallel to the normal upright northeast limb (**Figure 3** and **Figure 4V**). The fold lies below the Emigrant Trail thrust and above a subthrust imbricate of that fault (Sheep Creek subthrust). The Emigrant Trail thrust fault dips 30° to 35°NE (**Plate 1** and **Plate 2K**), as established by Amoco Production Company's Boulder Dome Unit 1-11 Federal (NW SW sec. 11, T28N, R92W) and Boulder Dome Unit 1-12 Federal (NW NW NW sec. 12, T28N, R92W). The subthrust dips 15° to 20°NE and merges with the Emigrant Trail thrust fault at a depth of approximately 4,000 feet (1,219 m). The Sheep Creek fold is an excellent example of the panel of recumbent strata encountered in the footwall of many low-angle thrust faults in the Rocky Mountain foreland.

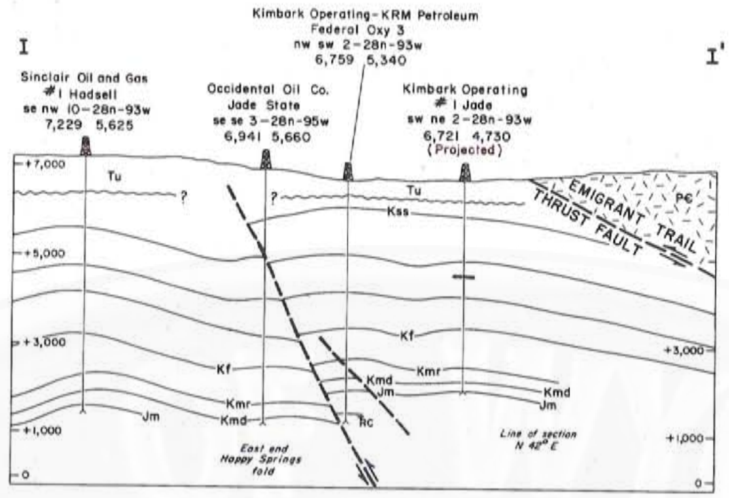
Eastern margin of the Great Divide Basin

The Great Divide (Red Desert) Basin lies south of the Wind River thrust fault. In the structurally deepest areas of the Great Divide Basin, the Precambrian-Phanerozoic rock interface is found at approximately -20,000 feet (-6,097 m) sea level elevation (**Plate 1**). The structural relief along the Wind River thrust varies from 0 in T26N, R91W to 20,000 feet (6,097 m) in T27N, R93W.

The structural divide between the Great Divide Basin and the Hanna Basin extends southward from the Lost Soldier anticline to the Rawlins uplift and eventually to the Sierra Madre south of Rawlins. A controlling factor for this structural divide is faulting in the Precambrian basement. A major reverse fault, West Lost Soldier fault, extends southeast from T26N, R91W to T24N, R89W. The fault is shown on **Plate 1** and **Plate 2L** through **O**. The structural divide in the area north of Bell Springs is not well defined.

Lost Soldier-Bell Springs segment

A complex of structures occupies the region south of the Emigrant Trail thrust fault and north of the Rawlins uplift. The most prolific oil fields in this area are Lost Soldier and Wertz (Ts26 and 27N, Rs89 and 90W). The fold complex trends N45°W. The folds are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Occidental Oil Co.
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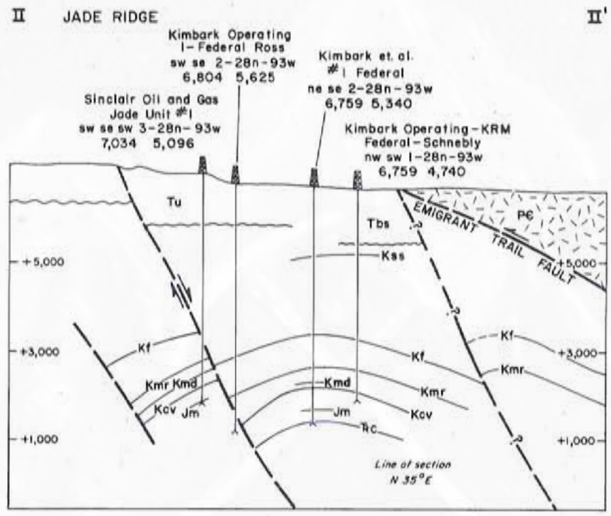
Happy Springs
fold
Line of section
N 42° E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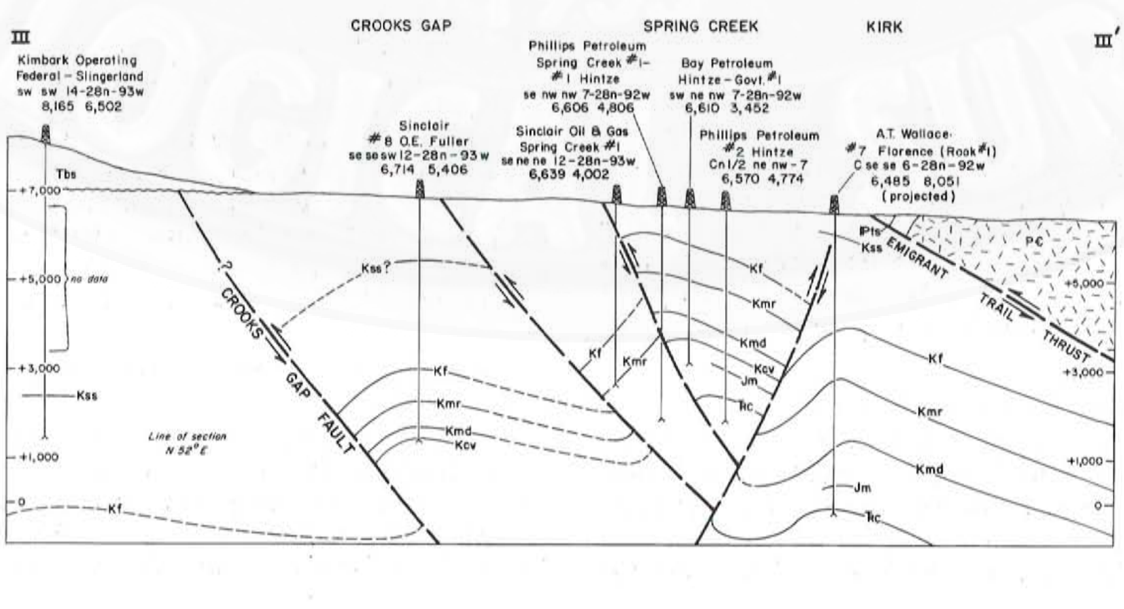
III
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Kimbark Operating
Federal-Slingerland
sw sw 14-28n-93w
8,165 6,502
Phillips Petroleum
Spring Creek #1-
#1 Hintze
se nw nw 7-28n-92w
6,606 4,806
Bay Petroleum
Hintze-Govt. #1
sw ne nw 7-28n-92w
6,610 3,452
Sinclair
#8 O.E. Fuller
se se sw 12-28n-93w
6,714 5,406
Sinclair Oil & Gas
Spring Creek #1
se ne ne 12-28n-93w
6,639 4,002
Phillips Petroleum
#2 Hintze
Cn1/2 ne nw-7
6,570 4,774
A.T. Wallace
#7 Florence (Rook #1)
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CROOKS GAP FAULT
EMIGRANT TRAIL THRUST
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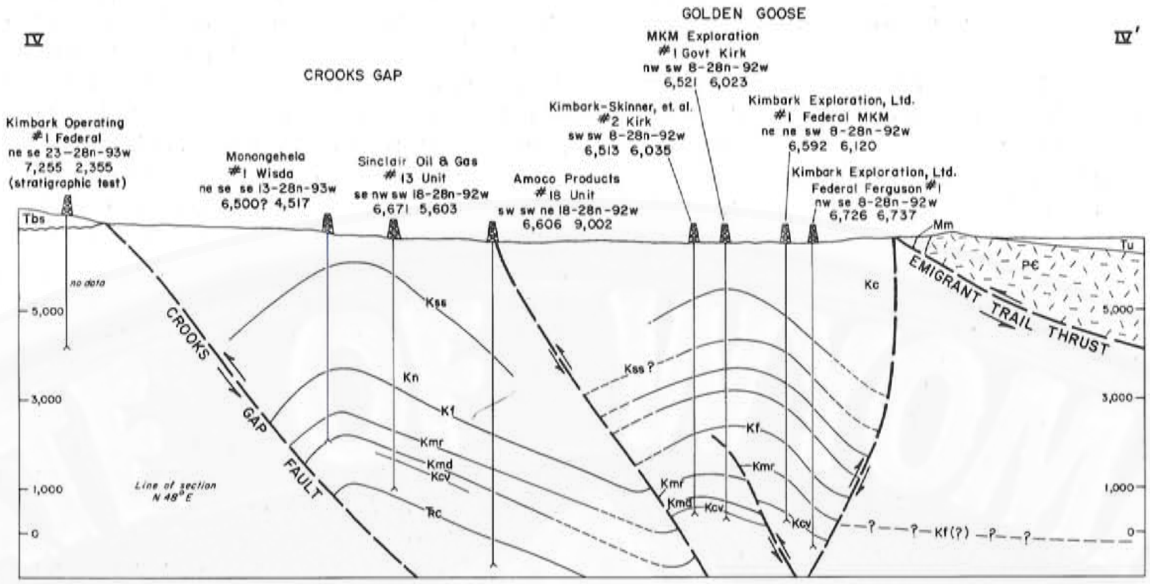

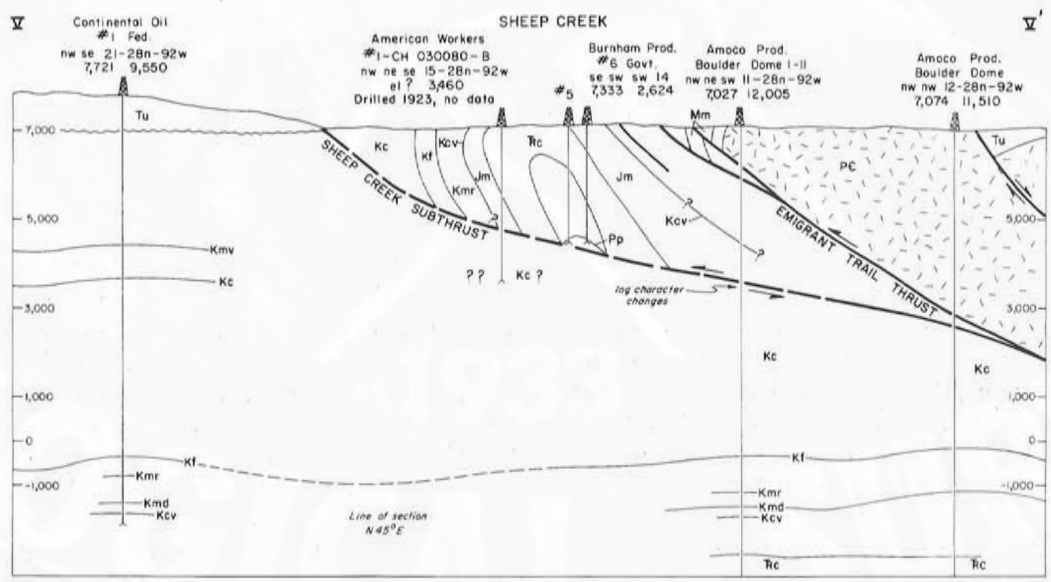

Figure 4. Geologic cross sections, Jeffrey City triangle area (locations on Figure 3; formation abbreviations and well data abbreviations and presentation in Table 1B). Vertical scales on all cross sections are in feet above or below mean sea level. No vertical exaggeration.

I. Cross section I-I', North Happy Springs.

II. Cross section II-II', Jade Ridge area.

III. Cross section III-III', Crooks Gap thrust fault to Kirk area.

IV. Cross section IV-IV', Crooks Gap anticline-Golden Goose area to Emigrant Trail thrust fault.

V. Cross section V-V', Sheep Creek anticline and Emigrant Trail thrust fault.

fault bounded and, in general, asymmetric to the southwest. The geology of the area was presented by Fath and Moulton (1924), Krampert (1923, 1949), and Reynolds (1971a and b). An unusual aspect of these fields is that Cambrian strata are a reservoir for hydrocarbons. Oil in the Cambrian is derived from Mesozoic source rocks that were placed in juxtaposition to the Cambrian by movement on the controlling faults. The relationships are shown on **Plate 1** and **Plate 2N**.

The Wertz anticline is the most northwesterly culmination of a line of folding that includes Baily Dome, Mahoney, West Ferris, and Ferris anticlines to the east. A second line of folding extends from SW T25N, R88W to the N 1/2 T24N, R85W. Individual highs along this trend (not shown on Plate 1) include (from west to east) Sherard Dome, O'Brien Springs anticline, East O'Brien Springs fold, and G.P. Dome. The low-relief folds are essentially symmetric.

Rawlins uplift

The Rawlins uplift occupies the southeastern part of the area shown in **Plate 1**. The uplift was discussed in detail by Barlow (1953) and reviewed later by Berry (1960). The uplift trends N25°W and has Precambrian basement exposed in the core. It is bounded on the northwest and west by the Bell Springs-Rawlins fault. In T23N, R88W, the fault changes trend to N55°E. The southern termination of the uplift, in T21N, R88W, approximately 5 miles southwest of Rawlins, is marked by a sharp change in the strike of the fault trace; the trend of the major bounding fault changes to approximately east-west and continues east to T21N, R86W. The result is a typical "corner" structure near the area of greatest elevation of the uplift. The east trending fault continues to and is reflected by the Grenville Dome, 3.5 miles (5.6 km) east of Rawlins.

The west flank of the Hanna Basin is the back limb of the Rawlins uplift, which dips approximately 15°E for a long distance into the basin. The Precambrian basement lies at a sea level elevation of -30,000 feet (-9,146 m) in the deepest part of the Hanna Basin (Blackstone, 1990).

Tectonic analysis

Geometric form of uplift margins

The configuration of the Precambrian-sedimentary interface in the Wyoming foreland province (Blackstone, 1990) reveals large uplifts and troughs with wavelengths varying from 50 miles (80 km) to 120 miles (193 km) and amplitudes of 1.13 miles (1.82 km) to 8.1 miles (13 km). The interface is definitely folded if the definitions given below are accepted.

> Folding - a process that bends planar surfaces to produce folds.
>
> Fold - a structure (geometric form) produced when an originally planar surface becomes bent or curved as a result of deformation.

The configuration of the Precambrian basement on the steep flank of an uplift or in the hanging wall of a fault-bounded uplift has been variously described (**Figure 5**). Blackstone (1940) viewed the bounding fault to be listric in form; as uplift continued, the angle of the fault plane was reduced to 25° by a new failure in the footwall.

Berg (1962) proposed an explanation for the fault-fold relationship based on drilling records and seismic profiles from several examples in the Rocky Mountain foreland and described the model as fold-thrust. A cross section of the western margin of the Wind River Range, Wyoming (Berg, 1962, Figures 2, 3, and 5) has been widely cited as the type for the model. Prucha and others (1965) viewed the bounding fault as near vertical at depth, avoiding the problem of providing space for true crustal shortening. Stearns (1971) viewed the bounding fault as a high-angle normal fault with subsidiary fractures. The unresolved problem in the last two models is the excess bed length of the involved strata. The fold form proposed by Prucha and others (1965) and Stearns (1971) was described as "drape folding" following the original usage of the term by Thom (1947).

Subsequent drilling and reflection seismic investigations (Gries, 1983) have revealed the existence of low-angle overthrusts of large magnitude on the flanks of some uplifts.

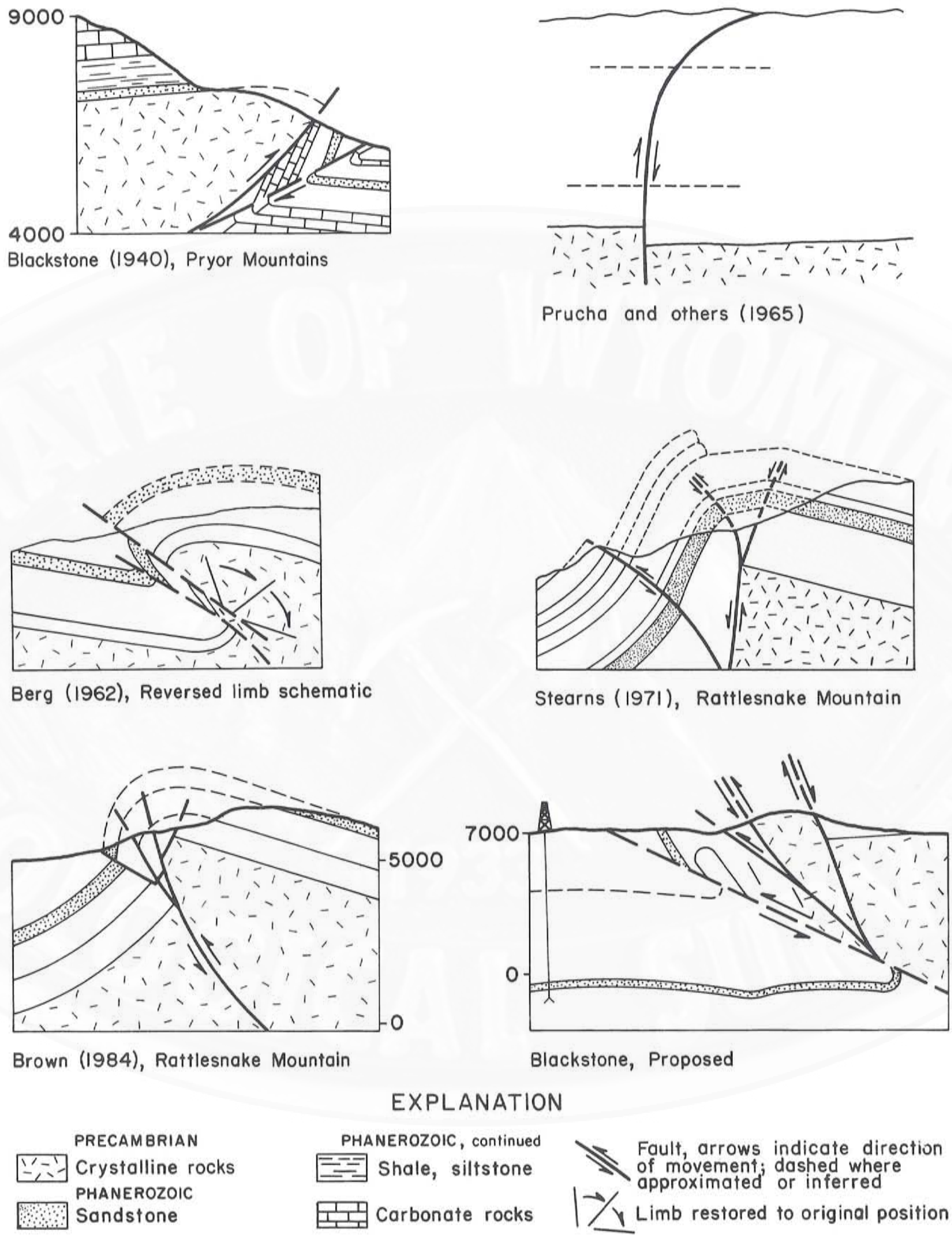

Figure 5. Selected cross-sectional interpretations of foreland faulting, 1940 to present.

Variations in structural trends

Variation in trend of faults and folds as well as changes in asymmetry or vergence exists throughout the foreland province. The asymmetry of folds and the attitudes of fault planes are variable but fairly consistent. The variation of such features in Wyoming is summarized on **Figure 6**. The variation has been attributed to basement control, to changes in the orientation of the stress field through time, and to random response of the basement to a uniform stress field.

Chamberlin (1945) recognized the tectonic pattern and commented as follows:

The outline of these ranges reflects both types of basement control. The transverse segmentation of the ranges into strips of alternating, oppo-

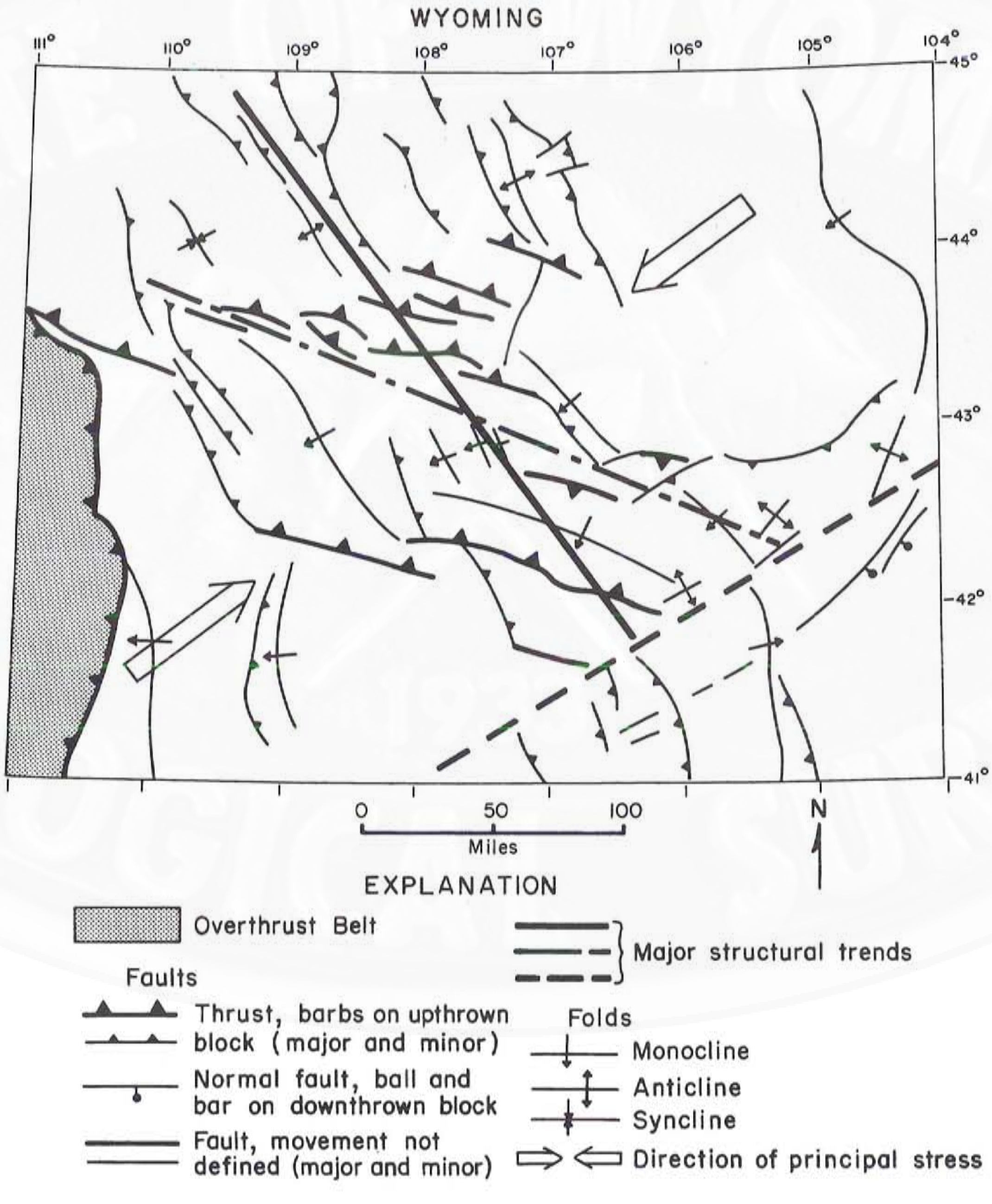

Figure 6. Major structural trends, Rocky Mountain foreland, Wyoming.

sitely directed asymmetry shows that the adjustments by differential horizontal movements affected a large area.

Four principal trends of major tectonic elements in Wyoming are:

1. N25° to 30°W
2. N70° to 80°W
3. N50° to 55°E
4. North-south

Three of the structural trends occur in the area under discussion and are shown on **Plate 1** and **Figure 6** and documented in cross sections. The variation in structural trends and the reversal of asymmetry of the folds in the Rocky Mountain foreland have been cited as evidence both for and against various orientations of the stress field that created the structures.

Stearns (1978) cited the variation in asymmetry as evidence against a uniform horizontally directed stress field and as evidence for a vertically directed stress field. Brown (1984) recognized that within individual fold trends and mountain uplifts there was further segmentation along faults with large components of strike slip (**Figure 5**). For this situation, he proposed the term *compartmental deformation*. He also considered the deformation to be due to a horizontally directed compressional stress field in a general northeast-southwest orientation.

Regional interpretations

The Rocky Mountain foreland includes diverse structures that have had a common tectonic history. Investigators have proposed tectonic activity on a regional scale to explain the existing structures. A brief review of these interpretations follows.

Sales (1968), in a sweeping discussion of regional structure based in part on an intuitive analysis of non-scaled models, attempted a synthesis of structures of the entire Western United States. He considered the structural features of central Wyoming to be the result of what he described as the *Wyoming couple*, left-lateral movement created by the eastward translation of the Colorado Plateau block relative to the unyielding Canadian foreland.

Stone (1969a and b) proposed a widespread system of wrench faults with this same general orientation that would explain all secondary structures. Essentially all structures were related to lateral slip on the major wrench faults. The difficulty with this approach is that very few if any of the proposed wrench faults can be demonstrated on the basis of hard evidence to have lateral slip of the magnitude necessary to accommodate the crustal shortening that is present.

Scheevel (1983) reviewed the pattern of failure of the continental crust in the Rocky Mountain foreland province and concluded that the stress field was one of uniform horizontal compression and that failure of the basement propagated from the top of the crust downward. The orientation of the individual structures reflected a variety of factors largely controlled by the nature of the Precambrian basement.

Gries (1983) proposed an additional explanation for the N70°W trending features and suggested that there were two episodes of tectonic activity with the principal stress directions oriented first north-south and subsequently east-west.

The writer proposes a different explanation for the regional structural orientations. The two major orientations (N25° to 30°W and N70° to 80°W) form a conjugate set of fractures intersecting at an acute angle of 30° (**Figure 6**). The writer suggests these two principal zones of weakness in the upper crust (Precambrian basement) existed in pre-Laramide time. The region was subjected to a uniform horizontally directed stress field (Scheevel, 1983) during the Laramide tectonic event and the two fracture systems reacted differently. The asymmetry of the structures is immaterial, since either plane of a classic 30° to 60° shear pattern may be the plane of relief of stress.

The writer finds little hard evidence of lateral slip on wrench faults at a magnitude sufficient to account for the amount of crustal shortening observed in the region.

Modification of the thrust-fold model

Berg (1962) developed the *fold-thrust* model based on a cross section of the west flank of the Wind River Range (**Figure 5**). The cross section has been reproduced several times and has become the type model for the concept. Stone (1984) suggested changing the term to *thrust-fold*, attempting to introduce a genetic connotation into the term.

The writer finds a flaw in Berg's cross section. The cutoff of the Cambrian section (Berg, 1962) in the hanging wall of the Wind River thrust fault is inferred, since the Paleozoic section has been stripped by erosion. At Boulder, Wyoming, the Cambrian was probably elevated to about 6,000 feet (1,929 m) (Love,

1950) and was located not more than 12,000 feet (3,658 m) west of the cross section as drawn. Gannet Peak, the highest point in the Wind River Range, is at an elevation of 13,804 feet (5,208 m) and it is assumed that the Cambrian sediments overlying the Precambrian core were at least at that elevation. The footwall cutoff of the Cambrian section is at an elevation of -25,000 feet (-7,622 m) with a separation in the plane of the fault of 60,000 feet (18,292 m) (Berg, 1962). The cross section (Berg, 1962) provides no source for the recumbent slab of Paleozoic strata lying in the footwall of the major thrust fault, yet at the same time it honors the hanging wall and footwall cutoff points. The inverted slab is inferred since it was not penetrated by a bore hole, though Berg (1962) reported similar inverted sections encountered in drilling elsewhere. If the inverted slab is folded back to the east to a normal and upright position, where it must have been before faulting (see **Figure 5** for possible movement), the footwall cutoff must be shifted at least 8.7 miles (14 km) to the northeast. Such a position would double the separation in the plane of the thrust fault. Such a separation is completely inconsistent with that reported by Royse and others (1975) and Smithson and others (1979). Because of this geometrical problem and also because of excessive bed length across the fold, the writer doubts the existence of an inverted slab in the footwall.

Evidence for inverted slabs in the footwalls of thrust faults in the Rocky Mountain foreland province is dubious and usually based on a single bore hole, limited samples or cores, and (or) poor seismic reflection records. More likely, what exists are extremely sliced or slivered Paleozoic sediments caught up in the actual shear zone, smeared out, and retaining little continuity.

The fold-thrust model of Berg (1962) is satisfactory, provided the fold is not viewed as recumbent but rather as an original, open, major bend of the upper surface of the Precambrian basement. The writer believes that the interpretation shown in **Figure 5** (Blackstone, proposed), a cross section through the Emigrant Trail thrust, is a more reasonable explanation of what occurs.

Extensional tectonics

The major tectonic units discussed in this paper developed during a period of compressional stress described as the Laramide tectonic episode. Erosion created a mature topography across the regions elevated during the Laramide deformation and subsequently buried under a sequence of Tertiary strata (beginning with the Oligocene White River Formation and culminating with the Miocene-Pliocene Moonstone Formation).

Following Tertiary deposition, extensional tectonism created a system of normal faults. Nace (1939) first recognized the major normal faults and described the Continental fault in the vicinity of Oregon Buttes (**Plate 1**). Love (1970), in his monograph on the Granite Mountains, named two major systems of normal faults: the North Granite Mountains system and the South Granite Mountains system.

The North Granite Mountains system lies along the northern flank of the Sweetwater uplift and trends east-west. The average displacement is approximately 800 feet (243 m) on faults that dip to the south, with movement down to the south. The South Granite Mountains fault system trends N70°W and closely parallels the trace of the Emigrant Trail thrust fault on the south flank of the Sweetwater uplift. Displacement on the fault system is as great as 2,000 feet (609 m) and movement is down to the north.

Love's cross sections (1970) depict the normal faults as vertical and superposed upon all earlier structure including the basement. He discussed the general structural result under the concept of *collapse of mountains*.

Additional data derived from mapping, drilling, and seismic profiling reveals that the normal faults are not vertical, but dip in the same direction as the thrust fault with which they are associated. They are best interpreted as listric normal faults similar to those described by Royse and others (1975). The surface traces of the listric normal faults lie in the hanging walls of the major thrusts and closely parallel the traces of the major thrusts. For example, the Continental fault (Nace, 1939) lies in the hanging wall of the Wind River thrust fault and parallels its trace. Such listric faults (see fault at right edge of **Figure 4V**) merge down dip into the sole of the thrust fault and result from reactivation of the thrust faults during the later episode of regional extensional tectonism.

The reactivation of the reverse fault with a sense of motion opposite the original displacement results in depression of the hanging-wall block. The depression of the hanging-wall block is relatively small when compared to the total differential displacement across the major fault. In the case of the Emigrant Trail thrust fault, the original vertical separation may have been as great as 27,000 feet (8,231 m). The maximum reported normal fault displacement is 2,000 feet (610 m), which is approximately 7 percent of total displacement.

Petroleum and natural gas

In 1986, the region depicted on **Plate** 1 had 13 producing oil and gas fields and 16 abandoned or potential oil and gas fields. Both extensive and intensive drilling occurred during the exploration for oil and gas in the region. Locations of exploratory tests and producing fields appear on **Plate** 1.

Three types of exploration plays were carried out in the area, with the following targets:

1. Large well-defined surface anticlines (*sheepherder anticlines*) controlled by faults in the Precambrian basement;
2. Subthrust structures lying in the footwalls of major, low-angle thrust faults;
3. Stratigraphic traps associated with low-relief structures.

The largest accumulation of hydrocarbons occurs in the Lost Soldier-Wertz compound fold of type 1 target category. The folds appear to have developed early in Laramide deformation and thus entrapped hydrocarbons earlier than other structures in the area.

Deformation in the footwall of a major thrust is a likely site for anticlinal folding and oil and gas entrapment. The detection of such features, which may lie beneath plates of crystalline rocks in the hanging walls of major thrust faults, is difficult. Rocks with high-velocity transmission of energy cause velocity "pull up" in the footwall that may be interpreted as an anticline.

Stratigraphic traps for oil and gas, like those in the Great Divide Basin, are the most difficult to define. Accumulations are probably the result of a combination of minor structural relief and lateral variations in the stratigraphy. Within the area discussed, well control is insufficient to fully define the nature of such traps.

Conclusions

The Wind River thrust fault extends 40 miles (64 km) southeastward from South Pass City and controls the structural pattern of the southeast plunging termination of the Wind River Range. The Emigrant Trail thrust fault and resulting crustal shortening controls the subsidiary structures southwest of the fault and northeast of the Wind River thrust fault. The major faults dip 30° to 35°, and horizontal movement on these faults has been as much as 20 miles (32 km). An episode of extensional tectonics of Late Cenozoic age created a system of listric normal faults closely related spatially to the traces of the low-angle thrust faults.

Acknowledgments

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