THE GEOLOGICAL SURVEY OF WYOMING
H. D. THOMAS, State Geologist

BULLETIN No. 33

STRUCTURE OF THE ELK MOUNTAIN DISTRICT, CARBON COUNTY, WYOMING

BY

R. H. BECKWITH

Reprinted from BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA, Vol. 52, pp. 1445-1486

UNIVERSITY OF WYOMING
LARAMIE, WYOMING
SEPT., 1941

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1445-1486, 2 PLS., 1 FIG. SEPTEMBER 1, 1941

STRUCTURE OF THE ELK MOUNTAIN DISTRICT, CARBON COUNTY, WYOMING

BY R. H. BECKWITH

CONTENTS

	Page
Abstract	1446
Introduction and acknowledgments	1446
Topography and drainage	1448
Pre-Cambrian rocks	1450
Stratigraphy	1451
General statement	1451
Notes on nomenclature	1451
Hanna and Carbon Basins	1454
Time of deformation	1455
Competence of rocks	1455
Drawing of folds	1457
Structure	1458
Elk Mountain	1458
Northeastern area	1460
Simpson Ridge anticline	1460
Halleck Creek syncline	1461
Bloody Lake anticline	1462
Fort Halleck syncline and vicinity	1463
Relation to Elk Mountain block	1463
Northwestern area	1464
Rattlesnake Creek syncline	1464
Sheephead Mountain anticline	1465
Anticline east of Sheephead Mountain	1466
Sheephead Mountain fault	1466
Reservoir fault	1466
Rattlesnake Pass fault	1467
Bear Butte fault	1470
Coad Mountain and Pennock Mountain area	1473
Bear Butte fault and vicinity	1473
Southwestern part of Coad Mountain	1473
Coad Mountain fault	1474
Pennock Mountain fault system	1475
Pass Creek Basin area	1478
Oil and gas possibilities	1479
General statement	1479
Bloody Lake anticline	1480
Simpson Ridge and Pass Creek anticlines	1480
Conclusions on Elk Mountain district	1481

	Page
Relation to structure of surrounding region	1482
Description	1482
Interpretation	1483
Works to which reference is made	1484

ILLUSTRATIONS

Figure	Page
1. Index map of southeastern Wyoming	1447

Plate	Facing page
1. Geologic map and structure sections of the Elk Mountain district	1480
2. Tectonic map of the region around the north end of the Medicine Bow Range	1482

ABSTRACT

The Elk Mountain district is at the northwest end of the Medicine Bow Range, where trend changes from northerly in the Southern Rockies to westerly in the Central Rockies of Wyoming. Deformation of pre-Cambrian crystallines and 17,000 feet of predominantly shaly Paleozoic and Mesozoic beds proceeded during and after the deposition of many thousand feet of Upper Cretaceous and Fort Union beds in the basin to the north. Folds trend generally north, and their axial planes dip west. The following unusual features are described and discussed in terms of genesis:

(1) Two westward-dipping thrusts pass laterally northward into west-striking tears, which cut across folds; deformation in a block on one side of a tear was more or less independent of that in the other block. (2) A thrust cuts diagonally across a major syncline and anticline. (3) Marked rotatory movement is shown by a northeast-striking tear, which terminates upward at a thrust, and by several smaller tears cutting across slices between thrusts. (4) A fault having the characteristics of a subsequent shear thrust is probably a combined break and erosion thrust. (5) A bedding thrust in the bentonite-bearing Mowry shale of the gentle west flank of an anticline crosses the axis and offsets the axial plane.

Oil and gas possibilities of the district and the possible effects of bedding thrusts on oil traps are discussed.

The structural pattern of the district and surrounding region (Pl. 2) diverges greatly from that produced by uniform stress applied to uniform rocks. This is attributed to effective compression acting in different directions and to the influence of such features as bedding, schistosity, contacts of igneous bodies, and faults in the pre-Cambrian.

INTRODUCTION AND ACKNOWLEDGMENTS

Three anticlinal mountain ranges extend into southeastern Wyoming (Fig. 1) from the south—the Laramie, Medicine Bow, and the Sierra Madre. The Sweetwater Arch, a broad belt of pre-Cambrian rocks, extends west-northwest for 100 miles from a point 35 miles north of the Medicine Bow Range and joins the Wind River Range in west-central Wyoming.

The Elk Mountain district at the northwest end of the Medicine Bow Range occupies a position of abrupt change from the northerly structural trends of the Southern Rockies to the westerly trends of central Wyoming. The present study was undertaken by the Geological Survey of Wyoming to obtain detailed information on this change and to extend present knowledge of relations of folds, thrusts, and tear faults. It was also hoped that certain structural relations shown in beds of the lower part

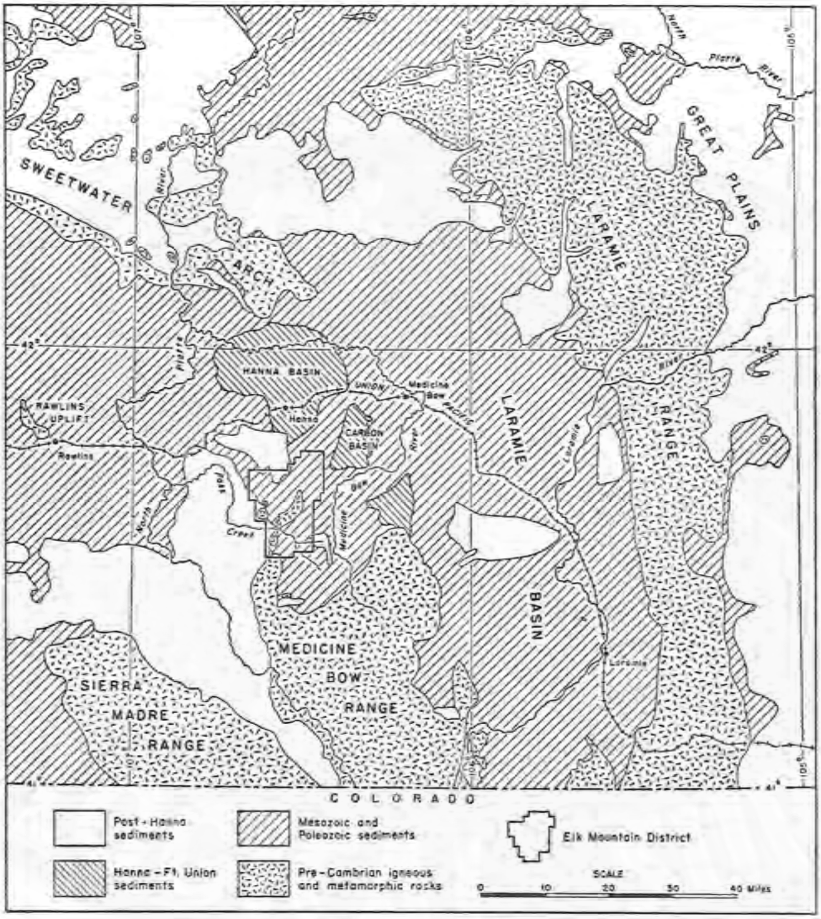


FIGURE 1.—*Index map of southeastern Wyoming*

of the stratigraphic column in areas of good exposures would facilitate interpretation in other areas where only isolated surface observations or subsurface data can be obtained, as in some of the oil fields in the surrounding region.

The area covered by the writer was first mapped in very generalized form by the Fortieth Parallel Survey (King, 1876, Map I). Veatch (1907) investigated the coal-bearing rocks in the northern part but grouped as a unit all of the older sediments not containing commercial coal. The map by Dobbin and associates (1929a) on a scale of 1 inch to a mile includes the Hanna and Carbon basins and adjacent territory. A strip one mile wide at the north end of the writer's map (Pl. 1) overlaps their area. Neely's reconnaissance of the north end of the Medicine Bow Range (Neely, 1934) included Coad Mountain and the southeast end of Elk Mountain. Isberg (1937) made a reconnaisance map of the west and north sides of Elk Mountain and a considerable area to the west.

All of the Elk Mountain district, except a strip 2 to 4 miles wide along the eastern border, is included in the Fort Steele sheet, a reconnaissance map by the U. S. Geological Survey on a scale of 1:125,000 and with contour intervals of 25 and 50 feet. Topography is not tied in with land subdivisions and is not accurately enough represented to serve as a base map for detailed geology.

Approximately 135 square miles is included in the mapped area (Pl. 1). With the exception of the interior parts of the pre-Cambrian cores of the mountains, the mapping was done with plane table on a scale of 1 inch=1000 feet for the northwestern third and 1 inch=1500 feet for the remainder. Field work was started in the summer of 1938 and completed in the fall of 1940.

The writer wishes to acknowledge the valuable suggestions and assistance received from his colleagues of the Geology Department of the University of Wyoming—Dr. S. H. Knight, Dr. H. D. Thomas, and Dr. A. F. Hagner. Mr. R. G. Greene of the Union Pacific Railway Company Exploration Department facilitated the assembling of data on the structure of the surrounding region by the loan of maps of certain areas for which there are no published data. The writer also wishes to express thanks to his field assistants, Milan D. Maravich, Waynard G. Olson, and Thomas L. Kirby.

TOPOGRAPHY AND DRAINAGE

The most prominent topographic feature of the district (Pl. 1) is the high broken ridge formed by the crystalline core of the western branch of the Medicine Bow Range. It extends from the southwest corner to the north-central part of the district. Most of the ridge crest is at elevations above 9000 feet and attains a maximum of 11,162 feet at the peak of Elk Mountain. The ridge is broken by two gaps. The elevation of the southern one, Oberg Pass between Pennock Mountain and Coad Mountain, is 8200 feet. Pass Creek has cut a canyon between Coad Mountain and Elk Mountain forming a second gap at an elevation of

7300 feet. All three mountains are markedly asymmetric, having steeper eastern faces.

From the eastern bases of the mountains alluvium-covered pediments slope eastward at angles as high as 7° and gradually flatten toward the Pass Creek Basin and the valley of the Medicine Bow River. At the north base of Elk Mountain the Cloverly conglomerate forms a prominent ridge that swings around to the west and south. The sandstones of the Mesaverde formation form another ridge up to 500 feet high extending northeastward across the northern part of the district. From the bases of both ridges a gently rolling alluvium-covered surface slopes toward the alkali lakes in the lower part of the basin of Halleck Creek at elevations around 7300 feet.

West of Elk Mountain the Cloverly conglomerate forms two high ridges on the flanks of a northward-trending syncline. Strike valleys on the adjoining shale outcrops drain north and south into Rattlesnake Creek and Pass Creek.

Sheephead Mountain in the northwestern part of the district is a strongly asymmetric mountain rising to 8700 feet. The east side is very steep and, in some places, is nearly vertical for several hundred feet. The slope toward the north is more gradual and is broken by a ridge of Cloverly conglomerate. About a mile north Rattlesnake Creek flows in a bend roughly parallel to the Cloverly ridge. Northeast and northwest from the bend the surface rises abruptly about 500 feet to the crest of the ridge formed by the Mesaverde sandstone. Sheephead Mountain is sharply cut off on the south by the valley of Hat Creek, which narrows to a canyon several hundred feet deep in crossing the upturned resistant sediments at the southeast end of the mountain.

Bear Butte is composed of granites and gneisses. The eastern part near the watershed is carved into sharp crags and pinnacles. Farther west the topography is more subdued and merges into the gently rolling surface cut on the non-resistant Tertiary beds, which extend westward from the mountains to the valley of the North Platte.

The northeastern part of the district is drained by a few small permanent streams and a number of intermittent streams tributary to the Medicine Bow River (Fig. 1). The northwestern part is drained by Rattlesnake Creek and Hat Creek, which enter Pass Creek a few miles west of the mountains. A large part of the embayment in the north end of the Medicine Bow Range drains into Pass Creek, which flows through the canyon between Elk Mountain and Coad Mountain and enters the North Platte about 20 miles to the northwest. That a continuous cover of younger Tertiary sediments once extended through the gap is indicated by the large areas of Tertiary sediments in the upper Pass

Creek Basin, the small remnants north and south of the east end of the canyon (Pl. 1) occurring as high as 1000 feet above the present flood plain, and the extensive area west of the mountains. Pass Creek is probably a superimposed stream. No Tertiary sediments were found above 9000 feet, and it is therefore improbable that the mountains were completely covered. It is suggested that before the deposition of the younger Tertiary erosion had cut a saddle along the Bear Butte fault between Elk Mountain and Coad Mountain.

Glaciation has played only a very minor part in land sculpture. A few of the stream valleys heading in the higher parts of Elk Mountain have broad cirquelike heads, and some of the material mapped as alluvium has the characteristics of glacial material. The V-shaped profiles of valleys below 9500 feet indicate that ice did not penetrate far below this elevation.

PRE-CAMBRIAN ROCKS

Detailed studies of the pre-Cambrian rocks were not made. In working around the borders of pre-Cambrian areas, however, various features were observed. The alluvial material along short streams also provided information on the rocks along their courses. The writer believes that structures in the pre-Cambrian complex exerted a considerable influence on those formed during the Laramide orogeny, and the following observations are therefore given.

The core of the Medicine Bow Range, 10 to 15 miles southeast of the embayment in the north end, contains an extensive area of metamorphic rocks. Blackwelder (1926) describes a succession of quartzites, dolomitic marbles, slates, schists, and metamorphosed pyroclastics occupying an area 5 miles wide and extending northeast for at least 12 miles. The succession is about 24,000 feet thick. The metamorphosed sediments and pyroclastics are cut by metadiabase and granite dikes and are enclosed in a complex of gneisses, schists, and granites. Beds strike northeast and dip steeply to the southeast. A major strike fault apparently has a high dip. A number of nearly vertical dip faults offset beds hundreds of feet.

The oldest rocks in the Elk Mountain district are hornblende schists and metadiabases; they were probably originally basalt flows and diabase sills and dikes. Some of the more micaceous schists may have been argillaceous sedimentary rocks. The writer has seen no evidence of metamorphosed sediments such as quartzites and marbles in the exposed parts of the pre-Cambrian, and the gulches heading in the mountains of the district do not carry quartzite pebbles. The abundant quartzite boulders and pebbles in the Tertiary sediments and alluvium of the Pass Creek Basin are undoubtedly derived from the known areas of quartzites to the southeast. The schists and metadiabases have been invaded by granites, predominantly of the potash variety, and have been stoped, absorbed, and injected to form gneisses. In addition there are extensive areas of massive granites.

STRATIGRAPHY

GENERAL STATEMENT

The stratigraphic section (Table 1) includes approximately 15,000 feet of Cambrian to Upper Cretaceous beds. Disconformities cut out part of a system or several systems, but in all cases the tilting and accompanying erosion were insufficient to produce noticeable angular discordance of beds. There are two angular unconformities, one at the base of the Madison or at the base of the thin underlying Cambrian quartzite lenses, and the other at the base of the North Park, which laps onto all older rocks.

Thicknesses of the Madison, Fountain, and Tensleep were obtained from widths of outcrop in the SE 1/4 sec. 4, T. 19 N., R. 82 W., where the beds are nearly vertical. The Chugwater was measured by steel tape and clinometer in the SW 1/4 sec. 28 and SE 1/4 sec. 26, T. 20 N., R. 82 W. A closely comparable thickness was obtained from mapped width of outcrop and dips in the southern part of the district in the NW 1/4 sec. 11, T. 18 N., R. 82 W. Thicknesses of the formations from Jelm to Carlile inclusive were measured by steel tape and clinometer in the W 1/2 sec. 29, T. 20 N., R. 82 W; those of the Niobrara to Lewis inclusive were obtained by scaling widths of mapped outcrops and dips in the northern part of the district at places where the two boundaries of the formation crop out at nearly the same elevation. The figures for the Medicine Bow and North Park are those of Dobbin and associates (1929a, p. 9-10) in the adjacent area to the north.

NOTES ON NOMENCLATURE

The stratigraphy is well known. The following notes are given to correlate stratigraphic terminology with that used in surrounding territory.

The quartzite lenses lying on the pre-Cambrian are erosional remnants left by pre-Madison erosion of Middle Cambrian quartzites, which attain a thickness of 412 feet at Rawlins 35 miles to the northwest (Dobbin, *et al.*, 1928, p. 176).

The Madison limestone, 298 feet thick in the northern part of the Rawlins uplift (Dobbin, *et al.*, 1928, p. 176), thins to the southeast and is absent 15 miles south and east of Elk Mountain (Neely, 1934, p. 4).

The limestones and redbeds here called Fountain lie between the Madison and Tensleep in the same position as beds of comparable lithology and thickness called

TABLE 1.—*Geologic formations in the Elk Mountain district*

Age	Formation	Thickness (feet)	Characteristics
Quaternary (?)		0–50 (?)	Floodplain and pediment gravels, land-slip debris, and probably some thin remnants of Tertiary sediments.
Miocene	North Park formation	0–400 (?)	Yellowish partially consolidated arkosic gravel and sand, and gray clay. Several hundred feet above the base are white unconsolidated volcanic ashes and silicified ash beds resembling limestones. Continental.
	Unconformity		
Upper Cretaceous	Medicine Bow formation	4000–6200	Gray to brown sandstones, light-colored to gray and carbonaceous shales, and thin coals.
	Lewis shale	3000	Predominantly dark-gray shale. Several bands of light-gray sandstone and sandy shale contain hard brown "ironstone" concretions up to 5 feet across. Marine.
	Mesaverde formation	3500	Brown, gray, and white sandstones alternating with light-gray to carbonaceous shales. Thin coals in the upper part. Lower part marine. Forms a ridge.
	Steele shale	2400	Predominantly dark-gray shale. In the upper 600 to 700 feet are the dark-gray thin sandstones of the Shannon member. Marine.
	Niobrara formation	700	Buff shaly limestones at the base, near the middle, and at the top. Above and below the middle limestone are gray to black shales. Marine.
	Carlile shale	420	Dark-gray to black shales containing light-gray calcareous concretions up to 2 feet across. Marine.
	Frontier formation	650	Black shale. At the top is the brown Wall Creek sandstone member about 30 feet thick. In the lower part are black septarian concretions up to 2 feet across. Marine.
	Mowry shale	165	Black siliceous shale that weathers silver gray; contains bentonite seams up to 2 feet thick. Marine.
	Thermopolis shale	110	Dark-gray to black shales with thin sandy beds. The "Muddy" sandstone, a few feet thick, is locally present at the top. Marine.
Lower Cretaceous	Cloverly formation	130	Upper member of locally quartzitic sandstone; middle member of gray and green sandy shale; lower member of conglomeratic sandstone. Partly continental. Forms a ridge.
Upper Jurassic	Morrison formation	300	Shales of various colors containing thin sandstones and fresh-water limestones. Continental.
	Sundance formation	280	Upper part of green shale and shaly sandstone. Lower part of massive white sandstone grading downward into alternating white and red sandstones. Marine.
Triassic	Jelm formation	150	Coarse-grained thin-bedded maroon and white sandstones. Lenses of maroon conglomerate with fragments of limestone and red shale. Red shales and orange sandstones. Continental.
Permian	Chugwater formation	850	Brick-red shales and shaly sandstones. A limestone up to 10 feet thick, probably the Forelle, is locally present about 120 feet above the base. Massive gypsum beds in lower part. Mainly continental.
Pennsylvanian	Tensleep sandstone	300	Buff cross-laminated sandstones. Several thin sandy limestones near the base. Marine. Forms a ridge.
	Fountain formation	150	Red sandstones, shaly sandstones, white limestones, and pink arkosic grits. Partly marine.
Mississippian	Madison limestone	40	White massive limestone. Marine. Forms a ridge.
Cambrian	Unconformity	0–15	Local lenses of gray quartzite. Mapped as part of the Madison.
Pre-Cambrian			Pink potash granites, gray to pink injection gneisses, black and green schists, and metadiabases.

Amsden in the Rawlins uplift (Dobbin, *et al.*, 1928, p. 177). Pink arkosic grits in the upper part of the succession in the Elk Mountain district indicate that the beds here are, in part, equivalent to the Fountain formation of the Laramie Basin (Knight, 1929, p. 6-48).

The term Tensleep designates the same beds as in adjacent areas.

The redbeds between the Tensleep and Sundance in the northeastern part of the Hanna and Carbon basins were divided by Dobbin and associates (1929a, p. 11-12) into the Embar(?) and Chugwater formations. Their Embar(?) consists of 143 feet of red, green, and brown shales, gray limestone, sandstone, and gypsum overlain by a 3-foot lavender limestone, which they consider as probably corresponding to the Forelle limestone of the Laramie Basin. Their Chugwater, 1300 feet thick, consists predominantly of red shales, in part sandy, in which occur beds of sandstone, limestone, and gypsum; at the top is a zone 150 feet thick consisting almost wholly of sandstone.

Neely (1934, p. 5-6) applied the name Embar to the 300 feet of red shales, gypsum beds, and purple limestones immediately above the Tensleep in the southern part of the Elk Mountain district, the name Chugwater to the overlying 1000 to 1200 feet of red shales and shaly sandstones, and Jelm to the upper 75 feet of red sandstones and conglomerates. His total thickness is 1375 to 1575 feet, a figure considerably higher than that obtained by the writer.

Thomas (1934, p. 1655) states that marine limestone and sandstone tongues extending southeastward from the Phosphoria and Dinwoody formations of west-central Wyoming and interfingering with red shales in the base of the Chugwater in central and southeastern Wyoming constitute the "Embar" of central Wyoming. The Forelle limestone is one of the tongues of the Permian Phosphoria.

Knight (1917) recognized that in the Laramie Basin the upper 250 feet of redbeds, which here consist of sandstones and conglomerates containing limestone pebbles, clay balls, and fragmentary Triassic vertebrate remains, is separated from the underlying redbeds by a disconformity. For this upper part he proposed the name Jelm formation.

The writer found it necessary to subdivide the redbeds differently from other workers in immediately adjacent areas in order to obtain clearly recognizable lithologic units. In the southern and western parts of the district a limestone, probably the Forelle, is locally present about 120 feet above the Tensleep. It ranges in thickness from 10 feet to a foot, apparently pinches out in a number of places, and is not a satisfactory horizon marker for differentiation of the underlying red shales as Satanka. Other beds higher in the lower part of the succession are not sufficiently distinctive or persistent to make the Embar recognizable. The upper sandy and conglomeratic redbeds standing out as a ridge form a useful unit for mapping.

The term Chugwater, as used by the writer, includes the Embar(?), most of the Chugwater of Dobbin, and all of the Embar and Chugwater of Neely. The beds called Jelm are approximately equivalent to the Jelm of Neely and to the upper 150 feet of the Chugwater of Dobbin.

The formations from Sundance to Niobrara inclusive are the same as those of Dobbin and associates (1929a, p. 12-17).

The term Benton group, used in the same sense as by Darton and associates (1910, p. 9) in the Laramie Basin to include the Thermopolis, Mowry, Frontier, and Carlile, was adopted because in most places the shales are covered by debris from the adjacent Cloverly ridge. Where adequately exposed, the formations were mapped separately.

Thomas (1936) has shown that the Carlile shale is of Niobrara age. The writer did not, however, include it in the Niobrara because, in most places, the Wall Creek sandstone immediately below is not well enough exposed for mapping.

In the Saddleback Hills quadrangle, which includes about 5 square miles of the northern part of the writer's map (Pl. 1), Dobbin and associates (1929a, Pl. 10) give as thicknesses of the Steele and Mesaverde 3600 feet and 2200 feet respectively. The writer obtained respective thicknesses of 2400 feet and 3500 feet. The columnar section by Dobbin and associates shows, beneath the base of their Mesaverde, sandstones and sandy shales 700 feet thick and beneath them a sandstone 500 feet thick. These beds were included by the writer in the Mesaverde in order to obtain units clearly recognizable by lithology and topographic expression. As used by the writer, the Steele consists of shales with a few thin sandstones and shaly sandstones, known as the Shannon member, 600 to 700 feet below the top; the Mesaverde consists of massive sandstone with thin shales and shaly sandstones.

The terms Lewis and Medicine Bow designate the same beds as in adjacent areas.

HANNA AND CARBON BASINS

Between the Medicine Bow and North Park formations in the Hanna and Carbon basins is a succession of sediments several miles thick. Lying upon the Medicine Bow in apparent angular accordance is the Ferris formation of which Bowen says (1918, p. 230-231):

"As defined the Ferris formation is approximately equivalent to the lower half of the 'Upper Laramie' of Veatch. The conglomerate at the base of the Ferris formation ranges through an interval of about 1,000 feet, in which massive sandstone, more or less conglomeratic, alternates with non-conglomeratic sandstone and shale. The conglomerate is sparingly developed at the base of the zone but increases in amount upward. It is succeeded by an alternating series of sandstone and shale containing numerous beds of coal. The maximum thickness of the formation is 6,500 feet.

"The Ferris formation contains fresh-water invertebrates, land plants, and bones of vertebrates. The shells and plants, which are found chiefly above the conglomerate zone, are regarded as of Fort Union age, whereas the vertebrate remains, thus far found only in the conglomeratic zone, consist of bones of turtles . . . and a few specimens that have been identified by C. W. Gilmore as *Triceratops*. The bones of *Triceratops* tend to show that the basal part of the formation should be correlated with the Lance of Wyoming and Montana and the Denver formation of the Denver Basin."

Of the overlying beds Bowen says (1918, p. 231):

"For the upper part of the 'Upper Laramie' as defined by Veatch the name Hanna formation is proposed. . . . The Hanna formation rests unconformably on the Ferris formation. A conglomeratic sandstone marks its base, above which conglomerate, sandstone, shale, and coal beds alternate to the top of the formation some 7,000 feet above the base.

"This formation differs from the Ferris in being highly feldspathic, in being conglomeratic throughout, and in the fact that the conglomerate contains an abundance of local material, notably granite, Mowry shale, and Cloverly conglomerate. . . .

"This formation contains an abundance of plant remains, all of which are referred to the Fort Union by Mr. Knowlton. The invertebrates are also regarded by Mr. Stanton as chiefly indicative of Fort Union age, though species near the top are said to resemble the Wasatch fauna."

The North Park formation rests unconformably on the Hanna and all older rocks (Bowen, 1918, p. 231).

TIME OF DEFORMATION

Stratigraphic relations in the Elk Mountain district show that deformation, other than possible slight warping, began after Medicine Bow time and before North Park time, an interval represented in the northern part of the Hanna Basin by some 13,000 feet of Ferris and Hanna beds. Little is known as to how much of this succession may have been deposited on, and subsequently eroded from, the area now occupied by the north end of the Medicine Bow Range. The problem hinges largely upon the question of the place from which the Ferris sediments were derived.

Bowen (1918, p. 234) presents evidence to show that the Ferris clastic material came from a distant source to the west. Knight (1937) concludes from conglomerate lenses in the lower Mesaverde of the northern Hanna Basin, and from conglomerates in the lower Medicine Bow in the embayment on the east side of the Medicine Bow Range (Fig. 1), that:

"(1) Local anticlinal folds were raised above the Cretaceous sea prior to Mesaverde time, (2) the Cloverly formation was exposed on at least one of these folds at the beginning of Mesaverde time, (3) the pre-Cambrian basement complex was locally exposed at the beginning of Medicine Bow time, (4) the late Upper Cretaceous sediments having a total thickness of 15,000 feet in this region, were locally derived from the rising mountains, rather than from the remote Central Cordilleran geanticline, and were deposited in the adjacent basins."

It is generally agreed that the Hanna sediments were derived locally and that pre-Cambrian rocks were exposed at that time.

The occurrence of several thousand feet of nonconglomeratic Medicine Bow beds within 5 miles of the north end of Elk Mountain indicates little or no movement in the district at this time. One mile east of the northeast corner of the district the basal Hanna beds lie on Lewis shale (Dobbin, *et al.*, 1929a, Pl. 27), indicating that folding and erosion occurred in pre-Hanna time. Folding and erosion may have proceeded in the Elk Mountain district during at least part of the time when the Ferris conglomerate was being deposited. Dips up to 30° in the Hanna beds of the southern Hanna and Carbon basins indicate continuation of deformation after Hanna time.

COMPETENCE OF ROCKS

The rocks subjected to deformation consist of a complex of pre-Cambrian metamorphic and igneous rocks overlain by 17,000 feet of sediments including the Medicine Bow formation. Possibly there was also several thousand feet of younger beds during the initial stages of movement. Stratigraphic relations of the Hanna formation indicate, however, a much smaller superincumbent load during the later stages.

The various types of pre-Cambrian rocks would necessarily deform differently under stress. Although the writer knows of no experimental work on mode of deformation of metamorphic rocks under subsequent stress applied in a direction different from that which produced the predominant metamorphic structure, it is probable that schists with excellent flow cleavage, under some conditions, deform by folding in much the same manner as well-stratified sedimentary rocks; gneisses show less tendency to slip along banding and are less subject to folding without faulting; and massive granites deform mainly by faulting or movement along closely spaced joints. In considering the influence of structural features of metamorphics during subsequent deformation, one must also take into account the probable orientation of later stresses with respect to cleavage, gneissic banding, faults, and contacts of massive igneous bodies in the metamorphics.

The 6600 feet of beds below the Mesaverde consists of shales and sandy shales with the exception of the massive limestones, grits, and cross-bedded sandstones in the lowest 500 feet of the succession, and the sandstones and conglomerates of the Jelm, Sundance, and Cloverly formations in the interval from 1350 to 2200 feet above the pre-Cambrian. These sandstone and conglomerate beds, all less than 100 feet thick, seem to have been of minor importance in transmitting stress and locally have acted somewhat differently from the shales mainly because of greater brittleness.

In the 275-foot interval above the Cloverly are numerous bentonite seams up to 2 feet thick. The writer believes that certain structural details described later were caused by ease of slipping along bedding in the bentonites, in contrast with difficulty of slipping in the coarsely cross-bedded Cloverly conglomerate.

The massive sandstones, up to several hundred feet thick, in the Mesaverde formation undoubtedly make this unit much more competent as a whole than the underlying beds. The shales and coals, however, permit bending without extensive fracture. The Mesaverde is the only unit in the area of tight folding with sufficient strength to lift at least part of its own weight from the crest of a growing anticline. This probably accounts for the common occurrence of "anomalous dips", apparently connected with drag folding, in the underlying Steele shale. It also explains, in part, the common difficulty of locating in depth the axial planes of unsymmetric sharp anticlines in the Steele shale and beds below.

DRAWING OF FOLDS

For parts of structure sections nearly normal to strike, surface dips were used as the primary control. Folds were drawn as concentric on the flanks, using as flank thicknesses the values given in Table 1. Crests of anticlines and troughs of synclines in the shale succession were rounded off; the few thin competent beds were drawn with constant thickness throughout. This procedure gives concentric folds in competent beds and a type of fold having the crest and trough thickening characteristic of similar folds in shales; it avoids the improbable relation of excessive flank thinning or even complete pinching out of beds required in the drawing of strictly similar folds with vertical or overturned flanks.

Because of changes of strike of beds in short distances, large parts of the sections are oblique to strike. For these parts the angles plotted were computed apparent dips. Vertical lines were drawn at points on the flanks near which surface dips are fairly constant for some distance normal to strike, indicating comparatively little variation of dip with depth. Along these lines were plotted depths computed from dip and flank thickness. Drawing across anticlines and synclines was carried out in the same manner as in cross sections normal to strike, except that flank apparent thicknesses were taken from a previously drawn part of the section controlled by depth lines.

The method outlined for drawing folds normal to strike of beds has been successfully used for many years by oil geologists in the Rocky Mountain region. The values they use for "thickness" in drawing beds that do not appear at the surface in an anticline are commonly obtained from exposures where the beds have a dip of 30° to 60° on the flank of a fold in the vicinity; the writer obtained the values for "thickness" in Table 1 by this procedure. Recent experimental work of Straley (1938) has shown that less competent beds in a succession of artificial sediments in a pressure box undergo thinning up to a 30-degree dip of limb, no thinning or even a slight thickening between 30° and 60°, and thinning from 60° to 90°. The value previously called "thickness" is therefore a close approximation to flank thickness for dips of 30° to 60°. As Straley's experiments were performed on materials for which strengths of competent and incompetent layers were known, his ratios of flank to crest thickness may be of doubtful applicability to a succession of rocks for which quantitative data on strength at the time of folding are not available. It is remarkable, however, how closely his ratios check with those derived from scalings of cross sections drawn by Bartram and Hupp (1929) across a number of sharp unsymmetric anticlines in the Rocky Mountains; in many cases correctness of drawing was later proved by drilling.

STRUCTURE

ELK MOUNTAIN

Elk Mountain (Pl. 1) is the eroded core of a strongly unsymmetric anticline. On the west side beds dip 15° to 30° W. The slope of the surface is only slightly less than the dip of beds, and consequently the resistant Madison, Fountain, and Tensleep extend far up the side of the mountain and form flatiron divides between deep gulches. On the east side the same formations dip at 65° or more and have reverse dips as low as 35°. The axial plane is closer to the east side, trends northeast at the south end, and a few degrees west of north at the north end.

East of the mountain base, pediment gravels and North Park sediments obscure structural detail. Between the pre-Cambrian and the few exposures of Cretaceous rocks, however, there is not enough space to accommodate the full succession of intervening beds; it is certain that there is a major fault here. The reverse dips of the Madison, Fountain, and Tensleep indicate that the fault is a thrust dipping west. On the basis of observed dips of the Bear Butte thrust farther west, in a similar structural environment, the dip of the Elk Mountain thrust is probably between 30° and 45°.

The thrust probably dies out southward in sec. 30, T. 19 N., R. 81 W., in the limb of an overturned anticline between the outcrop of Wall Creek sandstone in sec. 29 and the Mowry shale to the northwest. If the Wall Creek does not terminate against a fault beneath the alluvium or North Park, an improbably complex system of folds must be postulated. The fault between pre-Cambrian and Tensleep in sec. 9 of the same township is most likely a western branch of a multiple thrust fault. The horizontal distance of 4000 feet from the pre-Cambrian to the exposure of Steele in sec. 10 is sufficient to accommodate the full succession up to the base of the Steele with beds standing on edge. The 10-degree westward dip suggests, however, that the beds here belong to the east flank of a syncline and not to the east flank of Elk Mountain anticline. The multiple thrust consequently has a probable stratigraphic throw of several thousand feet. In the NW ¼ sec. 28, T. 20 N., R. 81 W., brown sandstones containing concretions up to 10 feet across undoubtedly belong to the lower part of the Mesaverde. The 60-degree dip away from the mountain front suggests upturning of beds in the block beneath the thrust. The stratigraphic interval of 6600 feet between the base of the Madison and the base of the Mesaverde, and the horizontal distance of 2500 feet from the Mesaverde exposure to the pre-Cambrian, indicate a stratigraphic throw of at least 4100 feet. Separation along the fault in section B′-B″ is 5500 feet.

At the north end of Elk Mountain the fault branches and changes strike from northwest to west. The high normal dips of beds near the branches in sec. 19 and the straight surface traces of faults across gulches indicate that the faults are nearly vertical and have the characteristics of tear faults rather than those of thrusts. The south branch clearly dies out in sec. 24. The north branch passes into nearly vertical shales of the Benton group in the NW ¼ sec. 19 and may continue westward to the Rattlesnake Pass fault. This would be difficult to demonstrate because the outcrop of the Benton group is in most places covered by debris from the Cloverly ridge, the width of the outcrop is sufficient to accommodate the full succession, and the fault, here nearly parallel to bedding, would produce little stratigraphic evidence of faulting even with large displacement.

The block between the two tear faults is cut by three transverse faults offsetting beds from Morrison to lower Frontier. The strike of the western fault is correctly represented, as exposures are fairly good and points within a few feet of the fault could be located for 1000 feet. Strikes of the other two faults may not be accurately represented. Both were mapped on the basis of a single observation of beds terminating along strike against younger or older beds; fault traces were drawn parallel to that of the western fault. Dips could not be obtained. Probably all three faults are genetically related to the apparent northeastward extension of the middle one.

North of the tear faults is a northward-pitching anticline, apparently the northward extension of the Elk Mountain anticline. Location of the axial plane could not be determined accurately enough to tell whether it is offset by faults or whether there are merely changes in trend. A fault striking northwest diagonally across the axial plane brings up older beds of the northwest flank. Dip and direction of dip of fault could not be obtained. If the fault dips southeast, it is normal and indicates elongation in this direction; all other features in the vicinity indicate shortening. If the fault is a vertical strike-slip fault, strike slip would have to be about 2500 feet to produce the offset shown by the Wall Creek and 1500 feet to produce that shown by the base of the Niobrara. Such large figures would require that the fault be propagated to the southwest and consequently offset the top of the Tensleep. The writer believes that the fault dips northwest as shown in section A-A′, and advances the following hypothesis to account for genesis.

The anticline developed under horizontal compression acting close to east-west; easiest relief was upward. Dips of beds increased until stratification in the shales and bentonites of the lower Benton group on the west flank was nearly parallel to the plane of maximum shear striking normal to compression and dipping west. Stratification was also parallel to the shear couple set up by the bending of the shales over the crest of the anticline in the competent beds of the underlying succession from Jelm to Cloverly. Movement then began parallel to stratification. It produced a fault which was propagated downward parallel to stratification and upward across stratification east of the crest of the anticline from upper Benton through lower Steele. Such a fault would die out both upward and downward. Other cases of similar faults for which field data are much more complete are described later.

The writer's conceptions of movement of the Elk Mountain block are as follows:

The mountain is underlain by a scoop-shaped fault dipping at angles of 35° to 45° along the east side and close to vertical at the north end. The block above the fault moved relatively upward and eastward. The central or north-central part of the block moved farthest east, bending the front of the block into a curve convex to the east. The block as a whole was also rotated clockwise in plan, pivoting on a point somewhere near the south end of the mountain. Horizontal movement at the north end was, in part, by strike slip on both the steep northern part of the Elk Mountain fault and the steep Rattlesnake Pass fault.

NORTHEASTERN AREA

Simpson Ridge anticline.—The Hanna and Carbon basins (Fig. 1) are separated by Simpson Ridge anticline, also known as the Saddleback Hills anticline, for 12 miles north from the Elk Mountain district. General trend of the anticline is about N. 15° E. Formations as young as the Ferris cross the axial plane (Dobbin, *et al.*, 1929a, Pl. 27). Hanna beds dip away from the axis at angles up to 20° on both sides but do not cross the axial plane. For about 8 miles along the east flank the Medicine Bow and Ferris formations are overlapped by the Hanna, which lies on Lewis shale. Inasmuch as the Medicine Bow and Ferris are now exposed on both sides of the anticline at distances of 6 miles or less, the anticline has probably had the history, (1) folding after Ferris time, (2) erosion of the crest at least down to the Lewis, (3) deposition of Hanna, (4) folding involving Hanna beds, and (5) erosion to the present land surface. If this is true, the present trend is representative of that of pre-Hanna folding.

Simpson Ridge anticline extends south for 2 miles into the Elk Mountain district with the same trend of S. 15° W. In sec. 2., T. 20 N., R. 81 W., it pitches north at angles up to 50°. Southward trend changes to about S. 30° E. for nearly 2 miles. From here the fold trends southwest for 3 miles to the base of Elk Mountain. In secs. 13 and 24 the Shannon sandstone of the east flank, judging from the poor exposures available, swings out to the east away from the outcrop on the west flank, indicating a dome, locally known as the Mill Creek structure, in secs. 13 and 14. The east flank is apparently the steeper. Various fold and fault complications are probably concealed beneath the alluvium. In order to work them out numerous pits, some many feet deep, would be required. The Midwest well in sec. 11 penetrated 1300 feet of Niobrara and yielded oil-saturated cores from the "Muddy" sandstone or Cloverly. The double thickness of Niobrara indicates drag folding, or faulting near the crest of the anticline.

From sec. 23 the anticline can be traced southwest into sec. 33. The few dips obtainable indicate that the southeast flank is the steeper. Shannon outcrops on the flanks projected beneath the alluvium are nearly parallel to the surface trace of the axial plane; as the land surface slopes from an elevation above 8000 feet in sec. 33 to about 7400 feet in sec. 23, the anticline pitches northeast. The thick cover of gravel and boulders, several feet in diameter in sec. 33, conceals relations of the anticline to the Elk Mountain block. The whole succession may change strike abruptly and be truncated by the thrust, or the anticline may continue beneath the fault and emerge as Pass Creek anticline. If this is true, the thrust has a displacement of several miles.

East from the south end of Simpson Ridge anticline is a gentle syncline trending southwest. The outcrops of Shannon sandstone dipping southeast in the NE 1/4 sec. 26 and the SW 1/4 sec. 23 indicate possible fault repetition on the northwest flank. The Shannon sandstone in sec. 24 outlines a syncline pitching southwest. The Shannon is repeated on the northwest flank by a high-angle fault striking east.

Halleck Creek syncline.—The Mesaverde forming the ridge in the northern part of the area outlines a sharp unsymmetric syncline with beds standing close to vertical on the west flank. Here and in the Lewis the fold pitches N. 20° E. at angles up to 20°. Within a mile beyond the north boundary of the map it dies out, as there is no appreciable swing in the outcrop of the Medicine Bow formation striking northeast from the west flank of Bloody Lake anticline to the west flank of Simpson Ridge anticline (Dobbin, *et al.*, 1929a, Pl. 27). South of the ridge the thick alluvial fill along Halleck Creek conceals the older rocks. It seems probable, however, that the syncline in secs. 15 and 16, shown by the exposure of a sandstone a few hundred feet above the base of the Mesaverde, is the same fold. Strikes of N. 60° E. strongly suggest that the syncline changes trend in the same manner as Simpson Ridge anticline. The Mesaverde exposed in the NW 1/4 sec. 21 is the same bed, and consequently the axis is close to the exposure. Previously described relations beyond the north edge of the map and the low flank dips near the mountain show that the central part of the syncline is the sharpest.

Bloody Lake anticline.—The map by Dobbin and associates (1929a, Pl. 27) covers a strip a mile wide at the north end of the Elk Mountain district. They gave the name Elk Mountain anticline to the fold in secs. 26 and 27. Structural relations to the south indicate considerable doubt that it is continuous with the anticline forming Elk Mountain. The writer consequently believes that the name Elk Mountain anticline should be reserved for the fold forming the mountain and has applied the name Bloody Lake anticline to the one in the northern part of the district.

The Mesaverde formation outlines a nearly upright anticline with flank dips of 60° to 80°. It pitches north at about 45° and dies out in this direction less than a mile from the map boundary. The Kasoming well in sec. 4, judging from its location with respect to exposures on three sides, started in nearly flat beds at least 1000 feet below the top of the Steele. On the basis of this assumption and normal thicknesses of formations, the "Muddy" sandstone should have been reached at 3400 feet. The driller's log shows that the well was abandoned at 4225 feet and did not reach the "Muddy" or Cloverly, both of which can be easily recognized from cuttings. Failure to reach beds below the Benton group can be explained by location of the well some distance off structure, or by deflection of the drill down one of the flanks, or by thickening of shales on the crest of the anticline.

A fault on the west flank produces a normal horizontal separation of 700 feet at the base of the Mesaverde. Northeast along strike sandstones in a zone up to 100 feet wide are offset by numerous steeply dipping fractures nearly parallel to stratification. Displacement decreases to the northeast, and the upper white massive sandstone member of the Mesaverde is not offset. Northwest of the fault the Lewis, Medicine Bow, and Ferris dip between vertical and 45° over a distance of 3 miles; the fault is therefore near the crest of the anticline. It is suggested that fracture and movement originated as follows:

The fold developed under nearly east-west horizontal compression and predominant upward relief. Sharp bending of the Mesaverde sandstones near the crest of the anticline produced a tension fracture when the flank dips of beds were lower than at present. The fracture was propagated downward toward beds lying nearly parallel to the westward-dipping plane of maximum shear. Stratification in the lower Mesaverde and upper Steele deflected the fracture to a position close to the plane of maximum shear. During the later stages of deformation both the beds and fault were tilted more sharply to the northwest, producing the present high dips. The block northwest of the fault moved upward and was rotated on the curved fault counterclockwise as seen looking horizontally northeast, thus giving the prevailing higher dips of beds west of the fault. The northwest block might have moved horizontally northeast; this type of movement alone would account for the offset but would not adequately explain other observed relations.

Fort Halleck syncline and vicinity.—The syncline is named from the site of Fort Halleck near the northeast corner of sec. 20, T. 20 N., R. 81 W. A mile north from here the lower several hundred feet of the Mesaverde outlines a gentle upright synclinal basin. The surface trace of the axial plane, which can be fairly accurately located in several gulches, is convex westward. Dips of the lower Mesaverde in the SW ¼ sec. 16 show a change of trend and direction of pitch to southwest.

Between Fort Halleck and Halleck Creek synclines there must be an anticline, possibly the southward extension of Bloody Lake anticline. If this is true, Elk Mountain and Bloody Lake anticlines are different folds, as the axis of Elk Mountain anticline in sec. 20 is west of Fort Halleck syncline.

Eastward dips of the Steele in the SE ¼ sec. 7 indicate a sharp anticline between Fort Halleck syncline and the Mesaverde ridge to the west. If Bloody Lake anticline extends through this interval and is continuous with Elk Mountain anticline, it must undergo two improbably sharp changes of trend in secs. 17 and 18. Although the area in secs. 7 and 8 is undoubtedly generally anticlinal, it is most likely affected by a complex of faults, some of which are genetically connected with fracturing in the overlying Mesaverde, and others with deformation along Rattlesnake Pass fault.

Relation to Elk Mountain block.—In the area northeast of Elk Mountain only one fold, Simpson Ridge anticline, persists more than a few miles. It may terminate at the Elk Mountain thrust or may pass under it and emerge as Pass Creek anticline. In either case there is no direct structural relation between the anticline and the thrust block. The other folds farther west die out northward less than 7 miles from the mountain. They terminate southward at the thrust, or at the tear faults forming the western extension of the thrust, or in the belt of nearly vertical beds west of the tears. Shortening in the northeastern area was predominantly by folding; in the area farther south it was predominantly by movement along the Elk Mountain fault. Both blocks were undoubtedly deformed, at least in part, during the same time interval, but the rocks yielded differently and more or less independently.

The structural pattern strongly suggests one produced experimentally in a pressure box by Link (1928). He applied uniform compression to a sheet of clay that had been strengthened by addition of cement in one corner of the box adjacent to the straight push block. A tear fault striking normal to compression developed between the areas of stronger and weaker materials. The weaker part was folded immediately in front of the push block; the stronger transmitted the stress.

Known lateral variations in lithologic character of the sediments of the Elk Mountain district indicate that the sediments had little lateral variation in strength. Observed relations north and east of Elk Mountain suggest that the rocks now constituting Elk Mountain were originally a more resistant mass in the pre-Cambrian basement complex analogous to the cement-strengthened mass in Link's pressure box.

Data on changes of trend of folds in the northeastern area are not entirely satisfactory because of poor exposures. The southern ends of several folds, nevertheless, seem to be offset east from their positions farther north. The following hypotheses are advanced to account for the offset.

1. Older folds trending north or northeast are affected by younger ones trending northwest. On the north side of the Hanna Basin (Pl. 2) major thrusts strike northwest. Folds northwest of the Elk Mountain district show the same trend; it appears, however, that some of them swing to south trend in the area west of Elk Mountain. The northwest-trending syncline in T. 22 N., R. 79 W., is definitely post-Hanna, as it affects beds of this age. Although these facts suggest a younger deformation producing northwest trends in the Elk Mountain district, they do not provide conclusive evidence of a younger cross folding intense enough to produce the indicated offsets of folds.

2. The S-shaped curves in surface traces of folds were produced by an eastward or northeastward movement of the sediments and basement rocks south of the curves after folds trending between north and northeast had been formed; movement was by bending of rocks or by strike slip along faults. The western part of the Elk Mountain fault shows this type of movement. Evidence is presented later to show that the block south of Rattlesnake Pass fault moved northeast.

NORTHWESTERN AREA

Rattlesnake Creek syncline.—The part of Rattlesnake Creek syncline west of Elk Mountain trends north. It is strongly unsymmetric; Triassic and Jurassic beds in the east flank have dips as low as 30°, and the same beds in the west flank are overturned in many places. East of Bear Butte the syncline is cut longitudinally by a number of faults. Farther north it is cut diagonally by Rattlesnake Pass fault. Exposures here are not good enough to tell whether the axial plane is offset. In the lower Mesaverde north of Rattlesnake Creek the syncline pitches north at about 75°. Farther north pitch decreases, and the syncline passes beneath the unconformity at the base of the North Park. Trend here changes to a few degrees east of north, judging from strikes and dips of the Mesaverde some distance out on the flanks. The fold probably continues for 7 miles beneath the North Park and emerges as the gentle syncline shown by the Hanna beds in the southern part of the Hanna Basin (Pl. 2).

Sheephead Mountain anticline.—Bear Butte is part of the core of an anticline. The exposed rocks are principally pink massive granites, which are extensively fractured along the east border in the vicinity of Bear Butte fault. The pre-Cambrian rocks exposed at the south end of Sheephead Mountain are mainly schists, granite gneisses, and granites showing metamorphic structures that survived magmatic assimilation. Most of the mountain top is underlain by Madison limestone. From here north to Rattlesnake Creek sedimentary rocks form an anticline pitching north at angles up to 50°. Beds on the west flank have dips of 45° to 60°; the same beds on the east flank have been turned as much as 45° beyond vertical. Strikes and dips in the lower Mesaverde near the north boundary of the map show that the fold is here very sharp, nearly upright, and has a low northward pitch. The strike in the northern part of sec. 9 gives some indication that the axis swings to the northwest beneath the North Park. Sheephead Mountain anticline is probably the same fold as the northwest-trending Pass Creek Ridge anticline, which emerges from beneath the North Park 4 miles to the northwest (Pl. 2).

The Madison, Fountain, and Tensleep near the top of Sheephead Mountain are cut by four faults nearly parallel to the trend of the anticline. In all cases the west sides are upthrown. The eastern fault forms the boundary between Madison on the west, dipping 15° or less in this direction, and vertical or slightly overturned Fountain and Tensleep on the east. Along the line of section C-C′ horizontal Madison lies on the edge of vertical Tensleep. Farther south the Madison lies on various horizons in the Fountain. The fault is nearly horizontal and has a maximum net slip of several hundred feet. It was apparently formed by eastward movement of the plate of Madison limestone on top of the anticline along the contact with the underlying pre-Cambrian and across the vertical beds of the east flank.

The two middle faults repeat the Madison and Fountain on top of the anticline and offset the top of the Fountain at the nose. The western fault, at its south end, repeats the Fountain and parts of the Madison and Tensleep. Displacement decreases northward, and only parts of the Madison and Fountain are repeated. The writer believes that the three western faults are high-angle thrusts or reverse faults dipping west at higher angles than the beds. Displacement is small, and consequently they may die out downward, as shown in the cross section, or may join the Sheephead Mountain thrust in depth.

Anticline east of Sheephead Mountain.—Formations from Jelm to Cloverly in secs. 33 and 34 outline the nose of a northward-pitching anticline. Southward the fold merges, in less than a mile, with the west flank of Rattlesnake Creek syncline. Three minor folds are superimposed on the anticlinal nose. These were probably caused by the competent beds in the succession between the Chugwater and Benton shales transmitting stress a short distance eastward from the Sheephead Mountain fault block. This conception was followed in drawing section C-C′; greater thickening of shales at crests of anticlines than in troughs of synclines produces minor folds that become less acute downward and merge into a simple anticline in the lowest beds.

Sheephead Mountain fault.—Sheephead Mountain fault, north of the junction with Rattlesnake Pass fault, brings Mowry shale into contact with Wall Creek sandstone. The beds here have a reverse dip of 45° W. Comparable reverse dips in other places, and the position of the fault between overturned anticline and syncline, indicate that it is a thrust dipping west at about 45°. North of the junction of the faults the Benton group outcrop widens, the Niobrara is not offset, and consequently the fault dies out in this direction. Southward older formations of the east flank of Sheephead Mountain anticline terminate against the fault. It then forms the boundary between this anticline and that to the east; the intervening syncline is faulted out. South of Hat Creek the Forelle limestone is offset only a few feet. The maximum stratigraphic throw of the fault is 650 feet, indicating maximum net slip of about 1000 feet.

Reservoir fault.—The town of Hanna obtains its water supply from a small reservoir located where Rattlesnake Creek crosses the outcrop of the Morrison in the SW ¼ sec. 26, T. 20 N., R. 82 W. A few hundred feet southeast the lower white sandstone of the Sundance is repeated by a fault. At the line of section B-B′ Morrison on the west is upthrown against Mowry. The fault here dips 55° W. A few hundred feet north it branches and surrounds a slice of Thermopolis between Cloverly and Mowry. The fault then continues into the Mowry, and the beds in the east block are locally dragged up to a dip of 60° E. West of the center of sec. 23 the "Muddy" sandstone is offset only about 100 feet. The small offset and the lack of stratigraphic evidence of faulting in the northern part of the Mowry outcrop do not necessarily indicate small displacement, as here fault and beds closely approach the conditions of a bedding fault, a type that gives no stratigraphic evidence of faulting. Farther northwest, the Cloverly in the center of the nose of a southwest-pitching anticline is repeated. Reservoir fault terminates at Rattlesnake Pass fault.

In drawing the part of section B-B′ in the immediate vicinity of Reservoir fault, surface dips were adequate for the part to the east and for that 1500 feet west. Thicknesses and the 45-degree dip of the Niobrara near the center of sec. 27 give a control point at the base of the Madison well up the east flank of the syncline close to one located by depth from the Cloverly east of the fault. If the fault penetrates down to the Madison with the same dip as at the surface, the west block is downthrown in depth and upthrown at the surface. This indicates that the fault cuts across stratification in the competent beds in the succession from Jelm to Cloverly and flattens out parallel to stratification in the Chugwater shales. Branching of the fault around the slice of Thermopolis and relations in the Mowry at the surface indicate that the fault flattens toward stratification in this part of the succession also. The fault was apparently initiated by tension fracturing of sandstones at a place of sharp flexure and, under horizontal compression, was propagated downward and upward close to stratification in shales.

Rattlesnake Pass fault.—The Niobrara formation standing close to vertical on the west flank of Rattlesnake Creek syncline is offset 1000 feet by a fault whose strike is nearly normal to that of the beds. Southwest 1000 feet from the nearest outcrop of Niobrara the Cloverly is not offset; it is concluded that Rattlesnake Pass fault terminates against Sheephead Mountain thrust. The lower Niobrara beds on the east flank of the syncline are exposed 1200 feet southeast of the base of the Mesaverde, indicating a stratigraphic throw of 1900 feet. At the crest of Rattlesnake Pass in the NW 1/4 sec. 23, where beds and fault have the same strike, exposures of lower Benton within 500 feet of the base of the Mesaverde show that the fault has a stratigraphic throw of 4000 feet. In the SE 1/4 sec. 14 at least 1600 feet of Steele shale is faulted out.

In sec. 13 the outcrops of nearly vertical Shannon and Niobrara diverge eastward providing, in the eastern part of this section, sufficient space to accommodate the full thickness of intervening beds. Dip of the fault could not be obtained. The fairly straight surface trace indicates that it is nearly vertical; dips of beds in the vicinity give no contrary indication.

Rattlesnake Creek syncline is clearly present on both sides of the fault, although exposures are not good enough to determine whether its axial plane is offset. Absence of offset of Mesaverde beds in the NW 1/4 sec. 23 shows that Reservoir fault terminates at Rattlesnake Pass fault. The sharp northwest-trending anticline in sec. 24 swings, farther west, parallel to Rattlesnake Pass fault; no anticline is found on the other side. The fact that some structural features terminate at the fault and cannot be matched on the other side indicates that Rattlesnake Pass fault is of rotatory type (Reid, *et al.*, 1913, p. 167). If small parts are considered as translatory, a fairly accurate conception of the rotatory movement as a whole can be obtained.

On the west flank of Rattlesnake Creek syncline, the Niobrara beds and Rattlesnake Pass fault approach conditions of vertical beds cut by a vertical fault. A large dip slip, in this case, produces no separation. Horizontal separation parallel to strike of fault is equal to strike slip. It is concluded that here the Niobrara in the southeast block moved horizontally northeast about 1000 feet, the observed horizontal separation parallel to strike of fault. In the NW 1/4 sec. 23 strike of fault and beds are the same. Strike slip on a strike fault produces no omission or repetition of beds; these are produced by dip slip only. On the basis of a vertical fault, observed omission of 4000 feet of beds, and 50° as the mean dip of the beds, the dip slip here is around 6000 feet. Relations in the SE 1/4 sec. 14 do not provide adequate data for obtaining approximate values for net slip or any of its components. Decrease in stratigraphic throw northeastward from sec. 23 indicates, however, that net slip probably decreases in this direction.

Underground relations along Rattlesnake Pass fault are believed to be approximately as shown in sections A-A′ and B-B′-B″. The dotted lines below ground east of the vertical fault in section B-B′-B″ represent the trace on the vertical fault of stratification in the north block; the trace is projected horizontally south onto the plane of section. The dotted lines to the west represent the trace on the vertical fault of the base and top of the Madison in the south block; the trace is projected horizontally north onto the plane of section. Rattlesnake Pass syncline has a low pitch, and consequently relations in depth as shown differ only slightly from those that would appear on a cross section in the plane of the fault. The section as drawn has the advantage of showing the vertical fault terminating upward and dying out westward against Sheephead Mountain thrust. Quantitative relations along the vertical fault in section A-A′ are probably inaccurately represented because the line of section for more than a mile to the east is nearly parallel to strike of beds with high normal and reverse dips. The writer believes that relations were produced as follows:

After Rattlesnake Creek syncline had been slightly folded a vertical fracture was formed. As the syncline became sharper, the anticline in secs. 23 and 24, and Reservoir fault were initiated. The block south of Rattlesnake Pass fault moved up to the east along Elk Mountain fault and along the vertical faults north of the block. While the south block moved as a whole, the anticline in sec. 23 was sharpened, dragged around to its present position, and cut by Reservoir fault. Later stages of deformation in the north block merely produced sharpening of the Rattlesnake Creek syncline. At some time, probably in a late stage, Sheephead Mountain thrust block moved east over the west end of Rattlesnake Pass fault.

The mode of origin of Rattlesnake Pass fault, a vertical fracture striking at about 45° to trend of major folds, is considered in the following hypotheses:

(1) The fracture coincides with a plane of weakness in the pre-Cambrian rocks such as a fault, stratification, schistosity, or an intrusive igneous contact. The plane of weakness forms the boundary between more competent crystalline rocks to the south and less competent rocks to the north. Under east-west compression, a fracture developed in the basement rocks and was propagated upward into the sediments. In the core of the Medicine Bow Range 30 miles southeast is a large area of metamorphics described by Blackwelder (1926). A summary of his description has been given in the preceding section on pre-Cambrian rocks. Bedding, schistosity, and a major fault strike northeast and dip steeply to the southeast. In the northern part of the Laramie Range foliation in schists strikes northeast, and contacts between schists and intrusive rocks are as a rule steeply inclined or nearly vertical (Spencer, 1916, p. 52). Therefore, a plane of structural weakness in the pre-Cambrian at Rattlesnake Pass fault is not improbable.

(2) The vertical fracture was formed under east-west compression with easiest relief horizontally to the north. Under these conditions the planes of maximum shear are vertical and strike respectively northeast and northwest. As previously pointed out in the section on time of deformation, it is generally accepted that the pre-Cambrian cores of rising mountains adjacent to the Hanna Basin were exposed during

Hanna time. Bowen (1918, p. 234) and Knight (1937) disagree as to whether the mountains began to rise at an earlier date. If, however, at some time during deformation under east-west compression, Elk Mountain stood out in relief above an adjacent basin to the north which was sinking under a load of new, poorly consolidated sediments, lateral relief to the north would be afforded. This hypothesis does not conflict with the first one; a vertical plane of weakness striking northeast in the pre-Cambrian basement would favor development of a fracture under east-west compression with easiest relief horizontally to the north.

Bear Butte fault.—In secs. 4, 10, and 23, T. 19 N., R. 82 W., Bear Butte fault crosses topography rugged enough to make it possible to obtain dips, which are from 35° to 45° W. The fault is a westward-dipping thrust. Near the center of sec. 4 it passes beneath Tertiary sediments. To the south in secs. 10 and 15 the branches numbered 1 and 2 surround a crescentic slice of rocks from pre-Cambrian to Chugwater in age, which belong to the west flank of Rattlesnake Creek syncline. Beds here are vertical or overturned with dips as low as 35° W. West of the center of the slice is a block of Madison, 1000 feet long and up to 150 feet wide, surrounded in plan by pre-Cambrian. The block could have reached its present position in a number of ways. The relation that seems simplest is shown in section D-D′. Fault 1 cut off a slice of Madison from the crest of a flexure below the present land surface and carried it upward onto the pre-Cambrian.

The high ridge formed by the Cloverly of the west flank of Rattlesnake Creek syncline in sec. 10 terminates abruptly in the south-central part of the section against beds of the Benton group. East of the south end of the ridge Thermopolis shale of the west flank of the syncline is exposed west of Frontier shale of the east flank. There are no intervening exposures of Mowry. The Mowry is probably absent, as it usually stands out in relief or occurs as silver-gray angular fragments in deeply weathered material covering the outcrop. Indications are that a thrust here cuts the Benton shales near the axis of the syncline. West of the south end of the ridge blocks of Jelm and Cloverly conglomerates up to 10 feet across are found along the outcrop of thrust 2 as far south as the outcrop of Cloverly in the north-central part of sec. 15. The blocks indicate that the Cloverly extends from the outcrop in sec. 15 beneath thrust 2 and is brought out to its position in sec. 10 by tear fault 5. This fault does not offset the Tensleep of the west flank of Rattlesnake Creek syncline or the Cloverly of the east flank. It is therefore concluded that fault 5 terminates upward at thrust 2 and downward at thrust 3.

Cross section D-D′ shows relations south of fault 5. A section a short distance north would be similar but would probably show, near the axial plane of the syncline, thrusting of younger beds onto older. This relation is found about 6 miles south (section L-L′) and also at several places in the southern part of the Medicine Bow Range (Beckwith, 1938).

Northeast of fault 4 the beds from Jelm to Cloverly belong to the vertical or slightly overturned west flank of Rattlesnake Pass syncline. In the block to the southwest, bounded by faults 4, 3′, 2, and the southward extension of 2 and 1, beds from Chugwater to Morrison dip northwest about 35° and are progressively younger to the northwest; the block obviously belongs to the east flank of the syncline. Fault 4 makes a straight trace across a steep gulch 150 feet deep and is therefore nearly vertical. It does not offset the Fountain to the northwest or the Cloverly to the southeast, indicating that it is a tear fault terminating upward at thrust 2 and downward at thrust 3′. The surface trace of fault 3′ trends northeast in the area of low relief near the bottom of the gulch and then swings sharply to the southeast up the side of a spur whose crest descends sharply to the northwest along line F-F′. Evidence indicates that fault 3′ near the surface is a thrust dipping northwest at an angle greater than the dip of the beds.

General relations shown in cross section F-F′ are similar to those in D-D′. The main difference is that in F-F′ the beds are overturned only in the extreme western part of the syncline. In cross section E-E′, which crosses tear fault 4, the eastern dotted line represents the trace of thrust 3′ on vertical tear 4; the trace is projected horizontally north onto the plane of section. The western dotted line represents the trace of thrust 3 on tear 4 projected horizontally south onto the plane of section. Relations shown suggest that thrusts 3 and 3′ are probably a single fault in depth and that folding north of the tear was independent of movement of rocks immediately to the south. Fault 4 is of marked rotatory type.

In the SW ¼ sec. 15 and the NW ¼ sec. 22 Bear Butte fault cuts southeastward across the axis of Rattlesnake Pass syncline and brings up older beds on the southwest. At the boundary between secs. 22 and 23 the Madison, Fountain, and Tensleep of the east flank of the syncline change strike abruptly and pass under an east branch of the thrust. They are brought up from beneath the pre-Cambrian east of the center of sec. 22 as slice blocks along a multiple thrust. Relations shown in cross section G-G′ are explained as follows: The two northeast faults near the surface dip at angles slightly greater than the beds. In depth below the junction of these two, dip of fault is less than that of beds, and the pre-Cambrian moved northeast across a small syncline whose core is formed by Tensleep. The Fountain and Tensleep in normal succession between the two southwest faults were carried up from the syncline along faults dipping more steeply than the beds. The overturned Madison and Fountain farther southwest form part of the overturned southwest flank of the syncline.

In the SW 1/4 sec. 23 a block of Tensleep 1200 feet long and 300 feet wide is completely surrounded, in plan, by pre-Cambrian. The sandstone is extensively brecciated and folded, but the predominant direction of dip is southwest. Probable relations shown in section H-H′ are, in general, closely similar to those in section G-G′. The normal fault shown in sections H-H′ and F-F′ has no relation to thrust faulting; it is a tension fracture formed by bending near the crest of Elk Mountain anticline. In the northern part of the slice block of Tensleep 50 feet east of the west fault there is an abandoned mine shaft 50 to 75 feet deep, judging from the size of the dump. All of the material is extensively brecciated Tensleep sandstone; a few fractures contain small amounts of malachite and chalcocite. Mineralization is definitely not genetically connected with igneous activity, as the nearest igneous rocks, other than pre-Cambrian, are on the west side of the Sierra Madre Range a few miles from the State line. Probably hot meteoric waters circulating along the fault zone at considerable depth dissolved small amounts of copper from pre-Cambrian metadiabases and hornblende schists and deposited it in the Tensleep.

Bear Butte thrust shows unusual structural relations. On the east side of the butte it occurs in the limb between overturned anticline and syncline in a common structural association. Southeast of Bear Butte it cuts diagonally across Rattlesnake Creek syncline and Elk Mountain anticline. Relations described later show that it dies out to the southeast in the limb between overturned anticline and syncline on the east side of Coad Mountain. The pre-Cambrian rocks exposed in Bear Butte are massive granites; those exposed near the thrust branches in secs. 22 and 23 are metadiabases and hornblende schists. The rocks of the southern part of Elk Mountain and the northern part of Coad Mountain are massive granites containing a few tabular remnants of metadiabases. Transgression of the central part of the thrust across axes of major folds might be explained by fault movement under northeast-southwest compression after the formation of folds under east-west compression. This hypothesis fails to explain why the northern and southern parts of the thrust strike parallel to trend of folds. The writer believes that deflection across trend was caused by differences in strength and structure of the rocks in the pre-Cambrian basement complex.

COAD MOUNTAIN AND PENNOCK MOUNTAIN AREA

Bear Butte fault and vicinity.—In the northern part of sec. 26, T. 19 N., R. 82 W., Bear Butte fault passes under the North Park formation. A steep gulch entering Pass Creek from the south near the center of the section is apparently cut along the trace of the fault. At the head of the gulch there is a saddle in the granite ridge that descends toward the creek. To the southeast steeply dipping beds from Madison to Chugwater on the east flank of Elk Mountain anticline terminate against the fault. In secs. 25 and 36 beds from Chugwater to Frontier outline a southward-plunging overturned anticline whose axial plane dips west. West of the anticline a fault dies out northward in the east flank of Elk Mountain anticline and joins Bear Butte fault to the south. At the junction of the faults pre-Cambrian of the east flank of Coad Mountain anticline lies on Thermopolis of the west flank of the small overturned anticline. This relation was apparently produced by movement of Coad Mountain anticline eastward across an intervening syncline as shown in section J-J′. A minimum value for the combined net slips of the two faults at this place is 2500 feet. The block of sediments from Madison to Chugwater between the two faults is part of the west flank of the syncline.

In the SW ¼ sec. 36 a branch of the thrust brings Cloverly of the east flank of Coad Mountain anticline onto Frontier of the south nose of the small overturned anticline. From here south fault displacement decreases rapidly. North of the center of sec. 1 the full thickness of the succession from Morrison to Niobrara is present with the exception of about 400 feet of Frontier. East of the center the short interval between exposures of overturned Mowry and Niobrara indicates faulting out of a few hundred feet of beds. The thrust probably dies out in overturned Steele shale in sec. 12. The Cloverly southeast of Coad Mountain is exposed in enough places so that one can trace the outcrop beneath cover. It is affected by several small folds pitching south or southeast. In the S ½ sec. 1 there is a sharp overturned anticline and a gentler syncline to the west. The short interval along the north boundary of this section from the outcrop of the Madison, projected beneath the North Park, to the Cloverly shows the presence of a branch of Bear Butte thrust, which probably dies out in the east flank of the overturned anticline. Changes of strike and dip of the Cloverly in the NW ¼ sec. 12 suggest another minor anticline.

Southwestern part of Coad Mountain.—Beds from Madison to Chugwater show, in secs. 3 and 10, an anticline pitching at a low angle toward Pennock Mountain. Trend of the northern part is a few degrees west of south, and that of the southern part a few degrees east of south. In secs. 2

and 3 the crest of the anticline is cut by six faults striking roughly parallel to trend of fold. Their straight surface traces indicate that the faults are nearly vertical. Offset and elevations of the base of the Madison in contact with the west fault indicate a throw of about 400 feet; throw of the others is less. In all cases the west block is downthrown. Occurrence of the faults in brittle beds and granites on the crest of an anticline, and the fact that the faults strike nearly parallel to its trend, indicate that they were formed as tension fractures during folding. It is shown later that a thrust sheet advanced from the west over the southern part of the anticline (sec. L-L′). Although the North Park obscures the structure of the older rocks west of the tension-faulted anticline, it was probably buried beneath the sheet. Such a sheet advancing eastward would successively load and depress the block west of each of the tension faults.

Coad Mountain fault.—Beds in the E ½ sec. 11 outline a gentle anticlinal nose pitching about 40° SE. Coad Mountain fault here cuts the beds nearly normal to strike. Farther north it strikes N. 25° E. parallel to strike of beds in the east block and at 45° to strike of beds in the west block. The fault trace, in crossing the gulch at the road, is convex westward, indicating that the fault possibly dips west at a low angle. If this were true, the trace south of the ridge formed by the Jelm in the east block should swing west in approaching the valley to the south. Curvature of the trace is therefore the result of a change of strike, not of erosion. The fault plane is nowhere well exposed, but, looking north along strike across the deep gulch at the road, it appears to have a dip between vertical and 60° W.

Maximum stratigraphic throw, about 800 feet, is shown where Madison in the east block is in contact with middle Chugwater. From here southeast, throw decreases, and the fault probably dies out in sec. 12. In sec. 2 the high normal and reverse dips of the Madison east of the fault suggest that it is a westward-dipping thrust beneath which there is a syncline containing beds as young as Chugwater. This relation is shown by Neely (1934, Pl. III, sec. G-H). The writer does not believe that this is true because the beds are not overturned west of the fault, and there is no independent evidence of a syncline along the strike of the fault. Evidence indicates that Coad Mountain fault is normal, as shown in section K-K′. The following hypothesis is given to account for relations shown.

During an early stage of deformation, Coad Mountain fault originated as a nearly vertical tension fracture near the crest of an anticline. Bear Butte thrust was later formed and cut Coad Mountain fault. The sedimentary rocks between the Tensleep and Mesaverde are almost entirely of types that bend easily; it is fairly certain, therefore, that the thrust was initiated in the pre-Cambrian and was propagated upward to the east into the sediments. Beds were warped into a steep monocline in front of the edge of the growing fracture. As the fracture penetrated eastward into the monocline, stratification in vertical to overturned beds deflected the fracture upward parallel to bedding, producing a thrust that steepens toward the land surface in the sediments and has a fairly constant dip in the pre-Cambrian. As shown in section K-K′, the block between Coad Mountain fault and Bear Butte fault is a wedge bounded below by a surface concave upward. Eastward movement of both blocks above the thrust would cause the wedge to move up with respect to the blocks on both sides. Shortening in the upper part of the wedge consisting mainly of sediments would give the beds a higher dip to the east, give Coad Mountain fault a lower dip to the west, and cause its footwall to move up. Southward change in strike of Coad Mountain fault is believed to be the result of movement on Pennock Mountain fault.

Pennock Mountain fault system.—In the SW ¼ sec. 10 the alluvial deposits have been stripped from the crest of a knob. From east to west there are exposed (1) Chugwater, (2) a fault omitting 1000 feet of beds, (3) Mowry shale overturned and dipping 50° SW., (4) Thermopolis, and (5) Cloverly. The Chugwater is in normal position on the west flank of the anticline extending south from Coad Mountain. The other beds become progressively older westward and consequently do not belong to the west flank of this anticline; they are part of the overturned east flank of the anticline whose pre-Cambrian core forms the ridge at the northwest end of Pennock Mountain. West of the center of sec. 10 Cloverly and Thermopolis of the east flank of the west anticline are exposed within 600 feet of Tensleep of the west flank of the east anticline. At least 1700 feet of beds is cut out by a fault beneath the valley fill. Evidence indicates that the west anticline moved eastward across a syncline and onto the east anticline as shown in section L-L′.

Normal to strike the distance from the westernmost Cloverly exposure to the pre-Cambrian is 1200 feet. The stratigraphic interval between them is 2080 feet. There must be, therefore, a fault between pre-Cambrian and Cloverly outcrops. It probably joins the other thrust in depth as shown in section L-L′.

The value for net slip obtained by scaling from a cross section is dependent upon accuracy of the section. Even with complete surface data the syncline beneath the thrust could not be drawn accurately. Minimum net slip is obtained if it is assumed that the syncline is closed and cut by a dip-slip strike thrust normal to the axial plane of the syncline. An open fold or a smaller angle between thrust and axial plane of syncline gives a greater value for net slip. In drawing section L-L′ the assumptions were made that the fold is closed, the thrust has about the same dip as other observed thrusts cutting the pre-Cambrian in the vicinity, and that the beds on the east flank of the syncline have a maximum dip of 65°. These assumptions give a conservative result. Separation along the lower thrust shown by the base of the Mowry is 4700 feet. Combined net slip for the two thrusts is considerably greater than a mile.

A possible indication of much greater displacement on the thrust is found near the center of sec. 11. Here a mass of pre-Cambrian rocks 200 feet across forms the crest of a knob. The contact with the underlying Mowry shale is nearly flat. At first glance the pre-Cambrian appears to consist of boulders similar to those in the lower part of the North Park formation. Many of the blocks, however, show no rounding, and tabular masses of metadiabase and pegmatite dikes in the gneisses can be traced laterally for 50 feet. It is concluded that the pre-Cambrian is a brecciated mass that reached its present position by movement as a whole. The mass is likely a klippe lying on part of the Pennock Mountain thrust, in which case net slip of the fault is several miles. An alternate explanation is that the pre-Cambrian block came from the south by creep and landslide at a time when the north face of Pennock Mountain stood out in higher relief than at present. Evidence against this hypothesis is the horizontal distance of 3000 feet from the block to the scarp, probable high dip of the fault at the base of the scarp, and the fact that the beds dip toward the main pre-Cambrian mass, thus presenting the most difficult possible conditions for the development of northward-dipping landslide faults.

The lower thrust has the characteristics of an inclined subsequent shear thrust (Billings, 1933, p. 147) in that it cuts across a fold at an angle less than the dip of axial plane and produces both thrusting of older rocks onto younger and thrusting of younger onto older. The writer believes, however, that the genesis implied by the term may not fit the case of Pennock Mountain thrust. Observed relations could have been produced as follows: (1) A break thrust cut the west limb of the syncline; (2) erosion reduced the surface of the east block nearly to its present level, or even lower near the thrust; and (3) the west block advanced over the erosion surface. Stratigraphic relations in the Hanna Basin previously described in the section on time of folding show that in adjacent mountain areas there were alternate intervals of deformation and erosion and that by Hanna time pre-Cambrian rocks were exposed. This history fits the conception that Pennock Mountain thrust is genetically a combined break and erosion thrust.

That the north end of Pennock Mountain is bordered by a fault is shown by exposures of Paleozoic and Mesozoic rocks closer to the pre-Cambrian than their respective stratigraphic distances above the pre-Cambrian. Neely (1934, Pl. III) shows a thrust continuing south for 8 miles along the east side of the mountain. The writer's conceptions of structure, movement, and genetic relations of the Pennock Mountain block are closely similar to those previously expressed for the Elk Mountain block and are summarized as follows: Pennock Mountain is underlain by a scoop-shaped fault dipping at angles of 35° to 45° along the east side and close to vertical at the north end. The block above the thrust moved relatively upward and eastward, and deformation within its northern part was more or less independent of deformation within the southern part of the Coad Mountain block. The rocks constituting Pennock Mountain block were originally a more resistant mass in a heterogeneous basement complex.

Evidence of high dip of fault at the north end of the mountain is shown in the southern part of sec. 11. Exposures of Wall Creek and Sundance are closer together than the thickness of intervening beds and dip south at an angle greater than 40°. A southward-dipping fault producing repetition of the Sundance and Morrison must have a dip greater than that of the beds, as shown in section M-M′. Eastward movement of the Pennock Mountain block is indicated by the eastward swing of Coad Mountain fault and the small anticline at the southwest end of Coad Mountain as they approach the tear fault.

Relations of the tear to the two thrusts west of the small anticline are obscure because of extensive alluvial cover. South of the eastern thrust a ridge rises in this direction toward the top of Pennock Mountain. Therefore, the thrust probably terminates laterally against the tear. South of the inferred position of the western thrust there is a deep valley in the pre-Cambrian; it is therefore likely that the thrust continues southward in the pre-Cambrian. On the crest of the pre-Cambrian ridge west of the deep valley a saddle on the strike of the tear indicates that the fault crosses the ridge. In the SW ¼ sec. 10 it is possible that, beneath the alluvium, the tear and western thrust intersect without one offsetting the other or with offset much less than would be expected from inferred net slips of faults. Absence of offset is, however, the relation that should occur, inasmuch as inferred directions of movement on both faults are nearly parallel to the line of intersection of the fault surfaces. A similar case of intersection of thrust and tear farther south in the Medicine Bow Range has been mapped (Beckwith, 1938, Pl. 1). An area of excellent exposures in sec. 26, T. 14 N., R. 77 W., shows a major thrust offset only several hundred feet by a tear having a net slip of at least 2000 feet. Beds here, however, show large offsets and omissions. Beds would show the usual stratigraphic criteria of faulting in the vicinity of thrust and tear intersection only when stratification parallels one of the faults and makes a trace on the second parallel to direction of movement on the second.

PASS CREEK BASIN AREA

In secs. 29 and 32, T. 19 N., R. 81 W., the Wall Creek sandstone outlines a north-trending open syncline pitching both north and south away from a point near the boundary between the sections.

Pass Creek anticline is a sharp fold trending north for at least 4 miles. It may continue south beneath the terrace deposits in sec. 8 and north beneath Elk Mountain thrust. The anticline is markedly overturned; the Wall Creek dips 30° to 55° on the west flank and is overturned as much as 40° beyond vertical on the east flank. East of the center of sec. 5, where the anticline is not faulted, it is a closed fold. A lenticular sandstone in the Frontier of the west flank dips 50°; on the east flank only 200 feet away the sandstone is overturned, as shown by cross lamination, and has the same dip. The pitch is low. Frontier is exposed in the core in the southern 3 miles except where the Mowry is brought to the surface by faults. The exposures in sec. 20 show that Carlile here crosses the axial plane. Although these exposures are 300 to 400 feet higher topographically than those of Mowry and Thermopolis to the south, the anticline definitely pitches north at a low angle.

In sec. 32 on line J-J′ full thickness of Frontier is present on the west flank, and approximately half is faulted out on the east flank. The Mowry in the core dips uniformly west at 40°. Its east contact is well exposed in transverse gulches up to 15 feet deep. The lower few inches is extensively brecciated and recemented along a fault dipping 40° W. parallel to bedding in the Mowry and cutting across the edges of Frontier beds, which are vertical to slightly overturned. The fault is a bedding thrust dipping toward the gradual flank of the fold, as shown in section J-J′. It probably dies out in the Mowry to the west and undoubtedly offsets the axial plane of the anticline. The restoration above ground shows the relation of decrease in slip upward to the east, where the fault plane cuts at progressively increasing angles across stratification and dies out in a sharp flexure.

The fault is genetically connected with differences in ease of slipping along stratification. The succession below it from Jelm to Cloverly contains massive sandstones and cross-bedded conglomerates; the Mowry is thinly laminated and contains numerous bentonite seams. Stratification in the west flank of the anticline coincides with one of the planes of shear of regional horizontal compression and also with the local shear couple set up by bending of beds over the anticline. The lower shearing strength of the Mowry parallel to stratification caused initiation of movement at this horizon on the west flank. This was followed by propagation of a fault downward to the west toward the syncline and upward across the crest of the anticline.

The exposures of Mowry and Frontier in the NE 1/4 sec. 29 indicate that there is a westward-dipping thrust cutting across the crest of Pass Creek anticline. The Mowry shows only westward dips; a few feet to the east the Frontier is nearly vertical.

In secs. 8, 9, and 10 the Carlile and Niobrara outline three small anticlines and two synclines. They pitch northwest, and their axial planes dip at high angles to the northeast. In the N 1/2 sec. 8 the western exposures along the creek show beds from Niobrara to Mowry that belong to the west flank of Pass Creek anticline. From 100 to 200 feet of the lower Frontier is faulted out. In further discussion and in the cross section this feature is neglected, as it fits in genetically with major features and is too small to draw on the scale used. The slice of Mowry is in fault contact to the east with Niobrara of the southwest flank of a small anticline. Stratigraphic throw of the fault is at least 1000 feet. Its dip could not be obtained. Probable relations as shown in section K-K′ are similar to those in section J-J′ except that displacement is greater. The minor folds east of the thrust indicate that some of the beds in the sedimentary succession were capable of transmitting stress several miles from the vicinity of the thrust. The competent beds from Jelm to Cloverly probably glided over the Chugwater shales and gypsums and underwent shortening by folding east of the thrust. Greater eastward or less westward movement of the competent beds as a whole in relation to the overlying incompetent beds would give folds whose axial planes dip east down to the Chugwater.

The fault in sec. 33 was formed by a landslide. The edge of the North Park forms a steep scarp above Steele shale. The block west of the fault slipped down and was rotated clockwise as seen looking horizontally north. The dips shown were caused by rotation and drag along the fault.

OIL AND GAS POSSIBILITIES

General statement.—Possible occurrence of oil and gas in commercial quantities in the Elk Mountain district is largely a matter of structural traps. Other types of traps are not known here or in the surrounding region. The Sundance, Cloverly, and "Muddy" sandstone member of the Thermopolis are the main potential producing horizons. A test well to the pre-Cambrian in Big Medicine Bow anticline (Pl. 2) about 10 miles east of the northern part of the district showed no oil in the Tensleep (Shoenfelt, 1938, p. 35). Small yields have been obtained from the Wall Creek sandstone in Rock Creek anticline located 20 miles east of Elk Mountain (Dobbin, *et al.*, 1929b, p. 147).

Bloody Lake anticline.—Dips of the Mesaverde on the flanks and nose of the anticline and in the northern part of Fort Halleck syncline seem to indicate a structural high in sec. 4. The fault on the west flank of the anticline, which has been interpreted as formed by tension fracturing followed by propagation of the fracture downward nearly parallel to bedding, indicates that similar faults may occur in the area partially enclosed by the Mesaverde. Probably the Steele is extensively drag folded, in which case structural detail near the surface does not necessarily indicate structure at potential producing horizons. The Kasoming well cannot be considered as an adequate test. The generalized driller's log shows that the well was abandoned at 4225 feet without reaching the "Muddy" or Cloverly. Failure to encounter one of these can be explained by location of the well off structure, or by deflection of the drill down one of the flanks, or by thickening of shales on the crest of the anticline.

Simpson Ridge and Pass Creek anticlines.—Strikes and dips of the Shannon sandstone in secs. 13, 14, and 24, T. 20 N., R. 81 W., indicate a dome, locally known as the Mill Creek structure, in the western part of sec. 13 and the eastern part of sec. 14. Judging from the writer's map (Pl. 1), the Midwest well in sec. 11 is north of the high point. The well penetrated 1300 feet of Niobrara and yielded oil-saturated cores from the "Muddy" or Cloverly. The double thickness of Niobrara indicates drag folding or faulting near the crest of the anticline. The Steele beneath the alluvium is probably affected by numerous folds and faults formed by crumpling of the shales a few hundred feet below the competent Mesaverde sandstones. Such folds and faults would not necessarily be present in the more competent beds in depth. The occurrence of a bedding thrust in the Mowry shale of the west flank of Pass Creek anticline, as shown in sections J-J′ and K-K′, indicates the possibility of a similar thrust at the same horizon in the Mill Creek structure. Such a thrust should die out parallel to stratification west of the anticline and in a flexure east of the crest of the anticline, possibly without reaching the present land surface. It should offset the axial plane so that the part of it above the thrust is east of the part below. A vertical boring at the axial plane just above the thrust would continue downward into steeply dipping younger beds of the east flank. The double thickness of Niobrara in the Midwest well is consistent with the occurrence of a thrust of this type.

From sec. 33, T. 20 N., R. 81 W., to sec. 23 Simpson Ridge anticline pitches northeast. The thick cover of gravel and boulders at the base of Elk Mountain conceals relations of the fold to the Elk Mountain block. The beds of the east block may change strike abruptly and be truncated by the thrust. If this is so, the thrust fault provides closure at the southwest end of the anticline, and the high points of beds in the anticline are beneath the pre-Cambrian. A well northwest of the surface trace of the axial plane close to the pre-Cambrian should reach the crest of the fold at a potential producing horizon considerably below its high point.

Another possibility is that Simpson Ridge anticline and Pass Creek anticline are parts of a continuous fold extending beneath Elk Mountain thrust, in which case the Elk Mountain block must have moved across a syncline. This relation does not seem improbable because the pre-Cambrian of the northeastern part of Coad Mountain lies on the sediments of the west flank of an anticline near the west boundary of sec. 36, T. 19 N., R. 82 W., and line J-J′. Section L-L′ also shows thrusting of an anticline across an adjacent syncline. Another possible indication of continuity of the two anticlines is the northward pitch shown by the northernmost exposures on Pass Creek anticline and the southernmost on Simpson Ridge anticline. If the folds are continuous and the pitch is constantly to the north beneath the thrust, the structural high is on Pass Creek anticline. The "Muddy," Cloverly, and Sundance are here so close to the surface that there is considerable possibility of escape of oil and gas, particularly in view of the occurrence of bedding thrusts in the Mowry at a number of places on the west flank of the anticline. The thrusts cut the fold so that in places there is no axial plane at the surface and the axial plane beneath the thrust is offset west from its position above the thrust.

CONCLUSIONS ON ELK MOUNTAIN DISTRICT

The general northerly trends of folds and strikes of thrusts in the Elk Mountain district indicate that deformation was caused by east-west compression with predominant upward relief. In detail, however, the structural pattern differs markedly from that produced experimentally by Mead (1920), who coated a stretched rubber sheet with paraffin or wax and permitted the sheet to contact. Under these conditions folds trend and thrust faults strike normal to compression; thrusts die out laterally in the limb between anticline and syncline. Many structural features in the Elk Mountain district, such as thrusts that pass laterally northward into west-striking tear faults, Bear Butte thrust cutting diagonally across a major syncline and anticline, and the northeast-striking Rattlesnake Pass fault, strongly suggest features that developed near the laterally expanding free edges of Mead's sheets and also those produced in a pressure box by Link (1928) under conditions of nonuniform compression applied to a homogeneous succession of artificial sediments, or uniform compression applied to a laterally varying succession. In the Elk Mountain district there is little facies variation in the sedimentary rocks. The pre-Cambrian igneous and metamorphic rocks here and in the surrounding region change markedly in character from place to place. The writer believes, therefore, that the structural pattern of the Elk Mountain district was produced by east-west compression applied to a heterogeneous basement complex and a relatively thin cover of laterally uniform sedimentary rocks. The pattern may have been influenced by northward lateral relief afforded by sinking of the basin to the north under the load of sediments derived from erosion of the rising mountains.

RELATION TO STRUCTURE OF SURROUNDING REGION

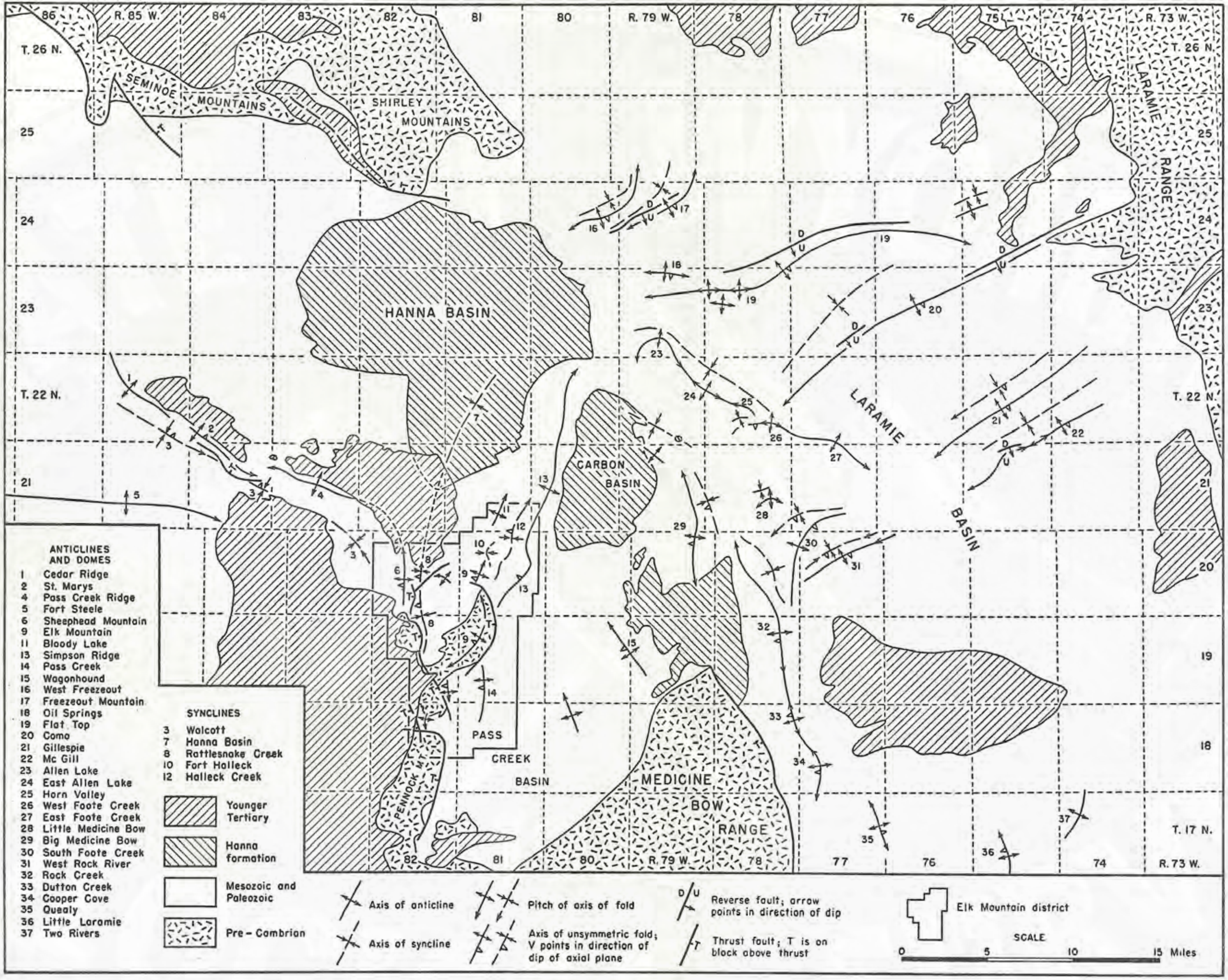
Description.—The map (Pl. 2) compiled from sources marked by an asterisk in the list of references shows the following:

(1) Folds in the Elk Mountain district trend north. Axial planes of unsymmetric folds and thrust faults dip west. Folds radiate in a fanlike arrangement from the northern part of the district.

(2) Thrust faults along the southern margin of the Seminoe and Shirley Mountains, which form the eastern part of the Sweetwater Arch (Fig. 1), dip north or northeast.

(3) Folds radiating from the western part of the Elk Mountain district trend west or northwest; axial planes of unsymmetric folds and a thrust fault dip northeast. Structures here suggest a genetic relation with the deformation processes that affected the southern margin of the Seminoe and Shirley Mountains.

(4) East of the Medicine Bow Range folds trend north. The axial planes of most of them dip west; the axial plane of only one, Quealy dome in T. 17 N., R. 77 W., dips east. The Arlington thrust fault, at the east base of the Medicine Bow Range, dips west. Folds extending north from the eastern border of the range swing to the northwest, and this trend is markedly shown in the northern part of the Carbon Basin and the area a few miles northeast.



TECTONIC MAP OF THE REGION AROUND THE NORTH END OF MEDICINE BOW RANGE

(5) Folds in the northeastern part of the Laramie Basin trend northeast, and their axial planes dip southeast. The northwest limbs of several anticlines are cut longitudinally by reverse faults or high-angle thrusts dipping southeast. This type of structure extends into T. 24 N., Rs. 79 and 80 W., within 12 miles of the northward-dipping thrust at the base of the Shirley Mountains. Surface traces of axial planes of folds are here convex to the southeast, yet a reverse fault dips in this direction. In the western part of the Laramie Basin in Ts. 20 and 21 N., Rs. 77 and 78 W., folds with northeast trend and southeast dip of axial plane occur only a few miles east of folds with north to northwest trend. Another fact not shown by the map is that the northeast-trending folds affect only the lower Mesaverde and older rocks in the lower 7000 feet of the sedimentary succession.

Interpretation.—The southern part of the Rocky Mountains in Colorado and New Mexico trends nearly north, and the northern part in Montana and Alberta fairly consistently trends northwest. In the Central Rockies of Wyoming, northwestern Colorado, and northeastern Utah major ranges extend west, northwest, and north. Minor folds have the same trends, and in addition a few trend northeast. Such an irregular arrangement cannot be explained by uniform compression or a simple shear couple such as that postulated by Chamberlin (1940) to account for trends of ranges and minor folds in northern Wyoming and southern Montana. It seems best to consider structural relations around the north end of the Medicine Bow Range in terms of effective compression, either primary or resolved in a force couple, and relative directions of movement of major mountain blocks. The following hypothesis is advanced to account for relations shown on the map (Pl. 2).

The predominant stress in the southern part was nearly east-west compression such as has been inferred for the Southern Rocky Mountains. If one accepts the hypothesis that thrust faults and axial planes of folds dip toward the active force, pressure was from the west. The gradual change of trend in the belt extending from the east border of the Medicine Bow Range to T. 22 N., Rs. 78 and 79 W., strongly suggests marginal folds wrapping around the north end of a relatively eastward-moving resistant mass.

Effective compression west of the Hanna Basin was close to north-south. Localization of sharp folding and thrusting in the belt southwest of the Hanna Basin is genetically connected with relative southward movement of the Rawlins uplift (Fig. 1), in which the pre-Cambrian core of the Fort Steele anticline appears at the surface.

In the Medicine Bow Range a few miles south of the Pass Creek Basin, bedding, schistosity, and a major fault in a thick succession of metamorphosed sediments and extrusives strike northeast and dip steeply to the southeast (Blackwelder, 1926). In the northern part of the Laramie Range foliation in schists strikes northeast, and contacts between schists and intrusive rocks are as a rule steeply inclined or vertical (Spencer, 1916, p. 52). It is believed that the folds trending northeast in the Laramie Basin were caused by Laramide deformation of weaker rock belts in the pre-Cambrian basement complex. North-south compression initiated vertical movement on planes of weakness dipping southeast. Relative upward movement of the hanging walls of the faults thus formed produced northwest-southeast shortening. Some of the faults were propagated far enough up into the sediments to reach the present land surface. These are confined to the northeastern part of the Laramie Basin, from which beds younger than lower Steele have been eroded. In Ts. 20 and 21 N., Rs. 77 and 78 W., where Steele and younger rocks are exposed, faults do not reach the surface. The folds near the east end of the Shirley Mountains suggest marginal folds changing trend around the east end of a relatively southward-moving mass, in which case faults and axial planes of folds should dip northwest. Dips are, however, to the southeast toward the outside of the arc, indicating that control was exercised by the structures in the pre-Cambrian.

WORKS TO WHICH REFERENCE IS MADE

Bartram, J. G., and Hupp, J. E. (1929) *Subsurface structure of some unsymmetrical anticlines in the Rocky Mountains,* Am. Assoc. Petrol. Geol., Bull., vol. 13, p. 1275-1289.

Beckwith, R. H. (1938) *Structure of the southwest margin of the Laramie Basin, Wyoming,* Geol. Soc. Am., Bull., vol. 49, p. 1515-1544.

Billings, M. P. (1933) *Thrusting younger rocks over older,* Am. Jour. Sci., 5th ser., vol. 25, p. 140-165.

Blackwelder, Eliot (1926) *Pre-Cambrian geology of the Medicine Bow Mountains,* Geol. Soc. Am., Bull., vol. 37, p. 615-658.

Bowen, C. F. (1918) *Stratigraphy of the Hanna Basin, Wyoming,* U. S. Geol. Survey, Prof. Paper 108, p. 227-235.

Brown, O. P. (1939) *Geology of the Difficulty—Little Shirley Basin area, Carbon County, Wyoming,* Unpublished master's thesis, Univ. Wyo.*

Campbell, M. R. *et al.* (1925) *Geologic map of Wyoming,* U. S. Geol. Survey.*

Chamberlin, R. T. (1940) *Diastrophic behavior around the Bighorn Basin,* Jour. Geol., vol. 48, p. 673-716.

Darton, N. H., and Siebenthal, C. E. (1909) *Geology and mineral resources of the Laramie Basin, Wyoming,* U. S. Geol. Survey, Bull. 364, 81 pages.*

* Used in compilation of Plate 2.

Darton, Blackwelder, Eliot, and Siebenthal, C. E. (1910) *Laramie-Sherman folio, Wyoming,* in *Geologic atlas of the United States,* U. S. Geol. Survey, folio 173.

Dobbin, C. E., Hoots, H. W., and Dane, C. H. (1928) *Geology and oil and gas possibilities of the Bell Springs district, Carbon County, Wyoming,* U. S. Geol. Survey, Bull. 796, p. 171-201.

———, Bowen, C. F., and Hoots, H. W. (1929a) *Geology and coal and oil resources of the Hanna and Carbon Basins, Carbon County, Wyoming,* U. S. Geol. Survey, Bull. 804, 88 pages.*

———, Hoots, H. W., Dane, C. H., and Hancock, E. T. (1929b) *Geology of the Rock Creek oil field and adjacent areas, Carbon and Albany Counties, Wyoming,* U. S. Geol. Survey, Bull. 806, p. 131-153.*

Giddings, H. J. (1935) *Geology of a portion of the Laramie Basin lying north of Como anticline, Albany County, Wyoming,* Unpublished master's thesis, Univ. Wyo.*

Greene, R. G., and Hand, H. D. (1937) *Structural map of West Allen and East Allen Lake anticlines and adjoining areas, Carbon County, Wyoming,* Union Pacific Railroad Co. Unpublished map.*

———, ——— (1938) *Structure map of the McGill anticline, Albany County, Wyoming,* Union Pacific Railroad Co. Unpublished map.*

Isberg, J. T. (1937) *Geology of a portion of east-central Carbon County north and west of Elk Mountain, Wyoming.* Unpublished master's thesis, Univ. Wyo.*

King, Clarence (1876) *Atlas, U. S. Geological Exploration of the Fortieth Parallel.*

Knight, S. H. (1917) *Age and origin of the red beds of southeastern Wyoming,* (abstract) Geol. Soc. Am., Bull., vol. 28, p. 168.

——— (1929) *Fountain and Casper formations of the Laramie Basin,* Univ. Wyo. Publ. Sci., Geol., vol. 1, no. 1, 82 pages.

——— (1937) *Origin of late Upper Cretaceous sediments of the Laramie and Hanna Basins, Wyoming,* (abstract) Geol. Soc. Am., Pr., p. 94.

Link, T. A. (1928) *En échelon folds and arcuate mountains,* Jour. Geol., vol. 36, p. 526-538.

Lovering, T. S. (1932) *Field evidence to distinguish overthrusting from underthrusting,* Jour. Geol., vol. 40, p. 651-663.*

Maravich, M. D. (1941) *Geology of Freezeout Mountain—Bald Mountain area, Carbon County, Wyoming,* Am. Assoc. Petrol. Geol., Bull., vol. 25. p. 883-897.

Mead, W. J. (1920) *Notes on the mechanics of geologic structures,* Jour. Geol., vol. 28, p. 505-523.

Neely, Joseph (1934) *Geology of the north end of the Medicine Bow Mountains, Carbon County, Wyoming,* Wyo. Geol. Survey, Bull. 25, 15 pages.*

Reid, H. F., Davis, W. M., Lawson, A. C., and Ransome, F. L. (1913) *Report of the committee on nomenclature of faults,* Geol. Soc. Am., Bull., vol. 24, p. 163-186.

Shoenfelt, C. E., editor (1935, 1936, 1938) *Résumé, Rocky Mountain oil and gas operations.* Petroleum Information, Inc., Denver, Colo., 105, 125, and 156 pages.*

Spencer, A. C. (1916) *Atlantic gold district and the North Laramie Mountains,* U. S. Geol. Survey, Bull. 626, 85 pages.

* Used in compilation of Plate 2.

Straley, H. W., III (1938) *Adjustments in small-scale non-concentric folding,* Geol. Soc. Am., Bull., vol. 49, p. 1545-1568.

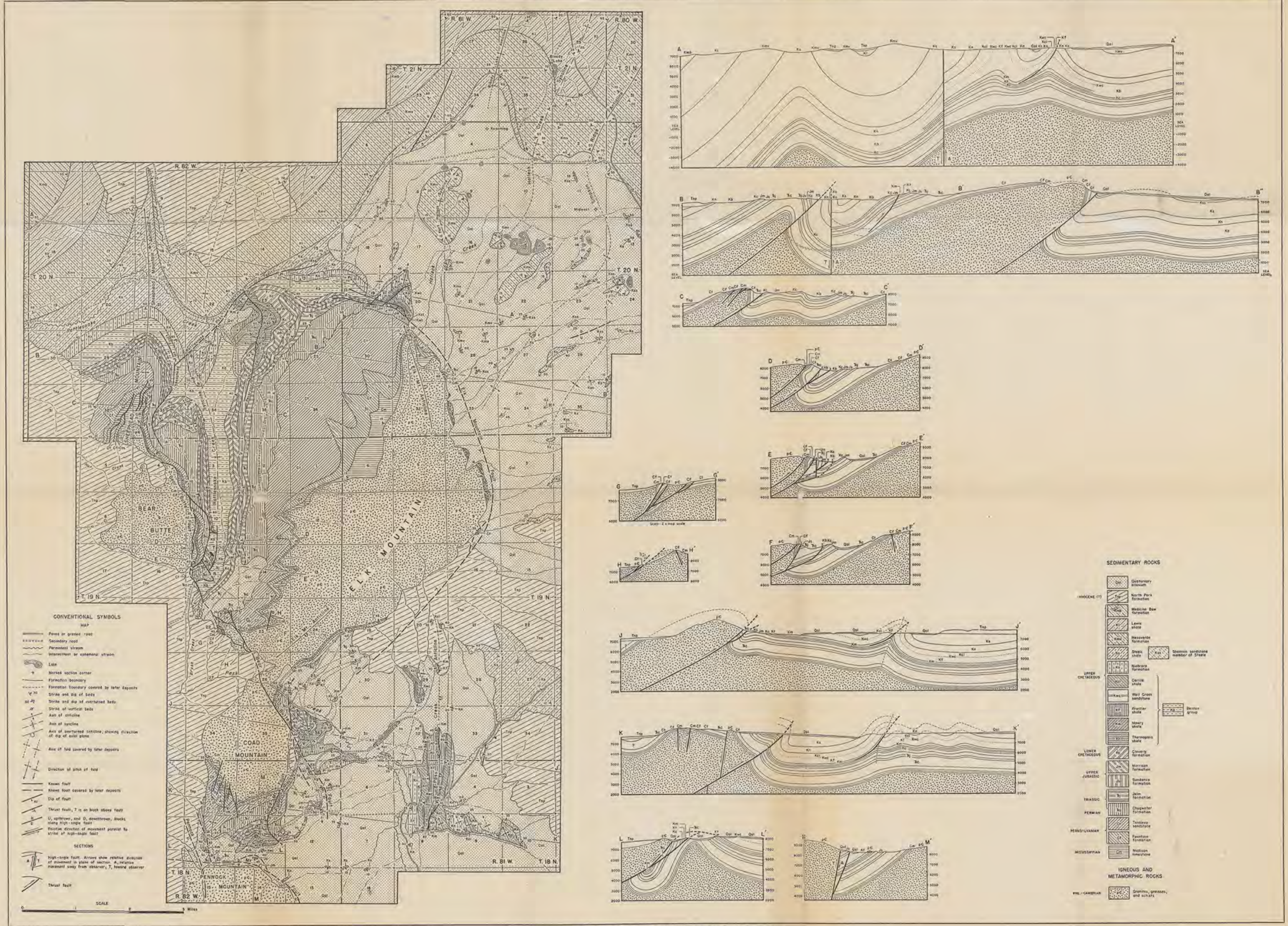
Thomas, H. D. (1934) *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming,* Am. Assoc. Petrol. Geol., Bull., vol. 18, p. 1655-1697.

——— (1936) *Frontier-Niobrara contact in Laramie Basin, Wyoming,* Am. Assoc. Petrol. Geol., Bull., vol. 20, p. 1189-1197.

Veatch, A. C. (1907) *Coal in east-central Carbon County, Wyoming,* U. S. Geol. Survey, Bull. 316, p. 244-260.

UNIVERSITY OF WYOMING, LARAMIE, WYOMING.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, APRIL 1, 1941.



GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE ELK MOUNTAIN DISTRICT