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STRUCTURE OF THE SOUTHWEST MARGIN OF THE LARAMIE BASIN, WYOMING

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ABSTRACT

The Laramie Basin is, in general, a northward-plunging syncline between the Laramie Range on the east and the Medicine Bow Range on the west. The dominant structural elements in the south end of the basin, near the junction of the ranges, are five northward-trending anticlines and the intervening synclines. The east flanks of three anticlines are cut by westward-dipping thrusts; northward, each thrust passes into a tear, which cuts westward across the axis of the anticline near the north end of the pre-Cambrian crystalline core. The thrust and tear constitute a scoop-shaped fault surface along which the block above the fault moved relatively upward to the northeast. The west flank of a fourth anticline is cut by an eastward-dipping thrust, which passes southward and eastward into a tear against which the pre-Cambrian core of the anticline terminates. It is believed that the folds, thrusts, and tears were formed under east-west compressive stress applied to a laterally uniform sheet of sediments overlying pre-Cambrian igneous and metamorphic rocks of varying competence.

Two en echelon synclines immediately east of the Medicine Bow Range are cut by westward-dipping thrusts. The west flank of the syncline has moved relatively eastward onto the east flank. Along the thrusts at the surface there are drag blocks younger than either of the two formations in contact along the fault.

INTRODUCTION

The Rocky Mountain Front Range of Colorado divides, a few miles south of the Wyoming State line, into two major anticlines, the Laramie Range (Fig. 1) on the east and the Medicine Bow Range on the west. Between the two is the Laramie Basin, a generally synclinal area. The Laramie Range extends northward across eastern Wyoming from the State line for approximately 100 miles, thence trends westward, and terminates in central Wyoming a few miles southwest of Casper. The range is an asymmetric anticline, whose exposed pre-Cambrian core varies in width from 15 miles, near the State line, to 30 miles southeast of Casper. The Paleozoic and Mesozoic beds on the west side of the range dip westward at low angles. In numerous places on the east side the beds are overturned and cut by westward-dipping thrusts. Less than 10 miles south of Casper a thrust of some thousands of feet displacement dips to the south. The Medicine Bow Range, whose maximum width is 30 miles, extends northward 50 miles from the State line and dies out approximately 40 miles east of Rawlins.

It has long been known that many of the anticlines in the Laramie Basin are strongly asymmetric, with steeper east limbs, and that in the border zone along the east side of the Medicine Bow Range there are westward-dipping thrusts. Nevertheless, published maps and structural studies along the west margin of the basin lack details necessary for an adequate understanding of the structure, and some of the interpretations are untenable in the light of recently acquired data. The present study was undertaken by the Geological Survey of Wyoming to obtain detailed maps and interpretations of the structure of the southwest margin of the basin, where the pre-Cambrian, Paleozoic, and Mesozoic rocks are best exposed. It is hoped that this information will advance the understanding of Rocky Mountain structure, particularly the genetic relations of en echelon folds, thrusts, and tear faults. The study may also facilitate structural interpretation in other areas where only isolated surface observations or subsurface data can be obtained, as in some oil fields in the Laramie Basin.

The area covered by the writer was mapped by the Fortieth Parallel Survey (King, 1876, Map I). Darton and Siebenthal (1909, Pl. I) mapped, on a scale of approximately 1 inch = 7 miles, the entire Laramie Basin and the borders of the adjacent ranges as far south as the Colorado line. Their structure sections (Darton and Siebenthal, 1909, Pl. VIII) show faults along the northeast side of Boulder Ridge, the east and west sides of Jelm Mountain, the east side of the portion of the Medicine Bow Range west of Jelm Mountain, the east side of Sheep Mountain, and along the southwest side of the Centennial Valley. All these faults are represented as vertical normal faults. Darton, Blackwelder, and Siebenthal (1910) provide a map on a scale of 1:125,000 of the southern part of the Laramie Basin as far west as the 106th meridian. The structure sections indicate that Darton and Siebenthal, the authors of the section on structure, had not changed their views as to the nature of the faults.

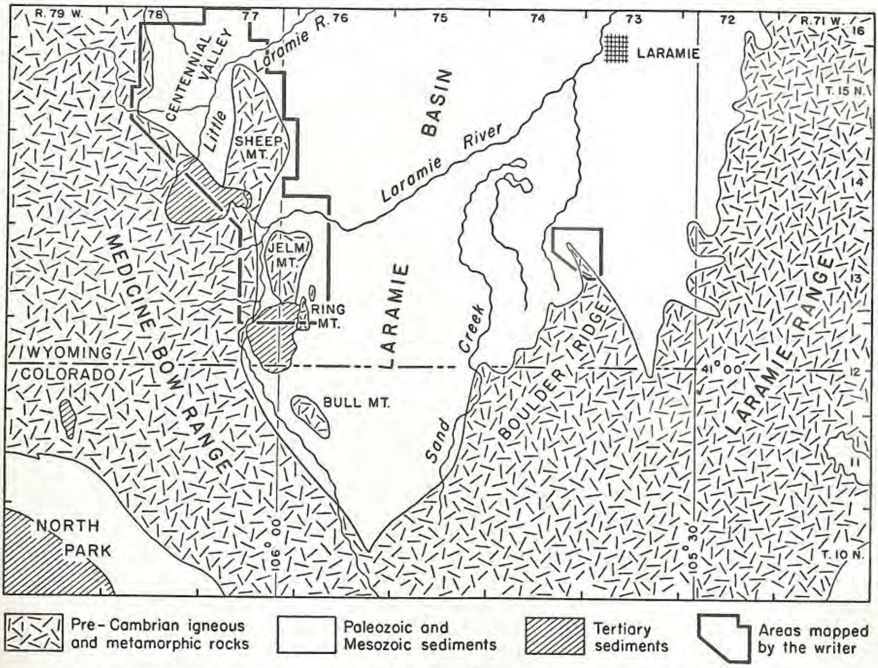

Figure 1.—*Index map of the south end of the Laramie Basin*

The entire area mapped by the writer is included in topographic sheets, the part east of the 106th meridian in the Laramie quadrangle, on a scale of 1:125,000 and a 50-foot contour interval, and the part west of this meridian in the Medicine Bow quadrangle, on the same scale, but with a 100-foot contour interval.

Approximately 150 square miles are included in the area mapped. All parts of the area where detailed observations could be made were mapped with plane table, generally on a scale of 1 inch = 1000 feet. The scale of 1 inch = 500 feet was used for several small areas where it was necessary to subdivide formations to obtain an understanding of the structure. Less than half of the 150 square miles was covered by plane table, inasmuch as large areas are composed of pre-Cambrian igneous and metamorphic rocks or are covered by alluvium. Field work was begun in the Fall of 1932 and finished in the Fall of 1937.

The writer acknowledges the valuable suggestions and assistance received from his colleagues of the Geology Department of the University of Wyoming, Dr. S. H. Knight, State Geologist of Wyoming, Dr. H. D. Thomas, and Mr. R. L. Nace. He also wishes to express thanks to his field assistants, C. E. Bradford, Joseph Neely, and J. H. Heathman.

TOPOGRAPHY AND DRAINAGE

The Laramie Basin (Fig. 1) is a rolling plain rising from altitudes of about 7000 feet in the north and central portions to 7500 feet near the Colorado line. From the east side of the basin there is a gradual ascent to the crest of the Laramie Range, which attains an altitude of about 8500 feet, 5 miles east of the edge of the basin. Eastward from the crest a gently rolling surface descends toward the Great Plains. Boulder Ridge, which projects into the southeast end of the basin, descends from 8700 feet at the State line to about 7500 feet at the north end. On the west border of the basin, Ring, Jelm, and Sheep mountains stand in front of the east border of the Medicine Bow Range. Their sides are steep, but their tops are beveled by a gently rolling surface at altitudes around 9000 feet. From the Centennial Valley and the Laramie River west of Jelm Mountain there is a steep rise to the rolling upland surface on the Medicine Bow Range at about 9500 feet. In the central portion of the range a prominent ridge—Snowy Range—reaches a maximum altitude of 12,000 feet in Medicine Bow Peak, 10 miles west of the Centennial Valley.

The south and southwest parts of the main embayment of the Laramie Basin are drained by Sand Creek and the Laramie River, a main tributary of the North Platte. The Centennial Valley is drained by the Little Laramie River, which joins the Laramie River approximately 10 miles beyond the north boundary of the index map (Fig. 1).

From the bases of the steep east faces of Ring Mountain and Jelm Mountain a gently sloping surface descends toward the lower part of the basin and bevels the Paleozoic and Mesozoic beds. In numerous places this surface is underlain by a thin layer of gravels consisting predominantly of pebbles and boulders of pre-Cambrian igneous and metamorphic rocks. This surface is probably a pediment. Similar pediment-like erosion surfaces flank the east, north, and west sides of Sheep Mountain and the east side of the Medicine Bow Range opposite the northern part of the Centennial Valley. The "terrace gravels", which cover large parts of the Laramie Basin and the Centennial Valley floors, are probably genetically connected with the cutting of the pediment-like surfaces.

STRATIGRAPHY

GENERAL STATEMENT

The stratigraphic units used for areal mapping are essentially those of Darton and others (1910, p. 5-14). Certain minor changes, principally in subdivision, were made as noted below. Since the stratigraphy of the Laramie Basin is well known, the writer did not make detailed measurements of the stratigraphic sections. The thicknesses given in the following table have been obtained from various publications or from data gathered by students and faculty of the University of Wyoming on the east side of the Centennial Valley. The thicknesses are probably accurate within ten per cent.

SPECIAL NOTES ON NOMENCLATURE

The Casper formation of Darton and others (1910, p. 5-6) was subdivided by Knight into Fountain and Casper. He discusses their genesis and gives thicknesses of both (Knight, 1929, p. 14, 52) in a number of localities in and adjacent to the area mapped by the writer.

A detailed section of the Satanka, Forelle, and Chugwater two miles south of Ring Mountain is given by Thomas (1934, p. 1690). He demonstrates that the lower part of the Chugwater is of Permian age and clarifies some misconceptions as to stratigraphic relations of the Satanka and Forelle.

The term Chugwater, as used by Darton and Siebenthal (1909, p. 22-25), designated all the red beds above the Forelle limestone. Knight (1917) says:

> "It is now known, especially throughout the Laramie Plains region, that the upper 250 feet of the Chugwater is separated from the underlying portion by a disconformity, and that the portion lying above the break is equivalent to the Dolores formation of southwestern Colorado. The evidence for correlating this upper 250 feet . . . with the Dolores lies in the presence of a pebble conglomerate composed of small limestone pellets, wood fragments, and fragmentary remains of Triassic vertebrates. This peculiar conglomerate is identical in its lithological and stratigraphical habit with the typical Dolores conglomerate, and it contains similar fragmentary remains."

He proposed that the name Jelm formation be used for the beds above the disconformity, restricting the Chugwater to the lower beds. The writer found this subdivision convenient because the Jelm stands out in higher relief than the Chugwater below and the Morrison and Sundance above; moreover, the Jelm is a thin unit in a part

TABLE 1.—*Geologic formations in the Laramie Basin*

Age	Unit mapped	Formation	Thickness (feet)	Characteristics
Quaternary(?)	Quaternary Alluvium		0–50(?)	Floodplain and pediment gravels, landslip debris, and probably some thin remnants of Tertiary sediments.
Oligocene	White River group		0–300(?)	Predominantly wind-blown and water-transported white and pink volcanic ash; few thin arkosic grit bands. Locally the lower few feet consist of talus breccias of fragments of pre-Cambrian igneous and metamorphic rocks embedded in an ash matrix. Continental.
	Unconformity			
Upper Cretaceous	Lewis shale	Lewis shale	3000	Gray sandy shale. Marine.
	Mesaverde formation	Mesaverde formation	2000	White, gray, and brown sandstones and gray sandy shales. Contains bands of brown "ironstone" concretions up to 10 feet in diameter. Uppermost part is white resistant sandstone. Upper part of formation contains few thin coals. Upper and middle parts are continental and lower part marine.
	Steele shale	Steele shale	2500	Predominantly gray sandy shales. Few thin intercalated sandstones in the zone of upward gradation into the Mesaverde. About 1000 feet from base is brown "salt and pepper" Shannon sandstone. Marine.
	Niobrara formation	Niobrara formation	350	Upper member of buff to white shaly chalky limestone; middle member of black shale and gray calcareous shale; lower member similar in lithology to the upper. Members approximately equal in thickness. Marine.
	Benton group	Carlile shale	250	Black and gray shale grading upward into gray calcareous shale. Marine.
		Frontier formation	650	Black shale. At top is gray to brown Wall Creek sandstone about 10 feet thick. Septarian concretions up to 2 feet across in the lower part. Marine.
		Mowry shale	120	Black siliceous shale, which weathers silver gray. Bentonite seams up to a foot thick. Marine.
		Thermopolis shale	40	Black shale. Marine.

Lower Cretaceous	Dakota group		350	Upper member of gray cross-laminated sandstone or quartzitic sandstone; 30 feet thick. Upper-middle member of black shale and gray platy shaly sandstone; 150 feet thick. Lower-middle member of slabby brown sandstone and gray and purplish sandy shales; 100 feet thick. Lower member of white conglomeratic sandstone or conglomerate with rounded chert pebbles up to half an inch across; 70 feet thick. Partly marine.
Upper Jurassic	Morrison formation	Morrison formation	275	Variegated shales containing white sandstone lenses, bands of chert concretions, and limestone lenses. Continental.
	Sundance formation	Sundance formation	0–70	Olive drab sandstones and gray shales with *Belemnites densus*. Marine.
Triassic	Jelm formation	Jelm formation	150–250	Coarse-grained brown sandstones which weather maroon. Lenses of maroon conglomerate with fragments of limestone and red shale. Red shales and orange sandstones. Continental.
	Chugwater formation	Chugwater formation	700	Red shales and sandy shales. Few thin beds of white sandstone and green shale near the top. Massive gypsum beds in lower part. Continental.
Permian	Forelle limestone	Forelle limestone	10–20	Upper, gray to dove crinkled ribbon limestone; middle, red sandy shale; lower, limestone similar to the upper. Marine.
	Satanka shale	Satanka shale	120–150	Red shale and red sandy shale. Locally gray to red thin-bedded limestone a foot thick near the middle and a gray crinkled limestone a foot thick at the bottom. Marine (?).
Pennsylvanian	Casper formation	Casper formation	280	Upper member of buff festoon cross-laminated sandstone 80 feet thick; upper-middle member of 30 feet of gray sandy shale; lower-middle member of 100 feet of red and white shaly sandstone; lower member of 70 feet of white festoon cross-laminated sandstone. Marine (?).
	Fountain formation	Fountain formation	400–700	Succession of beds and lenses of pink arkosic grits, orange, red, and gray sandstones, red shales, and thin gray limestones. Continental.
	Unconformity			
Pre-Cambrian	pre-Cambrian			Pink potash granites, gray to pink injection gneisses, gray, black and green schists, and metadiabases.

of the column where thin, easily distinguishable units are necessary for understanding the structure.

The Sundance formation is not recognized in the southern part of the area, but it may be represented by 10 to 20 feet of non-fossiliferous yellow sandstone below the Morrison shale. A few feet of beds bearing *Belemnites densus* is present at the south end of Sheep Mountain, and the formation thickens northward. Neely (1937, p. 744) gives a detailed section measured near Centennial.

The Morrison formation is so well-defined and generally recognized that no comment is necessary.

The term Cloverly formation was applied by Darton and others (1910, p. 9) to the lower and lower-middle members of the Dakota group (Table 1). They included the upper-middle and upper members in the Benton group. In the Rock Creek oil field, 25 miles north of the north end of Sheep Mountain, Dobbin and others (1929, p. 139) use the term Cloverly in the same sense. Because of the convenience of drawing contacts at the bottom of a well-defined conglomeratic sandstone and at the top of a ridge-forming sandstone, the writer preferred to place all the sandstones in one stratigraphic unit and to use the term Dakota group as defined by Lee (1927, p. 18).

The term Benton group, as used in this paper, is a restriction of the term Benton shale of Darton and others (1910, p. 9), since the top of the Dakota group is drawn higher than the top of their Cloverly formation. The division of the Benton group into formations is that of Dobbin and others (1929, p. 139), except that their Thermopolis shale includes the upper beds of the Dakota group. The writer's map (Pl. 1) does not show the subdivisions of the Benton group, because they can be distinguished only in areas of excellent exposures. They were recognized in the field in many places and were useful for structural interpretation. Thomas (1936) has shown that the fauna of the so-called Carlile of the Laramie Basin is of Niobrara age. This became known after a large part of the present writer's mapping had been finished. Shifting the lower boundary of the Niobrara formation down to the top of the Wall Creek sandstone also involves the practical difficulty of recognizing the Wall Creek, which, in the area mapped, is exposed only in a few places.

The terms Niobrara, Steele, Mesaverde, and Lewis are here used in the same sense as by Darton and others (1910, p. 9-10) and by Dobbin and others (1929, p. 139-142).

It is not certain that all the sediments mapped as White River are of that age. They are, however, closely similar in lithology to undoubted Oligocene sediments in the Great Plains area. A jaw with teeth found by S. H. Knight in the ash in the SW¼ sec. 12, T. 14 N., R. 78 W., was identified by Edwin H. Colbert of the American Museum of Natural History as belonging to the genus *Leptomeryx*. Colbert[1] states that the specimen is almost certainly of upper Oligocene (Brule) age.

STRUCTURE

GENERAL STATEMENT

The Laramie Basin is, in general, synclinal, but within the major syncline there are a number of minor folds. The northwesterly plunging Boulder Ridge anticline (Fig. 1) extends into the south end of the basin. Along the west side of the basin in Wyoming there are four anticlines whose pre-Cambrian cores are exposed. Of these, Ring Mountain, Jelm

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[1] Personal communication.

Mountain, and Sheep Mountain are in echelon arrangement with their north ends on a line extending north-northwest. Northeast of Ring Mountain a small exposed pre-Cambrian mass, not given a separate name on the topographic sheet, is here called East Ring Mountain. It is distinctly out of the north-northwest echelon arrangement of the other three anticlinal mountains.

One or more sides of each of the five smaller pre-Cambrian masses already mentioned, and also a large part of the west boundary of the Medicine Bow Range, are faulted.

FAULT TERMINOLOGY

Definitions of accepted and extensively used terms may here seem superfluous. Many terms, however, are used in various senses and with various restrictions.

A thrust fault, or thrust, is a fault with a dip of less than 45° and along which the hanging wall has moved upward relative to the footwall; movement parallel to the strike of the fault has been slight.

A reverse fault is a fault with a dip of more than 45° and along which the hanging wall has moved upward relative to the footwall; movement parallel to the strike of the fault has been slight.

A normal fault is a fault of high dip along which the hanging wall has moved downward relative to the footwall; movement parallel to the strike of the fault has been slight.

A tear fault, or tear, is a vertical or nearly vertical fault along which the major component of movement was horizontal and parallel to the strike of the fault.

A bed is followed along the ground surface to a fault. If the bed is found at the surface on the opposite side of the fault to the right of the course followed, the fault offsets the bed to the right; if the bed is found at the surface on the other side of the fault to the left of the course followed, the fault offsets the bed to the left.

BOULDER RIDGE AREA

The crest of Boulder Ridge (Fig. 2) is a narrow band of pre-Cambrian rocks, principally coarse potash granites. The Fountain and Casper formations lie in normal stratigraphic position on the southwest side of the ridge and dip 15° southwest. On the northeast side of the ridge the sediments from Fountain to Chugwater outline a strongly asymmetric anticline, which plunges northwest, except in section 19, where there is evidence of reversal of direction of plunge to southeast.

The dip of the Forelle in section 12 is 50° on the northeast flank, and 10° to 15° on the southwest flank. West of the anticline in sections 1, 2, and 12 is a strongly asymmetric syncline on the southwest flank of

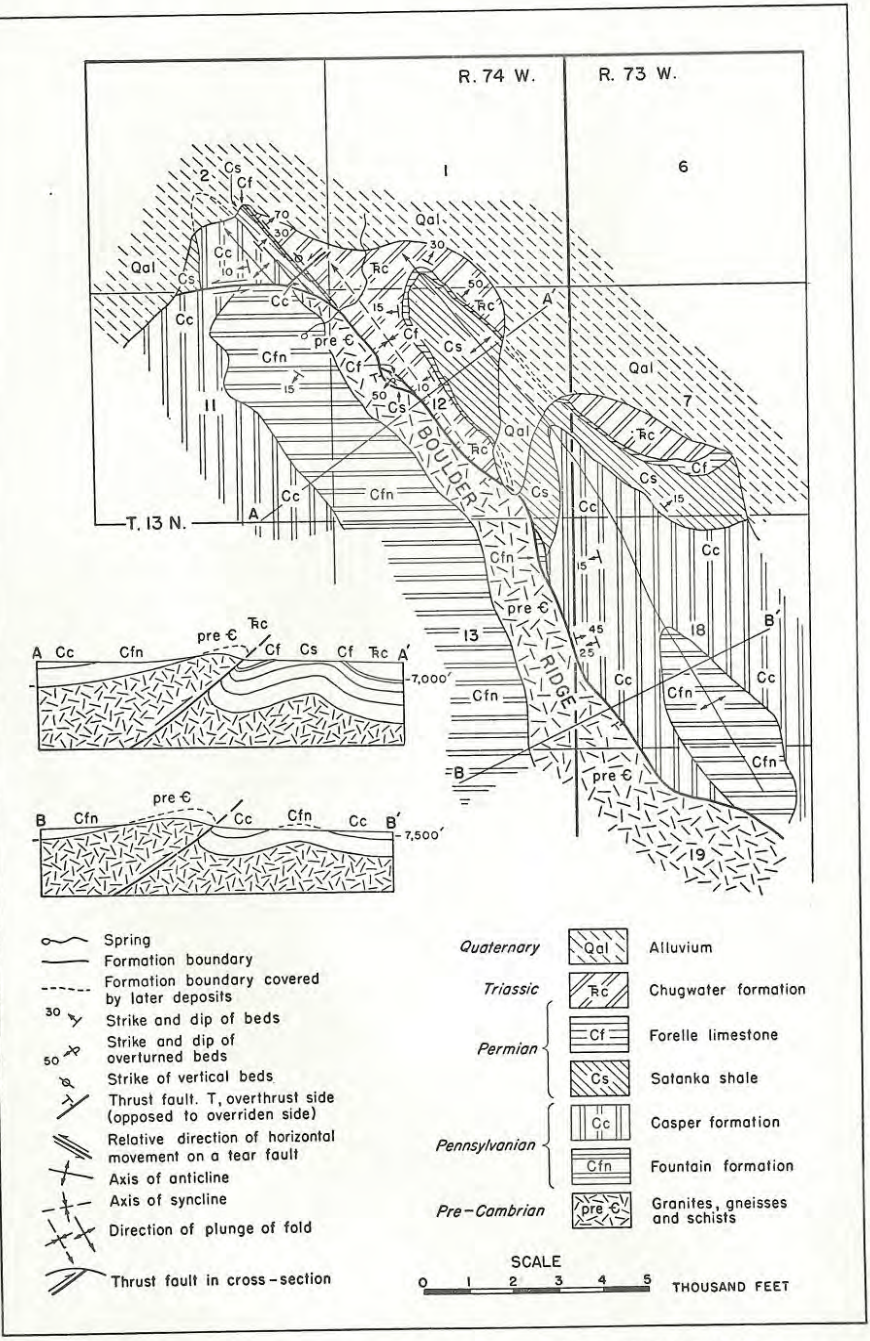

FIGURE 2.—*Geologic map and structure sections of the Boulder Ridge area*

which the Forelle stands vertically. Beyond the north end of the ridge, in section 2, the Casper and Satanka outline another asymmetric anticline. The axial planes of all three folds dip southwest.

The northeast boundary of the pre-Cambrian is a fault, which, in section 19, brings pre-Cambrian into contact with upper Fountain. To the northwest the pre-Cambrian is in contact with successively younger beds and, in section 12, pre-Cambrian rocks are in contact with the lower Chugwater. In section 13 a block of Fountain between a pair of branching and rejoining faults is bounded on the west by pre-Cambrian and on the east by upper Casper and lower Satanka. A similar block between faults in section 12 consists of Satanka lying on Forelle, which dips 50° to the southwest. Two facts show that the fault is a thrust dipping southwest: the location of the fault between the Boulder Ridge anticline and the syncline whose axial plane dips southwest and the overturning of beds near the fault. The minimum displacement increases from 500 feet at structure section B-B′ to 1000 feet at structure section A-A′. These figures do not, however, represent true displacement. They were obtained by scaling along the fault from the ground surface to the bottom of the Fountain in the block beneath the fault. Undoubtedly the bottom of the Fountain in the block above the fault was higher than the present surface trace of the fault.

In sections 12, 11, and 2 the strike of the fault changes from N. 45° W. to due west in a horizontal distance of approximately 1500 feet. The position of the surface trace of the axial plane of the Boulder Ridge anticline south of the fault cannot be accurately determined. If the conservative assumption is made that the surface trace here lies about in the middle of the pre-Cambrian, the surface trace has been offset left by the fault approximately 500 feet. Farther west the bottom of the Satanka in the block north of the fault is in contact with lower Casper in the block south of the fault.

In the SE ¼ sec. 2 a fault striking northeast offsets the Forelle and Satanka left 50 to 100 feet. Since the Forelle here stands vertically and the strike of the fault is normal to that of the Forelle, offset could be produced only by movement parallel to the strike of the fault. This fact and the location of the minor fault in front of a thrust indicate that the minor fault is probably a tear.

No deep gulches cross the northeast side of Boulder Ridge. Consequently it was impossible to obtain direct observations on the dip of the thrust. The 50° dip of the overturned Forelle in the NW ¼ sec. 12 and the dip of 40° for the thrust along the east side of Sheep Mountain in sec. 27, T. 14 N., R. 77 W., where pre-Cambrian is faulted against Fountain, indicate that the probable dip of the Boulder Ridge thrust is about 40°. The writer's conception of the shape of the fault surface and the relative movements of major blocks is as follows:

The Boulder Ridge block lies on a scoop-shaped fault surface. The northeast side of the scoop dips about 40° southwest near the present land surface. At the north end of Boulder Ridge the strike of the fault changes progressively from northwest to west. The dip of the fault also progressively steepens in the extreme northeastern part of section 11. The dip of the fault presumably approaches 90° in the NW ¼ sec. 11. The Boulder Ridge block moved relatively upward and northeastward along the scoop-shaped fault surface. The maximum displacement was in the SE ¼ sec. 12, where the pre-Cambrian now lies on the Forelle in the southwest flank of the next anticline northeast of Boulder Ridge. Southeastward from here the displacement of the fault decreases, and the fault dies out in this direction in the northeast flank of Boulder Ridge anticline. From the place of maximum displacement in the SE ¼ sec. 12, displacement also decreases northwestward. The front of the Boulder Ridge thrust block was thus bent into an arc with its convex side facing northeast.

At the north end of the ridge the block above the fault moved relatively northeastward up the steep northern part of the scoop-shaped fault. The direction of movement on the fault would thus be along a line plunging nearly southwest and making, on the fault, a large angle with lines drawn in the direction of dip of the fault. The fault here would be classified as a type intermediate between tear and reverse fault. The left offset of the surface trace of the axial plane of the Boulder Ridge anticline indicates that there was an important east-west component of horizontal movement. The fact that the bottom of the Satanka in the block north of the fault in section 2 is in contact with the lower Casper in the block south of the fault shows that, if the dip of the fault is here 90°, the plunge of the direction of motion must be greater than 15°, the dip of the beds at this place. Otherwise the bottom of the Satanka would be offset in the opposite direction.

SOUTHERN AREA

East and North Sides of Jelm Mountain.—The upper few feet of the vertical prospect shaft near the middle of the east boundary of section 25, T. 13 N., R 77 W. (Pl. 1), is in pre-Cambrian schists and metadiabases. The shaft is caved in, so underground observations could not be made. The size of the dump indicates that the shaft is probably not more than 100 feet deep. The last material thrown onto the dump consists of Fountain arkosic grits and red shales. Several hundred feet southeast of the shaft cross-laminated Fountain arkosic grits dip 60°

west. The pre-Cambrian clearly lies on the Fountain, either as a result of a westward-dipping fault or overturning of the east limb of the Jelm Mountain anticline.

Northeast from here in sections 24, 19, and 18 there is clear evidence of faulting. The pre-Cambrian is in contact with all formations up to and including the Chugwater. Two facts show that the fault is a westward-dipping thrust: the location of the fault along the flank of an anticline overturned eastward and the 45-degree dip of the overturned Fountain beds in the SW ¼ sec. 18. Near the center of section 18 pre-Cambrian lies on upper Chugwater. Beds approximately 1500 feet thick have been faulted out. A conservative minimum estimate is 2000 feet displacement. Inasmuch as the sediments have been eroded from the northwest block, true displacement cannot be obtained. In the NE ¼ section 18, the thrust divides. The two branches continue along roughly parallel courses northward to the northeast end of Jelm Mountain, here change strike to northwest, and continue in this direction to the floodplain of the Laramie River in section 31, T. 14 N., R. 76 W. The branches probably rejoin beneath the alluvium.

In sections 5 and 8, T. 13 N., R. 76 W., a minor fault extends southeast from the inner of the two major faults, offsets to the left beds up to and including those of the Dakota, and produces no comparable offset of the outer main fault. In sections 6 and 5 a minor fault striking northeast offsets beds up to and including the Dakota and offsets the outer fault approximately 50 feet. Four minor faults in the NE ¼ section 6 offset beds up to and including the Forelle. The outer fault may be offset, but it here forms the boundary between lower Chugwater and Jelm, a part of the column in which there are no easily distinguishable continuous beds. Because of the absence of positive evidence of offset, the outer main fault was mapped as continuous.

A branch fault striking west leaves the inner main fault in the NW ¼ sec. 6. Near the junction with the inner main fault, Satanka is in contact with lower Fountain. Farther west the bottom of the Casper is in contact with lower Fountain. The fault probably dies out in the Fountain in the NE ¼ sec. 1. The northeast corner of Jelm Mountain in sections 6 and 7 is a fault block bounded on three sides by a continuous fault consisting of the inner main fault and the branch fault. The fault blocks on the outside of this arc are all downthrown in relation to the block forming the northeast corner of Jelm Mountain, as shown in the southeast half of structure section C-C′ (Pl. 1).

An anticline is shown by the repetition of the Morrison on both sides of the strip of Jelm in sec. 31, T. 14 N., R. 76 W. The dip of 5° to the north in the Jelm, and the exposure of Dakota in the S½ sec. 30, indicate a northwest plunge. This anticline is probably expressed by the blunt northeastern projection of pre-Cambrian in section 6, in which case, the axial plane has not only been offset by the faults, but has been twisted in a horizontal plane through an angle of about 60°.

The writer's conceptions of the shape of the main fault surface and the relative movement of the main blocks, closely similar to those given for the Boulder Ridge area, are as follows:

The Jelm Mountain fault, at the southeast end of the Mountain, dies out in the overturned east limb of the Jelm Mountain anticline. The fault surface is scoop-shaped, with the southeast part dipping about 40° west-northwest. In sec. 18, T. 13 N., R. 76 W., the fault branches to form two scoop-shaped surfaces, which join in depth. In section 31, T. 14 N., R. 76 W., and sections 5 and 6, T. 13 N., R. 76 W., the two fractures dip steeply to the southwest. The Jelm Mountain block moved relatively upward to the northeast or east-northeast. The fault along the southeast side of Jelm Mountain is a thrust. The two main faults along the northeast side of the mountain are intermediate between a tear and a reverse fault. The faults dip steeply to the southwest, and the direction of movement on the faults plunges between southwest and west. One marked difference from relations at Boulder Ridge is that there is evidence, discussed more extensively in the section on the structure of the south end of Sheep Mountain, that the two faults along the northeast end of Jelm Mountain join beneath the alluvium of the Laramie River to form a single fault of modified tear type, which crosses the westward-dipping thrust along the east side of Sheep Mountain, and may continue west to the south end of the Centennial Valley.

The minor fault in sections 5 and 8 is probably a tear which permitted transfer of movement from one thrust to the other. Its position parallel to the two main faults along the northeast end of the mountain may, however, indicate that the fault is a modified reverse fault dipping southwest and having the direction of movement plunging between southwest and west.

The five minor faults in the E ½ sec. 6 and NW ¼ sec. 5 are probably tears.

The branch fault in the NW ¼ sec. 6 and NE ¼ sec. 1 is apparently of a different genetic type from the others. The block north of the branch fault is relatively downthrown, which seems to be inconsistent with the position of the fault between two generally westward-dipping thrusts shown in structure section C-C′ (Pl. 1). It may seem that the dip of about 40°, used in drawing the two faults at the southeast end of the section, is inconsistent with the previous statement that the two main faults steepen toward the surface where they swing northwestward around the northeast corner of Jelm Mountain. Since the angle between the line of section and the strike lines on the faults is only about 30°, the apparent dip of about 40° shown in the section is equivalent to a true dip of approximately 60°. The writer believes that the branch fault is a fracture initiated by shear, as are the tears in sections 6 and 5. The northeastward movement of the block south of the branch fault tilted the block so that the upward movement was greater at the junction of the branch fault and inner main fault than farther west on the branch fault.

Ring Mountain Area.—The syncline southeast of Jelm Mountain in the W ½ section 19, T. 13 N., R. 76 W., is strongly asymmetric with its axial plane dipping northwest. In the SE ¼ section 25 the beds of the west limb of the syncline are overturned. The anticline to the east, extending north from the north end of Ring Mountain, is apparently nearly symmetric, with its axial plane almost vertical. The next syncline to the east, in the E ½ section 19, is asymmetric, its axial plane dipping northeast. The two synclines and the anticline make a fan-shaped syncline between the east side of Jelm Mountain and the north end of East Ring Mountain. Farther north, the fan syncline changes to a simple syncline plunging northeast.

The west and southwest sides of East Ring Mountain are faulted. The evidence for faulting at the north end of the mountain is shown on the map. At the south end of the mountain, in the NW ¼ sec. 32, Fountain sediments within 100 feet of the pre-Cambrian granites strike N. 40° W. and dip 15° to the northeast. The boundary between the pre-Cambrian and Fountain here must be a fault. Near the SE corner of section 32 a strike of due north and dip of 3° to the east were obtained on good exposures of red shaly material in the middle Casper. The part of the Casper mapped in the NE ¼ sec. 32 and the E ½ sec. 29 is the lower white sandstone member and the middle red shaly sandstone member. The present positions of the outcrops of the Casper in section 32 indicate that the Casper is offset by a fault.

At the north end of East Ring Mountain the bottom of the Fountain on the east side of the fault is in contact with upper Casper on the west side. The west block is relatively downthrown, and beds 800 to 900 feet thick are faulted out. Along the southwest face of the mountain the block southwest of the fault is clearly downthrown, but the absence of sediments on East Ring Mountain makes it impossible to obtain more than a minimum estimate of displacement. In the E ½ sec. 32 the bottom of the Casper is offset left. If the fault here were normal or reverse and the south block were relatively downthrown, erosion following movement would have shifted the outcrop of the bottom of the Casper in the upthrown block eastward and produced offset to the right.

The position of the northern part of the East Ring Mountain fault along the steep east flank of an asymmetric syncline and the fact that a normal or reverse fault with the south block downthrown could not have produced the left offset of the Casper in section 32 led the writer to conclude that the fault along the west side of East Ring Mountain is an eastward-dipping thrust (east end of structure section A-A′, Pl. 1), and that the southeast extension of the thrust is a modified type of tear having a vertical component of movement.

If the thrust maintains constant dip from the surface downward, and the block above the thrust moved westward as a rigid block without rotation, the thrust should have a dip of less than 15°, the dip of the Casper north of the modified type of tear in section 32. If the dip of the thrust were more than 15°, the vertical component of movement on the tear would be great enough to produce, after reduction of both blocks to the same level, an offset of the bottom of the Casper opposite to that observed. It is improbable, however, that the thrust has a dip of less than 15°. The map also presents evidence that the block north of the modified type of tear fault was tilted during faulting. The width of outcrop of the Fountain measured along the north boundary of section 32 is approximately 3000 feet, and the mean dip is 15°. The width of outcrop of the formation measured along the south boundary of section 32 is approximately 6000 feet, and the mean dip is 8°. The writer believes that the East Ring Mountain thrust has a dip of about 45° near the present land surface, that the dip of the thrust decreases eastward in depth, and that the East Ring Mountain block not only moved relatively westward and upward along the thrust plane, but was at the same time rotated on a horizontal axis striking north so that, when viewed looking northward along the axis, the rotation on the axis would be clockwise and greater than 7°.

An arrangement of folds analogous to that of the Jelm Mountain and East Ring Mountain anticlines, which seems to support the interpretation that the East Ring Mountain fault is an eastward-dipping thrust, is known farther north along the west border of the Laramie Basin. From a point 10 miles north and 2 miles west of the northeast corner of the mapped area (Pl. 1) the axis of the Rock Creek anticline (Dobbin and others, 1929, Pl. 43) extends approximately N. 15° W. The axial plane of the anticline dips west. Quealy dome, 7½ miles north and 3 miles east of the northeast corner of the mapped area (Pl. 1), is approximately 2½ miles east of a line representing the extension of the axis of the Rock Creek anticline from the south border of Dobbin's map.

The major axis of Quealy dome (Shoenfelt, 1936, p. 26) trends approximately N. 15° W. The axial plane dips eastward. A well, beginning in the Steele shale, a short distance west of the surface axis, encountered vertical beds at depth. The steepening of the west flank of Quealy dome with depth indicates the possibility that near the pre-Cambrian floor the west flank of the dome may pass into an eastward-dipping thrust.

Laramie River Area.—The Fountain in the N ½ sec. 3, T. 12 N., R. 77 W., and S ½ sec. 34, T. 13 N., R. 77 W., stands vertically, so that its width of outcrop is approximately equal to the known thickness of the formation in this vicinity. The contact with the pre-Cambrian here is probably the surface upon which the sediments were deposited. Farther north, in the NE ¼ sec. 34, the width of outcrop of the Fountain decreases to 400 feet, and the sediments near the pre-Cambrian have a reverse dip of 80° to the west. The contact is here a fault. The slight overturning of the beds indicates that the fault is probably a westward-dipping thrust. The narrow strip of Fountain, about 150 feet wide and 600 feet long, extending from the main outcrop into the pre-Cambrian, confirms the probability that the fault is a westward-dipping thrust. A closely analogous relation is found in the W ½ sec. 26, T. 14 N., R. 77 W., where a crescentic block of Fountain is surrounded, in plan, by pre-Cambrian. Several hundred feet to the east a fault, undoubtedly a westward-dipping thrust, reaches the surface. It is believed that the block of Fountain was brought into its present position by a pair of faults of comparatively high dip, which join the thrust in depth at a place where it cuts across the upturned edges of the Fountain. The same explanation is proposed for the relations of the block of Fountain in the E ½ sec. 34, T. 13 N., R. 77 W.

Between Jelm and Woods the Paleozoic and Mesozoic rocks are covered, except in a few places, by White River sediments and floodplain deposits of the Laramie River. In a number of places, however, there is clear evidence that the east side of the Medicine Bow Range is bounded by a fault. In the SE ¼ sec. 27, Morrison and Dakota are exposed 300 feet east of pre-Cambrian. Benton is exposed in the SW ¼ sec. 23, 700 feet east of pre-Cambrian. In the SW ¼ sec. 11, Niobrara, which is 3500 feet stratigraphically above the pre-Cambrian, lies within 500 feet of the pre-Cambrian mass west of the road.

The East Woods fault was recognized by faulting out of beds. Where the fault is covered by the White River group the location is not necessarily accurate. Branches have been omitted in certain places, such as in the SE ¼, sec. 14, where there is a fault between Fountain and Casper. The direction and value of the dip of the East Woods fault could not be obtained. Inasmuch as the fault lies between the Jelm Mountain and West Woods faults, probably joins the latter in the vicinity of Woods, and strikes north toward, and probably joins, the Sheep Mountain fault, the writer believes that the East Woods fault is a westward-dipping thrust. If this is true, the dip must be greater than 35°, the maximum slope found on the west side of Jelm Mountain. The alternate possibilities (a) that the area between the two Woods faults is a fenster, and (b) that the East Woods fault dips east, are considered under a separate heading. The following discussion assumes that both faults dip west.

In the W ½ sec. 35, T. 13 N., R. 77 W., Morrison is in the center of a northward-plunging syncline. Dakota, Benton, and Niobrara occupy the center successively to the north. East of the syncline, in sections 35 and 26, is a northward-plunging anticline; the Dakota of both its flanks is faulted against pre-Cambrian. From the place in the SE ¼ sec. 26 where White River lies on the Dakota of the east flank of the small anticline, the succession of outcrops eastward is Benton, Morrison, Jelm, Casper, and pre-Cambrian. About 1500 feet farther north, the succession of outcrops eastward from the Dakota on the east flank of the small anticline is Jelm, Chugwater, Satanka, Casper, and pre-Cambrian. Inasmuch as the beds are successively older eastward, they must belong to the west flank of the Jelm Mountain anticline, not to the east flank of the small anticline. It is apparent that the westernmost branch of the East Woods fault cuts out a syncline and brings the east flank of the small anticline into contact with the west flank of the Jelm Mountain anticline.

The block of Benton between Morrison and Dakota in the SE ¼ sec. 26 is well exposed in a shallow prospect trench, and is the Mowry shale, a black shale which has weathered silver gray, contains bentonite beds, and cannot be mistaken for any other black shale in the succession. The Dakota west of the Benton is the slabby ferruginous lower-middle member. The fault east of the Benton block cuts out the Thermopolis shale, Dakota group, and part of the Morrison. The Mowry may be considered as a slice along a fault, but a slice composed of strata younger than either of the two formations with which it is in contact along the fault.

The western part of structure section A-A′ (Pl. 1) shows an interpretation which accounts for the faulting out of the syncline west of Jelm Mountain and for the position of the slice of Mowry between middle Dakota and Morrison. Perhaps there is another thrust on the west side of the overturned syncline of Fountain beneath the White River group. Less than half a mile north of the line of section, in the vicinity of the prospect shaft in the E ½ sec. 25, there is evidence that pre-Cambrian lies on Fountain. It is possible that the Jelm Mountain thrust extends as far south as the line of section, although stratigraphic evidence is lacking.

Structure section B-B′ is an interpretation which, in certain features, is closely similar to that represented in section A-A′ (Pl. 1). Surface relations in the belt between the Medicine Bow Range and Jelm Mountain are shown as resulting from "telescoping" of a syncline by thrusts. The high dip of the sediments close to the west side of Jelm Mountain indicates that the Jelm Mountain block, which includes the syncline beneath the Laramie River, was rotated. This motion can be described, when looking northward at the plane of section B-B′, as a counterclockwise rotation. Under compression, the east-west dimension of the lower part of the Jelm Mountain block may have decreased and the material thus displaced may have moved upward toward the crest of the anticline.

The area extending a mile north from Woods along the Laramie River is covered by alluvium. The exposure of Fountain in the NW ¼ sec. 11 provides the only clue to the structure. The writer believes that the most probable interpretation is that the East Woods and West Woods faults join beneath the alluvium to form the Sheep Mountain fault, which emerges in the NE ¼ sec. 3. Here, the west flank of a syncline lies beneath the pre-Cambrian. Satanka, probably repeated by minor folds, is exposed in the center of the syncline. The Satanka shown in the bottom of the syncline in structure section B-B′ is 5500 feet below the level of the Laramie River. Niobrara is exposed at the surface only a few feet south of line B-B′ and also a quarter of a mile southeast of Woods. It is probable that the Satanka in the core of the syncline approximately 1000 feet south of Woods is at about the same depth as in section B-B′. If the bottom of the syncline descends 5500 feet in a horizontal distance of 7000 feet—the distance scaled on the map from the southernmost exposure of Satanka to the northernmost exposure of Niobrara—the plunge of the fold is about 38°. This figure is not excessive for plunge of folds in the surrounding region and is comparable with the plunge of 30° obtained in the Morrison of the southern part of the same syncline in the NW ¼ sec. 35, T. 13 N., R. 77 W.

Area between Sheep Mountain and Jelm Mountain.—The Paleozoic rocks extending along the east side of Sheep Mountain from sec. 2, T. 13 N., R. 77 W., to sec. 26, T. 14 N., R. 77 W., are almost continuously exposed. This area was first mapped to obtain an understanding of the structural pattern in areas of poorer exposures. Subdivisions of the Casper formation were used and the mapping was done on a scale of 1 inch = 500 feet.

Exposures of pre-Cambrian metadiabase in the SE ¼ sec. 35 and the strikes and dips of the Fountain and Casper sediments in the vicinity suggest a structural dome on an anticline trending northward from the northwest end of Jelm Mountain. On the southwest side of the dome, the sediments dip westward beneath the pre-Cambrian, which is in fault contact with the Satanka. In the E ½ sec. 34 the fault branches to form seven faults. Some of these rejoin the main fault, and others die out to the northeast. A gulch 30 to 40 feet deep (omitted on the map to avoid obscuring geological detail) drains normal to the strike of the faults from the SE ¼ sec. 27 into the SW ¼ sec. 26. Dips of faults, probably accurate to ±5°, were obtained. The western fault dips about 40° northwest, and the next fault to the east dips about 30° northwest.

The block between these two faults consists of Fountain and Casper sediments, which dip 55° northwest. The beds are overturned, for truncation surfaces in cross-lamination in the Fountain are on the positional bottom, and, from the Fountain eastward, the succession of outcrops of Casper members is white, red, gray, and buff. Another method for determining relative age of beds, which, as far as the writer knows, had not been used before, gave the same result. In the Sand Creek embayment (Fig. 1), where the Fountain and Casper lie almost flat, sandstone dikes extend downward into the Fountain from the base of the Casper and ramify downward (Knight, 1929, p. 43-45). In the block between the two thrusts, sandstone dikes extend positionally upward from Casper into Fountain and ramify in the same direction.

East of this block, in sections 26, 27, and 35, Fountain is exposed in the center of a tight anticline, which plunges steeply to the southwest. About 800 feet southeast of the center of the anticline is a syncline, whose center at the surface in the NE ¼ sec. 34 is occupied by the lower limestone and a few feet of red shale of the Satanka and, farther northeast, by the upper buff member of the Casper. The syncline can be followed northeastward across several faults to the center of section 26. The southeast flank of the syncline, which merges with the northwest flank of the dome in section 35, is cut by several minor branch faults. The three easterly faults, in section 35 and the SW ¼ sec. 26, repeat the upper member of the Casper and the lower part of the Satanka. The fourth fault, which changes strike to northwest, offsets the bottom of the Casper to the right at a place where the beds dip southeast at a high angle.

The thrust between the pre-Cambrian and Fountain and four of the branch faults are shown in the northwestern part of section C-C′ (Pl. 1). The overturned beds between the westernmost pair of faults belong to a block that was carried relatively upward and southeastward from the overturned limb of a syncline beneath the pre-Cambrian.

Where the upper Casper and lower Satanka are repeated by the two easternmost faults the beds dip about 30° northwest. Repetition could be produced here by a fault dipping northwest only if the dip of the fault exceeds the dip of the beds. Since the pair of faults here considered can be traced laterally into a thrust, they probably dip at high angles near the surface and flatten out in depth.

The middle of the five faults in the northwest part of section C-C′ (Pl. 1) produces peculiar relations. On the map it resembles the Jelm Mountain fault in the sharp change in strike from northeast to northwest. The westernmost thrust apparently terminates laterally against the minor fault, although the thrust may continue northeastward into the pre-Cambrian. In the immediate vicinity of the intersection of the middle fault and line C-C′ the fault offsets the bottom of the Casper to the right. The beds here dip at a high angle to the southeast. If it is assumed that there was no component of horizontal movement parallel to the strike of the fault, the northeast block is relatively upthrown. If it is assumed that the only movement on the fault was parallel to the strike of the fault, the southwest block moved relatively to the northwest. If it is assumed that there was oblique movement on the fault—the most probable assumption—the southwest block has moved relatively downward in a direction between southwest and northwest. This is opposite to the relative direction of movement on the Jelm Mountain fault. It appears, therefore, that the middle fault of the five, at the place of sharp curvature on the map, is a normal fault, or a modified normal fault with direction of movement plunging close to the west. The writer believes that these peculiar relations were produced as follows:

The middle fault and the next one to the northwest surround a block which is, in the plane of section C-C′, roughly oval. The two faults converge downward into a single thrust and also converge upward, because of the steepening of the middle fault at the place where it sharply changes strike. Under compressive stress applied in a horizontal plane in an east-west direction, the block northwest of the middle fault could not move relatively upward. The next block southeast of the middle fault was not hindered from upward movement by upward convergence of bounding faults. The fault block southeast of the middle fault was thus caught between two faults, was squeezed like a wedge in the jaws of a vise, and moved upward and eastward or northeastward in relation to both adjacent blocks.

The structure of the west-central part of section 26 seems to be fairly simple. The width of outcrop of the Fountain, about 450 feet, is nearly large enough to accommodate the full thickness of the formation. The small block of Fountain completely surrounded, in plan, by pre-Cambrian leads the writer to believe, however, that the Fountain extends some hundreds of feet west beneath the thrust and that the block of Fountain was brought to its present position by two subsidiary faults extending upward from the main thrust. If this interpretation is correct, the major structural details, as shown near the northwest end of section D-D′, are similar to those near the west end of section C-C′.

The fault striking northwest across the N ½ sec. 26 produces no overturning of beds, such as one might expect if it were a thrust, nor is there much probability that it is a normal or reverse fault. Near the center of section 26 Morrison is in contact with Frontier shale. Only 600 to 700 feet of beds is faulted out. Approximately half a mile to the northwest, Fountain is in contact with Niobrara at the surface, and probably also with Steele beneath the alluvium. Here at least 3000 feet of beds is faulted out. The fault can be followed west up a gulch and across Sheep Mountain. On the west side of the mountain, schists and metadiabases are in contact with pink granite gneisses. Viewed from the upland underlain by the White River group in section 28 the contact appears to be nearly vertical. Probably the fault is a modified tear, involving a considerable vertical component, along which the southwest block moved, relatively upward and eastward.

The strike of the tear fault, near the center of section 26, is nearly the same as that of the two main branches of the Jelm Mountain fault in in sec. 31, T. 14 N., R. 76 W. The same general conception of movement is applicable in both cases. It is therefore probable that the tear fault crossing the southern part of Sheep Mountain is part of the Jelm Mountain fault. If this is true, the fault shows certain similarities with the "flaws" of the Jura Mountains (Link, 1928 b, p. 537), in that it stands nearly vertically, there is a large component of horizontal movement parallel to the strike of the fault, and folds cannot be matched across the fault. Marked differences from the "flaws" are that the fault does not extend outward normal to the trend of folds from the middle part of the convex side of a mountain arc, and the fault is not confined to the folded sediments in front of the arc. Instead it begins as a thrust in the limb of an asymmetric anticline, changes in strike through 90° around the end of the crystalline core of the same anticline, and cuts across another thrust farther northwest.

Alternate Interpretations.—During field work the writer was aware that Jelm Mountain might be a klippe and the Laramie River area a fenster resulting from erosion cutting through a single flat thrust. Fundamental objections to this hypothesis are:

(1) There is no evidence of a fault bounding Jelm Mountain on all sides.

(2) The Sheep Mountain fault, which is probably the northward continuation of the two Woods faults, dips 40° northwest in sec. 27, T. 14 N., R. 77 W.

(3) The minor faults in the southern part of the Laramie River area would all have to be beneath the flat thrust.

The following hypothesis, based on the experimental work of Link (1928a) on overthrusting and underthrusting, was suggested to the writer to account for relations along the west side of Jelm Mountain:

The East Woods fault dips eastward and terminates downward on the Jelm Mountain thrust. The two thrusts underlie a wedge, the upper part of which is Jelm Mountain. Under pressure applied horizontally in an east-west direction, the wedge was squeezed upward and eastward in relation to the main Laramie Basin block and upward and westward in relation to the block west of Jelm Mountain. If it is assumed that the movement involved in both folding and faulting was from west to east, the Jelm Mountain fault would be, in Link's terminology, an overthrust, and the East Woods fault an underthrust. The writer has presented evidence to show that the West Woods fault probably dips westward and would, therefore, be considered, on the assumption of unilateral movement from the west, as an overthrust. The writer believes that the East Woods fault is not an underthrust for the following reasons:

(1) The sediments in contact with and close to the pre-Cambrian along the west side of Jelm Mountain are not overturned to the west, as would be expected if the East Woods fault were an underthrust. Instead they stand vertically or dip west at high angles.

(2) The distance from the pre-Cambrian of Jelm Mountain to the pre-Cambrian of the Medicine Bow Range in the SW ¼ sec. 11, T. 13 N., R. 77 W., is only 1200 feet. Niobrara, stratigraphically 3500 feet above the pre-Cambrian, is exposed between the pre-Cambrian masses. If the Niobrara lies between an overthrust and an underthrust, erosion must have removed, while fault movement was proceeding, at least 3500 feet of sediments from each of the advancing fault blocks in order to permit them to approach each other to their present positions.

(3) Link (1928a, p. 835, fig. 7) shows that, if pressure and movement are sufficient to produce more than one overthrust, the uppermost overthrust prevents underthrusts from extending farther downward, and there are consequently no underthrusts extending downward from one overthrust to the next one below. If the East Woods fault is an underthrust, it extends downward from the West Woods overthrust to the Jelm Mountain overthrust.

NORTHERN AREA

East Side of Sheep Mountain.—The steep scarp along the east face of Sheep Mountain flattens eastward into a more gently sloping erosion surface, probably a pediment, which is underlain by a thick layer of débris derived from the pre-Cambrian mass. Talus slopes and cones are absent. Most of the fragments, even boulders 10 feet in diameter, are fairly well rounded. Hummocky topography, characteristic of landslides, is conspicuous in many places. Therefore, some of the small patches of Niobrara and Steele shown on the map have probably been carried eastward by landslides.

Although there are few exposures along the east side of the mountain, numerous small patches of Niobrara, Steele, and Mesaverde within a few hundred feet of the pre-Cambrian show that the east side of the mountain is bounded by a fault with a displacement of at least 4000 feet. Overturned beds dipping at low angles toward the pre-Cambrian indicate that the fault is a thrust. In the NE ¼ sec. 14, T. 14 N., R. 77 W., pre-Cambrian gneiss lies on Chugwater, which dips 40° to the northwest. The stratigraphic succession southeastward from here and the fact that truncating surfaces are on the positional bottom in cross-laminated sandstone beds in the Jelm show that the beds are overturned. The map shows overturned beds at several other places along the base of the mountain. Overturned position was recognized by one or both of the methods mentioned. The thrust splits into two main branches in the NW ¼ sec. 23, T. 15 N., R. 77 W. The east one passes between the exposures of Niobrara and Mesaverde in the S ½ sec. 10 and faults out most of the Steele. The west branch swings westward between the main pre-Cambrian mass and the exposure of Niobrara in the SW ¼ sec. 9.

Area North of Sheep Mountain.—The sloping pediment surface east of Sheep Mountain continues around the north end and onto the west side of the mountain. The floodplain deposits of the Little Laramie River almost completely cover the older rocks north of the pediment. The area north of the river is one of low relief and is almost continuously covered by gravels containing quartzite boulders up to 2 feet in diameter. The gravel and boulder sheet extends west to the vicinity of Centennial and completely covers the older rocks of the northern part of the Centennial Valley.

The west branch of the Sheep Mountain fault turns west around the north end of the pre-Cambrian core of the Sheep Mountain anticline in much the same manner as the faults which swing around the north ends of Boulder Ridge and Jelm Mountain. The interval of only 400 feet from Niobrara to pre-Cambrian in the SW ¼ sec. 9, T. 15 N., R. 77 W. shows that the fault here has a displacement of at least 3500 feet. As nearly as one can tell in an area of very few exposures, the fault continues westward into section 8. The top of the Casper north of the river in this section is too close to the bottom of the Fountain at the northwest corner of Sheep Mountain to accommodate all of the Fountain and Casper. About 200 feet of beds is faulted out. The writer's conception of the Sheep Mountain fault is similar to that previously explained in connection with the Boulder Ridge and Jelm Mountain faults. Near the center of section 8, the fault should dip steeply to the south and the direction of movement on the fault should plunge to the southwest. The strike of the beds is almost normal to that of the fault, and the beds dip west 35° to 40°. The intersections of bedding planes with the fault plane should, therefore, be lines plunging southwest. In other words, the traces of bedding planes on the fault walls should be lines making only a small angle with direction of movement on the fault. Movement on a fault which cuts beds whose traces on the fault walls are parallel to the direction of movement would not offset, repeat, or fault out beds. The concrete case here discussed probably closely approaches the conditions of the ideal case, and the displacement of the fault in section 8 is probably much greater than 200 feet, the thickness of the beds faulted out.

In the W ½ sec. 7 the Shannon sandstone member of the Steele shale strikes N. 80° W. and dips 25° to the north. One thousand feet to the northwest, beds of the upper part of the Steele, which consist of gray sandy shales and brown concretionary sandstone, stand on edge and strike N. 50° E. Between the two exposures there must be a very sharp flexure, or a fault with the upthrown block on the south. Farther west, in sec. 10, T. 15 N., R. 78 W., there is no evidence of faulting, but the Dakota changes strike through 30° and outlines a gentle anticline plunging steeply eastward. The fault probably dies out westward and passes into a fold.

The branch fault in the SE ¼ sec. 7, T. 15 N., R. 77 W., which is also shown near the center of section G-G′ (Pl. 1), was drawn on the basis of a few exposures and inferences from fault relations in a corresponding position near the north end of Jelm Mountain. The position of the bottom of the Dakota beneath the alluvium was inferred from the exposure of the conglomeratic member of the Dakota in the SE ¼ sec. 7 and the exposure of Chugwater and Jelm on the boundary between sections 7 and 8. The distance normal to strike from the inferred position of the bottom of the Dakota to the exposure of Niobrara in the SE ¼ sec. 7 is too small to accommodate the Dakota and the Benton. It is probable that the faulting out of beds was produced as follows:

The branch fault was initiated by shear during relative northeastward movement of the north end of Sheep Mountain. The north end of the Sheep Mountain block was thus underlain on the northeast by a scoop-shaped fault steepening toward the surface, and was bounded on the northwest by a nearly vertical fault terminating downward on the scoop-shaped fault. Movement of the north end of Sheep Mountain relatively upward and northeastward tilted the north end of the Sheep Mountain block so that an imaginary plane lying horizontally in the block before movement would, after movement, be inclined downward to the southwest. The block west of the branch fault did not undergo the same tilting.

The east branch of the Sheep Mountain fault probably extends northwest from sec. 10, T. 15 N., R. 77 W. and maintains the characteristics of a thrust. The distance of 3000 feet, scaled normal to strike from the bottom of the Benton in section 9 to lower Mesaverde projected southeastward from the exposures in the SE ¼ sec. 4, is insufficient to accommodate the Benton, Niobrara, and Steele. The distance from the Niobrara in section 4 northeastward to the Mesaverde is sufficient to accommodate the Steele standing on edge. It is probable, therefore, that the thrust dies out in section 4, and it is possible that a branch, of the general nature of a reverse fault with a considerable component of horizontal movement parallel to strike, may extend westward south of the exposure of Niobrara in the NE ¼ sec. 5.

Centennial Valley Area.—The Centennial Valley is a synclinal area complicated by faults on the southwest and west sides. On the east side and west side north of Middle Fork, alluvium-covered pediment surfaces slope toward the middle of the valley and merge with the heavily covered floor. At the south end a pediment slopes gently northward from the base of the scarp bounding the White River group. Between South Fork and Middle Fork the steep scarp cut on the pre-Cambrian descends to the level of the valley floor. Inasmuch as the valley floor is heavily covered, the central part of the Centennial Valley was not mapped by plane table. The drainage pattern of the central part of the valley (Pl. 1) was copied from the topographic sheet of the Medicine Bow quadrangle. The Paleozoic and Mesozoic succession is fairly well exposed along the east edge of the valley. The base of the pre-Cambrian scarp on the west side of Sheep Mountain and the adjacent Casper and Dakota hogbacks are well shown on the topographic sheet. There are no apparent structural complications in sec. 5, T. 14 N., R. 77 W. and secs. 32, 29, and 20, T. 15 N., R. 77 W., and this area was not mapped with plane table.

Between Middle Fork and South Fork a number of exposures of Paleozoic and Mesozoic sediments within several hundred feet of the pre-

Cambrian show that the boundary between the Medicine Bow Range and the Centennial Valley is a fault. The 40° reverse dip of the Mowry shale beneath the Dakota in the SE ¼ sec. 34, T. 15 N., R. 78 W. indicates that the fault is a thrust dipping southwest. In the SW ¼ sec. 12, T. 14 N., R. 78 W., Frontier shale dipping 40° to the southwest is in contact with the middle part of the Dakota. The southeast end of the band of Dakota terminates against a block of Fountain. The proximity of the exposures of Steele and Chugwater in the W ½ sec. 18, T. 14 N., R. 77 W. indicates a fault beneath the alluvium between the exposures. The doubtful thrust shown as passing beneath the White River in sections 13, 18, and 19 was inferred from the proximity of the Chugwater and pre-Cambrian in the N ½ sec. 13 and the reverse dip of the Benton in the NE ¼ sec. 19.

The map of the area within a radius of half a mile from the NE cor. sec. 19 shows striking similarities to that of the area in which a syncline is thrust out near the southwest end of Jelm Mountain. Along line E-E′ from the vicinity of the SE cor. sec. 17, the sequence is (1) pre-Cambrian, (2) Fountain, partially covered by White River, (3) Casper, (4) a fault cutting out the Satanka and Forelle, (5) Chugwater partly covered by White River, (6) Jelm, (7) a fault cutting out the Sundance, (8) Morrison, and (9) Dakota. The westward dip increases toward the west from 30° in the Casper to 60° in the Jelm. This succession belongs to the east flank of the Centennial Valley syncline. Eastward from the west end of the line E-E′ the succession is (1) White River, (2) Morrison, (3) Dakota, (4) Thermopolis, (5) Mowry dipping 50° westward, and (6) Frontier shale. This succession clearly belongs to the overturned west flank of the Centennial Valley syncline. Between the Frontier shale of the west flank and the middle Dakota of the east flank is a block of Niobrara approximately 50 feet wide and 150 feet long. Northwest and southeast of the block, Frontier of the west flank is in contact with Dakota of the east flank. The block of Niobrara is thus a drag block along a fault, but the block is younger than either of the formations in contact along the main part of the fault. The interpretation given in the western part of structure section E-E′ is essentially similar to those in sections A-A′ and B-B′, showing relative movement of the east limb of an anticline eastward across and beyond the axial plane of the next syncline to the east.

The evidence for the doubtful fault shown in the SE ¼ sec. 20, sec. 21, and sec. 28, T. 14 N., R. 77 W., is meager. Evidence has been presented to show that a tear fault extends from the east side of Sheep Mountain westward across section 27 to Fence Creek. From a few hundred feet north of the place where the fault passes under the White River, the contact between the pre-Cambrian and White River forms a fairly straight line extending westward to the vicinity of the area of thrust faults in section 20. The steep scarp cut on the pre-Cambrian north of the contact may be a pre-White River fault line scarp from which the sediments are now being removed.

Middle Fork Area.—The Centennial Valley fault passes into the pre-Cambrian near the west boundary of sec. 28, T. 15 N., R. 78 W. From here upstream the course of Middle Fork Canyon is approximately N. 30° W., the same as the strike of the fault across sections 28, 33, and 34. The course of the stream was probably determined by the fault. Two miles west of the western boundary of the map, Middle Fork Canyon abruptly changes its course to due north. It is probable, therefore, that the thrust continues at least 2 miles west from the mapped area.

A ridge extends southward from the main mass of the Medicine Bow Range and into the area west of the exposures of Fountain in the W ½ sec. 28. A few hundred feet southwest of the NW cor. sec. 28 there is a saddle in the crest of the ridge. The coarse massive granites between the saddle and the section corner are cut by numerous joints striking parallel to the Middle Fork fault and standing nearly vertically. The high dips of the joints and the fact that the Middle Fork fault extends nearly normal to the strike of the Centennial Valley thrust indicate that the Middle Fork fault is, in the vicinity of the section corner, probably of the general nature of a tear. Northeast from here, in the SE ¼ sec. 21, the overturning of the Dakota indicates that the fault probably dips northwest. Since the beds are here turned only 20° beyond vertical and both branches of the fault die out in less than a mile without undergoing a marked change in strike, there is no pronounced tendency to pass laterally from tear to thrust. The Middle Fork fault is probably, therefore, intermediate between a tear and a reverse fault.

STRESSES

The pattern of folds and faults in the area shows marked differences from patterns produced experimentally by Mead (1920) under conditions closely approaching uniform application of compression or shear to laterally uniform paraffin and wax sheets. The differences indicate either that stress was unequally applied or that there was considerable lateral variation in the ability of the crystalline rocks and overlying sediments to transmit stress. The sedimentary units in the stratigraphic column show little lateral variation in thickness and lithologic character. There is, however, marked lateral variation in the pre-Cambrian rocks. The oldest are schists and phyllites, probably originally sediments, and hornblende schists and metadiabases, probably originally basic intrusives and extrusives. These have been magmatically stoped by granites and, in large areas, have been injected to form gneisses. Uniform stress applied to such a heterogeneous basement complex would undoubtedly be resolved into components varying in direction and intensity.

The experiments of Link (1928b) on en echelon folds and arcuate mountains provide illuminating data on the probable causes of some of the structural details mapped. Link (1928b, p. 531) produced folds and faults by means of unequally applied horizontal compressive stress acting on a sheet of horizontal, laterally uniform, artificial sediments. If it is considered that the direction from which unequal pressure was applied in the experiment is west, the top view of the sheet of deformed sediments (1928b, fig. 4) nearly duplicates the pattern of folds and faults on the east and north sides of Jelm Mountain and in the Laramie River area west of Jelm Mountain. Link remarks (1928b, p. 530-531) that he knows of no case in nature which might have had an origin similar to the artificial system described. He also produced a tear fault striking parallel to the direction of application of compressive stress (Link, 1928b, fig. 10) by applying uniform pressure to a sheet of clay of uniform thickness, but which varied laterally in ability to transmit stress because cement had been added to the clay in front of one end of the push block.

The writer believes that the structural features of the area described were formed as follows:

The folds and faults were formed either by non-rotational regional compressive stress applied in an east-west direction, or by a regional rotational stress which could be represented by a force operating northwestward at some place northeast of the area and a force operating southeastward at some place southwest of the area. The change in trend of the northern part of the Laramie Range from north to west and the corresponding change of trend of minor folds within the arc of the Laramie Range in the northern part of the Laramie Basin indicate that the major regional stress was probably rotational. If this is true, the major stress in the southern part of the Laramie Basin can be conveniently considered as an east-west compressional component of the regional couple. Unequal transmission of stress by the heterogeneous pre-Cambrian basement complex caused the compressive stress to be resolved locally into stresses of different types operating in directions other than east-west.

SUMMARY OF CONCLUSIONS

The dominant direction of overturning of folds is eastward. The dominant relative direction of movement of blocks above thrusts is eastward, but there was also a component of relative northward movement of some thrust blocks near their north ends. One thrust, however, dips eastward. The writer believes that the structure, involving en échelon folds and oblique movement of thrust blocks on thrust faults passing laterally into tears, was caused by lateral variation in the ability of the pre-Cambrian basement rocks to transmit an east-west compressive stress. This stress may have been a component of a regional couple.

In two places along thrust faults, drag blocks were found which are younger than either of the two formations in contact along the fault. The criterion of younger drag blocks may be found useful elsewhere in recognizing thrusting of younger rocks over older, or thrusting of older rocks under younger rocks.

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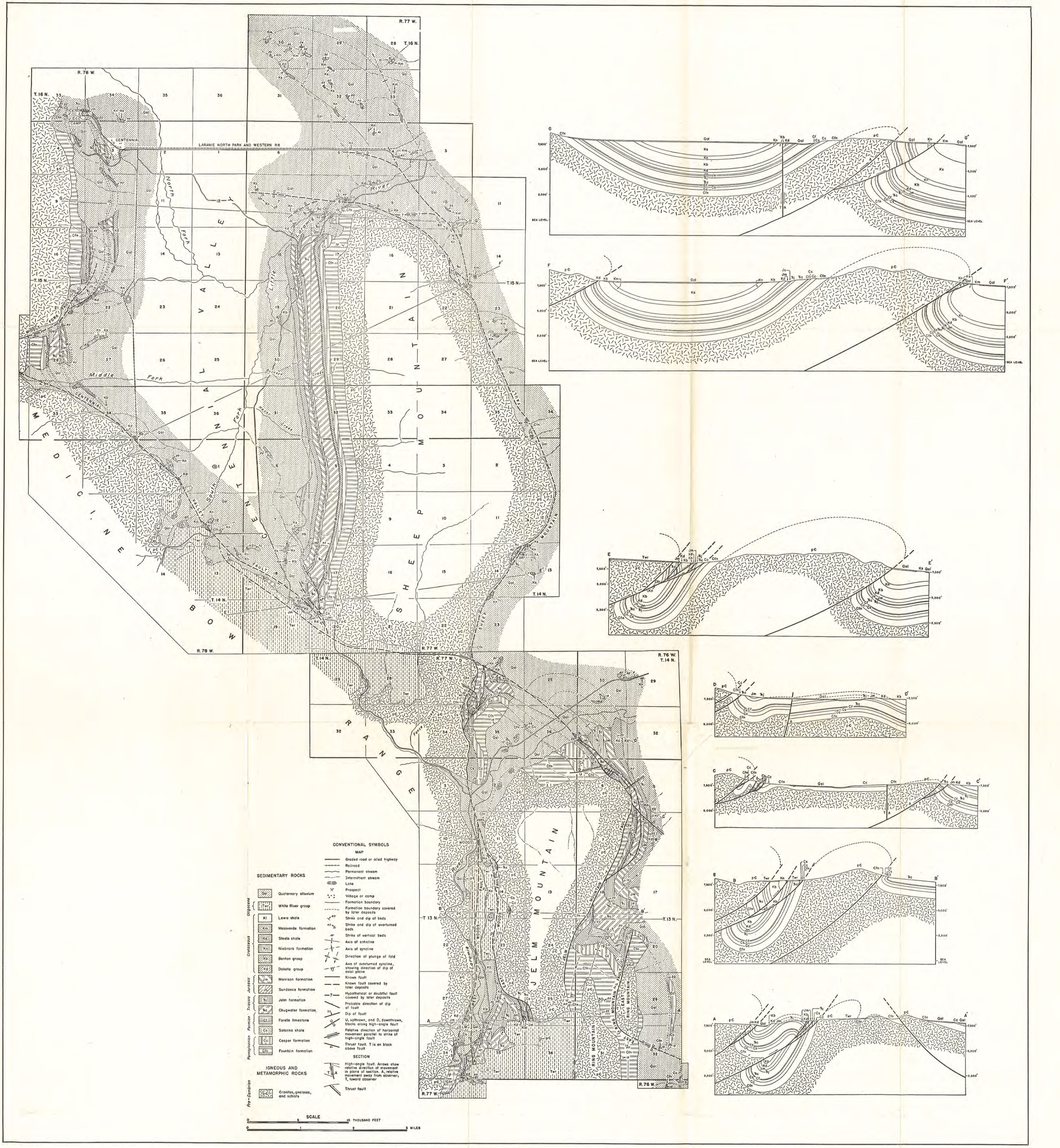

GEOLOGIC MAP AND STRUCTURE SECTIONS OF PART OF WESTERN MARGIN OF THE LARAMIE BASIN