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c) the magnetic anomalies in the northwestern half of the county may occur over a structural zone along which rocks of different magnetic susceptibility have been extruded, intruded or folded into juxtaposition on the basement complex surface;
d) structural domes in the Paleozoic rocks may be caused by draping of sedimentary rocks over topographic highs on the basement complex surface composed of resistant but weakly polarized crystalline rocks;
e) structural basins in the Paleozoic rocks may be caused by filling with sedimentary rocks in topographic lows on the basement complex surface composed of less resistant but moderately polarized crystalline rocks;
f) the inverse relationship between the magnetic and the Paleozoic structural features may be economically significant.

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Structural Analysis of the Shell Canyon Area, Bighorn Mountains, Wyoming[1]

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Abstract. The area is divided by Shell Canyon into two structurally dissimilar regions corresponding to the northern and central structural provinces of the Bighorn Mountains. The mountain trend changes abruptly from a N-S strike south of Shell Canyon to N 60°W north of the Canyon. The northern part of the area has steeper dips and fewer flexures, the uppermost being a chevron fold. The only fault in the north part is the Horse Creek Fault. It is vertical, runs oblique to axial traces for four miles in an E-W direction, attains a maximum of 450 feet of throw and may have strike-slip movement. South of the Canyon the front is lower, with more numerous and broader flexures. The upper flexure is concentric. There are two low angle thrusts dipping west with 45 feet and 210 feet of dip-slip. There are also three vertical faults. Planar fractures in the Paleozoic strata show definite preferred orientation. Each fracture pattern has one dominant direction which is interpreted as shear. This set is usually perpendicular to axial traces. The thrust faults in

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Trapper Creek agree in strike and dip direction with a weak set of fractures. The vertical faults in White Creek are aligned with the dominant set of fractures and are of similar origin.

Introduction

The objective of this paper is to present a description and interpretation of the structural geology of the Shell Creek area from Horse Creek to Trapper Creek. This fifty-five square mile area along the west flank of the Bighorn Mountains, is located in Bighorn County, Wyoming.

This paper represents a compilation of data obtained through detailed field studies during the summer of 1963 and information secured from literature on the area. Field work was conducted from the Iowa State University geology camp near Shell, Wyoming. Field mapping was done on aerial photographs having a scale of 1:20,000. Topographic maps with 20 and 40 foot contour intervals and a scale of 1:24,000 were used for additional control. The final geologic map was constructed by transferring the data from the photographs to the topographic maps.

Regional Structure

The ranges of the Middle Rocky Mountains are structural units formed through comparatively localized faulting and folding. The Bighorn Mountains have structures typical of the eastern portion of this province consisting of broad anticlinal folds whose margins have been ruptured and extended by high angle thrust faults. (Edmund, R. W., 1951)

The Bighorn uplift is divided into northern, central and southern provinces by its asymmetry. The apex of the uplift in the north sector lies near the steep western margin of the range. The mountain flank here has associated thrust faults and overturned sedimentary sequences that fade into a steep monocline. Upper Paleozoic and Mesozoic strata are exposed in hogback ridges with dips of high angles. In the central part, the asymmetry shifts to the eastern side of the range. Low monoclinal flexures with gently dipping strata mark the long slopes of the western flank. (Bucher, W. H., Thom, W. T., and Chamberlin, R. T., 1934)

North of the study area, the Five Springs and Beaver Creek faults form the western boundary of the northern structural province. Approaching the area of study from the north, the Five Springs Thrust, having 600 feet of heave and greatly overturned beds, gives way southward to the Beaver Creek Fault which is a high angle reverse and has a throw of more than 1500 feet. (Wingert, J., 1958, unpublished thesis)

The mountain front north of Shell Creek is formed by a steeply dipping monocline which approaches vertical. This part of the area lies within the northern structural province of the Bighorn Mountains, while that part south of Shell Creek is in the central structural province. South of Shell Creek the mountain front is formed by flexures of relatively low dip and it rises less impressively in a long gentle slope to the apex of the uplift in the Cloud Peak area. This division of the Bighorns was based on exposures of Precambrian crystallines and the change in general asymmetry of the range. If one were to 'draw a line' between the northern and central provinces it would pass through Shell Canyon. Here, if nowhere else in the range, this boundary can be accurately located. It locally finds expression in structural trends, types and intensity of deformation, fracture patterns and other aspects of the geology of the area.

Local Structure

In the study area, the sedimentary beds display five well-defined flexures which combine to form the overall monoclinal structure of the west flank of the mountains. (*see* fig. 1) The axial traces of the flexures were mapped and were found to serve as the boundaries which form a broad structural terrace, (*see* fig. 2, cross-section B-B'). In the far south part of the study area, in the vicinity of Trapper Creek, the five flexures with dips of no more than 15 or 16 degrees are spread out over the mountain front that is 5 to 6 miles wide. White Creek dissects the front between Trapper and Shell Creeks. At White Creek the same flexures converge, thus making the front steeper and narrower. The width of the mountain front is 3 to 4 miles here and the dips of the strata reach 30 degrees. Continuing northward to the south side of Shell Canyon these same flexures converge within an area slightly more than 2 miles wide. The Paleozoic strata attain dips of up to 65 degrees, (*see* fig. 2, cross-section C-C').

Throughout the area south of Shell Canyon the trend of the mountain front is generally N-S. This trend swings sharply to N 60°W within a mile north of the mouth of Shell Canyon. The five flexures described above are present but appear to be laterally displaced. The number of flexures diminishes as they converge to the northwest and in the vicinity of the north fork of Horse Creek (sections 36 and 25, T54N, R91W) the entire structural relief is accomplished in a single monocline, (*see* fig. 2, cross-sections A-A' & D-D'). The anticline that forms the upper flexure of the monocline is a concentric or flexure fold to the south of Shell Canyon. This same structure is exposed on the north wall of Shell Canyon as a chevron fold.

Faults. In the southern part of the study area, along Trapper

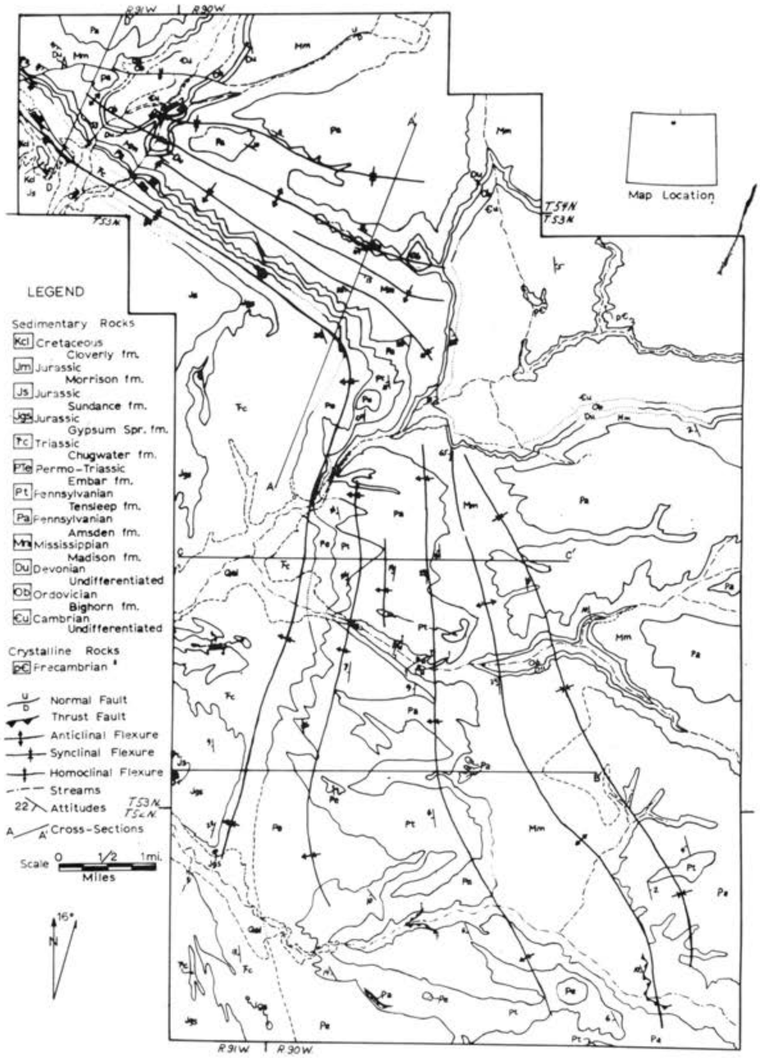

Figure 1. Geologic map of Shell Canyon Area, showing formation contacts; axial traces of flexures; faults; and structural cross-section lines A-A', B-B', C-C' and D-D'.

Creek, there are three thrust faults. In sec. 10, (*see fig.* 1, T52N, R90W), there is a thrust that can be traced for about ¾ of a mile and has a stratigraphic throw of 35 to 40 feet. It strikes N 33°W and dips 65° SW and is located in the upper flexure of the monocline where it displaces exposed beds of the Madison Limestone. The fault in sec. 5, (*see* fig. 1, T52N, R90W), strikes N 30°W and dips 18° SW and has approximately 70 feet of throw and 200 feet of heave. The fault in sec. 8, (*see* fig. 1, T52N, R90W), is a small high-angle thrust dipping to the southwest. It exposes a small window of Amsden through the Tensleep Sandstone.

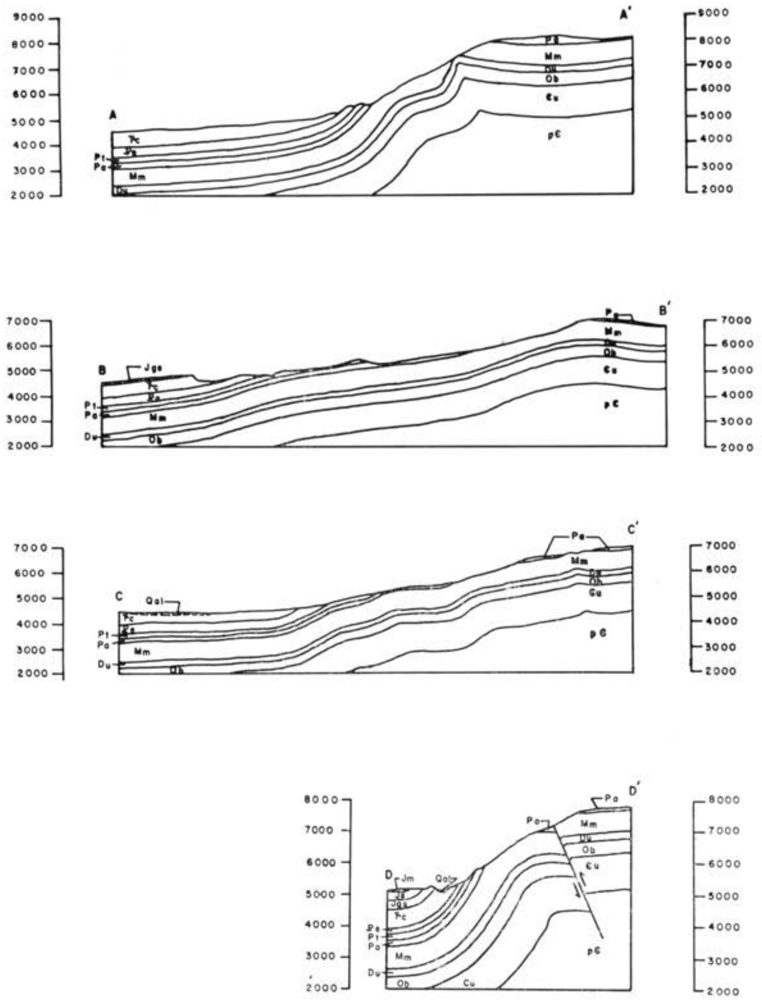

Figure 2. Structural cross-sections constructed by projecting surface attitudes. Vertical scale is the same as horizontal scale.

In sec. 28, (*see* fig. 1, T53N, R90W), three vertical faults cut across White Creek Canyon. They will be described from east to west. The first has a very small displacement and cannot be mapped for more than a quarter of a mile. The second has a throw of 40 feet on the north side of the canyon but decreases to 28 feet on the south wall. The fault strikes N 64°E and dips 75° SE and swings eastward at the north side of the canyon. The final fault of this set is about 300 yards from the second. The

GENERALIZED COLUMNAR SECTION

Period	Formation or group	Lith.	Thickness in feet	Description
Cret.	Cloverly fm.		80	Quartz sandstone, cross bedded.
Jur.	Morrison fm.		366	Interbedded sandstone and varigated silty shale.
	Sundance fm.		269	Green fossiliferous shale and very thin bedded limestone. Intraformational disconformity
	Gypsum Springs fm.		177	Gypsum at base with interbedded red silty shale and thin bedded limestone.
Trias.	Chugwater fm.		534	Red siltstone and sandstone interbedded with gray limestone and greenish gray siltstone. Some gypsum.
Perm.	Embar fm.		145	Red and green siltstone and shale overlain by thick bedded to massive limestone.
Penn.	Tensleep ss.		70	Quartz sandstone, cross bedded.
	Amsden fm.		219	Interbedded red siltstone, gray limestone and dolomite, plus sandstone and chert.
Miss.	Madison group		628	Thick bedded to massive limestone, some dolomite, some beds fossiliferous. Wavey bedding and solution cavities in upper part.
Dev.	Three Forks sh. Jefferson lms. Beartooth Butte		190	Limestone dominant in lower part. Interbedded thin ls. & sh. Channel fill at base.
Ord.	Bighorn dol.		300	Buff to gray massive to thin bedded dolomite, cherty in massive portion.
Camb.	Gallatin lms.		200	Thin bedded gray limestone with interbedded shale and flat-pebble limestone conglomerate
	Gros Ventre sh.		498	Greenish gray and purple shale with interbedded flat-pebble limestone conglomerate in lower and upper parts.
	Flathead ss.		282	Quartz sandstone, shale in part, conglomerate at base.

Figure 3. Generalized columnar section showing thickness and lithology of formation mapped. (Modified from Wingert, 1958).

attitude of the fault plane is N 84°E, 85° SE and it has 10 feet of throw. All of these faults exhibit horizontal slickensides. There are also several unmapped smaller thrusts associated with the steep flank of the anticline in White Creek. The attitudes of three of them were measured and found to be N 20°W, 48°W; N-S, 38°W, and N25°E, 74°W.

The largest fault in the study area is in the extreme northern part. Horse Creek Fault 'enters' the mountain front in the SE ¼ of sec. 26, (*see* fig. 1, T54N, R91W), and can be traced nearly four miles in an easterly direction where it loses expression on Sunlight Mesa. The fault strikes oblique to the structural trend of the mountain front. It is vertical and has a stratigraphic throw of about 200 feet where it crosses the ridge between the north and south forks of Horse Creek. Maximum displacement of 450 feet is attained in the west-central part of sec. 25, (*see* fig. 1, T54N, R91W). Here the fault has the attitude of a high angle reverse dipping 65° N. A half mile to the west, this fault dies out into a shear zone in the steeply dipping beds of Tensleep sandstone.

Three lines of evidence indicate that Horse Creek Fault may have a component of strike-slip movement. (1) Where it dies out into a shear zone, the dip of the strata in the upthrown block is 15° steeper than the dip measured in the downthrown block. The beds are vertical to slightly overturned on the hanging wall. (2) Within a half mile the displacement decreases from hundreds of feet to a shear zone that has little or no apparent displacement. (3) All slickensides are approximately horizontal. Except for this last point, the shear zone could be interpreted as a bedding plane fault.

Fracture Pattern Investigation

A fracture pattern investigation of the area was undertaken with the following objectives:

1) to determine the degree of preferred orientation of planar fractures
2) to determine the relationship of joints, folds and faults
3) to determine local stress directions
4) to determine the nature of deformation in the Precambrian rock
5) to contrast structural features north and south of Shell Canyon

In order to sample fractures from rock having the same physical properties, all stations with the exception of four in the Precambrian were taken in a conspicuous bed of calcareous siltstone about 10 feet thick. The bed occurs from 75 to 100 feet above the base of the Madison Limestone and is dense, well-beeded and from red to creamy buff in color. It is easily located by an overlying purple fossiliferous limestone unit containing two or three thin brachiopod coquinas, (*see* fig. 3).

Selection of sampling stations was determined by the following factors:

1) Where possible, stations were arranged in a line transverse to the folds. An attempt was made to locate one station below the fold, one above it and one in the steepest part of the flexure. Stations near faults were avoided where possible.
2) An attempt was made to provide uniform coverage of the entire area under study. However, the critical parts of the area were more thoroughly investigated.
3) The four Precambrian stations were located to detect folding in the Precambrian.

The attitudes of one hundred fractures were measured at each station without regard to apparent sets or patterns. The dips and strikes were then plotted on the lower hemisphere of a 10 cm. equal-area stereographic net. All stations taken where the strata dipped more than 5 degrees were corrected by rotating the bedding to a horizontal position. The resulting point diagrams were contoured to show areas of concenrtation by a combination of the free-counter and Mellis circle methods, (Turner, F. J., and Weiss, L. E., 1963). The 3, 5, 7, and 9 percent contours were drawn by the free-counter method. The 1 percent contour was drawn by the Mellis or circle method to show the configuration of vacant areas. The Mellis is a more desireable method, but the heavy concentration of points in some areas prohibited its use for the higher percentage contour lines. The consistent presence of large vacant areas in the diagrams together with the similarities between diagrams indicate definite preferred orientation, (*see* fig. 4).

Maxima representing the greatest density of similarly oriented fractures were selected by inspection. In most cases the maxima were few in number and clearly defined, thus all could be represented in rose diagrams which appear on the structure map, (see fig. 5). Each rose diagram is located at the station it represents.

Analysis

In nearly every rose diagram one set of fractures is dominant. This direction is approximately perpendicular to the nearest axial traces of the flexures. In many of the rose diagrams a second fracture direction forms an acute angle of approximately 60 degrees with the major set. These are adjudged to be conjugate systems of shear fractures, as exemplified by sets 'a' and 'b' in stations Nos. 4, 9 and 15, and set 'a' and 'c' in station #7. The vertical faults in White Creek are closely aligned with the NE striking shear direction, (*see* fig. 5, set 'a', station #15). If these faults were formed by strike-slip movement along the NE shear direction the sense of this movement would be right-lateral.

Since the strata dip about 20 degrees west, an apparent throw with the upthrown block to the south would result from right-lateral strike-slip movement. Only horizontal slickensides were found on the surfaces of these faults. This evidence suggests that these faults are strike-slip faults genetically related to the NE shear direction.

In general, sets 'a', 'b' and 'c' represent vertical fractures in all stations. Set 'd' is generally not vertical. The two thrusts in Trapper Creek are similar in strike and dip direction to the 'd' set of fractures in stations #1 and #17.

The Precambrian rocks have undoubtedly undergone many periods of deformation and the accurate interpretation of fracture patterns is difficult. But the fracture directions seem to be related to the change in trend of the fold axes. Sets 'a' in stations Nos. 5 and 10, set 'd' in #11 and set 'c' in #12 are all parallel. When viewed in light of their relation to the fold axes, these sets may be interpreted as tension joints. The predominant set to the northeast is perpendicular to this tension set, which may be interpreted as evidence for two different periods of deformation.

The configuration of diagrams Nos. 4, 9 and 15 seems to indicate that the deformational stress was essentially a horizontal east-west compression. Diagrams Nos. 1, 6, 16 and 17 are very similar and allow several interpretations.

1) They could be the result of couple deformation. By this interpretation, sets 'b' and 'c' in diagrams No. 1, No. 6 and No. 17 are shear directions and sets 'a' are tension fractures. In diagram No. 16 sets 'c' and 'd' are shear with 'a' also as tension.
2) Another possible interpretation is that the fracture patterns were affected by their location relative to the folds. By this interpretation stations Nos. 1, 6, 16, and 17 are influenced by ther location on synclinal flexures. Under these conditions the shear fractures are acute to the structural axis, even though compression is perpendicular to this axis.
3) A third possibility is that the fractures here were formed by horizontal compression. In this case, the local stress field was altered or the shear fractures formed at an unusually high angle to the maximum stress direction.

Of the four stations north and west of Shell Canyon, only #3 and #13 appear similar at a glance. Station #13 seems to be the result of NE-SW compression with sets 'a' and 'b' forming a conjugate system of shear fractures. Station #3 can be interpreted as the result of compression acting on a syncline if sets 'a' and 'b' are chosen as shear. This pattern may also result from simple horizontal compression. If sets 'b' and 'c' are considered to be the shear directions, the diagram can be interpreted as the result of a couple. Station #2 can be interpreted as formed by NE-SW compression with or without the influence of syn-

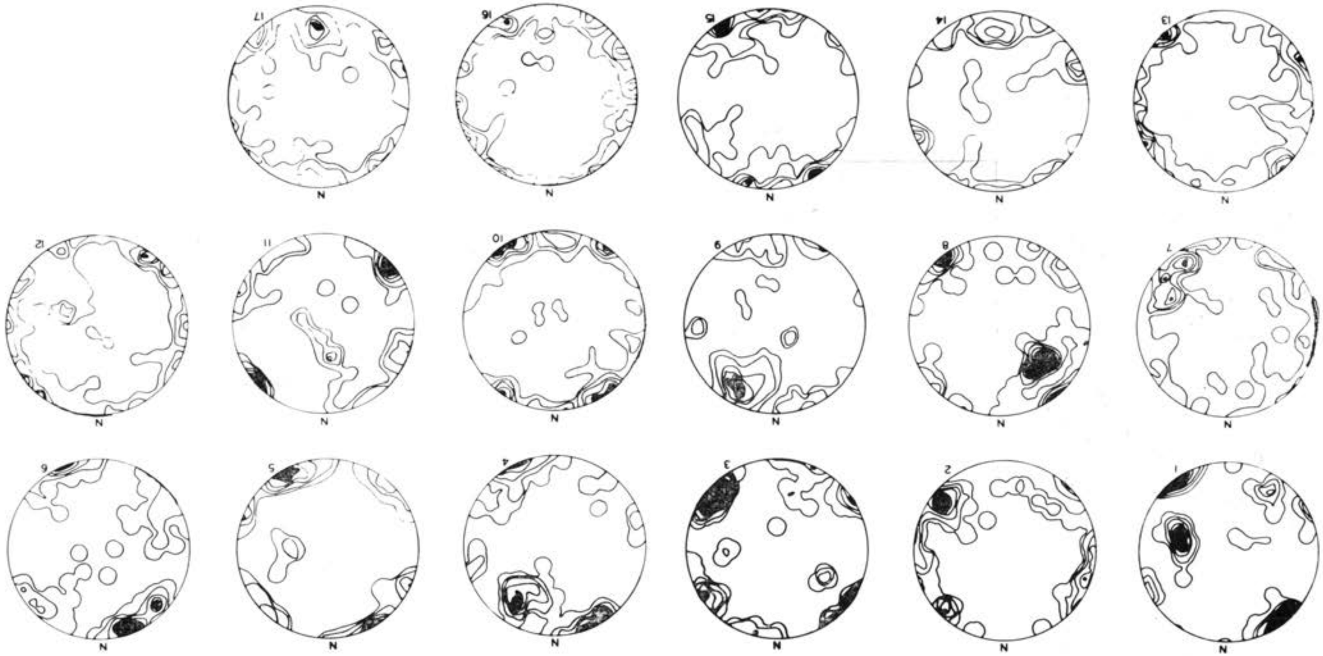

Figure 4. Contoured point diagrams showing the orientation of fractures. Each diagram represents one sampling station at which 100 fractures were measured. All fractures were sampled from a calcareous siltstone 75 to 100 feet above the base of the Madison Limestone except diagram numbers 5, 10, 11 and 12 which were sampled from Precambrian crystalline rocks.

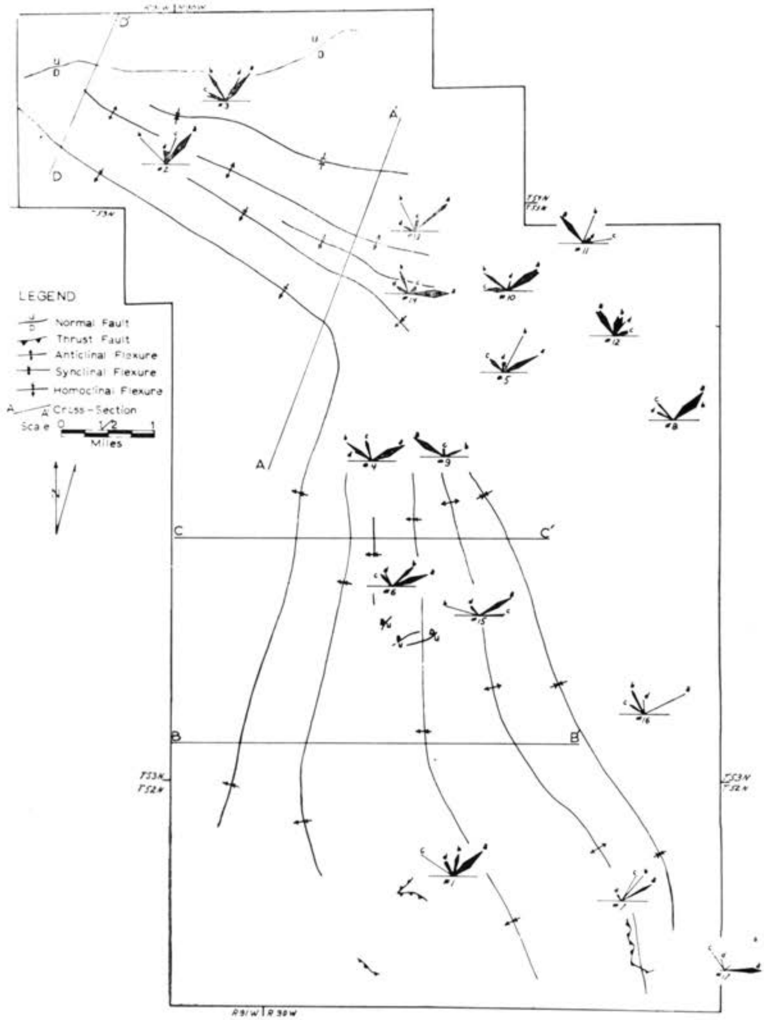

Figure 5. Structural map of Shell Canyon Area showing axial traces of flexures, faults and rose diagrams. Rose diagrams indicate strike, relative predominance and deviation of strike of each set of fractures. Set 'a' is the dominant fracture direction in each diagram. Relative predominance decreases through 'b' and 'c' to 'd'.

clinal flexuring. In either case, sets 'a' and 'b' are shear fractures. Since the station lies very near the axis of a monocline this configuration may be the result of NE-SW compression. Set 'c' then would be tension fractures parallel to the monocline. The fact that the shear fractures are acute about the structural axis is a result of this flexure. On the other hand, these same shear directions could be obtained in a couple. Taken together, these four stations can be interpreted as the result of compression in a NE-SW direction.

Conclusions

The similarity in strike between one of the fracture sets and the thrust faults along Trapper Creek is problematic. On the one hand it suggests a common origin for the two features. On the other hand, fracture patterns taken in steeply dipping beds more nearly approximate those of other stations when they are rotated back to horizontal, as seen in the rose diagrams. This seems to indicate that the fractures are a product of an earlier tectonic pulse and were rotated with later folding. The thrusts, however, appear to have been the culmination of folding and not to have preceded it. This may be indicative of two generations of fracturing.

The vertical faults in White Creek and the NE direction of shear fractures in this vicinity are concluded to be of similar origin. Also, fractures in the sampled bed show preferred orientation and form stress related patterns. Structural features north of Shell Canyon resemble those which characterize the northern structural province, while structural features south of Shell Canyon resemble those of the central structural province of the Bighorns.

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