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Topical Report

Description and Interpretation of Natural Fracture Patterns in Sandstones of the Frontier Formation Along the Hogsback, Southwestern Wyoming

Prepared by:
Sandia National Laboratories
Bureau of Economic Geology

Gas Research Institute

Drilling and Completion Group
January 1994

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TOPICAL REPORT

DESCRIPTION AND INTERPRETATION OF NATURAL FRACTURE PATTERNS IN SANDSTONES OF THE FRONTIER FORMATION ALONG THE HOGSBACK, SOUTHWESTERN WYOMING

Prepared by:

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Gas Research Institute
Tight Sands and Gas Processing Research Department
January, 1994

Title	Description and Interpretation of Natural Fracture Patterns in Sandstones of the Frontier Formation along the Hogsback, Southwestern Wyoming
Contractor	Sandia National Laboratories GRI Contract Number: 5089-211-2059
Principal Investigator	J.C. Lorenz
Report Period	June, 1991 - January, 1994
Objective	To develop an understanding of the origins of the natural fractures exposed in outcrops of the Frontier Formation, in order to provide a basis for predicting natural fracture orientations and distributions in subsurface reservoirs in the Green River Basin, Wyoming.
Technical Perspective	Large volumes of natural gas are present in naturally fractured sandstone reservoirs of the Frontier Formation, in the Green River Basin of southwestern Wyoming. Economical development of the resources in these low-permeability reservoirs requires access to the enhanced formation permeability provided by the natural fractures. In order to access fractures, an understanding of their origins is vital in order to predict 1) where they are developed in the basin, and 2) what their orientations are likely to be in these areas. Development and exploration wells must be sited in those areas with maximum fracture potential, and oriented in the optimum configuration for intersecting the maximum number of fractures. Moreover, the distribution of the fractures within the sandstone reservoirs is a major component of the reservoir heterogeneity that will dictate the rate and ultimate recovery of gas: wells must also be optimally oriented to circumvent the problems created by reservoir heterogeneity.

Technical Approach

Outcrops at the edge of the basin provide the only exposures of fractured Frontier Formation sandstones. Extensive study of these outcrops was carried out using off-road vehicles in order to take measurements of fracture dip, strike, position, and general character at outcrops along the 100 km extent of the ridge known as the Hogsback in southwestern Wyoming. Orientations of the host sandstones were also measured in order to provide a geologic/structural context for the fracture measurements. Surface field work was supplemented with low-altitude aerial photographs which provided information on continuity between otherwise separated outcrops, changes in fracture character along strike, and information on the structure of the Hogsback and remote outcrops. A literature search provided a tectonic framework within which the local structure and the fractures could be classified and interpreted as to origin.

Results

Fractures exposed in outcrop can be classified into three general groups: J1 fractures strike generally north-south and were formed early, in a regime of east-west extension during basin subsidence. These fractures have the greatest potential for extrapolation into the subsurface of the basin. J2 fractures formed during the subsequent onset of thrusting that led to the Hogsback escarpment; J2 fractures were created by a north-south dilatancy in response to east-west tectonic compression, and strike generally east-west. They may extend slightly east of the thrust belt. J3 fractures formed soon after J2 fractures as a mechanical response to local shear and torsion within the thrust plate. They will not exist beyond the limits of the thrust belt. Petrographic study of selected samples suggests that the mechanical properties that controlled fracture susceptibility changed through time, dictating the potential for the sandstones to fracture during given stress-producing tectonic events.

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DESCRIPTION AND INTERPRETATION OF NATURAL FRACTURE PATTERNS IN SANDSTONES OF THE FRONTIER FORMATION ALONG THE HOGSBACK, SOUTHWESTERN WYOMING

TOPICAL REPORT
January, 1994

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15. Supplementary Notes

Topical report on descriptions and interpretations of natural fractures in sandstones of the Frontier Formation.

16. Abstract (Limit: 200 words) Three categories of natural fractures are present in Frontier Formation sandstones along the Hogsback, a thrust-plate ridge in southwestern Wyoming. J1 fractures formed during basin subsidence prior to thrusting, and strike north-south parallel to the basin axis. J2 fractures formed as a result of north-south dilatency during early thrusting, and trend generally normal to the ridge. Tear faults and lateral ramps within the thrust plate produced localized J3 fractures with strikes that vary between locations. Diagenetic sequences in the Frontier Formation sandstones also controlled the development of fracture sets. At one outcrop, J1 fractures occur in sandstones that were cemented early with quartz, J2 fractures occur in sandstones that were not cemented early but that contain later calcite cement, and both fracture sets are present in sandstones that contain both cements.

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Tight gas sands, natural fractures.

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1.0 ABSTRACT

Three categories of bed-normal, natural extension fractures are present in the sandstones of the Frontier Formation exposed along the Hogsback, a thrust-plate ridge located in southwestern Wyoming. The first set of fractures (J1) formed during basin subsidence prior to thrusting, and strikes generally north-south parallel to the basin axis, sub-parallel to the present-day ridge. The second group of fractures (J2) formed as a result of north-south dilatancy during early stages of thrusting, and trends approximately normal to the ridge. Structures such as tear faults and lateral ramps within the thrust plate produced a third group of localized fractures (J3) with strikes that vary significantly from location to location. Diagenetic sequences in the Frontier Formation sandstones also controlled, in part, the development of fracture sets. At one outcrop, it can be shown that J1 fractures occur in sandstones that were cemented early with quartz overgrowths, J2 fractures occur in sandstones that were not cemented with early quartz but that contain later calcite cement, and both fracture sets are present in sandstones that contain both cements.

2.0 INTRODUCTION

The purposes of this study are (1) to document the patterns of natural fractures found in the Frontier Formation along the 100-km long escarpment called the Hogsback, located in southwestern Wyoming, (2) to place the fractures within their structural context, and (3) to interpret their origin. It is important to understand the characteristics, origin, and extent of these different sets of natural fractures, since fractures commonly have significant effects on permeability and permeability anisotropy in natural-gas reservoirs. Once the origin of the different fractures present in the outcrops can be interpreted, an attempt can be made to infer which, if any, of the observed fracture sets are present and effective in the stratigraphically equivalent natural-gas reservoirs to the east. This will aid in the exploration and development of gas from these reservoirs. The scope of this report is limited to describing the general character, variability, and probable origin of the outcrop fractures. Extrapolations of these data to the subsurface will be presented in a separate report (Lorenz, 1994).

The natural fractures discussed in this report are present in sandstone outcrops of the Frontier Formation at the southwestern edge of the Green River basin. These outcrops were created by the formation of the Hogsback, an escarpment that extends from a point about 30 km west-northwest of the town of La Barge, southward through Kemmerer, and nearly to the U.S. Interstate 80 highway at a point 24 km east of the town of Evanston (Fig. 1). North of Kemmerer, the ridge is commonly called Oyster Ridge due to the numerous beds of fossil oysters found along it, but the term "the Hogsback" will be used in this report for the entire length of this structural feature for the sake of simplicity. The Hogsback escarpment is a surface expression of the Hogsback thrust plate, which is part of the Idaho-Wyoming thrust belt forming the western edge of the Green River basin. The Hogsback thrust formed during early Eocene time, and was the last of a series of thrusts to form in this part of the basin (Wiltschko and Dorr, 1983; Rubey et al., 1975; Dixon, 1982).

Strata of the Frontier Formation in and adjacent to the Hogsback are about 600 m thick (Cobban and Reeside, 1952; Myers, 1977; Hamlin, 1991), and consist of an interlayered series of sandstones and mudstones with local intercalations

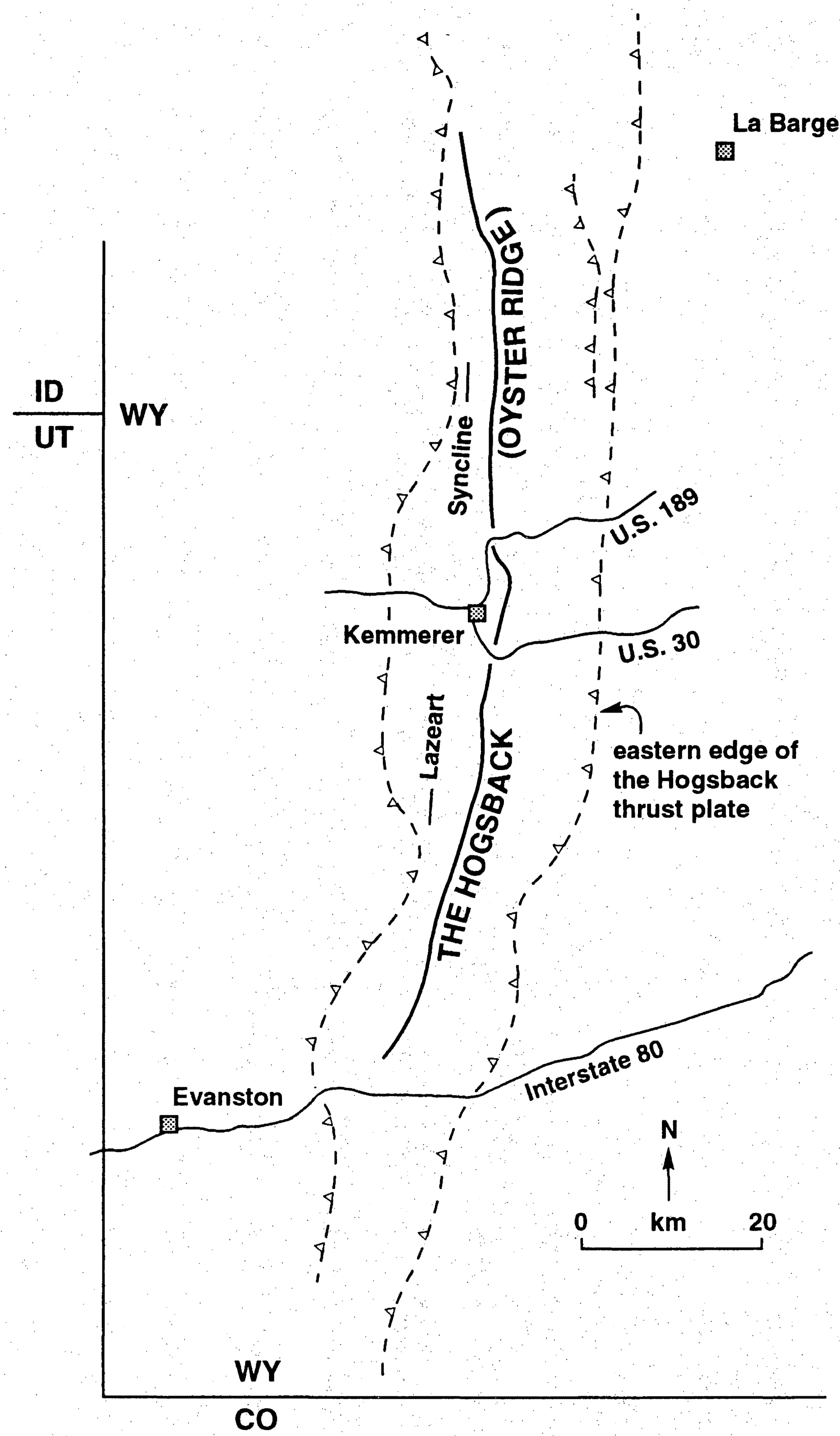


Figure 1. Location map of the Hogsback/Oyster Ridge in southwestern Wyoming.

of shales, coals, bentonites, and conglomerates (Fig. 2). The fractures documented in this report occur in the Oyster Ridge Sandstone Member of the formation. This erosion-resistant sandstone unit supports the topography that defines the Hogsback, and consists of overlapping lenses of sandstone deposited in shoreline, deltaic, and shallow marine environments (Myers, 1977). The member is 40m thick at Cumberland Gap, but varies in thickness along the ridge. The Oyster Ridge Sandstone Member is equivalent to the "Second Frontier" sandstone that produces natural gas in the Moxa Arch area of the Green River Basin to the east.

The Frontier Formation was subjected to several horizontal tectonic stress events, the most obvious event being the eastward-directed thrusting of the Sevier fold and thrust belt. Some of the tectonic events created stresses that led to regional fracturing in the sandstones. In addition, regional tectonism produced local structures, and the resulting stresses created local fracture sets within thrust plates.

Differing formation lithologies created by differences in composition and/or diagenetic history also apparently created variable rock properties. These rocks behaved differently under similar stress conditions, locally resulting in adjacent sandstone beds containing dissimilar fracture patterns. Some of the variability in the pattern of fractures exposed along the Hogsback may therefore have been a result of tectonic/stress changes through time and space, in combination with different lithologies.

Finally, the structural context of the strata has changed through time as the thrust plate in which the outcrop strata are now found propagated eastward. Although correlations between fracture patterns and present structural setting can be documented in many cases, some of the fracture patterns described here may have been the result of structures that the thrust sheet has since propagated beyond, leaving only anomalous fracture patterns in the strata as a record of passage.

Fractures in the Frontier sandstones are filled or partly filled with carbonate minerals, minor quartz, and locally, clay minerals. Fracture traces on bedding planes end laterally by intersecting other fractures or by gradually diminishing in width. Fractures end vertically within sandstone beds, or more commonly at bed boundaries.

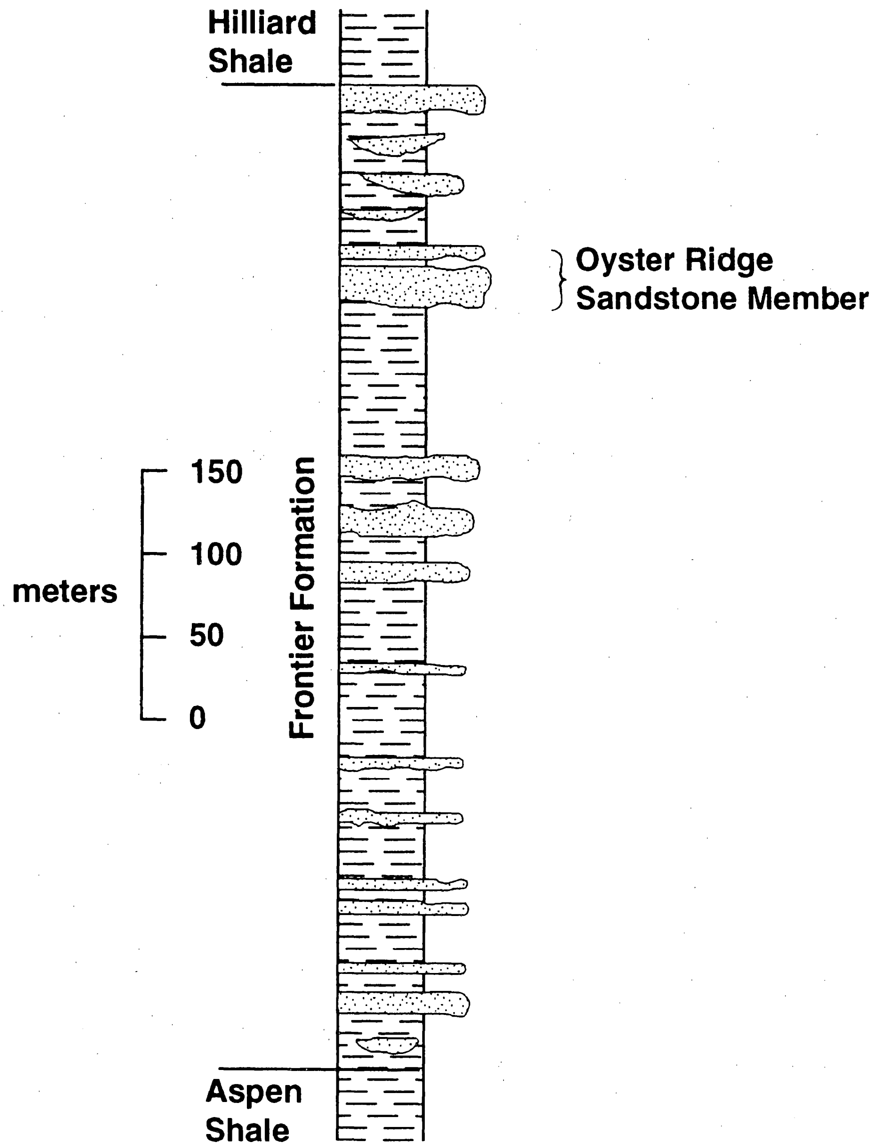


Figure 2. Generalized stratigraphic column of the Frontier Formation at Cumberland Gap in the Hogsback (after Cobban and Reeside, 1952). The fractures described in this report occur in the Oyster Ridge Sandstone Member of the formation, although similar fracture patterns are present in the thinner, less widespread sandstones above and below this unit.

Because they rarely cross the shales between sandstone beds, fracture heights are similar to or less than bed thicknesses, ranging from less than a centimeter to several meters. Fracture trace lengths, however, can be much greater than fracture heights, with length-to-height ratios greater than 10:1. Although maps of bedding-plane exposures greater than 1000 m^2 show that fractures with trace lengths of 3 to 30 m are common, a spectrum of fracture sizes is present, including microfractures normally visible only under the microscope and fractures longer than outcrop dimensions.

Three sets of fracture can be distinguished based on relative age relations revealed by abutting and crossing patterns, with J1 oldest and J3 youngest. J1 fractures strike approximately north-south, whereas J2 fractures strike approximately east-west. The sub-sets of the J3 fracture group have strikes that vary significantly between locations. Fractures of all sets are primarily joints or veins, showing opening-mode displacement rather than slip parallel to fracture walls. Both J1 and J2 fracture are aligned normal to bedding, a pattern that is consistent with fracture formation prior to folding. Shifts in J1 fracture strike of as much as 30 degrees occur over distances of as little as 10 meters. J2 fractures may strike anywhere between northeast and southeast, although strike is consistent within most outcrops.

Exposures of the fractures along the Hogsback are locally excellent, but they are not always easily accessible. Moreover, the large scale of fracture variability does not lend itself to stand-on-the-outcrop analysis: i.e., it is often difficult to see the forest for the trees. Fractures that gradually change strike by 20-30 degrees over several kilometers, or that maintain a constant orientation for several kilometers and then change abruptly within an obscured part of the ridge, are difficult to assess through the study of unconnected, localized exposures.

The roads that run along the base of the ridge allow the ridge to be viewed continuously along its entire length, but the angle of view is usually nearly parallel to the west-dipping bedding surfaces. The well-exposed fracture pavements are commonly not visible from this angle.

The continuity in fracture trends between the isolated, easily accessible outcrops, as well as many of the best fracture pavements along the ridge, are best viewed with low-altitude aerial photographs. This photography provides (1) nearly right-angle viewing of the fracture pavements that are common near the crest of the ridge, (2) locally continuous data on fracture trends along strike, and (3) details of fracture characteristics are not available from high-level photos. Low-altitude photos were used to construct the fracture trend map (Fig. 3) for the ridge.

Figure 3.

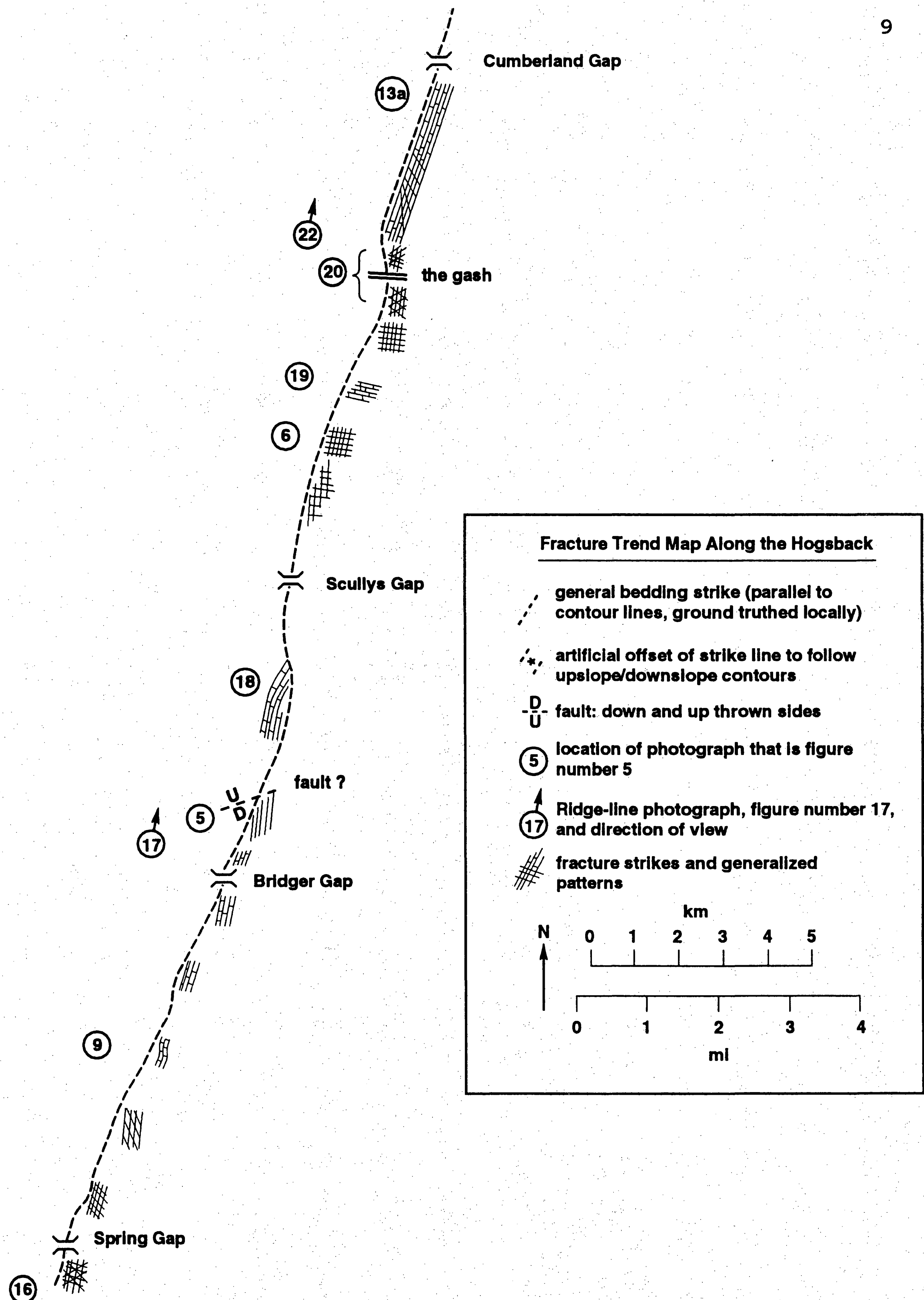
Figure 3 is a fracture trend map depicting generalized fracture patterns along the Hogsback. The fracture trends shown are schematic in that the fracture patterns are simplified in order to accommodate space constraints, although actual fracture orientations are indicated. The fracture patterns were derived from low-altitude photographic coverage of most of the unvegetated sandstone panel exposures along the ridge.

The locations of the specific photographs used in the text to illustrate different fracture patterns are shown in the circled numbers. Most of the photographs are of west-dipping slopes on the eastern limb of the Lazeart syncline, and thus present a view towards the east, with north to the viewer's left.

NOTE that the larger photos that follow as figures are oriented on the pages such that the viewer's left should be towards the bottom of the page. Locations of related photos are also noted directly on some photos.

The notations "(Transverse Structure?)" are at the approximate positions reported by Delphia and Bombalakis (1988) and Apotria (1993) for such structures in the older thrust plate immediately to the west.

The map is presented sequentially from south to north in four overlapping sections on the following pages, and will be referred to throughout the following text.


Cumberland Gap
13a
22
20
the gash
19
6
Scullys Gap
18
fault ?
U
D
5
17
Bridger Gap
9
Spring Gap
16
Fracture Trend Map Along the Hogsback
general bedding strike (parallel to contour lines, ground truthed locally)
artificial offset of strike line to follow upslope/downslope contours
D
U
fault: down and up thrown sides
5
location of photograph that is figure number 5
17
Ridge-line photograph, figure number 17, and direction of view
fracture strikes and generalized patterns
km
N
0 1 2 3 4 5
0 1 2 3 4
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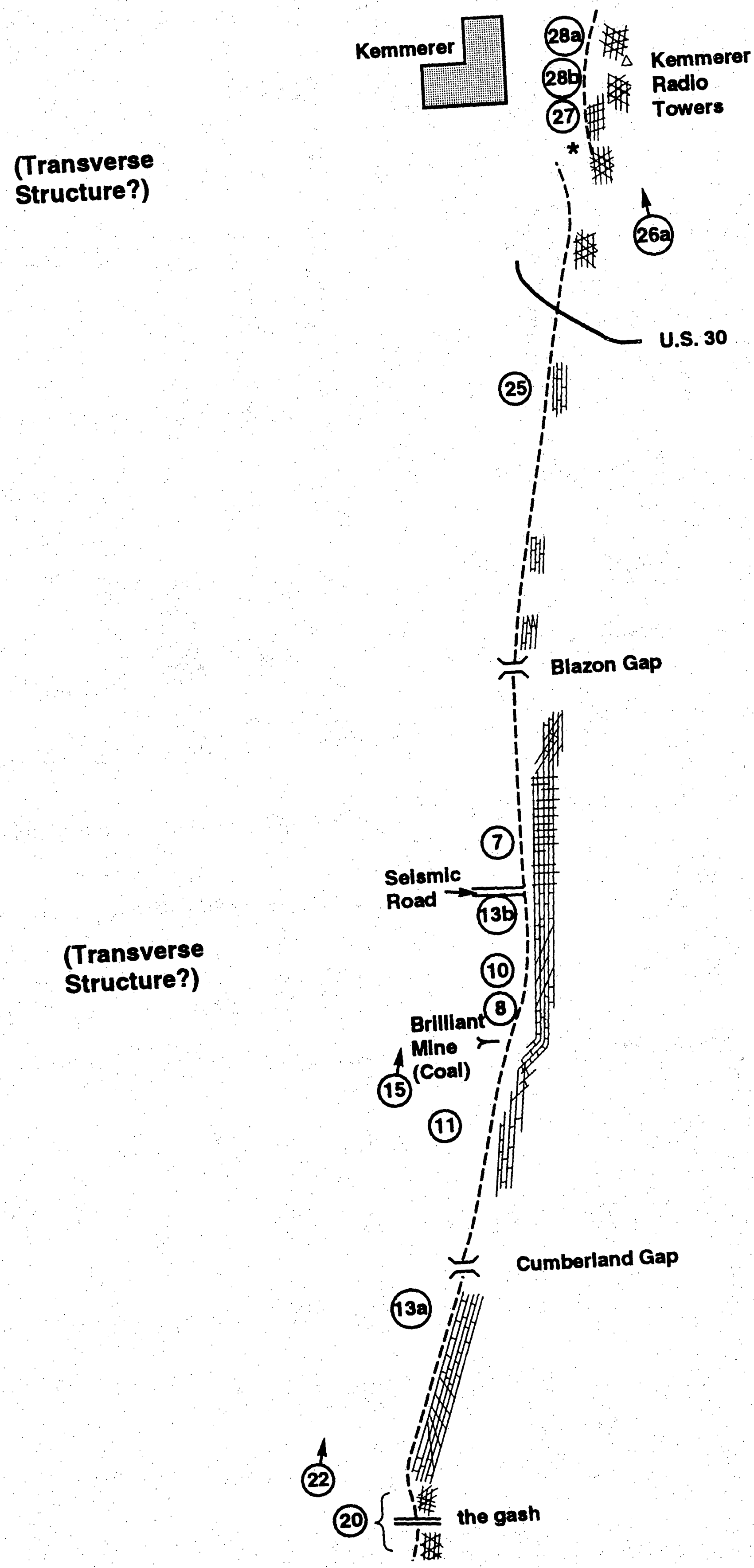
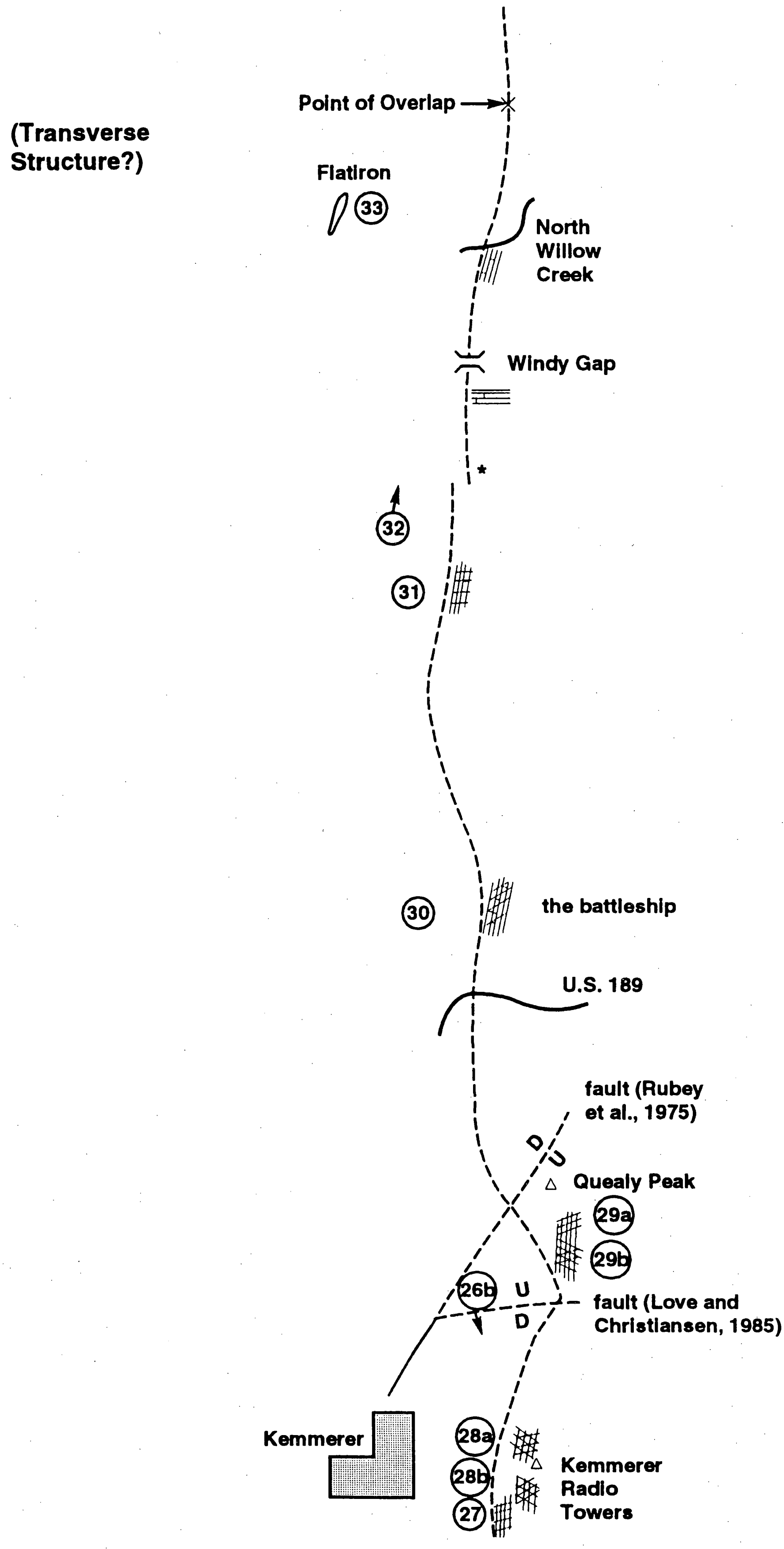
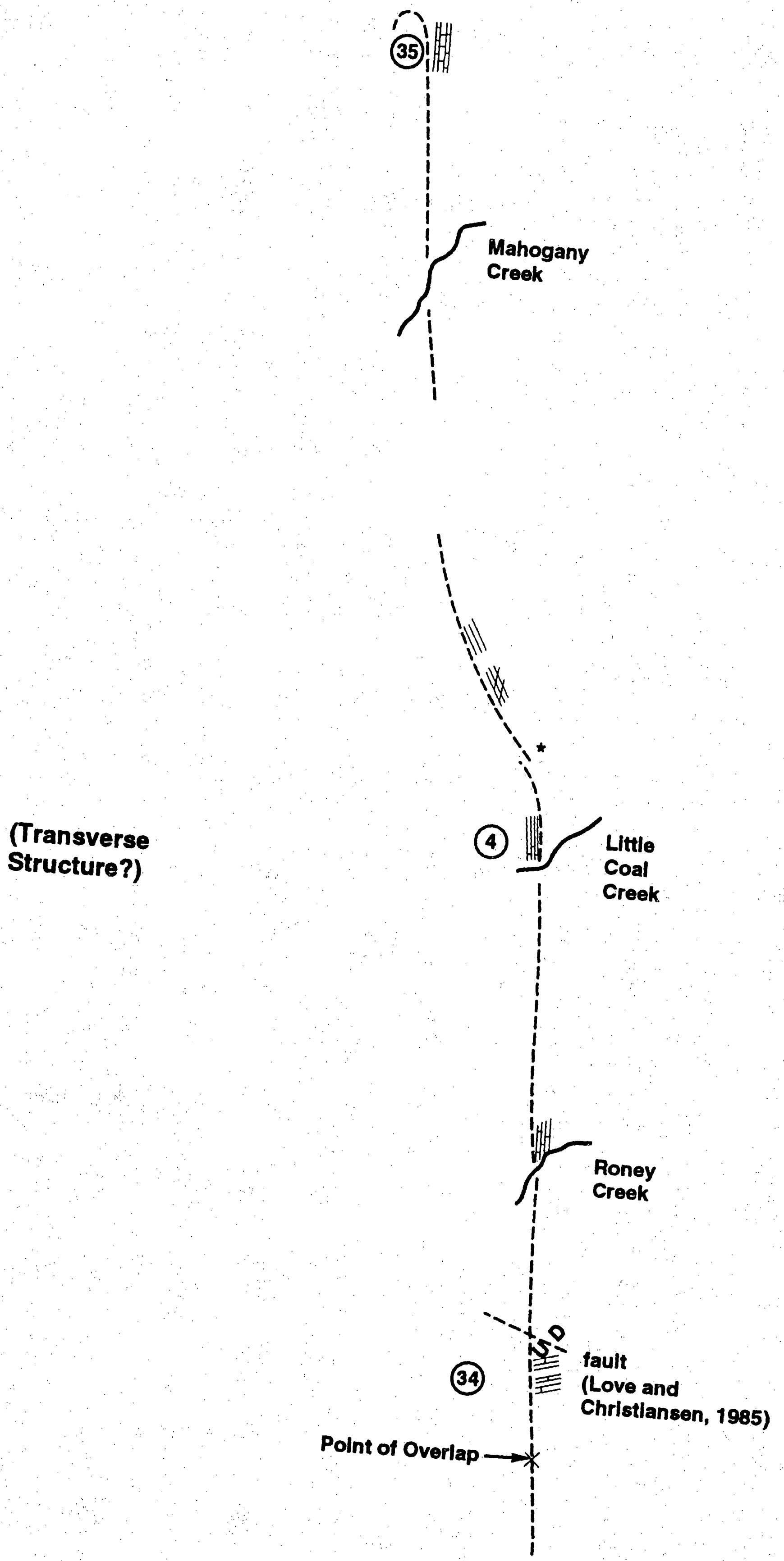

Kemmerer
28a
28b
27
Kemmerer
Radio
Towers
(Transverse
Structure?)
26a
U.S. 30
25
Blazon Gap
7
Seismic
Road
13b
(Transverse
Structure?)
10
8
Brilliant
Mine
(Coal)
15
11
Cumberland Gap
13a
22
20
the gash


Point of Overlap
(Transverse
Structure?)
Flatiron
33
North
Willow
Creek
Windy Gap
32
31
30
the battleship
U.S. 189
fault (Rubey
et al., 1975)
D
U
Quealy Peak
29a
29b
26b
U
D
fault (Love and
Christiansen, 1985)
Kemmerer
28a
28b
27
Kemmerer
Radio
Towers


35
Mahogany Creek
(Transverse Structure?)
4
Little Coal Creek
Roney Creek
U
D
34
fault (Love and Christiansen, 1985)
Point of Overlap

3.0 NATURAL FRACTURES ALONG THE HOGSBACK

3.1 Introduction

There are three groups of natural, vertical-extension fractures present along the Hogsback. The term "sets" is inappropriate for at least one, and probably two of these fracture groups in that the characteristics (especially strike) of the fractures that comprise the groups vary significantly along the 100 km length of the ridge. However, the different fracture groups may be recognized by common origin and relative age. For this report, the three fracture groups are termed:

(1) J1 fractures (oldest): throughgoing, regional set of extension fractures, created during basin subsidence and Laramide thrusting; average strike about 350 to 10 degrees; fractures commonly extend the length of an outcrop

(2) J2 fractures: extension fractures related to north-south stretching and dilatancy during Sevier thrusting; commonly trend nearly normal to the local strike of bedding and therefore striking in most outcrops within 30 degrees of east-west; may either cut across or terminate against J1 fractures, and therefore may be either short or long in average length depending on locality

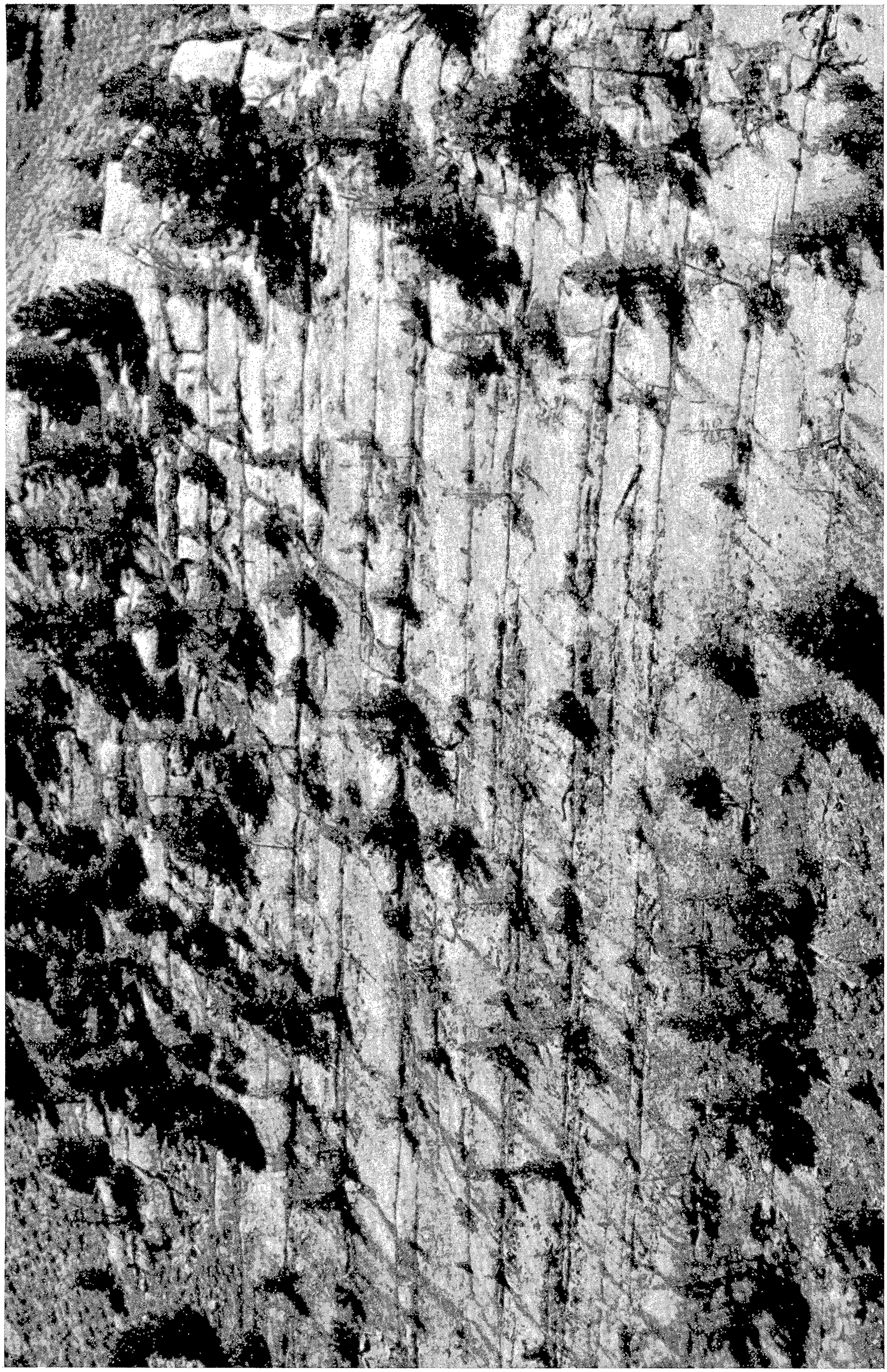
(3) J3 fractures (youngest): local sub-group sets of extension fractures related to local structures along the thrust plate; no characteristic regional strike or dimensions

Temporal overlap in the formation of groups 2 and 3 may have occurred locally, and creates ambiguity in the interpretations of these two groups.

3.2 J1 Fractures

Throughgoing fractures striking generally north-south are present in all but of four of the over 50 outcrops studied. At several outcrops these are the only fractures present except for a few short connecting orthogonal fractures (Figs. 4, 5). Abutting relationships show that where throughgoing J1 fractures are present, they always predate any other fractures present. This age relationship

Figure 4a. Dominant, north-south striking J1 extension fractures in an outcrop containing few J2 fractures: pavement just north of Little Coal Creek. Approximate north is to the left in this photo. (Center, sec. 16, T.25N., R. 115W., reference photo 1/16 of the master file kept at Sandia).



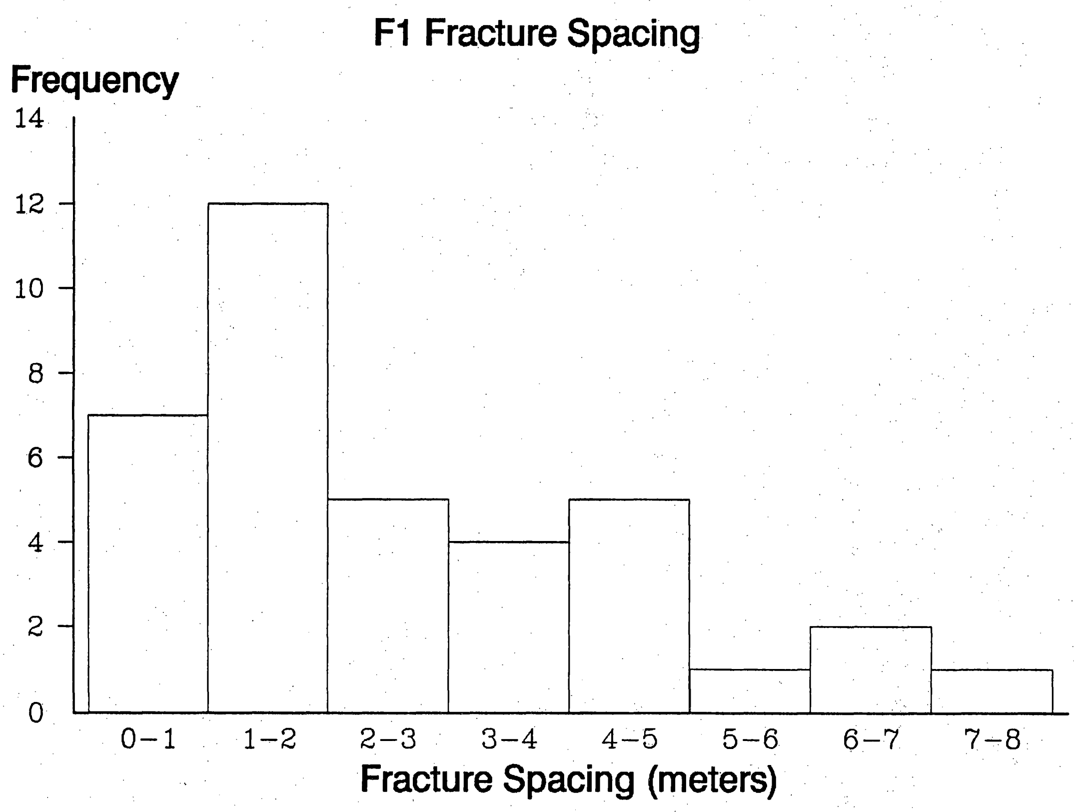


Figure 4b. Measured spacings of the J1 fractures shown in figure 4a, along a scan line across the middle of the outcrop.

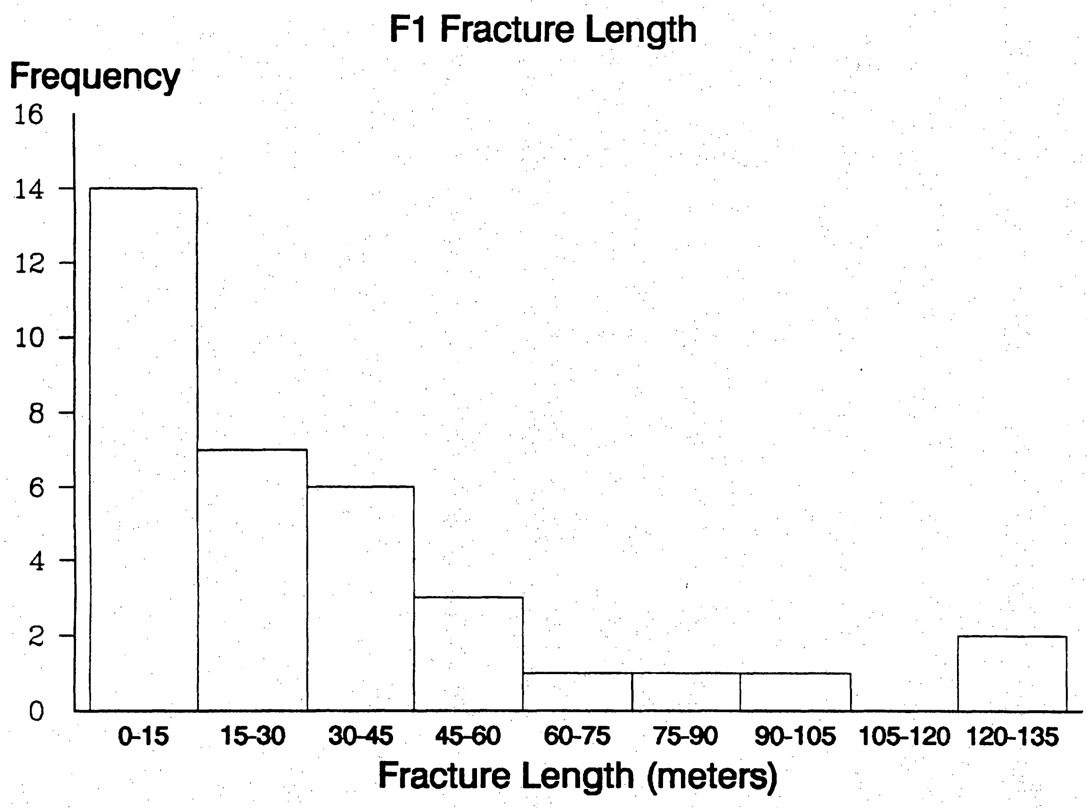
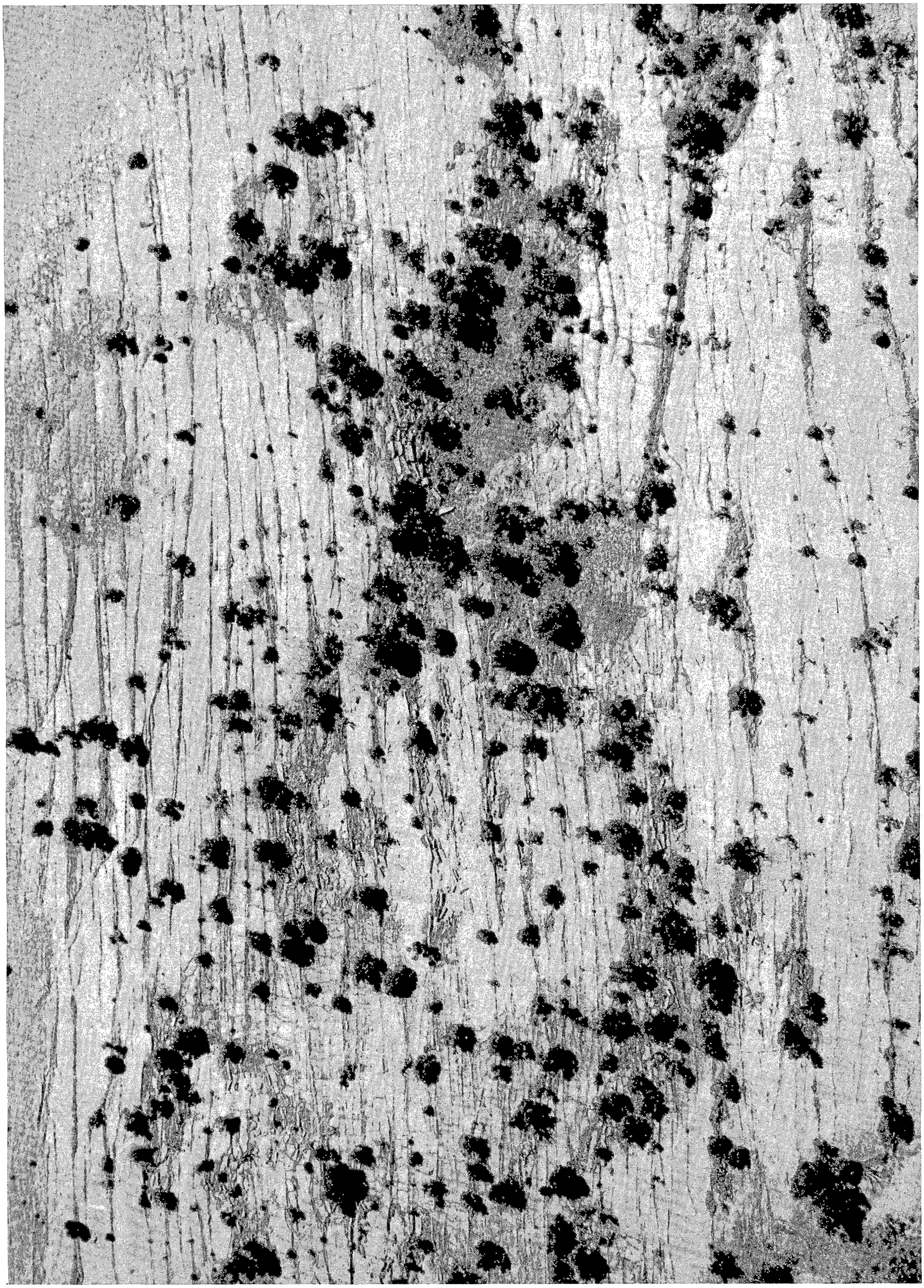


Figure 4c. Measured lengths of the J1 fractures shown in figure 4a, along a scan line across the middle of the outcrop.

Figure 5. North-south J1 fractures with few superimposed J2 fractures, north of Bridger Gap; fault is present just off the left edge of this photo. Approximate north is to the left in this photo. (NE 1/4 SE 1/4 sec. 34, T.17N., R.117W., reference photo 5/13).



may be subtle: superimposed J2 and/or J3 fractures are so numerous at some locations that the older fractures as well as the abutting relationships are obscured (Fig. 6). In other cases, younger fractures cut across the older fractures (Fig. 7) with only minor offsets at a small percentage of the intersections recording the age relationship.

J1 fractures occur in a wide range of lengths, with measured lengths at one outcrop varying between 6 m and about 135 m, and having an average of about 32 m (Fig. 4b). Significantly more short fractures are present than long fractures. Fracture spacings at this outcrop are irregular (Fig. 4b), varying from less than one meter to 7 m with an average of 2.4 m; again, more short spacings than long spacings are present. As a general rule, however, the fractures are uniformly distributed throughout the sandstones in that they do not occur in swarms.

In some areas, J1 fracture strikes remain relatively constant for up to 4 km (south of Blazon Gap, south of Cumberland Gap; Fig. 3). Elsewhere the strike of this fracture set changes abruptly by 20 degrees across a lateral distance of only a few tens of meters (Figs. 8,9). The causes for such changes in fracture strike are not apparent in outcrop; changes in stress orientation during fracturing may have resulted from changes in bed thickness or internal rock properties due to lateral changes in depositional environment. There are also several areas of apparently near-simultaneous development of two sub-sets of oblique J1 fractures (Figs. 3, 10, 11).

Despite their sub-parallel relationship to bedding strike, the J1, north-south striking fractures were not formed during folding or during migration of a fold hinge through the strata. Fractures parallel to bedding strike would be expected if hinge migration caused fracturing, whereas a 10-20 degree oblique relationship is more common. In addition, the surface ornamentation (plumose structure, arrest lines, etc.) preserved locally on fractures (Fig. 12) suggests that they rarely propagated from the base of a bed upward as would be expected of fractures resulting from a concave-upward fold hinge.

J1 fractures are not associated with the minor faults and other small structures that characterize the actual hinge where it is exposed at the north end of the Lazeart syncline. Moreover, the strata exposed on the dip slopes of the ridge are almost always planar, without any indication of folding about a north-south horizontal axis. Delphia and Bombalakis (1988) suggested that these planar syncline limbs rotated as a unit to their present dip as they rode up the frontal ramp of the thrust to form the present eastern limb of the Lazeart syncline.

The near-parallelism between strikes of J1 fractures and the strike of bedding is coincidental. Because the origin of younger fracture groups is related to thrust development, these earliest fractures must have predated thrusting. Their most likely origin is as extension fractures during maximum burial in the deep, narrow, Cretaceous foredeep, possibly in combination with thick-skinned Laramide thrusting of the Uinta and Wind River Mountains to the south and north (Laubach and Lorenz, 1992; Lorenz, 1993, 1994).

3.3 J2 Fractures

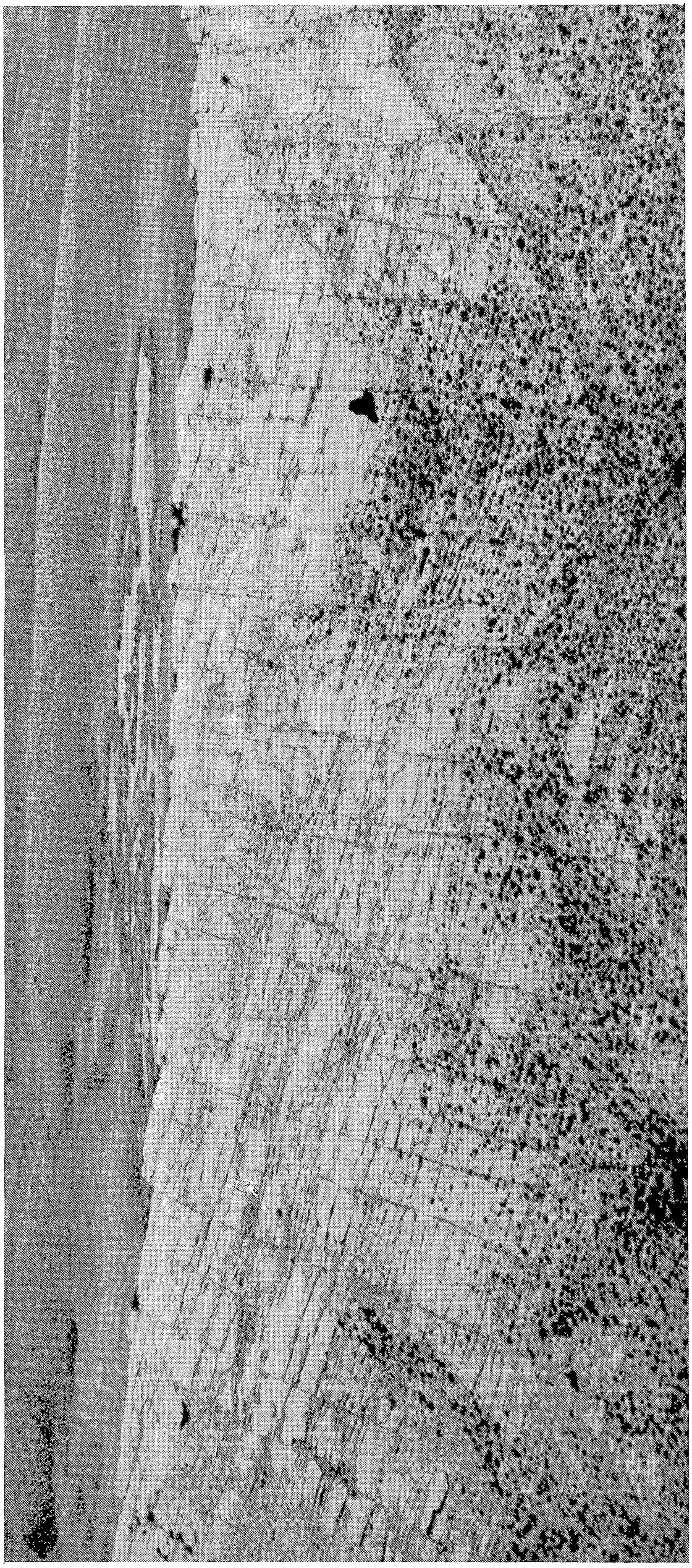
The next group of fractures to form in the Frontier sandstones commonly strikes approximately parallel to the dip direction of the strata on the ridge. Bedding strikes vary locally along the ridge and the ridge itself is slightly concave to the west overall, thus the strikes of the fractures within this group are diverse. However, these J2 fractures generally strike within plus or minus 30 degrees of east-west.

The character of the J2 fractures changes from locality to locality; in some places they consist of short, irregular, infrequent connecting fractures between the north-south J1 fractures (Fig. 13), whereas in other outcrops they are long, and nearly equal in length and planarity to the earlier J1 fractures (Fig. 7). They may even obscure J1 fractures (Fig. 6). J2 fractures are best developed, are most regular, and maintain a strike that is most closely normal to bedding strike where the ridge maintains a relatively constant strike (e.g., south of Blazon Gap and south of Cumberland Gap).

J2 fractures trending parallel or sub-parallel to the dip of the strata are common in all but two of the outcrops studied, although the degree of development of these fractures varies as noted. Additionally, J2 fractures comprise the throughgoing set in four of the studied outcrops, where only short north-south connecting fractures are present.

Figure 6. Well-developed J2 thrust-dilatancy fractures nearly obscuring earlier J1 fractures, north of Scullys Gap. Approximate north is to the left in this photo. (NE 1/4 NE 1/4 sec. 35, T.18N., R.117W., reference photo 4/37).

Figure 7. Well-developed J2 thrust-dilatancy fractures superimposed on J1 fractures, north of the seismic-line road. Approximate north is to the left in this photo. (Center S 1/2 SE 1/4 sec. 5, T.19N., R.116W., reference photo 3/24).



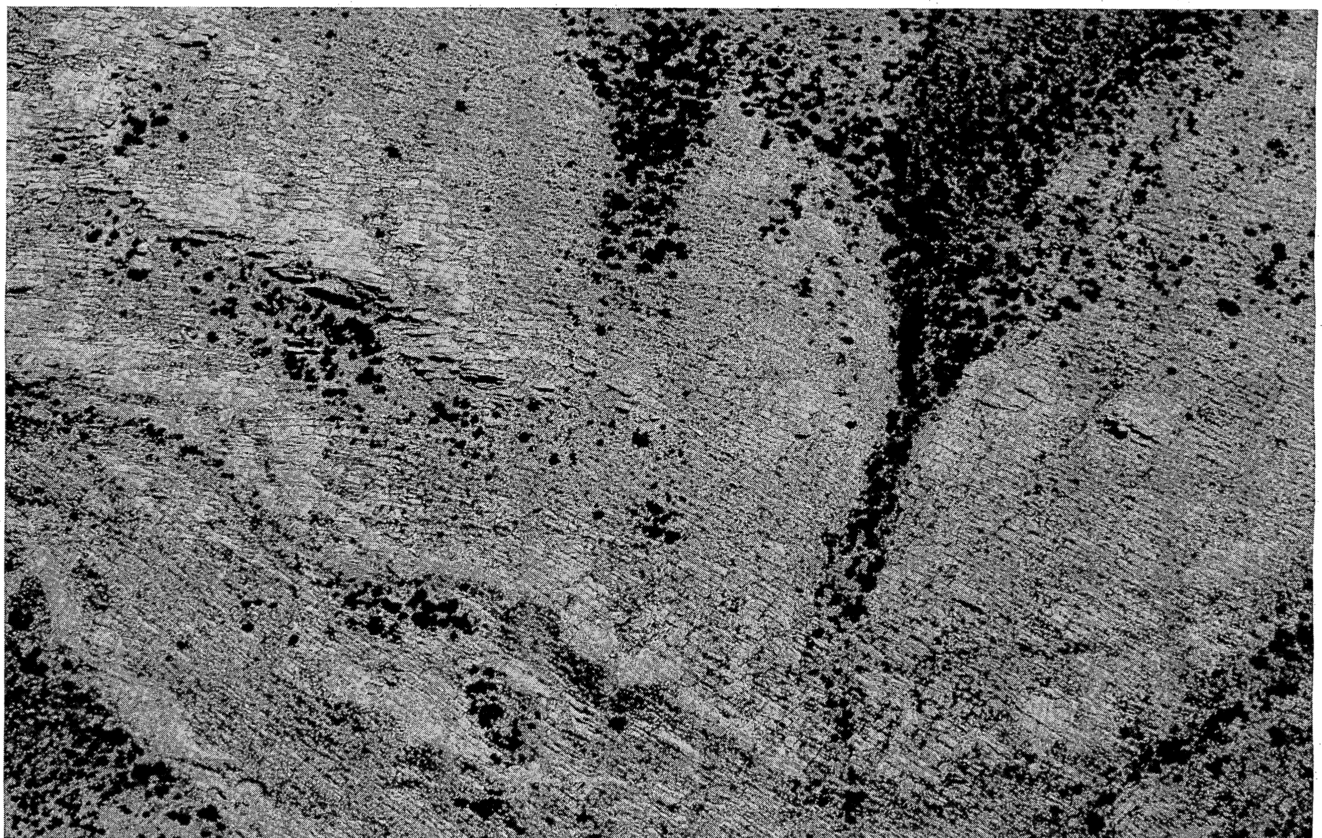


Figure 8. Local change in strike of the J1 fracture set just north of the Brilliant Mine. Approximate north is to the left in this photo. (Center E 1/2 SW 1/4 sec 17, T.19N., R.116W., reference photo 3/36).

Figure 9. Changes in strike of the J1 fracture set within a continuous sandstone pavement south of Bridger Gap. Black lines added to highlight fracture trends. Approximate north is to the left in this photo. (W 1/2 SE 1/4 sec.7, T.16N., R.117W., reference photos 5/23-24).

Figure 10. Two oblique sub-sets of J1 fractures, and short east-west J2 fractures. Numbers are ground-measured fracture strikes. Approximate north is to the left in this photo. (Center NE 1/4, sec. 17, T. 19N., R. 116 W., reference photo 3/33).


15
50

Figure 11. Two oblique sub-sets of J1 fractures, south of the Brilliant Mine. Approximate north is to the left in this photo. (SW 1/4 SW 1/4 sec. 20, T.19N., R.116W., reference photo 4/7).

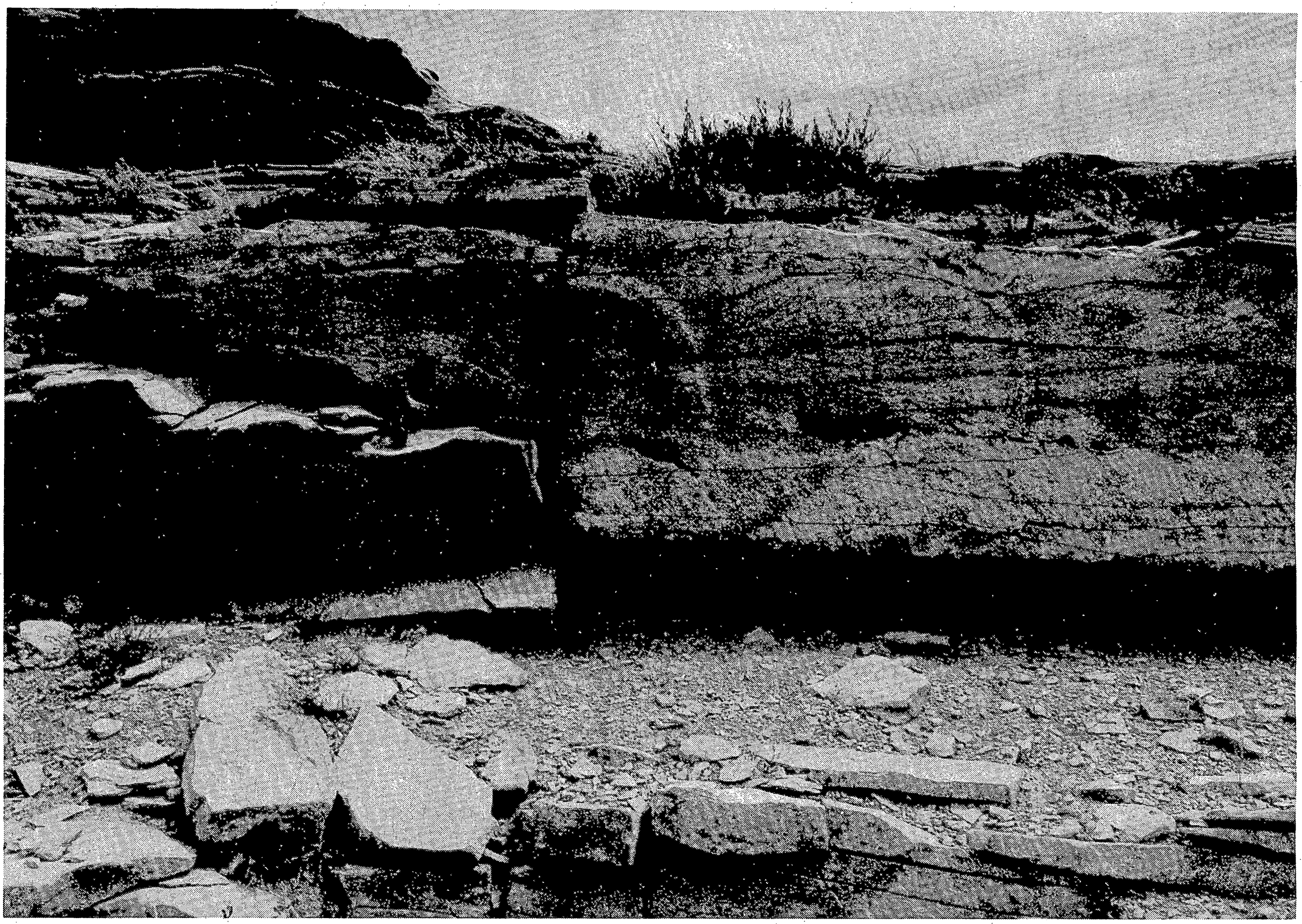


Figure 12. Plumose structure on a north-northeast-striking fracture surface near the Brilliant Mine, showing fracture initiation near the center of the bed (butt of the hammer handle), initial propagation at equal rates/distances vertically and horizontally, and subsequent propagation horizontally as the fracture became confined by bedding surfaces.

Figure 13a. Short J2 fractures terminating at well-developed J1 fractures: South of Cumberland Gap. Approximate north is to the left in this photo. (SW 1/4 SW 1/4 sec. 6, T.18N., R. 116W., reference photo 4/16).

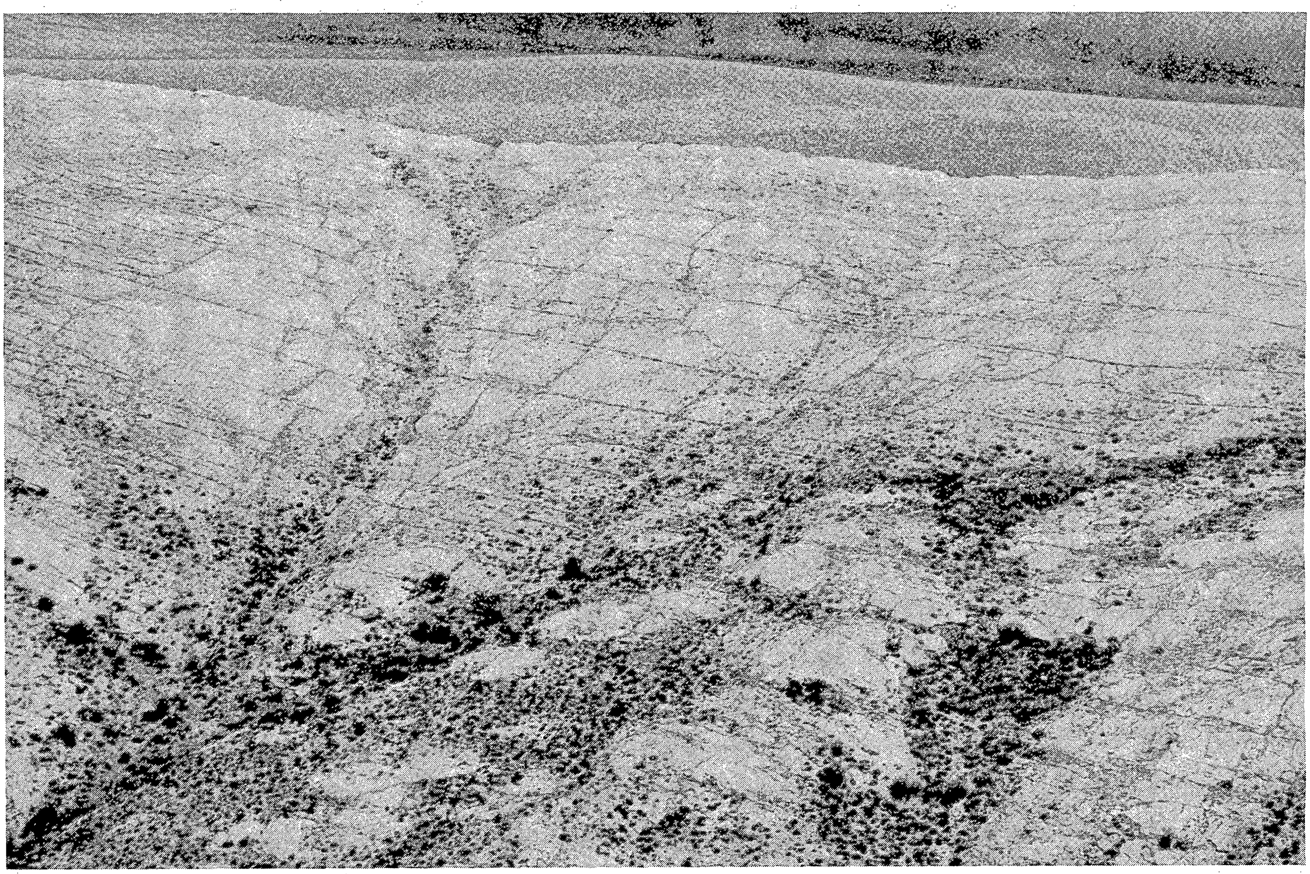


Figure 13b. Short J2 fractures terminating at well-developed J1 fractures: South of the seismic-line road. Approximate north is to the left in this photo. (Center SE 1/4 sec. 8, T.19N., R.116W., reference photo 3/29).

One of these outcrops is the near-vertical flatiron on the west limb of the syncline northwest of Windy Gap (see Fig. 3). Within this flatiron, fractures with a J2 orientation occur as swarms, where lenticular zones containing numerous fractures are interspersed with regions of rock that are relatively devoid of fractures (Laubach, 1991). For fractures more than one meter long, mean fracture length is 7 m, and the longest measured fracture is about 40 m. Fractures less than 15 m long are significantly more numerous than fractures between 15 and 40 m long (see Fig. 33c).

These measurements are not necessarily typical of the J2 fractures on the eastern limb of the syncline, where the J2 set has yet to be quantitatively characterized. Moreover, swarm patterns have not been documented in J2 fractures on the eastern limb of the syncline, although the variable development of J2 fractures noted above might constitute swarming on a much larger, kilometer-plus scale. As will be seen, however, the variable J2 development can usually be related to structural setting of the strata.

The J2 fractures are suggested to derive from a lateral spreading, or dilatancy, of the strata during thrusting. Such dilatancy has been suggested for strata in and in front of other thrust belts world wide (e.g., Hancock and Bevan, 1987). In this process, horizontal stress compresses the strata in one direction, while an absence of active lateral compression in the other horizontal dimension accommodates stretching of the strata, primarily by fracturing in the plane of the maximum compressive stress. A thrust-dilatancy fracture origin may be particularly applicable to J2 fractures in the Idaho-Wyoming thrust belt, where radial spreading or the thrust sheets into a concave-westward shape accompanied lateral translation (Fig. 14) (Crosby, 1969; Grubbs and Van der Voo, 1976).

Prominent, through-going, J2 thrust-dilatancy fractures (e.g., Fig. 7) seem to have developed in those sections of the ridge where the direction of thrusting and thrust-related compressive stress (indicated by the direction normal to the ridge-line) was nearly perpendicular to the previously formed north-south fractures. In these areas, the compressive stress would have acted to close the north-south fractures, and combined with the near-normal angular relationship to prevent the propagating east-west fractures from being significantly influenced by the pre-existing planes of weakness. Elsewhere, many of the J2 fractures propagated obliquely to the pre-existing J1 planes of weakness and were terminated by shear.

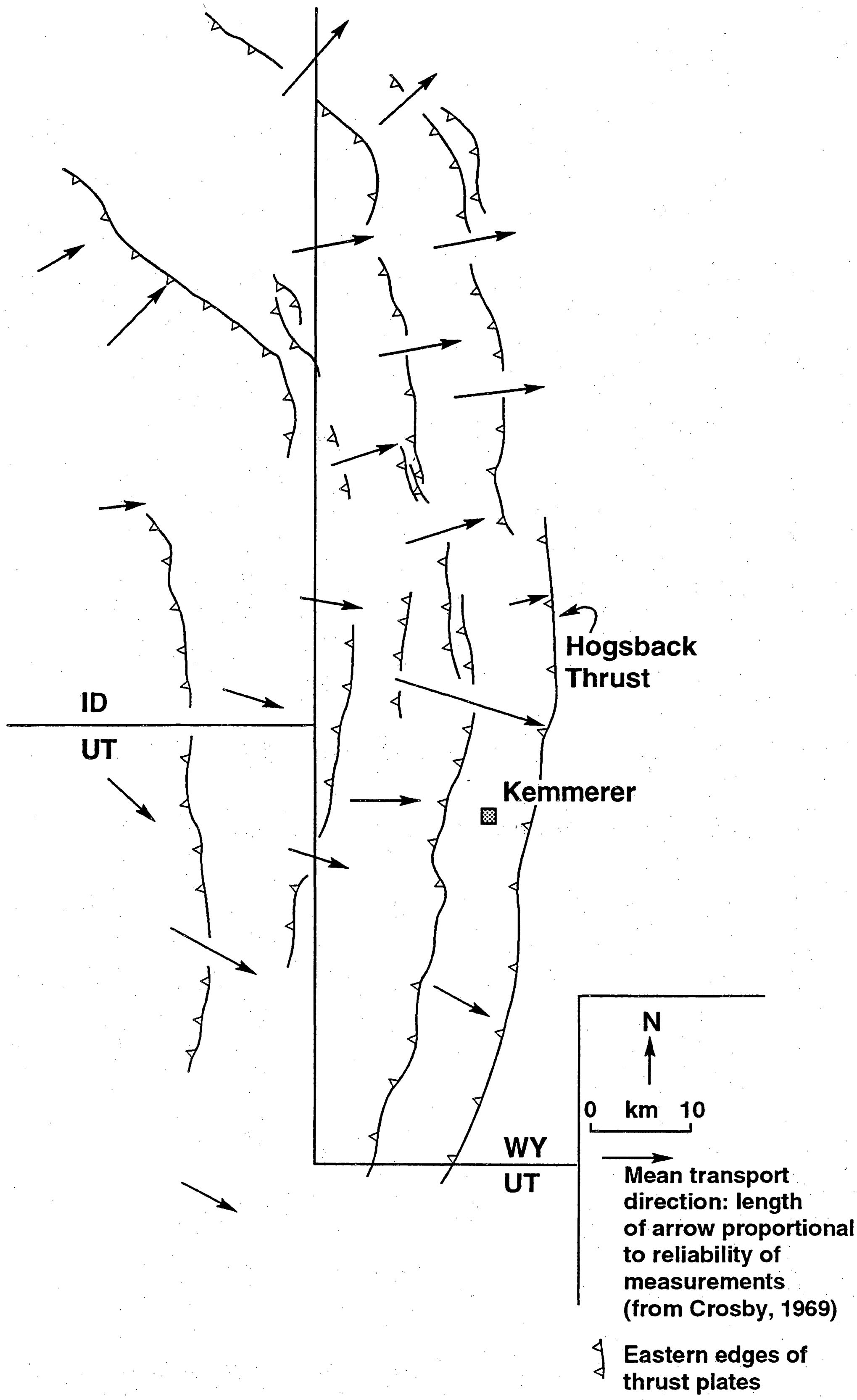


Figure 14. Radial divergence within the thrust system (Crosby, 1969), suggesting that thrust-related dilatancy and fracturing could be expected in/near this part of the thrust belt.

3.4 J3 Fractures

Individual sub-sets of the third group of fractures (J3) are commonly associated with specific kilometer-scale changes in the geometry of the Hogsback such as offset ridge-lines. These are most likely the surficial expressions of small transverse structures within the thrust plate such as minor tear faults, normal faults, and transverse/oblique ramps. These structures are manifested by changes in the strike and/or dip of the strata as well as by lateral offsets in the ridge, and are most easily observed in foreshortened low-altitude views of the ridge (Fig. 15). Such structures, particularly oblique ramps, can add local zones of compression and extension at the bends in thrust sheets, and can re-orient the local stresses along the segments of the sheet between bends (e.g., Apotria, 1993).

Delphia and Bombalakis (1988) suggested that large transverse structures (which they located only approximately in their text) exist at several places in the older thrust plate west of the Hogsback thrust, and several of their structures may correlate with anomalies evident from changes along the Hogsback (see Fig. 3). However, there is no real basis for extrapolating these particular transverse structures from that thrust plate eastward to the Hogsback thrust, although Fowles and Woodward (1992), and Apotria (1993) have each suggested that similar structural discontinuities can be traced across at least three adjacent thrust sheets. Most of the offsets described in this report are significantly smaller than the features usually recognized and described as oblique ramps in thrust sheets, and some of the small tear faults present in the west limb of the syncline clearly do not extend to the outcrops in the eastern limb.

Where structural complexities in the thrust plate are present, it becomes difficult to separate J2 thrust-dilatancy fractures from the J3 fractures created during the development of local structures. In some cases, fractures of one group can even be traced directly into fractures of the other group, suggesting that the two formed nearly simultaneously.

In a few locations (e.g., south of Scullys Gap; Fig. 3), local fracturing is so pervasive that not enough of the sandstone bedding remains to form a pavement. Conversely, an absence of complex fracturing or even of the J2 fractures

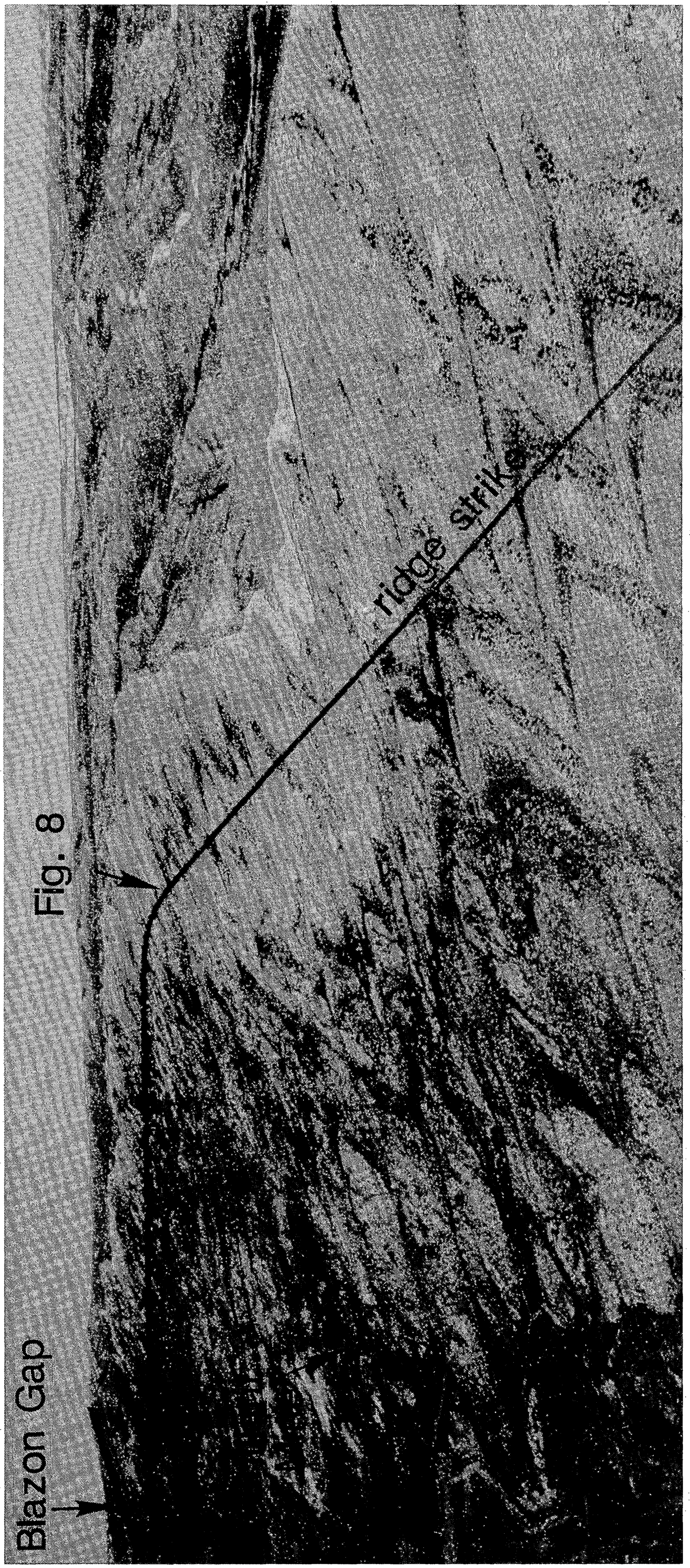


Figure 15. Ridge-line photo looking north from the Brilliant Mine area. Note the changes in strike of the ridge (Reference photo 4/6).

in at least three outcrops may be attributable to the relief of local stress by early transverse rupture of the thrust plate. This again argues for a nearly contemporaneous formation of the J2 thrust-dilatancy fractures, the local structures, and the J3 structural-anomaly fractures.

Locations where rupture and local stress relief are postulated to have preserved a virgin set of north-south J1 fractures include Little Coal Creek (Fig. 4), a pavement two km north of Bridger Gap (Fig. 5), and North Willow Creek. Rupture is possibly recorded by deep cuts in the ridge at the first and last outcrops. A mappable fault, with about 4 m of down-to-the-south throw and a lateral offset of unknown magnitude, is present at the north end of the pavement north of Bridger Gap.

3.5 Fracture Patterns Along Sections of the Hogsback

Because the local structures and their associated J3 fractures have so little in common with each other, segments of the ridge will be described individually. This description will also highlight the variability within the J1 and J2 fracture groups. Vegetation obscures and limits the continuity of outcrops north of Willow Creek, thus detailed analysis of the fracture patterns in this area is not attempted. The following figures and discussion are keyed to figure 3.

3.5.1 Spring Gap to Bridger Gap: The southern end of the Hogsback is onlapped depositionally by horizontal Tertiary strata, although the Hogsback thrust is mapped in the subsurface southward for another 30 km to the Utah border. Between the southernmost exposure at Spring Gap and a few km north of Bridger Gap, J1 fractures maintain a relatively constant strike of between 5 and 20 degrees, which is consistently 10-20 degrees oblique (counter-clockwise) to the strike of the strata along the ridge.

Irregularities in the topography suggests that four small left-lateral offsets are present in the ridge in this section, and a lateral jump in the ridge-line is visible from the ground at Bridger Gap. East-trending, J2 thrust-dilatancy fractures are present only as short, connecting fractures in the northern half of this segment, and they are conspicuously rare in the pavement at the northernmost extent of this segment (Fig. 5), probably due to stress relief along a fault as suggested above.

Sandstones of the southern third of this segment contain throughgoing, southeast-striking J2 fractures that may relate to southeasterly directed thrusting. A complex J3 fracture pattern is present at the southernmost exposure of the Frontier sandstone (Fig. 16), suggesting that the structural offset at Spring Gap created local stresses capable of fracturing the strata. Dixon (1982, his figure 18) mapped a right-lateral offset of 5-6 km on the structure-contour map of the Hogsback thrust south of Spring Gap, possibly accounting for the more pervasive deformation and J3 fracturing. The offset at Bridger Gap, although of similar magnitude, is suggested to have been more abrupt, rupturing the strata on a local scale and creating a gap rather than anomalous J3 fractures.

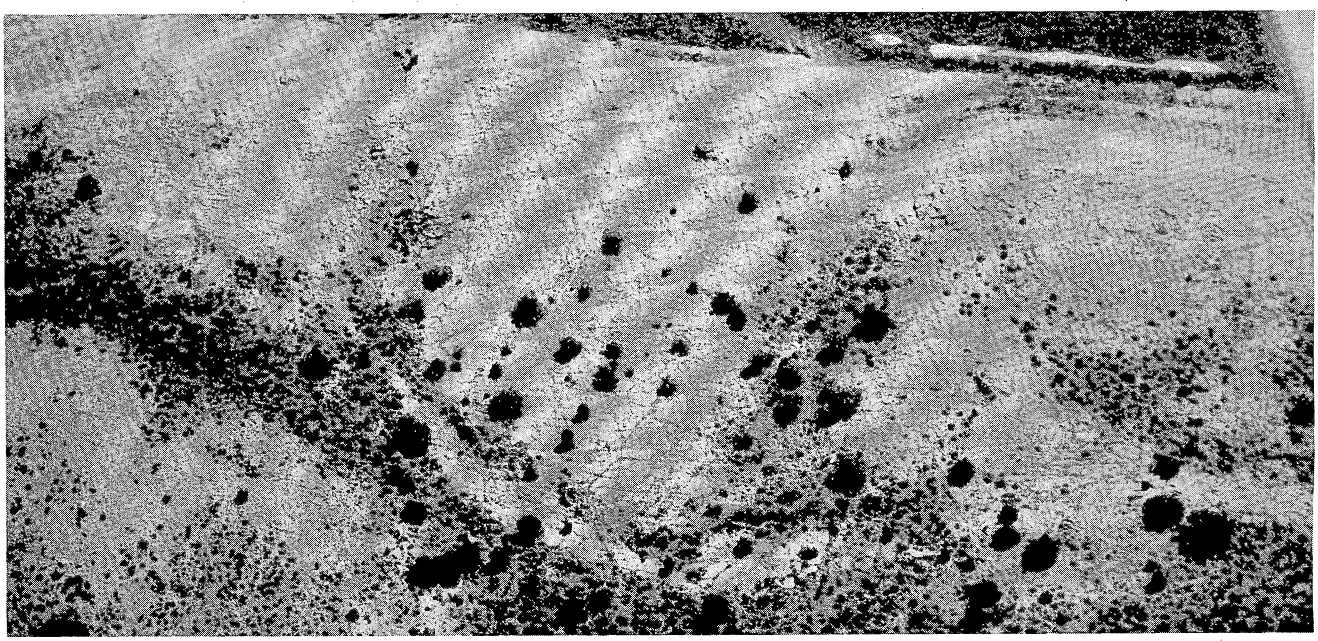


Figure 16. Multiple oblique fractures superimposed on the J1 fracture set, south of Spring Gap. Approximate north is to the left in this photo. (SE 1/4 SW 1/4 sec. 25, 16N., R.118W., reference photo 5/30).

3.5.2 Bridger Gap to Scullys Gap: A large bend in the thrust sheet, again left-lateral (Fig. 17), dominates this segment of the ridge. J1 fractures striking slightly east of north are common, trending highly oblique to the ridge-line at the middle of the dogleg (Fig. 18). Sandstone pavements in the area are scattered to locally absent, especially on the hilltop just north of the dogleg, possibly because abundant J3 fracturing has broken up the pavements and obscured the outcrops.

3.5.3 Scullys Gap to the gash: The Hogsback defines a gentle eastward-concave curvature north of Scullys Gap, changing strike by 15 degrees over about five and an half kilometers. The ridge then displays another left-lateral dogleg that is marked at its middle by a deep, narrow, cleft, informally called the "gash" for this study.

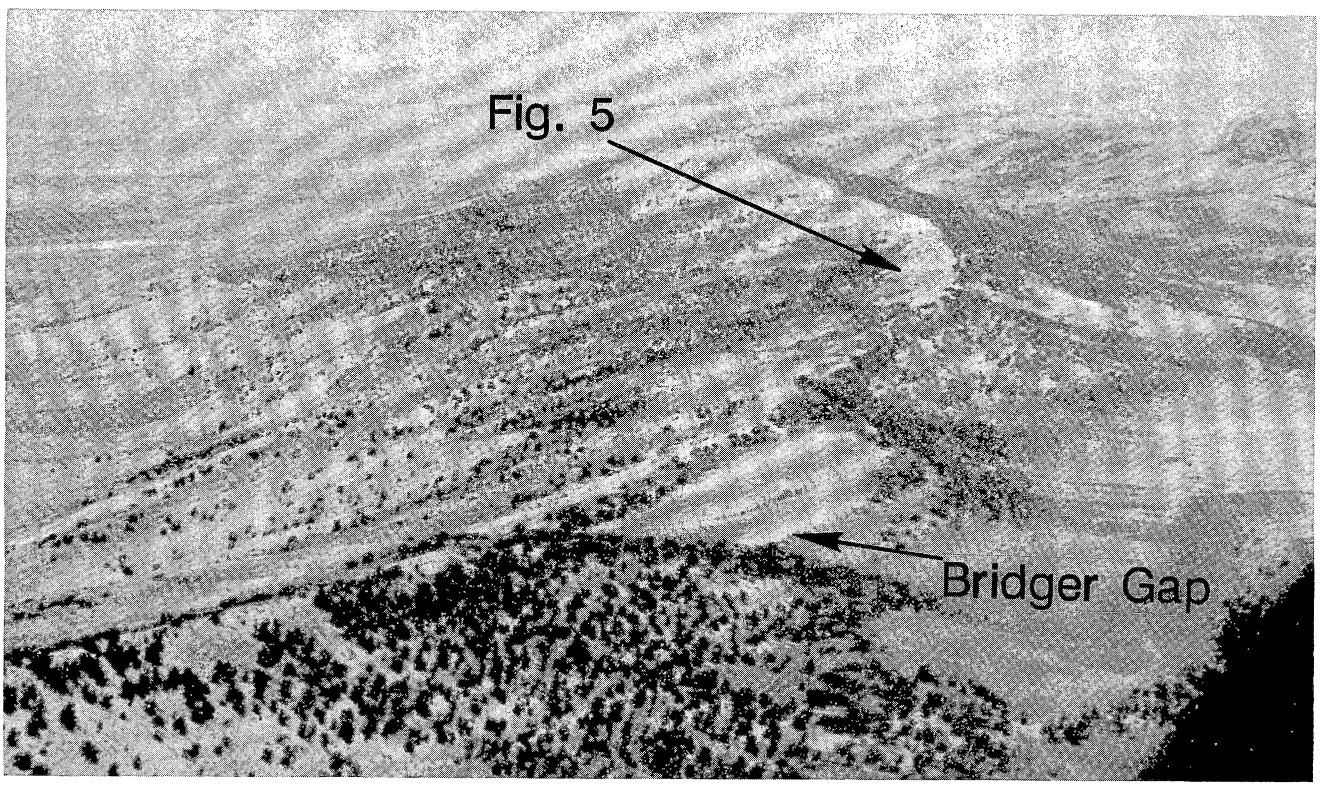


Figure 17. Ridge-line photo looking north across the change in strike at Bridger Gap. (Reference photo 5/12).

J2 thrust-dilatancy fractures are prominent on the gently curved section of the ridge (Fig. 6), the concave-eastward (and angled sightly downward) curvature possibly having contributed to stretching of the strata and the development of this group of fractures. These fractures locally obscure the older J1 fractures (Fig. 19).

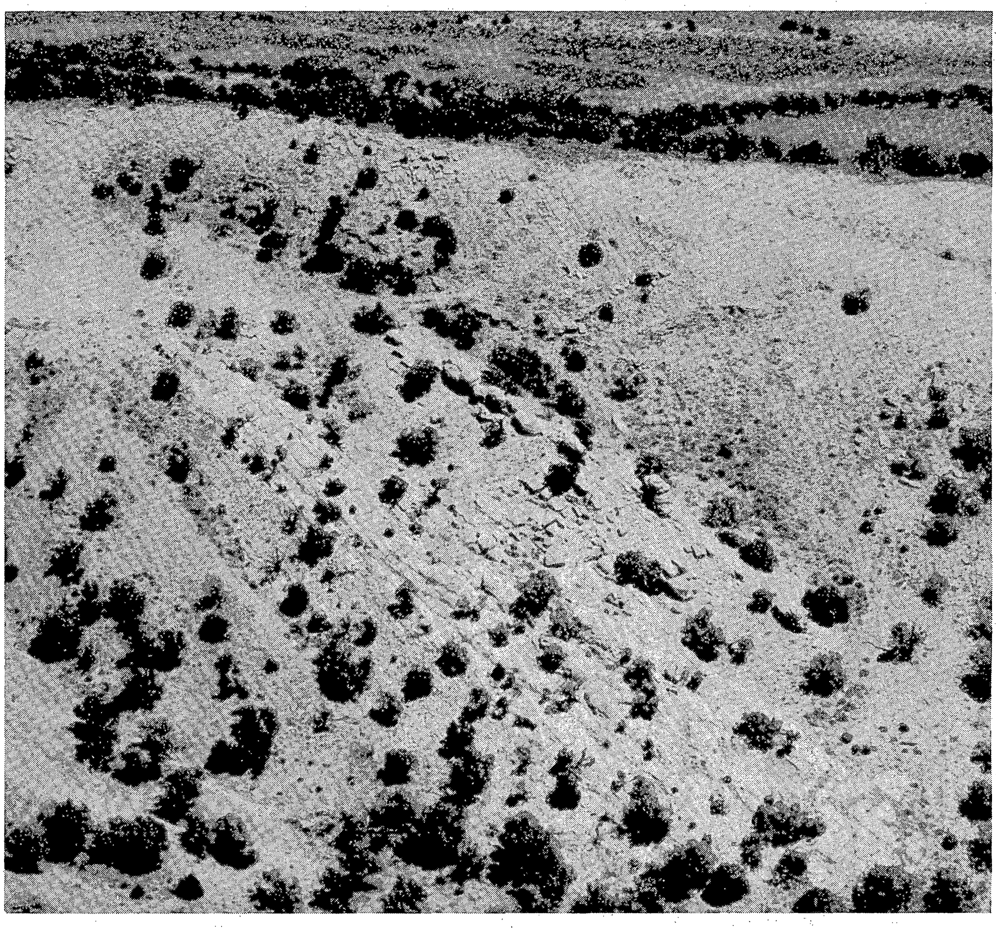


Figure 18. North-south J1 fractures trending highly oblique to strike of the strata in the north-northwest trending dogleg of the ridge south of Scullys Gap. Approximate north is to the left in this photo. (SE 1/4 SW 1/4 sec. 14, T.17N., R.117W., reference photo 5/5).

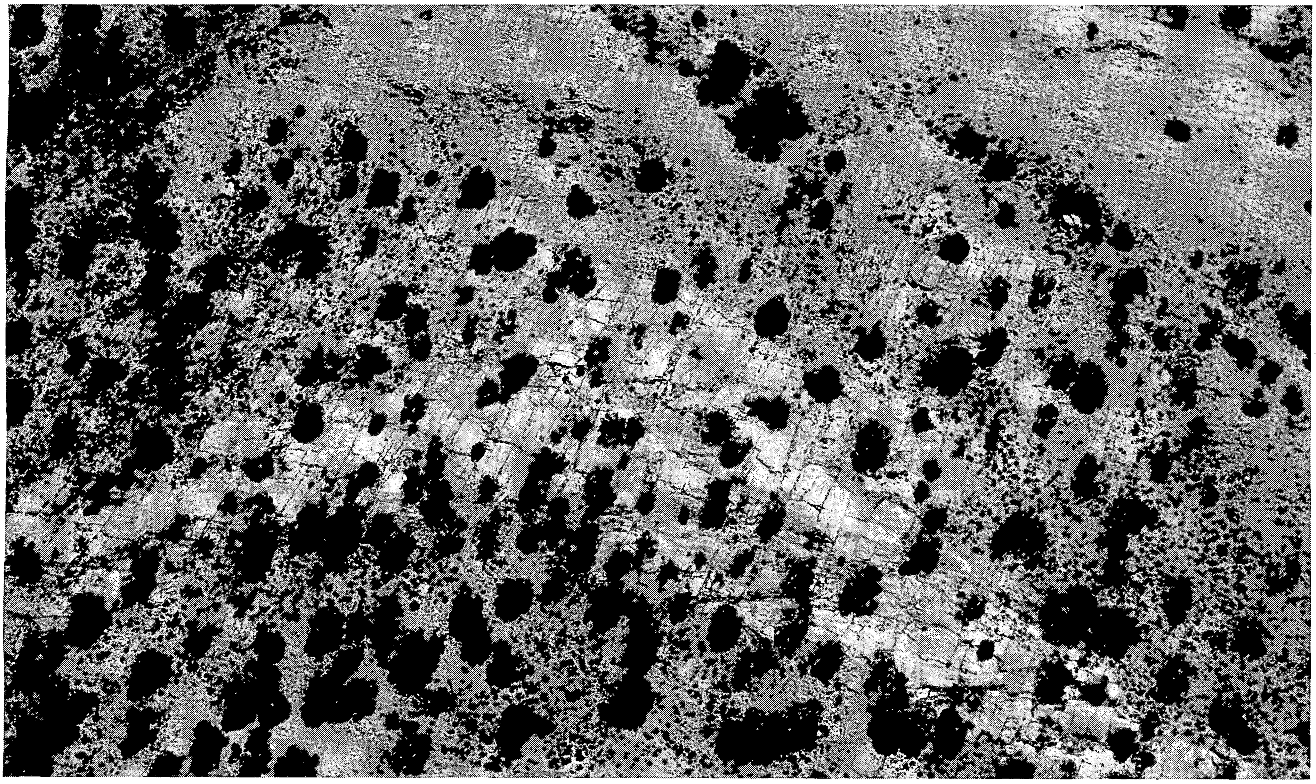


Figure 19. Well-developed J2 fractures nearly obscuring the earlier-formed J1 fracture set. Approximate north is to the left in this photo. (South of the gash, NW 1/4 SW 1/4 sec. 25, T.18N., R. 117W., reference photo 4/35).

Irregular J3 fracture patterns dominate the immediate vicinity of the gash in the middle of the left-lateral dogleg (Fig. 20). J1 fractures are still present, but they are visually overwhelmed by younger fracturing which displays northeasterly, easterly, and southeasterly trends. Just north of the gash, a unique fracture pattern suggests development of these secondary fractures in a stress field of changing orientation (Fig. 21): abutting relationships suggest that the post-J1 fractures initially propagated in an east-west (J2) direction, but distinct and congruent 55-degree bends in several fractures indicate that the stress

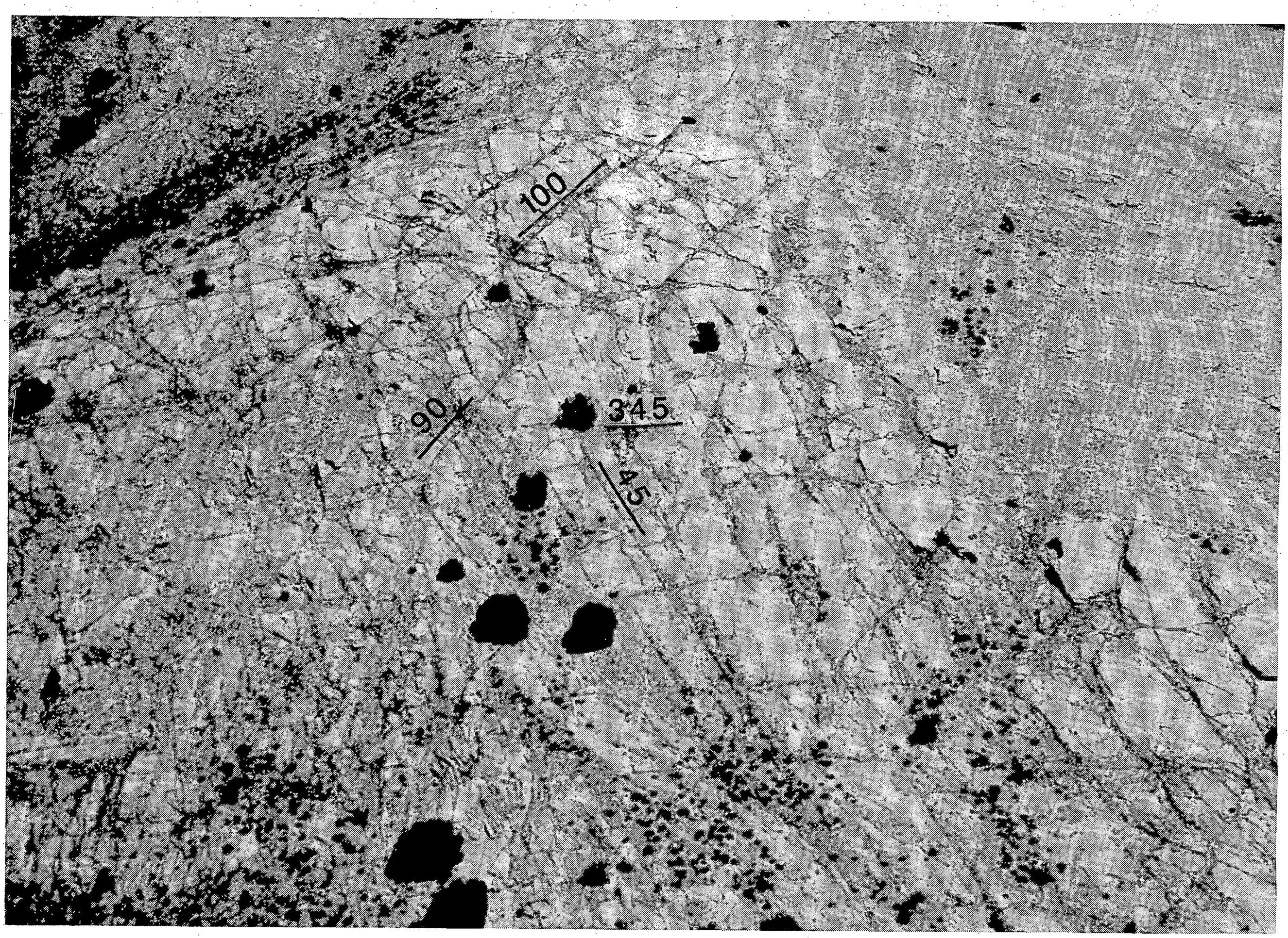


Figure 20a. Fracture patterns north of the gash. Numbers and lines indicate ground-measured fracture strikes. Approximate north is to the left in this photo. (Center, S 1/2 SE 1/4 sec. 13, T.18N., R.117W., reference photo 4/29).

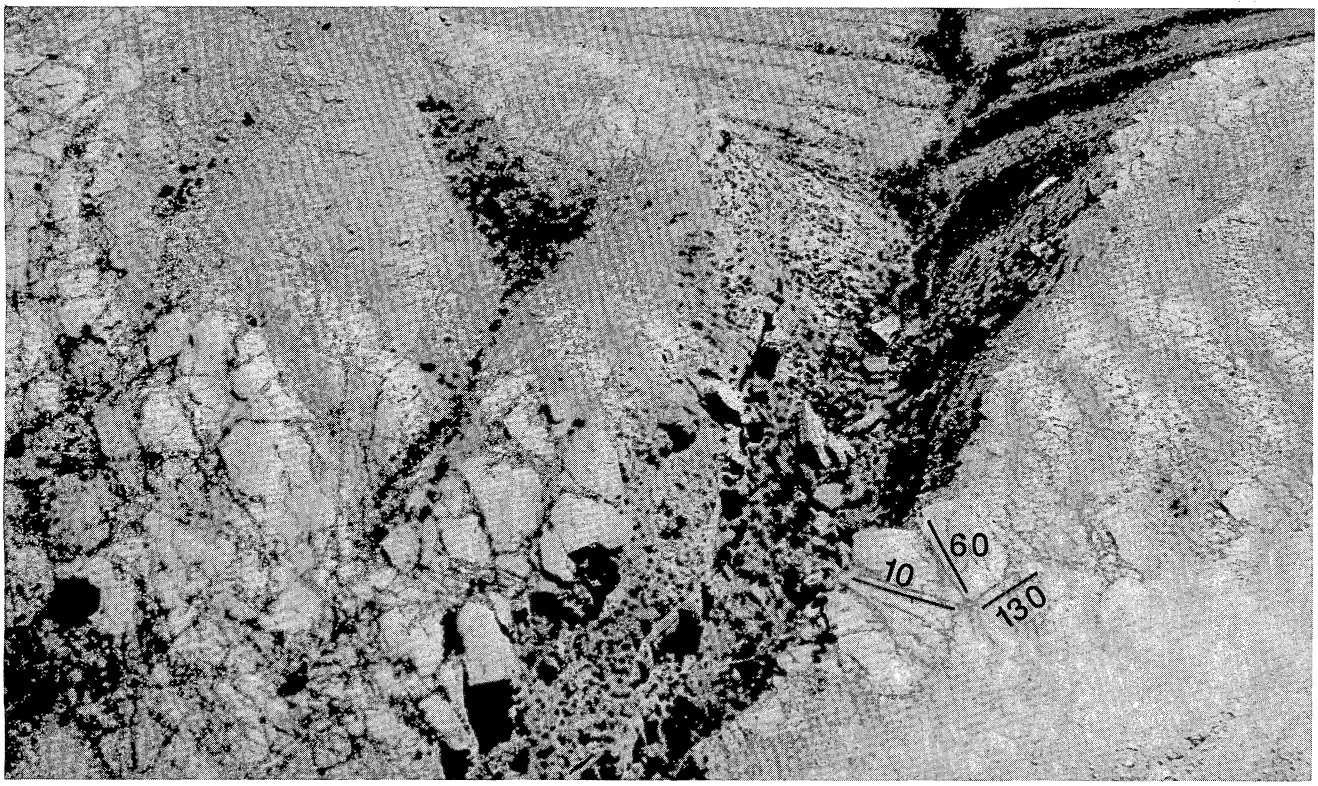


Figure 20b. Fracture patterns at the gash. Numbers and lines indicate ground-measured fracture strikes. Approximate north is to the left in this photo. (Center, S 1/2 SE 1/4 sec. 13, T.18N., R.117W., reference photo 4/30).

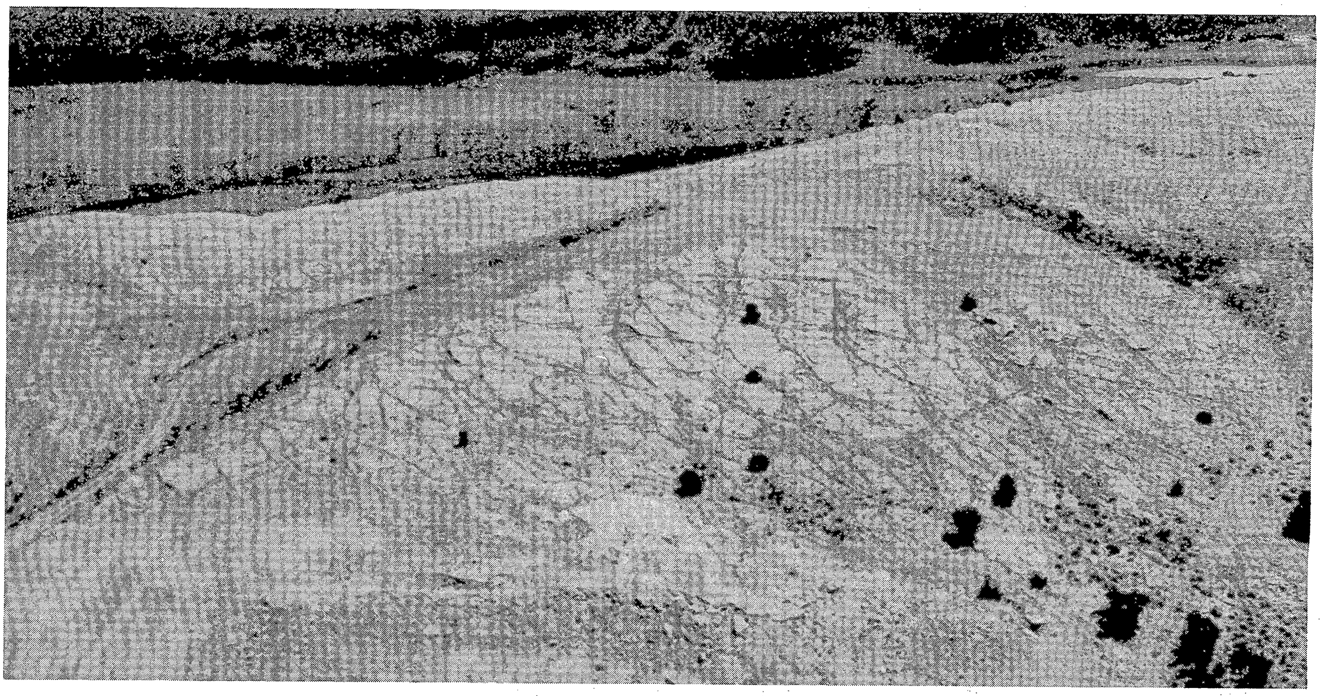


Figure 20c. Fracture patterns south of the gash. Approximate north is to the left in this photo. (Center, S 1/2 SE 1/4 sec. 13, T.18N., R.117W., reference photo 4/31).

field changed to a northeasterly compressive stress during fracture growth. Some of this pattern could be related to local fracture-tip interference during growth (central part of Fig. 21), although other, isolated fractures with similar orientations are also present. The dogleg in the ridge is interpreted as a response to the same shear-producing phenomenon that created the J3 fractures rather than a direct cause of the local J3 fracture pattern.

3.5.4 <u>The gash to Cumberland Gap</u>: North of the gash, the ridge-line trends northward for several kilometers before bending gently back to a north-northeasterly trend (Fig. 22). Fractures are obscured along the short north-trending segment south of the bend. East-west J2 fractures are well-developed just north of the bend, abruptly

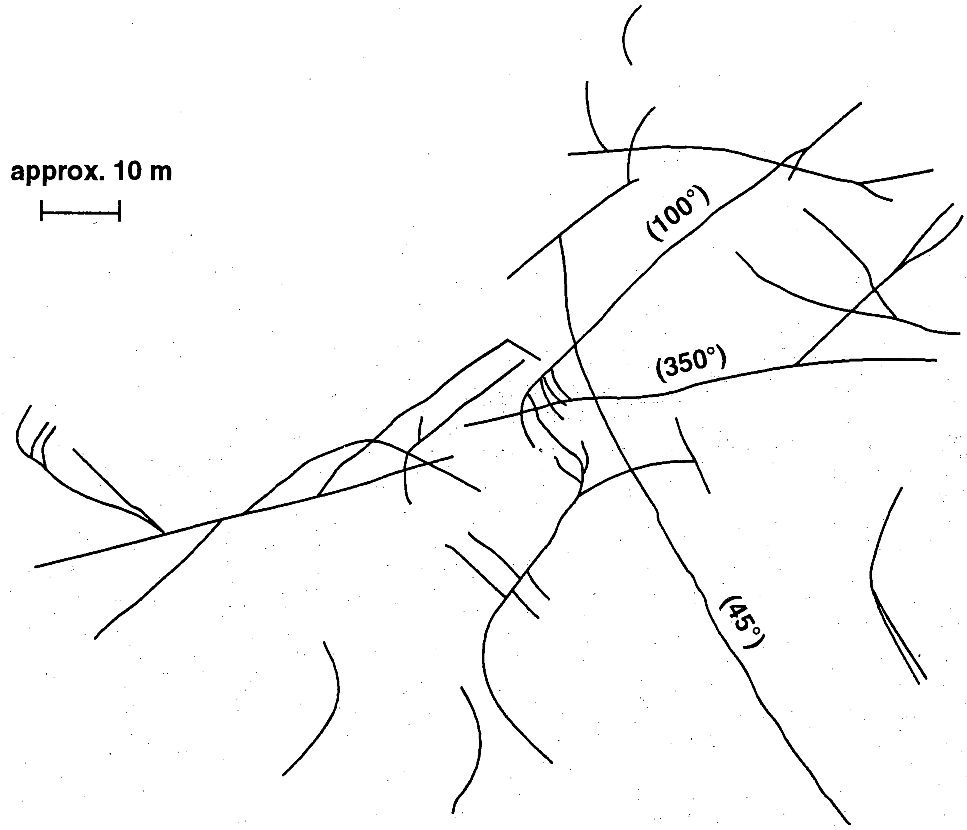


Figure 21. Tracing of the major fracture patterns shown on photograph Figure 20a, showing (1) an oldest north-south J1 fracture set, and (2) generally east-trending J2 fractures that locally grew into (3) youngest northeast-trending J3 fractures.

radiating to a south-southeast trend within the northern part of the bend (Fig. 23). Local stresses, as reflected by the changing fracture strikes within this fracture array, were apparently controlled during thrusting by the structure that created the ridge-line bend. Changes in dip angle may have created torsion that also played a role.

J2 thrust-dilatancy fractures become less prominent northward (Fig. 13a) along the relatively straight part of the ridge as it decreases in height leading into Cumberland Gap. This change in the character of the J2 fractures may

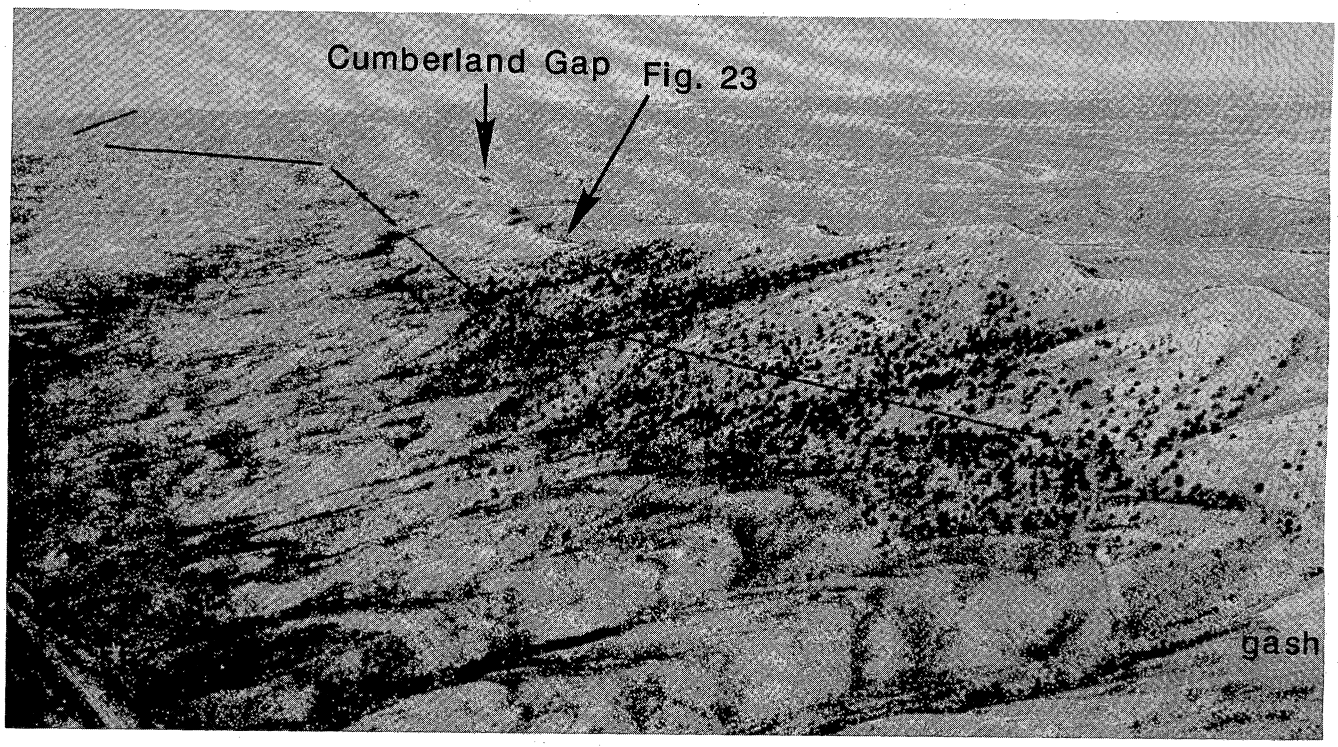


Figure 22. Ridge-line photo looking north from the area of the gash. Note the changes in ridge-line strike highlighted by the black line. (Reference photo 4/32).

have resulted from an increase in the north-south confining stress near this area, near the center of a relatively unbroken section of the thrust plate, during thrusting.

3.5.5 Cumberland Gap to Blazon Gap: This section of the Hogsback consists of two relatively straight segments, joined by a concave-westward bend of 16-18 degrees (Fig. 15) just south of what appears to be a relatively straight seismic-line road across the ridge. The north-south extension fractures are relatively complex here as noted earlier.

The J2, thrust-dilatancy fracture pattern in this section of the ridge mirrors the pattern south across Cumberland Gap, with short fractures nearer the gap (Fig. 13) and prominent, throughgoing fractures farther north (Fig. 7). Little structure is apparent at Cumberland Gap, even though it marks the widest and lowest break in the ridge-line. A subtle change of a few degrees in the strike of the strata on either side of the gap may be present, although exposures are poor in the low ridges adjacent to this pass.

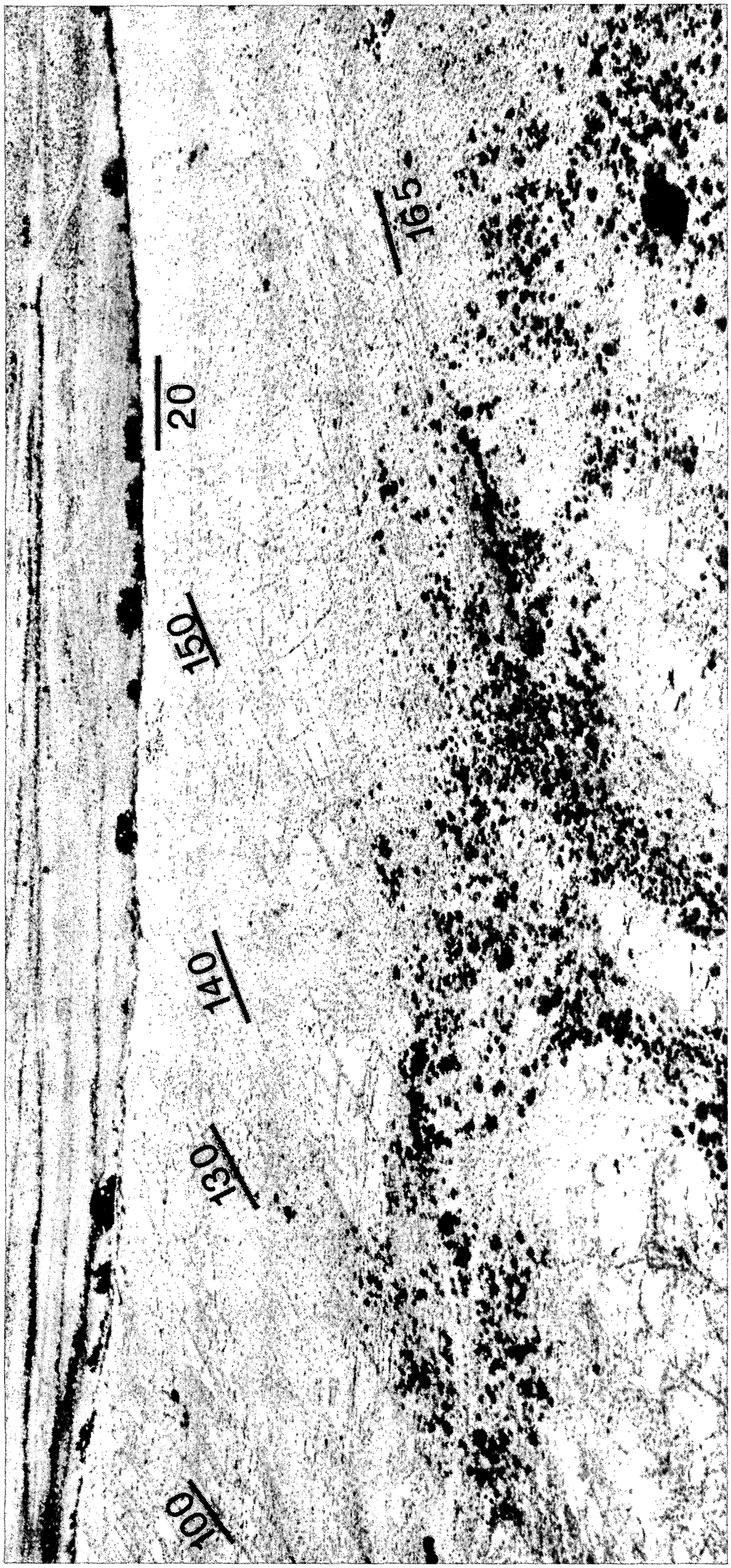
We suggest that the north-south confining stress during thrusting was greatest near the center of the relatively straight segment on either side of Cumberland Gap, resulting in short, confined, thrust-dilatancy fractures in this area. However, near the northern and southern ends of this section of the ridge, abrupt thrust-sheet bends (near the gash and near the seismic-line road) released some of the lateral confining stress and allowed propagation of throughgoing, prominent J2 fractures (Fig. 24).

J2 fractures again become short and less prominent approaching Blazon Gap, but here, in part, the fractures were no longer propagating normal to the north-south J1 fractures and were probably terminated by shear along the oblique planes of weakness. To the north, however, a continued pattern of short, sub-dominant J2 fractures suggests that the north-south confining stress may also have been high in this area.

3.5.6 Blazon Gap to Highway U.S. 30: The few outcrops along this straight, low-lying section of the Hogsback display relatively simple, J2 thrust-dilatancy fractures superimposed on nearly ridge-parallel, J1 extension fractures (Fig. 25). Little relief of the confining stress during thrusting seems to have been afforded by the structures responsible for Blazon Gap and the pass occupied by U.S. 30. The U.S. 30 gap may, in fact, have resulted from the presence of relatively thin (and therefore less erosion-resistant) sandstone deposits, rather than from structural complications.

3.5.7 Highway U.S. 30 to Highway U.S. 189: This 14 km length of the Hogsback displays the largest area of irregular fracturing present along the ridge. The section

Figure 23. J2 thrust-dilatancy fractures that change strike as they approach a bend in the strike of the ridge-line (to the right of the photo) north of the gash and just south of figure 13a. Approximate north is to the left in this photo. (Center E 1/2 E 1/2 sec. 12, T.18N., R.117W., reference photo 4/24).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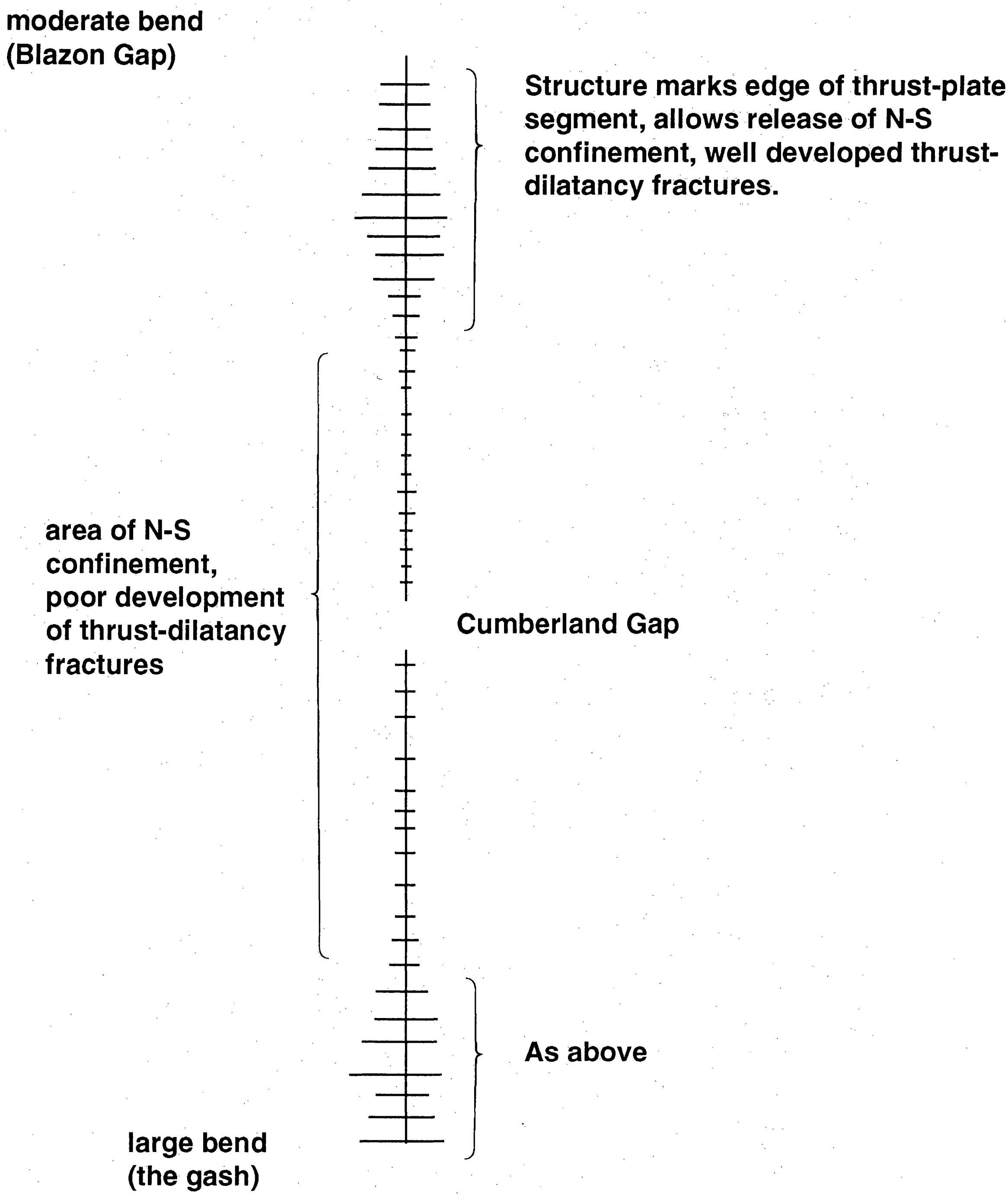


Figure 24. Schematic showing hypothetical development of different styles of J2 thrust-dilatancy fracturing within a segment of a thrust plate.

Figure 25. J1 fractures (with slightly divergent strikes in different beds) and poorly developed J3 fractures, south of U.S. 30. Approximate north is to the left in this photo. (Center N 1/2 NW 1/4 sec. 16, T.20N., R.116W., reference photo 3/6).

is bounded by deep erosional cuts in the ridge at the north and south, yet includes some of the highest topography along the ridge. Two faults have been mapped near the center of the segment, and the most radical changes in ridge strike occur within it: significant local structure is present though poorly defined (i.e., one of the faults is mapped only on the 1:500,000 state geologic map).

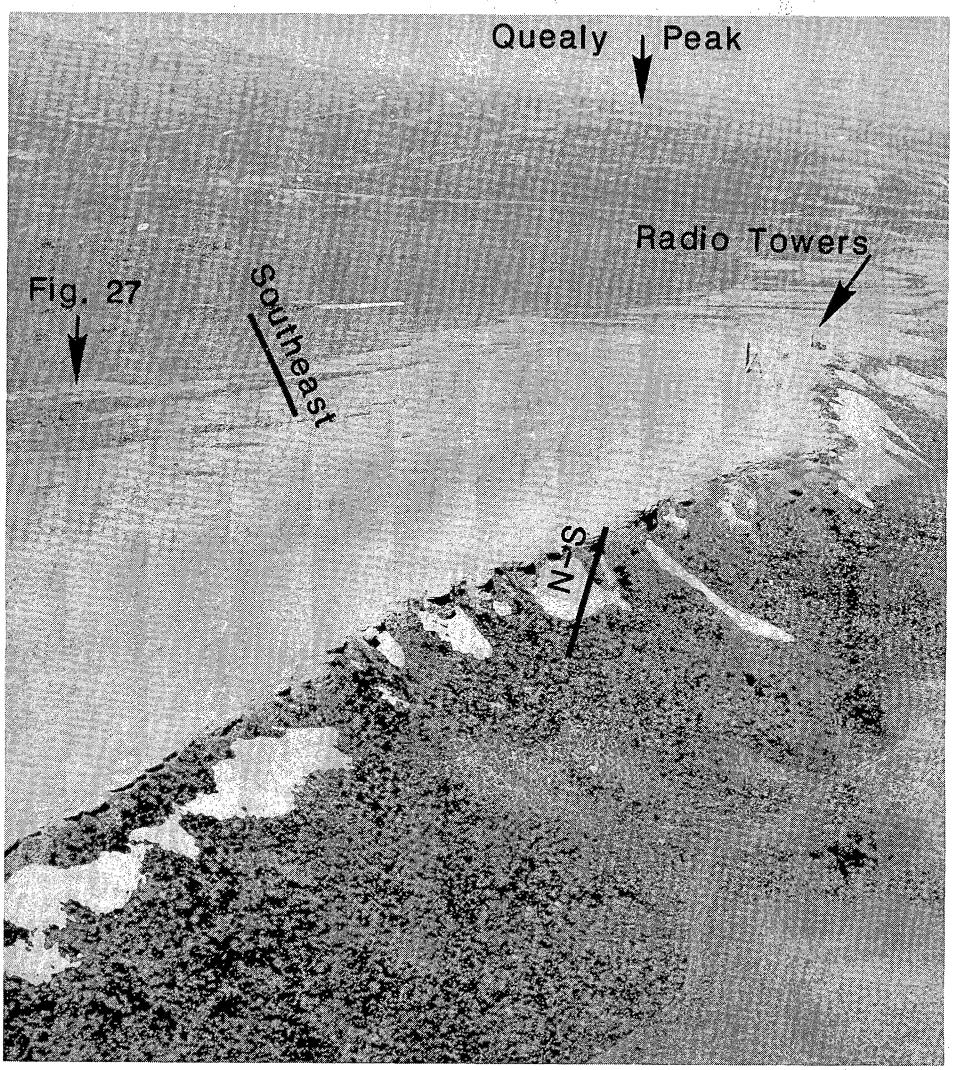


Figure 26a. Looking north along the ridge-line across across the large change in strike near Quealy Peak toward the Kemmerer radio towers. Local strike of the light-colored sandstones trends diagonally from the left center to the upper right of the photo, then bends back to the top-center of the photo below Quealy Peak. (reference photo 6/17).

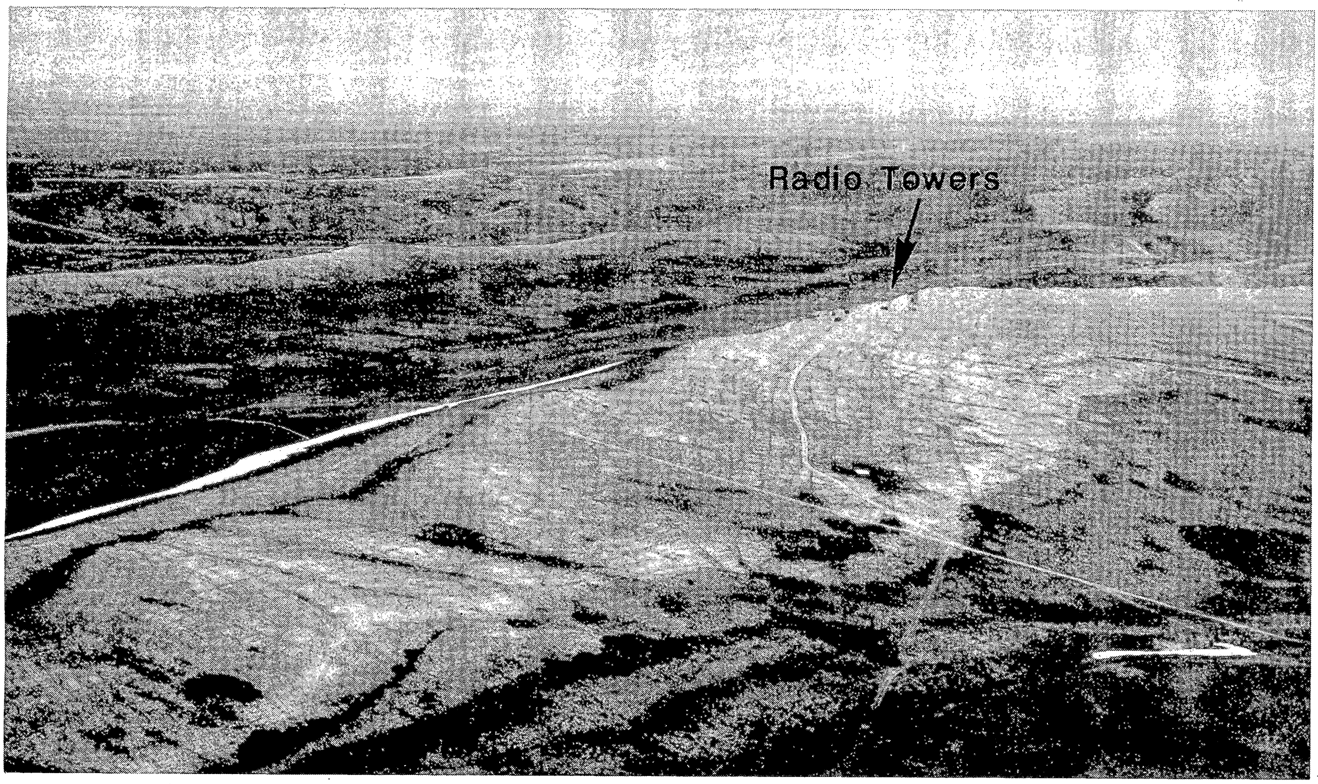


Figure 26b. Looking south along the ridge-line across the Kemmerer radio towers. Note the sandstone/ridge-line strike oblique to prominent J1 fractures, and snow-capped Uinta Mountains in the distance. (Reference photo 6/22).

The J1 extension fractures are again the first-formed fractures within this section. Viewed from the appropriate angles (Figs. 26a,b), a 10-20 degree variability in the strike of this set of fractures across the outcrop is apparent. Most outcrops also display east- to northeast-striking J2 fractures and/or southeast-striking (youngest) J3 fractures. The J3 fractures are interpreted to have formed soon after the J2 fractures during thrusting.

The large pavement east of Kemmerer (Figs. 26-28) provides insights into the origin and timing of these fractures. A relatively simple pattern of north- and east-striking J1 and J2 fractures is present in the thicker, massive white sandstone southwest of the radio towers at the topographic height of this pavement (Fig. 27). A third set of southeast-striking J3 fractures begins to appear in the flaggy, marine sandstones uphill and stratigraphically below this sandstone. Near the radio towers (Fig. 28), the southeast J3 fractures are an equally prominent set within the marine sandstones. Some of this change is due to spatial variations in the J3 stress field and differences in proximity to local structures, but this also illustrates a possible depositional facies control on the fractures patterns that is discussed further below.

Abutting and crosscutting relationships indicate that the order of fracturing in these beds was 1) J1 fractures, 2) J2 thrust-dilatancy fractures, probably formed during the early stages of thrusting, and 3) southeast to east-southeast J3 fracturing, locally growing from the ends of J2 fractures and curving into the new J3 orientation. The apparently penecontemporaneous formation of the latter two sets of fractures is similar to that seen on a smaller scale at the gash farther south on the ridge.

It is probable that space constraints along the thrust plate during the later stages of thrusting (i.e., after the formation of the J2 thrust-dilatancy fractures) led to local lateral compression at the eastern-most apex of ridge curvature, between Quealy Peak and the Kemmerer radio towers (Fig. 3). This produced an elevated structural block between the mapped cross faults. It also resulted in a local southeast-trending maximum horizontal compressive stress that was derived from a combination of east-west thrusting stress and north-south space-constraint stress.

As suggested by the widespread J3 fractures, reoriented stresses affected a large region within this ridge segment. Minor right-lateral shear along the existing east-west fracture planes may have played a part of this model, as evidenced by the common origination of southeast-striking J3 fractures at asperities along the southern edges of east-trending J2 fractures (Fig. 28).

Several fracture domains are present within the structural block south of Quealy Peak (Fig. 29), but high variability and incomplete exposure make detailed interpretations impractical. Fractures are also obscured immediately north of Quealy Peak although the incomplete exposures suggest a return to north-south and east-west fracturing.

3.5.8 North of Highway U.S. 189: The next well-exposed pavement is the western, dip slope of the large battleship-prow outcrop just north of the dogleg in highway U.S. 189. Fractures here consist of the J1 set, with superimposed, prominent northeast-striking J2 fractures and locally developed, southeast-striking J3 fractures (Fig. 30). The northeast fractures are interpreted to be the local representation of thrust-dilatancy, implying a northeasterly directed horizontal compressive stress in this area during thrusting. A late southeasterly-directed stress in this area may have created the southeast-striking J3 fractures and contributed to the Quealy Peak/Kemmerer complexities.

From highway 189 north, the ridge consists of isolated pavements interspersed with covered intervals. Most of the pavements display prominent J1 fracturing with varying developments of the superimposed J2 fractures (Figs. 4, 31). Several prominent bends occur between straight segments of the ridge (Fig. 32), although no correlations with local fracture patterns are exposed.

The north-northwest striking segment of the ridge north of Little Coal Creek (Fig. 3) displays north-northwest striking J1 fractures. This section is nearly due east of a much larger, northwest-striking oblique ramp in the adjacent Absaroka thrust, where the strata and included fractures have been physically rotated counter-clockwise about the vertical by the ramp (Apotria, 1993). A similar rotation over a related oblique ramp may explain the concurrent change in strike of the beds and fractures in this section of the ridge.

The Lazeart Syncline narrows in this area, and local exposures of Frontier sandstones occur on the west limb of the syncline as isolated, near-vertical, fractured flatirons (Laubach, 1991). The western, nearly vertical limb of the syncline was originally overturned by the previous overthrust from the west, and then rotated back to vertical and elevated to its present position during Hogsback thrusting (Delphia and Bombalakis, 1988). A clustered pattern of fractures with a J2 orientation was described

Figure 27. Strong J1 and J2 fractures developed in massive white sandstone (lower left), with additional incipient oblique fractures developed in flaggy marine sandstones stratigraphically below the massive sandstones. Numbers and lines indicate ground-measured fracture strikes. Approximate north is to the left in this photo. (Approximately 1 km southwest of the Kemmerer radio towers, SW 1/4 SW 1/4 sec. 19, T.21N., R.115W., reference photo 2/34).

Figure 28a. Well-development southeast-trending J3 fracture patterns on top of oldest north-south J1 and intermediate-age J2 fractures, immediately north of the Kemmerer radio towers. Numbers and lines indicate ground-measured fracture strikes. Dirt track for scale. Approximate north is to the left in this photo. (NW 1/4 NE 1/4 sec. 19, T.21N., R.115W., reference photo 2/29).

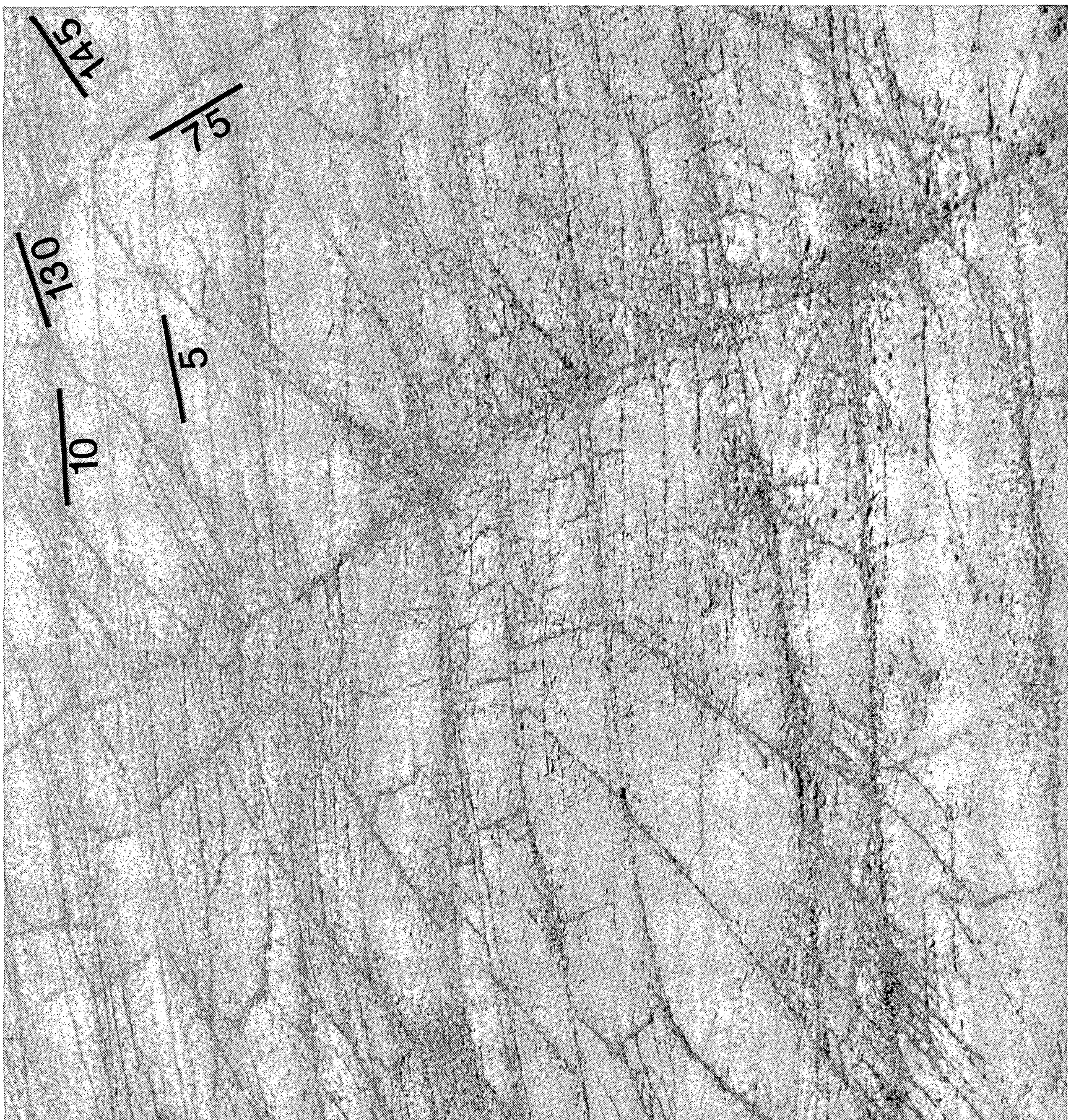

145
75
130
5
10

Figure 28b. Pavement at the Kemmerer radio towers, same location and fracture patterns as figure 28a. Approximate north is to the left in this photo. (Reference photo 2/30).


15
110
80
120
350

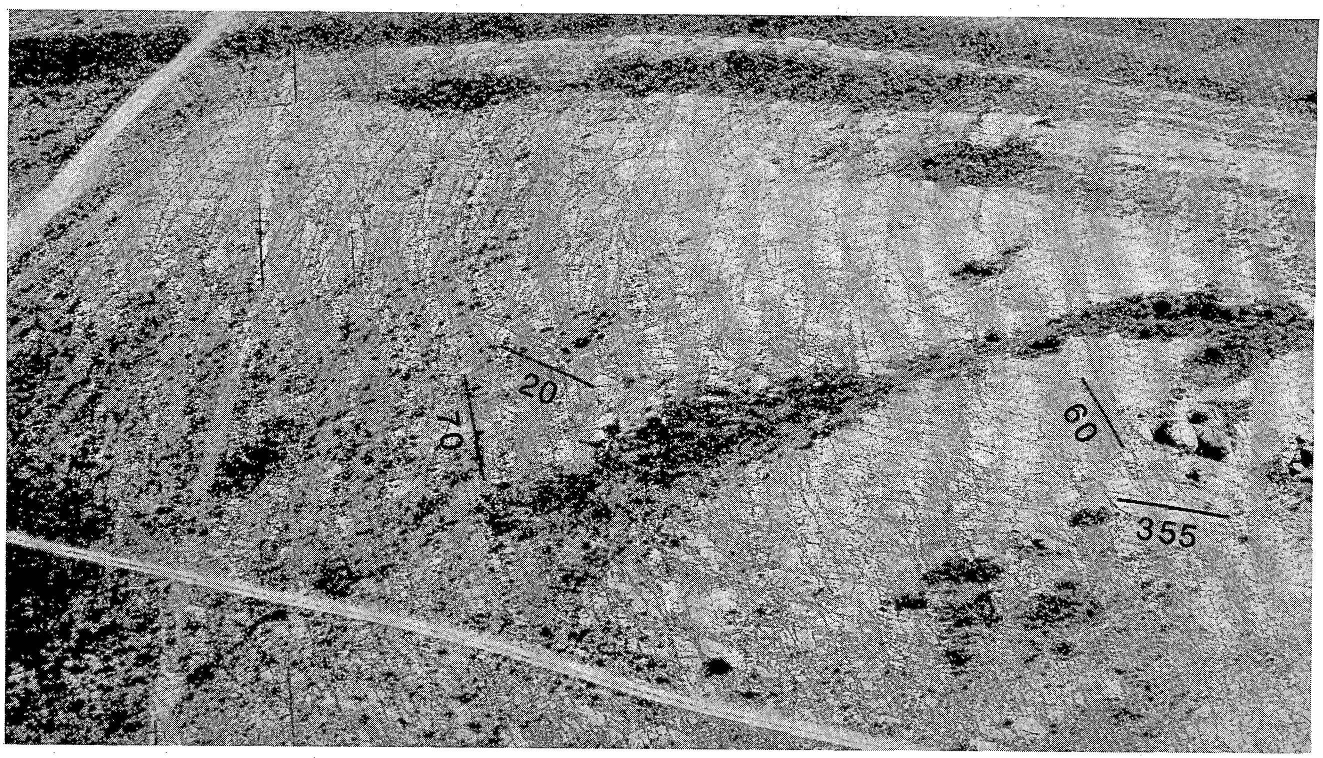


Figure 29a. Irregular J2 fractures superimposed on north-south J1 fractures, southeast of Quealy Peak. Numbers and lines indicate ground-measured fracture strikes. Approximate north is to the left in this photo. (Center NW 1/4 sec. 5, T.21N., R.115W., reference photo 2/23).

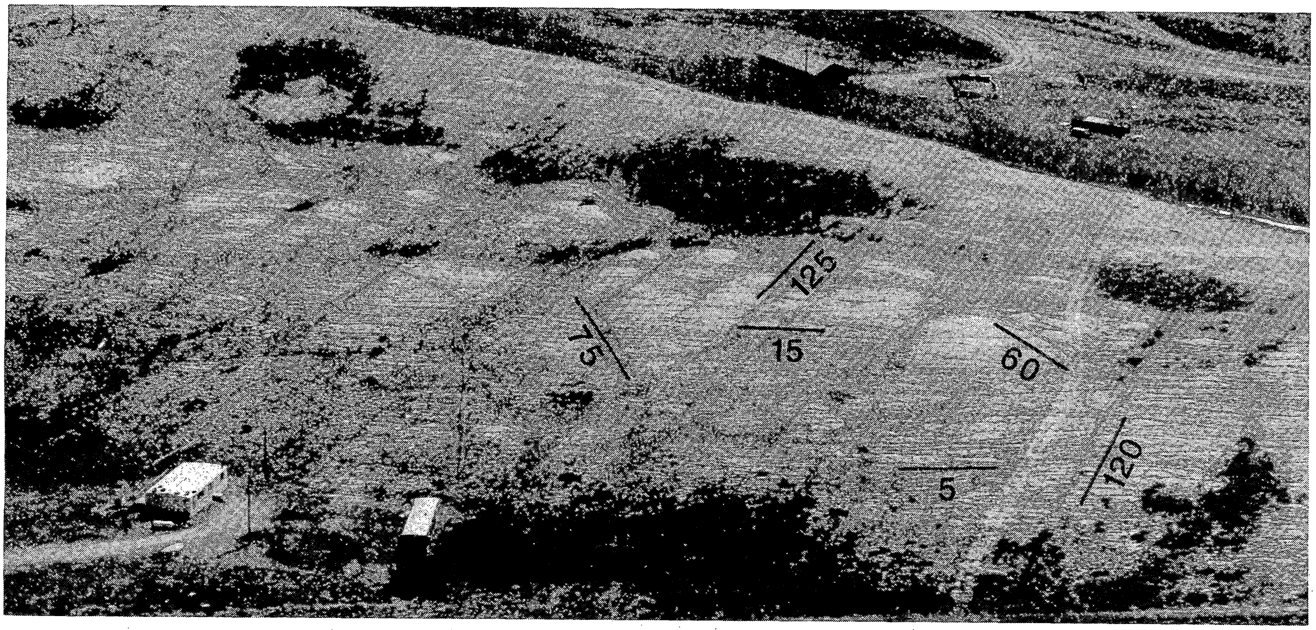


Figure 29b. Dominant southeast-trending J2 fractures, and less regular northeast-trending J3 fractures superimposed on north-south J1 fractures, approximately 1 km south of Fig. 29a. Numbers and lines indicate ground-measured fracture strikes. Approximate north is to the left in this photo. (Center N 1/2 SW 1/4, sec. 5, T.21N., R.115W., reference photo 2/24).

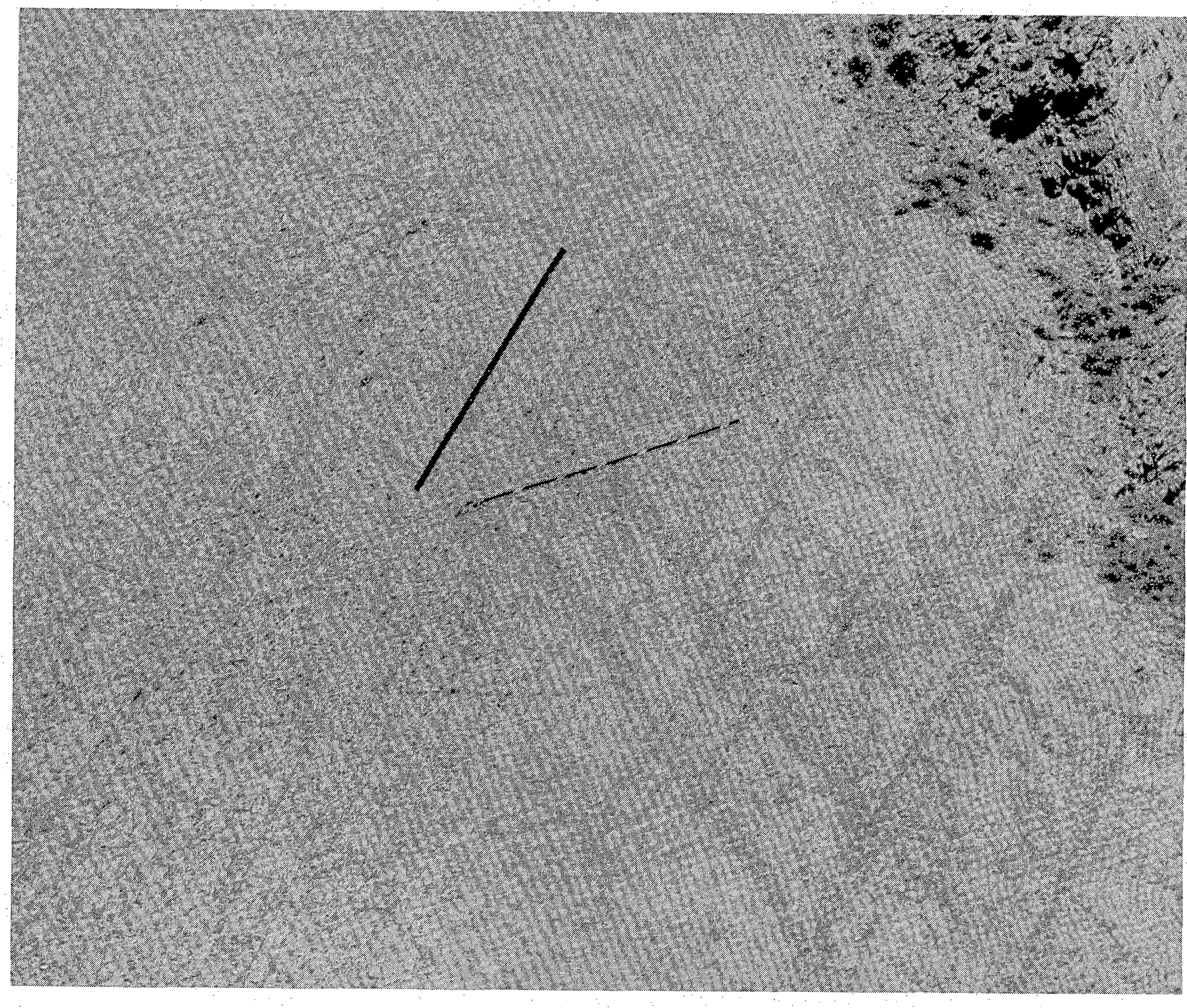


Figure 30. Strong northeast-trending J2 fractures (solid line), and southeast-trending J3 fractures. (The north-south J1 fractures are obscured in this photo). Approximate north is to the upper left in this photo. (Back slope of the battleship-prow outcrop, center W 1/2 SW 1/4 sec. 18, T.22N., R.115W., reference photo 2/15).

Figure 31. Closely spaced J1 fractures crossed by more widely spaced but equally throughgoing J2 fractures. Approximate north is to the left in this photo. (South of Windy Gap, center sec. 30, T.23 N., R.115W., reference photo 2/3).

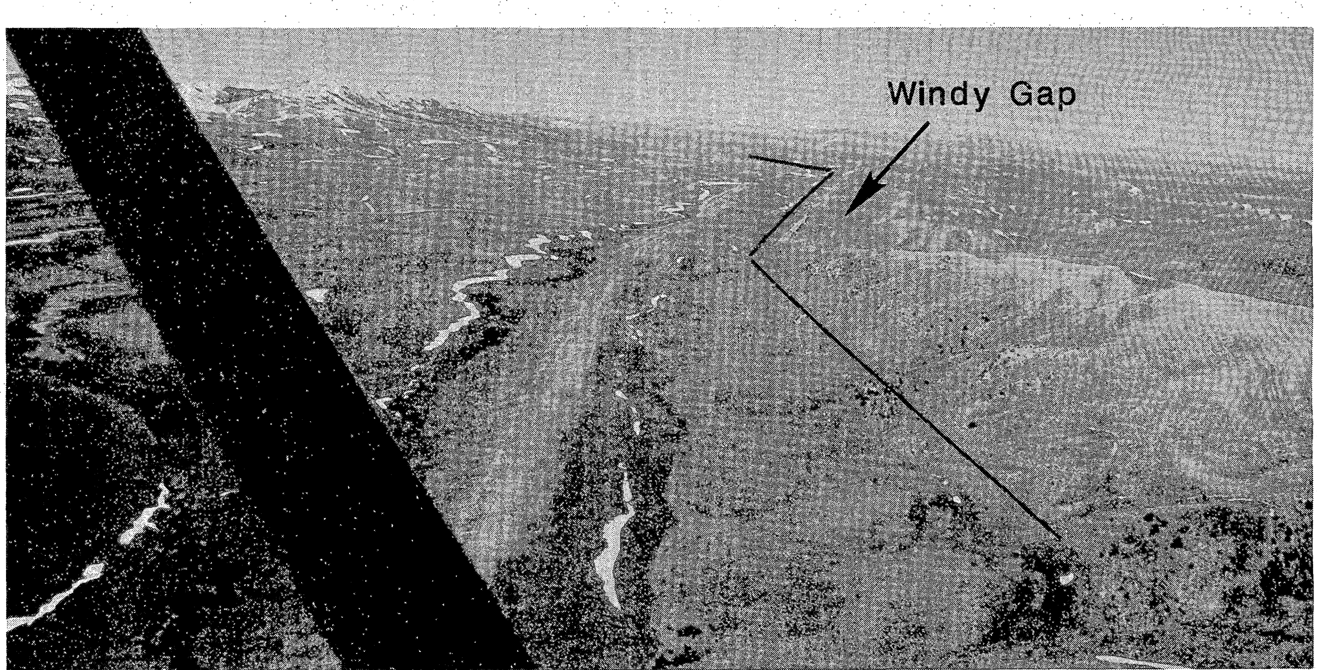


Figure 32. Change in the ridge-line strike (highlighted by black line) at Windy Gap. (Reference photo 6/28).

from an east-facing flatiron exposure northwest of Windy Gap by Laubach (1992). In this exposure (Fig. 33), opening-mode fractures are mainly oriented normal to bedding. Fractures generally strike east, but strike varies by more than 40 degrees, and many of the longest fractures are curved. Further data on fracture characteristics in this outcrop were presented in section 3.3.

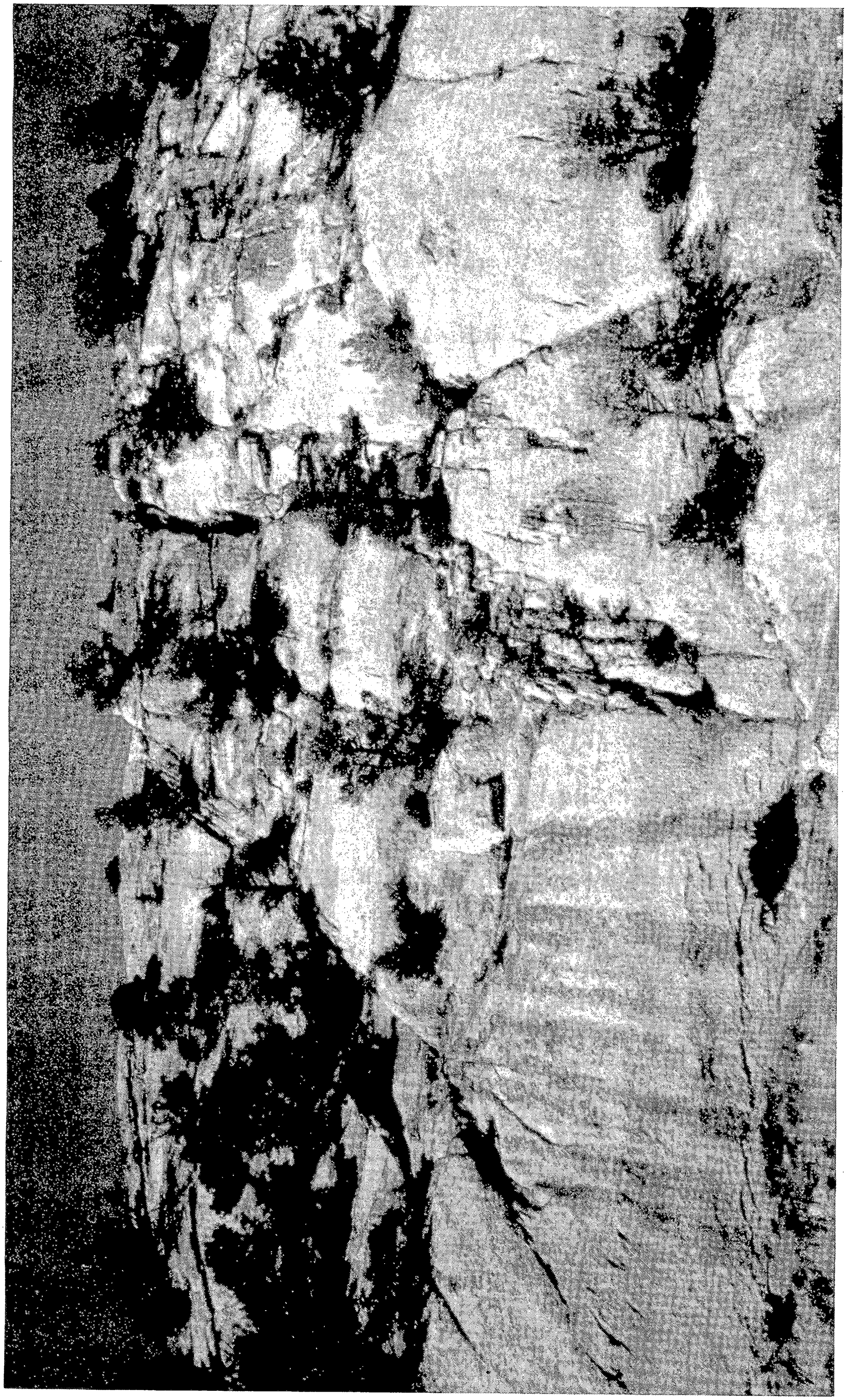
Fracture traces are clustered in the northern and southern parts of the outcrop, and in a band through the center of the outcrop where exposure is poor. There are also clusters of fractures within the main intact-rock panels of the outcrop. These clusters of swarms are evident on several scales. Small swarms are separated by rock that lacks fractures; large swarms are separated by areas of low fracture density.

Elsewhere along the steep west limb of the Lazeart Syncline, tilt domains are readily identified where dips change abruptly along strike, although sandstones and fracture patterns at the changes are poorly exposed. In the topographic gap on the south side of the flatiron, scattered small exposures and float contain numerous slickenlined fractures and networks of anastomosing veins; fractures in the area of the topographic gap south of the figure 33 flatiron may have been reactivated as small faults during thrusting. Tear faults in the west limb of the syncline occur in zones that trend parallel to extension fracture swarms, and it is possible that swarms were areas of weakness during thrust movement that localized tilt domains.

The straight section of the eastern limb of the syncline between North Willow Creek and Roney Creek displays dominant J2 fracturing, almost to the exclusion of all other fracturing (Fig. 34). The narrowness of the syncline in this area suggests strong east-west compressive stress during thrusting, which could conceivably have healed earlier, J1 fractures. A fault has been mapped in this area (Fig. 3), which may also have contributed to fracturing.

3.5.9 Lazeart Syncline Hinge: The hinge of the Lazeart Syncline in Frontier Sandstones is well exposed north of Mahogany Creek (T.27N., R.116W.). The overall shape of the hinge is a simple, angular, open asymmetric syncline with planar limbs. In detail, however, the hinge consists of discrete domains (panels) defined by planar bedding separated by areas of abrupt shift in strike and dip. The

Figure 33a. Foreshortened (from the base) view of east-west striking fractures in the flatiron outcrop, on the west limb of the Lazeart syncline northwest of Windy Gap (T.24N., R.116W.). Photo spans the areas of mapped fracture swarms 5 and 6 in figure 33b. Approximate north is to the **right** in this photo.



areas where strike and dip shift are narrow (on the order of meters wide) and are generally poorly exposed. Slight shifts in elevation of sandstone horizons suggest that some of the areas of bed-attitude change contain small faults or fault zones trending parallel to the fold hinge.

In the intact panels between areas of strike and dip shift, typical J1 and J2 fractures patterns are present (Fig. 35). A minor, locally developed set of joints is present in the hinge region. These joints curve to parallel shifting bed strike, and they post-date J1 fractures. They may also post-date J2 fractures.

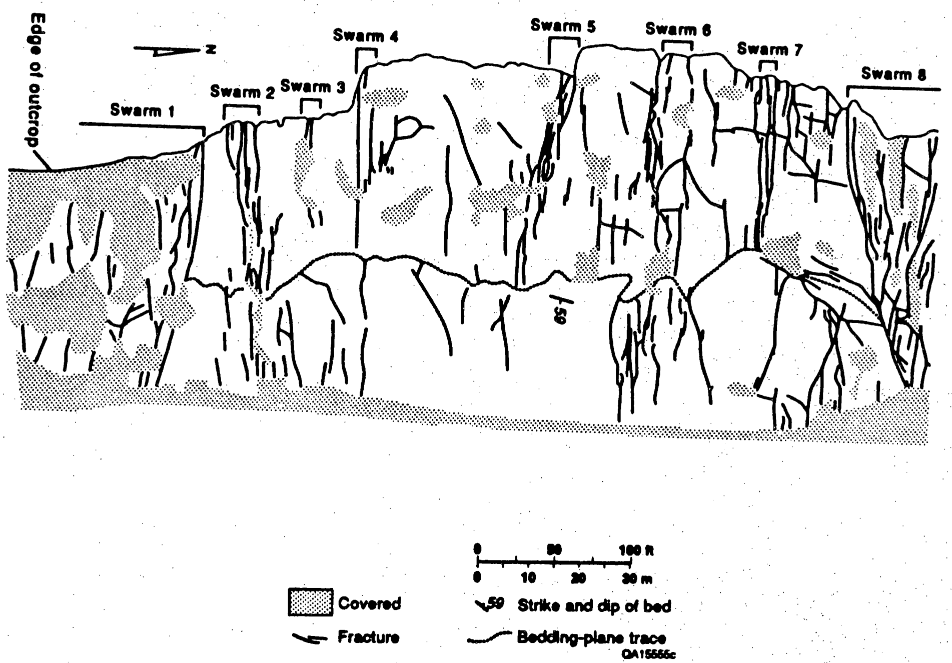


Figure 33b. Plan-view mapped fractures in the flatiron on the west limb of the syncline northwest of Windy Gap, showing fractures arranged in swarms (T.24N., R.116W.). (from Laubach, 1991). Approximate north is to the **right** in this figure.

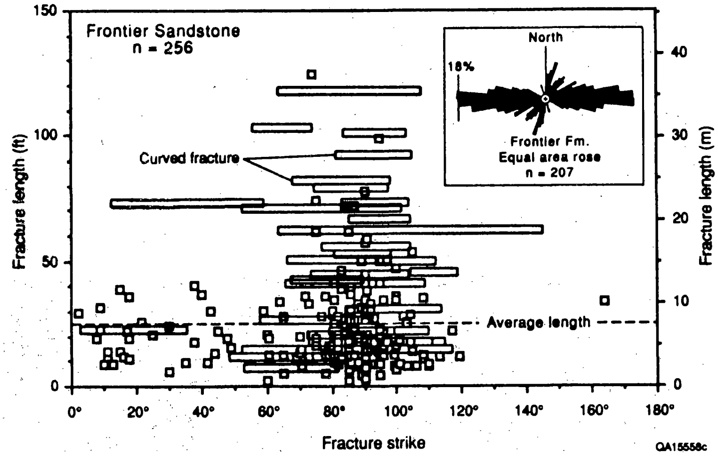


Figure 33c. Range of measured fracture strikes and lengths in the flatiron outcrop (from Laubach, 1991).

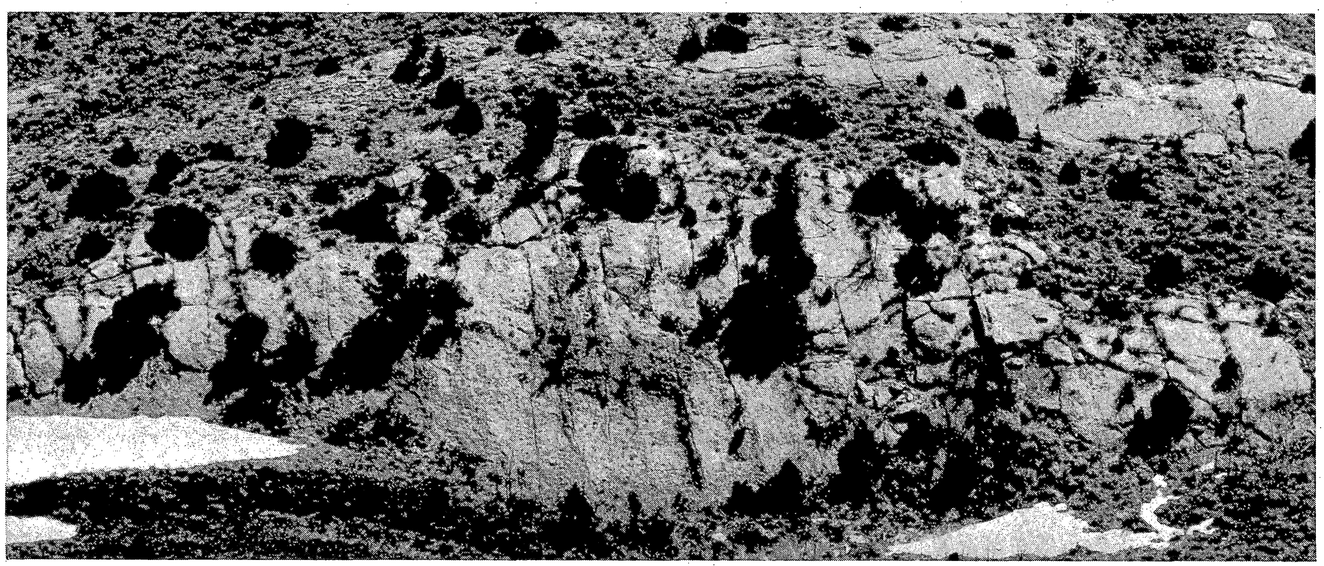


Figure 34. Dominant east-trending J2 fractures with subordinate north-south J1 fractures. Approximate north is to the left in this photo. (South of Roney Creek, center W 1/2 sec. 18, T.24N., R.115W., reference photo 1/19).

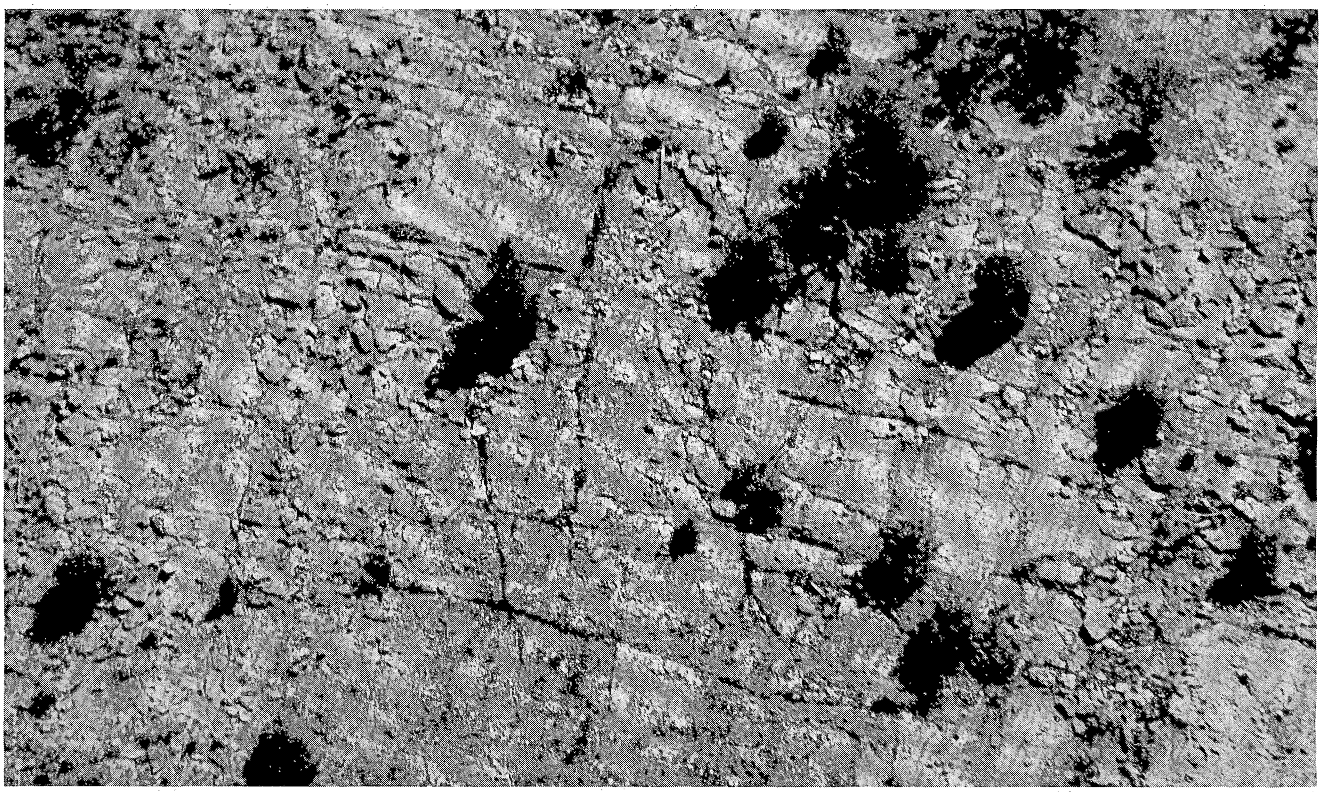


Figure 35. North-south J1 fractures at the northernmost end of the Hogsback, and subordinate J2 cross fractures. Approximate north is to the left in this photo. (North of Mahogany Creek, approx. sec. 36, T.27N., R.116W., reference photo 1/7).

4.0 FRACTURE ORIGINS

Numerous processes can create fractures that have similar appearances. The Frontier Formation in the Hogsback exposure has been subjected to a number of loading events that could have produced fractures having the observed geometric patterns. In approximate chronological order (some of these events overlapped), these include:

1. burial and stretching during basin subsidence
2. dilations on local and regional scales due to impingement of the Sevier orogenic belt to the west and/or the Laramide, thick-skinned thrusts to the north and south
3. deformations associated with translation and folding of the thrust sheet
4. stresses caused by uplift and erosion
5. extensional events (including those responsible for north-south striking normal faults along the western Green River Basin margin)
6. effects of recent topography.

The ultimate goal of this ongoing study is a prediction of which, if any, of the fractures observed in outcrops are present in the Frontier Formation reservoirs in the Green River Basin to the east. In order to make such predictions, interpretations as to which of the listed geologic events created which of the observed natural fractures must be coupled with tectonic reconstructions (in order to infer the extent of the regions affected). This extrapolation will be the subject of a separate report (Lorenz, 1994).

Fracture strike alone is insufficient to determine the age and cause of fracturing. The relative timing of fracturing can only be deduced from geometric and kinematic evidence. The main J1 and J2 fracture sets do not correlate with topographic features, and abutting and cross-cutting relations show that J1 fractures are consistently older than J2 fractures. Both sets occur in the same relationship on both limbs of the fold, and since fracture strikes of both sets are variable but nearly parallel and perpendicular (respectively) to the syncline hinge, graphically comparing fracture patterns on opposite fold limbs is not definative for determining whether fractures predate folding.

4.1 J1 fractures

On a purely geometric basis, J1 fractures could be interpreted as bc extension fractures (and similarly, J2 would be ac extension fractures) related to folding of the syncline (Stearns and Friedman, 1972). However, the consistent orientation of these fractures at right-angles to bedding, and their presence on fold limbs that are inferred to have rotated passively with little internal deformation (Delphia and Bombalakis, 1988), is consistent with J1 and J2 fracture development prior to folding. This is also consistent with the common slightly to moderately oblique angle between J1 fracture strikes and the fold axis.

If flexure at a hinge during fold development were the cause of J1 fractures, this fracture set should be concentrated in the fold hinge, but this is not the case. The J1 fractures might also possibly have been caused by migration of a fold hinge through rocks that are now in the planar fold limb. However, this process apparently did not occur during the development of the Lazeart Syncline (Delphia and Bombalakis, 1988). Moreover, there are several lines of reasoning that argue against applying this model to fracture generation in this case. First, such hinge migration would have had to have been remarkably uniform both along and across strike not to have produced highly curved fracture arrays and faults which might be expected from flexing and unflexing of beds (as seen in the actual hinge exposure). In addition, it is unlikely that this process would have left behind the observed uniformly planar limbs after hinge migration through the strata. Finally, the distinctive domainal features that are observed in the syncline hinge should have been preserved in the fold limbs had they ever existed there, and these features are not present.

Thus, we conclude that the north-striking J1 fractures did not originate as bc extension fractures produced during folding, nor by flexure at hinges of large-scale folds, but rather they predate thrusting, translation, and folding. The only tectonic/stress event that predates thrusting is burial and basin subsidence in the deep, narrow Cretaceous foredeep. There is a plausible loading history that accounts for J1 fracture development prior to thrusting: as the basin subsided during latest Cretaceous and early Tertiary time, strata could have been stretched east-west due to lengthening parallel to bedding, as the original nearly-flat depositional surface adjusted to conform to the asymmetric basin profile (Laubach and Lorenz, 1992). Concurrent indentation of the Wind River Mountains and the

Uinta mountains from the north and south respectively would have enhanced the horizontal stress anisotropy and the fracture potential of the strata at this time (Lorenz, 1993, 1994).

4.2 J2 Fractures

J2 fractures post-date J1 fractures. They also predate J3 fractures, although the J2-J3 geometries are locally suggestive of interaction. Since J3 fractures formed during thrusting (see below), J2 fractures must have formed just prior to or during the early stages of thrusting. East-directed tectonic shortening is inferred to have produced north-south extension, especially in the area of the foreland adjacent to a convex salient of the thrust belt, accounting for J2 fractures. Laubach et al. (1992) have shown that early-formed joints in Cretaceous coals that were likely undergoing coalification and fracturing during Sevier thrusting show a broad radial strike pattern around this salient. Craddock et al. (1988) documented similarly oriented extension fractures within the Idaho-Wyoming thrust belt farther to the north, and inferred a similar timing and origin for them.

4.3 J3 Fractures

J3 fractures are the youngest fractures, and the sub-sets of this group have no consistent orientation or characteristics along the length of the Hogsback. However, the apparent correlation of J3 fractures with structures within the thrust constitutes strong evidence for an origin during thrusting, translation, and folding. Thus, these fractures are interpreted to have formed due to local structural and spatial accommodations along the thrust plate during thrusting, and soon after, or even locally contemporaneously with, the formation of J2 fractures.

Although the strata were certainly stressed to some degree by the other three loading events listed above (uplift and erosion, Tertiary extension, and recent topography), no outcrop fractures can be correlated to these events.

In extrapolating these fracture patterns eastward into the subsurface, the J1 fractures are inferred to be widespread within the confines of the foredeep, and possibly eastward throughout the basin depending on the degree of influence of the Laramide uplifts north and south of the basin. In the basin, however, J1 fracture development and orientation may vary depending on local structures and the relative magnitudes of locally-created stresses. J2 fractures are the product of thin-skinned thrusting, and the stresses imparted to the undeformed strata east of the thrust belt dissipated rapidly away from the thrust front. The J2 fracture pattern is expected to be most prominent only within the thrust belt and immediately east of it. Similarly, the J3 fractures will be localized within transverse structures along thrust plates, and can not be extrapolated eastward into the deep basin. These ideas will be further developed in a future report.

5.0 DISCUSSION

J1 fractures are relatively uniformly distributed in Frontier sandstone beds of a given thickness and composition (Figs. 4,5). Although their spacing is not regular, these fractures are typically not clustered into swarms within individual outcrops. In contrast, east-striking fractures in the figure-33 flatiron outcrop on the western limb of the syncline are configured predominantly in swarms. Elsewhere, however, the outcrop-scale swarms that characterize the figure 33 flatiron are not apparent: J2 fractures on the eastern limb of the syncline may be either crosscutting and long relative to outcrop exposures (Fig. 7), or abutting and limited in length to the spaces between J1 fractures (Figs. 13a,b), but their spacings and distributions otherwise do not resemble the swarms documented in figure 33.

It is felt by one of the authors (JCL) that the east-striking fracture swarms present in the western limb of the syncline are not equivalent to the J2 fractures present on the eastern limb of the syncline. The other author (SEL) suggests that the east-striking fractures in these two areas are part of the same set. Insufficient data have been collected to resolve this yet: no length or spacing data have been collected from undisputed J2 fracture sets on the eastern limb that would allow comparison with the data set from the east-striking fractures in the figure-33 flatiron. However, visual comparison of photos of J1 and J2 fractures on the eastern limb of the syncline (Figs. 4, 5, 6, 7, 9, 10, 13, 19, 23, 27, 28, 31) offer no evidence of outcrop-scale swarms comparable to those on the west limb. It is possible that the change in character from short, abutting fractures to long, crosscutting fractures in the J2 fracture group may constitute a type of swarm characteristic on a larger, regional (kilometer-plus) scale, although the attempt was made above to relate these changes to local differences in the structure of the thrust plate.

If the attributes of J1 and J2 fractures do, in fact, differ, the differences could reflect contrasts in loading history during fracture propagation. Evenly-spaced, uniformly distributed fractures (such as the J1 fractures) are consistent with formation during slow burial and stretching. Irregularly spaced fractures, or fractures that occur in swarms and that are of unequal lengths, are consistent with formation under conditions of high compressive stress anisotropy. This latter mechanism could explain the swarms of fractures in figure 33.

6.0 LITHOLOGIC CONTROLS ON FRACTURES

Adjacent sandstone beds within the Frontier Formation locally may contain dissimilar fracture sets (Laubach and Lorenz, 1992). The reason(s) for this are not immediately apparent: bed thickness, structural context, and depositional environment have been considered as possible controlling factors, but none of these factors present consistent relationships with the varying fracture orientations.

However, a plausible relationship exists between fracture orientation and the petrophysical properties of the rock, properties which controlled the susceptibility of the rock to fracturing through time, and which are in turn a product of its composition and diagenetic history. Petrologic study shows that similar characteristics in different depositional facies resulted from parallel diagenetic sequences. On the other hand, in several cases different diagenetic sequences apparently produced similar rock properties, and hence similar fracture characteristics within otherwise disparate rocks.

A suite of sandstone samples was collected from the battleship-prow shaped outcrop north of highway U.S. 189. These sandstones came from different depositional environments and different fracture facies, and were thin-sectioned and compared petrographically. Probable petrophysical properties were inferred from this examination, and laboratory tests are being conducted to measure the actual mechanical properties of samples from the different fracture facies.

6.1 Diagenesis, Composition, and Fracture Facies

Outcrop examination suggested that there are four basic fracture facies in the sandstones. These are:

1. beds containing north-trending J1 fractures
2. beds containing northeast-trending J2 fractures
3. beds containing both of the above sets of fractures
4. beds without significant fracturing

Within each separate group, grain size, sorting, depositional environments, and porosity vary enough that none of these factors alone is likely to account for the observed differences in fracture orientations. Moreover, the basic mineralogic composition of the sand grains in all of the sandstones is similar, thus grain composition is unlikely to be a controlling factor.

The most important variable within the samples seems to be the diagenetic sequence, including several types and episodes of cementation and dissolution. However, matrix material such as clays and organic components that were introduced during initial deposition are also contributing factors to the variability in mechanical properties.

6.1.1 Fracture Facies 1: Rocks containing primarily north-trending J1 fractures at this location consistently exhibit 1) evidence for early quartz cementation by silica overgrowths on quartz grains and 2) later dissolution of much of the silica phase. This has resulted in a relatively high-porosity rock. In contrast to other fracture facies, there is little evidence for a later calcite cementation phase within rocks of this group. This is not a surficial weathering effect since the etching of quartz grains that is commonly associated with later calcite cementation in other rocks is not present, and because this facies is also recognized in sandstone core from the subsurface.

This observation is consistent with the proposed origin of the J1 fractures early in the history of the strata. Early silica cementation would have created brittle properties in the rocks, making them susceptible to fracturing contemporaneously with east-west extension of the strata during subsidence, and thus creating an essentially north-south fracture set.

Later dissolution of much of the early silica, combined with the absence of the subsequent calcite cementation phase, resulted in relative ductility of the rocks at a later time. The absence of the younger, northeast-trending J2 fracture set in these strata may then be attributed to more ductile properties during later, thrust-related stress events.

6.1.2 Fracture Facies 2: Rocks containing only the northeast-trending J2 fractures display the inverse diagenetic sequence, having little or no evidence for early silica cement but commonly containing significant amounts of later calcite cement. Calcite fills most of the porosity of these samples. Thus these samples are inferred to have been poorly cemented and relatively ductile during the stress phase which resulted in J1 fractures in most of the rocks, yet they were brittle and susceptible to fracturing during the later stress episodes that produced J2 fractures.

6.1.3 Fracture Facies 3: This facies characteristically contains both J1 and J2 fractures. Thus it is not surprising to find that samples from this facies typically display both early quartz and later calcite cements (separated by the silica dissolution phase). These samples are inferred to have been brittle due to cementation during both loading events. These rocks also have relatively low porosity.

Depositional environment may have influenced the diagenetic sequence to a degree; these samples are commonly from cleaner depositional facies such as hummocky cross-stratified shallow marine/lower shoreface sandstones where clays were rarely deposited. However, the sands include significant amounts of rock fragments and were never clean orthoquartzites.

6.1.4 Fracture Facies 4: This facies is characterized by the general absence of fractures in outcrop, and includes rocks from a diversity of depositional facies. Notably, it includes sandstones that were initially deposited in the same environment as the hummocky strata noted in group 3, but which were subsequently intensely burrowed. Bioturbation mixed a significant percentage of rock fragments, organic material, and detrital clay into the resulting rock. This facies also includes thick, white, amorphous sandstones believed to be upper shoreface deposits. The porosity of these samples ranges from very low to very high.

The absence of fractures suggests that the rocks were relatively ductile. The ductility of some of these samples derives from the mixture of clay and organic material into the sandstone, whereas in others it may be due to a high percentage of ductile rock fragments that comprise the sand fraction. In still another example, ductility may be attributed to a very high porosity (30%), and the resulting limited grain to grain contact. Thus there were several diagenetic and/or depositional facies that produced rock properties that were not susceptible to fracturing, although these strata account for only a small percentage of the Frontier Formation.

6.2 Application to Gas Production

The presence of different fracture facies in Frontier sandstones adds another level to the known heterogeneity of these reservoirs. It is usually accepted that primary sedimentary/diagenetic heterogeneity controls matrix permeability distributions (i.e., shale breaks in a sandstone are barriers to gas flow). It is also reasonably well understood that this heterogeneity in turn controls the distribution of natural-fracture permeability (i.e., fractures terminate at shale breaks, and therefore fracture permeability is also limited by such reservoir heterogeneities). The above observations on fracture facies suggest that the sedimentary and diagenetic history of the strata may also control 1) the likelihood of a particular sandstone facies being fractured, and 2) the orientation of the fractures expected. A similar case of fractures localized by non-uniformly distributed early cement has been documented in Paleozoic sandstones in Texas (Marin et al., 1993).

The results from this one outcrop should not be extrapolated in toto to the entire basin, since the controlling force is the tectonic history of the strata whereas the composition and diagenesis of the rocks are passive factors. Nevertheless, these factors should be taken into consideration when deviated holes are being considered for the development of a fractured reservoir, since the drainage efficiency of a deviated hole drops off rapidly as reservoir heterogeneity increases (Lorenz, 1992).

7.0 CONCLUSIONS

Natural fractures in sandstones of the Frontier Formation exposed along the Hogsback in southwestern Wyoming fall into three groups. The first fractures (J1) formed prior to thrusting and comprise a set of generally north-south striking fractures that are present along most of the ridge, trending sub-parallel to ridge strike. The second group of fractures (J2) formed during early stages of the thrusting that formed the ridge, and trends generally normal to the ridge (and thus approximately normal to the earlier fractures) in most outcrops. Local structures within the thrust plate such as tear faults and lateral ramps produced a third group of fractures (J3) with strikes that vary significantly from one location to the next, and that are present only near the structural irregularities in the thrust plate.

There are three diagenetic sequences in the Frontier Formation sandstones that seem to correlate with the age and orientation of fracture sets seen in outcrop north of highway U.S. 189: 1) north-south J1 fractures occur in sandstones that were cemented early with quartz and that did not undergo later calcite cementation; 2) northeast-trending J2 fractures occur in sandstones that were not cemented with the early phase of quartz overgrowths but that contain the later calcite cement; and, 3) both fracture sets are found in sandstones that contain both cementation stages. Depositional and/or diagenetic environments created ductile properties in other facies, and little or no fracturing took place in these rocks.

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Topical Report

Description and Interpretation of Natural Fracture Patterns in Sandstones of the Frontier Formation along the Hogsback, Southwestern Wyoming

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