of attack, much greater luminosity can occur.

One assumption made throughout the study is that the air is in thermodynamic equilibrium. It is distinctly possible that non-equilibrium thermodynamic effects can be significant. This point requires further investigation.

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*Geological Significance of Fracture Traces**

LAURENCE H. LATTMAN *and* RICHARD H. MATZKE,
Dept. of Geology, The Pennsylvania State Univ.,
University Park, Pa.

ABSTRACT: *Fracture traces, as now mapped in a variety of landscapes, are parallel or sub-parallel to joints in areas of flat or very gently folded rocks but are not parallel to the dominant joint sets in folded rocks. They apparently extend downward to depths of at least 3,000 feet at Bisbee, Arizona, where ore pods, which are fracture-controlled, are parallel to surface fracture traces. A probable wrench fault in Alaska separates two areas of different fracture-trace orientations, but fracture-trace orientations are identical on both sides of a thrust fault in central Pennsylvania. Extrusive and intrusive igneous rocks in the same area of Alaska show different fracture-trace orientation.*

INTRODUCTION

FRACTURE traces (also known as micro-fractures and linears) have been defined (Lattman, 1958) as natural linear features that have less than one mile of continuous expression, as viewed on aerial photographs. These features are rarely visible except on aerial photographs, and hence are of particular interest to the photogeologist. Recent investigations have revealed systematic relationships among fracture traces, joints, faults, folds and rock types. It is the purpose of this paper to collate this scattered information, much of it as yet unpublished, so that photogeologists may be made aware of current progress in understanding the geologic significance of fracture traces.

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FRACTURE TRACES

ORIGIN

Nearly all workers in this field (Blanchet, 1957; Mollard, 1957; Lattman, 1958) have considered that fracture traces are the surface expression of joints or zones of joint concentration. No investigator has been able to demonstrate this hypothesis conclusively. In most areas a cross-section of a fracture trace cannot be found, owing chiefly to the absence of bedrock exposures at the critical locality. But in the Powder River Basin of Wyoming, a mapped fracture trace passes across a vertical sandstone cliff. Here a zone of joint concentration can be seen to underlie the fracture trace (Figures 1 and 2). Strong circumstantial evidence, described by the investigators named above, supports the con-

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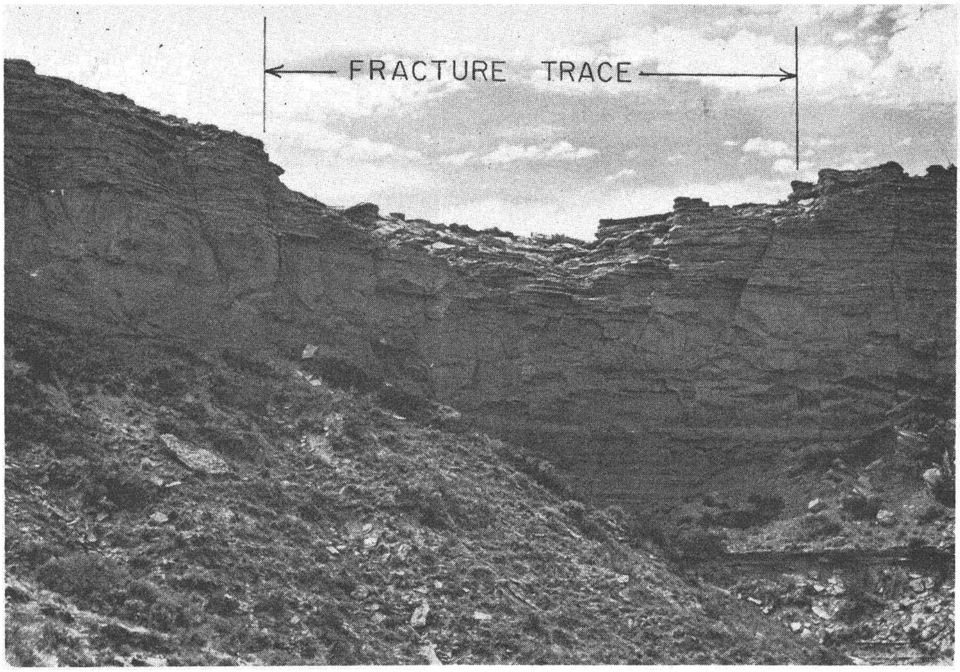

FIG. 1. Zone of joint concentration underlying a fracture trace in the Powder River Basin, Wyoming The fracture trace extends directly away from the observer at the top center of the scarp. There is no offset in the beds beneath the fracture trace, but a slight topographic sag which forms the surface fracture trace may be seen. Notice that the joints underlying the fracture trace are more closely spaced than those on either side. The width of cliff exposed in this view is about 50 feet.

cept that concentrations of joints are responsible for the occurrence of fracture traces.

RELATIONSHIP TO JOINTS

Photogeologic mapping of fracture traces has been combined with ground mapping of joints in several recent studies. Lattman and Nickelsen (1958) found a marked parallelism between dominant fracture-trace and joint sets in flat to gently folded Carboniferous rocks of the Allegheny Plateau in central Pennsylvania. This relationship was confirmed in a later study by Hough (1959). Subsequently Keim (1961), working in the folded and faulted terrane around Bisbee, Arizona, found that the dominant fracture-

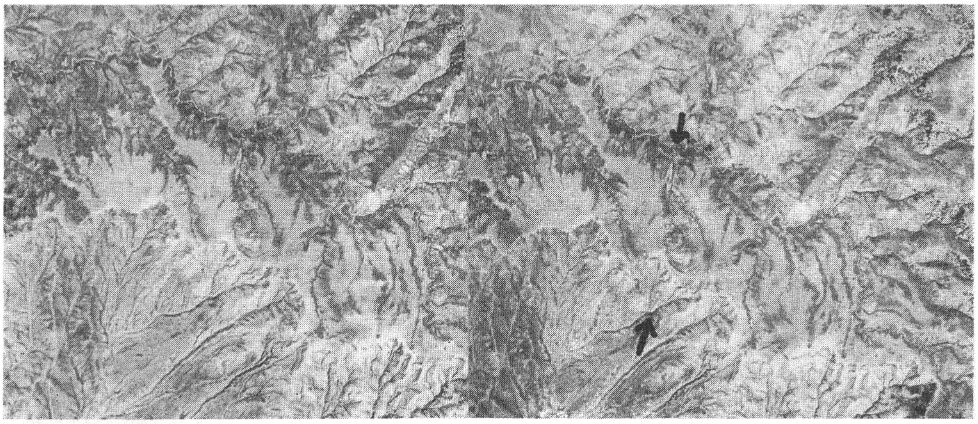

FIG. 2. Stereo pair showing fracture trace seen in cross section in Figure 1. The fracture trace is expressed by drainage alignments in the western Powder River Basin, Wyoming. The fracture trace is indicated by the two arrows.

trace sets and joint sets are not parallel. Similarly Matzke, (1961), in a study of relationships in the Folded Appalachians near State College, Pennsylvania, found that the dominant fracture-trace and joint sets differ in trend by as much as 45 degrees.

On the basis of these limited investigations, it appears that fracture traces and joints are parallel to sub-parallel in areas underlain by flat to gently folded (dips less than 5 degrees) rocks, but that they are not parallel in areas of strongly folded rocks.

RELATIONSHIP TO LITHOLOGY

In a study of a published map of one of the Aleutian Islands of Alaska, Lattman and Segovia (1961) found that fracture-trace orientations differ according to whether the area is underlain by extrusive or intrusive igneous rocks. This difference may be due to contrasting responses of these two rock types to the same deforming force or to contrasting structural histories of the rock bodies. On the other hand, Matzke (1961) found that fracture-trace orientation is constant across several formations of limestone and dolomite in central Pennsylvania.

These results appear to indicate that in a single area, orientation of fracture traces can vary significantly according to major changes in rock type, but that minor lithologic differences may have no marked effect on orientation.

RELATIONSHIP TO GEOLOGIC STRUCTURE

Little detailed work has been done on the relationship of fracture traces to folding. Matzke (1961) found that the regional pattern of fracture-trace orientation is unaffected by strongly compressed anticlines and synclines in the Folded Appalachians, where joint sets are parallel and perpendicular to the strike of bedding. He also noted that, whereas the fracture traces are unrelated to local structures, they lie at a constant angle of 52 degrees with respect to the regional structural trend. In the area of study this trend shifts from N50°E to N62°E, and the predominant fracture-trace direction shifts accordingly to maintain the angular relationship.

Keim (1961) and Lattman and Segovia (1961) found that high-angle normal and lateral faults commonly separate areas of different fracture-trace orientation. Matzke (1961) noted that the Birmingham thrust, a low-angle fault in central Pennsylvania, has no effect on fracture-trace orientation.

These results indicate that high-angle faults may separate crustal blocks within each of which fracture-trace orientations are fairly constant; each block, however, can be distinguished by a different orientation pattern. Low-angle faults may have no effect on fracture-trace patterns.

SUMMARY

The study of fracture traces is only beginning, and meaningful data are sparse and widely scattered. Later work may well contravene some of the generalizations suggested herein; the results summarized below are very tentative:

1. Fracture traces, which probably represent zones of joint (and small fault) concentration, are parallel to the trends of major joint sets in areas of flat to gently dipping rocks but are not parallel to the trends of joint sets in areas of steep (greater than about 5 degrees) dip.
2. Within a small area fracture trace orientations are not the same on rock types that are markedly different. No significant differences in orientation are found on similar lithologic types within a small area.
3. Steeply dipping faults may bound areas of different fracture-trace orientations. The orientations are, however, relatively constant within blocks bounded by such faults. One low-angle fault studied did not separate areas of different fracture-trace orientation.
4. In folded rocks the fracture trace orientations are not affected by local folds but do maintain a constant angular relationship to the regional structural trend.

CONCLUSIONS

From their constant angular relationship to regional structural trend and apparent indifference to local folds it is postulated that fracture traces are related to regional tectonics rather than local structural deformation.

Blocks separated by steeply dipping faults may each undergo a distinct tectonic history which gives rise to fracture trace directions which are constant in each block but perhaps different from block to block.

To explain parallelism and non-parallelism of fracture traces and joints, the following working hypothesis is advanced. In areas of little or no structural deformation most of the joints are parallel to fracture traces because they are the result of the same regional forces which produced the zones of joint concentration which give rise to fracture traces. In strongly folded rocks the local structures give rise to joints not related to the regional pattern. Plots of orientation rosettes of joints in such areas therefore show a non-parallelism between preferred directions of fracture trace and joint concentration.

By mapping fracture traces, which are visible only on aerial photographs, the photogeologist is in a position to make a unique contribution to our knowledge of the fracture pattern of the earth's surface. The greatest need at the present is for detailed information on the origin of fracture traces and possible significance of different types of fracture traces. The major effort now being expended on these features is in careful mapping and supporting field work. From the progress already made, it appears that photogeologic fracture trace mapping is a promising part of photo interpretation.

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