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**Determination of Paleotectonic Principal
Stress Direction, Including Analysis
of Joints by Optical Diffraction**



UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7706

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Stress Direction, Including Analysis
of Joints by Optical Diffraction**

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UNITED STATES DEPARTMENT OF THE INTERIOR
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DETERMINATION OF PALEOTECTONIC PRINCIPAL STRESS DIRECTION, INCLUDING ANALYSIS OF JOINTS BY OPTICAL DIFFRACTION

by

Robert C. Steckley¹

ABSTRACT

A study of joints in Marathon County, Wis., was made to determine the orientation of regional paleotectonic stresses and to develop a method of using optical diffraction analysis (ODA) in studying joint orientations and spacings. Standard geologic and petrofabric techniques employing the use of a geologic compass and a Schmidt net were used in gathering, describing, and reducing joint orientation data.

Analysis of selected outcrops with ODA indicates that ODA can be applied to study both joint orientations and spacings. ODA is shown to be a rapid method that can be used to complement standard petrofabric techniques, especially in the study of joint spacings.

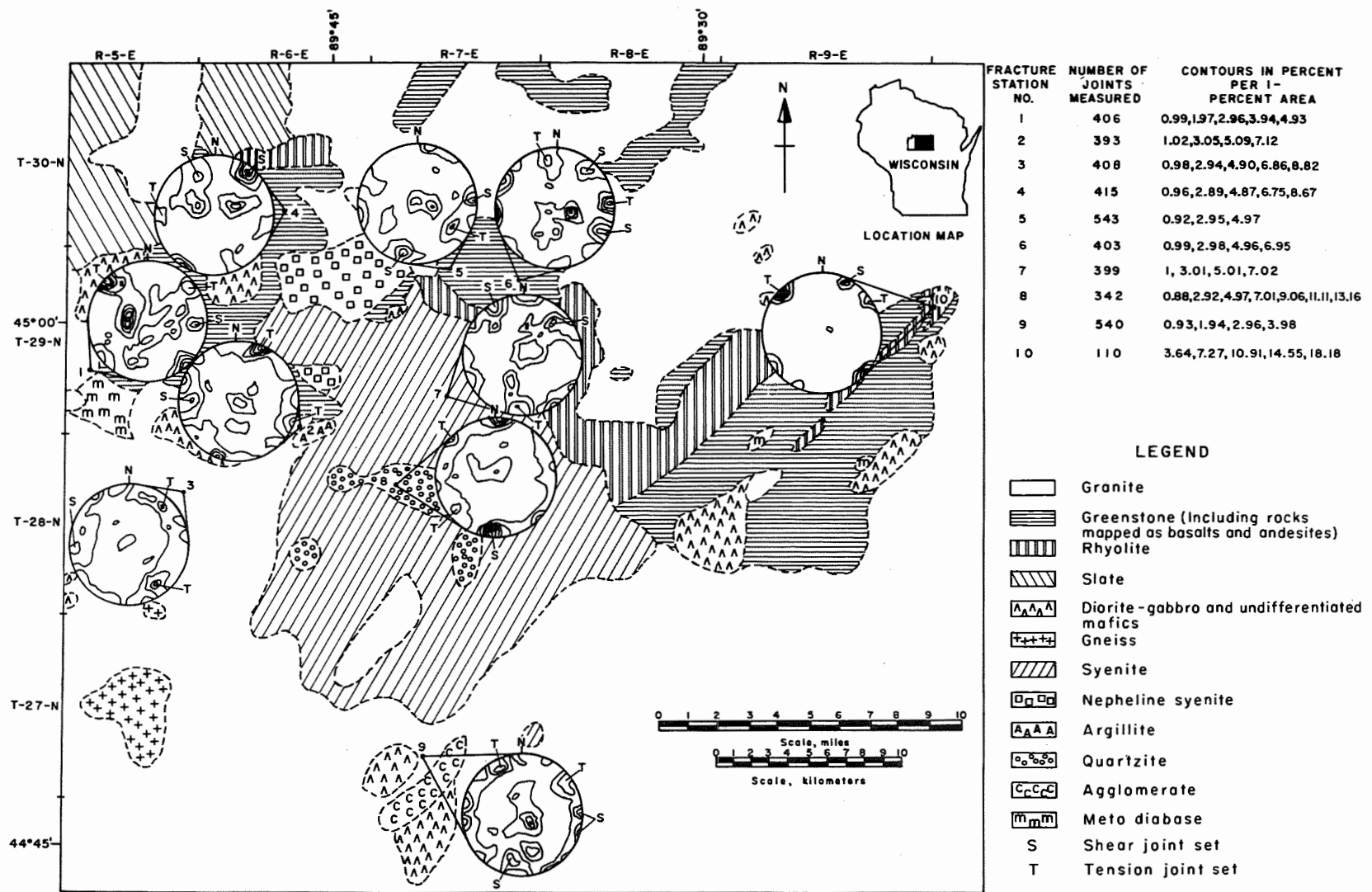
INTRODUCTION

Purpose

The purpose of studying joints was twofold. First, based on the work of Sheldon (23),² Bucher (4), Anderson (1), Hafner (11), Price (20-21), Brace (3), Jaeger (13-14), and others, it is possible to determine the orientation of paleotectonic forces from a study of fractures and fracture symmetry. Studies of similar scope have usually led to inferences on the orientation of paleotectonic forces from analysis of large-scale deformation features such as folds that formed at the same time as the fractures. In these cases, study of the fracture symmetry is not usually essential since examination of the synchronous deformation features yields the same information. Unfortunately large sections of our country contain only small, scattered outcrops, which yield little information on large-scale deformation features. These large-scale features are also hard to observe in underground mines. These areas do, however, lend themselves to a systematic study of joints. Marathon County is thought to be typical of such areas.

¹Geologist.

²Underlined numbers in parentheses refer to items in the list of references at the end of this report.



Geology compiled from Weidman, 1907; Snyder, 1947; Weiss and LaBerge, 1969; and Voight, 1970.

FIGURE 1. - Geologic Map of Central and Eastern Marathon County, Wis., With Lower Hemisphere Equal-Area Contour Diagrams of Poles to Joints.

Secondly, the more we know about the physical properties of rock, the better we will be able to control its use. Earlier Bureau reports show that fractures can be dominant structural features in rocks and can greatly affect rock physical properties such as rock anisotropy and strength (10, 16). Because analysis of the symmetry of fractures in rock has been shown to be an effective way of statistically studying and defining physical anisotropy, it was decided to try to quantify fracturing at some of the outcrops studied. To do this a unique technique of studying joint orientations and densities was developed which employed ODA use (6, 19, 24).

Geologic Setting

A limited number of Precambrian igneous and metamorphic rocks crop out in Marathon County and in part consist of interbedded Archean basic-acid flows and metamorphosed clastic sedimentary rocks (8, 25-28). These rocks are extensively intruded by granite, syenite, and basic rocks of batholithic to dike proportions (fig. 1). Few bedrock exposures exist because most of the area is covered by 1 to 15 feet of glacial till (18). Because outcrops are limited to roadcuts, waterways, and ditches, structural interpretation is rather difficult. Despite the scarcity of exposures, Marathon County is regarded as being structurally complex. Emmons and Snyder (8) concluded that the area has undergone two periods of folding followed by the intrusion of large granitic bodies, and a period of rotational pressure, which caused mild faulting with synchronous dike emplacement in the country rock.

Mesoscopic deformation features (features that range in size from hand sample to large, continuous field exposures) observed at the outcrops studied are joints, faults, calcite and quartz veins, mafic and aplite dikes, and foliation. Joints transect all other observable deformation features (with the possible exception of one fault) and are therefore thought to be the youngest deformation features in the area. Almost all of the joints examined were undeformed planar features. A few joints were found to have curved surfaces coated with a black mineral (possibly hornblende or chlorite). These curved joints are believed to have formed along healed fractures that had formed earlier in the geologic history of the rock and that were reopened during subsequent joint formation. Based on cross-cutting relationships and the apparent lack of movement along joint surfaces, the origin of all open joints is attributed to a single deformation and the joints are believed to be synchronous.

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The guidance of H. J. Pincus, professor of geological sciences, University of Wisconsin-Milwaukee, is gratefully acknowledged. The author is also grateful to the Department of Geological Sciences, University of Wisconsin-Milwaukee for use of its facilities.

ORIENTATION DATA

Discussion

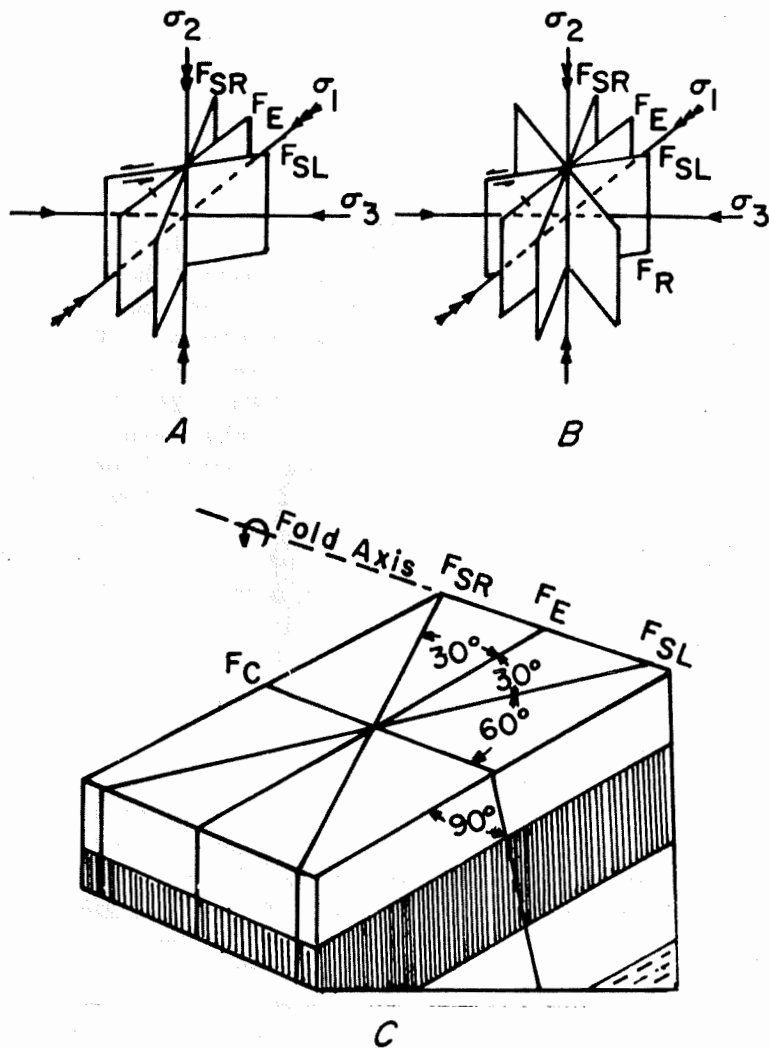
The fundamental principles for making statistical analyses of deformation features in rock (petrofabric analysis) were developed by Bruno Sander (22) and in a publication by Knopf and Ingerson (15). Sander realized that the symmetry of deformation features and the symmetry of the movement creating deformation features are closely related. Sander also realized that the orientation of the stresses that occur in a rock during deformation can be inferred from the symmetry of the deformation features, which in this study are joints.

Hypotheses explaining the relations between the symmetry of joints and stresses are abundant in the geologic literature. Many early hypotheses are now totally or in part disproven as a result of a better understanding of the processes of fracture formation. Improved hypotheses have resulted chiefly from applications of mechanics and well-understood geologic principles. Studies that have contributed to this improvement include those made by Coulomb (in Jaeger (14)), Mohr (in Obert and Duvall (17)), Griffith (in Jaeger (14)), Sheldon (23), Bucher (4), and Price (20-21).

Coulomb (in Jaeger (14)), Mohr (in Obert and Duvall (17)), and Griffith (in Jaeger (14)) indicate in reports on the formation of fractures in brittle materials that an analysis of the symmetry of fracture attitudes can yield information on the orientation of principal stresses during deformation. They state that two planes of shear failure are likely to form in a rock that has undergone nonhydrostatic (triaxial) loading. These planes of failure pass through the axis of the intermediate stress, σ_2 , and make angles of between 0° and 45° with the maximum principal stress, σ_1 , direction.³

Bucher (4) uses this same mechanism in postulating a shear hypothesis of joint formation in brittle rock. Bucher states that conjugate sets of shear joints form so that the direction bisecting their acute angle corresponds to that of the greatest principal axis of compressive stress, and the bisectrix of the obtuse angle parallels the direction of the least stress which, in many cases, represents tensile stress. A similar mechanism explaining the formation of shear joints is presented by Friedman (9) (fig. 2). Tensile stresses can also cause jointing, especially in rocks that are being folded (2, 23). Generally, as a parallel fold develops, tension occurs along the upper surface of an anticline or along the bottom surface of a syncline. This tension

³"If a body is stationary under a system of forces, it is possible to choose at any point three mutually perpendicular planes, intersecting in the point and so oriented that the resultant stresses on the planes are wholly normal stresses or tractions. The three lines along which the planes intersect are known as the principal axes of stress and the stresses acting along them are the principal stresses at the point considered." (12, p. 82.) Because the principal stresses are usually unequal, there exists a maximum principal compressive stress, σ_1 , an intermediate principal compressive stress, σ_2 , and a minimum principal compressive stress, σ_3 .



causes fractures to develop parallel to the axes of the folds (longitudinal joints). Because of extension parallel to the axis of the fold, a second set of fractures is formed at right angles to the fold axes (transverse joint). Tension joints also form in unfolded rocks. Here one set of joints is oriented parallel to the plane containing σ_1 and σ_2 (normal to σ_3) and are considered extension joints; a second set of joints, which forms parallel to the σ_2 - σ_3 plane, are considered relaxation joints that formed upon the release of stored elastic strain energy (9) (that is, tensile fractures formed after the release of σ_1). The formation of shear joints does not preclude the formation of tension joints or vice versa, and previous publications (5, 9) have described the occurrence of both types of joints at one locality.

Joints

Methods

Attitudes of deformation features present at 50 outcrops in the study area were measured. Ten of the largest outcrops were selected for an extensive analysis of joint orienta-

tions and spacings (fig. 1). Selection of these outcrops was based on the size of the outcrop, accessibility, and areal distribution relative to each other. These 10 outcrops are referred to as fracture stations. An average of approximately 400 joint orientations per outcrop were measured at fracture stations 1 through 9. One hundred and ten joints were measured at fracture station 10. Joints that had an exposed surface area of greater than 35 square inches (large enough to be measured with a geologic compass) and that were in place (that is, joint surfaces that had not moved from their original

FIGURE 2. - Idealized Geometric Relationships Between Principal Stresses and Fractures: A, Two Shear Fractures (F_{SL} and F_{SR}) With the Enclosed Extension Fracture (F_E); B, a Relaxation Fracture (F_R) Is Added to the Configuration in A; C, an Additional Extension Fracture (F_C) Is Added to the Geometry in A in Folded Beds Only (9).

position in the outcrop) were measured in selected portions of each outcrop. The portion of the outcrop selected for study was chosen because it appeared to contain joints representative of the entire outcrop.

Classification of Shear and Tension Joints

Two major types of joints are found in the study area: shear joints and tension joints. Wherever possible surface features were used to help distinguish between shear and tension joints. Shear joints are fractures that formed as the result of stresses that tend to shear one part of the rock past an adjacent part. Shear joints were usually found as planar features whose attitudes were not effected by changes in lithology. They tended to cut across foliation, pebbles in conglomerates, etc., without a change in their planar direction. Tension joints are fractures that formed as the result of stresses that tend to pull the rock apart. Some tension joints were found to be irregular, tending to follow minor variations in lithology. A few tension joints also exhibited plumose or feather structures on their surfaces. Many joints displayed no distinctive surface features. These joints were classified as either shear or tension joints on the basis of their symmetry; that is, joint sets forming an acute angle of approximately 60° were inferred to be shear joints.

Joint Orientations

Two of the dominant joint sets at fracture stations 1, 2, 3, 6, 8, 9, and 10 are tensional joint sets. These joint sets are designated by the letter "T" on the fabric diagrams of figure 1. At each of these stations one of the tensional joint sets is believed to have formed parallel to a surface that was normal to the least principal stress, σ_3 , and the second set formed at approximately 90° to the first set. From an examination of only the tension joints, it is equally probable that either joint set was oriented parallel to this surface; therefore, two possible least principal stress directions, σ_3 , and two possible maximum principal stress directions, σ_1 , could have existed during the formation of the tension joints at fracture stations 1, 2, 3, 6, 8, 9, and 10.

A somewhat similar situation exists at fracture stations 4, 5, and 7. At these fracture stations only one set of tension joints is believed present; however, there is no way to tell if the joints were formed parallel or perpendicular to the plane normal to σ_3 . Two possible principal compressive paleotectonic stress directions could also explain the origin of these joints.

An examination of the shear joints at the 10 outcrops resolves this ambiguity in the orientation of σ_1 .

At stations 4, 5, 6, 7, and 9, two sets of shear joints form conjugate pairs. The acute bisectrix of the conjugate pairs parallels σ_1 and the line of intersection parallels σ_2 . A line perpendicular to the plane containing σ_1 and σ_2 parallels σ_3 . For fracture stations 4, 5, 6, 7, and 9, the orientation of the principal paleotectonic stress directions are inferred from the analysis of the conjugate sets of shear joints (table 1). Examination of figure 2

indicates that these principal stress directions were also oriented so that they could account for the tension joints found at these fracture stations.

TABLE 1. - Paleotectonic principal compressive stress directions inferred from the analysis of joint sets at fracture stations 1-10, Marathon County, Wis.

Fracture station ¹	Principal compressive stress		
	Maximum, σ_1	Intermediate, σ_2	Minimum, σ_3
1	4°, N 44° W	83°, S 15° E	4°, N 45° E
2	2°, N 67° W	88°, S 40° E	2°, N 24° E
3	13°, S 47° E	75°, N 82° W	10°, N 51° E
4	13°, N 88° W	71°, S 38° W	11°, N 7° E
5	19°, S 54° E	68°, N 27° W	10°, S 39° W
6	2°, N 15° W	74°, S 73° W	16°, N 75° E
7	13°, S 82° E	68°, S 38° W	18°, N 4° E
8	0°, N 42° W	78°, N 47° E	14°, S 41° W
9	21°, S 47° E	66°, N 21° W	9°, S 46° W
10	2°, N 37° W	82°, S 37° W	7°, N 47° E

¹Orientations are given as plunges and bearings.

An examination of the angular relationship between a single set of shear joints and two sets of tension joints yields the orientation of the paleotectonic principal stress directions at stations 1, 2, 3, 8, and 10. The maximum paleotectonic principal compressive stress direction, σ_1 , should parallel one of the tension joint sets and form an angle of approximately 30° with the set of shear joints. By measuring the angles formed by the set of shear joints and each of the two possible directions of σ_1 inferred from the analysis of the tension joints, it was possible to see which of the possible directions came closer to forming this expected 30° angle. The direction that came closer to forming the 30° angle was considered the direction of the σ_1 that was induced in the rock during joint formation. Table 2 presents the results of these angular measurements, and table 1 contains the inferred principal stress directions during joint formation at each of the fracture stations. Examination of table 2 indicates that the angle between the shear joint set and σ_1 departs considerably from 30° at stations 2 and 8. As shown by DeSitter (5, p. 130), the value for station 2 (16°) is well within the lowest observed limit for this angle (8°). The larger value at station 8 (47°) slightly exceeds the highest theoretical or observed value for this angle (45°). This discrepancy could have occurred if the rock was anisotropic and contained a direction of easiest breakage. It should also be noted that for station 8 the difference between the two possible angles (47° and 51°) appears to be within the range of observational error. However, as stated earlier, the lower value (47°) was picked because it was closer to 30°.

TABLE 2. - Angular relationship between maximum paleotectonic principal compressive stresses (inferred from analysis of tension joints) and the orientation of shear joint sets at fracture stations 1, 2, 3, 8, and 10

Fracture station	Orientation of shear joint set	Orientation of the two possible directions of σ_1 inferred from analysis of tension joints	Angle between the shear joint set (column 2) and the possible direction of σ_1 (column 3)	Angle in column 4 closest to 30°
(1)	(2)	(3)	(4)	(5)
1	N 1° W, 79° SW	4°, N 44° W 4°, N 45° E	34° 54°	34°
2	N 8° E, 68° SE	2°, N 67° W 2°, N 24° E	16° 62°	16°
3	N 8° W, 81° NE	13°, S 47° E 9°, N 50° E	34° 54°	34°
8	N 88° W, 78° NE	0°, N 42° W 14°, S 41° W	47° 51°	47°
10	N 70° W, 83° SW	2°, N 37° W 7°, N 47° E	33° 62°	33°

Further examination of table 1 reveals that σ_1 is consistently oriented in a northwesterly-southeasterly direction. This strong northwesterly trend of σ_1 is graphically represented in the equal area plot of figure 3.

Joint sets that have low angles of dip are represented by central maximums on the fabric diagrams for all of the fracture stations (fig. 2). These joint sets are composed of tension joints. The formation of these tension joints is attributed to the upward expansion of the rock on the relief of load due to the removal by erosion of the former rock cover.

Poles to the sets of joints present at the 10 fracture stations were plotted on the lower hemisphere of a single equal-area net and contoured (fig. 4). From an examination of this diagram, regional trends of joints, represented as maximums on the diagram, were deduced. Based on the mean orientations of the maximums enclosed by the 5.13- and 7.69-percent contours in figure 4, these regional trends have the following approximate orientations:⁴

⁴The joint set orientation list is based on intensities of maximums picked from the joint subfabric diagram. Maximums are listed in order of decreasing intensities.

1. N 40° W, vertical

2. $\left\{ \begin{array}{l} \text{N } 50^{\circ} \text{ E, } 82^{\circ} \text{ SE} \\ \text{N } 5^{\circ} \text{ E, } 85^{\circ} \text{ SE} \\ \text{N } 79^{\circ} \text{ W, } 70^{\circ} \text{ NE} \\ \text{N } 15^{\circ} \text{ W, } 20^{\circ} \text{ SW} \end{array} \right.$

Maximums representing these joint sets appear in at least one girdle in the fabric diagram. A broken peripheral girdle contains the N 40° W, vertical; N 79° W, 70° NE; N 50° E, 82° SE; and N 5° E, 85° SE maximums. A second girdle, which is a broken band, includes the N 15° W, 20° SW; N 40° W, vertical; and N 79° W, 70° NE maximums.

Relation of the Inferred Paleotectonic Maximum Principal Compressive Stress to Regional Structural Features

As stated in a previous section, joints are the youngest deformation features found in the study area. Therefore, the maximum principal compressive stress in the rock at the time of joint formation is considered the most recent maximum principal compressive stress to exist in the rock during formation of the deformation features. Earlier deformation features may or may not have formed as a result of these stresses. If earlier deformation did take place in association with this maximum principal stress, the orientation of these features should be geometrically related to the orientation of the stress. An examination of the angular relationships between the older deformation features and the inferred σ_1 was therefore made.

Mapping by Weiss and LaBerge (28) reveals a northeast trend of the rhyolite and greenstone bodies in the eastern part of Marathon County. This trend is clearly evident at fracture station 10 where foliation, faults, mafic dikes,

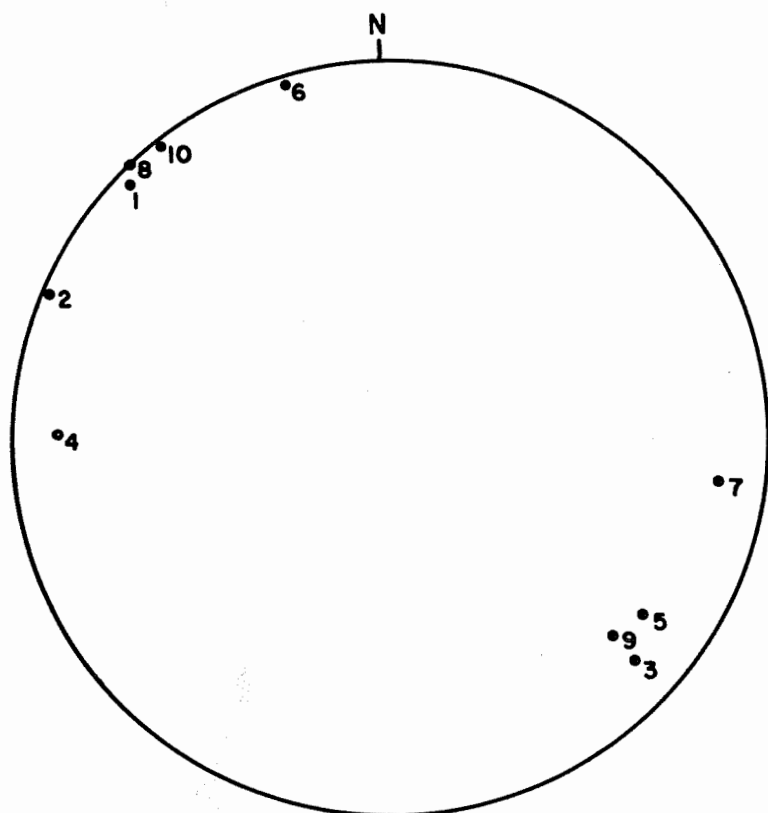


FIGURE 3. - Lower Hemisphere Equal-Area Plot of the Maximum Principal Paleotectonic Stress Directions, σ_1 , Determined From Analysis of Joint Symmetry at Fracture Stations 1-10. Data obtained from table 1.

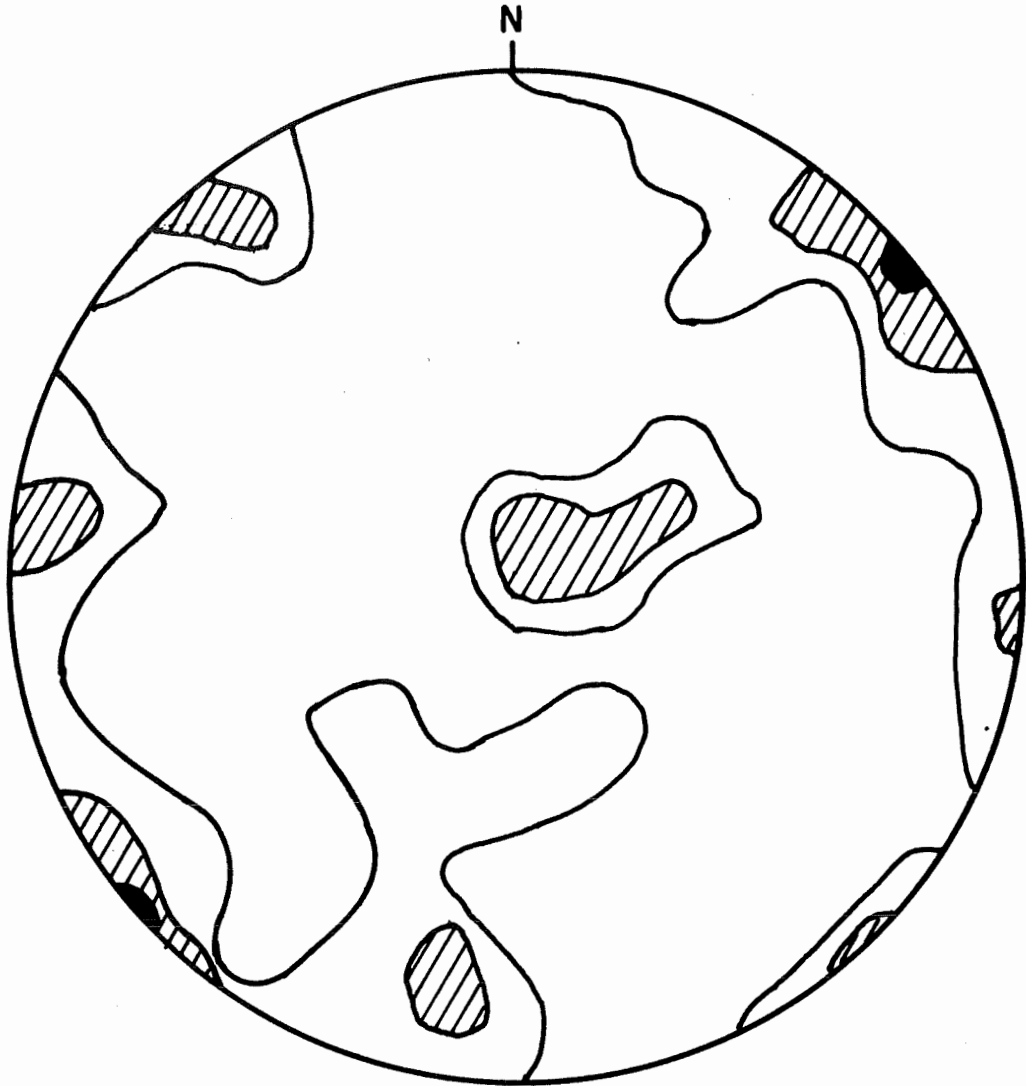


FIGURE 4. - Lower Hemisphere, Equal-Area Contour Diagram of Poles to Joint Sets at Fracture Stations 1-10. Joint set data obtained from figure 2.

and quartz veins all trend N 40° to 50° E, and have nearly vertical dips. Further evidence of this structural trend is found as northeasterly oriented mafic dikes at fracture stations 1 and 9; northeasterly oriented aplite dikes and/or quartz veins, at fracture stations 2, 3, and 9; northeasterly foliation, at stations 1, 2, and 3; and northeasterly trending shear zones, at stations 1, 3, and 4. Additional evidence for the northeasterly trend can be found at many of the smaller outcrops in the area.

The orientation of the maximum paleotectonic principal compressive stress, as deduced from the analysis of jointing, is northwest-southeast, approximately perpendicular to the northeast-southwest structural trend. The northeast-southwest trend of the rock bodies may have been formed at the time that this principal stress prevailed; that is, the trend of the rock bodies is

due to folding along northeastern trending fold axes. Likewise the foliation oriented northeast-southwest may have been formed by a compression oriented normal to it--northwest-southeast. This foliation, however, may also be a result of shearing in a northeast-southwest direction. Since dikes tend to form parallel to the maximum principal compressive stress prevalent at the time of their formation (1), it would not appear that the northwest-southeast maximum principal compressive stress is related to the northeast-southwest structural trend of the dikes.

Because all of the early deformation features cannot be related to the principal stress direction prevailing during joint formation, it is possible that the area has undergone more than a single period of deformation.

The geologic origin and the geologic time of occurrence of the forces inducing the northwest-southeast oriented principal stress into the rock is not known. Besides the relative cross-cutting relationships of the deformation features, no data were obtained concerning this matter. However, mechanisms that could have provided these forces existed during the Paleozoic era when several uplifts occurred in the central Wisconsin area. These uplifts produced a pronounced dome by Mississippian time (7), and were probably capable of producing jointing in Marathon County.

OPTICAL DIFFRACTION ANALYSIS

The previous sections presented data on the orientation of joints at the 10 fracture stations. The methods used to collect, prepare, evaluate, and present these data are slow (approximately 20 hours per outcrop) and yield no information on spacings between joints. Since knowledge of the spacing between joints may be essential in designing excavations in rock, a method for acquiring data on both orientation and spacing of joints is a desirable tool. Because ODA is a relatively fast method (approximately 8 hours per outcrop) that yields both orientation and spacing data, it was used in examining the jointing at some of the fracture stations in this study. The purpose of using ODA was to investigate its potential and limitations in handling joint fabric studies.

The optical principles on which ODA is based, the equipment used to perform ODA, and practical applications of ODA to geologic problems have been discussed by many authors: Dobrin, Ingalls, and Long (6), Shulman (24) and Pincus (19), to name a few. The basic technique used in ODA is spectral analysis by diffraction (19). Coherent, monochromatic light is passed through a two-dimensional diffraction grating (in this case, a reduced transparency of a photograph of an outcrop containing joints) of unknown spatial frequency. In analytical terms, the resulting diffraction pattern is a two-dimensional Fourier amplitude transform of the input (19). The transform is a statistical representation of two-dimensional spacings and orientations occurring in the original data (the photograph).

Joint orientations at fracture stations 5, 6, 7, and 9 were studied by ODA techniques. These stations were selected for ODA studies because photographic negatives of these stations were of good quality (high contrast and

high resolution) for use as ODA inputs. After photographs were taken of the joint systems at each fracture station, the orientations of selected joints were measured. These orientations were recorded on the photographs. Because ODA operates with two-dimensional inputs and joints are three-dimensional geologic features, certain conditions and assumptions were necessary in this type of application. These conditions and assumptions are described, as needed, in the text.

Two geologic inputs, consisting of photographic negatives of the same portion of each outcrop, were analyzed per fracture station. The two geologic inputs were of different sizes. One input was a 35- by 22-millimeter negative (approximately 1/275 the size of the outcrop); and the other was a 2- by 1-millimeter negative (approximately 1/4800 the size of the outcrop). The joints analyzed had a spatial frequency⁵ between 50 and four lines per millimeter on both sizes of input (19). The larger input yielded information on the orientation and densities of joints with high spatial frequencies (between 0 to 6 joints per 5 feet of outcrop); the smaller input yielded information on joints with low spatial frequencies (between 0 to 5 joints per 40 feet of outcrop).

The transform produced for a given input was initially examined on a closed circuit television for shape, size, and intensity in the Optical Data Processing lab of the University of Wisconsin-Milwaukee. Photographs of the transform were later taken to provide a permanent record and were used for further examination of the transform.

Figure 5A shows the bedrock exposure at fracture station 5 used to generate its transform (fig. 5B).

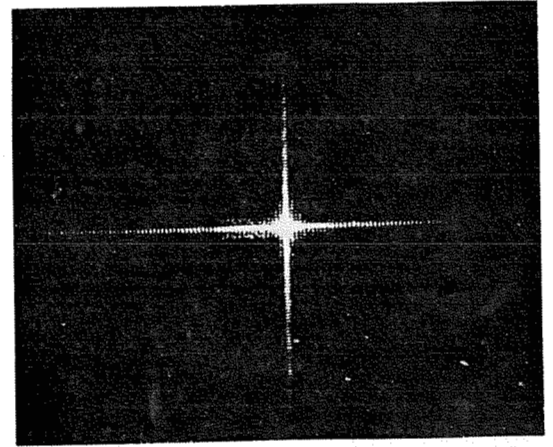
The transform in figure 5B was rotated 90° from its original orientation. The 90° rotation aligns elongations in the transform parallel to the linear input elements generating them (19). These elongations, and the joint sets inferred to have generated them, are presented in figure 5C. The cross that appears in the transform, and which is represented by the solid lines in figure 5B, was caused by a rectangular aperture used in the ODA.

Directional filtering and analysis of the transform and reconstructed images on a closed circuit television screen aided in inferring joint orientations from elongations in the transform (6, 19, 24). By blocking (filtering) out parts of the diffraction pattern, a filtered, reconstructed image was produced (figs. 5E and 5F). By rotating the position of the filter, joint sets could be removed (filtered) in the reconstructed image that appeared on the closed circuit television screen. Comparing the reconstructed image with the original input delineated specific joint sets. Because the orientation of selected joints were recorded on a photographic print of the input, the

⁵Spatial frequency refers to the spacing between elements, which in this case are joints. A spatial frequency between 50 and four lines per millimeter indicates that the lines are spaced from 0.02 to 0.25 millimeter apart. Closely spaced lines (0.02 millimeter) have a high spatial frequency; widely spaced lines (0.25 millimeter) have a low spatial frequency.

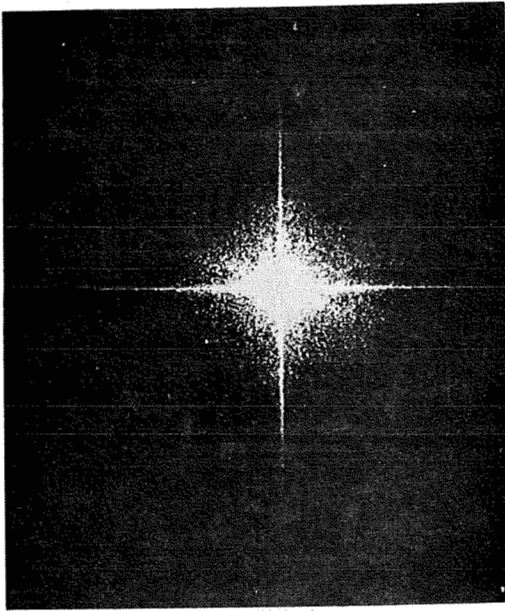


A



0 1 2 3 4 5 6

D

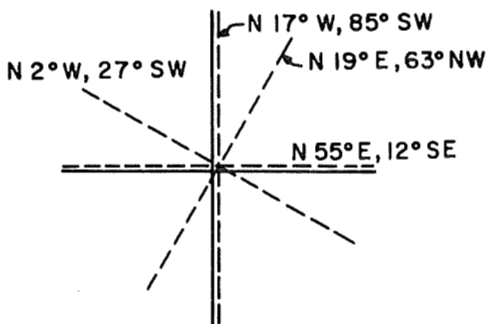


0 1 2 3 4 5 6

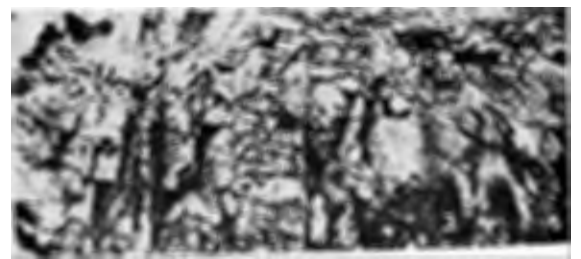
B



E



C



F

FIGURE 5. - ODA Analysis of Fracture Station 5: *A*, Bedrock Exposure; *B*, Transform Generated by 35- by 22-Millimeter Input; *C*, Elongations Found in Transform With Joint Set Orientations They Are Inferred To Represent; *D*, Calibration Transform of Graph Paper Which Contained 10 Lines per Inch; *E*, Transform With Filters in Place; *F*, Reconstructed Filtered Image of Bedrock Exposure.

orientation of the delineated joint sets could be inferred by comparing the filtered image with the photographic print. For example, if a particular joint whose attitude was measured and recorded in the field was part of a filtered out joint set, the entire joint set was inferred to have an orientation the same as, or similar to, that of the single joint. In this manner, orientations were estimated of all the joint sets occurring in the outcrop, and their corresponding directional positions and intensities in the diffraction pattern were recorded. With a combination of directional filtering and closed circuit television, some elongations barely visible in photographs of the transforms were determined to be present. Directional filtering also aided in detecting widely spaced or poorly formed joint sets by filtering out the dominant joint sets that masked the weaker sets.

Figure 5D is a calibration transform. This transform was produced by a calibration input, which was a photographic negative of a sheet of graph paper that contained 10 lines per inch (calibration input was 1/50 the size of the original sheet of graph paper). The calibration transform was photographed with an optical setup identical to that used for the geologic transforms. The scale of the calibration transform has a known relation to the scale of the geologic transforms, and it was used to determine spatial frequencies of joints represented in the geologic transforms. Scales derived from the calibration transform are presented under the fracture station transforms (fig. 5B). The scale relates radial distances from the center of the geologic transform to spatial frequencies of joints.

Table 3 is a compilation of the orientations and spatial frequencies inferred from ODA to be present at fracture stations 5, 6, 7, and 9. For each station, all of the joint set orientations inferred from ODA were equated to the closest joint set orientation obtained from the fabric diagrams of figure 2. This procedure was possible because the orientations of the joint sets inferred from ODA were found to plot within maximums of the fabric diagrams in figure 1. The orientations obtained from ODA were equated to those in figure 1 in order that a comparison could easily be made between the two. The 35- by 22-millimeter input and transform of fracture station 5 are presented as illustrations of ODA techniques used to collect the data listed in table 3.

Analysis of the transforms generated by the 35- by 22-millimeter inputs indicates that all joints present at the four stations studied have a spatial frequency between zero to 10 joints per 5 feet of outcrop. The 2- by 1-millimeter input yielded a range of spatial frequencies between zero and six joints per 40 feet of outcrop. The frequencies provided by the 35- by 22-millimeter inputs fall within the range of frequencies obtained from the 2- by 1-millimeter inputs.

The spatial frequencies of joint sets inferred from measurements made in the field and the spatial frequencies obtained from analyses of the transforms showed a close correlation. Field measurements indicate that at stations 5, 6, 7, and 9 between five to 10 joints are present per square yard of outcrop. By assuming that all of these joints transect a line contained in a given square yard of rock, and which is 1 yard in length, a spatial frequency of

8.33 to 16.67 joints per 5 feet of outcrop is obtained. These joints belong to many sets, and the spatial frequency determined for them as a whole should be higher than that determined for any one set. Therefore, the spatial frequencies of individual sets, determined with ODA (zero to six joints per 5 feet of outcrop), is consistent with the higher value of spatial frequencies determined by measurement in the field (8.33 to 16.67 joints per 5 feet of outcrop).

TABLE 3. - Joint set orientations and spatial frequencies, inferred from optical diffraction analysis of inputs from fracture stations 5, 6, 7, and 9

35- by 22-millimeter inputs		2- by 1-millimeter inputs	
Strike and dip of joint set	Spatial frequency (number of joints per 5 feet of outcrop)	Strike and dip of joint set	Spatial frequency (number of joints per 40 feet of outcrop)
FRACTURE STATION 5			
N 2° W, 27° SW	0-6	N 2° W, 27° SW	0-4
N 17° W, 85° SW	0-5	N 17° W, 85° SW	0-5
N 19° E, 63° NW	0-3	N 19° E, 63° NE	0-5
N 55° E, 12° SE	0-6	N 55° E, 12° SE	0-4
FRACTURE STATION 6			
N 4° E, 26° NW	0-10	N 4° E, 26° NW	0-5
N 79° E, 75° SE	0-8	N 79° E, 79° SE	0-5
FRACTURE STATION 7			
N 26° W, 89° NE	0-4	N 26° W, 89° NE	0-6
N 9° W, 22° SW	0-5	N 9° W, 22° SW	0-6
N 54° W, 5° SW	0-5	N 45° E, 9° SE	0-6
N 45° E, 59° SE	0-6		
FRACTURE STATION 9			
N 38° W, 78° SW	0-6	N 38° W, 78° SW	0-5
N 59° E, 82° SE	0-3	N 59° E, 82° SE	0-5
N 44° E, 24° NW	0-4	N 80° W, 70° NE	0-5

Orientations of joint sets inferred from analyses with ODA also compared favorably with orientations determined from the field study. All of the major joint sets, except those forming small angles with the surface of the outcrop, were detected by ODA. Since the joint sets forming small angles with the surface of the outcrop are oriented almost parallel to the plane of the input (the picture taken in the field); they appear as flat planar surfaces on the input and not as lineaments. The basic techniques used in ODA are dependent on the existence of lineaments in the input to act as a diffraction grating. If a given joint set is present as a planar surface and not a lineament, it will not be detected. In other words, the joints must intersect the rock face at a high angle if they are to be recorded on the input photograph and studied with ODA.

SUMMARY AND CONCLUSIONS

Based on an analysis of joint orientations at 10 fracture stations, a northwest-southeast regional paleotectonic maximum principal compressive stress, σ_1 , is inferred to have existed in central and eastern Marathon County, Wis., during joint formation. Joints are the youngest deformation features found in the study area; therefore, the σ_1 in the rock at the time of joint formation is considered the most recent maximum principal stress to have existed in the rock during the formation of deformation features. However, because it is impossible to relate genetically the northwest-southeast σ_1 with all of the older deformation features, it is assumed that the area has undergone more than one period of deformation.

Based on examinations of outcrops at four fracture stations using ODA it was shown that ODA is an effective tool for analyzing orientations and spatial frequencies of joints in exposures of rock. Similar analyses can be extended to include characterization and quantification of joints and joint data with ODA. Although this study made no attempt to determine regional paleotectonic principal stress directions based on ODA data such a determination is certainly not beyond the capabilities of this method. This observation does not imply that ODA should be considered a tool that will replace traditional methods of collecting joint orientation data; however, when it is used in conjunction with these field methods, it gives the investigator accurate orientation and spacing data quickly. ODA also permits an examination of the trends and spacings (spatial frequencies) of other geologic and mining features. This application could include studying macroscopic or regional features such as folds or faults from areal photographs; mesoscopic blast damage on quarry walls, from 35-millimeter slides; and microscopic features such as microfractures from photomicrographs. Additional work can also be performed with ODA to refine the techniques and maximize the amount and quality of the data obtained.

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