PETROFABRICS AT THE FALLS OF THE STURGEON, DICKINSON COUNTY, MICHIGAN

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PETROFABRICS AT THE FALLS OF THE STURGEON, DICKINSON COUNTY, MICHIGAN

By

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ABSTRACT

This petrofabric study of the Sturgeon quartzite was made in the immediate vicinity of the Falls of the Sturgeon. Near the Falls of the Sturgeon are two faults with horizontal components of movement. The object of the study was to determine if the faulting, or forces responsible for the faulting, had influenced the fabric of the adjacent rocks, and to determine what effect that influence had if it was detectable.

Samples were taken at graduated distances from the two faults and the standard petrofabric analysis was made.

It was discovered that the fabric of the rocks farthest from the faults has characteristics of a B-tectonite. Several fabric diagrams show girdles, a regional fabric pattern. Higgins (1945) found horizontal A-C girdles in his fabric diagrams, but the girdles in the sample area are not horizontal. Many of the fabric diagrams show preferred orientation patterns that are too complex to be easily interpreted. The fabric of the rocks closest to the faults has characteristics of an S-tectonite. The S-tectonite fabric appears to be superimposed on the B-tectonite fabric.

It is postulated that the girdle fabrics are the result of regional folding and deformation and that the S-tectonite fabrics are the result of later forces which caused the faults.

Independent evidence of two periods of deformation was found in the petrographic and petrologic study of the samples.

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INTRODUCTION

Location of Sample Area

The Falls of the Sturgeon are about 2 miles northeast of Loretto, a small town 12 miles east of Iron Mountian on United States Highway No. 2, in southern Dickinson County, Michigan. The sample area is in the eastern half of section 8, T. 39 N., R. 28 W. It is just inside the northern boundary of the Menominee iron-bearing district, a trough of Huronian (Animikie) meta-sediments.

Purpose

The intention of this project was to make a petrofabric study of a small area with already well-known structural features, such as the area shown in the pocket map. It was hoped that by taking samples at graduated distances from structural features, such as faults, it might be possible to determine what effect the faulting, or the forces that cuased the faulting, have had on the present fabric of the surrounding rock. Even if the study did not reveal much about the effect of the faulting, it was hoped

that some knowledge of the number and types of deformative forces exerted on the area would be gained.

Methods

Two sample traverses were made (Pocket Map). The northernmost crosses both faults in the map area and is partly in the basal and partly in the upper Sturgeon quartzite. The southern series of samples crosses only the western fault and is entirely in the upper Sturgeon quartzite.

For each sample a plane was found on which it was possible to determine accurately the strike and dip. The orientation and the sample number were marked on the rock while the rock was in place. The sample was then detached and collected.

Three slides were cut from samples 98, 96 and 95. Two slides were cut from each of the other samples.

The orientations of 200 to 300 c-axes of quartz crystals were determined on each slide, using a Leitz microscope and a 4-axis Universal stage. The plotting was done on the lower hemisphere of a "Schmidt" equal-area net. The concentrations of the c-axes were determined by standard center and peripheral counters of 1.0 cm radius. The counting grid had distances of 1.0 cm between intersections.

The largest quartz crystals were marked separately from the smallest crystals in plotting the diagrams to see if there is a difference in the preferred orientation of the two. There is no difference. All sizes of quartz crystals have the same preferred orientation in each diagram.

It was not possible with the procedures used to determine which flakes of mica were sericite and which muscovite in the thin sections. It is assumed that both varieties are present. Sericite is used to mean the finer-grained mica.

GEOLOGY

Geology of the Surrounding Area

Stratigraphy

Directly to the north of the sample area and within section 8 is a complex of Archean gneiss and granite. The southern edge of the Archean complex extends to the northwest and to the east of the sample area.

The sample area is at the northern limit of a belt of Lower Huronian (Animikie series, Chocolay group) sediments including the Fern Creek formation, the Sturgeon quartzite and the younger Randville dolomite. The belt of Lower Huronian sediments follows the southern edge of the Archean granite and gneiss mass. The Sturgeon quartzite, the only formation within the sample area, averages about 1,000 feet in thickness.

To the south is the Upper Huronian (Animikie series, Baraga group) Michigamme slate. The Sturgeon quartzite, Randville dolomite, Middle Huronian (Animikie series, Menominee group) Vulcan iron-formation and Michigamme slate appear in two northwest-striking belts faulted into their present place.

Still farther to the south are the greenstones of the Quinnesec formation (altered basaltic lava flows and pyroclastics) and granitic rocks. (See Dutton, 1958; Pettijohn, 1943.)

Structure and Structural History

The Huronian (Animikie) sediments form a tongue between the Archean granites and gneisses to the north and the volcanic rocks to the south.

The trough has three major faults, all striking northwest. Two are on the north edges of belts of Lower, Middle and Upper Huronian sediments within the trough, and one separates the Huronian rocks from the volcanic rocks on the south flank of the trough.

The forces responsible for the trough and the three major faults within the trough were probably approximately north-south compressional forces. (See Dutton, 1958; Higgins, 1947; Pettijohn, 1943.)

All the formations within the Huronian trough either dip steeply to the south or are overturned and dip to the north.

According to Higgins (1945) there have been two deformations in the area:

> The earliest post-Archean deformation in the area is recorded in the folded and upturned position of the Lower Huronian strata. These strata were folded into a monocline which faced southwest along a front extending at least sixteen miles northwest from section 9, T. 39 N., R. 28 W. The consistent strike of the quartzite indicates that the front of the folded structure was very straight.
>
> Subsequently, the area has been intensely faulted. Faults are the tear type***The strikes of these faults are remarkably consistent, ranging between N. 43° E. and N. 85° E.

Geology of the Sample Area

The geology of the sample area can be best understood by referring to the map of the sample area.

All strata are overturned and dip 60°-80° NE. Ripple marks and cross bedding are obvious and common and it is easy to determine the top of a bed. The only formation in the sample area is the Lower Huronian Sturgeon quartzite.

The basal beds of the Sturgeon quartzite, however, are somewhat different in appearance, texture and composition from the upper beds. The basal beds have a greenish color when seen in the field and contain a larger percentage of sericite and muscovite than the upper beds of the Sturgeon quartzite. The amount of muscovite and sericite ranges from 7 percent to 20 percent in the basal beds. In samples with the most sericite and muscovite there is a megascopically observed tendency to develop schistosity. The orientation of the schistosity could not be measured because of its indefiniteness and very poor megascopic development. Under a microscope the alignment of sericite and muscovite is obvious.

The upper beds of the Sturgeon quartzite are usually white, or reddish white where there is some hematite which acts as pigment, and are extremely tough vitreous quartzite. The amount of sericite is small, ranging from less than 1 percent to about 7 percent. There is no megascopic schistosity.

Two metadiabase dikes are in the sample area. Each follows a fault. In some exposures the metadiabase is deeply weathered. It appears to have been sheared.

Two prominent jointing directions can be seen along the access road of the map area. One has a strike of N. 30°-40° E. and a dip of 80°-85° SE.; the other has a strike of N. 70°-80° W. and a dip of 40°-45° NE.

The dips of the fault planes is not known as the fault planes cannot be observed in the sample area or the immediately surrounding area.

In Higgins' (1945) study of the structure of the Pine Creek area, he mentions the two faults in the sample area. The relative horizontal movement along the fault planes is shown on the map. According to Higgins the southeast block of the western fault moved 100 feet northeast, and the southeast block of the eastern fault moved 330 feet northeast.

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PETROLOGY AND PETROGRAPHY OF SAMPLES

Samples of the Southern Traverse

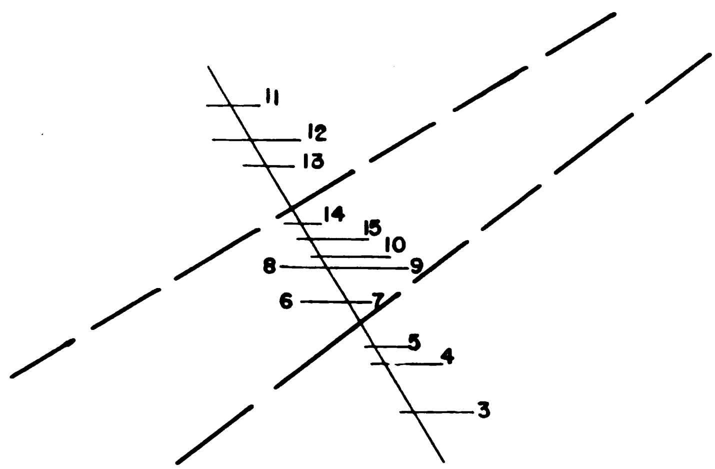
Sample 98.--Sample 98 contains very little sericite, 1 to 2 percent, but what is present has a definite planar orientation. In addition to the quartz and sericite there is hematite dust, a few grains of water-worn rounded zircon and some water-worn topaz. At least 98 percent of the rock is quartz. The quartz shows extensive fracturing and undulatory extinction. There are quartz crystals with gas bubbles and liquid inclusions and also quartz crystals that are corroded. The corroded crystals show undulatory extinction and slight fracturing.

Sample 96.--Less than 1/2 percent of the total volume of the rock is sericite. A few scattered grains of zircon and hematite dust are present.

The hematite dust is arranged in planes within the quartz crystals. The planes cross crystal boundaries without distortion or offset. The quartz is recrystallized, and has an annealed texture. The hematite planes are not completely parallel to each other, but may vary from their average direction 5 to 7 degrees. A few large quartz crystals, porphyroblasts, are isolated among much smaller quartz crystals. The porphyroblasts have curved planes of hematite inclusions, or helicitic texture.

DIAGRAM OF DISTANCES OF SAMPLES FROM FAULTS

NORTHERN TRAVERSE



SOUTHERN TRAVERSE

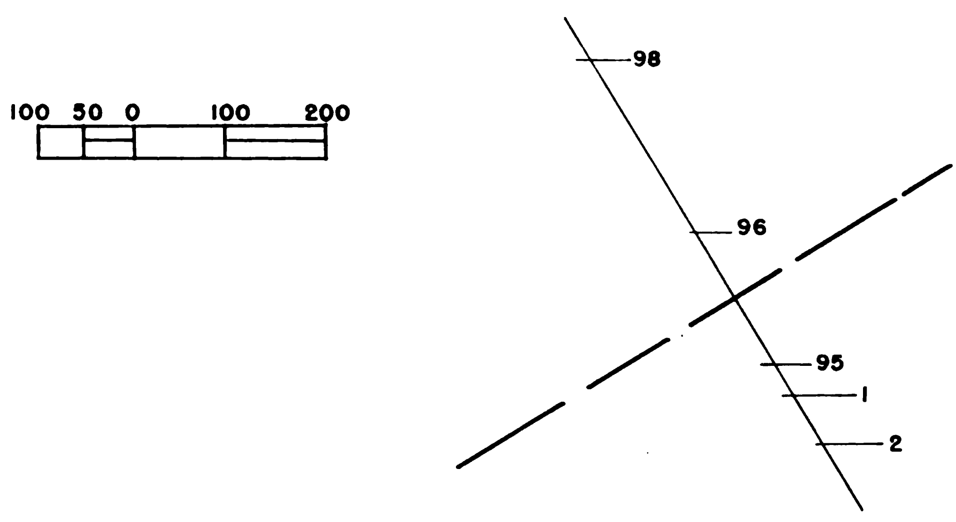


Figure 1.

Some of the larger quartz crystals are strained and fractured. In the largest crystals there is extreme undulatory extinction. There appears to be a definite plane of elongation of the larger quartz crystals, which parallels the orientation of the few sericite crystals. This plane is not the same as the one including the hematite dust. There appears to be an acute angle of about 25° between them.

From the helicitic texture one can deduce that at least some crystals were rotated during their growth in the metamorphic fabric and that there was paratectonic crystallization. The hematite inclusions that do not occur in rotated porphyroblasts, but cut straight across crystal boundaries, are perhaps in post-tectonically formed crystals. These crystals show little strain, undulatory extinction or fracture and occur in groups showing annealed texture with no signs of granulation about the boundaries of a crystal.

The difference in orientation between the plane of hematite dust and the plane of elongated quartz and sericite can be explained by internal rotation, or multiple sets of s planes. The author assumes that the plane of hematite inclusions represents an original s plane of the fabric, and that the plane of the elongated quartz crystals and sericite represents a present s plane. The present s plane, or rather the components of the rock which make the s plane noticeable, once favored the expression of the hematite dust plane, but have now been rotated to a new position. The plane of hematite dust might be called a relict s plane, or perhaps part of a relict fabric.

It is not necessary to explain the change in orientation by rotation. The same change could be effected by recrystallization of quartz and mica, the present direction of elongation being a favorable growth direction.

Sample 95.--Sample 95 is similar to sample 98. It need not be given separate attention.

Sample 1.--Sericite is less than 1 percent of the total volume of the rock. The quartz crystals are small. Their greatest length is from 0.05 mm to 0.10 mm in the plane of the thin section. A few scattered hematite grains are present.

Sample 2.--The quartz crystals show undulatory extinction and some fracturing. The smallest crystals are less than 0.10 mm in their greatest length and the largest are more than 1.00 mm. The rock has less than 1 percent sericite. Some of the sericite has formed in cracks in the quartz crystals and is parallel in elongation to the cracks. There are also quartz crystals that are included within larger quartz crystals of different optical orientation. The sericite in the cracks of the quartz crystals is of para-tectonic or post-tectonic growth.

Since most secondary growth of quartz is in optical continuity with the original grain, there must be some particular reason why it is not in this sample. The "original grain" in this sample is probably not an original detrital grain, since it is idioblastic. There may have been two periods of deformation and crystal growth. The first produced the included quartz crystals, which perhaps grew in optical continuity with the original detrital quartz. The second period produced an additional growth of quartz of which the optical orientation was controlled by the forces exerted during the second deformation. The forces were different from the forces of the first deformation.

Samples of the Northern Traverse

Samples in the basal Sturgeon quartzite

Sample 12.--Sericite and muscovite are approximately 8 percent of the total volume of the rock. The sericite and muscovite form elongated lens-shaped patches that appear to have a consistent orientation. The quartz crystals are small. They range from 0.05 mm to 0.50 mm in length in the plane of the thin section.

Sample 11.--Sericite and muscovite are about 7 to 8 percent of the total volume of the rock and form a sort of matrix for the quartz crystals. The quartz crystals range in length from 0.05 mm to 0.50 mm. Some crystals have gas or liquid inclusions and some show what may be Böhm striations. The quartz crystals appear to be thoroughly strained.

This is the only sample which includes any feldspar. A few fragments of microcline and orthoclase are in the finer-grained parts of the rock. Since sample 11 is the sample closest to the base of the Sturgeon quartzite and to the Fern Creek formation below the Sturgeon quartzite, perhaps the feldspar is an indication of the changing composition of the quartzite as it grades into the arkosite and greywacke of the Fern Creek formation.

The most interesting feature of this sample is a small quartz vein which can be seen megascopically on the sample and on both thin sections cut from the sample. The vein strikes N. 45° E. and dips 55° SE. The quartz crystals in the vein are large and are fractured and show undulatory extinction. The width of the vein is 0.50 cm and the walls are sharply defined and very straight.

Since the quartz crystals show evidence of strain and deformation, there must have been deformation after the quartz vein was emplaced.

Sample 13.—The greatest lengths of the quartz crystals range from 0.05 mm to 5.00 mm in the sample. Many of the large crystals show undulatory extinction, and a few show fractures. The sericite and muscovite, which are 7 to 8 percent of the total volume of the rock, have a planar orientation which is easily seen under the microscope.

Sample 9.--Sericite and muscovite occur in large elongated lens-like patches and make up 10 to 15 percent of the total volume of the rock. The lenses have a definite planar orientation. The quartz crystals range in length from 0.05 mm to over 1.00 mm. The larger quartz crystals have very marked undulatory extinction.

Sample 7.--About 20 percent of the rock by volume is sericite and muscovite. The mica forms a sort of matrix around the quartz crystals. Most of the quartz crystals are of approximately the same size, around 0.50 mm. The quartz shows strain and fracture. The mica and the quartz are aligned in the same planar orientation.

Some of the quartz crystals have inclusions such as patches of smaller-sized quartz crystals and a few include zircon crystals. The inclusions are again an indication of two cycles of crystal growth. The small included quartz crystals are idioblastic and certainly not detrital quartz.

Samples in the Sturgeon quartzite

Sample 14.--The quartz crystals range in length from 0.05 mm to 0.50 mm in the plane of the thin section. The sericite, 5 to 7 percent of the total volume of the rock, has a definite planar orientation.

Sample 15.--There are some extremely large quartz crystals showing fractures and undulatory extinction. There are also areas of very small quartz crystals. Sericite is about 1 to 2 percent of the total volume of the rock.

Sample 10.--The sample is very similar to sample 15. Some inclusions of sericite occur in large quartz crystals. The quartz crystals have little undulatory extinction and no fracturing.

Sample 8.--Some quartz crystals are very large, over 5.00 mm. The large crystals show some fracturing and undulatory extinction. Some quartz crystals are inclusions within larger quartz crystals, as in sample 2. Sericite is 3 to 4 percent of the rock and is often segregated in patches free of quartz crystals. No planar orientation is visible under the microscope.

Sample 6.--The rock contains 2 to 3 percent sericite. Quartz crystals range in length from 0.05 mm to 1.00 mm and are elongated in a definite direction.

Sample 5.--Some quartz crystals are greater in length than 5.00 mm, but there are also the usual small quartz crystals of 0.05 mm to 0.10 mm. The sample has some tendency toward foliation. The large crystals and small crystals are in fairly distinct parallel zones. Zones of 5 to 6 percent sericite are present. In the other zones about 1 percent of the rock volume is sericite.

<u>Samples 4 and 3</u>.--Both samples are similar to sample 1 except that they have no hematite.

<u>Samples 16 and 17</u>.--Both samples are taken from metadiabase dikes. The rocks appear to have been sheared, and perhaps dynamically metamorphosed. The minerals present are biotite, quartz (less than 5 percent), hematite, actinolite, hornblende and chlorite.

The mineral assemblage, the absence of feldspar and the appearance of the rock in the thin sections strongly suggest low grade metamorphism from a normal mafic igneous dike rock. The metamorphic facies is the Greenschist facies, and probably the Biotite-chlorite subfacies.

Remarks

No detrital quartz grains are apparent, all quartz being crystalloblastic. The zircon and topaz, and perhaps the feldspar of sample 11, are original detrital grains. Higgins (1945) felt that the larger-sized quartz crystals of the Sturgeon quartzite are original detrital grains, and that the small quartz crystals that often surround the large crystals or are in the interstices between larger crystals are "crush" quartz and are evidence of a cataclastic texture. The author plotted large crystals separately from small crystals on all diagrams and found the preferred orientation to be the same for both. If the texture is cataclastic it is not likely that both crushed and uncrushed crystals would

have the same preferred orientation. It is the author's opinion that the quartzite has been recrystallized and that the largest quartz crystals are porphyroblasts.

The only microscopic original structures or signs of microscopic relict texture are the planes of hematite dust in sample 96. Megascopic original or relict texture can be seen in the bedding planes, cross bedding and ripple marks.

It is difficult to say much about the metamorphism which has taken place, except that there may have been several crystal growth stages; perhaps each accompanied a different deformation or different stages of deformation in one comprehensive event. The reasons for suspecting two periods of crystal growth and deformation are:

1. Idioblastic quartz crystals show undulatory extinction, fracturing, and corrosion.

2. Some planes of hematite inclusions are curved and some are not; the first indicates paratectonic crystallization and the second post-tectonic crystallization.

3. Idioblastic quartz crystals are inclusions in larger quartz crystals.

Petrographic characteristics of samples

Sample number	Stratigraphic position	Percent mica in total volume of rock	Size of quartz crystals (millimeters)
98	Sturgeon quartzite	1 to 2	----------
96	------do-----------	1/2	----------
95	------do-----------	1 to 2	----------
1	------do-----------	1/2	0.05 to 0.10
2	------do-----------	1/2	0.10 to 1.00
12	basal Sturgeon	8	0.05 to 0.50
11	------do-----------	7 to 8	0.05 to 0.50
13	------do-----------	7 to 8	0.05 to 5.00
9	------do-----------	15	0.05 to 1.00
7	------do-----------	20	0.50
14	Sturgeon quartzite	5 to 7	0.05 to 0.50
15	------do-----------	1 to 2	0.05 to 5.00
10	------do-----------	1 to 2	0.05 to 5.00
8	------do-----------	3 to 4	0.10 to 5.00
6	------do-----------	2 to 3	0.05 to 1.00
5	------do-----------	1	0.05 to 5.00
4	------do-----------	1/2	0.05 to 0.10
3	------do-----------	1/2	0.05 to 0.10

PETROFABRICS

Previous Work

The most detailed petrofabric and structural study available on the area surrounding the Falls of the Sturgeon is by James W. Higgins. Higgins' doctorial dissertation rather than his journal article is the source of quoted material in this work.

Higgins finds two types of deformation have taken place. In rock containing a mica matrix for the quartz grains, as the basal Sturgeon quartzite, the original clastic grains have been dislocated along prism planes and the dislocation has been followed by external rotation of grains in the matrix. In rocks containing little or no mica those grains which were originally oriented favorably have yielded along their prism zones, and those not oriented favorably have been crushed and granulated. Some of the crushed quartz has been annealed into unstrained grains of intermediate size.

Although the two types of rocks have responded in different ways, Higgins finds no significant differences in their fabrics.

Higgins finds that rock fabrics near faults exhibit split A-C girdles, a product of rotational shear, and probably the result of the second deformation of the area. Since the A-C girdles are horizontal, the B axis of rotation must be vertical. Generally, the fabrics he finds are horizontal girdles, and near the sample area the preferred orientation of the c-axes is east-west. Higgins postulates that this preferred orientation is due to faulting. He states (1945):

> From the arrows which indicate relative direction of movement of fault blocks, it can be visualized that the maximum orientation of the c-axes corresponds very well to the direction of elongation of a strain ellipsoid acted upon by a shear couple.

Samples of the Southern Traverse

The intensities of the maxima increase away from the western fault. The order is not perfect, but it is suggestive. Sample 98 is about 290 feet from the fault and has a 5 percent maximum and a definite girdle fabric. Sample 2 is 180 feet from one fault and 100 feet from the other and also has a 5 percent maximum and a girdle fabric. Sample 1 is 120 feet from one fault and 160 feet from the other, but has only 3 percent maxima. Sample 96 is 80 feet from the western fault and has a poorly defined fabric pattern with two 3 percent maxima. Sample 95 is also 80 feet from the fault and has 2 percent maxima.

Sample 98.--The fabric diagram (Fig. 2) has triclinic symmetry, which has no plane of symmetry, but a center of symmetry. Triclinic symmetry results from one-direction flow which has been dragged to the side by some frictional resistance or from the superposition of two movements that did not have coinciding axes.

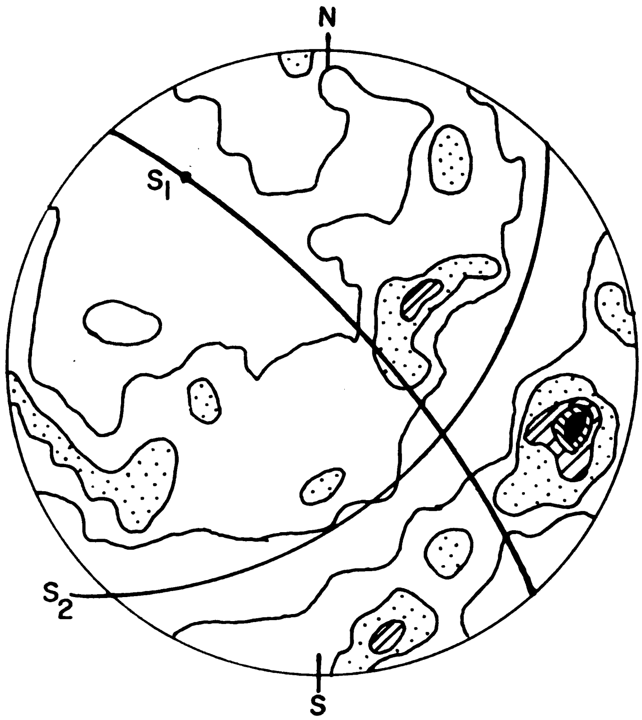


Fig. 2. Sample 98, 600 quartz c-axes. Contours 5-4-3-2-1 %. S_1 is the bedding plane, S_2 a joint surface.

The girdle may be parallel to the ac plane, and be similar to the girdles found by Higgins in the Pine Creek area. It is a B-tectonite fabric. A B-tectonite girdle may indicate either the orienting influence of multiple sets of slip planes developed by internal rotation or external rotation of the slip planes by flexural movement. Since there is no indication in the hand specimen or under the microscope that flexural movement, bending of s planes, has taken place, the fabric must have been developed by internal rotation. Either type of movement changes the position of the slip planes, but the slip planes throughout the movement are parallel to an axis normal to the plane of the girdle. The axis to which the slip planes are parallel is the b axis if the girdle is an ac girdle. Assuming the girdle is an ac girdle, the b axis, the axis of rotation, is in the bedding plane and the ac girdle is normal to the bedding plane. The joint surface is roughly parallel to the ac plane.

Sample 96.--Sample 96 (Fig. 4) has two 3 percent maxima and one large and well-defined peripheral north-south minimum. The bedding plane and the joint surfaces marked on the diagram appear to have little relation to the pattern of preferred orientation shown. The diagram represents a somewhat deformed girdle seen on edge. The girdle plane is vertical east-west and the axis normal to the

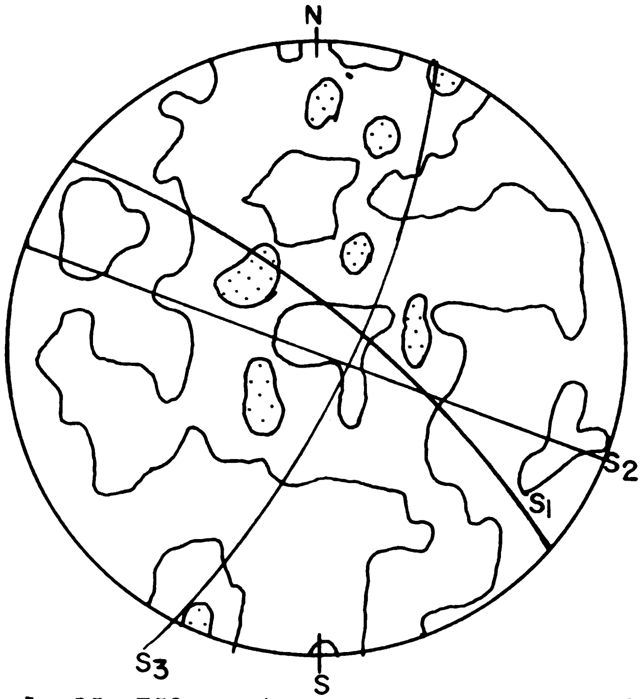


Fig. 3. Sample 95, 750 quartz c-axes. Contours 2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

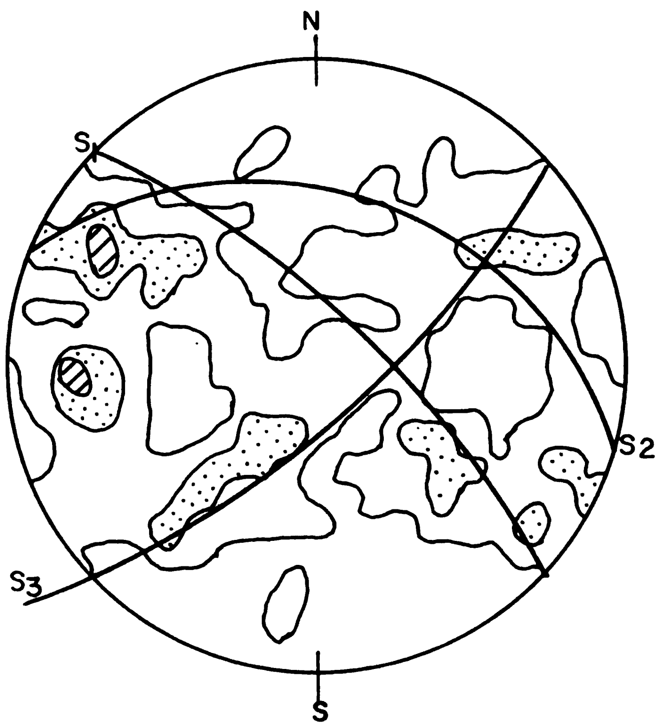


Fig. 4. Sample 96, 600 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

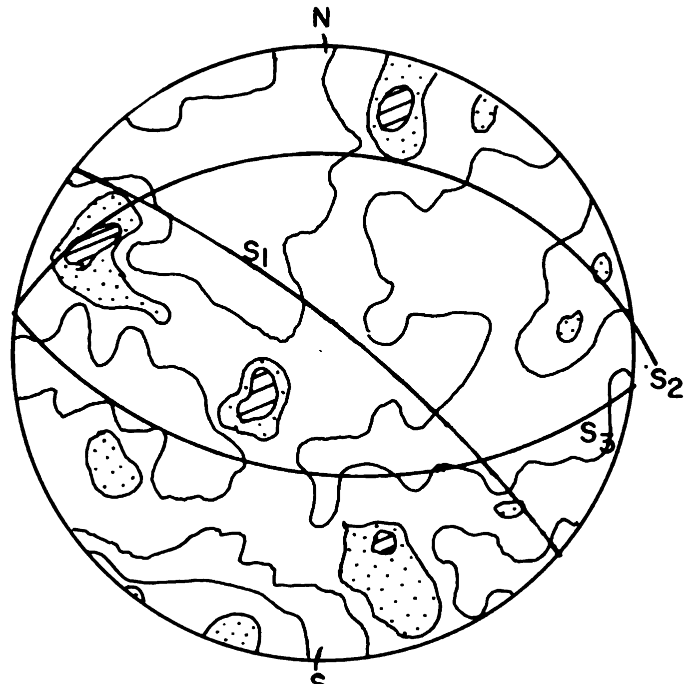


Fig. 5. Sample 1, 300 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

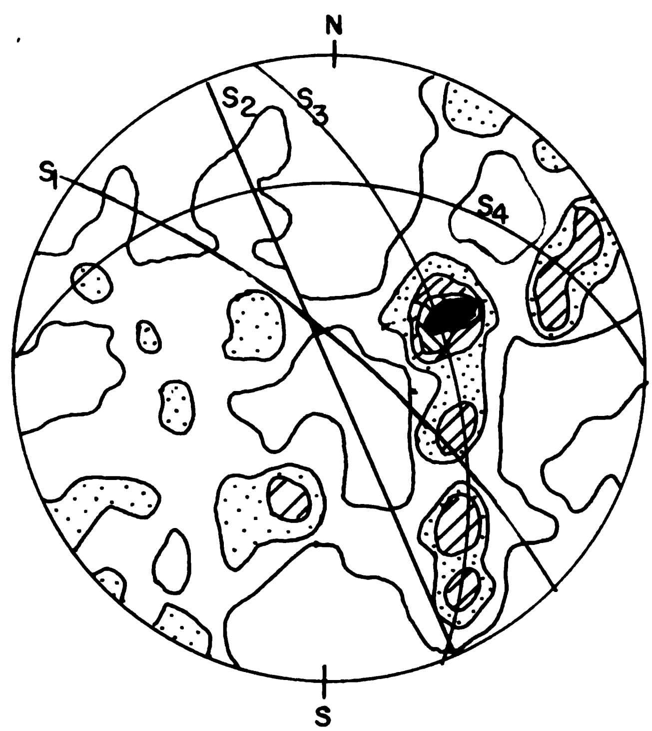


Fig. 6. Sample 2, 300 quartz c-axes. Contours 5-4-3-2-1 %. S_1 is the bedding plane. S_2, S_3 and S_4 are joint surfaces.

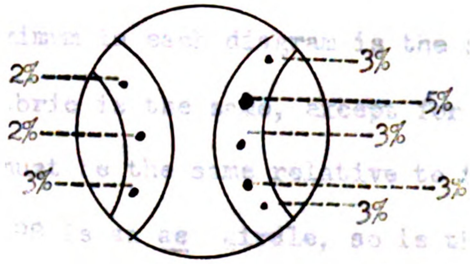
girdle is horizontal north-south. If the fabric diagram of sample 98 represents an _ac_ girdle, this also may be an _ac_ girdle, but with different directions of fabric axes than the girdle of sample 98.

Sample 95.-- Sample 95 (Fig. 3) shows little preferred orientation in the fabric diagram. The maxima are of low intensity. There is a faint suggestion of two girdles, both seen in the diagram upon edge. Bedding and joint planes appear to have little relation to the pattern of preferred orientation.

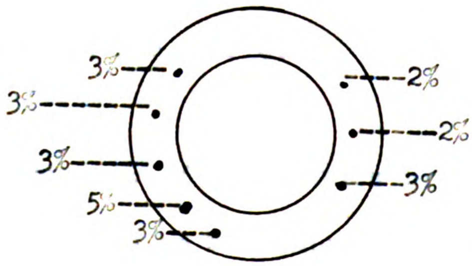
Sample 1.--Again, it is not possible to assign any definite pattern to the fabric shown in the diagram (Fig. 5). The author's guess is that it is a disrupted girdle and that perhaps some maxima have been oriented by faulting forces. The maxima are better defined than in sample 95.

Sample 2.--In sample 2 (Fig. 6) there is a clearly defined girdle with a 5 percent maximum and several 3 percent maxima, but it has a different directional orientation than the girdle in sample 95.

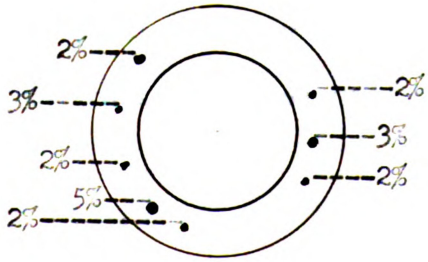
Here the girdle is seen as



which, when rotated, will appear as



This fabric is identical with the fabric of sample 98. If the fabric diagram of sample 98 is rotated to the horizontal, it will appear as



The only differences are in the exchange of position of some 2 and 3 percent maxima. The number of maxima and the position of the 5 percent maximum in each diagram is the same.

Since the fabric is the same, except for its direction, the fabric axes must be the same relative to the fabric. If the girdle of sample 98 is an <u>ac</u> girdle, so is the girdle of sample 2. The <u>ac</u> plane must be approximately vertical and north-south and the <u>b</u> axis is no longer in the bedding plane, but is approximately horizontal and east-west. The joint surface shown on the diagram does seem related to the fabric.

In a brief summary of the samples in this series, the following points should be mentioned. Sample 98 and sample 2 have the same fabric, possibly <u>ac</u> girdles, but the fabric is differently oriented in the two samples. Assuming the girdles are parallel to the <u>ac</u> plane, in sample 98 the <u>b</u> axis is oblique, plunging northwest, and in sample 2 it is approximately horizontal and east-west. The girdles evidently are neither the result of faulting, nor the result of forces that brought about faulting, as the fabric is best developed away from the faults. Near the faults the girdle pattern is confused or unrecognizable.

Samples of the Northern Traverse

Samples in the basal Sturgeon quartzite

Sample 12 is 110 feet from the nearest fault, sample 11 is 130 feet from a fault, and sample 13 is 40 feet from a fault. Sample 9 is 70 feet from the western fault and 100 feet from the eastern fault. Sample 7 is 30 feet from the eastern fault.

All diagrams have 3 percent maxima.

Sample 11.—Of the samples in the series, sample 11 (Fig. 10) is the only one in which a girdle fabric can be recognized. The girdle is not perfectly formed. As in sample 98 and sample 2, there is a tendency for the maxima of greater intensity to be in one half of the girdle. The axis normal to the plane of the girdle dips a few degrees south, probably between 10° and 15°. The girdle may be an ac girdle. Since the fabric has many similarities to the fabrics of sample 98 and sample 2, there is reason to assume that the girdle is the same type of girdle. If it is an ac girdle the b axis is not in the bedding plane but is almost perpendicular to it and the bedding plane is roughly parallel to the ac plane, as is the joint plane in sample 98.

Sample 11, 130 feet from the nearest fault, is farther from the faults than the other samples in the series. From the previous information about the behavior of fabric patterns toward and away from the faults, it is expected that this sample would have the most clearly formed girdle pattern in the series.

Fig. 7. Sample 12, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

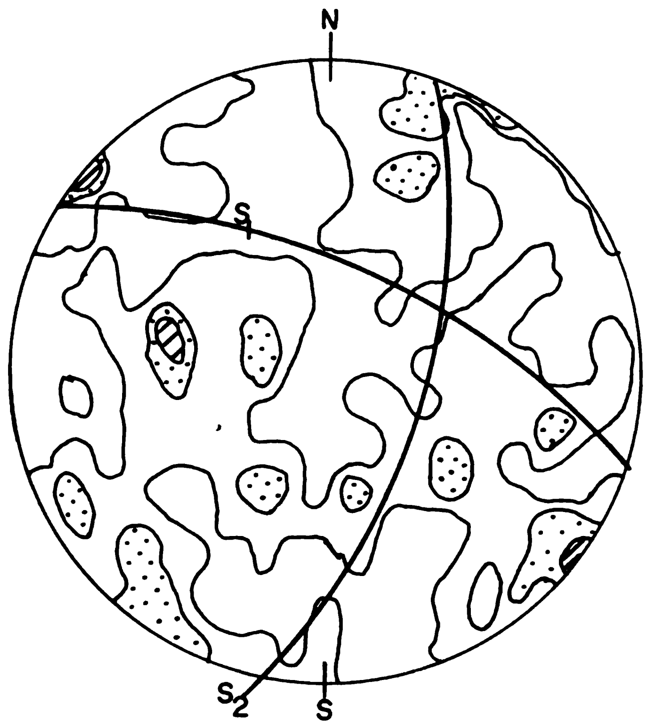


Fig. 8. Sample 13, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

Fig. 9. Sample 11, 100 quartz c-axes from quartz vein. Contours 9-7-5-3-1 %. S_1 is the surface of the vein walls.

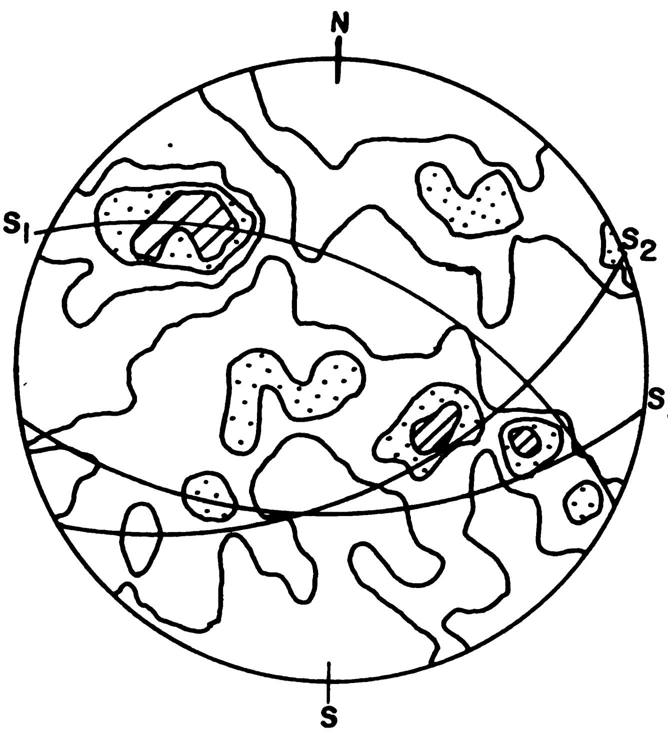


Fig. 10. Sample 11, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

The fabric diagram of the vein quartz in sample 11 (Fig. 9) shows that the concentrations of the c-axes of the quartz crystals are either parallel or subparallel to the vein walls. This is not a tectonic fabric but a growth fabric.

The maxima parallel to the vein walls are the c-axes of crystals that grew with their prism faces parallel to the vein walls. Perhaps the maxima subparallel to the vein walls are the c-axes of quartz crystals that grew with their rhombohedral faces parallel to the vein walls. The 9 percent maximum is about 40° from the vein wall. The unit rhombohedron has an interfacial angle of 38° with the unit prism parallel to the c-axis of quartz crystals.

It is not possible to determine precisely the time of the quartz vein intrusion. Since the fabric shows little sign of disturbance from its original growth pattern, it was probably emplaced after the deformation responsible for the girdle which can be seen in the fabric diagram of sample 11 (Fig. 10). It may or may not have been emplaced after the faulting. The effect of the faulting on the rock fabric apparently did not extend as far from the fault as sample 11. However, the crystals do have signs of strain.

Sample 12.--The fabric pattern (Fig. 7) is hard to define. It would require a difficult stretching of the imagination to call the fabric a girdle fabric. The fabric appears to be another example of the confusion of fabric pattern that is found in the quartzite near the faults. Yet the sample is only 20 feet closer to the western fault than sample 11, which has a recognizable girdle.

One joint surface and the bedding plane appear to have some relation to some of the maxima of the diagram.

Sample 13.—This fabric (Fig. 8) is also difficult to explain. Both sample 12 and sample 13 have peripheral maxima on their fabric diagrams, but they do not have the same orientation in the two samples. A northwest-southeast maximum is present in both samples. None of the other maxima have much correlation.

Sample 9 and sample 7.--No definable fabric pattern can be recognized in the diagrams (Fig. 11 and Fig. 13). The bedding plane in both diagrams appears to be unrelated to the fabric, but one joint surface passes through several 2 percent maxima on each diagram. On both diagrams the 3 percent maximum strikes approximately N. 40° W. and plunges approximately 60° SE. Both sample 7 and sample 9 have a planar arrangement of quartz grains when viewed in the thin section.

Perhaps the fabric diagrams show a fabric which was partially reformed from a B-tectonite fabric to an S-tectonite fabric. (See the discussion of sample 14.) The 3 percent maxima probably indicate that the quartz crystals have been reoriented by a direction of shear related to the faulting and that the fabric is partially that of an S-tectonite. The increase of area of the 3 percent maxima toward the fault supports the idea. As the orientation of the fault plane is not known it cannot be determined if the 3 percent maxima are directly related to movement in the fault plane.

A new fabric pattern, one of an S-tectonite, appears toward the fault in this series of samples. The girdle fabric occurs in only the sample farthest from the faults. The possible S-tectonite fabric is in only the two samples between the faults. These samples are the two samples most affected by the faulting and the forces responsible for the faults.

Samples in the Sturgeon quartzite

Sample 14 is 20 feet from the western fault, sample 15 about 50 feet from the western fault, and sample 10 about 65 feet from the western fault. Sample 8 is 110 feet from the western

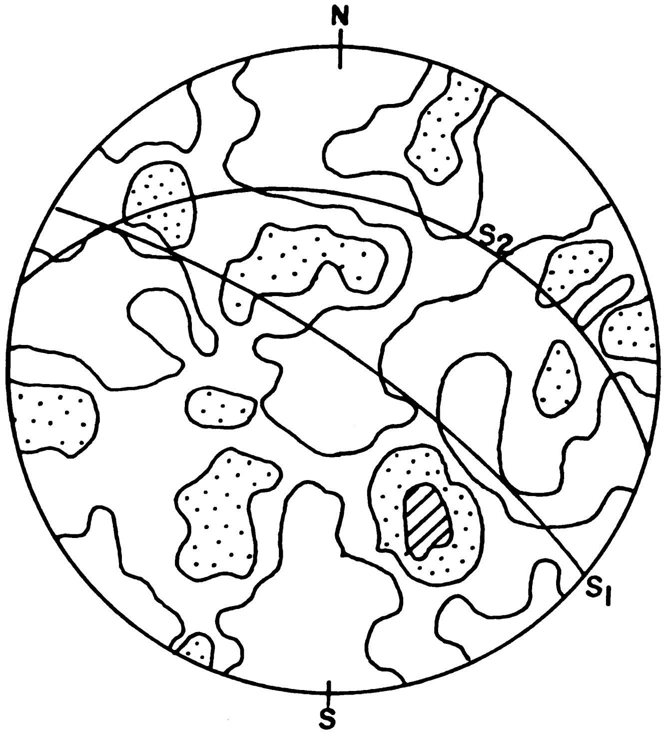


Fig. 11. Sample 9, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

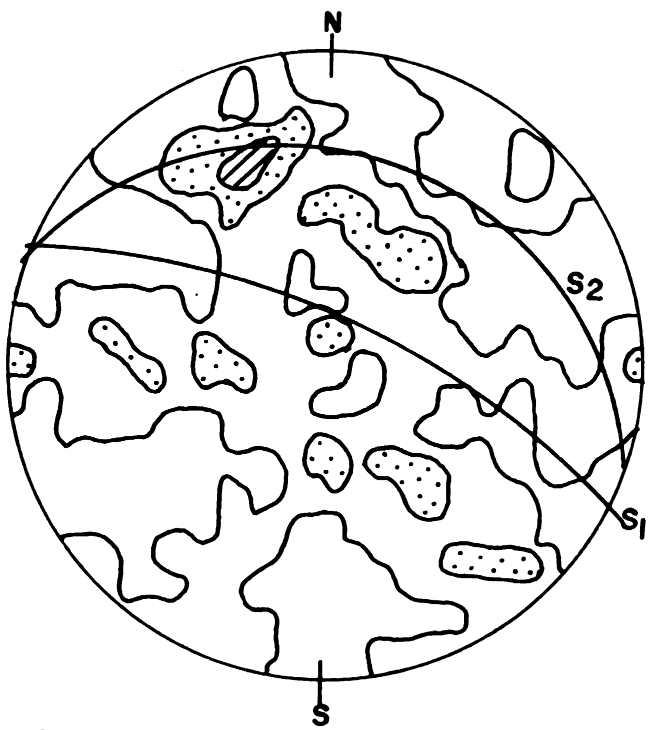


Fig. 12. Sample 10, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

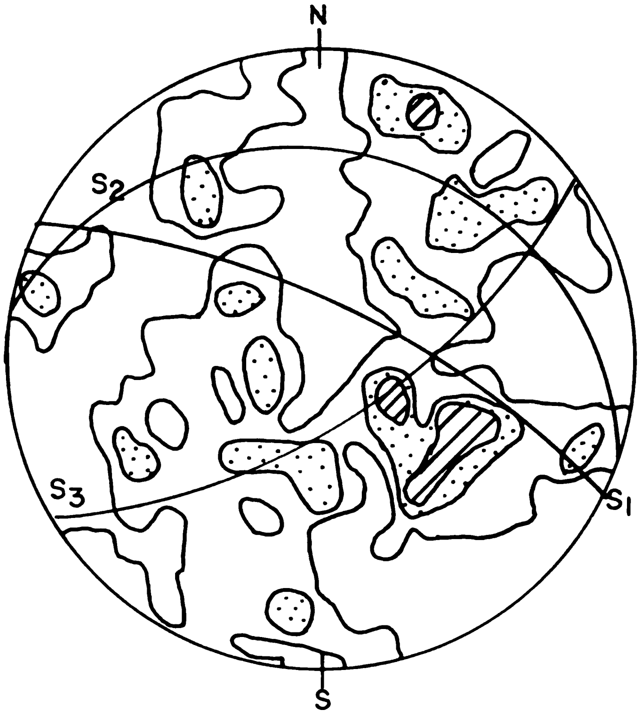


Fig. 13. Sample 7, 500 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

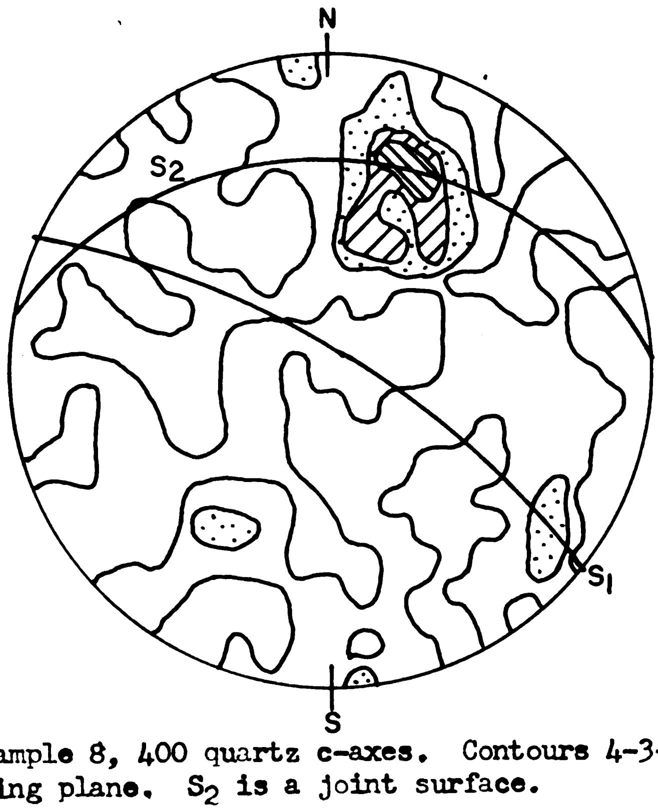


Fig. 14. Sample 8, 400 quartz c-axes. Contours 4-3-2-1 %. S_1 is a bedding plane. S_2 is a joint surface.

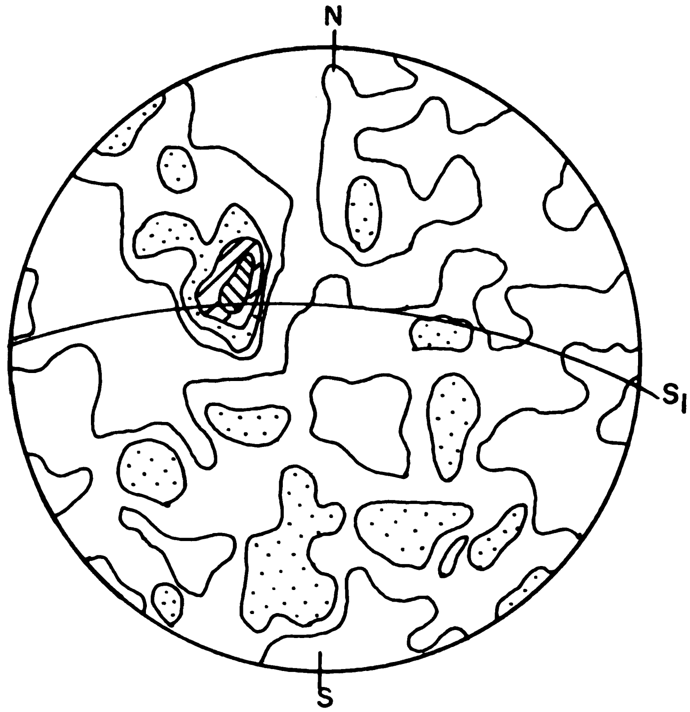


Fig. 15. Sample 14, 400 quartz c-axes. Contours 4-3-2-1 %. S_1 is the bedding plane.

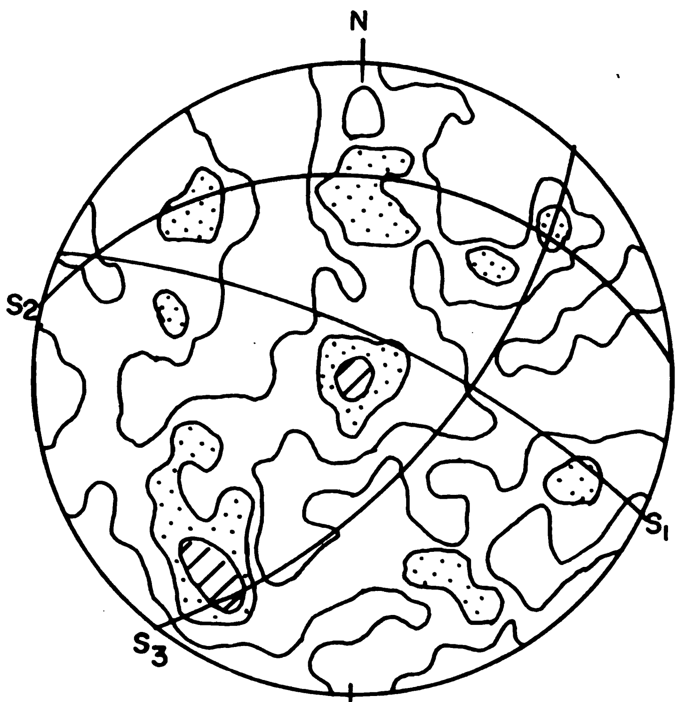


Fig. 16. Sample 15, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 and S_3 are joint surfaces.

fault and 70 feet from the eastern fault. Sample 6 is 40 feet from the eastern fault. Sample 5 is 30 feet from the eastern fault, sample 4 about 50 feet, and sample 3 about 110 feet.

Sample 14.--Sample 14 (Fig. 15) has one maximum of greater intensity than other maxima of the diagram--the 4 percent maximum in the northwest quadrant of the diagram. Point maxima indicate S-tectonites. S-tectonites are rocks in which the structures most important in the formation of the fabric of the rock are s planes. Movement of the rock during deformation is influenced by the s planes. In some rocks movement along the s planes orients the component grains, and the rocks are called "slip tectonites." Because of the sample's proximity to the western fault plane, it is reasonable to assume that the faulting, or forces producing the faulting, have helped to form the fabric shown in the diagram. It is also reasonable to assume that slip occurred along s planes close to the fault.

The c-axes represented in the maximum strike approximately N. 50° W. and plunges 60° NW.

Sample 15, sample 10 and sample 6.--Sample 15 (Fig. 16) has two 3 percent maxima; sample 6 (Fig. 18) has three 3 percent maxima; and sample 10 (Fig. 12) has one 3 percent maxima. The maxima are not in the same positions on the three diagrams, nor are they similar to the fabric of sample 14 or sample 8. One might be tempted to say sample 10 has a random fabric.

The fabrics of sample 15 and sample 6 may, in part, be the result of the reorientation of quartz crystals due to the forces of the faulting. Probably the fabrics of the three diagrams are partly disrupted and confused girdles.

Sample 8.--The 4 percent maximum (Fig. 14) in a sample not close to either fault and not of the same orientation as the maximum of sample 14 requires a different explanation.

Sample 8 is about midway between the two faults. If the movement of the two faults is considered relative to the block between them, it can be surmised that the axis of greatest strain, but least stress, the A tectonic axis, is nearly north-south. Higgins (1945) uses this direction as an explanation of his composite diagrams, which show definite maxima in this direction, and attributes the maxima and fabric to the forces of faulting. Perhaps the maximum of sample 8, not exactly horizontal, but tilted as one would expect if the movement on the faults has not been entirely horizontal, is an expression in the fabric of the direction of least stress. The fabric is that of an S-tectonite.

It is interesting that sample 1 (Fig. 5), also about midway between the two faults but farther from both faults, also shows a maximum in the direction of the maximum of sample 8. In sample 1, however, there are several other equally strong maxima that may be part of a disarranged girdle.

Sample 5, sample 4 and sample 3.-- Sample 3 (Fig. 19), though it is 110 feet from a fault, has no recognizable girdle pattern, nor do the other samples closer to the fault.

The three diagrams are quite similar, but there are differences between them. Sample 5 (Fig. 17) has one 3 percent maximum in the northern half of the diagram and an extensive 2 percent area surrounding it. Sample 4 (Fig. 20) has two 3 percent maxima and one strong 2 percent area. Sample 3 has three 3 percent maxima; the 2 percent areas of sample 4 apparently have become areas of higher concentration away from the fault. Sample 5 has a 3 percent maximum in the southwest quadrant of the diagram, sample 4 a well-marked 2 percent concentration in approximately the same location, and in sample 3 the maximum of the southwest quadrant has disappeared.

The fabric changes progressively in two ways going away from the fault. The maximum in the southwest quadrant gradually disappears, and there is an increased intensity and number of maxima in the northern half of the diagrams.

Fig. 17. Sample 5, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

Fig. 18. Sample 6, 400 quartz c-axes. Contours 3-2-1 %. S_1 is the bedding plane. S_2 is a joint surface.

Samples 9 and 7 (Fig. 11 and Fig. 13) show the same maximum in the southwest quadrant increasing in intensity toward the fault. Clearly this maximum is related to the faulting. The maxima of the northern half of the diagrams may be an expression of the girdle fabric gradually reasserting itself away from the disrupting influence of the fault and a superimposed S-tectonite fabric.

CONCLUSIONS

Two types of preferred orientation are found in the sample area. One is the regional fabric pattern, the girdles, also found by Higgins (1945) in his study of the Pine Creek area. It is a B-tectonite pattern. The girdles can be seen on the diagrams of three samples--sample 98, sample 2, and sample 11. The three samples are the samples farthest from the fault zones. The girdle fabric is probably the result of regional folding which took place before the faulting. The second pattern is that of an S-tectonite and is best shown in the diagrams of sample 14 and sample 8. Sample 14 is only 20 feet from the western fault and sample 8 is midway between the two faults. Other samples have indications of a partially developed S-tectonite fabric (samples 9, 7, 5, 4 and 3). All such samples are close to the fault zones and the intensity of the S-tectonite fabric decreases as distance from the faults increases.

Higgins (1945) postulates that the girdle fabric is the result of faulting. The evidence of this study indicates the B-tectonite girdle fabric is not the result of faulting but of the regional orienting forces and processes of the folding previous to the faulting. The S-tectonite fabric is the fabric which shows the influence of faulting.

Higgins (1945) also found vertical B axes and horizontal A-C girdles. The girdles found in this study are not horizontal, but they may be *ac* girdles. If the girdles are parallel to *ac*, the *b* axes are either inclined or nearly horizontal. The possible inclined *b* axis is from the sample farthest from the faults. It may be that the undisturbed regional girdles do have vertical axes normal to the plane of the girdle and that the girdles in this study are all so close to the faults that the fabric has been disturbed by the faulting forces. That the girdles are not always in the same orientation is illustrated by samples 98 and 2.

The many fabrics which cannot be defined are probably fabrics that originally had girdle patterns. The fabric of these samples has been disrupted and partially reoriented by faulting, but not sufficiently reoriented to clearly show an S-tectonite fabric pattern. Since two types of fabric are present, one of later origin than the other and local in occurrence, it is reasonable to expect "transition" fabrics that show the influence of both orienting processes.

The petrographic and petrologic study of the quartzite indicated that there have been two periods of crystal deformation and growth in the area. This is independent evidence that agrees well with the fabric patterns found--one earlier and regional and the second later and local.

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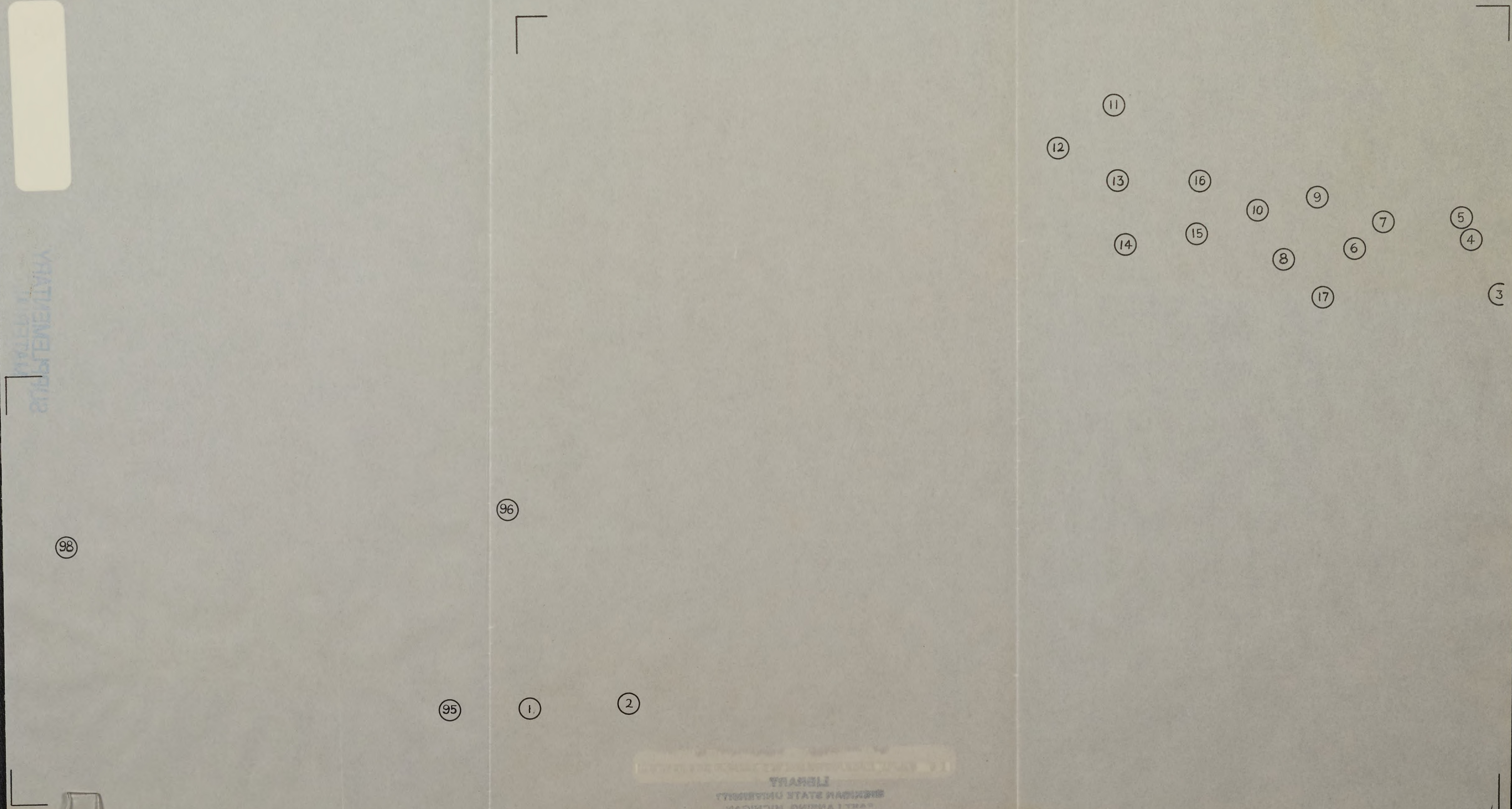
GEOLOGICAL MAP OVERLAY

(1) SAMPLE LOCATION



GEOLOGIC MAP OF THE FALLS OF THE STURGEON AREA
MENOMINEE DISTRICT, MICHIGAN

AFTER JAMES W. TROW, 1945