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A Finite Strain Study of the Baraboo Quartzite:
Observation from Quartz Grain Shapes

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James M. Raab

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of the requirements for

Masters degree in Geology

Major professor

Dr. Cambray

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A FINITE STRAIN STUDY OF THE BARABOO QUARTZITE: OBSERVATION FROM QUARTZ GRAIN SHAPE

by

James Michael Raab

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ABSTRACT

A FINITE STRAIN STUDY OF THE BARABOO QUARTZITE : OBSERVATION FROM QUARTZ GRAIN SHAPES

by

James M Raab

Quartz grains and pebbles of the Baraboo Quartzite are the strain markers used in this study. It is observed that the maximum finite elongation of these grains is parallel to the fold axis of the Baraboo Syncline. Petrographic observations, correlation with tension gash data, and paleocurrent directions oriented obliquely to the long axis of the strain ellipsoid suggest the grains show tectonic deformation.

There are two models that could explain the deformation of the Baraboo Syncline. The first model involves vertical compression followed by horizontal compression. The second model is the opposite of the first model and entails an initial horizontal compression followed by vertical flattening. The vertical flattening could be due to crustal loading from an overlying thrust sheet. Structures such as folded cleavage planes and quartz veins, and north-south oriented boudinage on the southern limb of the fold support a late stage vertical compression.

ACKNOWLEDGEMENTS

A special thanks goes to Dr. Cambray for sparking my interest in this structural analysis and for his guidance and assistance. I would also like to thank Ed, Bill, Dave, and Jim for taking the time to discuss my thesis and for their helpful suggestions. I would especially like to thank my typist, field assistant, and morale booster, who also happens to be my beautiful wife, Shari, who stood by me the entire time. I am also grateful to all my new friends who have helped me out in many ways over the past few years.

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INTRODUCTION

The Baraboo Quartzite, exposed in south central Wisconsin, has been deformed into a doubly-plunging asymmetric syncline. The proposed age of deposition (1.78 - 1.63 Ga., Van Schmus,1976) and deformation (1.63 Ga.) and geographic setting has caused some problems in correlation of Great Lakes area Precambrian stratigraphy . The Baraboo Quartzite was deposited and deformed after the Penokean Orogeny (1.8 - 1.9 Ga.) and before the Keweenawan event (1.2 Ga). The time period between deposition and deformation has been termed the Baraboo Interval (Dott,1983). This study involves the strain determination of the Baraboo Quartzite to achieve a better understanding of the Baraboo Interval deformation.

Ideally, the best measurement of finite strain in deformed rocks is dependent upon finding strain markers of known original shape and orientation that have undergone homogeneous deformation with no volume change. However, rarely are undeformed rocks containing the same strain markers found in close proximity to their deformed equivalents. Therefore, several assumptions have to be made. As a general case, some knowledge of predeformational geometry must be assumed. The strain marker used in this study is the shape of the quartz grains in the Baraboo Quartzite. The first assumption involves the sphericity of the grains. The composition of the Baraboo Quartzite ranges from a quartz arenite to a quartz wacke. Studies of quartz grain shapes of this composition range in compacted, undeformed rocks indicate that the quartz grains were not truly spherical, but subspherical in shape (Curray and Griffiths, 1955; Griffiths, 1967; Elliott,1970;and Holst,1982). Holst (1982) calculated an average X/Z ratio of 1.26 and Curray and Griffiths (1955) determined a X/Z ratio of approximately 1.35. The long dimension was usually oriented in the bedding plane. This variation must be considered when analyzing the finite strain figures measured in this work.

In addition to the shape and orientation, finite strain measurements will be affected by the behavior of the strain markers used. One assumes homogeneous deformation at constant volume in the ideal case. Quartz grains have a characteristic size and in quartz-rich sandstones should have a statistically homogeneous distribution (Fry,1979). To obtain homogeneously deformed samples, areas that contained any anomalous features such as large quartz pebbles and thick cleavage domains were avoided.

The magnitude of volume change is very difficult to assess because there is no apparent way to quantify the volume changes that occur after deposition. Calculations by Wood (1973) show that volume changes of 15 percent or less are negligible, but greater volume changes would introduce significant errors in the strain values measured. Jank

(1982) suggests that pressure solution is the major mechanism of cleavage development in the Baraboo Quartzite which indicates volume change may have occurred. The presence of quartz overgrowths indicate that material dissolved during pressure solution was redeposited, but some material may have migrated from the system. For this reason, the strain values measured have to be treated with some reservation.

The two dimensional strain analysis method developed by Fry (1979) allows rapid measurement of object-object separation and is the method used in this study. From these two dimensional measurements, finite principal strain axes were obtained.

The only previous deformation studies published on the Baraboo Quartzite were by Riley (1947) and Dalziel and Stirewalt (1975). Both studies examined deformation lamellae to determine stress orientations. Quartz deformation lamellae are thought to occur early in deformational history (Dalziel and Stirewalt, 1975) and therefore offer little indication of the total strain experienced during deformation. Dalziel and Stirewalt (1975) also measured strain orientations from tension gash bands. These results differ from the deformation lamellae and are thought to occur late in the deformational history. Dalziel and Dott (1970) proposed that the Baraboo Quartzite has undergone a single continuous deformation with the various structures merely recording stages within this continuous strain history. This study uses final quartz grain shapes to determine a finite strain pattern. Principal finite strain axes and magnitudes were determined from samples throughout the Baraboo Syncline. These results will be incorporated with other mesoscopic features to determine variations in strain patterns to derive a deformational history. This final deformational history will then be used to make certain implications about the tectonic setting.

GEOLOGIC SETTING

In the area surrounding Baraboo, Wisconsin, Lower Proterozoic rocks are locally exposed beneath a cover of Paleozoic rocks. These Proterozoic rocks were unconformably deposited upon silicic volcanic rocks. The Baraboo Quartzite directly overlies the volcanics and is the most extensively exposed and thickest formation of the sequence (see Figure 1). Other metasedimentary rock units associated with the Baraboo Quartzite include, from oldest to youngest, the Seeley Slate, the Freedom Dolomite and Iron Formation, the Dake Conglomerate, and the Rowley Creek Slate. (See Table 1 for the Precambrian stratigraphy of the Baraboo district.) These formations have been reported in drilling and iron mining records, but have not been positively identified in outcrop (Dalziel and Dott, 1970). At Baraboo these rocks have been folded into a doubly-plunging asymmetric synclinorium, known as the Baraboo synclinorium. The axial surface of the fold strikes east-northeast and dips steeply to the north. The geometry of the fold is such that the northern limb dips steeply to the south and in some locations is overturned, while the southern limb dips gently (20 - 40°) northward. The Baraboo synclinorium is approximately 25

Figure 1. Location map of study area showing outcrop locations of Baraboo Quartzite in the area of Baraboo, Wisconsin. Insert map shows regional setting. (From Dalziel and Stirewalt, 1975.)

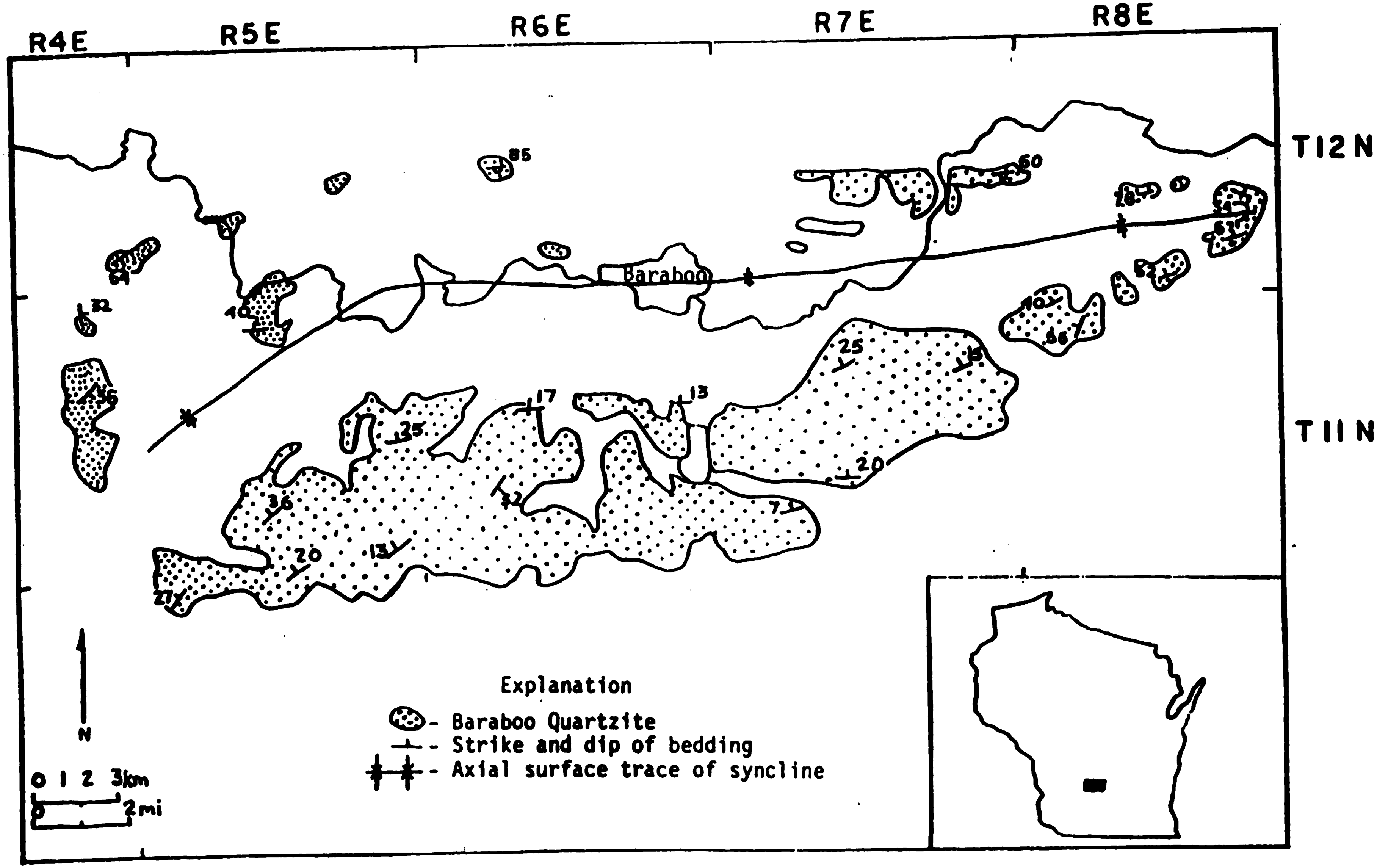

R4E
R5E
R6E
R7E
R8E
T12N
T11N
Baraboo
N
0 1 2 3km
0 2mi
Explanation
- Baraboo Quartzite
- Strike and dip of bedding
- Axial surface trace of syncline

Figure 1

TABLE 1

PRECAMBRIAN STRATIGRAPHY OF THE BARABOO DISTRICT

Rowley Creek Slate (maximum known thickness = 149 ft.)

Dake Quartzite (maximum known thickness = 214 ft.)

(Unconformity ?)

Freedom Formation (minimum thickness = 1000 ft.)

Seeley Slate (maximum known thickness = 370 ft.)

Baraboo Quartzite (thickness over 4000 ft.)

(Unconformity ?)

Rhyolitic "basement" (thickness unknown)

(Taken from Dalziel and Dott; 1970)

miles in length and 10 miles in width and rises 700 - 800 feet above the level of the Wisconsin River Valley, forming the Baraboo Ranges. (See Figure 1). From this Figure, one can see that in the eastern closure the strike of bedding changes very abruptly, while in the western closure the change in strike of bedding is very gradual. The western half of the Baraboo Syncline contains minor folds. These fold hinges parallel the major synclinal fold hinge (Figure 1).

Rb-Sr and U-Pb ages of the underlying rhyolitic complex indicates maximum age dates of 1.78 +-.02 Ga. for the Baraboo Quartzite. Intrusive plutonic rocks south of the Baraboo Syncline (Greenberg and Brown, 1984) yield a minimum age of 1.5 Ga. This interval, from 1.78 to 1.5 Ga is referred to as the Baraboo Interval. As a result of the age dating of the Precambrian succession, Van Schmus (1976) noticed that the Rb - Sr rock and mineral ages throughout the Great Lakes region were reset to 1.63 +- .03 Ga. There are no igneous rocks of this age exposed near the Baraboo Syncline and therefore, it is proposed that the wide spread generally low grade metamorphism that occurred during the middle Proterozoic Baraboo Interval was coincident with deformation of the region (Van Schmus, 1976, Dott,1984). Because of this proposed date of deformation, the age of the Baraboo Quartzite can be narrowed down to between 1.78 and 1.63 Ga.

In the subsurface, the Baraboo Quartzite is thought to exist from the Wisconsin - Iowa - Minnesota boundary, across Wisconsin and may extend as far east as the western shore of Michigan (Dott, 1983, See Figure 2). The great thickness (over 4000 feet) and areal extent of the quartzite has sparked much interest regarding its depositional setting. The deposition of a quartzose sedimentary unit over 4000 feet thick suggests that the depositional setting was a stable, slowly subsiding continental margin. This stable continental margin was located on the southern edge of Proto - North America (Dott, 1983, Greenberg and Brown,1984). The generally excepted theory is that after the 1.8 - 1.9 Ga. Penokean Orogeny to the north, there was a peroid of quiescense. Uplifted Penokean plutonic and anorogenic rocks were the sources of sediment for the Baraboo Quartzite. The substantial sediment thicknesses developed during the Baraboo Interval are greater than what would be expected from a simple eustatic sea level rise. However, subsidence of the continental margin was thought to be slow due to the shallow water nature of most of the sediments (Greenberg and Brown, 1984). Marine transgression is thought to have begun during deposition of the Baraboo sands, because the youngest strata overlying the Baraboo Quartzite, namely the black slates and iron formation - bearing dolomite are considered to be marine.

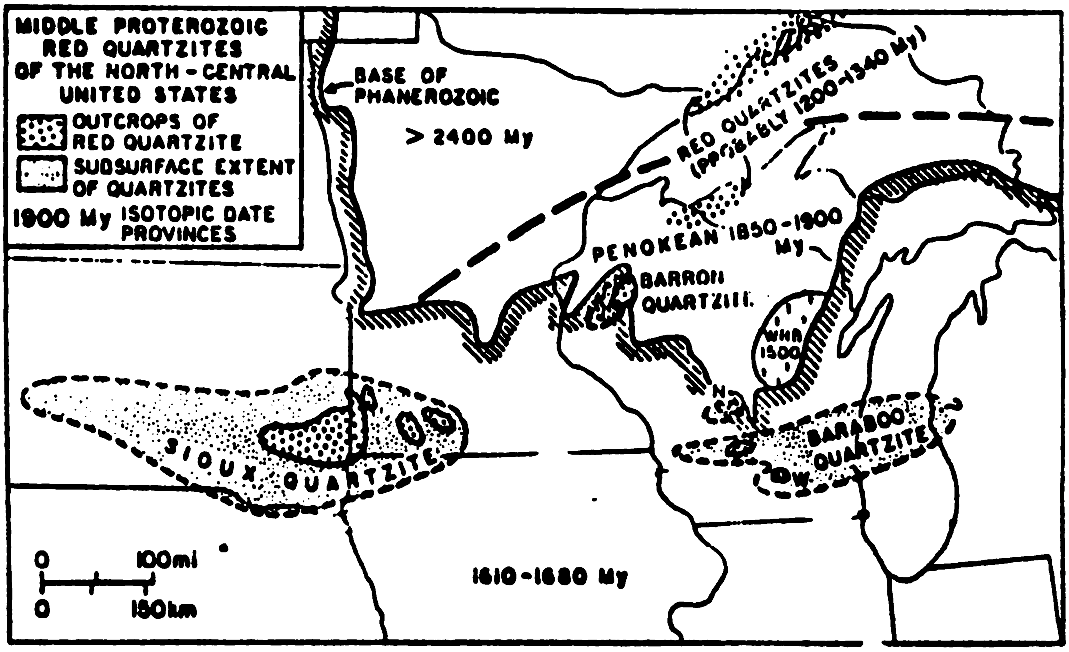


Figure 2. Present distribution of Proterozoic red quartzites in relation to other major Prepaleozoic tectonic features in the north-central United States.(N-Necedah, Wisconsin; W-Waterloo, Wisconsin; WRB-Wolf River batholith). From Dott,(1983).

PREVIOUS STUDY

Baraboo Region

The first and most comprehensive study of the structural geometry of the Baraboo Quartzite was done by Wiedman (1904). Wiedman was the first to correctly report the synclinal nature of the Baraboo Quartzite. Van Hise, however was the first to give a full account of the structural relationships of bedding and cleavage. For a full discussion see Dalziel and Dott (1970).

Steidtman (1910) studied the Baraboo Quartzite and noticed that some secondary structures particularly joints and cleavages, were related to the folding of the Baraboo Quartzite. He also observed that the geometry of some of the cleavage planes and joints were not indicative of a simple folding process. Steidtman noticed that the attitude of approximately 75% of the joints on the southern limb and 50% of the joints on the northern limb were oblique to the strike of bedding. The orientation of most of these joints are N60E and N30W with a vertical dip. The origin is uncertain, but a large percentage of these are probably tension controlled and related to larger structural features than the Baraboo Range (Steidtman,1910).

Hendrix and Schaiowitz (1964) studied cleavages in the southern limb of the Baraboo Syncline and noticed a reverse sense of shear along the bedding planes. These reverse structures are small scale planar structures whose strike approximates that of bedding but dips in the opposite direction. They observed that the reverse folds are asymmetric with steep limbs down dip suggesting that the upper beds have moved down dip relative to the lower beds.

Dalziel and Stirewalt (1975) studied the quartz subfabric in the Baraboo Quartzite. They interpretted a stress history by observing the orientation of quartz deformation lamellae.They compared their results to Riley's (1947) structural study using quartz c-axis orientations. Their combined results are illustrated in figure 3. On the scale of the syncline σ_3 is nearly vertical and lies in the plane perpendicular to the fold hinge . Analysis of the results from different domains of the fold are as follows: 1) in both the eastern and western closure, σ_1 and σ_2 lies parallel to the bedding plane; 2) on the fold limbs, σ_1 is approximately parallel to the fold hinge while σ_3 is nearly vertical for both the steep dipping northern limb and the gentle dipping southern limb. Contrary to Riley's (1947) conclusion that the quartz subfabric in the quartzite resulted from stresses later than and unrelated to the development of the syncline, Dalziel and Stirewalt (1975) suggest that the stress system reflected by the quartz

Figure 3. Equal-area lower hemisphere stereoplots summarizing the orientations of stress axes from the studies of Dalziel and Stirewalt (1975), and Riley (1947). Circled numbers refer to Dalziel and Stirewalt's data, numbered dots to Riley's data. Numbers 1,2, and 3 indicate the orientations of σ_1 , σ_2 ,and σ_3 respectively. Bedding is depicted as a solid line. The dashed line represents quartzite cleavage. A; data from the whole syncline. B; data from the northwestern domain. C; data from the northeastern domain. D; data from the south limb. E; data from the eastern closure. F; data from the west central domain. G; data from the western closure. (From Dalziel and Stirewalt, 1975)

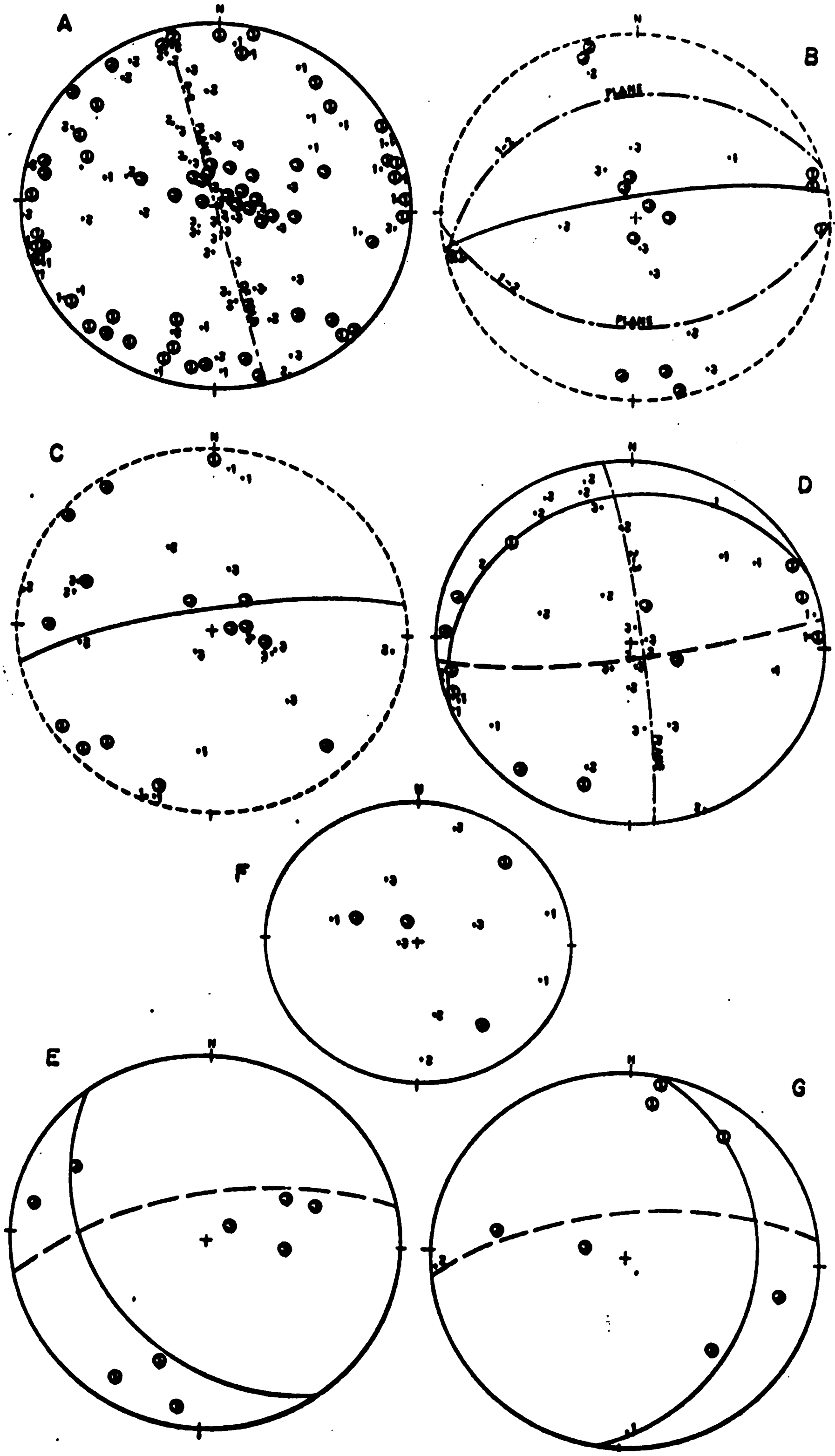


Figure 3

subfabric is related to the formation of the syncline. In addition to studying quartz deformation lamellae, Dalziel and Stirewalt (1975) observed the orientation of tension gashes throughout the syncline. These stress orientations show that the maximum stress was from a north-south direction and the least stress direction parallels the fold hinge of the syncline (Figure 4). These results differ greatly from the quartz deformation lamellae and are thought to be a late stage event (Dalziel and Stirewalt, 1975).

All of these structural studies suggest a more complex deformational pattern than was initially thought. This will be discussed later in regards to a model of the total deformational history of the Baraboo Quartzite and associated Precambrian rocks.

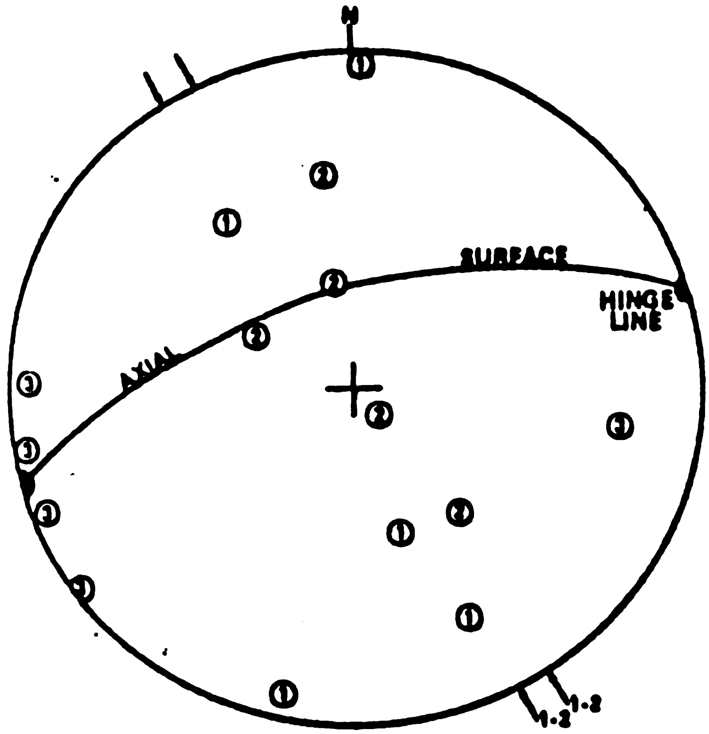
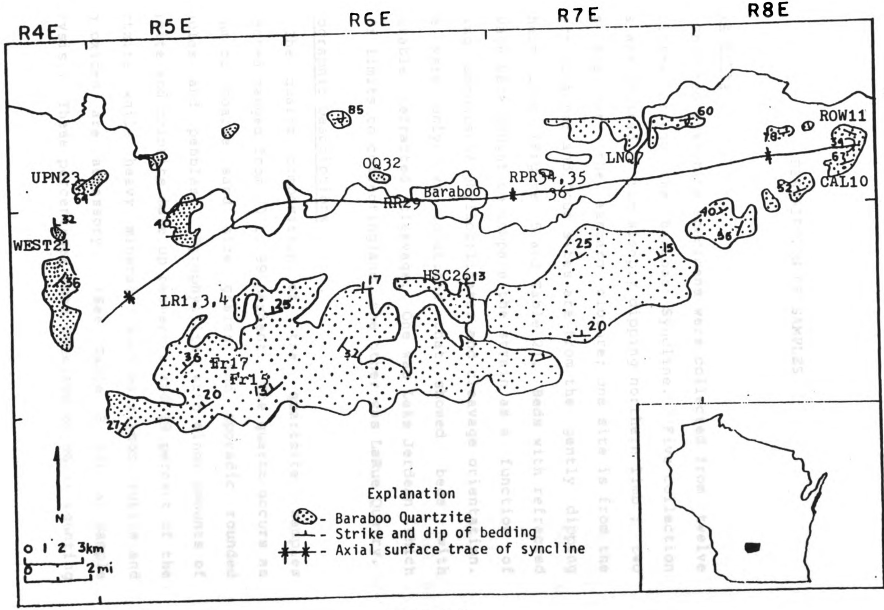


Figure 4. Equal area lower hemisphere stereoplot illustrating orientations of stress axes deduced from the tension gash data of Dalziel and Stirewalt. Numbers 1,2,3 indicate orientations of σ_1, σ_2, and σ_3. From Dalziel and Stirewalt (1975).

Figure 5. Location map of study area showing outcrop locations of Baraboo Quartzite in the area of Baraboo, Wisconsin. Sample locations are shown. (From Dalziel and Stirewalt, 1975.)



R4E
R5E
R6E
R7E
R8E
T12N
T11N
ROW11
CAL10
LNQ
RPR34,35
Baraboo
RR29
OQ32
UPN23
WEST21
HSC26
LR1,3,4
Fr17
Fr15
Explanation
- Baraboo Quartzite
- Strike and dip of bedding
- Axial surface trace of syncline
N
0 1 2 3km
0 2mi

FIGURE 5

DESCRIPTION OF SAMPLES

Sample Sites

Oriented quartzite specimens were collected from twelve localities around the Baraboo Syncline. Five collection sites are located on the steeply dipping northern limb ; two sites are near the eastern closure; one site is from the western closure; and four sites are from the gently dipping southern limb (Figure 5 and Table 2). Beds with refracted cleavage were sought to compare the strain as a function of varying amounts of phyllosilicates and cleavage orientation. There were only two locations that showed beds with measurable refracted cleavage. One was Lake Jerdean (which is off limits to collecting)and, the other was LaRue Quarry.

Petrographic Descriptions

The quartz composition of the quartzite samples collected ranged from 70 to 99 percent. The quartz occurs as medium to coarse sand size grains and sporadic rounded granules and pebbles. Pyrophyllite with minor amounts of sericite and chlorite make up between 1 and 29 percent of the quartzite while heavy minerals such as zircon, rutile and iron oxides are accessory. (See Table 3 for a sample analysis.) These percentages were obtained by point counting

TABLE 2

DESCRIPTIVE LOCATION OF SAMPLE SITES

Sample Name	Location
Upn23	Along Hwy 154 in Narrows Creek Gorge
OQ32	West Baraboo Quarry off Hwy 136, 1 mi. W of Hwy 12
RPR34,35,36	1/2 mi. N of Rte 33, 200 yds E of Rocky Point Rd.
RR29	Along RR tracks and Baraboo R., W of Hwy 12
LNQ7	Netspan Quarry in Lower Narrows, W of Rte 33
ROW11	E end of Rowley Rd., 100 yds N
CAL10	Field on E side of Beich Rd. at crest of hill as it climbs the South Range
HSC26	E side of Skillet Creek, S of Hefty Skillet Creek Cmpgd
FR15	Freedom Rd, 1 mi. S of County Rd PF
FR17	Freedom Rd., 2 mi. S of County Rd PF
LR1,3,4	LaRue Quarry
WEST21	Western Closure, 2 mi. SW of UPN23

TABLE 3

COMPOSITION OF QUARTZITE SAMPLES

Sample	% Quartz	% Phyllosilicate	Other (zircon, rutile, Fe oxides)
UPN23	96	3	<1
OQ32	95	4	<1
LNQ7	86	13	<1
ROW11	92	7	<1
Cal10	91	8	<1
HSC26	89	10	<1
FR15	94	5	<1
FR17	98	1	<1
LR1	77	22	<1
Lr3C	80	19	<1
LR3T	73	26	<1
LR4B1	70	29	<1
LR4B3	76	23	<1
WEST21	95	4	<1

300-400 grains per sample. The maximum confidence interval obtained is 4% according to Pettijohn, Potter, and Siever (1973).

Internal recrystallization of the quartz grains is not apparent because undulatory extinction and deformation lamellae are present. Incipient recrystallization however, is indicated by the presence of polygonized quartz at the boundaries between quartz grains (Figure 6). Dust rims of iron oxide surround some quartz grains which make it easy to identify quartz overgrowths in most thin sections (Figure 7). Sutured boundaries between quartz grains is fairly common. This indicates that recrystallization has occurred. The phyllosilicates usually have a preferred orientation throughout a thin section. This preferred orientation is parallel to the cleavage planes and is also subparallel to the overall preferred quartz grain elongation direction. Figure 9 is a histogram showing the frequency difference in quartz and phyllosilicate grain orientation. In most of the thin sections, the phyllosilicates were seen to interfinger with the quartz grains in a direction parallel to the cleavage planes (Figure 8). In rocks with less than five percent phyllosilicates, where cleavage planes are not easily discernable, phyllosilicate grains are arranged with their elongated direction parallel to the elongation direction of the quartz grains.

Figure 6. Polygonized quartz at grain boundaries. Scale = 1 inch : .11 mm..

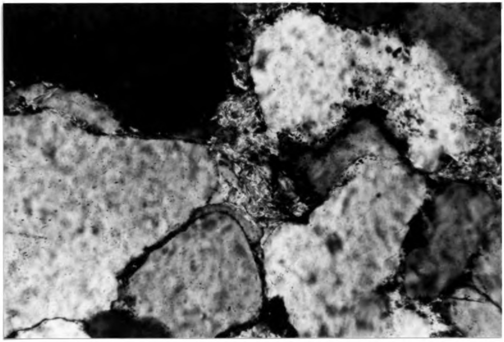


Figure 7. Dust rims and quartz overgrowths. Scale = 1 inch : .11 mm..

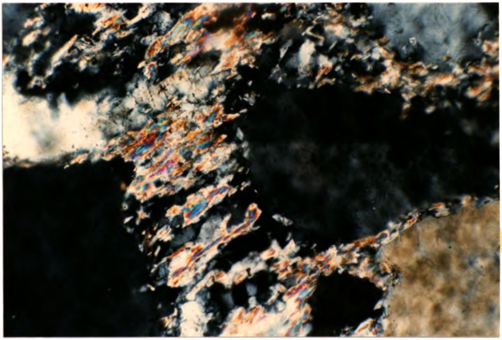


Figure 8. Interfingering of quartz and phyllosilicates.
Scale = 1 inch : .11 mm..

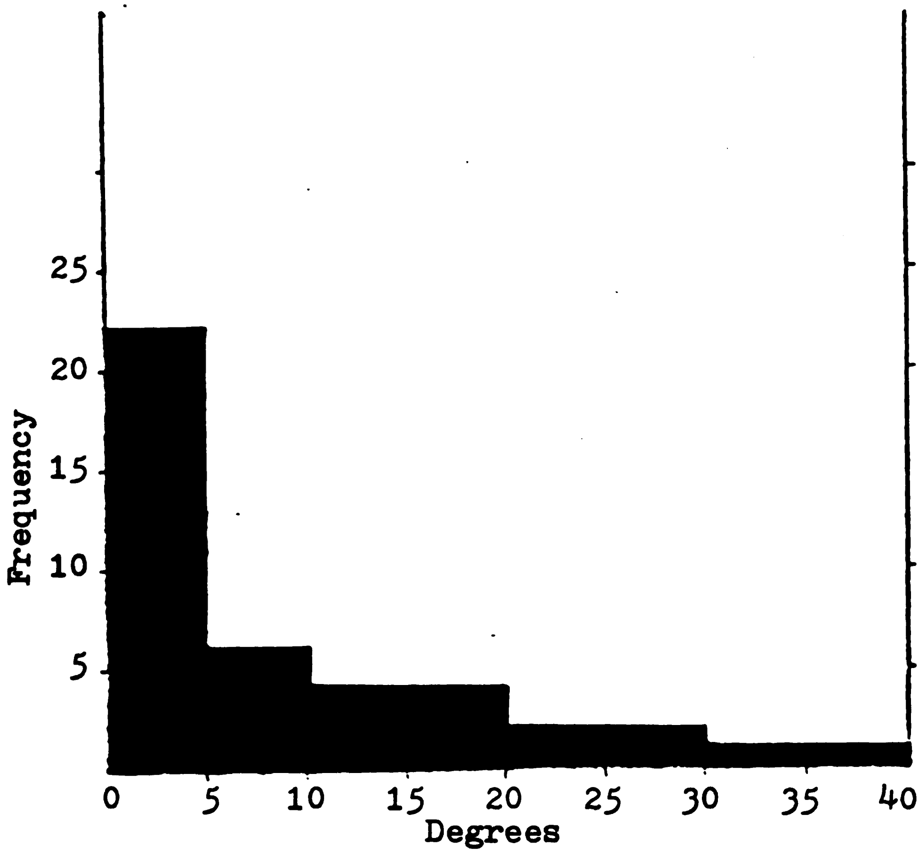
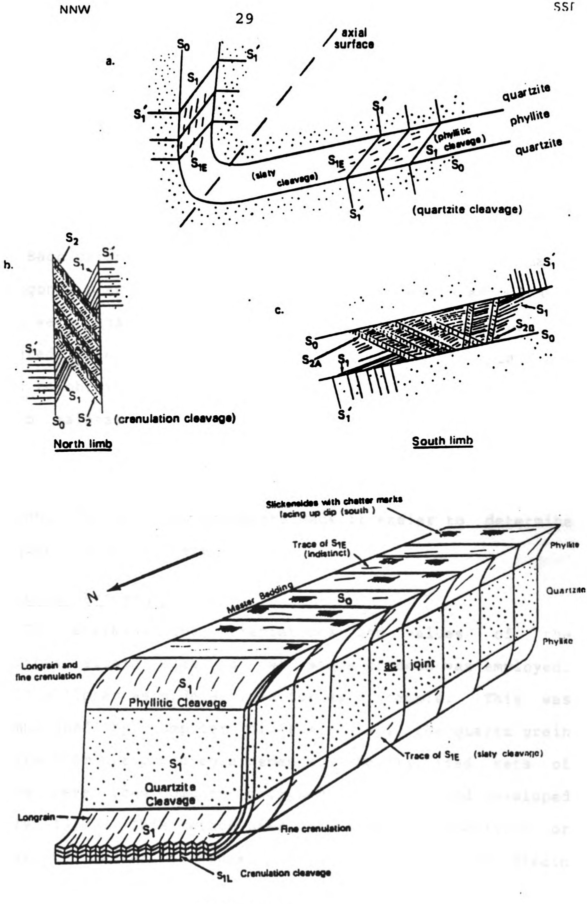


Figure 9. Histogram of orientation difference between the long axis of quartz grains and phyllosilocate elongations.

Cleavage

Dalziel and Dott (1970) describe the major types of cleavage found in the Baraboo Quartzite as: a penetrative slaty cleavage in the phyllite which extends into the quartzite ; a fracture cleavage in the phyllite which they refer to as phyllitic cleavage ; and a closely spaced parting in the quartzite which they term "quartzite cleavage". This "quartzite cleavage" is similarly known as spaced cleavage by other authors. (See figure 10 for the description of these mesoscopic structures.) "Quartzite cleavage" will be used throughout to indicate spaced cleavage present in the quartz-rich beds. All samples collected for this study contained the quartzite cleavage. Over half of the samples also contained the phyllitic cleavage while only a few contained the slaty cleavage. Jank (1982) observed that the width of the spaced cleavage planes ranged from .1 to 1 mm. with the number and width of the spaced cleavage planes increasing with increasing phyllosilicate content in the rock. Samples with wide cleavage bands and high phyllosilicate content were avoided due to the heterogeneous nature of those samples.

Figure 10. Mesoscopic Structures Associated with the Baraboo Syncline (after Dalziel and Dott, 1970).



NNW
SSE
a.
S_0
S_1'
S_1
S_{1E}
axial surface
quartzite
phyllite
quartzite
(phyllitic cleavage)
(slaty cleavage)
(quartzite cleavage)
b.
S_2
S_1
S_0
(crenulation cleavage)
North limb
c.
S_{2A}
S_{2B}
South limb
Slickensides with chatter marks facing up dip (south)
Trace of S_{1E} (indistinct)
N
Master Bedding
S_0
Phyllite
Quartzite
Phyllite
Longrain and fine crenulation
Phyllitic Cleavage
"ac" joint
Quartzite Cleavage
Trace of S_{1E} (slaty cleavage)
Longrain
Fine crenulation
S_{1L} Crenulation cleavage

FIGURE 10

ANALYTICAL METHODS

Sample Preparation

Each oriented specimen was cut to expose three mutually orthogonal planes. For the conglomerates, the three polished faces were analysed, but for the quartzite samples, an oriented thin section was made from each plane. Care was taken to obtain three orthogonally oriented thin sections so as to maintain homogeneity between both the quartz grain content and cleavage orientation. Eight by ten inch negative photographic prints were made directly from each thin section. The photo enlargements made it easier to determine the quartz grain centers.

Analytical Procedure

To determine the orientations and values of the principal strain axes, a two stage process was employed. Strain ellipses were determined for each sample. This was accomplished by computer digitizing all the quartz grain centers from the photo enlargements. The digitized sets of points were then computer analyzed using a method developed by Fry (1979). This method uses object-object separation or center to center distances to calculate relavant strain ellipses. The basis of Fry's method is to make clustering or anticlustering visible. One of the original digitized points was placed at the center of the desired plot, retaining exact orientation. Then the positions of all the other points of the original pattern were plotted. Then a second grain center of the original pattern was placed at the center of the plot and the resulting positions of all the other grain centers were added to the derived plot. This procedure was continued until all the points of the original data set had been used as the center point. The resulting pattern shows the frequency with which points in the original pattern had neighboring points at different distances in different directions. (See Figure 11.) The vacancy in the center of the plot arises from the fact that any two original particles cannot come to lie closer than the sum of their radii. If the strain marker was initially spherical, this vacancy of points would give an average strain ellipse for the planar section. Care must be taken in assuming the initial distribution of grain centers because a Poisson random initial distribution will deform into a Poisson random distribution (Fry, 1979). A statistically uniform initial distribution of points can be assumed in quartz rich sandstones and quartzites (Fry, 1979). The quartz grains have a characteristic initial size, which means that the center to center separation of nearest grains is controlled by the geometric constraints of the packing.

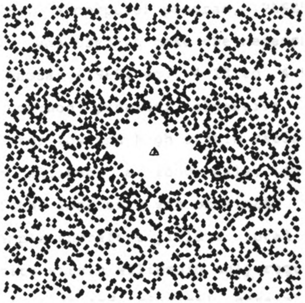


FIGURE 11. An example of a two dimensional Fry plot, from sample LR3C. See text for an explaination.

Having determined the strain ellipse for all three orthogonal thin sections, it is possible to determine both the orientations and values of the three principal axes of the strain ellipsoid (Ramsay, 1967; Siddans, 1981; and Oertel and Miller, 1979). A computer program, (PASE5,obtained from Roy Kligfield), was used to make the necessary calculations as outlined by Ramsay (1969, eq. 4-23 to 4-51 and 5-4 to 5-17). This method provides objective results and is especially good for low and high strain ratios.

From each ellipse, a long axis, short axis and orientation of the long axis was obtained. The three strain ellipses per sample therefore yield a total of nine data. Because the finite strain ellipsoid only requirs six terms to define its orientation and principal strain values (Ramsay and Huber,1983), the measured data exceeds the minimum data required for the solution and provides internal checks on the accuracy and consistency of the measurements obtained. (See the Appendix for a more detailed explanation of the procedure followed by the computer program PASE5.)

Five conglomerate samples were analyzed by the Fry method. To provide a check on the accuracy of Fry's method on conglomerates, direct length-width ratios along with the orientation of the long axis were also measured on the three orthogonal faces of the rock. R_f/ϕ plots (Ramsay, 1967) were made to obtain the average ellipse ratio and orientation for each face. Both sets of data were subsequently analyzed using PASE5. Comparison of the results indicates that the two methods are consistent . These results are also consistent with the quartz grain shape results and therefore will be treated together in the discussion of the results.

RESULTS

Finite Strain Orientations

The Baraboo Syncline can be divided into four inferred homogeneous deformation domains; a northern limb, a southern limb, an eastern closure, and a western closure. Figure 12 A-E are equal area lower hemisphere stereographic plots of the principal strain axes measured in the syncline. Figure 12A is a composite of all the strain data encompassing the entire syncline. From this data it is seen that even though there are strikingly different mesoscopic structures, the principal axes of strain are consistently grouped. The direction of maximum elongation is gently plunging to horizontal in a direction of 250 degrees. The direction of maximum shortening plunges gently (30^{o}) in a direction of 150 degrees.

Figure 12B shows the orientations of the principal finite strain axes from the northern limb. The maximum principal extension closely parallels the bedding-cleavage intersection. The Z direction is approximately perpendicular to cleavage, while the Y axis plunges steeply (80^{o}) to the east.

There is more scatter in the data for the southern limb (Figure 12C). The Z axes have the greatest consistency and

Figure 12. Equal-area lower hemisphere stereoplots summarizing the strain orientations of this study. Stars represents the X direction, squares the Y direction, and circles the Z direction. A; data from the whole syncline. B; data from the north limb. C; data from the south limb. D; data from the eastern closure. E; data from the western closure.

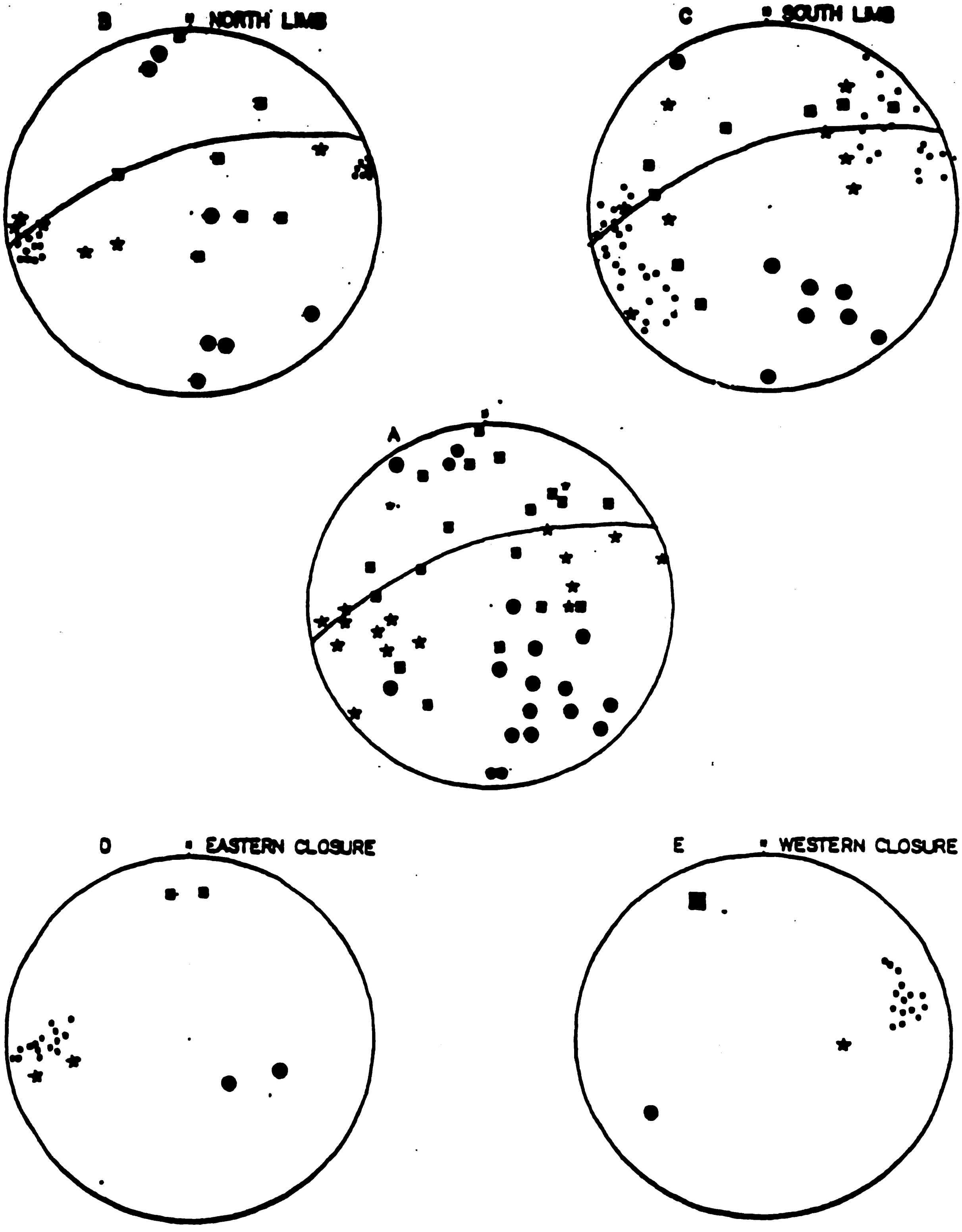

B
NORTH LIMB
C
SOUTH LIMB
A
D
EASTERN CLOSURE
E
WESTERN CLOSURE

Figure 12

lie in a field perpendicular to the quartzite cleavage. The scatter of X and Y may be due to the more complex folding of the western half of the southern limb. As previously mentioned, the western half of the Baraboo Syncline contains minor folds with hinges parallel to the major fold hinge. Sampling from various locations on these minor folds could lead to the scatter of data. Sample Fr 15 was taken from the southward dipping limb of the subsidiary Happy Hill Anticline while sample Fr 17 was taken from the north dipping limb. Even with the scatter, the X axes approximately parallels the fold hinge.

Figure 12D shows the orientations of the principal strain axes for the eastern closure. Although the X axes are consistent with the rest of the syncline, the Y and Z axes vary. The Z axis plunges 58/122, while the Y axis has an orientation of 22/358. The maximum extension closely parallels the bedding-cleavage intersection which has an average orientation of 20/268.

Sample West 21 was the only sample collected from the western closure and is plotted in figure 12E. The X axis plunges 55/095, while the Z axis plunges 28/234. The plunge of the fold axis in the western closure approximately parallels the X direction.

From these data it can be seen that the Z axes lie approximately perpendicular to cleavage. This indicates that the X and Y strain axes lie in or close to the cleavage plane. This is commonly reported for deformation and cleavage development (Williams,1976, Siddans, 1972, and Wood,1974). However, it is unusual that the orientation of the principal elongation axis parallels the fold hinge of the Baraboo Syncline. The X direction plunges gently to the west on both the northern and southern limbs but plunges to the east in the western closure and to the west in the eastern closure.

Finite Strain Values

The principal strain values were also determined in this study. These values are plotted on a Flinn diagram (Figure 13). The K=1 line denotes plane strain and seperates ellipsoids of apparent flattening from those of apparent constriction. Most of the samples lie in the apparent constrictional field although a few lie in the apparent flattening field. "Apparent" has to be used, because constant volume is assumed in this figure. If volume loss occurred during deformation, the plane strain division line would have the same slope, but would shift to the right. Jank (1982) suggests that pressure solution is a major mechanism of cleavage formation in the Baraboo Quartzite, which indicates that volume change may have occurred. Assuming volume loss occurred in the Baraboo Quartzite, most of the samples would show true constrictional strain. The computer program, PASE5, calculated the percentages of flattening and stretching for each sample using the following equations: % flattening = $(1-\lambda_3) * 100$, and the % stretching = $(\lambda_1 - 1) * 100$. It is observed from these values that every sample underwent more stretching than flattening. Even the samples that fall in the field of apparent flattening were calculated to have undergone more stretching than flattening.

Geological occurrences of true constrictional strains are few. In the development of cleavage, large amounts of flattening are thought to occur (Wood, 1973, 1974; Siddans, 1972). In Cloos' (1947) study of oolites in the South Mountain fold of the Appalachians, he measured more apparent flattening than constriction. Hossack (1968) measured constrictional strains in the Bygdin Nappe and attributed it to thrusting followed by vertical compression due to overburden of the thrust sheet. Ramsay and Wood (1973) noticed that in rocks that have undergone pretectonic compaction, the initial deformation increments can give rise to apparent constrictive finite strains with the X axis at right angles to the tectonic X axis. However, Holst (1982) observed that depending upon the initial grain orientation, the strain magnitudes measured differed from the true simulated strain, but the strain orientations were quite accurate with respect to the true strain.

It has been shown (Ramsay,1967; Elliott,1970; Mukhopadhyay,1973; Lisle,1979; Seymour and Boulter,1979; and Holst,1982) that the finite strain values determined from

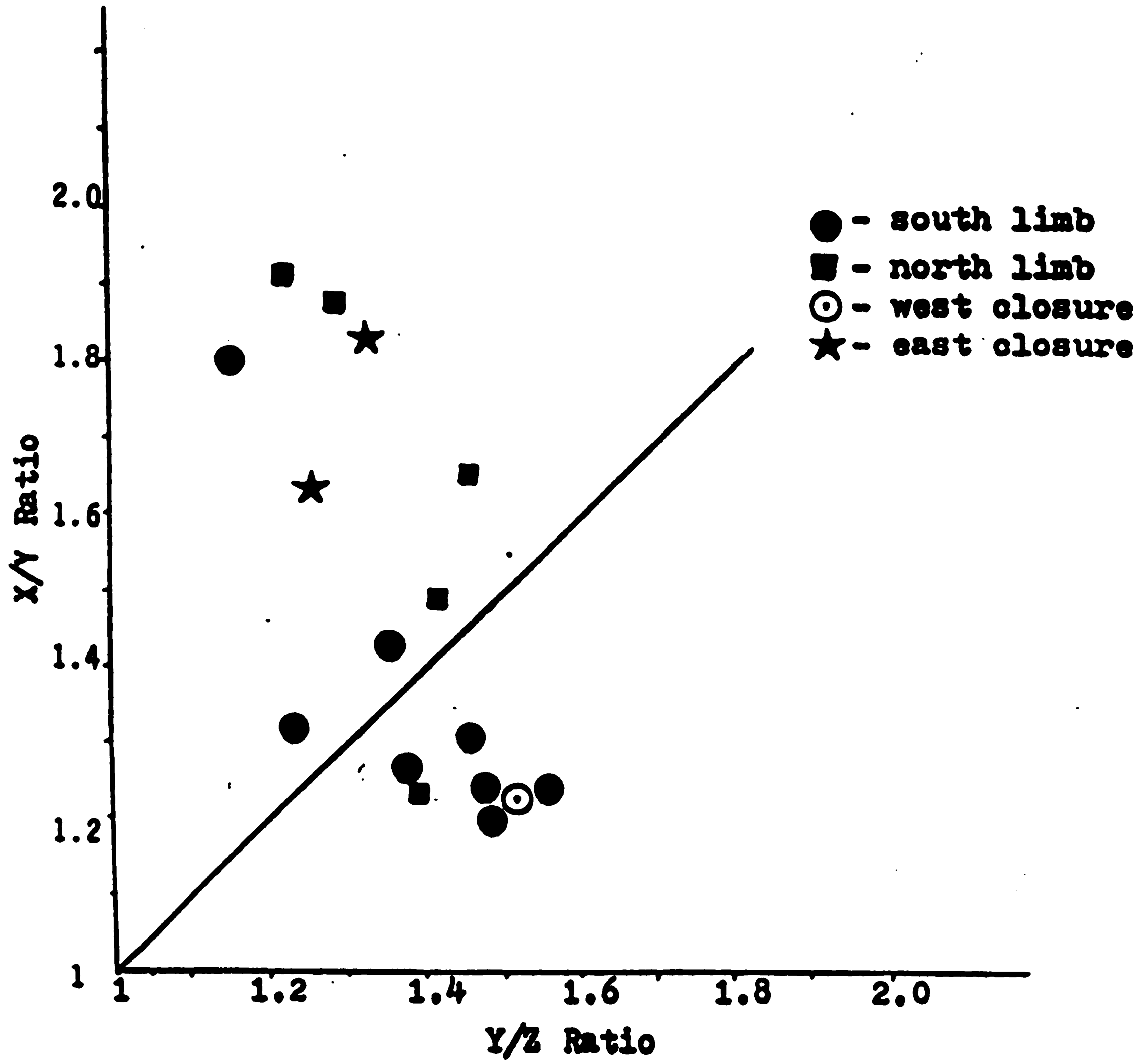


Figure 13. Flinn diagram of strain values of this study.

strain markers are a function of initial grain shape and the homogeneity of the sample. In experiments when the rocks underwent deformation with an axial ratio greater than 1.2, the orientation of the strain axes measured by the grain shapes coincided with the induced strain axes. The strain values, however, varied as a function of initial orientation and shape. This could also apply to two or more superimposed strains. Because this study uses grain shapes as an indicator of finite strain and since sedimentary fabrics and compaction effects of the Baraboo Quartzite are not known, the strain values measured more than likely are approximate compared to the true amount of tectonic strain, and should be treated with some reservation.

Reproducibility of Data

According to Fry (1979) approximately 300 quartz grains are needed to effectively produce a well defined pattern. Experimentation by the author confirmed this estimate. To achieve more reliable results, the photo enlargements were divided into six rectangular areas, each containing at least 300 quartz grains. The Fry method was applied to each area. Axial ratios and long axes orientation were averaged. These averages for each face of a sample were computer analyzed to obtain the orientation and values of the principal strain axes. Standard deviations ranged from 3 to 14 percent. This could be due to heterogeneities from one area of a thin section to another.

To compare the consistency of a sample, individual areas of sample LR 3C were compared. This sample was chosen because it had the most variation in orientation from the other LaRue quarry samples. The axial ratio and orientation of the long axis for an individual area from one face was plotted against axial ratios and orientations of individual areas of the other two faces to determine the orientations of the principal strain axes. Results are plotted in figure 14. It is seen that in the 12 different runs, the principal strain axes have a fairly consistent orientation.

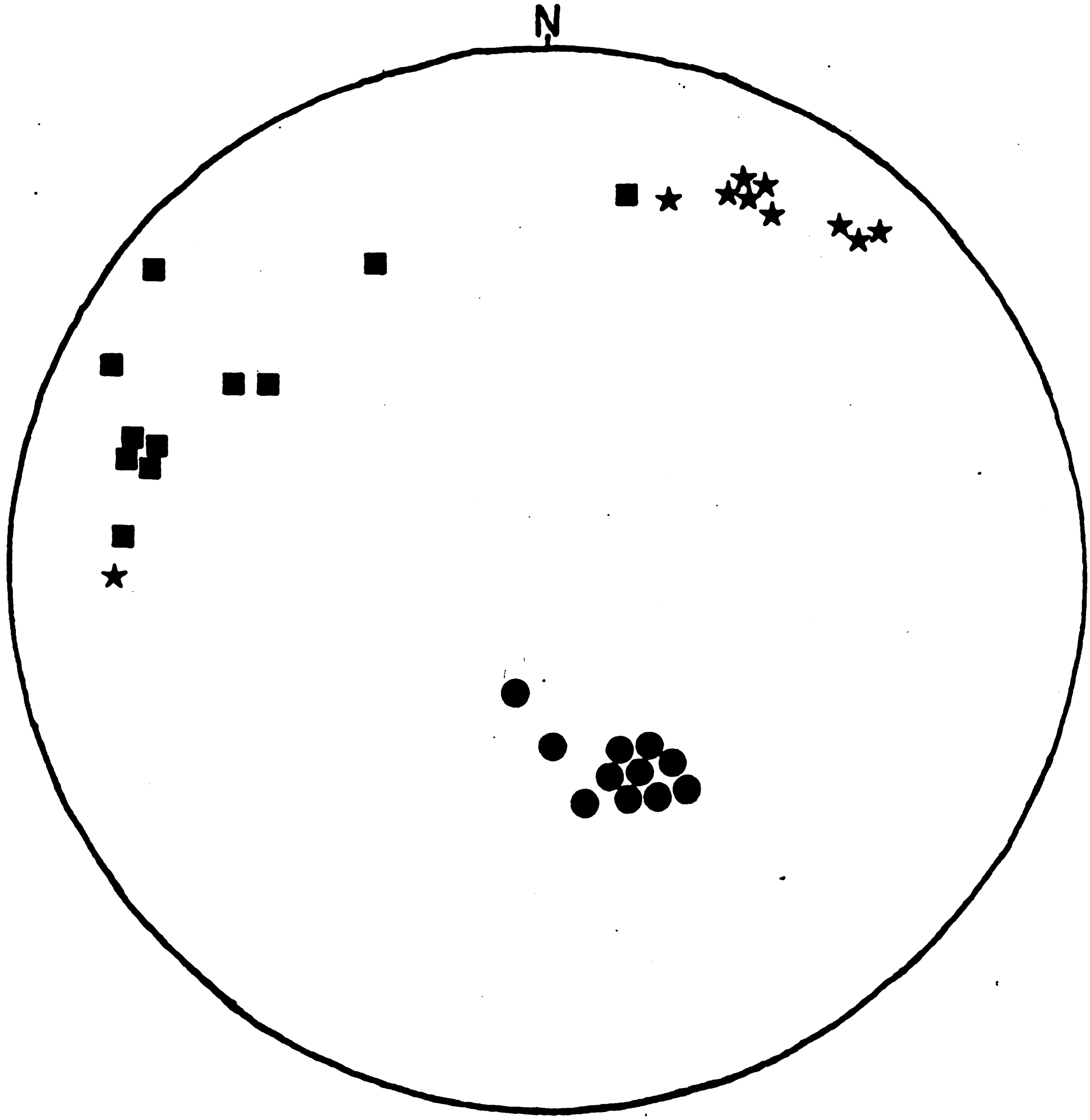


Figure 14. Equal-area lower hemisphere stereoplot of sample LR3C showing the reproducibility of data. Stars represent λ_1, squares represent λ_2, and circles represent λ_3.

DISCUSSION

Extension Parallel to the Fold Axis

The results of this study show that the finite maximum extension observed in the quartz grains and conglomerates is approximately parallel to the fold axis of the Baraboo Syncline. It is clear from this and previous studies (Dalziel and Dott, 1970, and Dalziel and Stirewalt, 1975) that the quartz grains orientation is a function of the tectonic strain. The quartz grains show a preferred orientation which is oblique to the cross stratification and ripple marks. Dalziel and Dott (1970) observed that the orientation of the pebbles and quartz grains were elongated and probably tectonically controlled. Dalziel and Stirewalt (1975) measured the orientations of stress from tension gashes in the Baraboo Quartzite. They observed maximum extension parallel to the fold hinge. The direction of maximum shortening has an average orientation of 10/170. These results parallel the results from the quartz grain shapes and add support to the idea of tectonically controlled extension parallel to the fold hinge. Rotation of the pebbles and quartz grains can not be ruled out, but is thought not to be an influential mechanism in relieving stress in the Baraboo Quartzite (Jank, 1982).

Nickelsen (1966) and Engelder and Engelder (1977) studied fossil distortions in Appalachian folds and observed extension of fossils parallel to the fold axis. Engelder and Engelder (1977) suggested that axial extension is due to layer parallel shortening normal to the fold axis. This process alone will not provide maximum extension parallel to the fold axis unless it is more efficient to accommodate shortening by extension parallel to the fold axis. Most work seems to contradict that statement. Several studies (Chapple and Spang,1974; Cloos, 1947; Engelder, 1979; and Wood,1973) indicate that the maximum extension direction is nearly vertical and perpendicular to the fold axis for most upright folds. Their explanation of deformation was horizontal compressive stresses with the easiest direction of extension being vertical. Deformation involving maximum elongation parallel to the fold axis indicates that the fold history must be more complex. Spang and Groshong (1981) explained axial parallel extension as a result of two deformations. The first deformation involved a vertical maximum compressive stress followed by a second deformation consisting of horizontal compression . They do not mention the cause of the initial vertical maximum stress, but it was probably associated with compaction and burial. They also observed a later horizontal extension in secondary features such as tension gashes which would indicate that a late stage vertical compression had also occurred. At least two thrust events are proposed for this area of the Appalachians (Perry,1978). Cloos (1947) noticed that extension parallel to the fold axis can occur in such areas as the culmination of doubly plunging folds where the fold axis is steep. This situation is observed in both the western and eastern closures of the Baraboo Syncline. Davidson (1983) measured the strain in deformed granitic rocks in Ontario, Canada that had undergone two stages of folding. He observed an extension parallel to the F_1 fold axis. The F_1 fold axis is approximately horizontal and trends northwest. The F_2 fold axis plunges steeply to the north at approximately 70 degrees. He explained that modification of a nearly recumbent, isoclinal similar F_1 fold by buckle folding and pre-existing fabric anisotropy in the granitic rocks resulted in the maximum extension being parallel to the F_1 fold axis. Flinn (1956) attributed extension parallel to the fold axis as being a combination of pure and simple shear caused by thrusting.

There are no known publications reporting the depth of burial or degree of compaction of the Baraboo Quartzite. Other studies (Curray and Griffiths,1955; Griffiths,1967; Mukhopodhyay,1973; Elliott,1970; and Holst,1982) have shown that compacted, undeformed sand grains have an orientation subparallel to bedding with initial axial ratios averaging 1.30. Holst (1982) determined that this initially perferred orientation with small axial ratios had little to no effect on the orientations of the tectonic strain axes. These studies along with the fact that the long dimension of the grains are oblique to paleocurrent directions indicates that the quartz grains and pebbles record the tectonic strain undergone during deformation of the Baraboo Quartzite.

Deformational History

Dalziel and Dott (1970) proposed that the Baraboo Quartzite has undergone a single continuous deformation which resulted in many phases of mesoscopic structural development. (See table 4 for a comparison of structures of Daziel, 1970;, Riley, 1947; and Hendrix and Shaiowitz, 1964.)

Two models are proposed by the author to explain the deformational history of the Baraboo Quartzite. The first model is uniaxial flattening in the bedding plane followed by horizontal compression which formed the syncline. The flattening stage produces disc shaped quartz grains with both the X and Y directions in the bedding plane with approximately equal values (i.e. pure flattening ; see Figure 15a). If the later horizontal compression produces a flattening strain, extension would occur in all directions parallel to the axial plane of the syncline, with shortening perpendicular to the axial plane . Superimposing these two events on the quartz grains leads to a final grain shape that is elongated parallel to the fold hinge (Figure 15b).

The second model involves initial horizontal compression followed by vertical flattening. The initial stage is

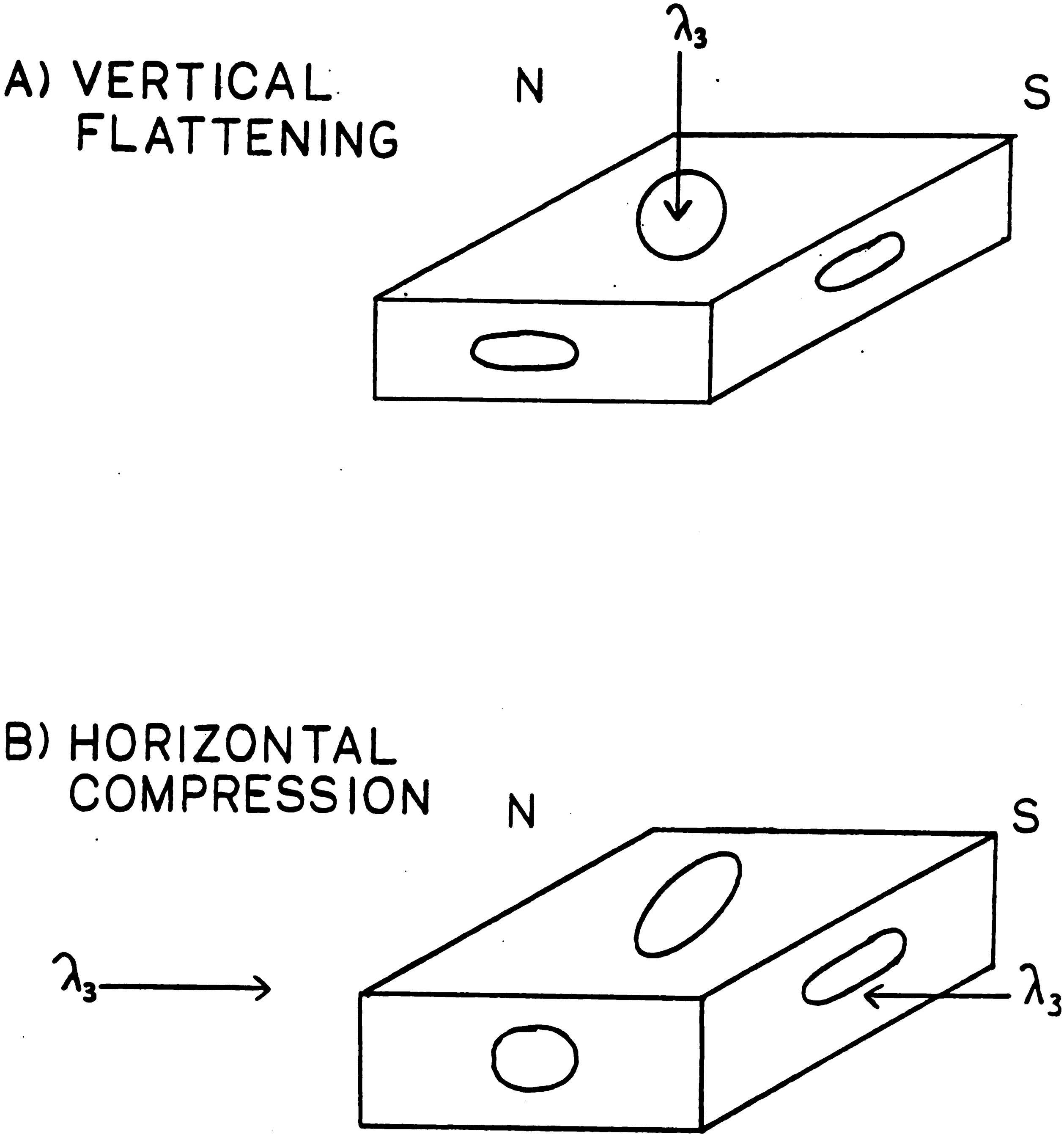


Figure 15. Deformational model involving initial vertical flattening followed by horizontal compression.

NNW-SSE horizontal compression which formed the syncline. During this compressive stage, the maximum extension would be in a vertical direction and be perpendicular to the fold hinge while the intermediate strain direction would be parallel to the fold hinge. Again, if this was a flattening strain, extension would occur in both the X and Y directions (Figure 16a).

A late stage vertical flattening is suggested by the asymmetry of the Baraboo Syncline and other mesoscopic structures (see Table 4). Most of these later stage structures suggest that the vertical flattening may be related to an added overburden caused by thrusting from the north over the Baraboo Region (Cambray, pers. comm.). The weight caused by the overburden produces flattening in the horizontal direction and shortening in the vertical direction (Figure 16b). In this stage of proposed events, the direction parallel to the fold axis undergoes continuous extension. During horizontal compression, the X direction is vertical but during vertical compression, the Z axis is vertical . In this case the X and Z strain directions interchange from horizontal to vertical compression. Superposition of the two deformations causes final maximum extension parallel to the fold hinge.

Figure 16. Deformational model which involves initial horizontal compression followed by vertical compression.

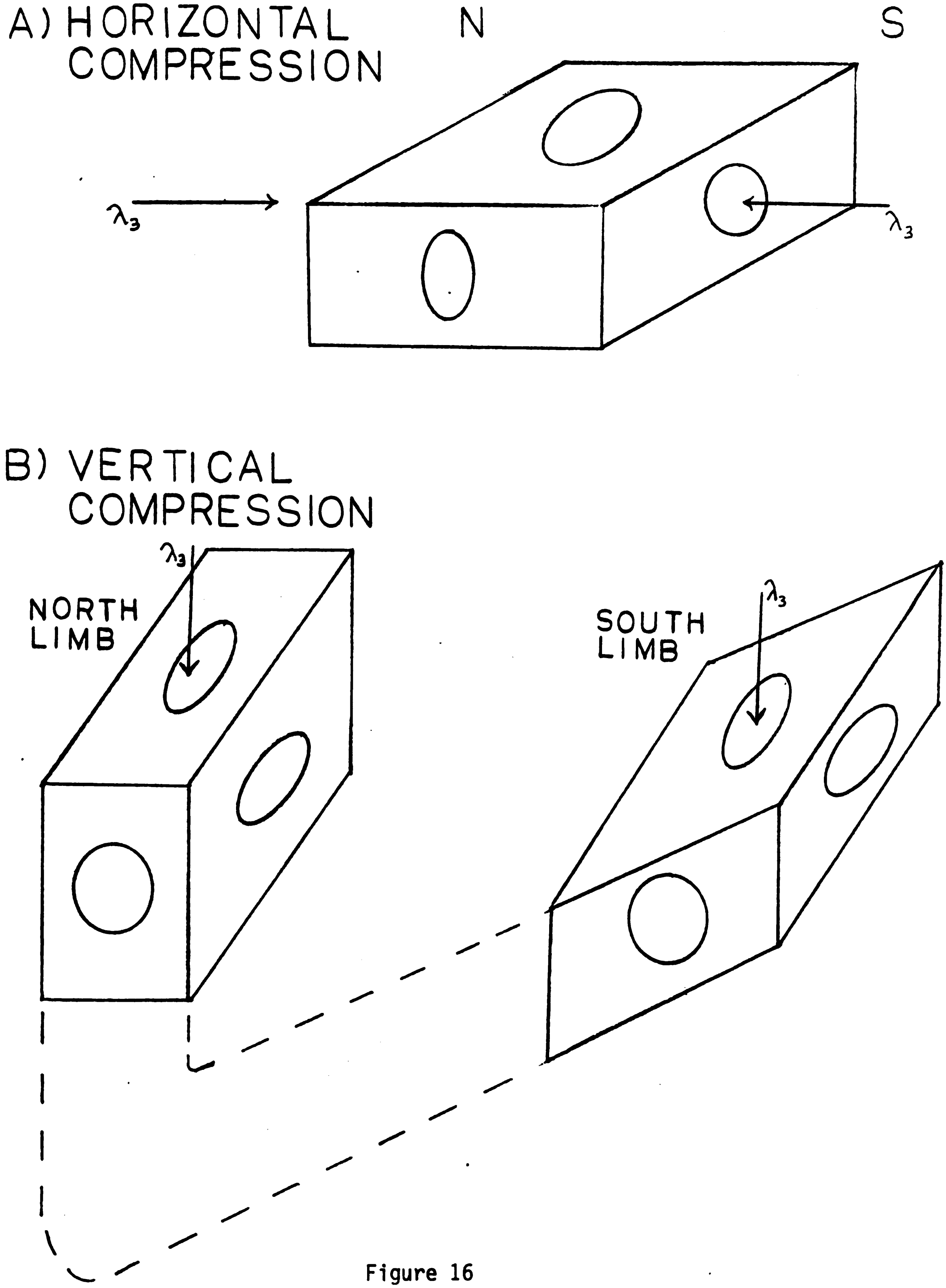

A) HORIZONTAL
COMPRESSION
N
S
λ_3
λ_3
B) VERTICAL
COMPRESSION
λ_3
NORTH
LIMB
λ_3
SOUTH
LIMB

Figure 16

COMPARISON OF TERMINOLOGY USED FOR MESOSCOPIC STRUCTURES
IN THE BARABOO QUARTZITE

Dalziel (1970)	Riley (1947)	Hendrix & Schaiowitz (1964)
PRIMARY STRUCTURES		
(S_o) Bedding (master bedding)	Bedding and bedding plane foliation (principal foliation of south limb)	Bedding
EARLY MAIN PHASE STRUCTURES		
(S_{1E}) Slaty cleavage* (S_o/S_{1E}) Bedding/slaty cleavage intersection (indistinct)	---	---
MAIN PHASE STRUCTURES		
(S_1) Phyllitic cleavage**	Axial plane foliation (north limb only)	Normal rock or fracture cleavage
(S_1') Quartzite cleavage ***	Shear fracture	---
(S_o/S_1) Bedding phyllitic cleavage intersection	Bedding/axial plan foliation/ intersection	---
(S_o/S_1') Bedding/quartzite cleavage intersection	Bedding/shear fracture intersection	---
Axial surfaces of tight minor folds	---	Axial planes of normal drag folds
Longrain (mineral elongation lineation)	Grain elongation (?)	---
Slickensides on bedding	---	a lineation on bedding
Boudin axes	---	Boudin axes
LATE MAIN PHASE STRUCTURES		
(S_{1L}) Faint strain-slip or crenulation cleavage	---	---
Axes of fine crenulations	---	---
SECONDARY PHASE STRUCTURES		
(S_2) Strain-slip or crenulation cleavage	---	Reverse slip or rock cleavage; reverse shear zones
Axial surfaces of minor chevron folds	---	Axial planes of reverse drag folds
Axes of crenulations and minor chevron folds	Crests and troughs of chevron or buckling folds	Axes of reverse drag folds
LATE PHASE STRUCTURES		
Axial surfaces of open minor folds	---	---
Axes of open minor folds	---	---
STRUCTURES OF VARIOUS AGES		
Joints; quartz-filled joints	Joints; quartz-filled joints	Joints
Slickensides	Slickensides	Slickensides
Quartz "veins"; quartz filled tension gashes in bands, some deformed	Quartz veins; quartz filled ladder tension fractures; deformed and S-shaped, quartz filled gash veins	Quartz filled joints
Breccia zones	Breccia zones	---
STRUCTURES OF DOUBTFUL AGE		
Cleavages in quartzite other than S_1'	Shear fractures (?)	---

** "Fracture cleavage" of Van Hise, C. K. Leith and other geologists of the "Wisconsin school."

*** "Strike jointing" of geologists of the "Wisconsin school".

(Taken from Dalziel and Dott,1970)

Tectonic Implications of Baraboo Interval Deformation

The asymmetry of the Baraboo Syncline suggests initiation of compressional forces from the north. This would cause thrusting away from the Proto-North American craton (see Ghosh, 1966). In the northern Midwest, the Baraboo Quartzite sits in a location where the basement rock is progressively older to the north and younger to the south. This age progression southward suggests continental accretion which supports the existence of some form of plate tectonics. The elongated outcrop pattern of the Baraboo Quartzite and the correlative Souix Quartzite in Minnesota and North Dakota parallels the suture belt of the Penokean Orogeny (1.8-1.9 Ga). This area south of the Penokean Orogenic belt could represent a foreland basin which was infilled by sediment from the Orogenic belt and younger anorogenic rocks. This area was later deformed by NNW-SSE compressional forces. Forces responsible for this deformation were probably a continuation of the tectonic processes that were active during the Penokean Orogeny. The fold thrust belt of the Penokean could have been reactivated due to lithospheric plate interactions which in turn caused thrusting over the Baraboo region. The Appalachian and Cordilleran Orogenies each had several orogenic events. The Appalachian Orogeny had three orogenic events extending over a period of approximately 300 million years. The Baraboo Interval rocks were deformed around 170 million years after the Penokean Orogeny.

Other strain studies in thrust zones (Flinn; 1956, Hossack; 1968, and Engelder and Engelder; 1978) have shown extension parallel to the fold axis and also parallel to the strike of the thrust plane. These studies were conducted in the footwall of thrusts.

CONCLUSION

From this study of finite strain in the Baraboo Quartzite, it was observed that the finite elongation of the quartz grains and pebbles are parallel to the fold axis. Other reports of extension parallel to the fold axis have proposed at least two deformational events. Mesoscopic structures observed in the Baraboo Quartzite also points to a more complex deformational history. There are two possible deformational models that apply to the Baraboo Syncline. The first model involves initial vertical compression followed by horizontal compression which formed the Baraboo Syncline. The second model entails a deformational history which is similar to Appalachian folds and involves an initial NNW-SSE horizontal compression, forming the Baraboo Syncline, followed by vertical compression due to crustal loading from an overlying thrust sheet. Most of the late stage structures found in the Baraboo Quartzite support a late stage vertical compression. Either model, however, can explain maximum elongation parallel to the fold hinge.

The tectonic setting proposed for the Baraboo Quartzite is a foreland basin located to the south of the Penokean Orogeny. Erosion of these rocks along with younger anorogenic rocks were the source of sediment for the Baraboo Quartzite. This basin was later deformed possibly as a continuation of the tectonic processes that were active during the Penokean Orogeny.

APPENDIX

Methodology of 3-Dimensional Strain Program

This program, given to me by Dr. Roy Kligfield is used to combine two dimensional strain data from three mutually perpendicular planes to give a complete three dimensional strain analysis. The basic tensor relationships were provided by Owens(1969, 1984) which parallel the analysis given by Ramsay(1967,p. 142- 147, p. 199-200). Provided strict adherence to a right-hand- down cartesian reference frame, the interpretation of the matrix of direction cosines, relating the principal axes of the strain ellipsoid to the reference frame, is unambiguous (Owens,1984). The solution for the eigenvectors given by Ramsay(1967) requires that the choice of sign of each direction cosine be made by inspection, which may in some instances be ambiguous (Kligfield, pers. comm.).

The two dimensional data is referred to a right hand down reference frame which is defined by the three mutually perpendicular planes. The matrix representation of the ellipse tensor, A, referred to its principal axes, in a diagonal form is

$$A = \begin{vmatrix} 1/R^2 & 0 \\ 0 & 1 \end{vmatrix}$$

where R is the axial ratio of the ellipse. This ellipse may be referred to the specimen reference axes by the tensor transformation:

$$E=B.A.B'$$

where B is the two dimensional rotation matrix:

$$B = \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix}$$

and B' is the transpose of B. Three such matrices, one in each reference plane, can be set up :

$$E_{xy}= \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \quad ; \quad E_{yz}= \begin{vmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{vmatrix} \quad ; \quad E_{zx}= \begin{vmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{vmatrix}$$

By defining scaling ratios

$$k_1=a_{11}/\ c_{22} \quad ; \quad k_2= a_{22}/\ b_{11} \quad ; \quad k_3= c_{11}/\ b_{22}$$

the two dimensional ellipse tensors, (E_{xy},E_{yz},E_{zx}) may be combined in six independent ways to derive the ellipsoid tensors of the specimen. Where there is redundant data, there could be a degree of mismatch between the three sections and thus the scaling ratios are used to distribute the error appropriately (Owens, 1984).

The six ellipsoid tensors, two on the basis of each plane, with their internal inconsistency level are as follows: On the basis of xy plane:

$$S(1,2)= \begin{vmatrix} a_{11} & a_{12} & c_{12}*k_1 \\ a_{21} & a_{22} & b_{12}*k_2 \\ c_{21}*k_1 & b_{21}*k_2 & b_{22}*k_2 \text{ or } c_{11}*k_1 \end{vmatrix}$$

$$\text{Internal inconsistency level} = \frac{|b_{22}*k_2 - c_{11}*k_1|}{b_{22}*k_2 + c_{11}*k_1}*100$$

On the basis of yz plane:

$$S(3,4) = \begin{vmatrix} a_{11}/k_2 \text{ or } c_{22}/k_3 & a_{12}/k_2 & c_{12}/k_3 \\ a_{21}/k_2 & b_{11} & b_{12} \\ c_{21}/k_3 & b_{21} & b_{22} \end{vmatrix}$$

$$\text{Internal inconsistency level} = \frac{|a_{11}/k_2 - c_{22}/k_3|}{a_{11}/k_2 + c_{22}/k_3}*100$$

On the basis of zx plane:

$$S(5,6) = \begin{vmatrix} c_{22} & a_{12}/k_1 & c_{12} \\ a_{21}/k_1 & a_{22}/k_1 \text{ or } b_{11}/k_3 & b_{12}/k_3 \\ c_{21} & b_{21}/k_3 & c_{11} \end{vmatrix}$$

$$\text{Internal inconsistency level} = \frac{|a_{22}/k_1 - b_{11}/k_3|}{a_{22}/k_1 + b_{11}/k_3}*100$$

The internal inconsistency level is the degree to which the two ellipsoids differ.

Since the two dimensional ellipse tensors are symmetric, the three dimensional ellipsoid tensors, S1 to S6 are also symmetric. Each of the ellipsoid tensors are diagonalized using subroutine EIGEN, and from the eigenvalues the following parameters can be determined;

AFLIN=x/y ; BFLIN=y/z ; FLINK=AFLIN-1/BFLIN-1 (FLINN,1962)

ARAM=ln(x/y) ; BRAM=ln(y/z) ; RAMK=ARAM/BRAM (Ramsay,1967)

The percentages of flattening and stretching are also determined.

All six analyses are performed and the results printed out. The best ellipsoid is then computed by averaging the components of the six ellipsoid matrices, S.

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