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FINITE STRAIN IN THE PRECAMBRIAN KONA FORMATION, MARQUETTE COUNTY, MICHIGAN

By

David B. Westjohn

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ABSTRACT

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Kona slates contain reduction spots and deformed veins. Each feature has been used elsewhere to measure strain in rocks. Reduction spots and veins at Harvey were used independently to determine the dimensions and orientation of the minimum finite strain ellipsoid. Reduction spots west of Harvey were used to test for strain variation in the Marquette Trough.

Strain values from the reduction spots and veins at Harvey were similar. Both demonstrated a 45% flattening along a horizontal Z axis, with extensions of 60% and 15% on X and Y respectively. Reduction spots west of Harvey show similar extensions. Strain axes had similar orientations at all locations.

It is suggested that Kona slates were shortened by at least 45% normal to the Marquette Trough margins by a flattening style of deformation. The agreement of strain values from reduction spots and deformed veins supports a

conclusion that either feature can be used to measure finite strain in deformed rocks.

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INTRODUCTION

The concept of strain allows one to evaluate the orderly adjustment produced in rocks by a system of tectonic stresses and it can be measured if certain information is known about the predeformation state of the rocks. The analytical techniques that have been developed (see Ramsay, 1976, for a discussion of the known methods) rely on some knowledge of the predeformation shape or size of a strain marker which was embedded prior to deformation, and such features as oolites (Cloos, 1947), pebbles (Gay, 1969), fossils (Houghton, 1856 and Tan, 1970), reduction spots (Sorby, 1856, and Wood, 1965) and deformed veins (Talbot, 1970) have been used as a means of estimating strain in rocks. However, there is uncertainty as to how accurate the values are, since errors result from the assumptions which must be made to use the features as a measure of natural strain. For example, it was assumed in previous studies that pebbles, oolites and reduction spots (Gay, 1969; Cloos, 1947; and Wood, 1975) were initially spherical, and their ellipsoidal form resulted from the distortion suffered by the host rock during deformation. Strain can be quantified using those features by evaluating the shape change an equal volume sphere would have to undergo to produce the resultant ellipsoid. Obviously, any deviation from initial sphericity would produce error. All techniques that have been developed require assumptions which cannot be demonstrated, and therefore, one cannot be sure that the strain values from the known methods are accurate.

The primary goal of this study was to test two independent methods of finite strain analysis (finite strain refers to the final strain state of the rocks). Reduction spots and deformed veins occur in Kona slates at the Harvey Syncline allowing one to calculate the strain for one deformation domain using two independent techniques (Wood, 1975; Talbot, 1970). By nature of the assumptions inherent in the methods, the features can be used to define the shape and orientation of the minimum finite strain ellipsoid, and since they occur in the same deformation domain, reduction spots and deformed veins should yield similar values.

There were two secondary goals. Kona slates have a well developed slaty cleavage and it has been suggested (Wood, 1974) that cleavage precisely parallels the XY plane of the minimum finite strain ellipsoid. The goal was to test that suggestion by comparing the orientation of slaty cleavage to the XY plane orientation determined from the strain indicators. It was recognized from Taylor's work (1973), that Kona slates at Harvey were mapped as part of the gray green argillite member, and his stratigraphic map was used to locate 8 sites where reduction spots occur (see figure 2). The goal was to measure strain at other locations to test for strain variation in the Marquette Trough.

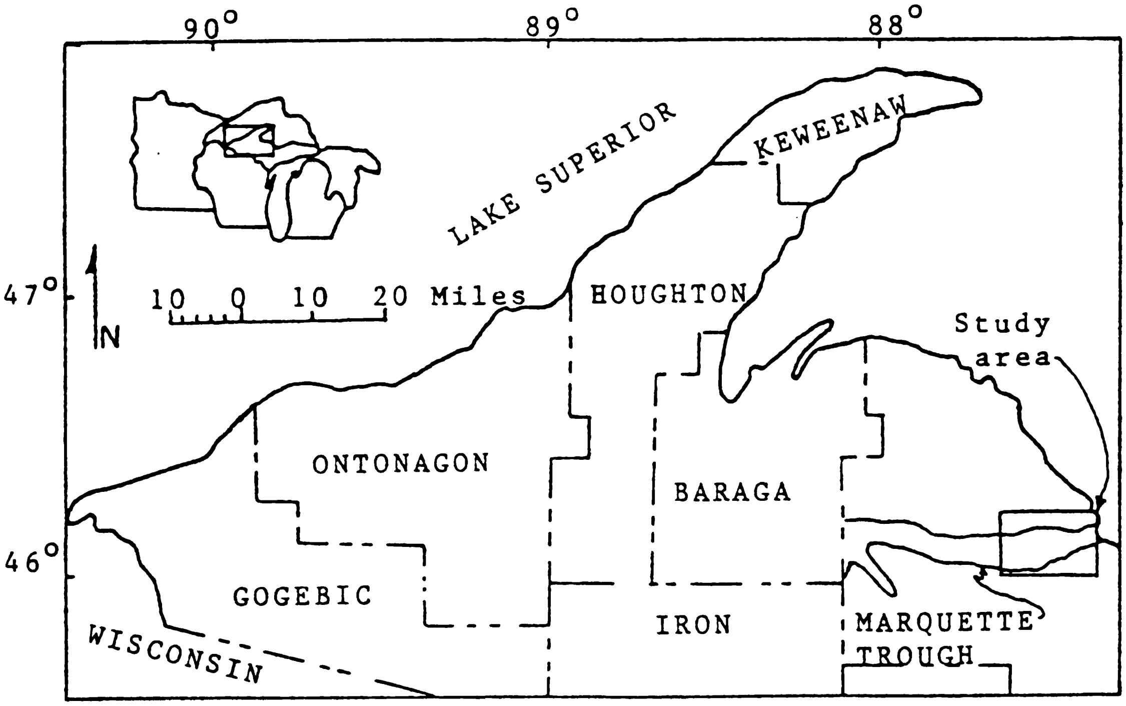
GEOLOGIC SETTING

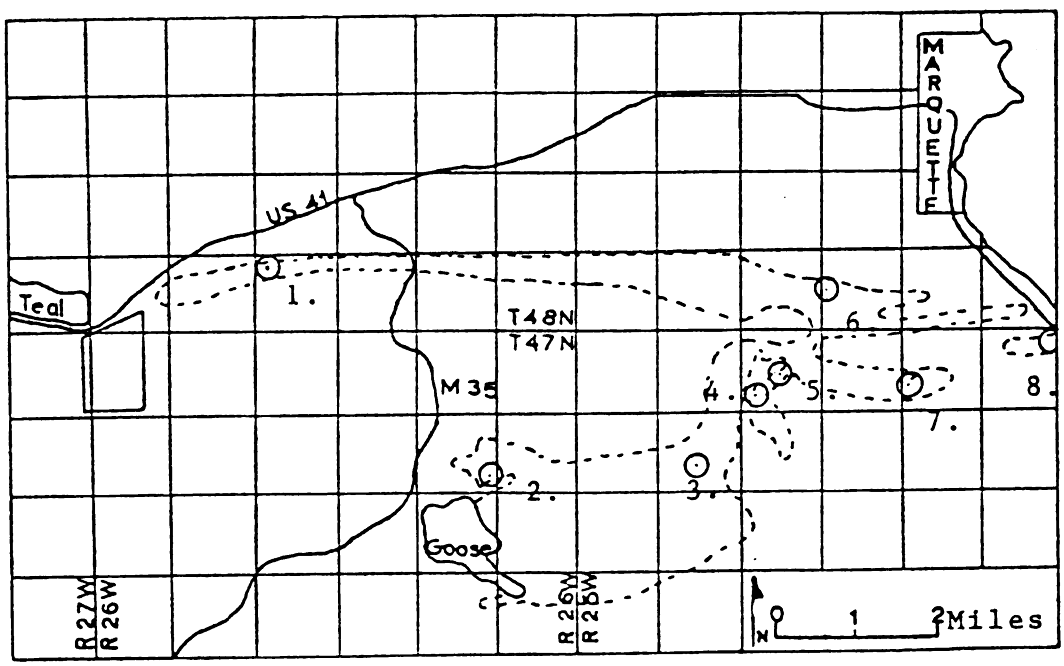
The study area lies along the southern margin of the Canadian Shield, and the location is outlined in Figures 1 and 2. An extensive geologic report by Van Hise and Bayley (1897) interprets the Proterozoic history of most of the Upper Penninsula of Michigan, and only a few significant changes have resulted from later investigations. Gair and Thadden (1968) mapped the eastern portion of the study area and Puffet (1974) mapped the western part near Negaunee (see location map, Figure 2), but all authors credit Van Hise's contributions as a basis for their work. As with most Precambrian terrains, no universal nomenclature exists and in this report, Cannon and Gair's (1970) revised stratigraphic nomenclature will be used. The term "Marquette Supergroup" proposed by those authors was assigned to the deformed Middle Precambrian metasediments of the Marquette area. The formations of the supergroup are described in detail by Gair and Thadden (1968), and the Kona Formation, which is of particular interest in this study is described in detail in Taylor's work (1973). The reader is referred to those papers for complete lithologic descriptions.

The major structural feature of the area is the

Figure 1. Map of the Northwestern Upper Peninsula of Michigan showing the study area location.

Figure 2. Map showing 8 sites where reduction spots occur. The areal extent of the Kona Formation is the area inside the dashed line.


90°
89°
88°
47°
46°
N
10 0 10 20 Miles
LAKE SUPERIOR
KEWEENAW
HOUGHTON
Study area
ONTONAGON
BARAGA
GOGEBIC
IRON
MARQUETTE
TROUGH
WISCONSIN


MARQUETTE
US 41
Teal
T48N
T47N
M 35
Goose
R27W
R26W
R26W
R25W
0 1 2 Miles
N
1.
2.
3.
4.
5.
6.
7.
8.

Marquette Synclinorium, which is a west-trending trough of deformed Middle Precambrian metasediments (the Marquette Supergroup). Deformation in the trough is attributed to the Penokean Orogeny (Cannon, 1973), which occured approximately 1.85 - 1.95 b.y. ago (Van Schmus, 1976). The tectonic event included deformation, metamorphism, extrusive and intrusive igneous activity.

Cannon (1973) suggests the style of the deformation is indicative of an extensional environment, and he proposes that vertical tectonics best explains the folding present in the Marquette Supergroup. He suggests that the supergroup was deposited on a peneplaned Archean basement, and the sediments were subsequently folded by two processes. It is proposed that after regional gravity sliding produced gentle folds, vertical motion along faulted Archean basement rocks draped the folded supergroup into the Marquette Trough. The model has recently been restated by Klasner (1978), who proposes 3-4 phases of deformation to explain the fold patterns. The deformation history of the Marquette Synclinorium is by no means clear, and although Cannon's model is viable, more geologic evidence is needed to support or reject it.

Part of the evidence needed to evaluate the style of deformation is the nature of the strain induced in the Marquette Supergroup. The Precambrian Kona Formation provided an opportunity to collect such information. The Kona is one of the best exposed lithologies in the trough (see

Gair and Thadden, 1968, enclosures) and it is particularly interesting from a structural standpoint because it contains easily recognizable primary features and the slaty units in the lower part of the formation have a well developed secondary fabric. Furthermore, as pointed out by F.W. Cambray (personal communication), slates at the Harvey Syncline (site 8, Figure 2) contain reduction spots and deformed veins, and those features were the major stimulus for this work. The strain values for Kona slates were determined using those features, and the procedure for obtaining the data will now be discussed.

METHODS

Reduction Spots and Wood's Method

Although Sorby (1853) is credited with recognizing reduction spots as natural strain indicators, Wood's (1973, 1974 and 1975) recent publications have been most useful, and the basic procedure he employed to measure strain using reduction spots was only slightly modified for this study. Several assumptions are necessary to use the features as a measure of natural strain, and before discussing the techniques used, the assumptions will be reviewed.

Reduction spots are yellow to pale-green bodies in maroon to red colored ferruginous rocks, which are thought to develop under localized reducing conditions (Ramsay, 1967). Tullis and Wood (1975) state that a predeformation origin can be demonstrated, but no evidence was published with their work. A literature search produced one citing on the origin of reduction spots and reduced beds in red beds. Miller and Folk (1955) discuss a diagenetic origin for reduction bodies; those authors noted the absence of detrital magentite and illmenite in the reduced spots and they suggest the minerals dissolved under local reducing conditions. This author has observed reduction spots in the undeformed Jacobsville Formation near Marquette, Michigan, where the features must have had a diagenetic origin. The origin is very important since it must be assumed that the reduction spots were present in the rocks prior to deformation. Although it cannot be directly demonstrated, most evidence supports a predeformation, diagenetic origin.

The most important assumption, that reduction spots were initially spherical is the most difficult to support. Tullis and Wood (1975) state it can be "demonstrated that these bodies are of diagenetic origin, were present prior to deformation, and were initially spherical in form." It must be assumed that the reduction spots were initially spherical, and any deviation from that form induces error in the strain values. Aside from some geometric evidence which is discussed later in the paper, the only support for a predeformation spherical form was found in Miller and Folk's work (1955). Those authors observed two types of reduction spots, the most abundant having an irregular geometry, while less abundant forms were spherical. Reduction spots were observed in the Jacobsville Formation by this author, and their shapes confirm Miller and Folk's report; although many spots were spherical, that was not the most common geometry. Although some evidence supports Wood's assumption, it has not been directly demonstrated and assuming initial sphericity is probably the greatest limitation to the method.

It must also be assumed that any volume loss undergone after the formation of reduction spots has a negliable effect. Ramsay and Wood (1973) discuss the geometric effects of volume change, and Wood (1973) evaluates the errors which might result from various volume losses. Quantifying the volume loss is a difficult problem, as pointed out by Shackelton (1962). Density change has been used as a measure of volume reduction, but the removal of solids by dissolution or pressure solution mechanisms would not be accounted for by simple density contrasting. There is no apparent way to quantify the volume loss, but Wood's (1973) calculations show that reductions less than 20% could be neglected, while greater volume losses would produce significant error in the strain values.

Any analysis of natural strain in rocks is limited by the necessity of assuming that deformation was homogeneous on the scale of the strain marker. This assumption can be demonstrated for reduction spots, but it poses definite limitations on other types of strain indicators. For example, oolites and pebbles have been used in other studies (Cloos, 1947, and Gay, 1969), but homogeneous deformation is unlikely where a ductility contrast exists between the matrix and the strain marker. However, there appears to be no mechanical difference judged petrographically between reduction spots and their enclosing matrix. Although there are mineral and grain anisotropies which prevent homogeneous deformation, it can be assumed with confidence that deformation on the reduction spot scale was homogeneous.

When one considers the assumptions which must be made, it is immediately evident why some geologists question the accuracy of strain values. Hence, the Marquette area provides a unique tectonic environment, because it contains 2 types of natural strain indicators in one deformation domain. The reduction spots occur with deformed veins (the method developed by Talbot, 1970, is discussed later in the paper) at the same outcrop, and if all the assumptions are valid, each feature should yield the same values of strain. Before the results of the study are presented, the methods of Wood (1974) and Talbot (1970) will be discussed in detail.

For Wood's method, each reduction spot is inferred to be a deformation ellipsoid, and the volume of the ellipsoid can be calculated using the maximum, intermediate and minimum axial lengths ($V_e = (4/3)\pi XYZ$). The volume calculated for the ellipsoid is assumed to be equal to that of the original sphere, and the radius can be calculated from the volume equation $V_s = (4/3)\pi r^3$. The radius of the original sphere is then compared to the axial lengths of the deformation ellipsoid, and the finite strain is evaluated in the following manner.

The equation $e = (l-l_o)/l_o$ gives the relative change in length in terms of the elongation e, by comparing the original length l_o (original sphere radius) to the deformed length l (axial length of the ellipsoid).

The principle extensions of the ellipsoid axes are thus calculated, and are represented by the variables e_1, e_2 and e_3 for the maximum, intermediate and minimum axes. Wood (1974) uses the convention $X > Y > Z$ for the axes of the deformation ellipsoid, such that the extension along the X axis would be the e_1 component. To interpret the finite strain using the ellipsoids, Wood graphs the log X/Y versus log Z/Y, where the principle finite strains along axes X, Y and Z are $1+e_1$, $1+e_2$, and $1+e_3$ respectively (Hobbs, et.al. 1976).

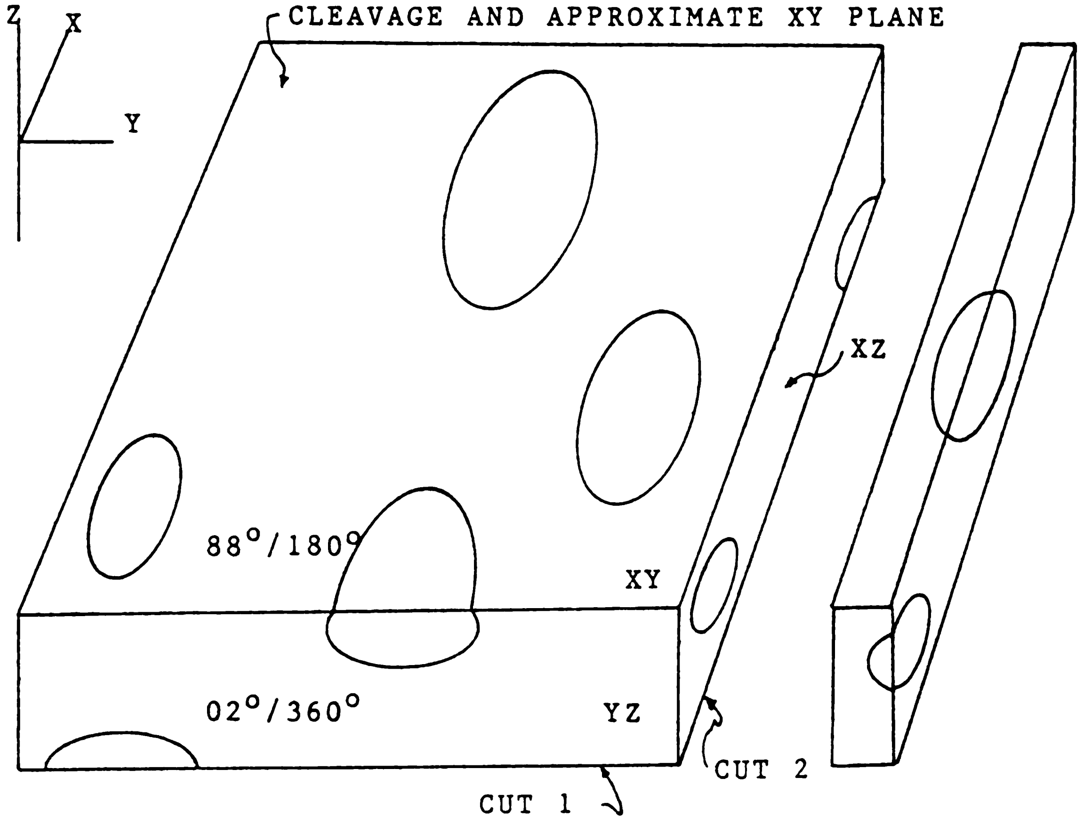
The graph is an adaptation of the Flinn Diagram, the only difference being Wood uses the minor axis divided by the intermediate (the inverse of Flinn, 1962). However, the diagram yields essentially the same information in a more convenient form. The extension along each of the principle axes can be read directly from the diagram (see Figure 6 for example). Accurate measurement of the ellipsoid axes requires a technique which is tedious and time consuming. Wood's technique is illustrated in his 1975 article, and Figures 3-5 show the method used in this study. Wood's method was modified in attempt to improve the accuracy and to allow error calculations.

Reduction Spots: Westjohn's Method

For this study, oriented specimens containing reduction spots were collected at 8 locations (see location

Figure 3. Block diagram illustrating the cuts necessary to define the XY plane orientation. Mutually orthogonal planes to cleavage expose XZ and YZ principle sections, and the trace of the X and Y axes on those surfaces was used to determine the orientation. The slice shown with the diagram represents one of 16 slices cut from the initial block. All ellipses exposed on these sections were used to determine the XY plane orientation.

Figure 4. The block diagrams illustrate a sequence of ellipses exposed on the surfaces ground parallel to the XY plane. Each block in the sequence from 1-4 has had a 0.01 inch slice ground away. The Z spacing (0.01 in. for this example) refers to the amount of the Z axis removed with each grinding cycle.


Z
X
Y
CLEAVAGE AND APPROXIMATE XY PLANE
XZ
88°/180°
XY
02°/360°
YZ
CUT 2
CUT 1

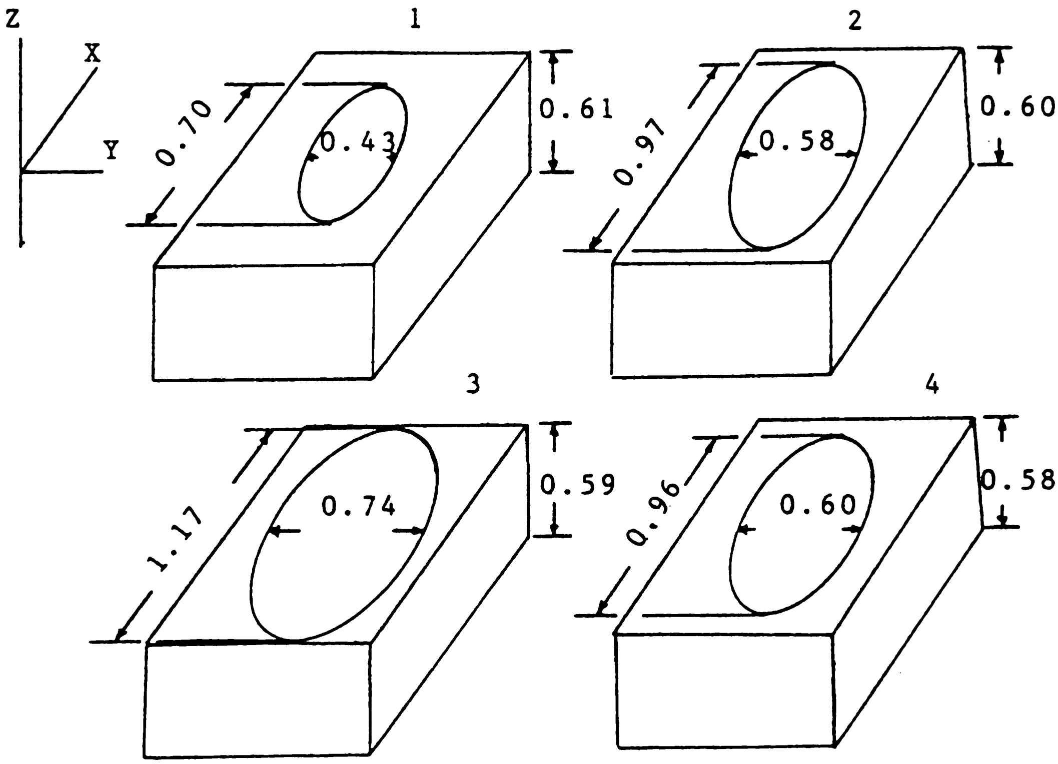
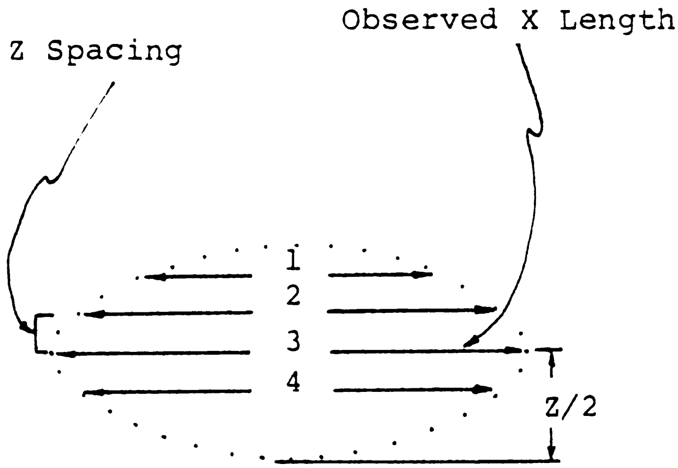

Z
X
Y
1
0.70
0.43
0.61
2
0.97
0.58
0.60
3
1.17
0.74
0.59
4
0.96
0.60
0.58

Figure 5. Construction of XZ and YZ principle planes from XY sections 1-4 (Figure 4). For illustration purposes, the axial lengths have been exagerated. (X and Y 2 times and Z is exagerated 10 times the scale in Figure 4)

XZ PLANE



YZ PLANE

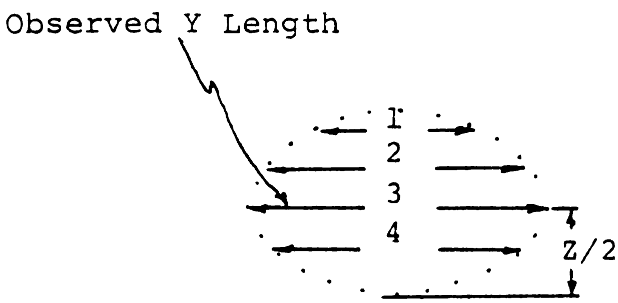
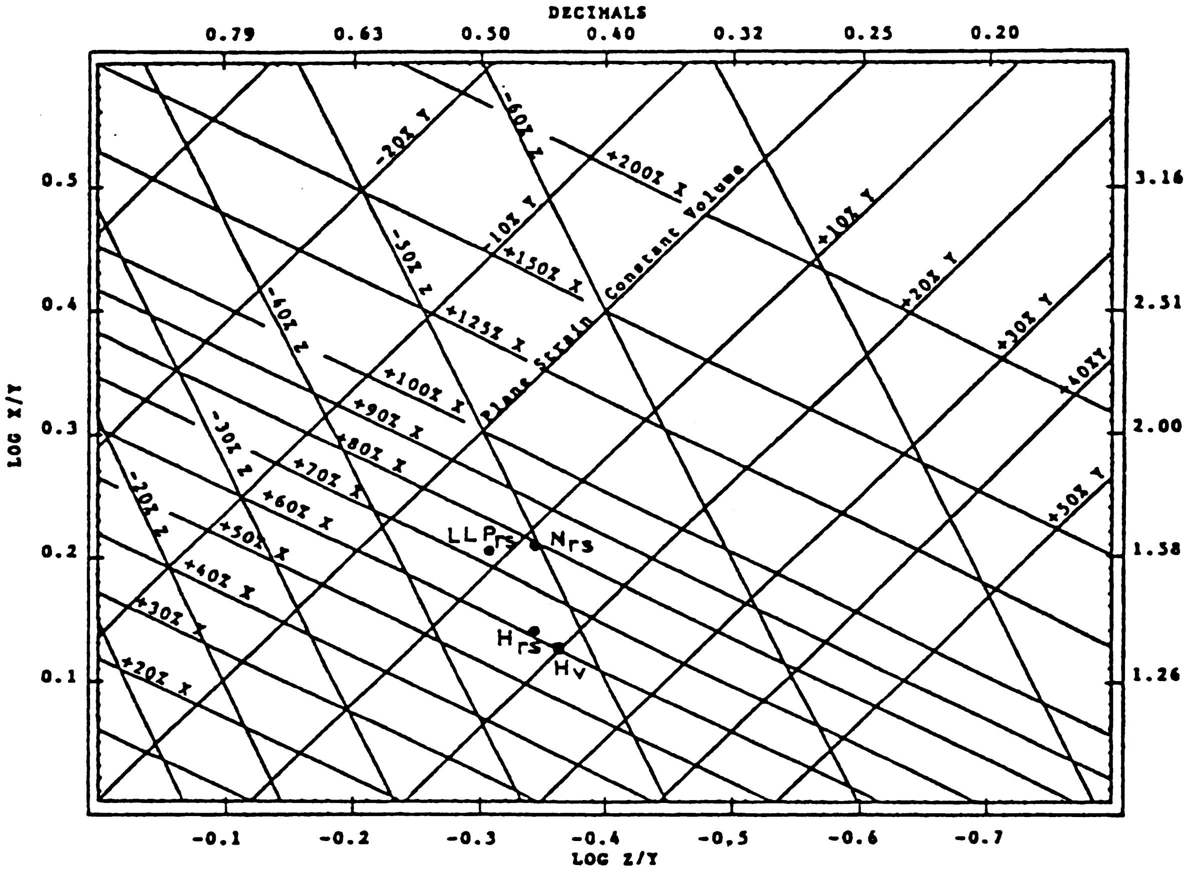
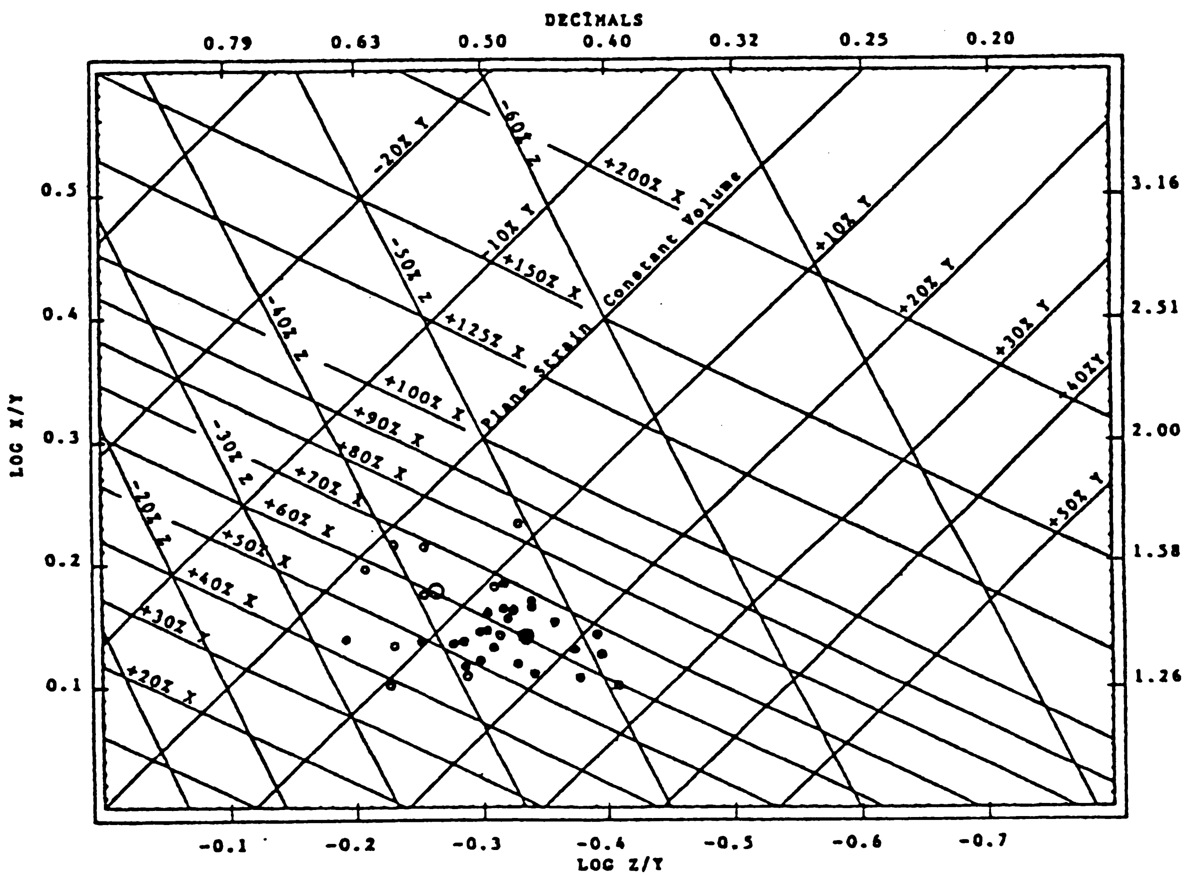


Figure 6. Plot of the strain data from 3 sites. The letter by the plot refers to the location. (Hrs = mean of 25 reduction spots, Harvey; Hv = plot from deformed veins, Harvey; Nrs = mean of 35 spots, site 1; LLPrs = mean of 10 spots, site 4.)

Figure 7. Plot of 35 deformation ellipsoids to show the variation in the data for the Harvey Syncline. (Each ● represents 1 ellipsoid, axes measured by Westjohn method. Each ○ represents 1 ellipsoid, via Wood's method. Means are plotted with large symbols).


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
0.5
0.4
0.3
0.2
0.1
3.16
2.51
2.00
1.58
1.26
-60% Z
-50% Z
-40% Z
-30% Z
-20% Z
-20% Y
-10% Y
+10% Y
+20% Y
+30% Y
+40%Y
+50% Y
+200% X
+150% X
+125% X
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
Constant Volume
Plane Strain
LLPrs
Nrs
Hrs
Hv
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
LOG Z/Y


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
0.5
0.4
0.3
0.2
0.1
3.16
2.51
2.00
1.58
1.26
-60% Z
-50% Z
-40% Z
-30% Z
-20% Z
-20% Y
-10% Y
+10% Y
+20% Y
+30% Y
+40%Y
+50% Y
+200% X
+150% X
+125% X
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
Constant Volume
Plane Strain
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
LOG Z/Y

map) in the Marquette Synclinorium. All samples were maroon slates of the gray green argillite member (as mapped by Taylor, 1973), and the samples were selected from various structural domains in the synclinorium where the reduction spots occurred.

Large specimens were obtained (some greater than 60 pounds) because considerable trimming was needed to prepare the specimens for measurements. The field orientation was determined on a cleavage surface, which turned out to be useful in the lab because in general the cleavage was parallel to the XY plane of the deformation ellipsoids. Each specimen was trimmed in the manner depicted in Figure 3. Two planes were selected orthogonal to the cleavage, so as to expose XZ and YZ sections of the ellipsoids. The mean XY plane orientation was determined based on the ellipsoids exposed during trimming, and in all cases the cleavage orientation was parallel to the XY plane, that is it was within the degree of accuracy for the measurements presented in this study.

The oriented specimens were mounted in a grinding chuck, and the XY plane was oriented parallel to the table of a Brown and Sharpe surface grinder. Two thousandths of an inch intervals were ground from the XY surface, and after each grinding cycle, the X and Y axes of any exposed ellipse were measured with a 20X Bausch and Lomb graduated lens. The idea behind this technique was to expose enough

XY sections of each ellipsoid, so as to determine the maximum dimensions of the X and Y axes. The axial lengths were recorded for each ellipsoid as grinding progressed, and eventually each ellipsoid was entirely ground away. The grinding records were then used to calculate the axial lengths.

With a properly oriented specimen, each grinding cycle removes 0.002 in. of the Z axis, and the length of the Z axis for each ellipsoid was graphically determined as illustrated in Figure 5. The X and Y axes were assumed to be the largest dimensions measured while the depth of grinding gave the Z axis length (see inferred X and Y lengths, Figure 5).

Errors associated with this technique are evaluated in the error analysis section. Obviously, there were variations in the axial ratios for deformation ellipsoids at each site, and Figure 7 displays the variation for the Harvey Syncline.

The axial orientations of the ellipsoids principle axes were determined as follows. The trace of the axis on the XY plane completely defines the orientation of all axes. With the XY plane orientation determined from the field orientation, the Z axis is normal to the plane, and the orientation of the X axis can be solved stereographically from its trace on the XY plane. The Y axis has to be perpendicular to X and Z axes.

Two techniques were employed to observe the variation in the axial orientations. According to Wood (1974), cleavage is precisely perpendicular to the Z axis of the reduction spots, and although "precisely" may be overstating the case, it was found to be generally true in this study. Figure 8 displays the variation of 25 X axes, whose orientations were measured as follows. Ellipses exposed on cleavage surface were assumed to be principal sections (same assumptions as Wood, 1974). The pitch of the X axis on the cleavage was measured directly at the outcrop, and the orientation was determined stereographically from the cleavage orientation and the pitch of X on that plane.

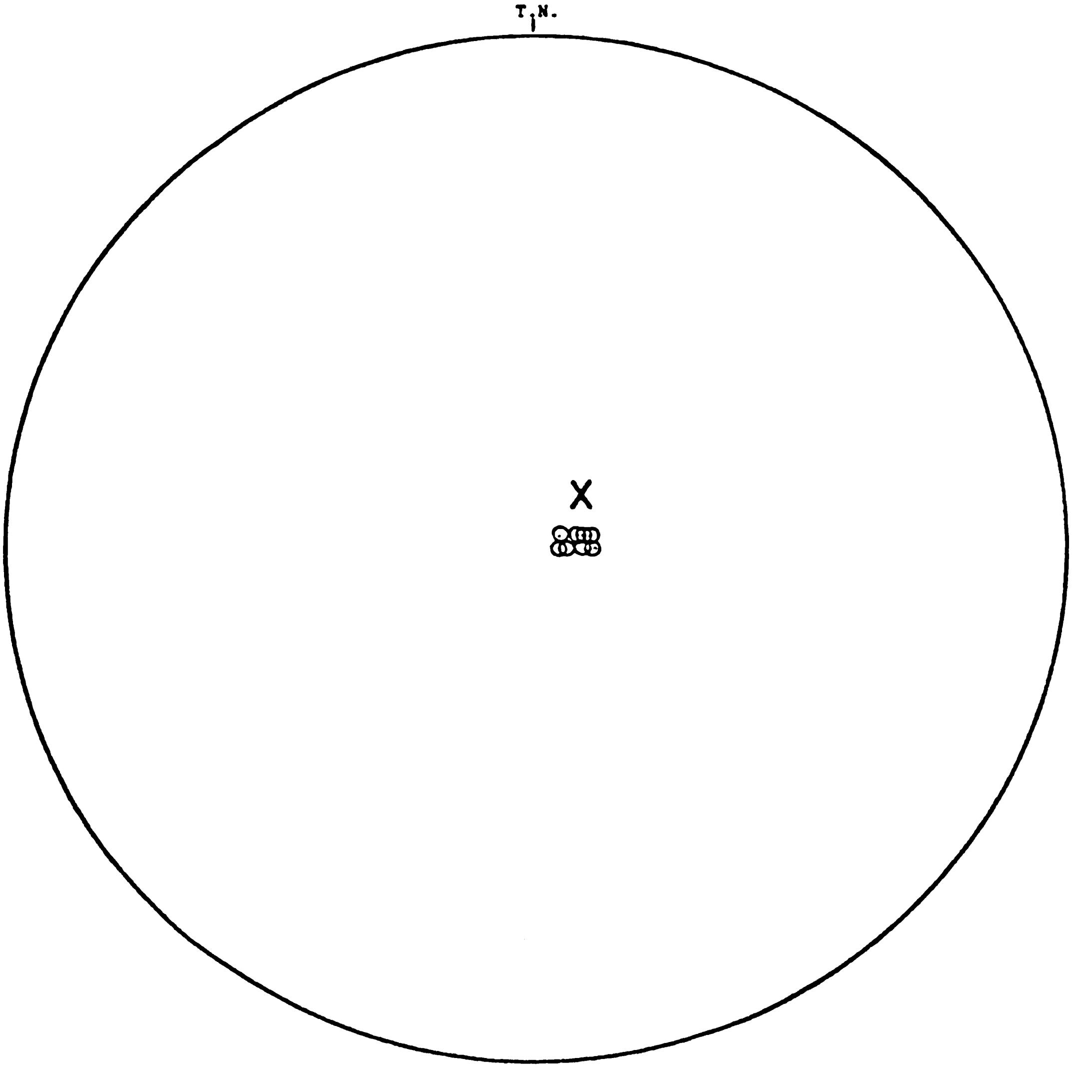
As discussed earlier, the orientation of the XY plane was defined using XZ and YZ sections of ellipsoids exposed during trimming (see Figure 3). The trace of the X axis was measured on that plane from ellipses exposed during grinding and the variation is displayed in Figure 8b.

All the strain data determined from reduction spots is presented in the discussion section, and the attention will now be focused on Talbot's (1970) method of finite strain analysis.

Deformed Veins: Talbot's Method

Flinn (1962) initially proposed the idea, and Talbot (1970) worked out in detail a technique to use deformed veins as a means of measuring finite strain, and

Figure 8. Equal area projection illustrating the variation observed in the X axis orientation of 15 deformation ellipsoids.


T.N.

their methods were used exclusively for this part of the study. The goal of the method is to define the shape and orientation of the surface of no finite longitudinal strain (s.n.f.l.s.). This theorectial surface contains all lines which have not changed length during deformation, and the shape of the surface depends on the style of deformation. Strains which are geologically realistic produce a s.n.f.l.s. which has the shape of a double cone (see Figure 9). The apices of the cones meet at the center point of the strain ellipsoid (also the center of the parent sphere), and the cone rims represent the intersection of the ellipsoid with the parent sphere.

One can determine the orientations and extensions of the principle strain axes using deformed veins, if the shape and orientation of the s.n.f.l.s. can be defined for a particular domain. The method relies on knowledge of the orientations of extended and shortened elements, since these features can be used to limit the orientation of the s.n.f.l.s. In practice, boudinaged and folded veins are used to determine the orientation of extended and shortened planes respectively. With a sufficient number of vein orientation known, the poles to these features (on equal area projections) can be used to interpret the shape and orientation of s.n.f.l.s. This is demonstrated in Figure 10.

As with reduction spots, certain assumptions must

Figure 9. Diagram illustrating the surface of no finite longitudinal strain. Note that the poles to extended veins plot inside the s.n.f.l.s., and planes to shortened (folded) veins plot outside the surface.

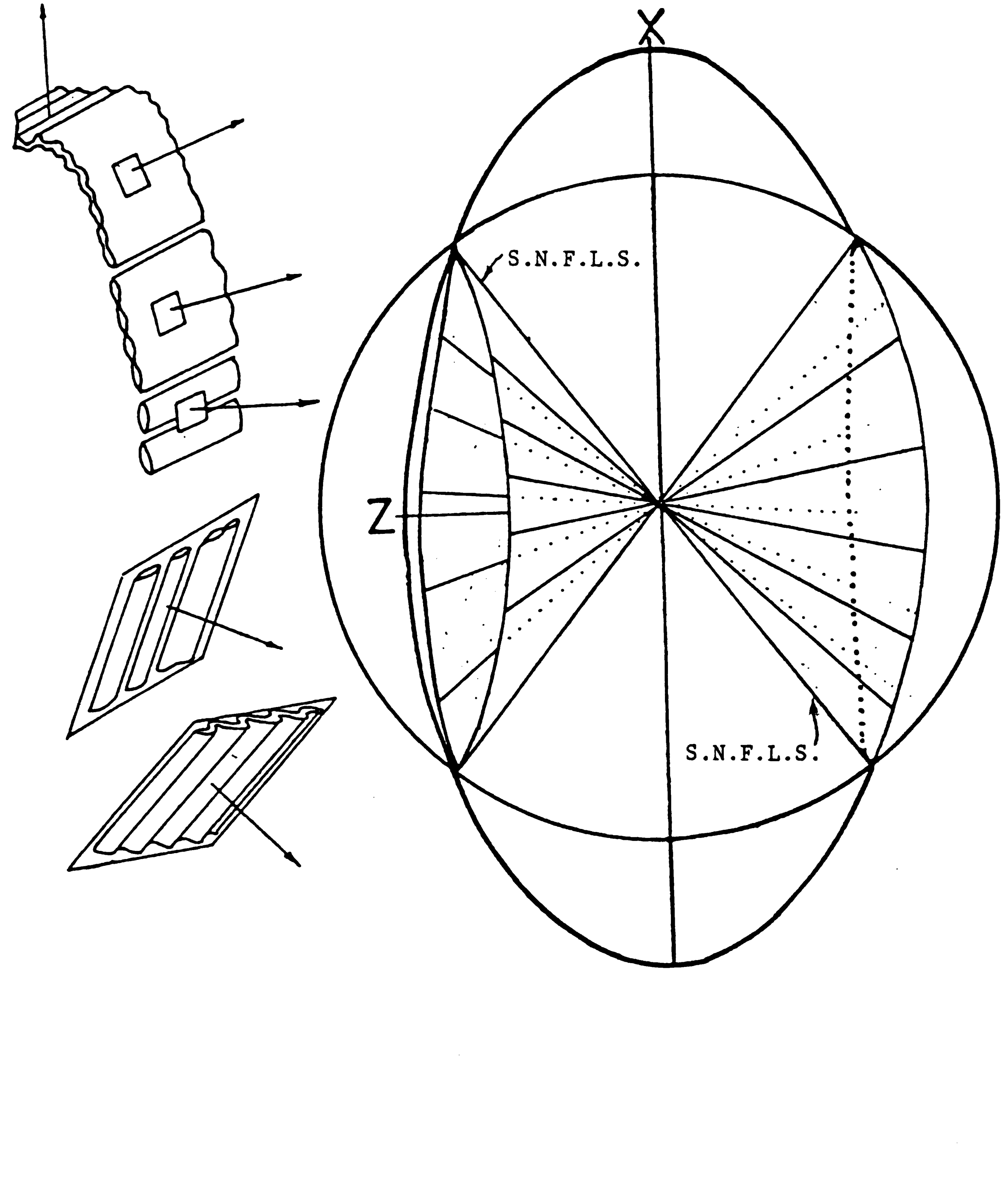
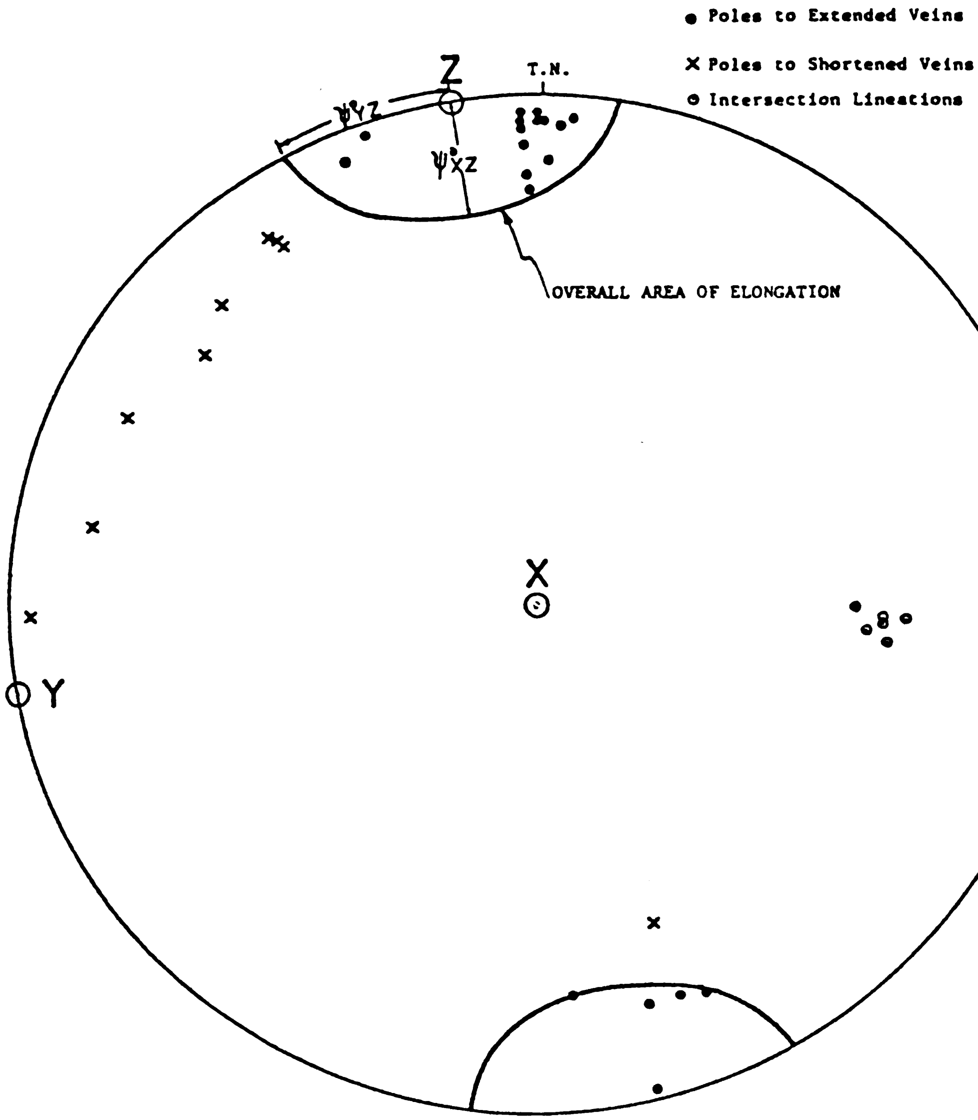

X
S.N.F.L.S.
Z
S.N.F.L.S.

Figure 10. Plot of 28 vein poles. All orientations determined in the laboratory from Kona slates, Harvey Syncline.


● Poles to Extended Veins
X Poles to Shortened Veins
⊙ Intersection Lineations
Z
T.N.
ψ°YZ
ψ°XZ
OVERALL AREA OF ELONGATION
X
Y

be made about the veins, and they are the subject of the following discussion. (All are discussed in detail, Talbot, 1970, and Ramsay, 1976).

It must be assumed that the veins were present before deformation. This is because the veins experience only the strain induced in the rocks after they are emplaced. If the veins develop after some period of deformation, that strain would not be recorded. Obviously, multiple events of vein emplacement further complicates the matter, and although the assumption may be valid for some situation, it cannot be directly demonstrated for most cases.

It must also be assumed that the veins had a wide range of planar orientations before deformation. The ideal situation would be a random orientation, but that is unreasonable to expect. A diversity of pre-deformation orientations is necessary because the structures which allow one to recognize shortened (folded) versus extended (boudinaged) planes in the rock only develop in veins with the proper orientation before deformation. The greater the diversity of vein orientations before strain, the better one can define the shape and orientation of the s.n.f.l.s., since this surface must lie within the area separating poles to extended and shortened veins.

The strain induced in the rocks must have involved no volume loss (same assumption Wood made). As mentioned earlier, this is a difficult problem to assess, and any large volume loss would produce error in the strain values.

It also must be assumed that the domain from which the vein orientations were measured deformed homogeneously. This concept is a matter of scale. Certainly near the margin of a rigid vein in slate, deformation must be inhomogeneous. But in general, the deformation structures which developed in the veins (boudins, folds, dislocations, etc.) result because the veins fail to keep pace with deformation in the surrounding more ductile matrix. So on a larger scale, deformation away from the vein in statistically homogeneous in slates, and the technique requires one to select a domain which can be considered to have deformed homogeneously (Talbot, 1970).

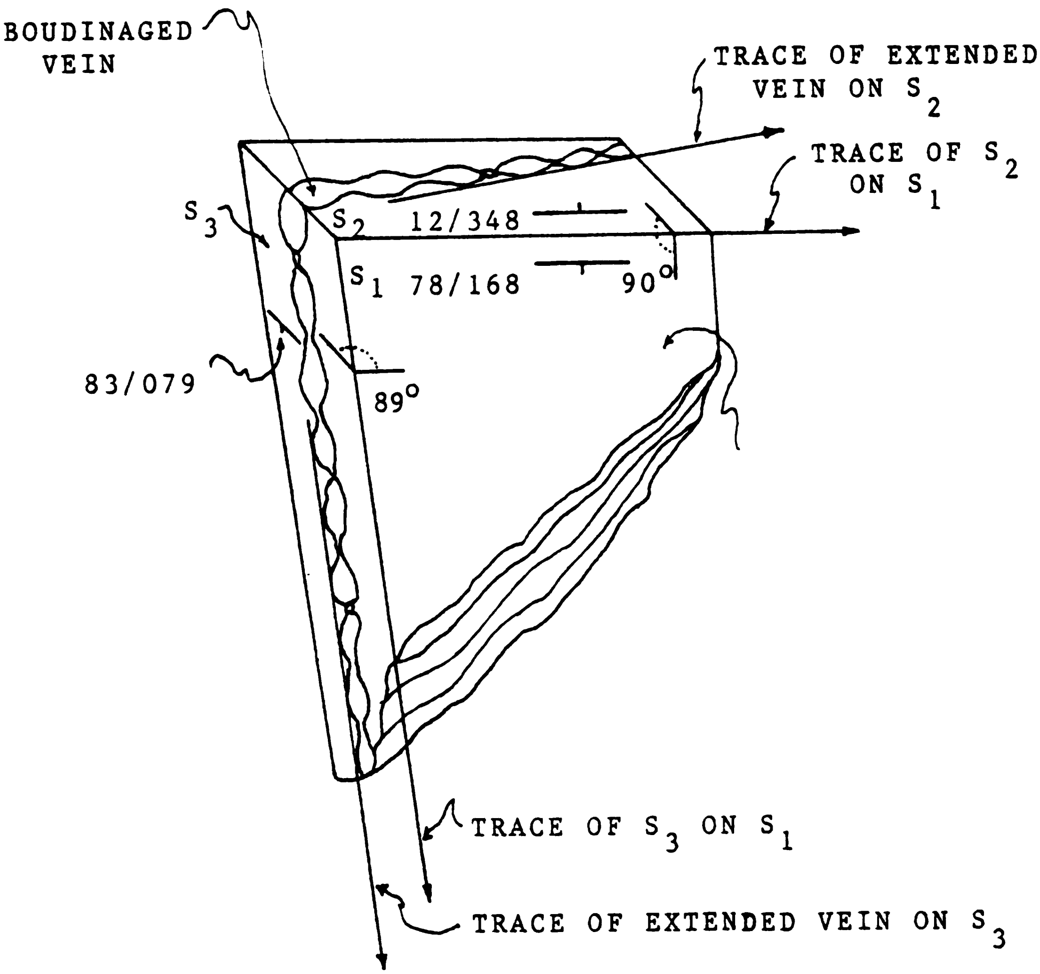
As Talbot (1970, see abstract) points out, "the frequency and original orientation of the elements (e.g., segregation veins, igneous sheet intrusions, etc.) making up the sub-fabric is the greatest limitation to the method."

The assumptions for both methods are discussed in other papers (e.g. Ramsay, 1976) and the technique described by Talbot (1970) will now be presented.

For this study, 161 vein orientations were measured along the north limb of the Harvey Syncline. It is the poles to extended and shortened veins which are used to define s.n.f.l.s., and Figure 10 illustrates the procedure. The three dimensional exposures of extended veins was good, because they were near cleavage in orientation, while shortened veins were poorly exposed (generally perpendicular to cleavage) and the errors associated with the field measurements are considered in the error analysis section. Oriented specimens were collected for laboratory measurement, and the procedure for determining accurate vein orientations is illustrated in Figure 11.

The veins were plotted in equal area projections, and from the distribution of the poles, one can limit the s.n.f.l.s. to the area between extended and shortened vein poles. The overall area of elongation (see Talbot, 1970) is constructed to enclose all the poles to extended veins, and the axial lengths of the minimum finite strain ellipsoid can be calculated as follows. The Z axis is centered on the area of elongation, and the X axis is 90° away in the direction in which the elongation field extends the larger angle. Obviously, Y is 90° to both the X and Z axes. The two angles subtended by the Z axis (see Figure 10 ψXZ and ψYZ) with the overall extension field in the direction of the X and Y axes are used to determine appropriate a and b values ($a = X/Y$, $b = Y/Z$) from the graph in Talbot's work (1970, p.61). The graph constructed by Talbot is based on Flinn's (1962) equations, and the reader may refer to Flinn (1962) for a complete treatment of the theory.

Figure 11. Diagram to illustrate how vein orientations were determined in the laboratory. The 3 surfaces visible are slaty-cleavage (S_1) and 2 cuts (S_2 and S_3) approximately orthogonal to cleavage. The trace of the vein on the 2 cuts defines the planar orientation.


BOUDINAGED VEIN
TRACE OF EXTENDED VEIN ON S2
TRACE OF S2 ON S1
S3
S2 12/348
S1 78/168
90°
83/079
89°
TRACE OF S3 ON S1
TRACE OF EXTENDED VEIN ON S3

DISCUSSION AND RESULTS OF THE STUDY

The results of the study which are presented in this section make a contribution to several geologic arguments concerning natural strain in rocks.

The values reported are for a minimum finite strain. They are independent of rotations and translations which may have been produced by faulting or chaotic mixing. No attempt was made to relate the strain to the system of stresses which produced the deformation, and as Ramsay (1967) nicely states, "the problem of determining the changing stress history from an end product which reflects the sum total of all the distortion produced by the stresses is generally insoluble." So the data now presented reflects only the end product of deformation, and hence, finite strain.

Three arguments will be discussed in the following order:

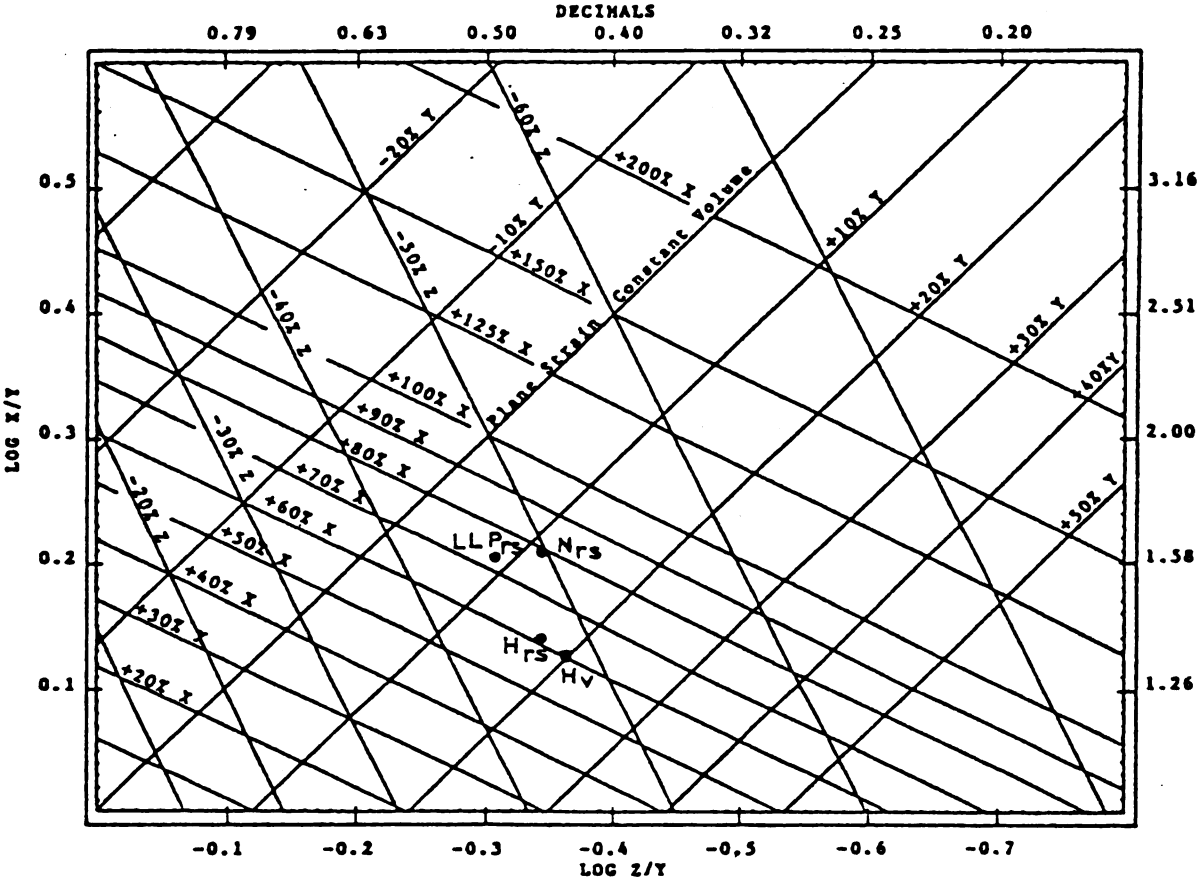
1. The Measurement of Strain in Deformed Rocks.
2. The Relationship of Slaty Cleavage to Finite Strain.
3. The Style of Deformation in the Marquette Synclinorium.

The Measurement of Strain in Deformed Rocks

Recent interest in plate tectonics has stimulated reams of literature on the analysis of strain in deformed rocks. Some new techniques have been developed (e.g. Talbot, 1970) and old ones have been modified (see Ramsay, 1976, a paper which discusses the known techniques.) For example, Sorby (1853) attempted a two dimensional strain analysis using reduction spots and inferred the amount of shortening in Welsh slates nearly 120 years before Wood (1971) developed a technique to use the same features to analyze strain in three dimensions. Arguments have been proposed about the accuracy of the values from all known techniques, and most of the speculation is based on the assumptions necessary to the methods. Wood (1974) and Talbot (1970) discuss the limitations to their techniques and their assumptions were presented in the methods section. Although it was not possible to directly test any particular assumption, reduction spots and deformed veins were tested as natural strain indicators by calculating the strain for a single deformation domain using each feature. That test produced some interesting results and they are now presented with a discussion of their geologic significance.

Figure 12 displays part of the data for this study, and it should be noted that the extensions observed on the X, Y and Z axes were similar from both the spots and deformed

Figure 12. The top diagram shows the mean plot for 4 sites, and the bottom illustrates the variation observed for the Harvey site.


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
LOG Z/Y
-20% Y
-60% Z
+200% X
-10% Y
+150% X
-30% Z
+125% X
Constant Volume
Plane Strain
-40% Z
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
-30% Z
-20% Z
+10% Y
+20% Y
+30% Y
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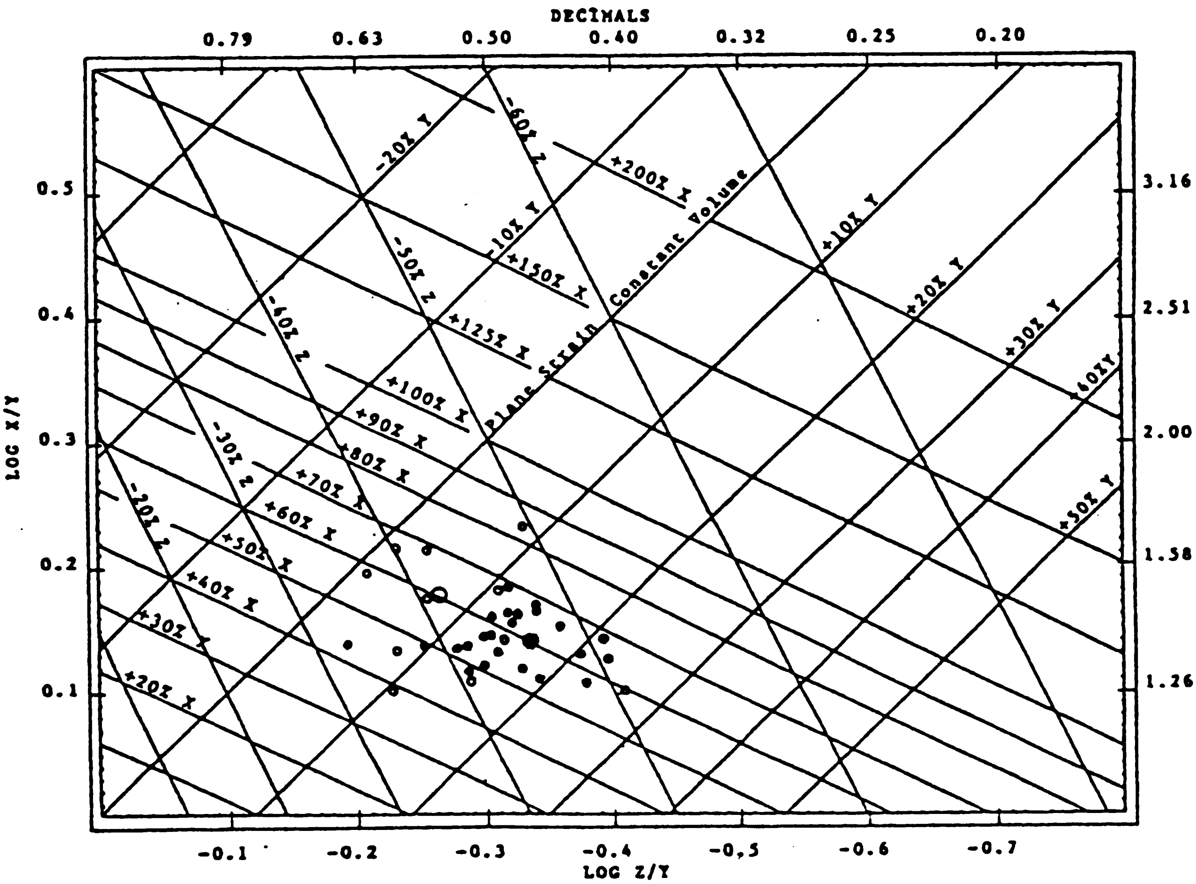
+50% Y
LLPrs
Nrs
Hrs
Hv
3.16
2.51
2.00
1.58
1.26


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
LOG Z/Y
-20% Y
-60% Z
+200% X
-10% Y
+150% X
-30% Z
+125% X
Constant Volume
Plane Strain
-40% Z
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
-30% Z
-20% Z
+10% Y
+20% Y
+30% Y
+40% Y
+50% Y
3.16
2.51
2.00
1.58
1.26

veins and the axial orientations (see Figure 13) were also similar.

The value plotted for reduction spots is the mean of 25 deformation ellipsoids from 3 samples (Gair, 1967, Plate 5, stations 576 & 637). The plot for deformed veins is based on vein orientations measured in the laboratory. (The specimens were collected at stations 567, 576, 590, 636, and 637, see Gair 1967, Plate 5.) The similarity of the values leads me to suggest the following.

Finite strain can be measured using either of the features, and no large errors result in making the necessary assumptions. However, it is appropriate to make the following comments.

To calculate strain from the vein orientations, the overall area of elongation was drawn to enclose all extended vein poles. This is precisely how Talbot (1970) calculated strain in his publications (also Borradaile, 1976) and Figure 10 shows this construction. However, it should be recognized that the extension field as drawn encloses the smallest area possible. Since the area is inversely proportional to the amount of strain, a second overall area of elongation was constructed (see Figure 14) to enclose the largest area possible. This area was constructed to enclose all extended poles, but was drawn to just exclude poles to shortened veins. This represents the absolute minimum strain, and it is suggested the real value is somewhere between the two. Since the s.n.f.l.s.

Figure 13. Equal area projection of the strain axes from 5 analyses. Plots 1-3 and 5 are mean axes for reduction spots, plot 4 is the axes determined from the deformed veins.

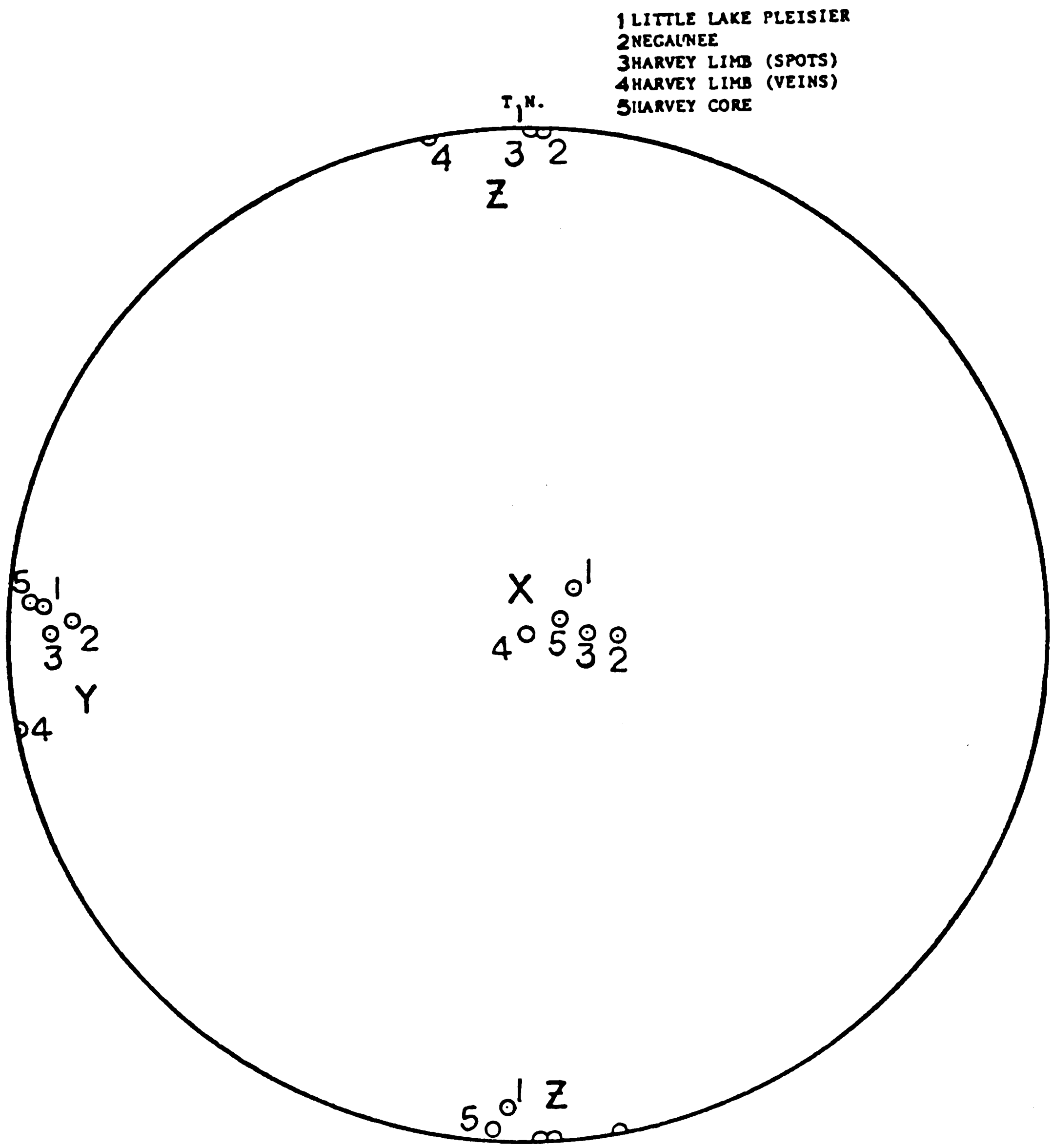
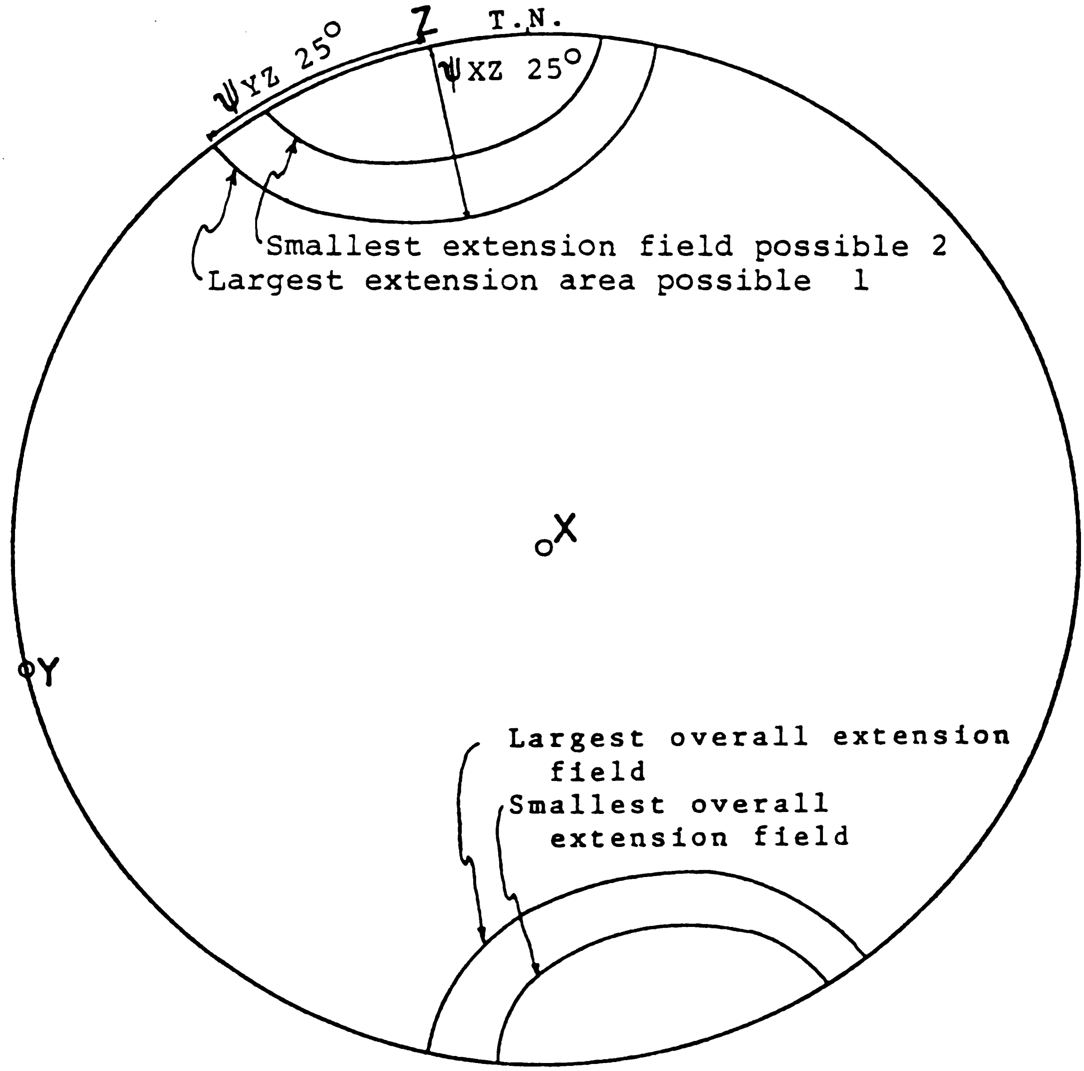

1 LITTLE LAKE PLEISIER
2 NEGAUNEE
3 HARVEY LIMB (SPOTS)
4 HARVEY LIMB (VEINS)
5 HARVEY CORE
T.N.
Z
X
Y
Z

Figure 14. Equal area projection showing 2 possible over-all areas of elongation.



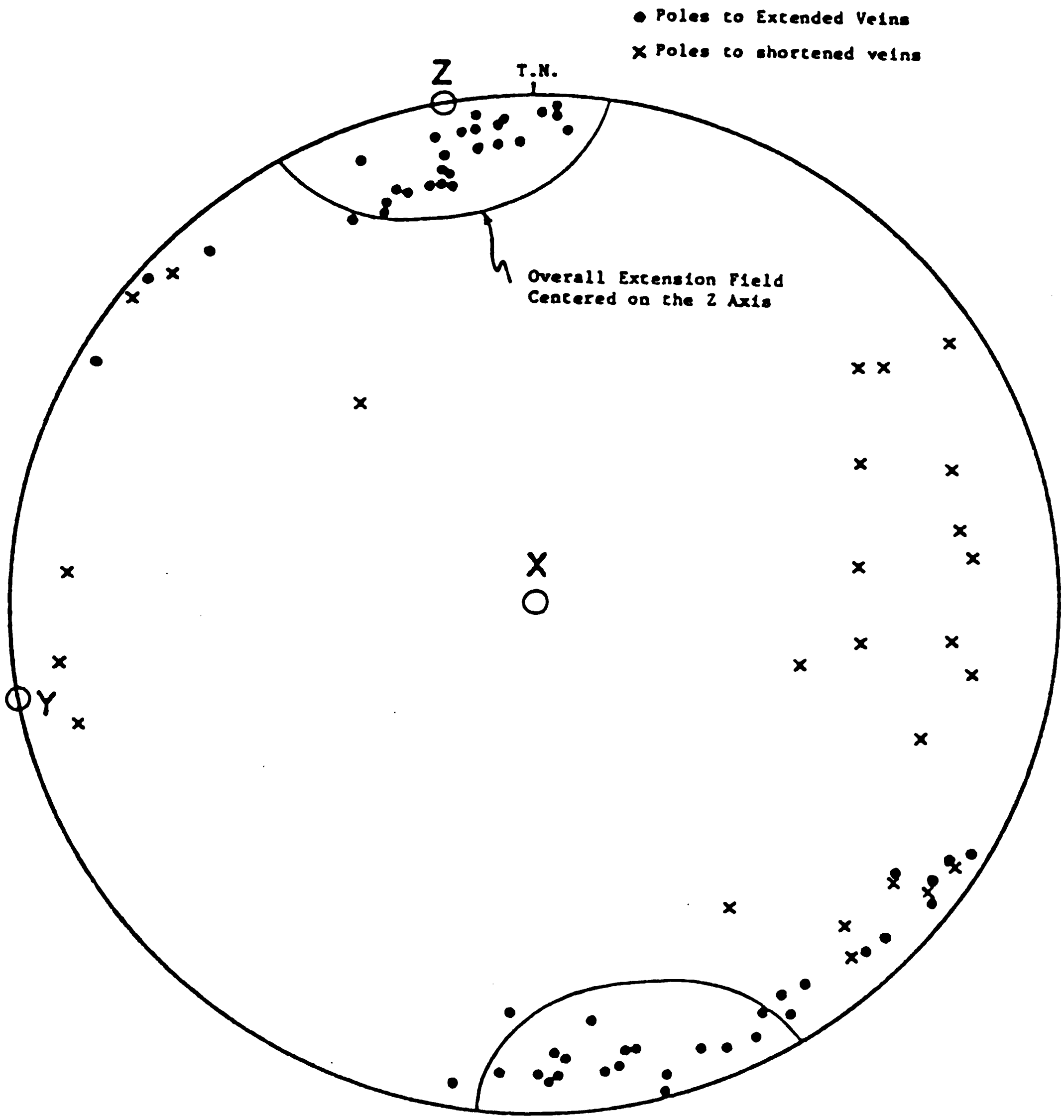
	a	b	X	Y	Z
1	1.2	1.5	1.29	1.08	0.72
2	1.3	2.5	1.61	1.24	0.50

has to lie between poles to extended and shortened veins, one cannot be sure which of the constructions is most reasonable based on the 28 vein orientations.

Obviously, more vein orientations are needed to further limit the position of s.n.f.l.s., and Figure 15 shows the poles to 82 veins (all field measurements). The overall area of elongation constructed from the laboratory measurements was drawn on the projection, and two things should be noted. First, the data supports that the strain was inhomogeneous on the scale of those measurements (600 sq. ft.). This is because some of the near vertical veins striking NE were shortened, while others were extended and this could only result by inhomogeneous strain.

Second, not all the extended vein poles fall in the overall extension area constructed from the laboratory measurements. As mentioned earlier, the field measurements were taken along 100' of the north limb and sandy dolomite, chert, and quartzite interbeds should have prevented homogeneous deformation. It is unreasonable to expect the field data (for boudinaged veins) to fall in the extension field, since the data was collected over a large deformation domain. However, it should be noted that only six poles fall outside the area if one excludes the poles that are mixed with those to shortened veins.

Figure 15. Plot of 82 poles to extended and shortened veins. Data from Kona slates, north limb of the Harvey Syncline. Outcrop area approximately 600 sq. ft.


● Poles to Extended Veins
x Poles to shortened veins
Z
T.N.
Overall Extension Field
Centered on the Z Axis
X
Y

It should be emphasized that both reduction spots and deformed veins gave very similar results when strain was calculated in the manner prescribed by Wood and Talbot. It is unlikely that two independent methods would show the same strain geometry and amount as a matter of pure coincidence. Even though some of the assumptions which must be made are tenuous, it is apparent that no large errors result in using these features as a measure of strain.

The Relationship of Slaty Cleavage to Finite Strain

It has been proposed by Wood (1974 and 1975) that slaty cleavage precisely parallels the XY plane of the minimum finite strain ellipsoid. Wood draws that conclusion from finite strain analysis on the Cambrian slates of Wales. Wood states (1974, p. 375) "In all cases, the principle plane XY of the deformation ellipsoid is parallel to cleavage. There can be no question that cleavage is precisely perpendicular to the direction of maximum finite shortening." Tullis and Wood (1975) support the term precise with an X-ray diffraction study on the orientation of micaceous minerals in spotted slates (by showing a parallelism between cleavage and the XY plane determined from reduction spots).

Other authors ridicule Wood's use of the term precise, and Bayly (1974) remarks "surely we all know that slaty cleavage does not parallel the XY plane of the finite strain ellipsoid." Bayly argues that slaty cleavage is a material phenomenon, and more than one mechanism may control its orientation. He suggests that several mechanisms may be operative during its formation; crystal glide and or rotation, pressure solution, cataclasis, etc. and he points out that the strain rate, mineral abundance and type, water content and temperature are factors which may control the orientation of cleavage. Bayly's objections are from a theoretical point of view and he doubts that cleavage has a clearcut relationship to strain.

Williams (1976) addresses the same argument and he concludes that slaty cleavage "will not be precisely parallel to a principle plane of finite strain in the general case", and adds that there are special cases where it is geologically feasible. For example, he suggests that cleavage would form parallel to the XY plane if the strain history was coaxial, but he suggests that since many orogenic zones have experienced non-coaxial strain, a universal parallelism of cleavage to the XY plane is not likely. Williams pointed out that he had observed reduction spots with diverse orientations, and he reported a measurable variation between cleavage and the XY plane of the deformed ellipsoids. Data included with this thesis shows variation in agreement with William's observations, and it seems doubtful Wood intended the term precise to be interpreted in the literal sense.

To contribute to this argument, 165 cleavage orientations were measured along the north limb of the Harvey Syncline (in the same domain as the strain analyses). The poles were plotted on an equal area projection (Figure 16) and contoured at a 3% interval. This projection should be compared to Figure 13. Note that the Z axes from all strain analyses lie within the 6% contour interval, and 3 plots fall in the highest density region.

Figure 17 shows the overall area of elongation (described by Talbot, 1970) constructed from the reduction spot mean (cleavage and spots from the same domain). This area should enclose the poles to all extended elements, and when Figures 16 and 17 are compared, it will be noted that over 95% of the poles to cleavage lie within the area of elongation.

From the data, one might suggest the following. The orientation of slaty cleavage is directly related to strain geometry. Cleavage is truly parallel to the XY plane and the variation observed (see Figure 7 for example) means that the minimum strain ellipsoid has a range of orientations for the domain sampled. This is a logical conclusion for this study, since the slates are interbedded with sandy dolomite, quartzite, and cherty layers, and those beds should have prevented a uniform strain pattern across the limb. However, one could equally take

Figure 16. Density diagram constructed from 165 cleavage poles. All data from Kona slates, north limb of the Harvey Syncline. Contour interval 3%.

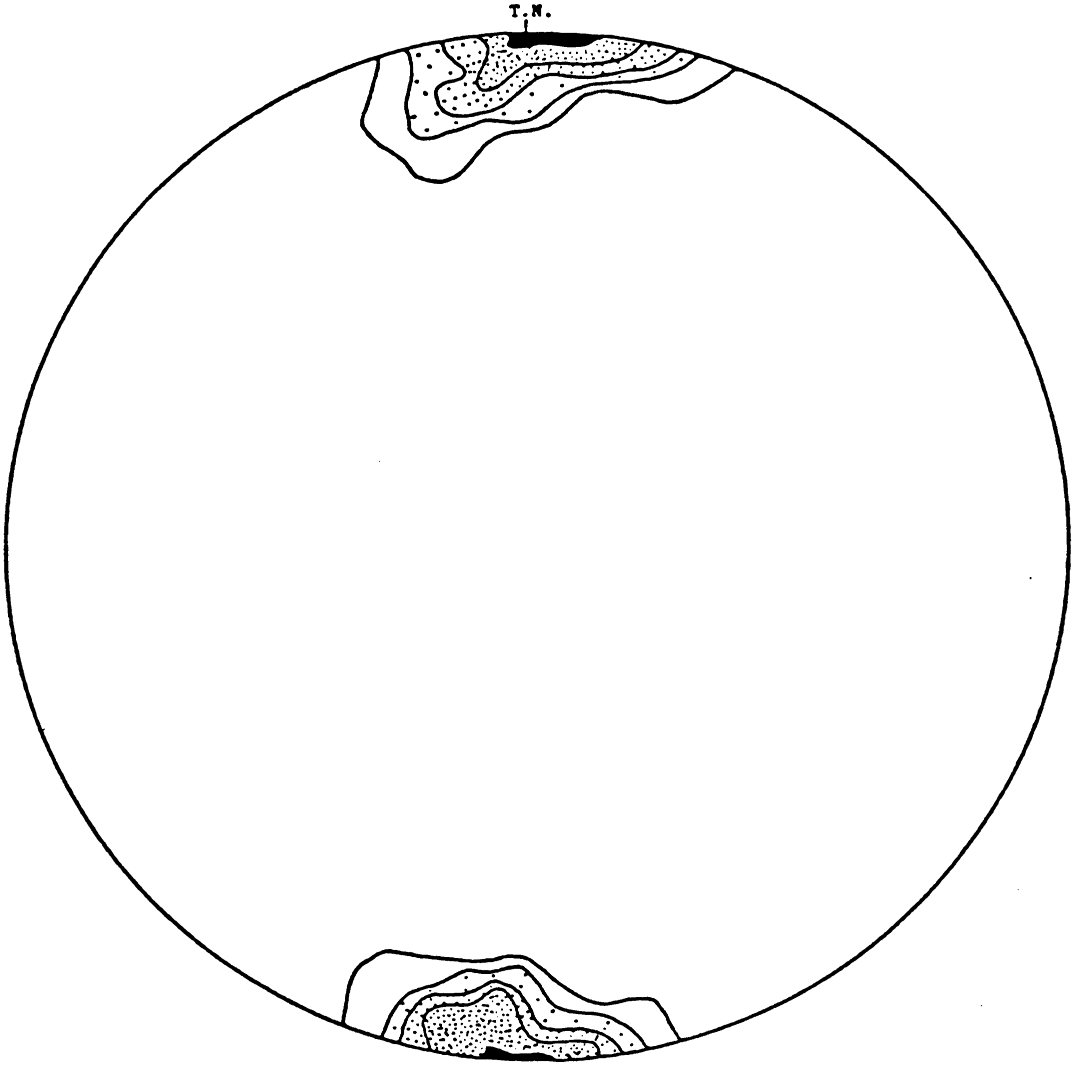
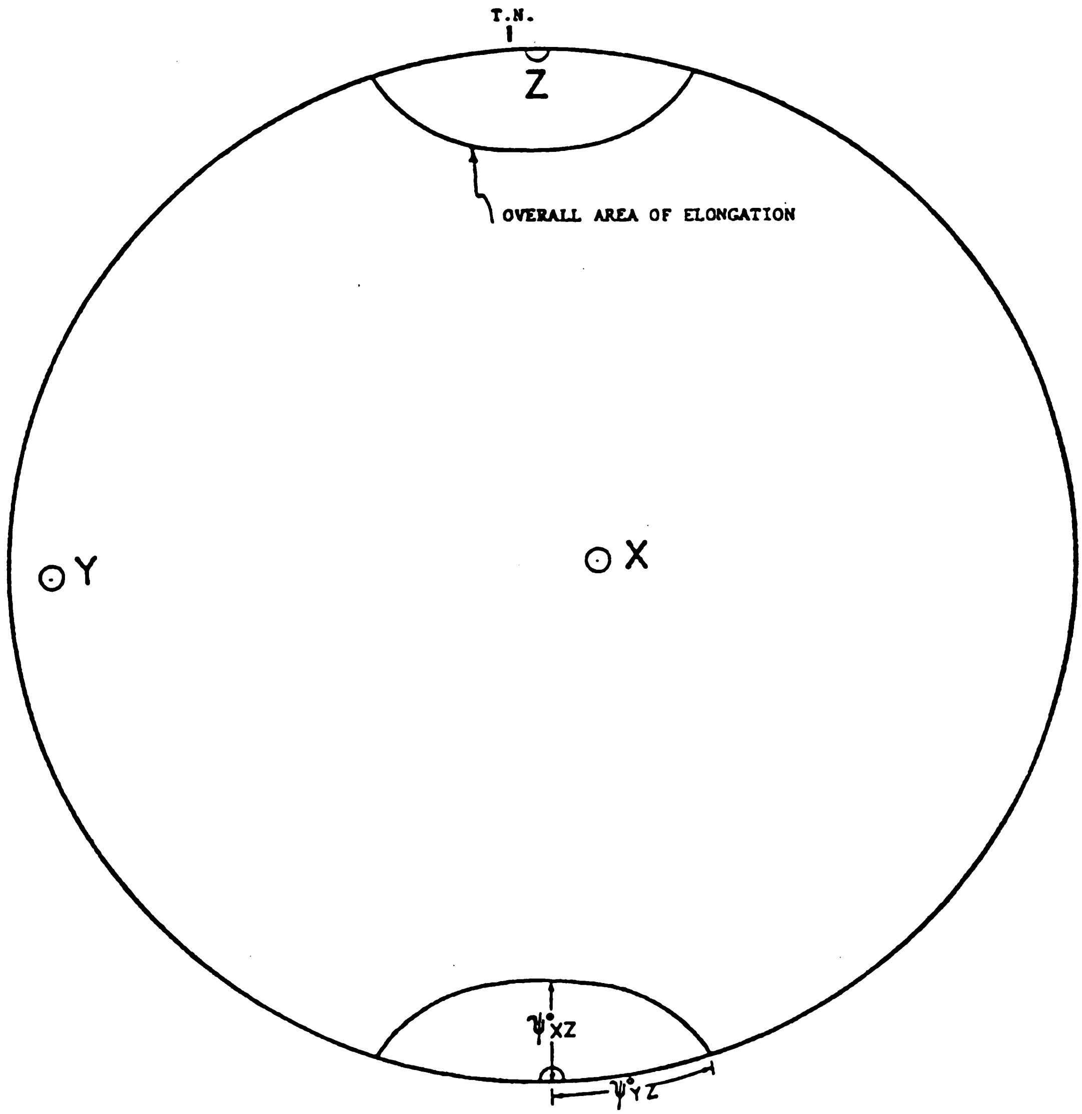

T.N.

Figure 17. Equal area plot of the overall area of elongation, calculated from the mean of Harvey reduction spots (Appropriate values: a = 1.34, b = 3.12, ψ XZ = 21^{o} ψ YZ = 18^{o}).


T.N.
Z
OVERALL AREA OF ELONGATION
Y
X
ψ°_{XZ}
ψ°_{YZ}

Williams (1976) explanation. The mapping of the cleavage poles in the extension field may be the result of a coaxial strain history. This is certainly possible, since the slates show evidence of only one penetrative deformation.

However, other evidence supports an alternate conclusion. There were minor occurrences of reduction parallel to cleavage. This is significant because Borradaile (1976) has shown that the orientation of cleavage has a relationship to the thermal conductivity of slates. Results from experimental work on spotted slates shows that the direction of maximum conductivity coincides with the X direction of the deformation ellipsoids, and the Z axis was parallel to the direction of least conductivity. On the basis of that evidence, one might suggest that reduction spots and cleavage formed late, and reducing fluids were selectively channeled by oriented layer silicates, such that the reduction patterns were crystallographically controlled. Thus, the ellipsoidal shape of reduction spots could then be explained by conductivity anisoptropies as suggested by Borradaile (1976), and that would negate their use as natural strain indicators.

Another explanation might be offered. If reduction spots are diagenetic as suggested by Tullis and Wood (1975) and Miller and Folk (1955), then the dewatering hypothesis proposed by Maxwell (1969) could be used to explain the reduction along cleavage. Maxwell (1969) has an audience of believers (Powell, 1969 and Klasner, 1978, for example) who hold that cleavage develops during tectonic dewatering, and the mineral orientation which produces cleavage results during the expulsion of pore water. Thus, the reduction along cleavage could be attributed to a chemical reduction during dewatering. However, other evidence does not support Maxwell's hypothesis for this case. In fact, petrologic observations show cleavage cuts deformed veins, and appears to be later than those features.

It should be recalled that evidence exists to support a predeformation, diagenetic origin for reduction spots, and Tullis and Wood (1975) state it can be demonstrated. Although there are minor occurrences of reduction along cleavage, this author suggests it could be explained by remobilization of reducing fluids after cleavage formation, since the reduced trends in general bear no spatial relationship to cleavage.

The results of this study suggest the following. For a variety of strain domains in the Marquette Synclinorium, two techniques of finite strain analysis show slaty cleavage approximately parallels the XY plane of the finite strain ellipsoid. However, from the evidence presented, the exact relationship of cleavage orientation to the XY plane of the minimum finite strain ellipsoid could not be determined. This is because the measurements are only accurate to the degree one can attain from field orientations (see error analysis section).

The Style of Deformation in the Marquette Synclinorium

Cannon (1973) presented a model to explain the style of deformation characteristic of the Middle Precambrian metasediments of the Upper Penninsula and he suggested that the complex fold patterns can best be explained using two different mechanisms. He proposed that regional gravity sliding produced gentle E-W trending folds, and the diversity of fold trends characterized by the Republic, Felch and Marquette Troughs resulted when the metasediments were draped into basins formed on down dropped blocks of Archean basement.

Cannon's model is not directly tested in this study, but some data is contributed which helps to evaluate the style of deformation in the Marquette Synclinorium.

All the data suggests that the Kona slates have been shortened by approximately 45% normal to the trough margins. The style of strain was somewhat variable between the three sites (see Figure 2); the western most exposure (Neguanee #1) deformed by near plane strain (Y axis unchanged) and slates at the Harvey Syncline (#8) were flattened, while the slates at Little Lake Pelesier (#3) showed strains similar to Negaunee slates. A slight increase in strain was observed to the west (see Figures 12, 13, 18 and 19).

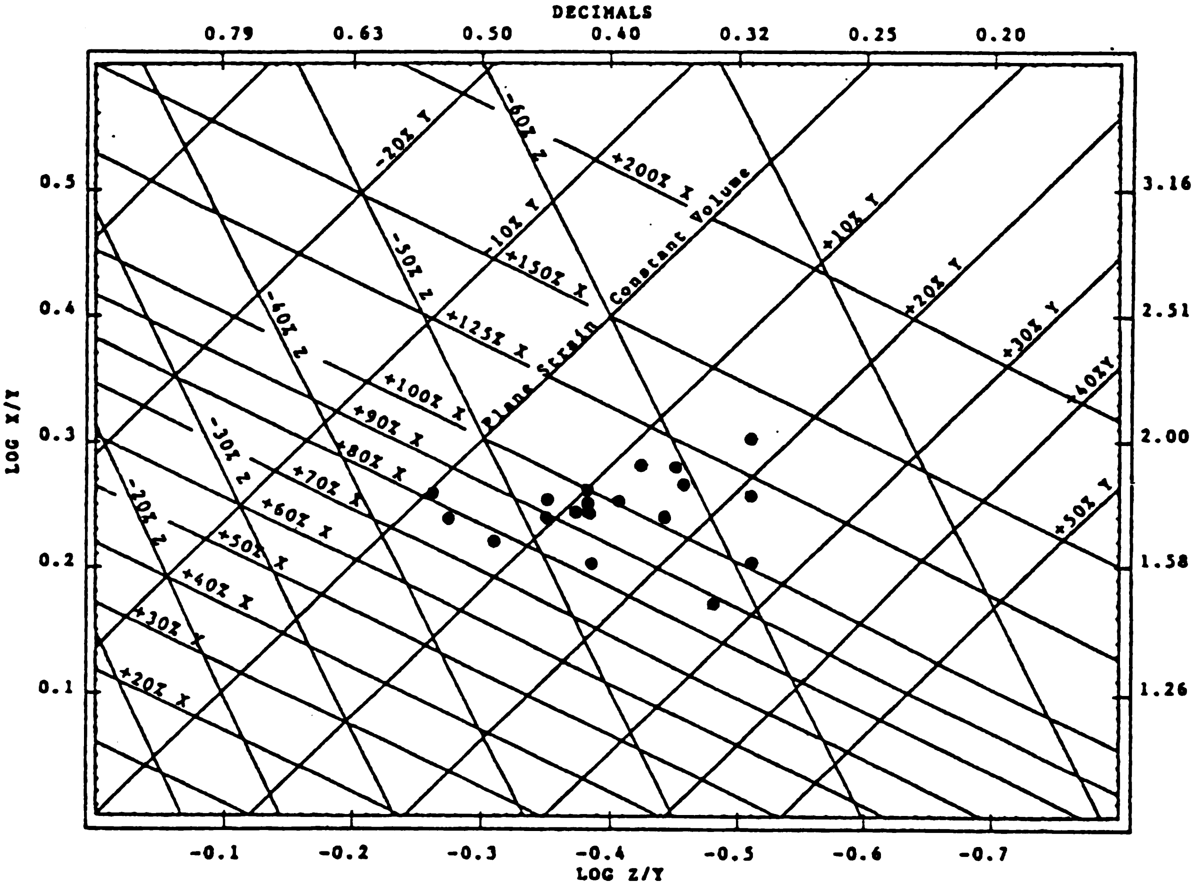
It is apparent from Figure 13 that very little variation was observed in the orientations of the principle strain axes for the three sites. This suggests that the strain geometry for this tectonic environment is independent of bedding and fold plunge, since the strain axes had similar orientations even though the beds ranged from 45° - 80° dip and the plunge varied from 35°E to 6°W.

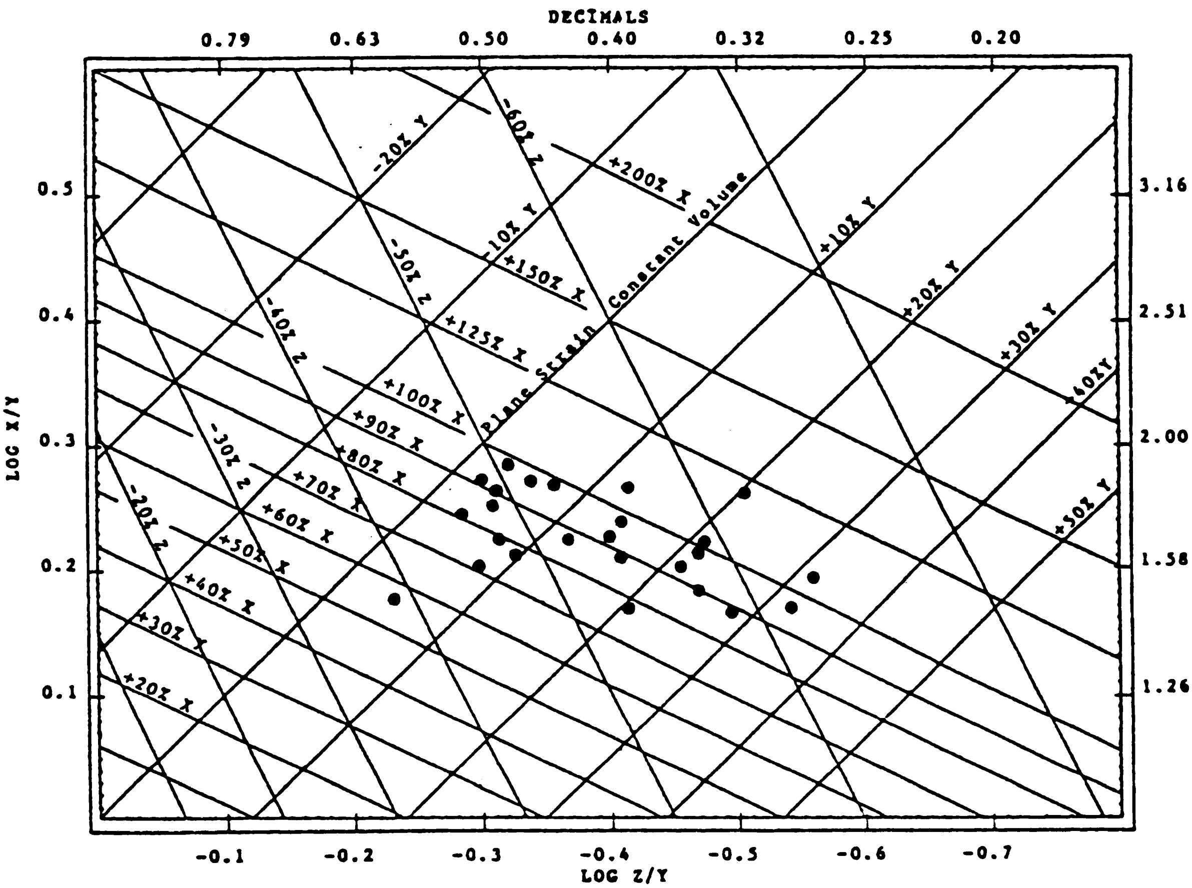
From the strain data, it is apparent that the folded slates best fit Ramsay's (1962) description of similar folds; that is the limbs are thinned and the cores are thickened. Finally, the constant orientation observed for the strain axes (see Figure 13) suggests that no large rotations occurred after the strain was induced. The strain geometry also supports a coaxial strain history, and this possibility was discussed in the section on slaty cleavage.

The style of strain observed suggests a single penetrative deformation in the Kona slates. This is reasonable since the secondary fabric shows evidence of only one phase of deformation. Although Cannon's (1973) model cannot be discarded on the evidence presented, it is suggested that the style of deformation can be better explained by a model presented by Cambray (1978). This model attributes the deformation to a compressional event, which closed the Marquette Trough during the Penokean Orogeny. This model is preferred because the deformation can be explained

Figure 18. Plot to show the variation observed for 19 ellipsoids using Wood's method (Neguanee outcrop).

Figure 19. Plot to show the variation observed for 25 ellipsoids using Westjohn's method (Negaunee outcrop).


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
0.5
0.4
0.3
0.2
0.1
3.16
2.51
2.00
1.58
1.26
-20% Y
-10% Y
+10% Y
+20% Y
+30% Y
+40%Y
+50% Y
-60% Z
-50% Z
-40% Z
-30% Z
-20% Z
+200% X
+150% X
+125% X
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
Constant Volume
Plane Strain
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
LOG Z/Y


DECIMALS
0.79
0.63
0.50
0.40
0.32
0.25
0.20
LOG X/Y
0.5
0.4
0.3
0.2
0.1
3.16
2.51
2.00
1.58
1.26
-20% Y
-10% Y
+10% Y
+20% Y
+30% Y
+40%Y
+50% Y
-60% Z
-50% Z
-40% Z
-30% Z
-20% Z
+200% X
+150% X
+125% X
+100% X
+90% X
+80% X
+70% X
+60% X
+50% X
+40% X
+30% X
+20% X
Constant Volume
Plane Strain
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
LOG Z/Y

without using 3-4 phases as suggested by Klasner (1978). Cambray (1978) proposes that the Marquette Trough was the depositional basin for most of the Marquette Supergroup (all sediments after the Mesnard Quartzite). He suggests that the troughs (Republic, Felch, Marquette, etc.) formed during extension of the Archean rocks, (in agreement with Cannon (1973) and Klasner (1978)), but attributes the fold patterns to the normal and shear stresses which would result from closing the troughs (see Michigan Basin Society Field Trip Guide for a summary of the model). All of the following can be demonstrated with this model; a coaxial strain history in the Marquette Trough, the style of finite strain reported in this work, the single penetrative fabric observed in the synclinorium, and the similar folds which according to Ramsay (1962), result from compressional rather than tensional stresses.

ERROR ANALYSIS

Several sources of error limit the accuracy of the strain values. An attempt was made to evaluate them, but it is admitted the methods are unorthodox and the error values are only estimates (none of the publications used evaluated possible errors). The maximum error is calculated in all cases.

Possible Errors from Talbot's Method

1. Field measurements:
   a. Extended veins $\pm 2^{\circ}$ Dip
      $\pm 2^{\circ}$ Strike
   b. Shortened veins $\pm 5^{\circ}$ Dip
      $\pm 5^{\circ}$ Strike
   c. Stereoanalysis $\pm 1^{\circ}$

   The errors are large due to the poor three dimensional exposure of the veins, especially shortened veins. The values are based on the precision of repeated measurements for the same vein.

2. Laboratory measurements:
   a. Field orientation on cleavage surface $\pm 1^{\circ}$.
   b. Cut orientation solved stereographically from field orientation $\pm 1^{\circ}$.
   c. Error in measuring trace of the vein or cut surface $\pm \frac{1}{2}^{\circ}$.

d. Error in solving vein orientation on stereonet $\pm 1^{\circ}$.

The vein orientations as measured in the laboratory are within 3° of the actual orientation, and this figure was used to estimate the possible error.

Strain Values	ψ XZ	ψ YZ	a	b	X	Y	Z
1. As reported	22	19	1.3	2.5	1.61	1.24	0.50
2. Values if all veins had actual dips 3° larger	27	22	1.2	2.0	1.42	1.18	0.67
3. Values if all veins had actual dip 3° less	21	16	1.5	2.0	1.88	1.26	0.42

Possible Errors from Wood's Method

The errors involved in using reduction spots are more difficult to evaluate. Wood (1973, 1974 and 1975) did not calculate errors for his publications, and after trying his technique, it is realized why. It is difficult if not impossible to accurately estimate his errors, and Wood's technique was modified in attempt to evaluate the error involved in measuring the ellipsoid axes.

Figures 12, 13, 18 and 19 show the variation observed in the extensions on 87 ellipsoids axes for the various domain studied. Some plots represent measurements using Wood's (1974) technique, and the remaining plots are values determined using the Westjohn method. There is little difference in the mean between the techniques, and each method shows the same amount of variation in the data.

This variation could be the result from many factors. For example, some of the reduction spots may have been initially ellipsoidal, or less likely, the strain variation may be real.

Figure 20 shows XZ and YZ sections constructed from the grinding records for a reduction spot (actual dimensions X=0.202 Y=0.139 Z=0.079). The error involved in determining the axial lengths was estimated as follows:

1. Accuracy of measure ± 0.002 in (Bausch and Lomb 20X graduated lens).
2. Grinder stroke accuracy ± 0.005 in.
3. Error if the ellipsoids were oriented 10° from the calculated XY plane (10° was the maximum variation observed).
4. Errors if spots were initially sub-spherical are discussed below.

As previously mentioned, the greatest limitation in using reduction spots as natural strain indicators results from the assumption that reduction spots were initially spherical. Tullis & Wood (1975) state that initial sphericity can be demonstrated. No evidence was published with their paper. This author suggests that some of the features may have been initially sub-spherical. This could explain some of the variation observed in the axial orientations and extensions for the deformation ellipsoids. A geometric argument can be made that the spots had to be either initially spherical or ellipsoidal, since those are the only predeformation geometries which could result in near perfect ellipsoids after deformation. Thus the variation in the data could be explained as follows. The reduction spots (ellipsoidal before deformation) which show the largest extensions could have coincided orientation wise with the tectonic strain axes early in the deformation history, while the spots showing the least strain may have been ellipsoids oriented oblique to tectonic axes before deformation.

For this case, initially spherical spots would show extensions between the maximum and minimum, and the mean value for several reduction spots should give realistic values for the extensions on the principle axes of the minimum finite strain ellipsoid.

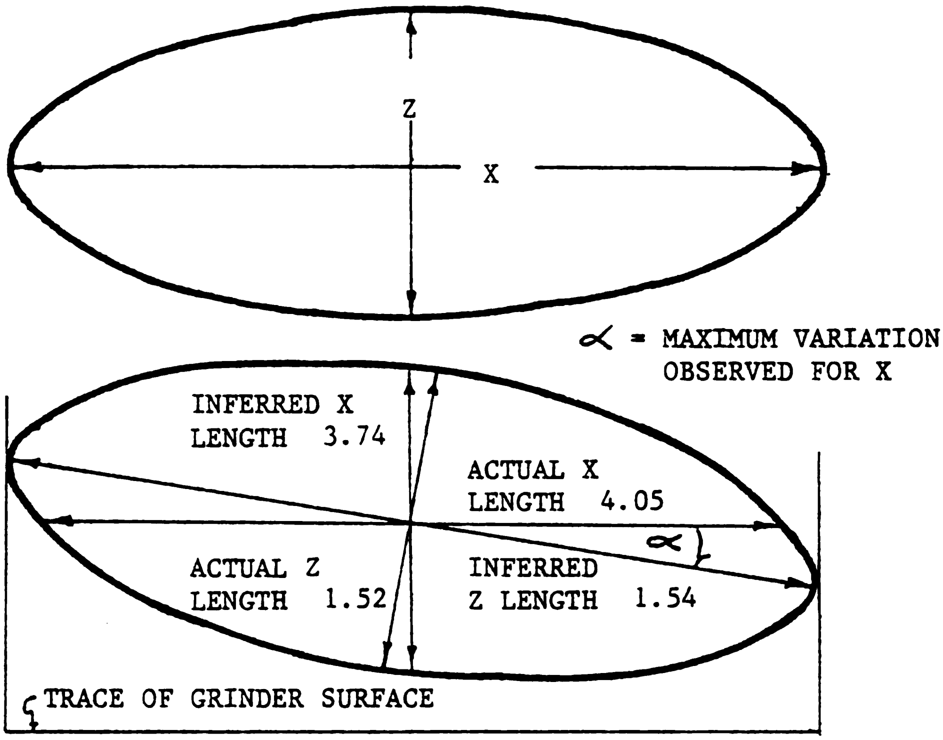
The error section on reduction spots is concluded with the following discussion: Wood, (1974) calculates the possible error which would result by making the assumption of zero volume loss. He concludes that a volume loss less than 20% after the formation of reduction spots would produce less than a 4% error in the strain values. With all of the errors considered, it is suggested that the strain values are within 10% of the actual strain suffered by the slates. The largest error would be in the extension calculated for X (see Figure 20) while the error on Y would be the least, and Z would be intermediate.

Figure 20. The ellipses were constructed from the grinding data and XZ and YZ principle sections are drawn to scale. An attempt was made to evaluate the error which would result when the Z axis was not normal to the grinding surface. With the maximum variation observed in the axial orientations, the error due solely to the grinding technique would be:

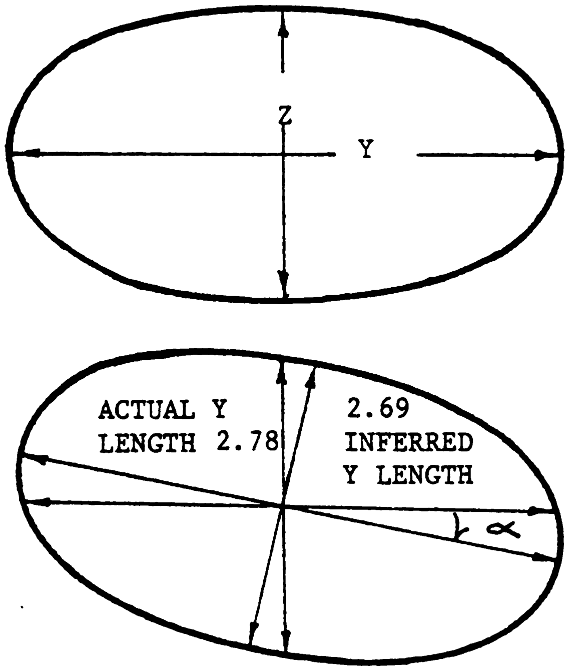
	X	Y	Z
Actual	1.57	1.08	0.59
Measured	1.50	1.08	0.62
	-7%	0%	+3%

Since 90% of all ellipse sections varied by less than 5^{o} in orientation from the grinding surface, it is suggested that the error is an over estimate. It should be noted that the largest error was observed for the X axis, while Y and Z had negligible errors.

XZ PRINCIPLE PLANE (CONSTRUCTED FROM 37
XY PRINCIPLE SECTIONS, 20X EXAGERATED).



YZ PRINCIPLE PLANE (CONSTRUCTED FROM 37
XY PRINCIPLE SECTIONS, 20X EXAGERATED).



CONCLUSION

It is concluded from the data presented in this thesis that the Precambrian Kona slates were shortened by approximately 45% normal to the Marquette Trough axis during a ductile deformation which folded the Marquette Supergroup. The style of strain was variable in amount but not in orientation. The mode of deformation was by flattening and appears to have resulted through a coaxial strain history. The data also suggests that strain was greater in the west.

One can be confident in these conclusions because two independent strain measurement techniques gave similar results when tested on the same deformation domain. The values reported are minimum estimates of the finite strain in Kona slates. They represent a significant improvement over those reported in previous studies (e.g., Talbot, 1970) because the measurements were made in the laboratory in an attempt to obtain accurate results and allow for error calculations. The close agreement of the strain values from reduction spots and deformed veins when used as prescribed by Wood (1974) and Talbot (1970) allows a conclusion to be made that either feature can be used as a measure of strain in deformed rocks. The assumptions which must be made may limit the accuracy of methods, but large errors could be inherent in the techniques only if it was a coincidence that they gave the same values for a single strain domain.

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