STRAIN ANALYSIS OF BOUDINAGE AND PTYGMATIC FOLDING IN THE LILY POND LAKE AREA, MANITOBA

A Minor Thesis

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Master of Science

by

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ABSTRACT

Boudinage and ptygmatic structures can be observed within a vertical outcrop of amphibolite in the Lily Pond Lake area. Two well-developed joint directions facilitate measurement of the dimensions of the ptygmatic folds and boudinage structure in two directions. Their dimensional measurements are the basis of the interpretation of strain.

A study of the boudinage structure provided for extensional strain measurements from which the extensional strain axes of the strain ellipse were derived. A study of the ptygmatic structures provided for the amount of compressive strain the host rock had undergone and from which the compressive axis of the strain ellipsoid was derived.

The major axis of the strain ellipsoid strikes 062° with an extensional strain ratio of $\frac{3.50}{1.00}$ and the intermediate strain axis strikes 152° with an extensional strain ratio of $\frac{1.65}{1.00}$. The major and intermediate strain axes are in the plane of layering. The minor axis of the strain ellipsoid shows compression ratios ranging from $\frac{4.40}{1.00}$ to $\frac{7.70}{1.00}$ with a mean of $\frac{5.90}{1.00}$.

A predicted, compressional strain ratio of $\frac{5.77}{1.00}$ based

on the extensive-strain ratio data, compares favourably with the mean compressional ratio of $\frac{5.90}{1.00}$ derived from field observations.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. W.C. Brisbin for his assistance and valuable criticism during the course of the study.

Special thanks are extended to R. Pryhitko and his staff for their technical support.

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LOCATION AND ACCESS

The area of study is located in southeastern Manitoba, in the Whiteshell Provincial Park. Specifically, the area is located in the southwest corner of Tp. 19, Rge. 17E along Manitoba Provincial Highway 44, at Lily Pond Lake. Lily Pond Lake is approximately 8 miles from West Hawk Lake and 11 miles along Highway 44 from the east junction of the Trans-Canada Highway and Highway 44. The location of Lily Pond Lake is shown on the index map (Figure 1).

Convenient access from Winnipeg is via the Trans-Canada Highway to West Hawk Lake and then north on Highway 44 to Lily Pond Lake. West Hawk Lake is approximately 100 miles east of Winnipeg.

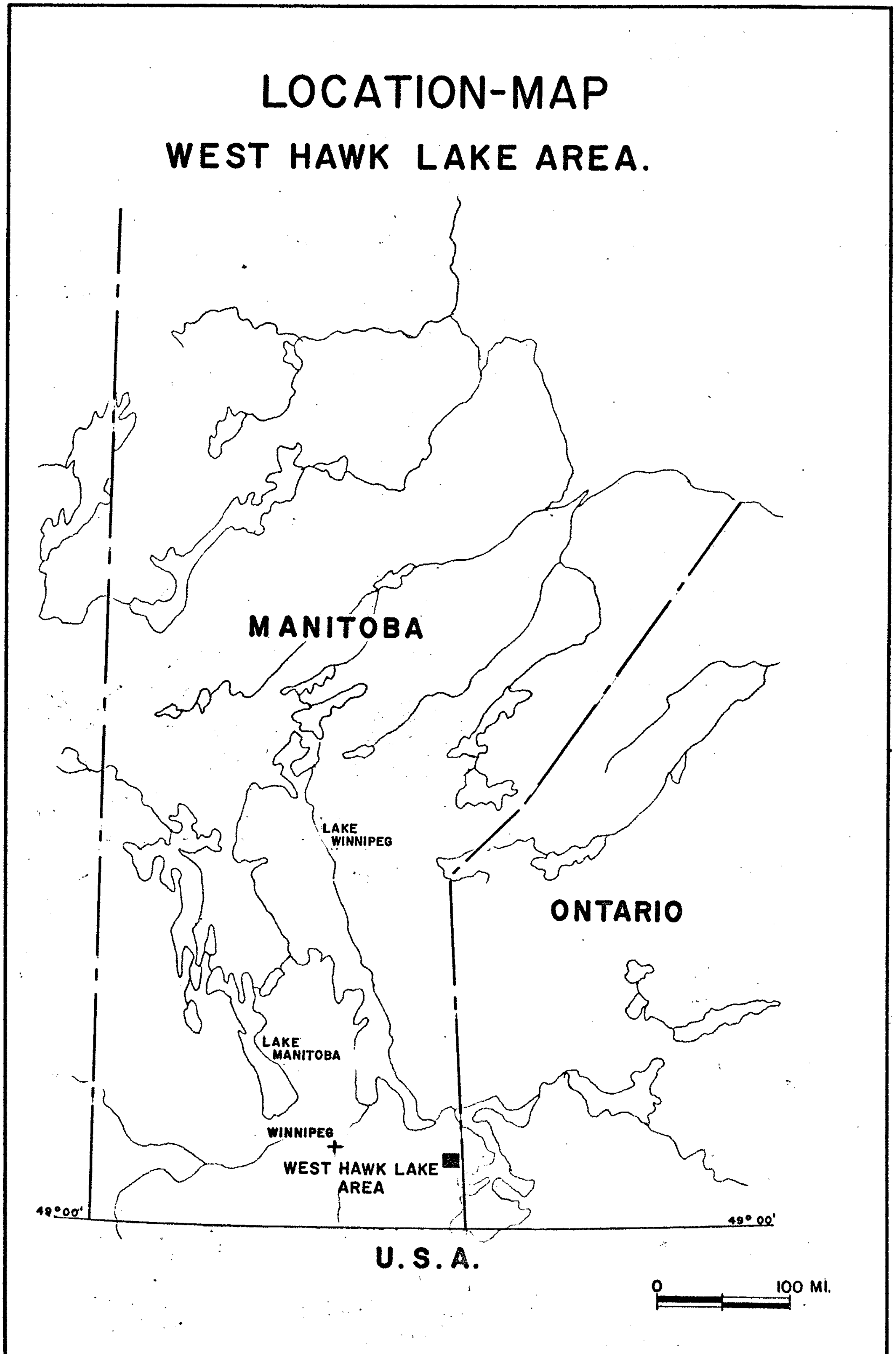
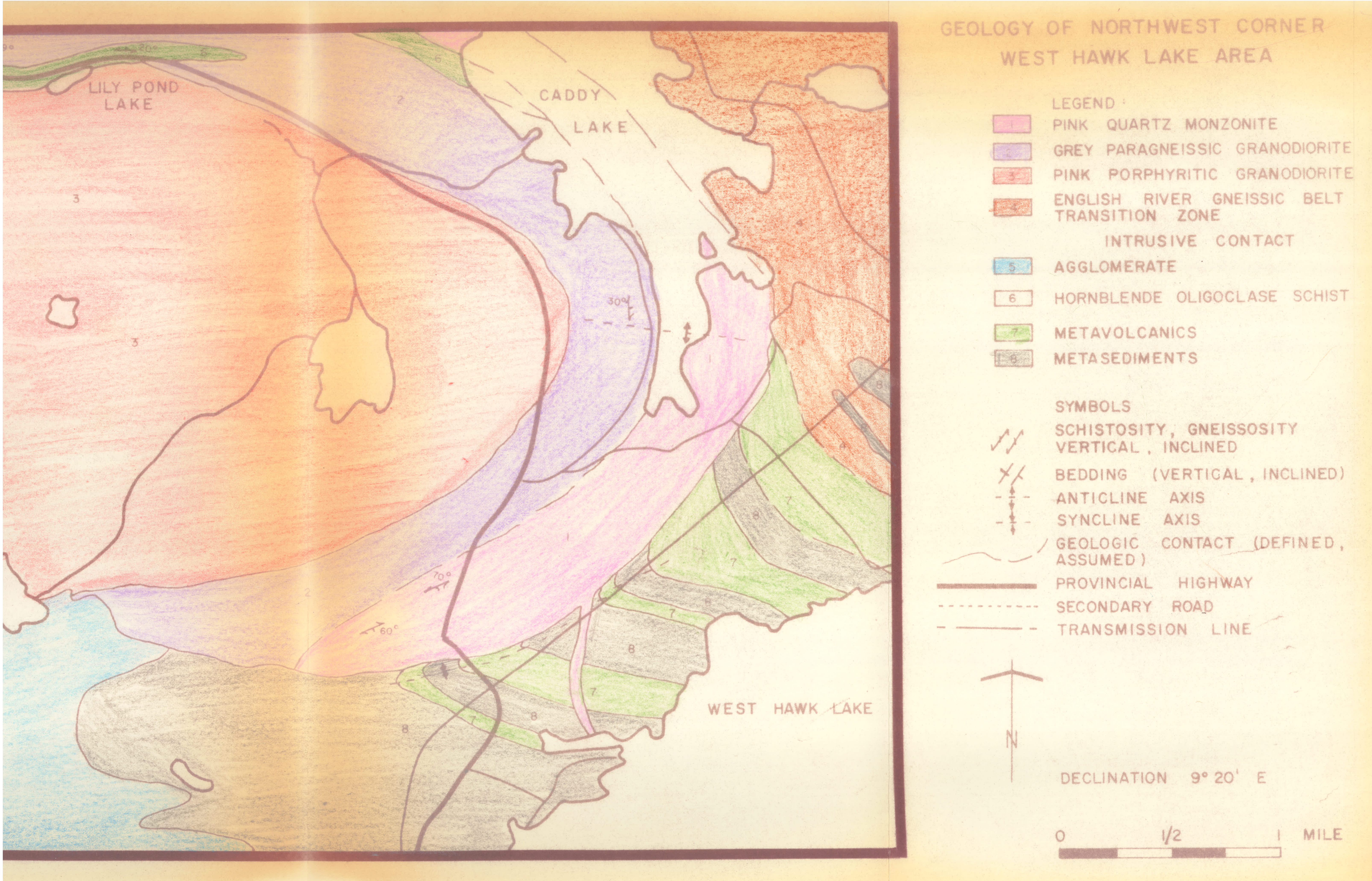

LOCATION-MAP
WEST HAWK LAKE AREA.
MANITOBA
LAKE WINNIPEG
ONTARIO
LAKE MANITOBA
WINNIPEG
WEST HAWK LAKE AREA
49°00'
49°00'
U.S.A.
0
100 MI.

Figure 1

STATEMENT OF PROBLEM

This thesis presents the results of an analysis of boudinage and ptygmatic structures observed within a unit of amphibolitic rock exposed on the north shore of Lily Pond Lake, West Hawk Lake area, Manitoba (Figure 2).

At Lily Pond Lake boudinage and ptygmatic folds can be observed in a vertical outcrop which has two well-developed vertical jointing directions which facilitate measurements in two separate planes. Measurements of the boudinage and ptygmatic structures provide information on the amount of extensional and compressional strain that the host rock has undergone. Previous authors have indicated that ptygmatic folding and boudinage structure are a result of a single deformational event and there is no evidence to the contrary that the origin of these features is different at this location. Consequently, the compressional and extensional strain can be manifested by these features and related to a single strain ellipsoid. The purpose of this thesis is to determine the dimensions of the strain ellipsoid and ascertain its orientation.


GEOLOGY OF NORTHWEST CORNER
WEST HAWK LAKE AREA
LEGEND
PINK QUARTZ MONZONITE
GREY PARAGNEISSIC GRANODIORITE
PINK PORPHYRITIC GRANODIORITE
ENGLISH RIVER GNEISSIC BELT TRANSITION ZONE
INTRUSIVE CONTACT
AGGLOMERATE
HORNBLENDE OLIGOCLASE SCHIST
METAVOLCANICS
METASEDIMENTS
SYMBOLS
SCHISTOSITY, GNEISSOSITY VERTICAL, INCLINED
BEDDING (VERTICAL, INCLINED)
ANTICLINE AXIS
SYNCLINE AXIS
GEOLOGIC CONTACT (DEFINED, ASSUMED)
PROVINCIAL HIGHWAY
SECONDARY ROAD
TRANSMISSION LINE
N
DECLINATION 9° 20' E
0 1/2 1 MILE
LILY POND LAKE
CADDY LAKE
WEST HAWK LAKE

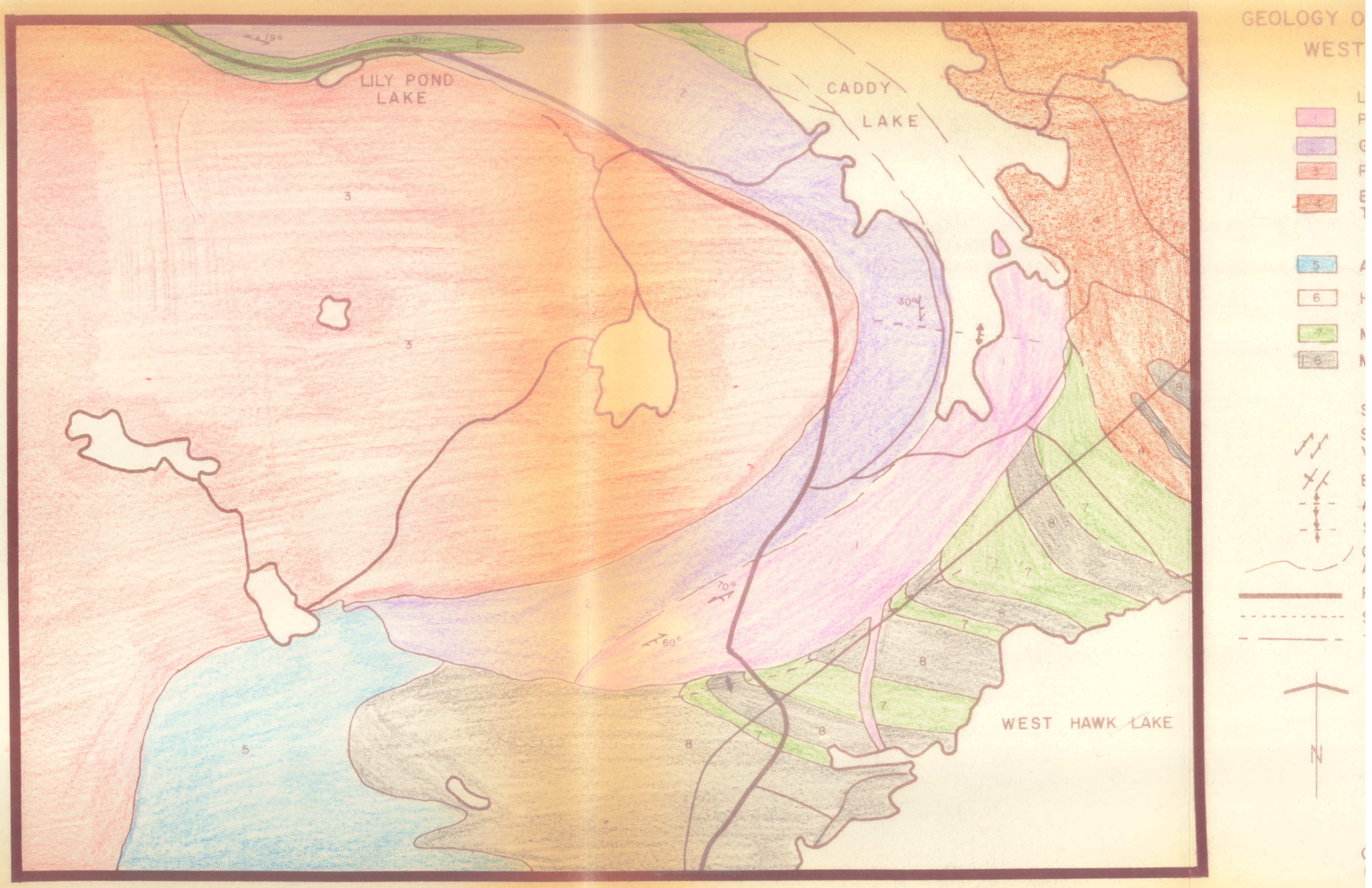

GEOLOGY O
WEST
LILY POND LAKE
CADDY LAKE
WEST HAWK LAKE
19°
20°
30°
70°
60°

FIGURE: 2

PREVIOUS WORK

The first geological work done in the area surrounding Lily Pond Lake was by A.C. Lawson (1885) working for the Geological Survey of Canada. Lawson proposed that the volcanic-sedimentary sequence of the area be termed "Keewatin" after the type sequence to the east. The Manitoba Mines Branch published geological maps of the area in 1952 and 1954 on the basis of work done by Springer (1951) and J.F. Davies (1953), respectively.

M.Sc. student, A. Michalkow (1954), also worked in the area and prepared a map (scale 1 mile = 1 inch) which delineates the geology of the area for some 90 square miles surrounding Lily Pond Lake.

GENERAL GEOLOGY

Regional Geology

The accompanying geological map (Figure 2) presents the regional geological setting for the present study. The map is a compilation based on the published maps of Springer (1952) and Davies (1954); and on the unpublished maps of Michalkow (1954) and the students attending the University of Manitoba geological field school during the 1968 summer session.

The present author has not attempted to add to the regional geological picture but has drawn his information from the above reports and maps.

Springer (1952) writes:

> "All consolidated rocks in the area are of Precambrian age. The oldest rocks form a group of volcanic and sedimentary rocks, which are designated Keewatin ... These rocks have been intruded by a number of stocks and batholiths most of which are granodiorites."

The dominant geological feature which can be observed on the map (Figure 2) is a pink porphyritic granodiorite pluton which occupies the core of a shallow, east-plunging antiformal structure.

Above the pink porphyritic granodiorite core the following sequence of rocks can be observed:

i) a discontinuous band of amphibolite on the north flank of the antiform, north of Lily Pond Lake,

ii) a band of grey paragnessic granodiorite,

iii) a band of pink quartz monzonite.

A steeply west-plunging synform occurs to the south of the antiform (Figure 2). The north limb of the synform has been truncated by the rocks of the antiform. The rocks of the synform consist of an intercalated sequence of metasedimentary and metavolcanic rocks.

Local Geology

The narrow band of metavolcanic rocks (amphibolite) north of the antiform core contains the boudinage and ptygmatic structures investigated by the author (Figure 2). Structurally this band occurs on the north limb of the antiform, which is parallel to Highway 44 near Lily Pond Lake. This east-west trending unit dips approximately 20 to the north and forms a discontinuous cliff approximately 40 feet high forming three outcrops on the north side of Lily Pond Lake (Figures 3, 4, and 5).

The rocks of the antiform are significant to the study, in a spatial sense, therefore, the petrology of each unit is given below. Michalkow (1954) describes the pink quartz monzonite as a pink to greyish pink in colour,

Figure 3. Easternmost outcrop.

Figure 4. Central outcrop.

Figure 5. Westernmost outcrop

fine to medium grained, and massive to slightly gneissic. An average analysis shows 7.1 per cent quartz, 45.0 per cent plagioclase, 40.8 per cent potash feldspar, 0.6 per cent biotite, 4.5 per cent hornblende, 1.4 per cent magnetite, and 0.6 per cent apatite-zircon. Springer (1952) writes of the grey paragneissic granodiorite:

> "parallelism of the ferromagnesian minerals gives this rock a definite lineation. Average composition is 45 per cent oligoclase, 30 per cent quartz, 10 per cent microcline, 10 per cent biotite, and the remainder, accessory minerals. The granodiorite was probably formed by granitization of old sedimentary and volcanic rocks."

The narrow metavolcanic band consists of amphibolite which Michalkow (1954) has determined to be oligoclase hornblende schist. The boudinage and ptygmatic structures occur within this amphibolite unit. The amphibolite unit is overlain by the paragneissic granodiorite unit. Figure 6 shows the contact between the amphibolite and overlying paragneissic granodiorite.

The amphibolite unit pinches out in the easternmost and westernmost outcrops and attains its maximum thickness of approximately 35 feet in the central portion of the westernmost outcrop (Figure 5). On close inspection layering can be observed within the amphibolite. The layering is identified by mineralogical and textural changes and is interpreted as bedding. Although there is no completely diagnostic evidence the composition suggests that the amphibolite represents a bedded basic tuff unit. The bedding

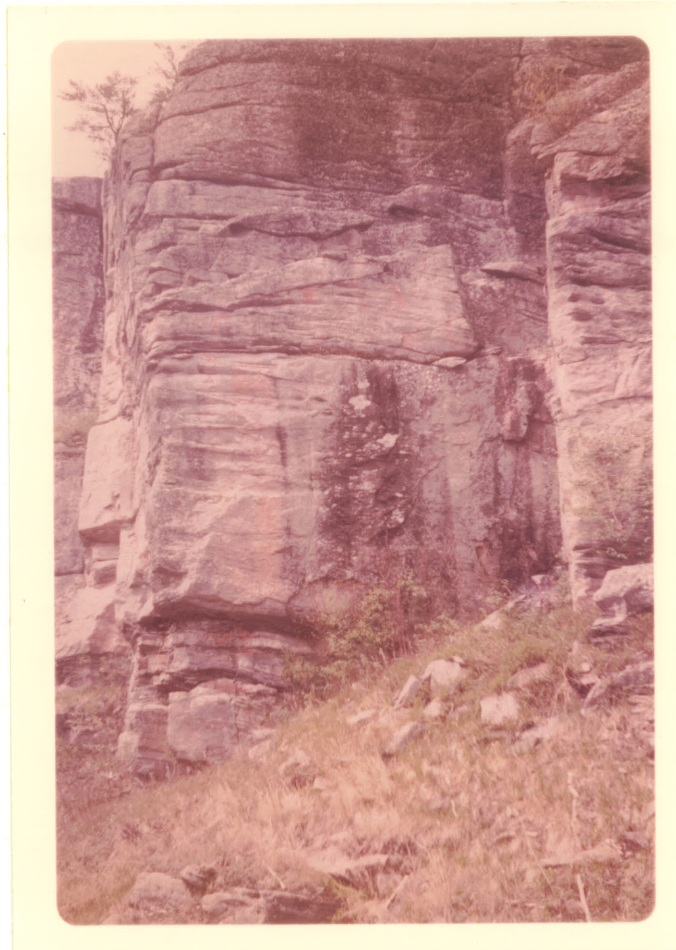


Figure 6. Contact between amphibolite and paragneissic granodiorite, north side Lily Pond Lake, Manitoba. (Vertical cliff is approximately 25 feet high).

provided control for the injection of numerous granitic sheets concordant with the beds. The sheets were subsequently deformed to produce boudins but their concordant relationship with the host rock is still clearly visible (Figure 7).

Several granitic sheets were discordantly injected into the sequence and were deformed into ptygmatic folds. These discordant intrusions cut the bedding at shallow and steep angles. The pre-deformational attitudes of the discordant intrusion is unknown.

Several generations of granitic material are represented within the amphibolite. Figure 8 represents a close-up of a portion of a boudin and at least three ages of intrusion of granite can be identified. The proximity of the adjacent batholith which forms the core of the antiform and directly underlies the amphibolite unit suggests that the intrusive material may have been derived from the batholith. No systematic study of features observed within the younger intrusive material was carried out. Only deformational features related to older intrusive dikes and sills were studied by the author.

Boudinage Structure

The development of two sets of joints throughout the amphibolite unit has led to excellent exposures of the boudins in two planes.

All observations have led to the interpretation that

Figure 7. Boudins show concordant relationship with host rock.

Figure 8. Large (3 feet) boudin showing multiple generations of granitic material.

the boudins were formed by plastic necking prior to brittle failure. The resulting boudins are all lenticular in both of the observational planes (Figure 9). There are numerous examples of boudins in which necking has taken place but in which separation has not developed. Later discussion shows that the necking process prior to brittle failure is indicative of similar competencies within the host rock and the vein material. In a few places amphibolite boudins were also found (Figure 10).

Individual boudins observed in the Lily Pond Lake outcrops range from the order of 2 inches long to 20 feet long. Most of the boudins fall in the range 1 foot to 2 feet long with widths of approximately 1 inch to 2½ inches. Within any boudin layer the boudins are mostly the same size.

Evidence of deformation of the rock in which the boudins are resting is not visible everywhere. Where such evidence can be observed it is usually in the form of drag features in the host at the ends of boudins (Figure 11). These features are a result of greater amounts of slippage progressively away from the boudin-host contact.

Ptygmatic Folds

Although numerous ptygmatic folds can be observed in the Lily Pond Lake area, only five were suitable enough for strain measurements. The others were either discontinuous, too irregular or too poorly exposed for measurement.

Figure 9. Lenticular boudins.

Figure 10. Amphibolite boudin.

Figure 11. Drag fold features at boudin end.

Figures 12, 13, and 14 show various forms of ptygmatic folds observed in the outcrop. Figure 12 shows a well-developed ptygmatic fold in the upper left hand side of the picture. The thickness of the vein and amplitude of the fold are fairly constant throughout the fold suggesting that the exposure face is oriented at right angles to the plunge. Figure 13 shows a granitic dyke (approximately 1.5 feet thick) which has been folded to form an asymmetric ptygmatic fold. Figure 14 shows a vein which has been tightly folded. This vein consists of several flexures so tightly folded that the vein appears as a single mass with complex internal features.

The joint system has permitted unique exposure of ptygmatic folds in some locations. In Figure 15, two elliptical ring-like features of pink granite can be seen with a third identical feature which is not so distinct. (Note that the larger mass of granitic material is a boudin belonging to another layer.) In the center of the ring-like features amphibolite host material can be seen. These features represent the trace of a ptygmatic fold on two joint faces which have intersected the ptygmatic fold in the manner shown in Figure 16.

Figure 12. Small ptygmatic fold (upper left).

Figure 13. Granitic dyke (approximately 1.5' wide) ptygmatically folded.

Figure 14. Complex ptygmatic fold.

Figure 15. Elliptical-like ptygmatic fold.

EVOLUTION OF ELLIPTICAL PTYGMATIC OUTLINES ON JOINT FACES

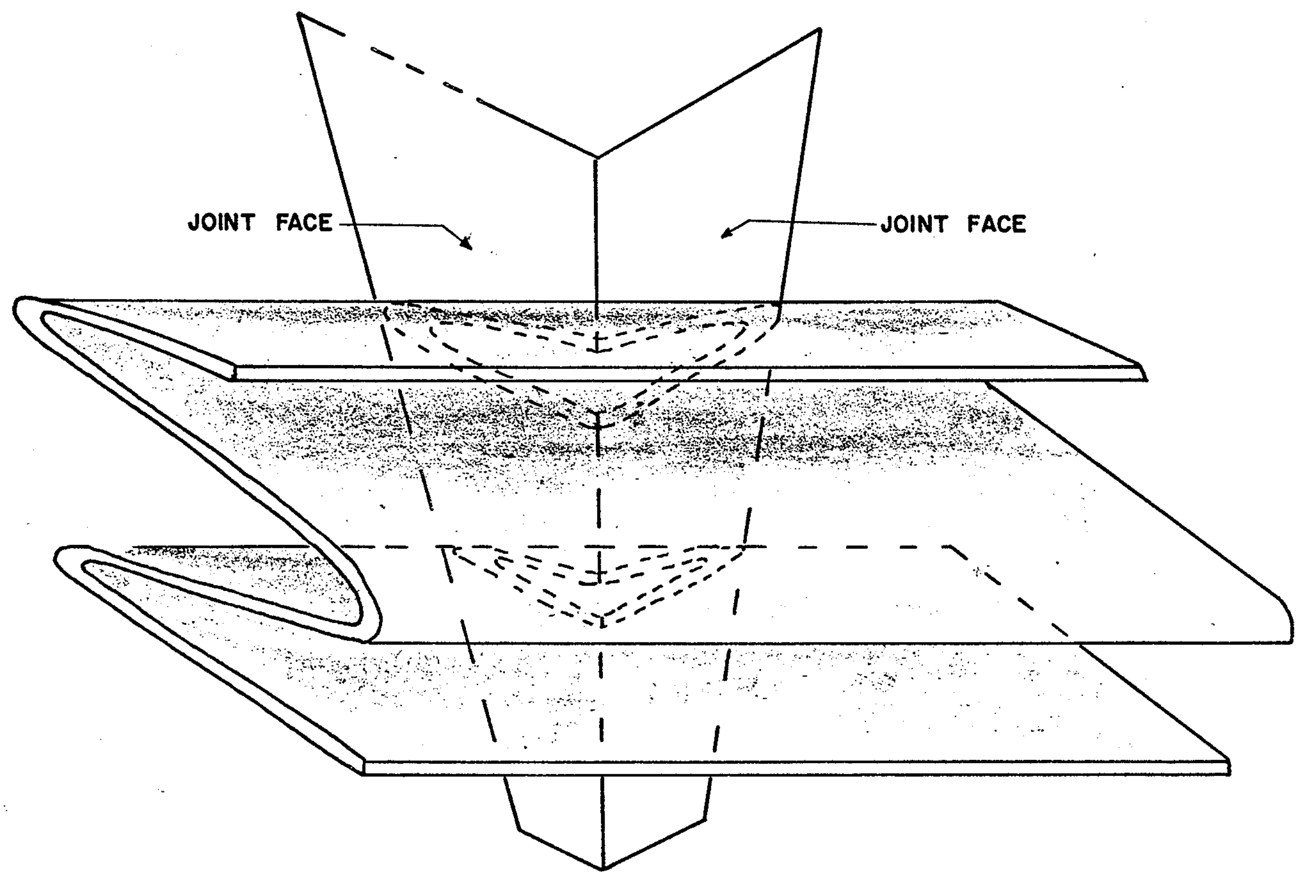


Figure 16.

THEORY RELATING TO BOUDINAGE AND PTYGMATIC FEATURES

The literature concerning boudinage and ptygmatic features is not extensive. The following discussion by no means represents an exhaustive literature search but does show the lines along which the theory regarding boudinage and ptygmatic features developed. The present author has drawn his basic assumptions regarding boudinage and ptygmatic features from observations made by others mentioned in the following sections.

Boudinage

Ramberg (1955) in an important paper on boudinage structure cites three mechanisms for the formation of the structure. Ramberg (1955) refers to boudinage structure as

> "a fractured sheet of rock situated between non-fractured schistose or gneissic rocks. In many cases each fragment of the fractured rock resembles a boudin or a sausage and the whole array of separated fragments often looks like a chain of sausages."

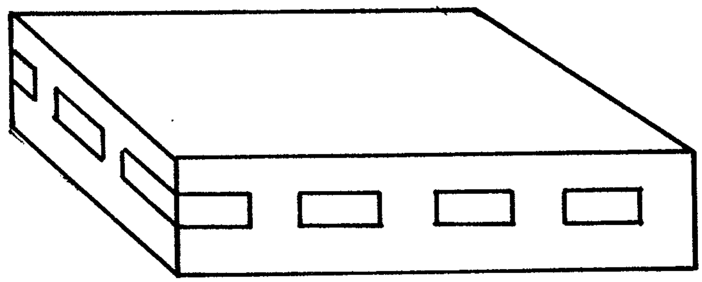
Plate 17 represents different types of boudins which have been observed by various authors.

Mechanism of Evolution of Boudinage Structure

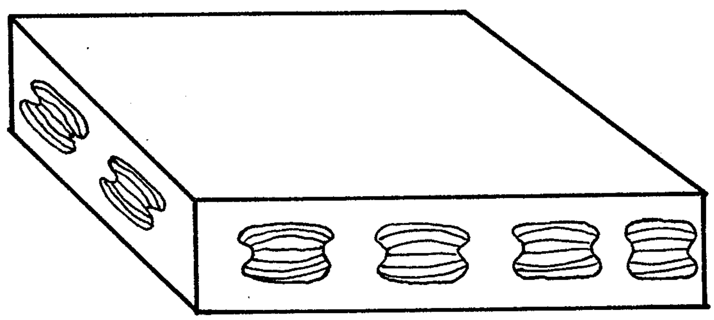
The mechanism for the production of boudinage

TYPES OF BOUDINS

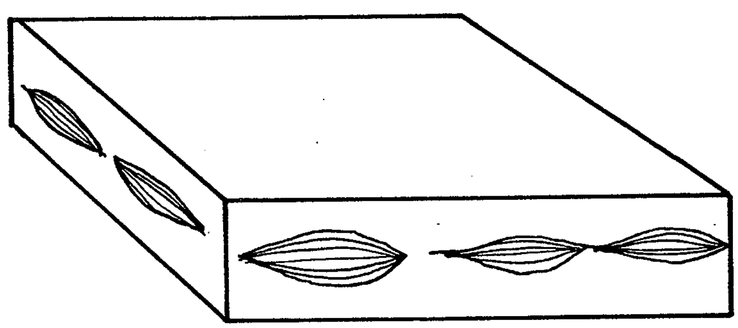
(FROM RAMBERG 1955)



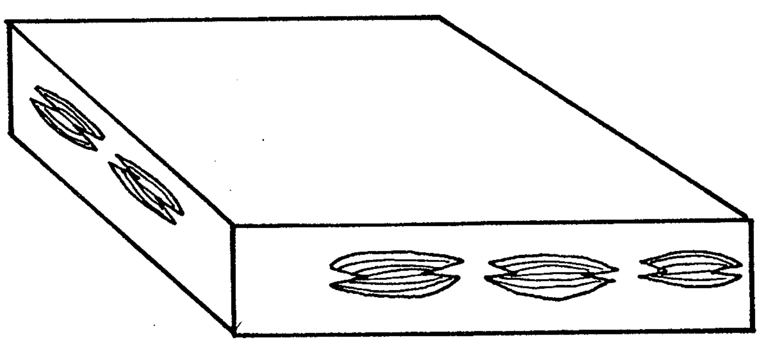
(a) ideal boudins



(b) barrel-shaped boudins



(c) lenticular boudins



(d) incomplete necking in boudins

Figure 17

structure is stated by Ramberg (1955):

> "the evolution of this structure requires a competent rock layer situated between incompetent rocks. It is furthermore commonly held that elongation parallel to the layering of such a rock complex causes the competent rock to break, whereas the incompetent rocks yield by plastic flowage."

Wegmann and Cloos are cited by Ramberg (1955) as agreeing with the above premise, and Ramberg goes on to write

> "The general structural pattern of boudinage shows that the boudin layer was under tensile stress and ruptured along tension joints at the time (or necked down plastically) at the time of evolution of these structures. The structural pattern indicates, furthermore, that the separation of the individual boudins was caused by plastic elongation in the adjacent incompetent layers. ... the structure of the incompetent rocks adjacent to boudins, as observed by the writer and desribed in the literature (Wegmann, 1932; Cloos, 1947) shows that the basic reason for the elongation of the incompetent rocks in by far the most cases must have been a compressive stress perpendicular (or at an obtuse angle) to the boudin layer."

The present author accepts the above as the principal mechanism for the formation of boudinage structure. Although this view is held by many geologists (as cited) there are some who propose a completely different mechanism for the formation of boudinage structure. Ramberg (1955) cites Quirke as proposing that compression parallel to the layering is necessary for the evolution of boudinage structure. Ramberg (1955) states

> "Quirke thought that this was indicated by the barrel like shape of many boudins. He assumed that the boudins had bulged out in response to compressional stress parallel to the original layer."

The barrel-like shape, however, can be explained by compressional stress at obtuse angles to the layering and is more in accord with other features observed in indicated boudins. These details are explained later.

Size and Shape of Boudins

Two Dimensional Size and Shape

Usually, boudins can only be observed in the field in two dimensions. Many of the features described below have been observed by the author. Ramberg (1955) states

> "Boudins are usually oblong bodies with the shortest dimension perpendicular to the schistosity in the enclosing rocks and the longest dimension parallel to the schistosity."

Concerning the size of boudins Ramberg (1955) states that the thinnest boudins he has observed are about 1 cm thick calcite vein and the thickest have been about 20 m (recrystallized and bondinized diabase dikes). As for the length of boudins Ramberg (1955) states

> "The lengths of the observed boudins have varied from a little more than the thickness to many times the thickness."

Regarding the shape of boudins, Ramberg (1955) states the following

> "The most regular and symmetric shape is represented by rectangular bodies with almost perfectly sharp corners." (Figure 17a)

> "Barrel-shaped boudins are common. This shape usually arises from plastic flowage and lateral elongation in the outer portion of the boudins posterior to the break." (Figure 17b) "This plastic flowage of the outer parts of the boudin

has in some cases been so extensive that lens-shaped bodies were produced." (Figure 17c)

"Other lenticular boudins did not develop by plastic flowage posterior to tensional rupture as mentioned but rather by a complete necking-down during plastic stretching prior to separation of the individual boudins." (Figure 17d)

Three-Dimensional Shape of Boudins

Three-dimensional exposures of boudins are rarely observed. Usually outcrops present sections through boudins. Ramberg (1955) states

"Many boudins are more or less equidimensional in the plane parallel to the layering, commonly shaped like rhombs or parallelograms in this plane. This means that many boudins actually are parallelopipeds spaced along certain conformable planes in schist-gneiss complexes."

Structure of the Enclosing Rocks

The plastic flowage of the incompetent rocks past the incompetent rocks produced friction creating the tensile stresses necessary to produce boudinage structure. Evidence of plastic flowage can be observed directly as drag features in the incompetent rocks. A most interesting strain feature observed in the incompetent rocks is described by Ramberg as follows:

"Typical of most boudinages is a structure resulting from plastic flowage in the incompetent rocks parallel to the schistosity, along directions pointing away from the central region of the boudins toward their margins and the space between them. This flowage is caused by elongation in response to the compressive stress, but because of frictional drag along the surface of the boudins, shearing parallel to the schistosity took place.

> Layers close to the boudins were less elongated than layers further away. When the competent boudin layer broke under the tensile stress and the fragments tended to separate, tension also developed in the contact layers of incompetent rock in the region between the boudins. After a smaller or larger plastic stretching, the contact layers in many instances broke and curled around the edge of the boudins. This situation is ideal for indicating a sort of drag fold when the outer layers of the incompetent rocks continue to slide over the contact layers."

The present author has observed this feature within the study area (Figure 11), and has interpreted it as plastic flowage of the incompetent rock material.

Ptygmatic Features

Kuenen (1968), in an important paper on ptygmatic features, outlines a history of thought on the subject and offers a definition and interpretation for ptygmatic features. In his paper (1968) he writes

> "Ptygmatic features are multiple tortuosities of a sheet of rock embedded in a host showing a simpler pattern (or none at all)."

He also states

> "a search for the correct interpretation is important because ptygmatic features may mean either zero reduction in thickness of the host rock, or conversely, up to six-fold thinning."

Kuenen (1968) cites five other authors (Wilson, Dietrich, Sederholm, Read, Milch) who have offered explanations for the formation of ptygmatic features. Four of these proposals are more or less discarded by Kuenen for reasons presented in the following discussion.

Kuenen (1968) cites Wilson (1952) as stating that ptygmatic injection is a result of extrusion of a viscous magma into a stratum of even greater mobility than the vein magma. The extrusion is produced by hydrostatic pressure out of a slot (nozzle) configuration in a strong rock. The extruded ribbon advances through the incompetent host until it meets a resistant layer that it cannot penetrate, causing the layer to buckle, forming a ptygmatic vein. Kuenen discards this theory for the following reasons:

> "Ptygmatic veins have been observed which follow the bedding or schistosity of the host where there is no competence difference demanded by Wilson's theory."

> "Ptygmatic veins have been observed which connect two parallel planar veins. This does not allow for either a nozzle or for a resistant layer because the buckling is against veins." (that is, the parallel planar veins and the ptygmatic vein are of the same material).

Dietrich (1959, 1960) is cited by Kuenen (1968) as proposing that ptygmatic folds originate by anatexis in a passive host. Dietrich says of ptygmatic folds:

> "the tortuosities formed concommitantly with their development ... by at least partial anatexis, local migration of the resulting magmatic solutions, reactions between the migrating material and the remainder of the rock which promotes changes in position and shapes of the interfaces, and subsequent consolidation."

Kuenen (1968) credits Dietrich with his observations on partial anatexis, but Kuenen finds that the main failing of the theory is that it does not explain the most typical property of the ptygmatic vein, namely the meandering.

Sederholm (1907, 1913, 1926) is cited by Kuenen (1968) as proposing that the ptygmatic features are a result of viscous flow but Kuenen discards this theory on the basis of unsound flow mechanics.

Read (1928, 1931) and others are cited by Kuenen (1968) as attributing the veins to injection into a tortuous joint. Kuenen (1968) quotes his earlier objection to this hypothesis:

> "Kuenen (1938) raised numerous objections to this theory, the principal one being that the walls of the 'meanders' do not fit and that the thicker veins show larger contortions."

Following Kuenen's views the present author favours the hypothesis proposed by Milch (1900) for the origin of ptygmatic features. Milch's theory is that of crumpling of an original planar vein by subsequent compressions. Kuenen (1938), Ramberg (1959) and Ramsey (1967) have provided experimental evidence to support this hypothesis. Milch's theory for the origin of ptygmatic features forms the basis for the interpretation of the observed ptygmatic features in the Lily Pond Lake outcrop.

Relationship Between Boudinage and Ptygmatic Folds

De Sitter (1964) diagrammatically illustrates the relationship between boudinage and ptygmatic folding (Figure 18). Two fields with different types of strain are illustrated. Stress acting on a bed dipping less than 45° to the compressive stress direction tends to increase the dip of the bed to 45° and the resulting strain in this field of shortening is ptygmatic folding. If the stress field is maintained past this 45° limit, the dip of the bed is increased further but the bed deforms by extensive strain and boudins develop. This is the field of stretching, i.e., boudinage development.

Figure 18 represents the gradual compression of a flat layer of rock in tem per cent stages of increasing compression. De Sitter points out that if the flat layer had a slight dip at the start of compression (i.e., at

RELATIONSHIP BETWEEN BOUDINAGE AND PTYGMATIC FOLDS

(FROM DE SITTER 1964)

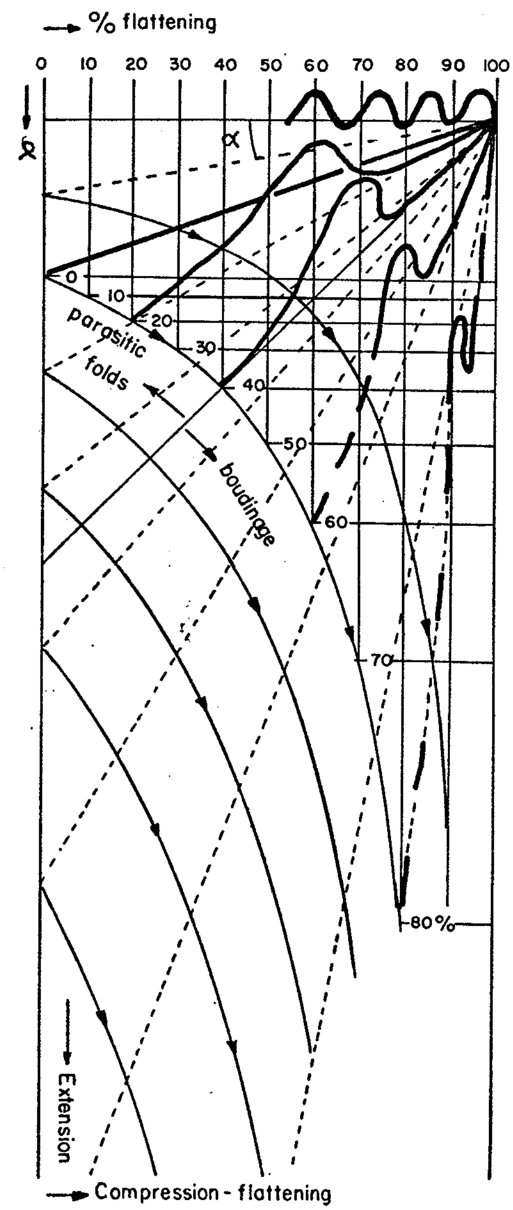


Figure 18

least 20°) the layer will gradually increase its dip with compression and be shortened by ptygmatic folding until it reaches a dip of 45°. Past this 45° limit the layer begins to stretch and boudinage begins to develop.

From Figure 18 De Sitter also points out that if the dip of the bed is zero before deformation begins, a compressive stress system will only produce compression of the layer and it will never be stretched. If the dip of the bed is only a few degrees prior to deformation, a stress system will only produce asymmetric parasitic folds and the bed will not reach the 45° limit.

The important aspect of De Sitter's treatment is that boudinage structure and ptygmatic structure are related. In the unique case where the major compressive stress acts exactly perpendicular to a layer, boudinage structure only is produced. In the case where there is a layer parallel to the major compressive stress direction, ptygmatic folds are developed. The two different types of strain exhibited offer a unique opportunity for quantitatively studying the relationship between compression and extension.

FIELD PROCEDURES AND RESULTS

Procedures

All of the structural measurements were made on boudinage and ptygmatic structures within the amphibolite unit. The amphibolite unit can be traced for approximately six hundred feet and is exposed discontinuously along the road cut. Bedding within the amphibolite unit trends 085°/18°NE.

Two well-developed joint sets within the amphibolite provided for several measurements in two directions. These two directions were 109°/79°W and approximately 206°/77°W. A third set of measurements was made in a direction 059°/80°S.

Boudinage Structure

Measurements were made only on boudins which showed a concordant relationship with the layering in the amphibolite unit. Figures 7 and 9 show several examples of concordant boudins and the typical lenticular form of the boudins. The lenticular form of the boudins is due to plastic flow prior to brittle failure, and, as such, no accurate extensive strain measurements can be made by simply measuring the distance between adjacent boudins.

Figure 19 illustrates the process by which a measure of the extensional strain was determined. Fundamental to this procedure is the concept of extensive strain ratio which is

$$\text{Extensive strain ratio} = \frac{\text{post-deformational length } (L_o)}{\text{pre-deformational length } (L_1)}.$$

Post-deformational length is defined as the length of 'n' boudins plus 'n' gaps. The pre-deformational length must be computed with the computation based on the following considerations.

i) Post-deformational length (L_o) is measured.

ii) Maximum thickness (T_o) of boudins is measured.

iii) Post-deformational area (A_o) of competent rock within L_o is determined with a planimeter (Figure 19).

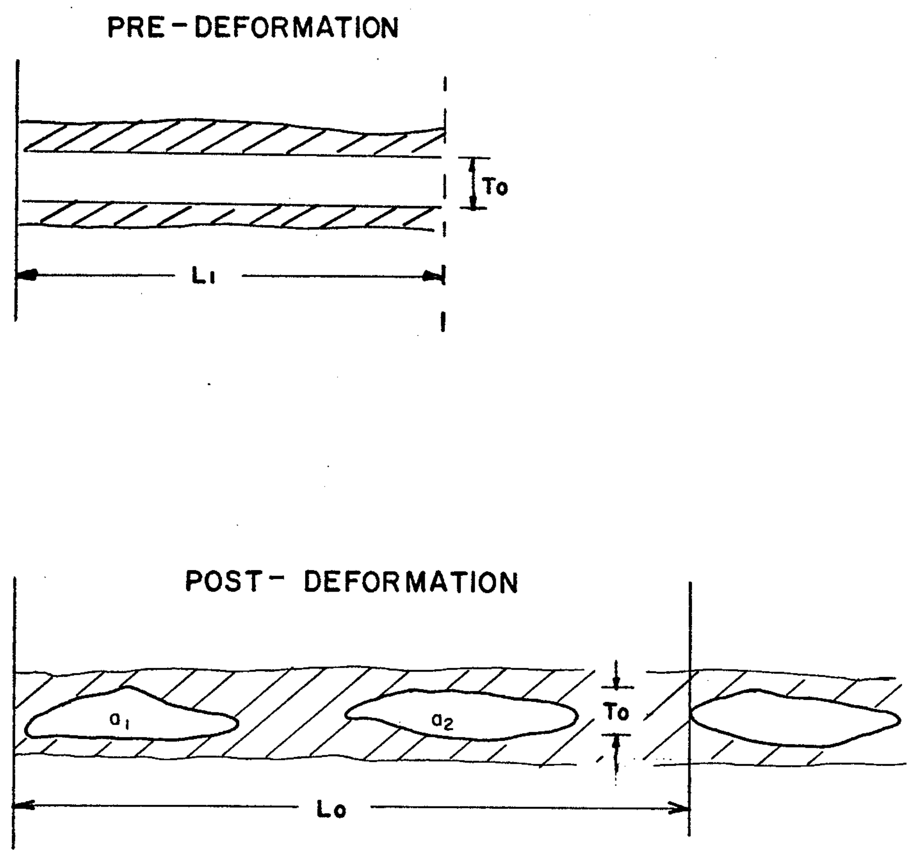
iv) If the maximum thickness (T_o) of boudins represents the original thickness of the competent layer before deformation then the pre-deformational length (L_1) is calculated as

$$L_1 = \frac{A_o}{T_o}$$

Once L_o and L_1 have been determined the extensive strain ratio is calculated as

$$\text{Extensive strain ratio} = \frac{L_o}{L_1}.$$

EXTENSIONAL STRAIN RATIO



$$a_1 + a_2 = A_o$$

$$L_1 = \frac{A_o}{T_o}$$

$$\text{EXTENSIONAL STRAIN RATIO} = \frac{L_o \text{ (POST DEFORMATIONAL LENGTH)}}{L_1 \text{ (PRE-DEFORMATIONAL LENGTH)}}$$

Figure 19

The assumptions that have to be made in order to derive the extensive strain ratio are as follows.

(i) It is assumed that there is no volumetric change of competent rock between deformed and the undeformed states. This implies that in any cross-sectional exposure of boudins the area of the competent rock in the section is the same as it would have been in the unstrained state. This assumption seems reasonable because volumetric changes due to recrystallization would be slight.

(ii) It is assumed that the maximum thickness found in any boudinages sheet approximates reasonably the thickness of the undeformed sheet. This assumption may not be valid, for some thinning may have taken place prior to the development of the boudinage structure. If this thinning took place, the analyses of extensional strain leads to minimum values only.

(iii) It is assumed that the granitic layers from which the boudins were produced were of uniform thickness prior to deformation. The assumption seems reasonable because the maximum thickness of boudins within any layer is fairly constant.

All measurements were made on projection slides made from photographs of the individual exposure faces. The areas of the boudins were determined with a planimeter. Since the analysis is concerned with ratios no proportionality constants had to be introduced.

Ptygmatic Folds

Measurements of compressional strain were obtained from ptygmatic folds. Only six ptygmatic folds were exposed sufficiently well in the Lily Pond Lake outcrop to make measurements with any degree of confidence.

As pointed out in an earlier section, ptygmatic folds can form only if the dip of the vein is less than 45° to the direction of maximum compression. The ideal case, of course, is when the dip of the vein and the maximum compressional direction are the same.

The chief hazard in obtaining compressional strain measurements from ptygmatic veins is the absence of data bearing on the original dip of the vein and its orientation relative to the stress field. If the vein was originally at a high angle to the stress field, say 30°, it will show considerably less compressive strain than one which was 0° to the stress field.

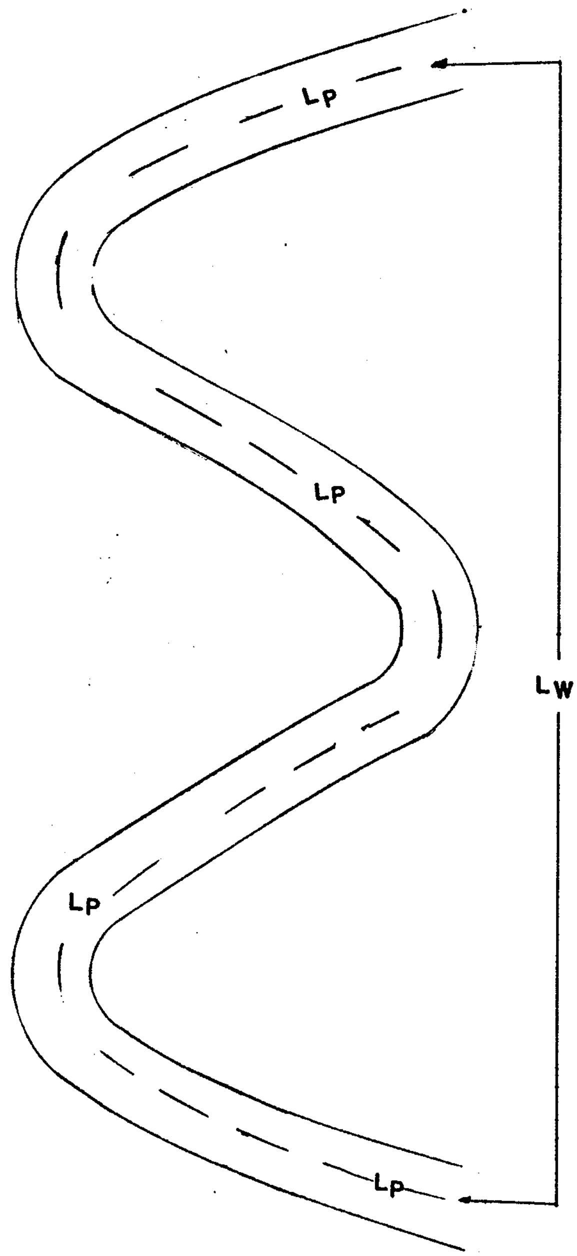
Another difficulty in obtaining compressional strain measurements from ptygmatic folds results in the fact that they are exposed only on one place and hence the plunge of the folds cannot be determined. In order to obtain an accurate measure of shortening, measurements must be made in a plane orthogonal to the plunge. Consistency of thickness throughout the ptygmatic fold and consistency of fold amplitude and wavelength are indicative of a section at right angles to the plunge. Only one such fold was observed. The compressional strain ratios were determined by dividing the length along the folded vein (L_p) by a straight line length (L_w) taken in the wave length direction (see Figure 20).

Data were also obtained from ptygmatic folds which are quite uniform in thickness and cut by two joints resulting in the fold appearing on both joint faces. The result is elliptical-shaped outlines of granitic material when both joint faces are viewed simultaneously (Figure 15). Values of L_p were obtained by geometric projection and the compressional strain ratios calculated as above.

Results

The extensional and compressional strain ratios are given in Table I along with the direction in which the extensional measurements were obtained. From the table, it can be seen that the extensional strain ratios are consistent in any given direction. Two of these directions which are roughly 90° apart yield similar results, i.e. in direction 09°/79°W the mean extensional strain ratio equals $\frac{2.11}{1.00}$ and in direction 206°/76°W the mean extensional strain ratio equals $\frac{2.24}{1.00}$. From geometric considerations either the

COMPRESSIONAL STRAIN RATIO



COMPRESSIONAL STRAIN RATIO = $\frac{LP}{LW}$ (PRE DEFORMATIONAL LENGTH) / (DEFORMATIONAL LENGTH)

Figure 20

Table I

Extensional Measurements

Direction	Mean Direction	Extensional Strain Ratio	Mean Extensional Strain Ratios
109°	109°	2.25 : 1.00	2.11
109°		2.26	
109°		2.10	
109°		1.98	
109°		2.00	
210°	206°	2.10	2.24
210°		1.68	
203°		1.53	
203°		2.23	
205°		3.07	
205°		2.31	
205°		2.56	
205°		2.53	
205°		2.19	
059°	059°	3.25	3.44
		3.25	
		3.09	
		4.20	

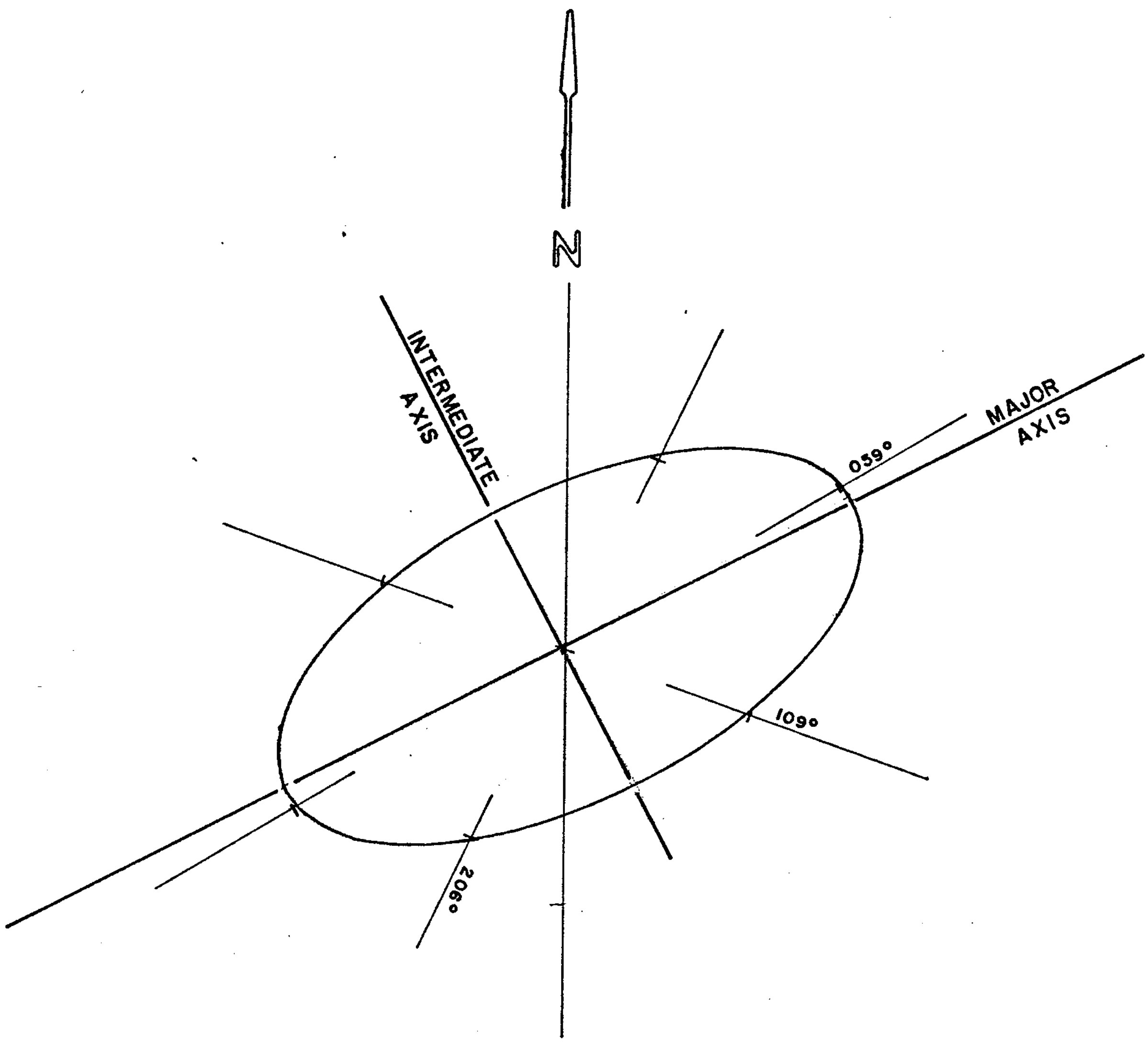
Compressional Measurements

	Compressional Strain Ratios	Mean Compressional Strain Ratio
Single ptygma on one joint face	5.8	5.9
Ellipsoidal ptygma	4.4	
	6.4	
	7.7	
	5.0	

strain ellipse is approximately circular or the directions in which the measurements are taken fall symmetrically on either side of a symmetry plane of the ellipse. The third joint set exposure which has direction of 059°/80°S indicates that the latter of these two alternatives is correct. The larger extensional strain ratio of $\frac{3.44}{1.00}$ which has been observed in the third joint set coupled with the approximately equal strain ratios of $\frac{2.11}{1.00}$ and $\frac{2.24}{1.00}$ observed in the other two sets, permits the determination of the major and intermediate axes of a strain ellipsoid. The direction and the amount of strain in each direction was plotted on paper and the strain ellipse in Figure 21 was graphically constructed. The orientation of the major axis is 062°. The orientation of the intermediate axis is 152°. The plane of the ellipsoid which contains the major and intermediate extensional strain axes is contained within the plane of layering. It should be noted that since the extensional strain ratios are consistent in any given direction, the assumption made must be valid, otherwise, the data would be widely scattered.

The compressional strain ratios show considerable variation. The variation is probably due to the fact that the initial attitude of the ptygmatically folded sheets is unknown. From the compressional data the minor axis of the strain ellipsoid shows compressional strain ratios ranging from $\frac{4.40}{1.00}$ to $\frac{7.70}{1.00}$ with a mean compressional ratio of $\frac{5.90}{1.00}$.

SECTION OF STRAIN ELLIPSOID THROUGH MAJOR AND INTERMEDIATE AXES



SCALE: 1" = 2/1 EXTENSIONAL RATIO

Figure 21

Predicted Compressional Ratios

From the extensional strain ratios it is possible to calculate an expected value for the compressional-axis ratio. This calculated value can be compared to the observed value of the compressional-axis ratio as a check on the validity of the technique used to obtain these ratios.

The derivation of the formula for the above clacula calculation is as follows:

Assume you have a sphere of unit radius (R) deformed into an ellipsoid having axes a, b and c. The volume is assumed to remain constant. Equating the volume of the two solids the resulting equation is

$$\frac{4}{3}\pi R^3 = \frac{4}{3}\pi abc$$

or

$$R^3 = abc$$

Now $R \equiv 1.00$ hence $R^3 = 1.00$,

and $a = \frac{3.50}{1.00}$ and $b = \frac{1.65}{1.00}$ from Figure 21,

hence $c = \frac{1.00}{5.77}$.

This means that the minor axis is $\frac{1.00}{5.77}$ of its original dimension.

The predicted compressional-strain ratio from these calculations is $\frac{5.77}{1.00}$. The compressional strain ratios derived from field observations range from $\frac{4.40}{1.00}$ to $\frac{7.70}{1.00}$ with a mean of $\frac{5.90}{1.00}$. The observed and predicted values compare very favourably and the author interprets this result to be a verification of the technique used to obtain the ratios.

CONCLUSIONS

The strain ellipsoid in the Lily Pond Lake area is oriented with the major extensional axis striking 062° and the intermediate extensional axis striking 152°. Extension on the major and intermediate axes is approximately $\frac{3.50}{1.00}$ and $\frac{1.65}{1.00}$ respectively. The compressional axis is orthogonal to the plane of the other two axes and has a mean value of $\frac{5.90}{1.00}$ compression.

The predicted compressional strain ratio has a value of $\frac{5.77}{1.00}$ which compares very favourably with the mean derived from field observations. The author interprets this as a verification of technique.

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