THE UNIVERSITY OF MANITOBA

STRUCTURAL ANALYSIS OF A SIMILAR-TYPE FOLD; BOOSTER LAKE, MANITOBA

by

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ABSTRACT

A similar-type fold is outlined by a unit of meta-conglomerate in the Booster Lake area of Manitoba. This anticline merges into a major syncline which extends 25 miles westward to Lac du Bonnet. The anticline has deformed an Archean sequence of metagreywacke, meta-conglomerate and a second unit of metagreywacke. A granite pluton was intruded into the core of the fold.

The orientation of the Booster Lake fold is defined by its plunge and the dip of its axial surface. On the basis of its orientation and closure, it is a tight inclined anticline.

Assuming cylindrical folding, a right section is constructed to enable classification of the style of folding. Three parameters: dip isogons; orthogonal thickness, t; and axial planar thickness, T, show the fold style to be complex. It almost ideally belongs to Ramsay's (1967) Class 2 in the hinge area but is of Class 1C in the limbs.

The style of folding, foliation, lineations, and textures are inconclusive in defining the type of strain which produced the fold, but four types of strain are considered possible: heterogeneous pure shear; homogeneous flattening superimposed on a flexural fold; flexural folding followed by heterogeneous or homogeneous pure shear and heterogeneous simple shear; and heterogeneous or homogeneous

pure shear followed by heterogeneous simple shear. The mechanism was that of passive flow contemporaneous with metamorphism. The granite pluton may have been involved in the folding as it was either syn-folding or post-folding.

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CHAPTER I

INTRODUCTION

THE PROBLEM

The purpose of this study is: (1) to document and analyze the geometry of a fold outlined by a meta-conglomerate unit in the area immediately to the north of Booster Lake, Manitoba; (2) to investigate the nature of the strain producing the fold; (3) to relate the deformation to the metamorphism and (4) to examine the role of the granite pluton in the development of the fold.

LOCATION AND ACCESS

The Booster Lake area is approximately 90 miles northeast of Winnipeg, Manitoba and 35 miles northeast of Lac du Bonnet, Manitoba (Figure 1). The area is accessible by road; Provincial Road 315 cuts through the northern edge of the thesis area.

TOPOGRAPHY

Outcrop is plentiful in the area north of Booster Lake and there is a general relief of approximately 50 feet. The area has a good forest cover and thick moss covers most of the outcrop.

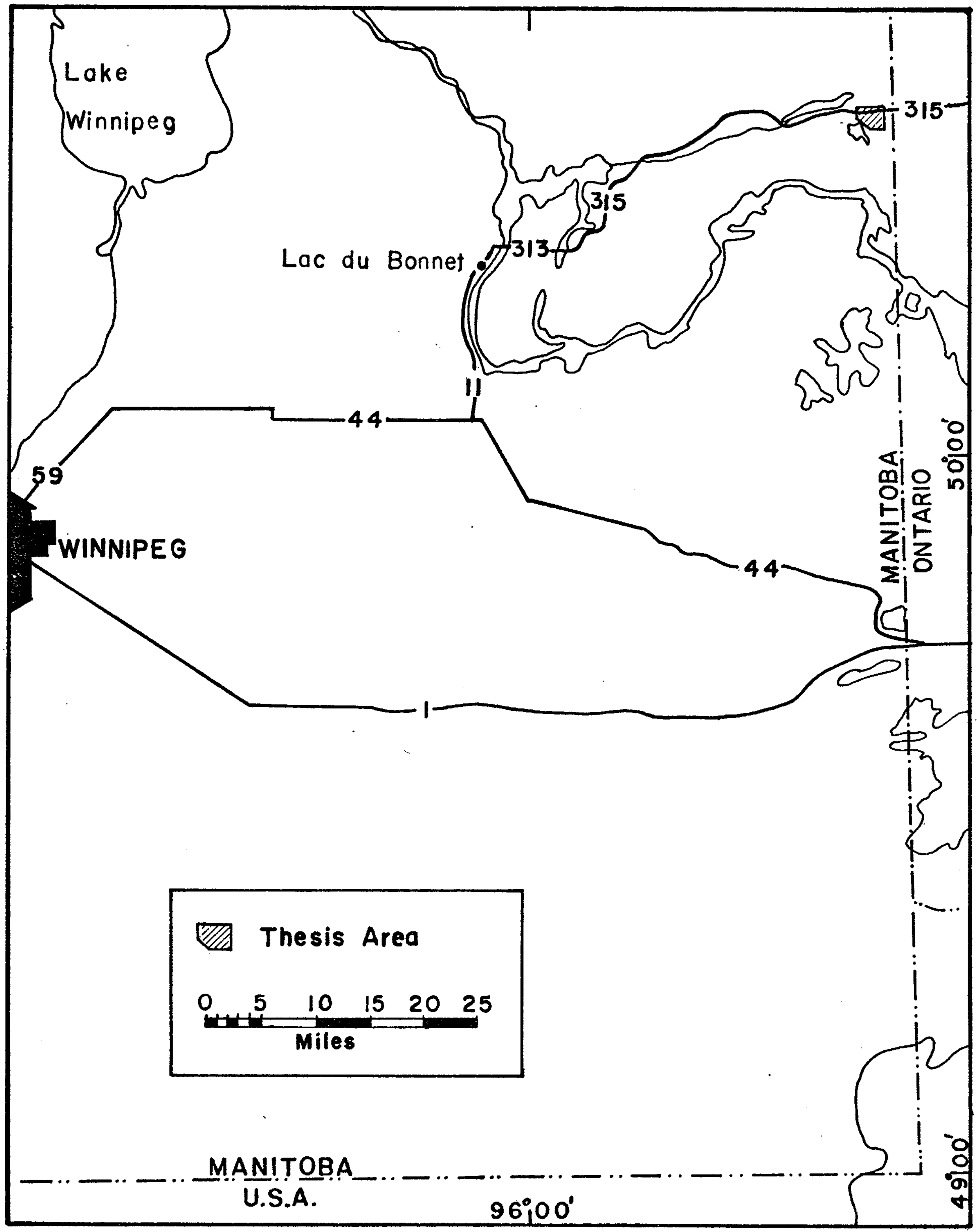

Figure 1: Map of southeastern Manitoba showing the location of the thesis area.

PREVIOUS WORK

Springer (1949) produced the first detailed geologic map of the area at a scale of one inch to one mile. It was not until the area was re-mapped by Davies (1956) at a scale of one inch to one thousand feet, however, that the conglomerate unit was found to outline a fold.

Butrenchuk (1970) carried out a study on the metamorphic grade of the rocks in the Bird River area, including those within the present area of study. He concluded that 3 periods of metamorphism have affected the metavolcanic and metasedimentary rocks of the Bird River area. The first period of metamorphism was a thermal event. The effects of this event have been obliterated in the Booster Lake area by the second metamorphic event. This second period of metamorphism was a dynamo-thermal type and produced a regional foliation parallel to the bedding in the volcanic and sedimentary rocks. During this period, the sedimentary rocks within the Booster Lake area were metamorphosed to the almandine-amphibolite facies (with epidote). The third period of metamorphism was dynamic and the effects were related to deformation of the regional foliation by faulting. This event does not appear to have affected rocks of the Booster Lake area.

PRESENT WORK

The field data were collected in the fall of 1970 over a period of ten days. Traversing, at a spacing of approximately 500 feet, was carried out across the nose of the fold. Less detailed work was done on the flanks and in the core of the fold. The geological map published by Davies (1956) was used as a basis for the field work. The area was not re-mapped, but more structural data were gathered to augment those gathered by Davies.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. W. C. Brisbin of the University of Manitoba Department of Earth Sciences for not only suggesting the topic, but also for his valuable assistance during the study.

The Manitoba Mines Branch prepared the thin sections used in the study.

Aerial photographs of the thesis area were taken by Abitibi Paper Company and are at a scale of one-quarter mile to the inch.

The geology of the area was mapped by Dr. J. F. Davies of the Manitoba Mines Branch in 1955 and his map (Davies, 1956) provided a valuable basis for the thesis.

D. L. Trueman carried out detailed studies in the Bird River area for the Manitoba Mines Branch and his comments and discussion have been very helpful.

CHAPTER II

GENERAL GEOLOGY

REGIONAL GEOLOGY

A belt of metasedimentary and metavolcanic rocks extends eastward from Lac du Bonnet into the Booster Lake area (Figure 2). These rocks are Archean in age and belong to the Rice Lake Group (Springer, 1949; Davies, 1955, 1956). According to Davies (1955, 1956) the volcanic rocks are the basal rocks of the group (Table 1). The rocks of the belt have been folded into a syncline with the metasedimentary rocks now in the core of the fold. The axis of the syncline runs down the centre of the belt but bifurcates south of Bird Lake. The axis of the northern branch of the bifurcated syncline is cut off by the fault which passes through Bird Lake. The axial trace of the southern branch passes through Booster Lake. The anticline between the two subsidiary synclines is the subject of this study and is referred to as the Booster Lake anticline. The relationship of the anticline to the major syncline is shown in Figure 3. The metavolcanic and metasedimentary rocks have been intruded by basic rocks of the Bird River sill and by large granitic batholiths which bound the belt to the north and south.

D. L. Trueman (personal communication) has noted outcrops of conglomerate along the metavolcanic-metased-

LEGEND

Quartz diorite, granodiorite, granite	Geological boundary
Bird River Sill	Fault
Conglomerate	Trace of anticline
Greywacke, arkose, quartzite	Trace of syncline
Andesite, basalt	

Figure 2: Regional geology of the Lac du Bonnet-Booster Lake area (after Davies et al, 1962).

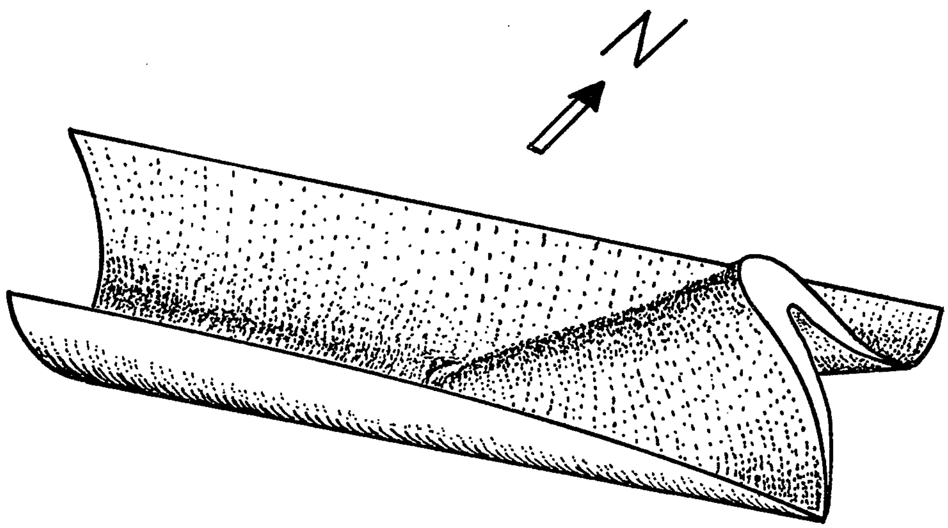

Figure 3: Three-dimensional sketch of the anticline in relation to the easterly trending syncline. This view of the structure is prior to faulting of the north limb.

Table 1: Table of Formations (after Davies, 1956)

Recent and Pleistocene		Glacial sand and clay
MAJOR UNCONFORMITY		
PRECAMBRIAN	Map Unit	
	6	Granodiorite
	5	Grey Granite
		intrusive contact
		Bird River Sill
		intrusive contact
		RICE LAKE GROUP
	4	Silicified Zone
	3	Metagreywacke
	2	Meta-conglomerate
	1	Metagreywacke
		Andesite, Basalt

Note: Map-unit numbers identify those rocks present in the Booster Lake thesis area.

imentary contact. Along this contact, the conglomerate contains clasts of metavolcanic rocks. Metavolcanic clasts are notably absent from the meta-conglomerate exposed within the Booster Lake area. The Booster Lake conglomerate may be straigraphically equivalent to the other conglomerate, but, at present, there is no basis for such an interpretation.

AGE RELATIONSHIPS AND STRATIGRAPHY

The oldest rocks within the thesis area (Figure 4) are the Rice Lake Group metasedimentary rocks consisting of metagreywacke, meta-conglomerate and a second unit of metagreywacke. Although the contact between units 1 and 2 (Table 1) was not exposed it would appear that it is gradational. Small pebbles of tonalite were found in exposures of the lower metagreywacke approximately 100 feet across strike from exposures of the meta-conglomerate, and the matrix of the meta-conglomerate is similar in composition to the metagreywacke.

These age relationships indicate that there was continuous sedimentation of greywacke composition on top of volcanic rocks. During the sedimentation, however, an influx of granitic and arkosic pebbles from an unknown source resulted in the intervening unit of conglomerate.

The silicification of the upper metagreywacke to form the silicified zone is of questionable age. The silicification process did not affect the meta-conglomerate nor any of the lower metagreywacke within the core of the fold.

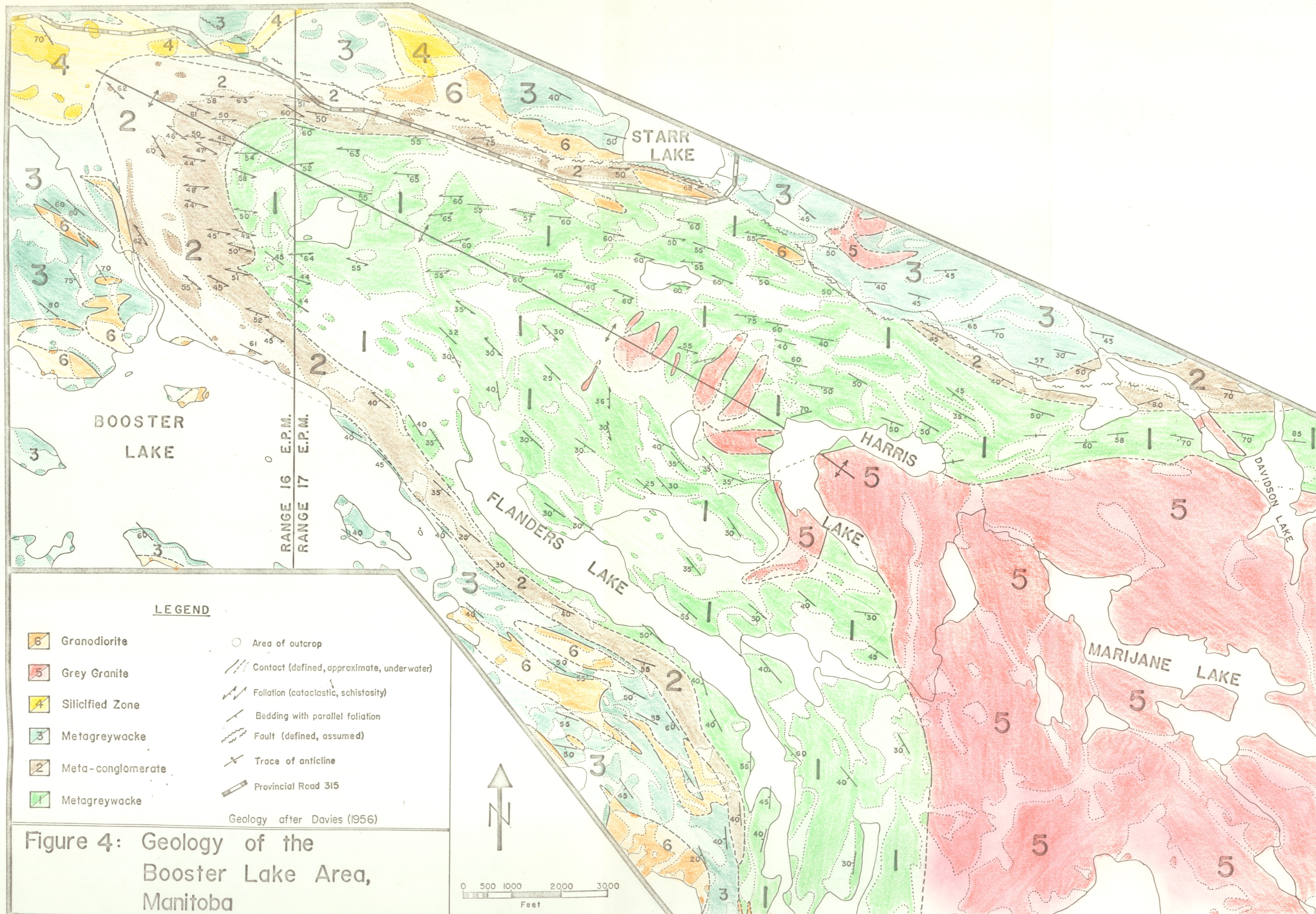

Figure 4: Geology of the Booster Lake Area, Manitoba

The granitic intrusive rocks are definitely younger than the metasedimentary rocks. The lower metagreywacke has been locally deformed by intrusion of the granodiorite which also contains inclusions of the upper metagreywacke near the contact.

LITHOLOGY AND DISTRIBUTION OF ROCK TYPES

Metagreywacke (1)*

The lower metagreywacke unit underlies the meta-conglomerate and is exposed in the core of the Booster Lake anticline (Figure 4). This metagreywacke is medium to dark grey in colour, fine-grained and schistose. It is composed of quartz, plagioclase, biotite, and locally hornblende, all of which have been recrystallized. The quartz grains are strained and the biotite grains have a preferred orientation which imparts a schistosity to the rock. Hornblende, where present, also shows a preferred orientation. In spite of recrystallization, rounded feld-spar grains, comprising a relict clastic texture, were observed in thin sections from two localities. Bedding was observed locally in the metagreywacke. Davies (1956) also observed bedding at localities which the writer was unable to visit.

Meta-conglomerate (2)

This unit, which outlines the fold under study, is a

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* Map-units are shown in Figure 4.

metamorphosed polymictic conglomerate. It varies in true orthogonal thickness from 350 feet in the limbs to 3000 feet in the hinge area of the Booster Lake fold. The meta-conglomerate is poorly sorted and consists of tonalite pebbles and, to a lesser extent, of arkose pebbles in a grey, fine-grained, recrystallized quartzo-micaceous matrix. Both types of pebbles have been deformed such that their long dimensions plunge to the southwest in the plane of foliation. Layering was observed locally in the matrix of the conglomerate on the limbs of the fold, but was not found in the hinge zone.

The recrystallized matrix consists of quartz, biotite, and plagioclase. The quartz is strained and the biotite shows preferred orientation. Biotite is also concentrated around the margins of the arkose and tonalite clasts.

The pebbles of coarse-grained white tonalite range from 1 inch to 12 inches in diameter, and have responded more competently to deformation than the surrounding matrix. The tonalite pebbles have been recrystallized and the quartz and feldspar are anhedral but are not aligned. Biotite grains are poorly aligned, but this weak foliation is parallel to the foliation in the matrix. Quartz commonly forms pressure shadows at the ends of pebbles (Figure 5).

The arkose pebbles are white, fine-grained, and highly deformed in such a manner that they wrap around the tonalite pebbles (Figure 5). Biotite is only a minor con-

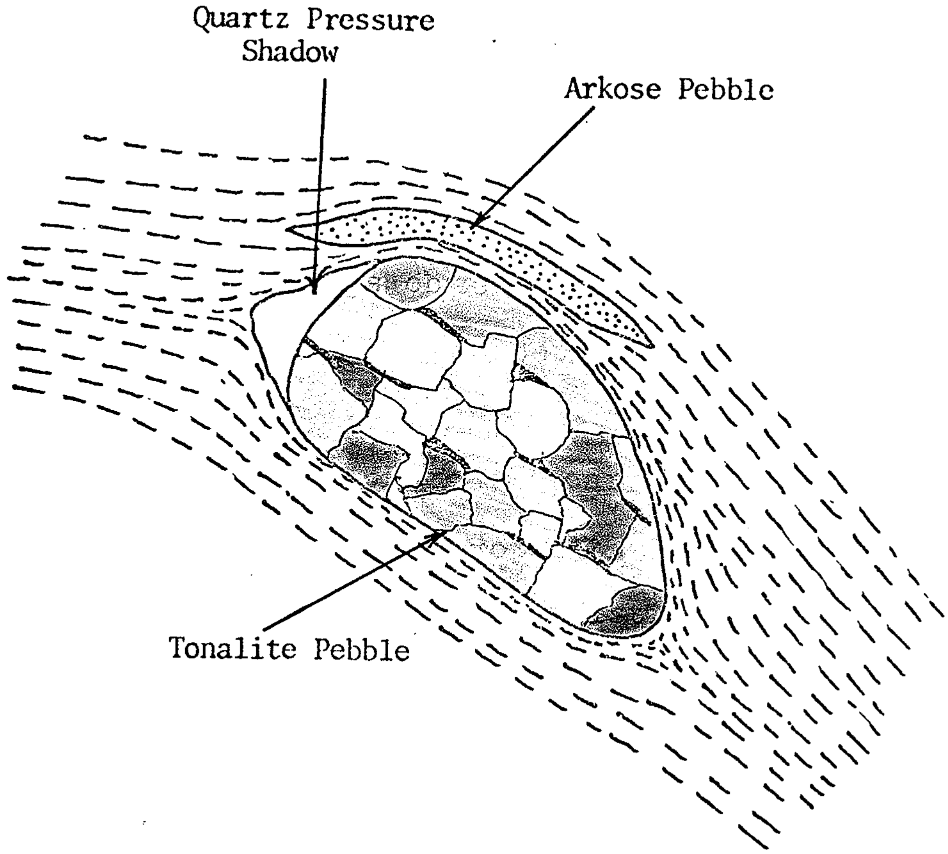


Figure 5: Tonalite pebble flattened in the plane of foliation with quartz pressure shadow. Arkose pebble is flattened and tends to wrap around the tonalite pebble.

stituent in these recrystallized pebbles, but again the grains are oriented parallel to those in the matrix.

Metagreywacke (3)

The upper metagreywacke unit bounds the upper surface of the meta-conglomerate and extends westward to Lac du Bonnet (Figure 2). Although this unit is of a different age than the lower metagreywacke unit, both are alike in all respects. Bedding was observed in the upper metagreywacke on the north shore of Booster Lake.

Silicified Zone (4)

A silicified zone outcrops at the nose of the anticline. This zone has an irregular distribution and is "probably the result of replacement of greywacke by silica-bearing and, in some cases, sulphur-bearing hydrothermal solutions." (Davies, 1956, p. 10).

These rocks are fine-grained, cream-coloured, cherty looking rocks with rusty surface weathering. Mineralogically, they are composed of quartz, microcline, muscovite, and pyrrhotite and pyrite.

Grey Granite (5)

Coarse-grained to pegmatitic grey granite occurs within the core of the fold around Marijane Lake (Figure 4). It forms a large body, the outline of which conforms to that of the fold itself. Several smaller isolated bodies also occur to the northwest of the main body.

The grey granite is a heterogeneous unit composed of quartz, microcline, plagioclase, and biotite in variable proportions. The composition of the rock ranges from a granite to a granodiorite. Springer (1949) also observed some quartz dioritic phases. The rock is massive to strongly gneissic and contains xenoliths of older rocks (Davies, 1956).

Granodiorite (6)

Several outcrops of grey, coarse-grained granodiorite occur to the south of Starr Lake (Figure 4). This unit is massive and contains xenoliths of upper metagreywacke adjacent to the contact with that unit. The granodiorite is composed of quartz, plagioclase, and minor biotite. Pyrite was found in the contact zones along with the xenoliths of metagreywacke.

STRUCTURAL GEOLOGY

The major structural feature within the thesis area is the Booster Lake anticlinal fold. Certain other structural elements including foliation, lineations, and a fault were recognized and are documented here because of their relationships to the fold.

The Fold

The Booster Lake fold, as outlined by the meta-conglomerate, appears to be a similar fold closing to the northwest (Figure 3). The meta-conglomerate unit is thin near Flanders Lake but thickens in the hinge zone, north of Booster Lake. The thickness of the meta-conglomerate in the north limb is not known because that limb has been faulted.

Foliation

The foliation in the metagreywacke units and in the matrix of the meta-conglomerate is produced by the preferred orientation of biotite and, to a lesser extent, quartz and plagioclase. The foliation is parallel to the layering in the limbs of the fold, but cuts across the bedding in the hinge area. The foliations for the north and south limbs respectively, converge in the hinge zone.

The foliation in the matrix of the meta-conglomerate is deflected around the deformed clasts (Figure 5). Biotite grains are concentrated at the margins of the pebbles and are oriented parallel to the biotite grains in the matrix.

A weakly preferred orientation of the biotite in the tonalite and arkose pebbles in the meta-conglomerate is parallel to the foliation in the matrix.

The pebbles in the meta-conglomerate have been flattened so that the plane of flattening coincides with the plane of foliation.

Lineations

The pebbles are elongate as well as flattened. The rounded nature of the outcrops permitted only the general observation that the pebbles have a moderate to steep southwesterly plunge in the plane of foliation.

A series of slabs was cut through several oriented samples enabling approximate measurements of the plunge. The plunges of the long axes vary but, in general, were found to be 30 to 50 degrees at 220° to 245°. This method was found to be slightly inaccurate due to difficulties in defining the exact long axis of each pebble. It must be concluded therefore that the above values of plunge are not completely reliable.

Faulting

An east-southeasterly striking fault cuts the meta-conglomerate in the northern limb of the fold. This fault was observed by the writer to be a large shear zone dipping steeply south. The distribution of the meta-conglomerate between Starr and Davidson Lakes (Figure 4) suggests that this fault has a right-lateral horizontal component of displacement of approximately 8000 feet.

CHAPTER III

ORIENTATION, CLOSURE, STYLE AND ASYMMETRY OF THE BOOSTER LAKE FOLD

ORIENTATION AND CLOSURE

Attitudes of the Limbs

The number of layering measurements taken in the field was insufficient to conduct a statistical stereographic analysis of the fold. Consequently, it was necessary to determine the character and orientation of the limbs in a less conventional way, making use of the metaconglomerate as a marker unit.

The orientation of each limb of the fold is defined by its respective strike and dip. The strikes of the north and south limbs could be measured (100 and 130 degrees respectively) from the plan view (Figure 4). These strikes coincide with those of the layering observed in the limbs of the fold (Figure 6). The dips of the layering are therefore assumed to represent the general dip of the limbs. The average dip for each given strike is assumed to be representative for that limb. The attitude of the north limb is $100^\circ/54^\circ$ S and that of the south limb is $130^\circ/59^\circ$ SW.

Plunge of the Fold

Ramsay (1964) points out that if the orientations

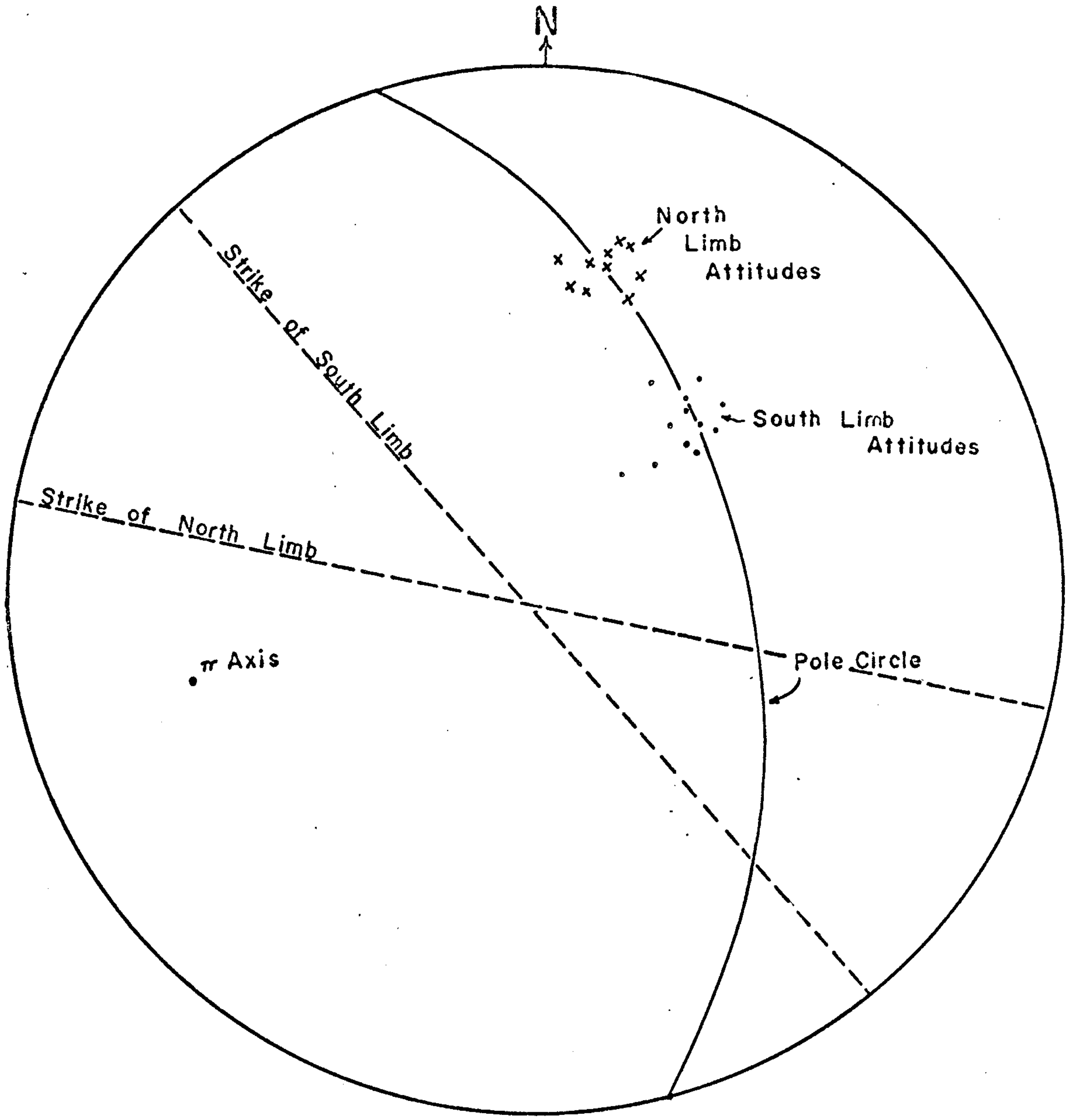


Figure 6: Equal area projection of poles to layering. The π axis is perpendicular to the pole circle and coincides with the fold axis. The strikes of the north and south limbs were taken from the geologic map (Figure 4).

of the bedding planes on the limbs of a fold are known, then their intersection (β axis) can be determined on a stereonet and it will be parallel to the fold axis. Figure 7 shows the intersection of the two planes representing the north and south limbs of the Booster Lake fold. These planes are normal to the point of maximum concentration of poles to layering (Figure 6) for their respective limbs. The fold axis plunges 36 degrees in the direction 251 degrees azimuth.

The Axial Surface

The axial surface of the fold is determined from the axial trace and the fold axis. The axial trace, drawn through the points of maximum curvature of the bedding planes of the meta-conglomerate, defines the strike of the axial plane. The axial plane contains both the strike line and the fold axis (Badgley, 1959) and is shown on Figure 7. The orientation of the axial surface is $295^\circ/46^\circ$ SE.

Interlimb Angle

The closure of a fold is given by the interlimb dihedral angle. The dihedral angle between the north and south limbs of the Booster Lake fold is 26 degrees. This angle is less than 30 degrees, and consequently the closure of the fold is classified as "tight" (Fleuty, 1964).

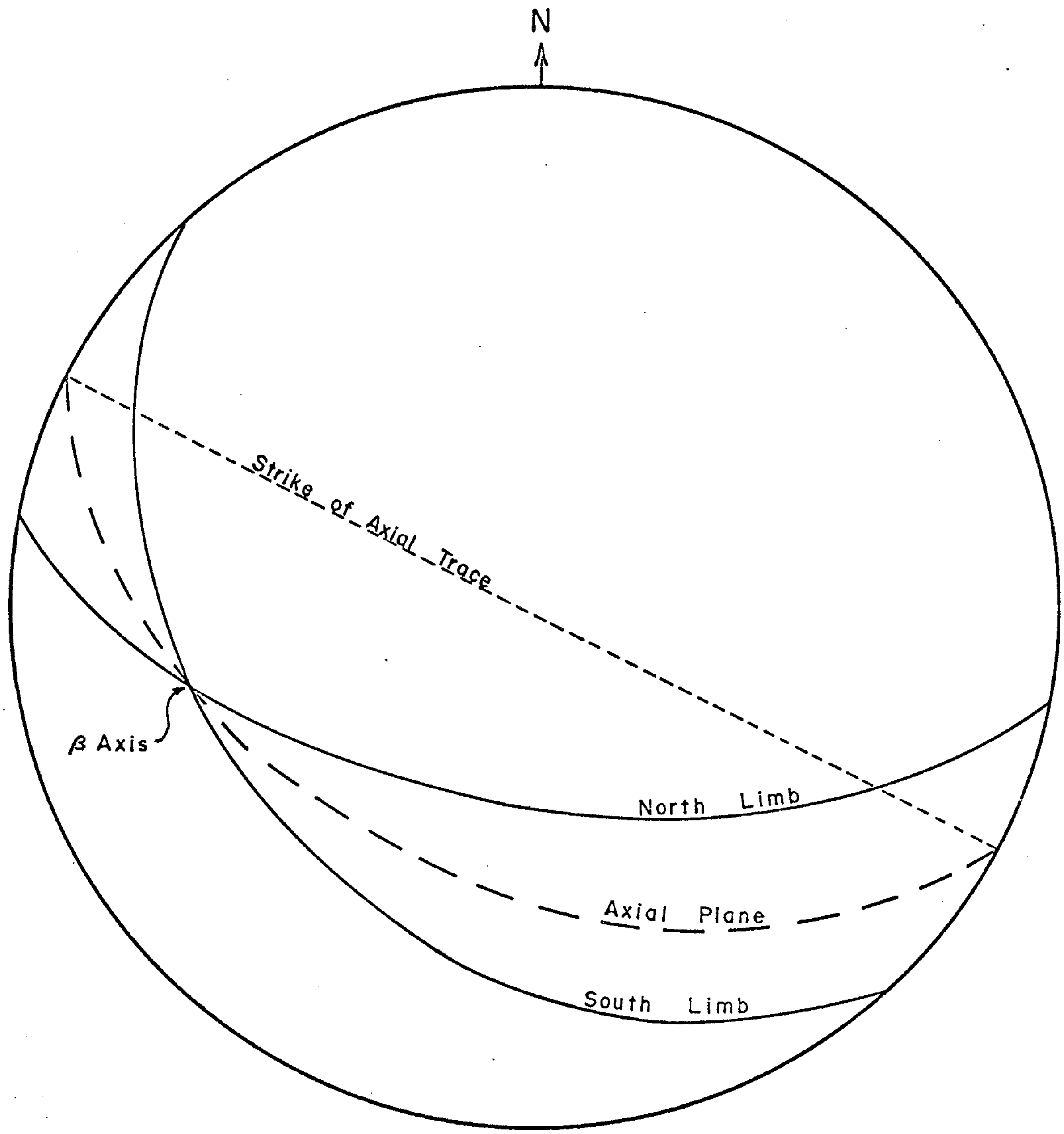


Figure 7: Beta-diagram showing the intersection of the planes of the fold limbs with the axial plane. The β axis is the line of intersection between the three planes and coincides with the fold axis. The strike of the axial trace was obtained from the geologic map (Figure 4).

Summary

The geometric properties of the Booster Lake fold can be summarized as follows:

(i) orientation of north limb	$100^\circ/54^\circ$ S
(ii) orientation of south limb	$130^\circ/59^\circ$ SW
(iii) plunge of fold	$36^\circ/251^\circ$
(iv) orientation of axial plane	$295^\circ/46^\circ$ SE
(v) interlimb dihedral angle	26°

Orientation Classification of the Fold

Analysis of the orientation of the fold (Figures 6 and 7) together with the distribution of the meta-conglomerate (Figure 4) shows that the fold is plunging toward the west and is closing upward. The fold is therefore an antiform (Fleuty, 1964). This term describes the fold solely on the basis of its structural form and orientation. The depositional sequence is not inverted (see Chapter II) and therefore the fold can be termed properly an anticline.

Fleuty (1964) set forth a descriptive classification for folds based on the plunge of the fold and the attitude of its axial plane. Using this classification (Figure 8), the Booster Lake fold can be termed a moderately inclined, moderately plunging anticline. This is a rather cumbersome description of the fold, and it is much easier to use Rickard's (1971) D.P.P. (Dip, Plunge, Pitch) triangular diagram (Figure 9). This classification is

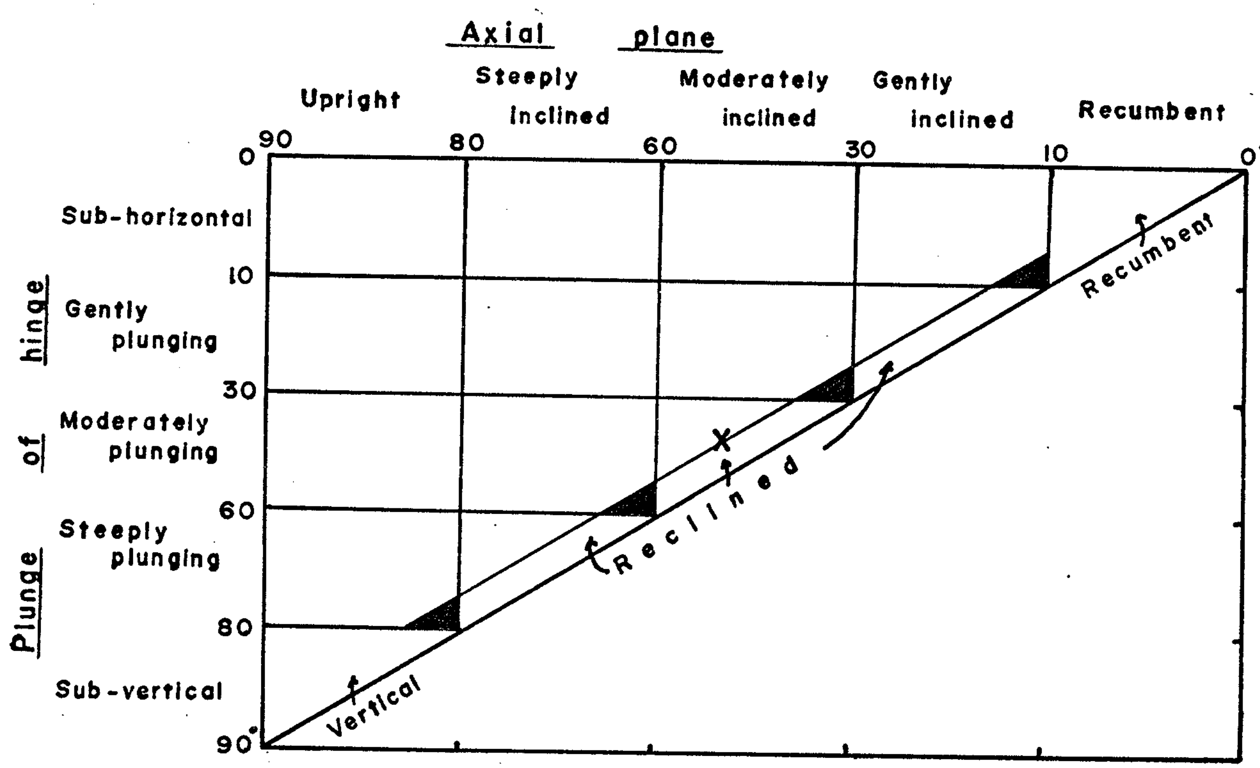


Figure 8: Fleuty's classification of folds (after Fleuty,1964). The position of the Booster Lake fold in this classification is indicated by X.

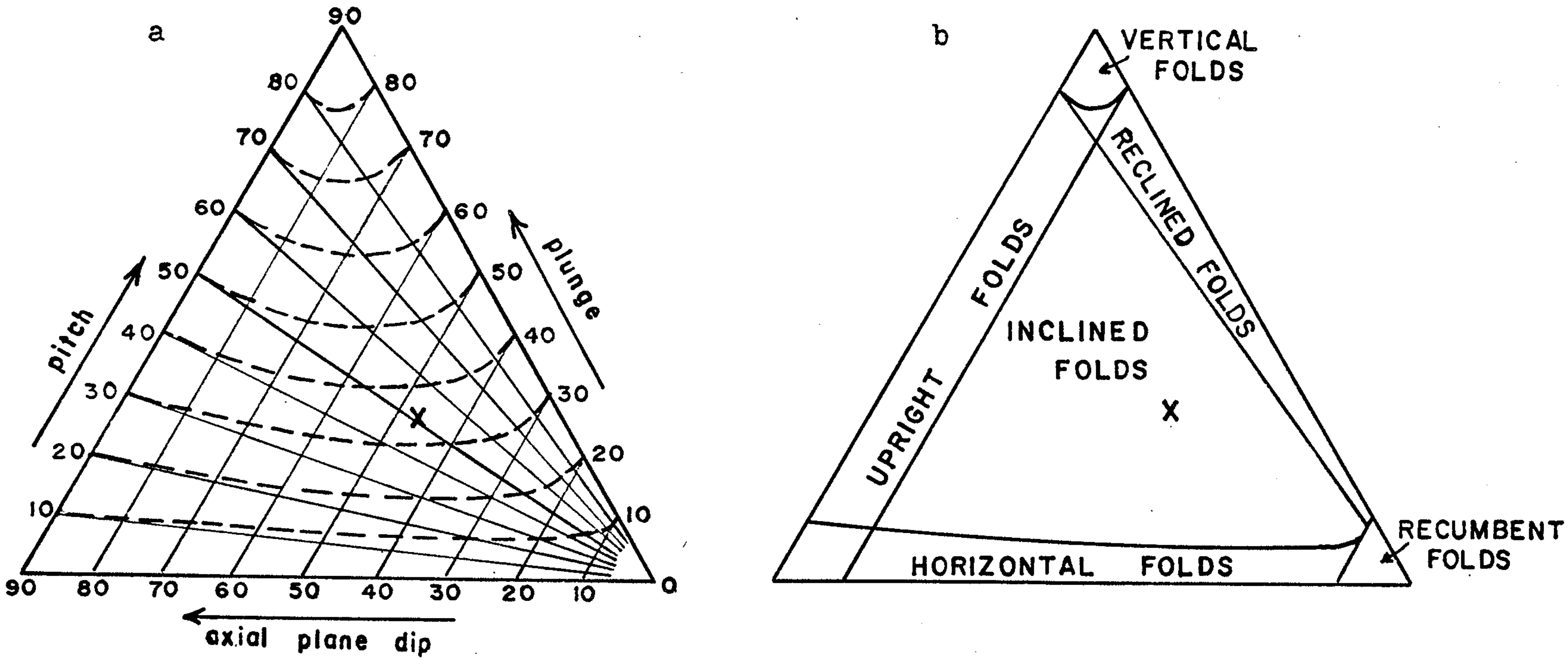


Figure 9: Classification of fold types on a triangular diagram (after Rickard, 1971). X denotes the position of the Booster Lake fold in this classification.

9a: Triangular net; plunge is plotted on the dashed lines varying from 0° on the base line to 90° at the apex of the triangle.

9b: Fields of the main fold types.

effected by plotting three variables: dip of axial plane, and plunge and pitch of fold axis, on a special triangular diagram (Figure 9). The Booster Lake fold is an inclined fold, but because the inclined field is large, the fold can be more accurately described by using the dip (D) of the axial plane and the plunge (P) of the fold axis after the descriptive name: inclined fold (D. 295°/46° SE: P. 36°/251°).

STYLE AND ASYMMETRY

Introduction

Determination of the cylindricity of the fold and construction of a right section (section perpendicular to the fold axis) are necessary before style of folding in the Booster Lake area can be compared with styles of folding given by Ramsay's (1967) classification. The section perpendicular to the fold axis is the one upon which Ramsay's classification is based. The cylindricity of the fold must first be known because there are two different methods for the construction of right sections, one for cylindrical folds and the other for conical folds.

Cylindricity of the Fold

A great circle has been drawn through the two pole concentrations in Figure 6 and the fold is assumed to be cylindrical. This assumption is in question because the two concentrations of poles could also fit a small circle and the fold could have a conical character. Without information on the dip of the layering in the hinge zone, it is impossible to state categorically whether the fold is cylindrical or conical. According to Badgley (1959) conical folding is rare in nature. Consequently, a decision was made to proceed with the analysis on the assumption that the fold is cylindrical. Subsequent geometrical analysis will indicate that this assumption is valid, for the geometry of the fold closely approaches the ideal cylindrical case (see below).

The Right Section

Using the method described by Stockwell (1950), a right section of the fold was prepared (Figure 10). The meta-conglomerate unit has been used as the marker unit and is used further in classifying the style of the fold. The true thickness of the meta-conglomerate could not be determined over most of the north limb of the fold because the limb has been cut by a fault.

Style of Folding According to Ramsay's Classification

According to Ramsay (1967) it is possible to express changes in shape within a fold and to classify the fold using any of the following parameters:

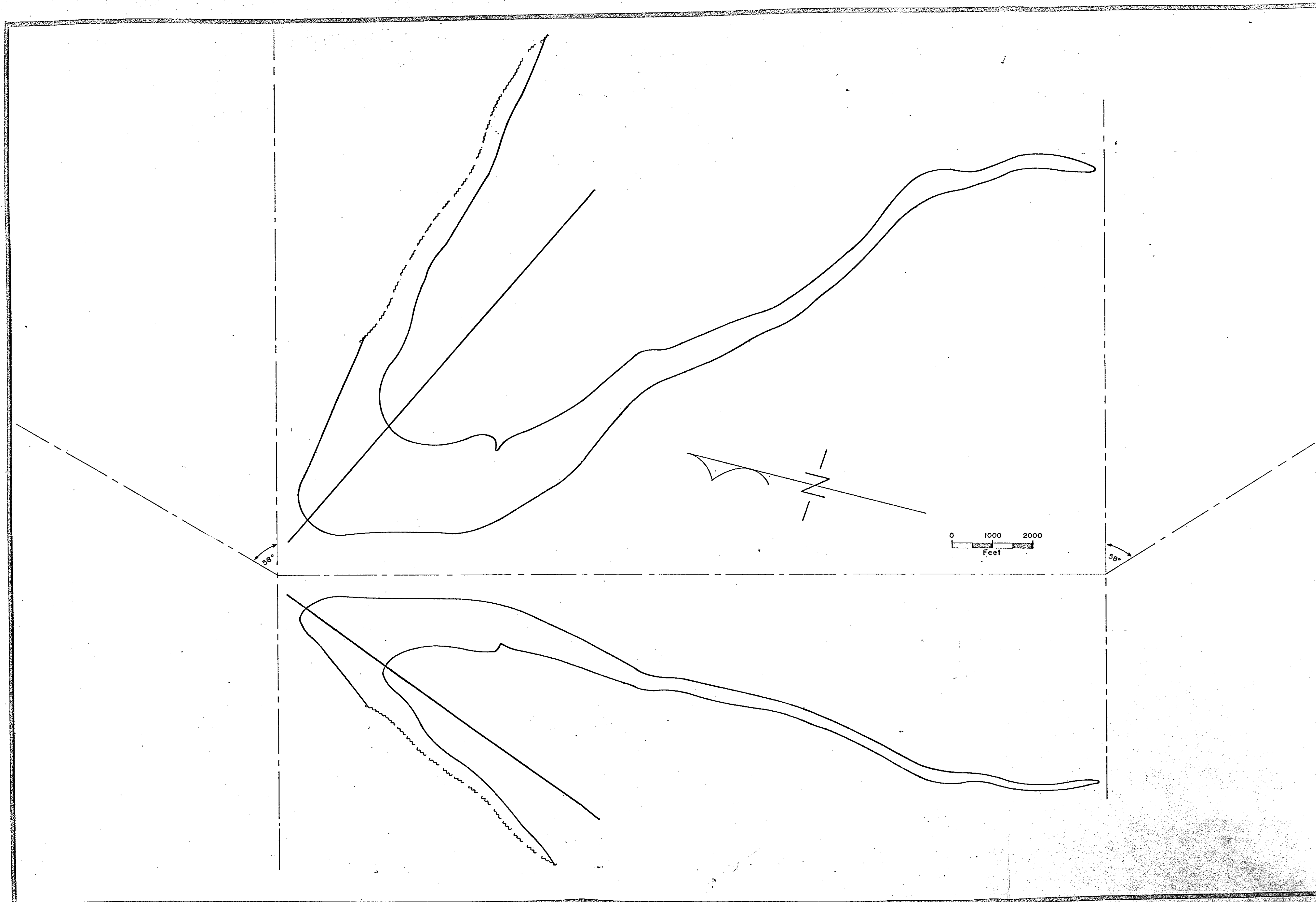


Figure 10: RIGHT SECTION OF THE FOLDED META-CONGLOMERATE UNIT

(1) the inclination of the dip isogons

(2) the axial planar thickness, T, of individual layers involved in the fold

(3) the orthogonal thickness, t, of individual layers involved in the fold

The author has attempted to classify the fold using the above three parameters applied to the meta-conglomerate unit. The north limb could not be completely classified because it has been cut by the east-west fault.

(1) Inclination of dip isogons

Using the right section of the fold, it is possible to determine the slope of any point on the folded surface with reference to the normal to the axial surface. A tangent to the surface at the given point will make an angle α (angle of inclination) with the normal to the axial surface in the plane of section (Figure 11). Lines joining points of the same slope on adjacent folded surfaces are called dip isogons (Ramsay, 1967). Figure 12 shows the distribution of these isogons at ten degree intervals for the upper and lower surfaces of the meta-conglomerate unit. Comparing these results with Ramsay's (1967) fundamental types of fold classes (Figure 13) it can be seen that the fold is complex. The isogons are essentially parallel to the axial plane in the hinge area, characteristic of a Class 2 fold, but bordering on Class 3 because of a slight

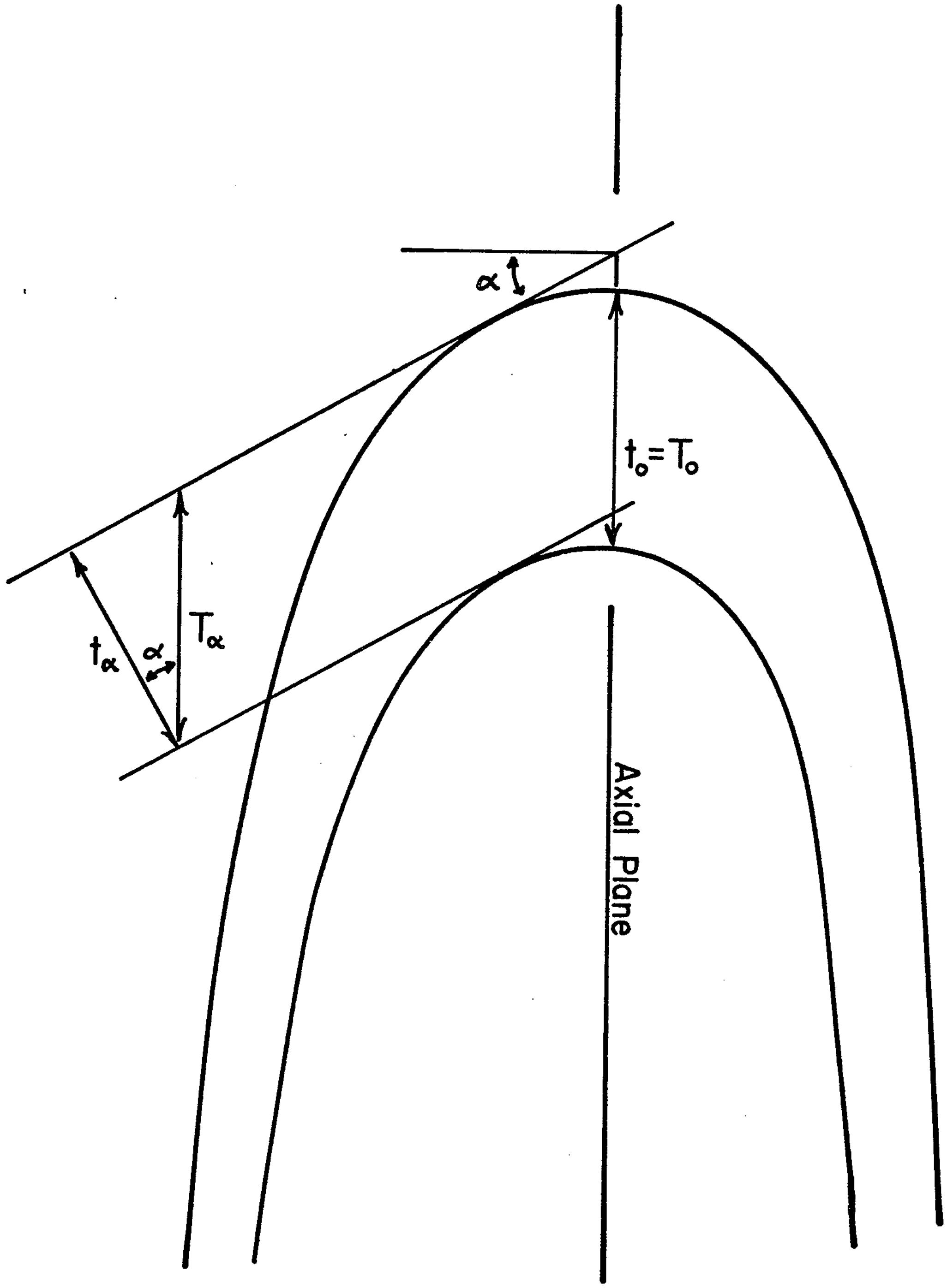


Figure 11: Definition of α. The angle of inclination α is the angle between the horizantal tangent at $\alpha=0^\circ$ and the tangent for a point on the folded surface. (After Ramsay, 1967).

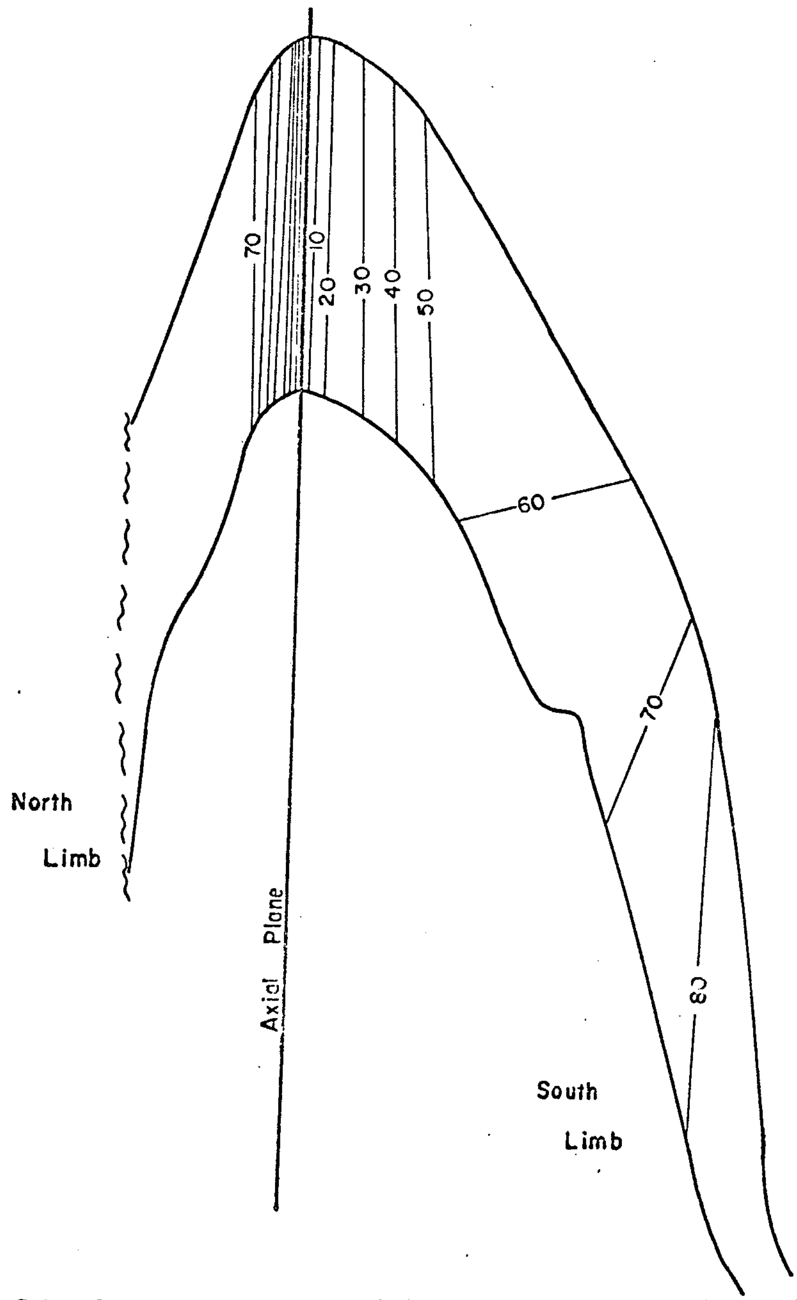


Figure 12: Nose of the fold in right section showing dip isogons drawn between the inner and outer surfaces of the meta-conglomerate at 10 degree intervals. The isogons are not drawn for the whole fold, but only for $\alpha = 0°$ to $80°$ on the south limb and for $\alpha = 0°$ to $70°$ on the north limb.

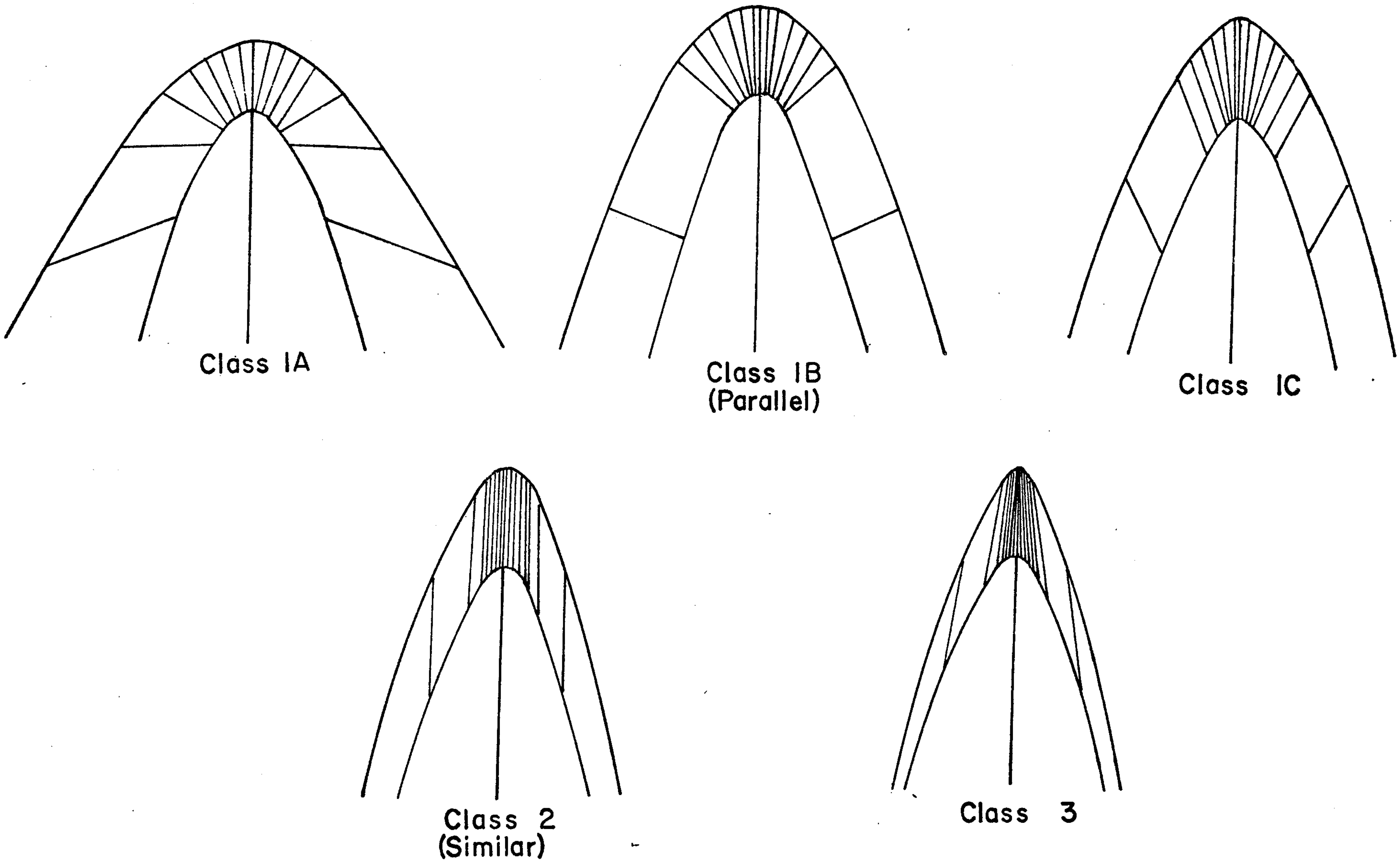


Figure 13: Classification of ideal folds using dip isogons. Isogons are drawn at 10 degree intervals. (After Ramsay, 1967).

divergence of the isogons. However, where $\alpha > 55°$, the south limb has convergent dip isogons with respect to the axial plane, characteristic of Class 1C folds. The amount of convergence increases between $\alpha = 55°$ and $\alpha = 60°$ and then decreases again when $\alpha > 60°$.

(2) Axial planar thickness, T

The axial planar thickness, T, is the thickness of the unit between two tangents at the same inclination α, on adjacent surfaces, measured in a direction parallel to the axial plane of the fold (Figure 11). T_o is the thickness of the unit along the axial surface for $\alpha = 0°$. T_α is the thickness of the unit at any given inclination α. The variation through the fold can be expressed by the relationship $T_\alpha' = T_\alpha / T_o$. A plot of T_α' versus α (Figure 14) has been prepared for each limb of the fold. The curves for both limbs show the hinge area of the fold to be only slightly divergent from a Class 2 (similar) fold. Away from the hinge area, the south limb deviates from a Class 2 fold and at $\alpha > 60°$ becomes a Class 1C fold.

(3) Orthogonal thickness, t

The orthogonal thickness t is the thickness of the unit between two tangents at the same inclination α on adjacent surfaces (Figure 11) measured at right angles to the tangents. The thickness of the unit, t_α, at any given incli-

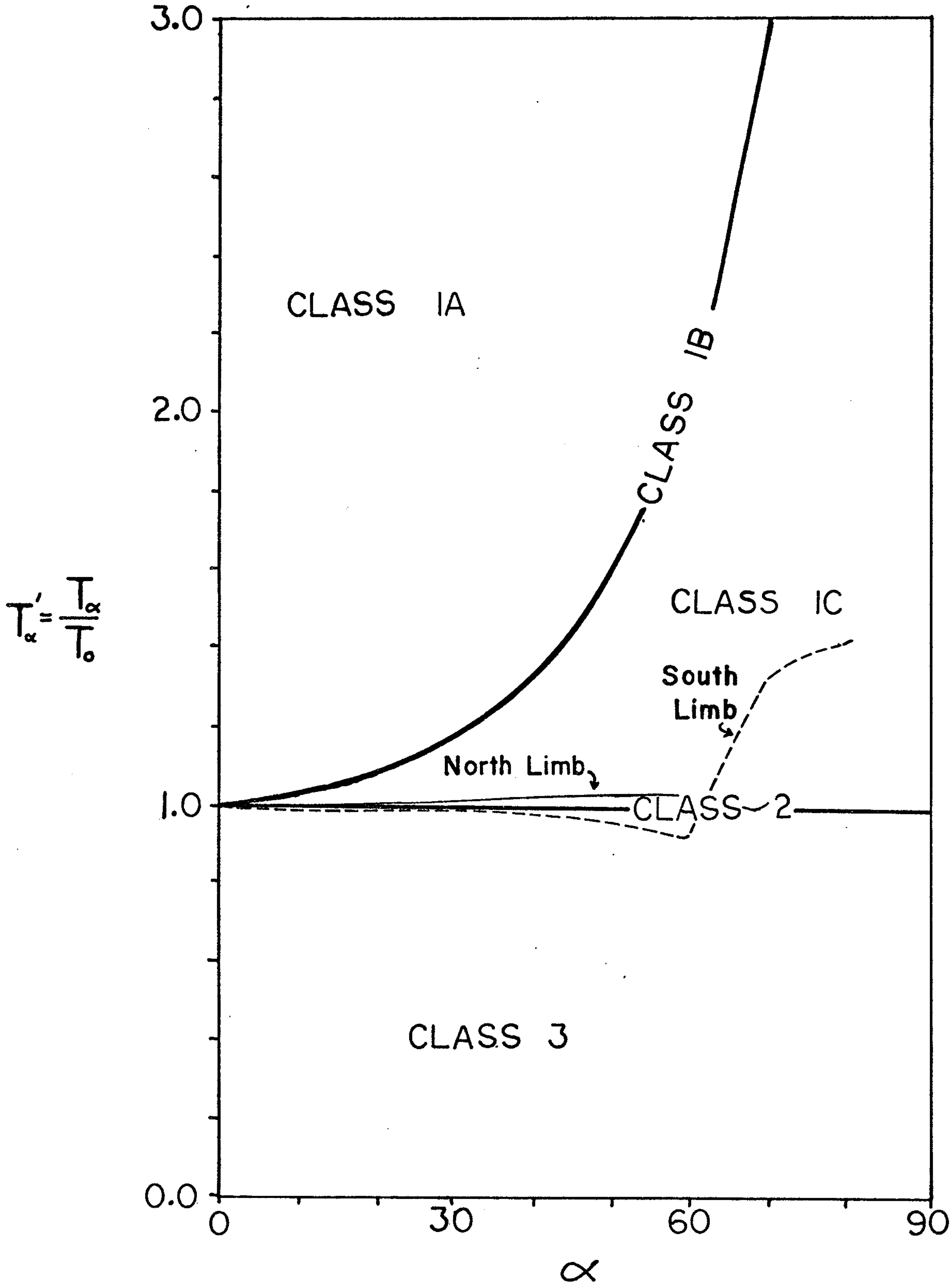


Figure 14: Plot of T'_α versus α for the north and south limbs of the Booster Lake fold. The ideal fields are outlined (after Ramsay, 1967).

nation, α, from the normal to the axial plane can be related to the orthogonal thickness in the hinge zone (t_o) by the relationship $t'_\alpha = t_\alpha / t_o$. The variation in t'_α with changes in α can be represented as a curve (Figure 15). This plot shows that the fold closely approximates a Class 2 fold although there is some variance of the north limb into the Class 1C field and of the south limb into the Class 3 field. The south limb crosses into the Class 1C field at $\alpha > 63°$.

In summary, all three parameters show that the fold is complex and cannot be placed in any one ideal class of Ramsay's classification (Table 2). The nose of the fold, however, is close to the morphology of an ideal similar fold (Class 2). Away from the nose of the fold ($\alpha > 55°$ to $\alpha > 63°$, depending on the parameter used) the morphology changes to that of Class 1C. The close approximation of the style to the ideal case leads the author to classifying the Booster Lake fold, based on the meta-conglomerate unit, as a similar-type fold. The south limb of the fold is of Class 1C, possibly due to modification of the similar fold by intrusion of the grey granite batholith. Alternatively, the meta-conglomerate may have had some original variation in thickness, causing deviation from the ideal case (Figures 13 and 14) and accounting for the reversal in orientation of the dip isogons on the south limb where $\alpha \approx 60°$ (Figure 12).

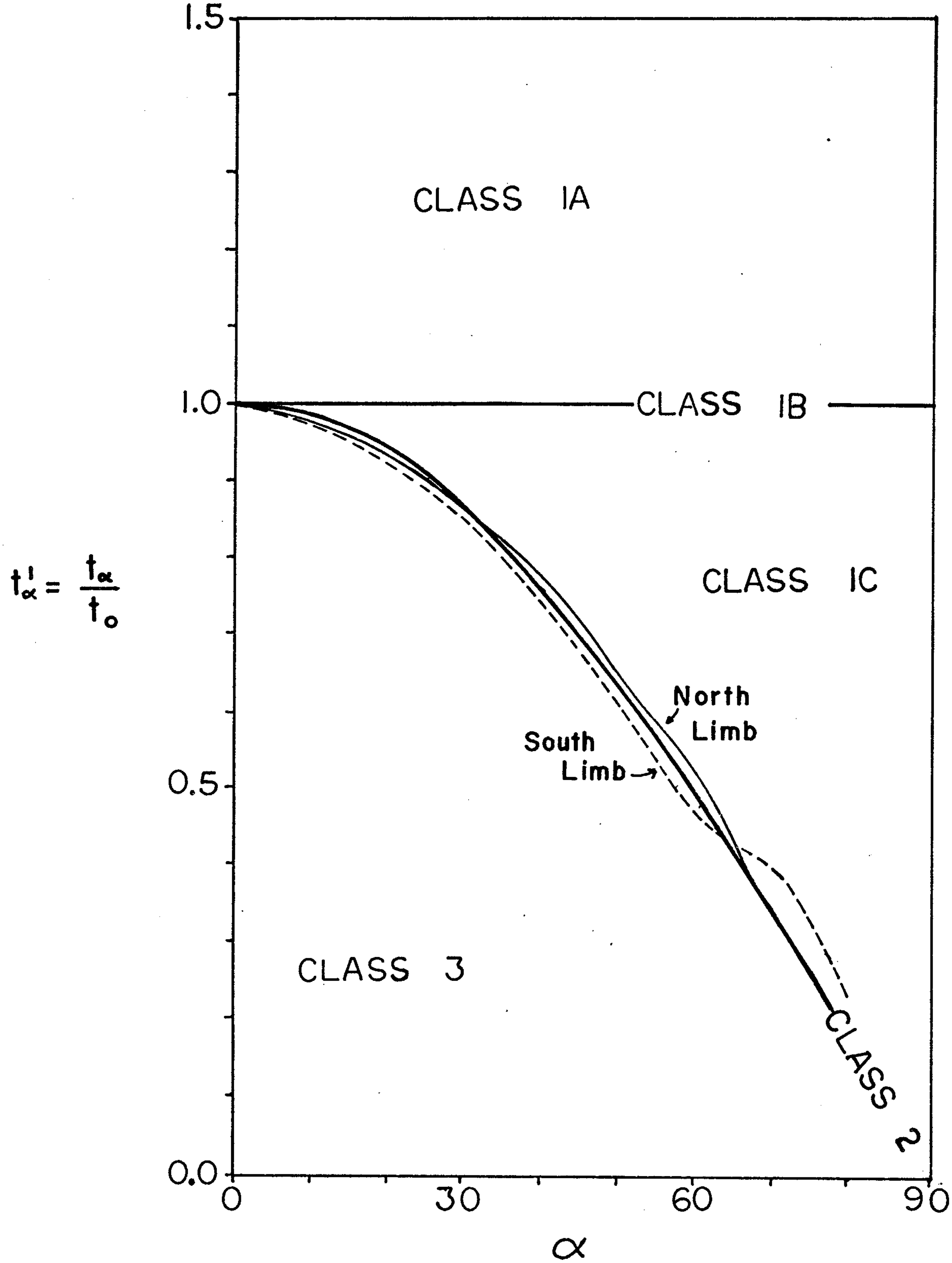


Figure 15: Plot of t'_α versus α for the north and south limbs of the Booster Lake fold. The ideal fields are outlined (after Ramsay, 1967).

Table 2: Summary of analysis of the fold style.

Parameters	Hinge Zone	South Limb	α of change in Class
Dip isogons	Class 2	Class 1C	$\alpha = 55^{\circ}$
Axial planar thickness T	Class 2	Class 1C	$\alpha = 60^{\circ}$
Orthogonal thickness t	Class 2	Class 3	$\alpha = 63^{\circ}$

Asymmetry of the Fold

The north limb of the Booster Lake fold has been cut off by a fault, therefore precluding any general observations about the symmetry of the fold. However, the dip isogons on the north limb, for $\alpha \leq 70^\circ$ are very closely spaced whereas the isogons of the south limb, for $\alpha \leq 50^\circ$, have a wider spacing (Figure 12), indicating that the curvature of the south limb is gentle compared to that of the north limb, and suggesting that the fold is asymmetric.

CHAPTER IV

MECHANICS OF DEFORMATION

STRAIN PRODUCING THE FOLD

Introduction

A prerequisite to proposing a possible mechanism for the formation of the Booster Lake fold is an analysis of the strain inherent in its development. The strain is reflected in the style of folding, the relationship of foliation to the fold, the textures of the folded rocks, and the linear structures. Taken alone, each of these features will not be revealing, but collectively, they indicate the type of strain.

Style of Folding

Analysis of the Booster Lake fold (Chapter III) illustrated that it is a complex similar-type fold. It is a Class 2 fold in the hinge zone but Class 1C on the south limb.

Similar-type folds may be produced by heterogeneous pure shear (differential flattening) (Ramsay, 1962) and by homogeneous flattening superimposed on a flexural fold (Ramsay, 1962; Donath and Parker, 1964). The variation in axial planar thickness of the Booster Lake fold

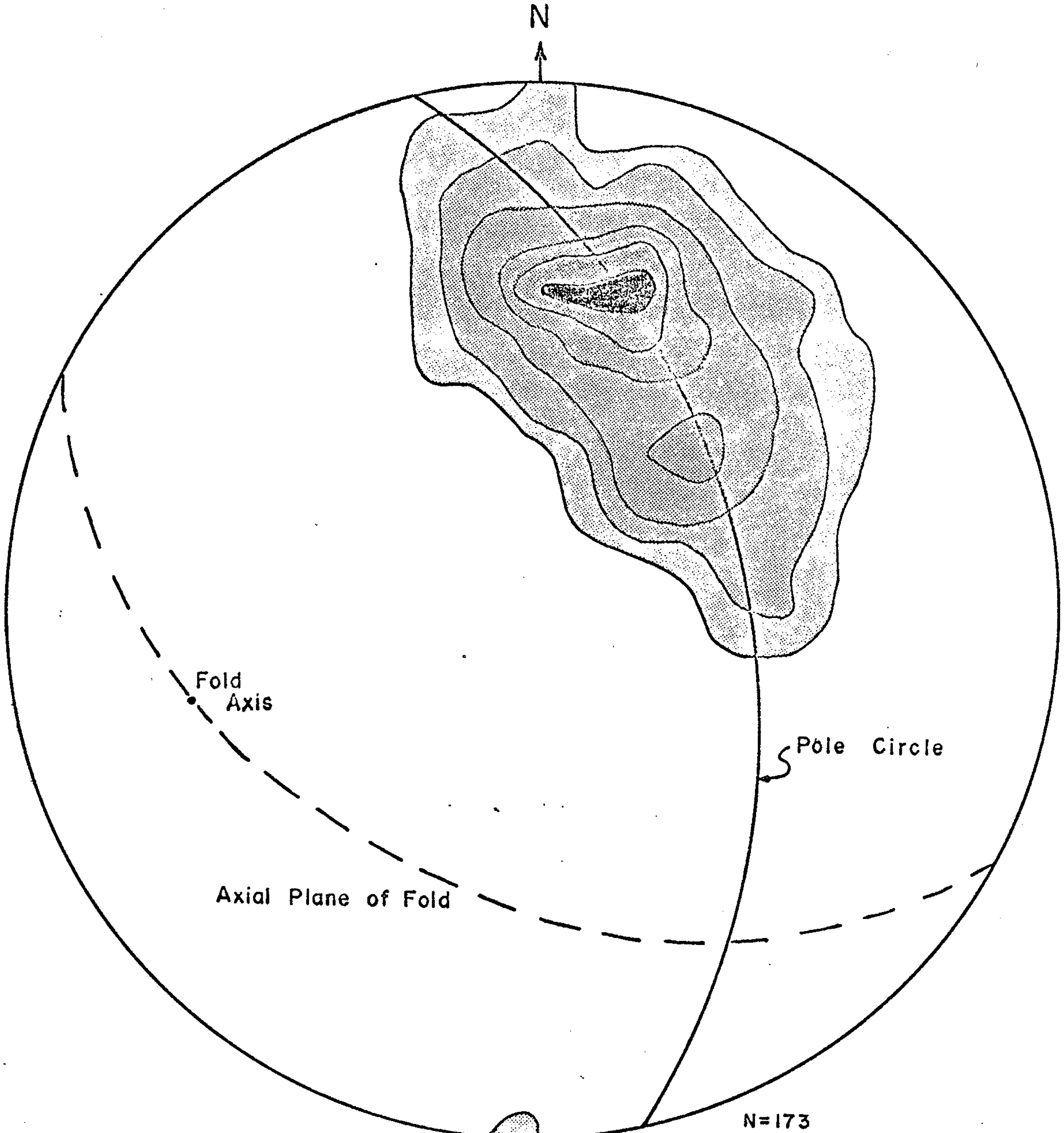
(Appendix) is characteristic of differential flattening, but the minimum thickness (axial planar) in the hinge zone is indicative of homogeneous flattening superimposed on a flexural fold.

Simple shear may produce ideal similar folds (Ramsay, 1967) and could possibly have been part of the strain inherent in the development of the Booster Lake fold. Considering simple shear, two other types of strain could have produced this fold: (1) flexural folding followed by heterogeneous or homogeneous pure shear and heterogeneous simple shear, and (2) heterogeneous or homogeneous pure shear followed by heterogeneous simple shear.

Relationship of Foliation to the Fold

The equal area projection of poles to foliation (Figure 16) shows two major concentrations of points although there is substantial scatter about these concentrations. These concentrations correspond to the concentrations of poles to layering (Figure 6), indicating that there is some parallelism between foliation and layering in the limbs.

The scatter of poles in Figure 16 indicates that foliation is not everywhere parallel to the layering. This is particularly evident in the nose of the fold (Figure 4) where the cross-cutting relationship of the foliation suggests that the fold may be passive, thus supporting the theory that this is a shear fold.



Contour Interval: 1, 2, 5, 10, 13, 16%

Figure 16: Equal area projection of poles to foliation. The pole circle is almost coincident with the pole circle in the plot of poles to layering (Figure 6) because the foliation is mostly parallel to the layering.

If the fold were a flattened flexural fold, the foliation would only transect the layering in the hinge area and would be parallel in the limbs (Hobbs, 1971). Also, the foliation may be folded depending on the amount of flattening. The distribution of points for the Booster Lake fold (Figure 16) shows that the foliation has not been folded. There is a 90 degree change in the azimuth of the foliation planes from 090° to 180°, but if the foliation were folded there would be a distribution of poles along the remainder of the pole circle to represent a complete wrap around of the attitudes of the foliations.

The orientations of the foliation planes diverge from the axial plane. This divergence becomes greater away from the nose of the fold in the area where the grey granite pluton has been emplaced, especially around Davidson and Flanders Lakes.

Textures

Thin section examination reveals that the upper and lower metagreywacke units and the meta-conglomerate unit have been recrystallized. Harker (1932) and Turner and Weiss (1963) state that minerals, especially micas, are oriented perpendicular to the principal stress direction. According to Ramsay (1962), this preferred orientation of micas is due either to mechanical rearrangement of individual pre-existing mica flakes or to syntectonic growth of micas perpendicular to the major compressive stress direction during folding. Recrystallization indicates that the latter case is true for the Booster Lake area. The biotites have grown in situ under stress so that they are aligned producing the schistosity in the rocks. The schistosity is perpendicular to the principal stress direction and so represents a principal plane of strain. There is no textural indication of movement to suggest simple shear during deformation.

Lineations

The pebbles in the meta-conglomerate have been deformed (Figure 17). Numerous authors, including Ramsay (1967), Hossack (1968), Gay (1969), and Elliot (1970) have shown how deformed pebbles can be used in determining finite strain. This determination, however, necessitates measurement of at least two of the three axes of the ellipsoidal pebbles. In the Booster Lake area, accurate measurements of these axes were precluded by the rounded nature of the outcrops and absence of joint planes; only approximate measurements could be made.

The pebbles are flattened in the plane of foliation with their intermediate and long axes contained within the plane of foliation and their shortest axes perpendicular to the foliation. The longest axes plunge southwesterly although accurate measurements could not be made (see

Figure 17: Flattened pebbles in the meta-conglomerate.

Chapter II). It was not possible to determine whether the general plunge of the pebbles is parallel to the plunge of the axis of the fold.

The flattened pebbles indicate that flattening was involved in the deformational process. In addition, the presence of quartz pressure shadows at the ends of the pebbles is further evidence of flattening during deformation (Hills, 1963).

Discussion

The properties of the Booster Lake fold provide insufficient information to define the type of strain inherint during folding. The flattened pebbles and associated quartz pressure shadows of the meta-conglomerate indicate that flattening was important. Foliation is oblique to the layering suggesting the fold is a shear fold. Simple shear would appear to be ruled out by the lack of evidence of movement within the rocks, but effects of movement could have been destroyed by recrystallization. The physical dimensions of the fold suggest two different types of strain.

In conclusion, it can only be said that the fold is a similar-type fold and could have been formed by any of the following strain patterns:

(1) heterogeneous pure shear

(2) homogeneous flattening superimposed on a flexural fold

(3) flexural folding followed by heterogeneous or homogeneous pure shear and heterogeneous simple shear

(4) heterogeneous or homogeneous pure shear followed by heterogeneous simple shear.

THE FOLDING MECHANISM

The above discussion has outlined the type of strain inherent in the development of the fold, but there still remains the problem of which mechanism, slip or flow, was active in the formation of the structure.

The Booster Lake fold is passive insofar as the layering has not influenced the folding. The passive nature of the fold is further substantiated by its similar-type style and its shear strain.

According to Donath and Parker (1964), when slip cannot be discerned with the naked eye along planes inclined to the layering, the deformation is sufficiently continuous to be classed as flow. Such is the case in the Booster Lake area where the process of flow was accompanied by recrystallization. This interpretation is supported by the fact that the foliation is penetrative, and oblique to the layering. Recrystallization was contemporaneous with folding and therefore the foliation has an axial planar orientation.

The level of metemorphism during deformation was to the almandine-amphibolite facies (with epidote) (Butrenchuk, 1970). According to Turner and Verhoogen (1960), deformation must have taken place under 4000 to 8000 bars confining pressure at a temperature of 500°C to 750°C.

RELATIONSHIP OF THE GRANITE PLUTON TO THE FOLDING

A large pluton of grey granite occupies the core of the Booster Lake anticline (Figure 4) and extends 15 miles eastward into Ontario. The outline of the batholith conforms to the outline of the anticline, but it was observed in the field that the granite had disrupted the lower metagreywacke within 10 feet of the contact with the granite; the metagreywacke having been dragged upward. Air photo lineaments (Figure 18) generally conform to the outline of the fold. Northwest of Harris Lake, however, there are several gently arcuate lineaments reflecting the isolated lensoid bodies of granite in that area (Figure 4). These lineaments further illustrate the minor discordancy of the granite to the general shape of the Booster Lake fold.

The large scale conformity of the batholith to the anticline suggests structural control during emplacement of the granite. The intrusion was only disruptive on a minor scale as evidenced by local disruptions of the metagreywacke and the small discordant granitic bodies. These factors do not provide the complete answer to the role of

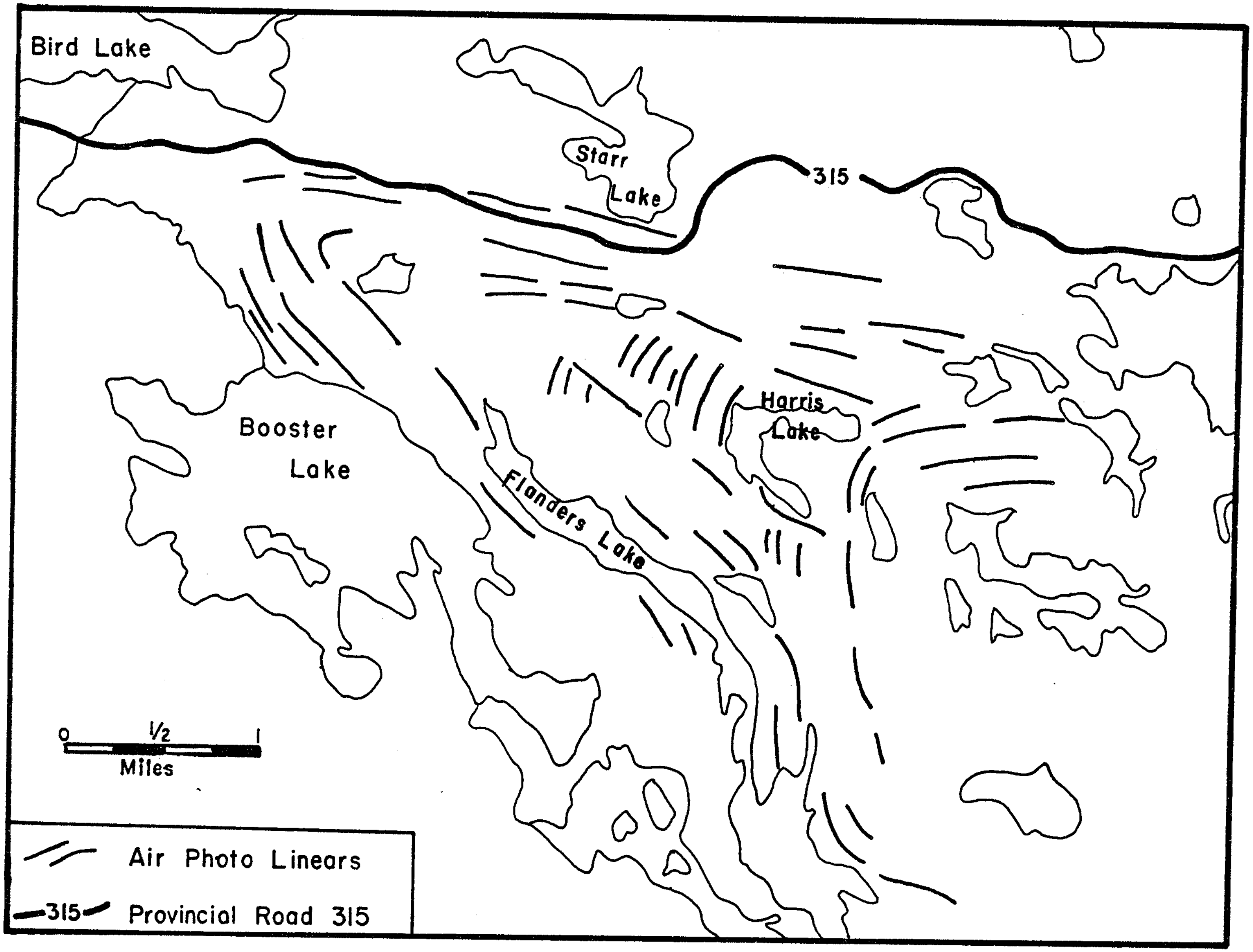


Figure 18: Air photo linear map of the Booster Lake area.

the granite in formation of the fold. The granite is not deformed and is therefore syn-folding or post-folding. If the granite were syntectonic, it may have been the upward force that was responsible for the formation of the anticline in the Booster Lake area.

CHAPTER V

CONCLUSIONS

1. The fold is cylindrical and is an inclined anticline (D. 295°/46°SE: P. 36°/251°).

2. Analysis of the style of the fold using dip isogons, axial planar thickness, T, and orthogonal thickness, t show that the geometry is essentially Class 2 (ideal similar fold) in the hinge zone and Class 1C in the south limb. Any one of these three parameters could have been used in classifying the fold style.

3. The style of folding, foliation, lineations, and textures are inconclusive in indicating the type of strain which produced the fold but there are four possibilities:

   (i) heterogeneous pure shear

   (ii) homogeneous flattening superimposed on a flexural fold

   (iii) flexural folding followed by heterogeneous or homogeneous pure shear and heterogeneous simple shear

   (iv) heterogeneous or homogeneous pure shear followed by heterogeneous simple shear.

4. The deformation was attained by a passive flow mechanism contemporaneous with metamorphism.

5. The anticline is a similar fold which was intruded by a granite pluton. The granite may have been syn-folding or post-folding.

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APPENDIX:

THICKNESS DATA FOR GEOMETRICAL ANALYSIS

Table A : Orthogonal and axial planar thicknesses of the meta-conglomerate.

α	t_α (ft.)		T_α (ft.)	
	N. Limb	S. Limb	N. Limb	S. Limb
0	2440	2440	2440	2440
10	2380	2380	2440	2420
20	2300	2260	2460	2400
30	2120	2100	2460	2420
40	1900	1820	2480	2380
50	1580	1520	2500	2360
60	1260	1140	2500	2240
70	840	1000	2440	3240
80	740	580	3560	3480

Table B : Values of t'_α and T'_α .

α	t'_α		T'_α	
	N. Limb	S. Limb	N. Limb	S. Limb
0	1	1	1	1
10	.975	.975	1	.99
20	.943	.926	1.01	.984
30	.869	.861	1.01	.99
40	.778	.746	1.02	.975
50	.647	.623	1.025	.967
60	.516	.467	1.025	.918
70	.344	.41	1	1.33
80	.278	.238	1.46	1.43