STRUCTURAL GEOLOGY OF A SICKLE OUTLIER

NEAR NOTIGI LAKE, MANITOBA

A Thesis

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Masters of Science

by

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ABSTRACT

The area of study is located thirty-five miles northwest of Nelson House, Manitoba, and is underlain by a meta-arkose to diatexite gneiss outlier, of Sickle-type rocks, approximately 25 square miles in area. The Sickle rocks differ considerably from the underlying Wasekwan-type gneisses which constitute the predominant rock type around the Sickle outlier.

The deformational history of the outlier is based on ground attitude measurements backed up by detailed air-photo interpretation, and interpreted stratigraphy. The rocks have undergone at least three, and probably four, folding events, plus two periods of brittle deformation: folding of original sediments into isoclinal folds (f_1); weak open folds developed perpendicular to f_1 axial planes (f_2); refolding of f_1 and f_2 axial planes by f_3 isoclinal folding; refolding of f_1, f_2 and f_3 axial planes about a north-south axial plane (f_4) to produce the present configuration of the Sickle outlier. Extensive amphibolite grade metamorphism accompanied f_3 folding, resulting in partial anatexis and flow in less competent layers.

Late brittle deformation consisted of early jointing (D_5), along which pegmatite later intruded. This was followed by a period of jointing (D_6). Two periods of post-f_4 faulting occurred with the earlier northeast striking faults offset by a north-south striking late period of faults.

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CHAPTER I

INTRODUCTION

Statement of Problem

The purpose of this study is to analyse the structure and delineate the deformational history of an outlier of Sickle-type rocks in the Churchill Province of the Precambrian of northern Manitoba.

Location and Access

The area studied encompasses approximately twenty-four square miles of Township 80, ranges 13W and 14W. The area is located sixty-five miles west-north-west of Thompson, Manitoba (Figure 1).

Access is restricted to float-equipped aircraft which may land on any one of four lakes bordering the area. The area is characterized primarily by dense bush and tree-covered outcrops which restrict helicopter landing sites to large pegmatite outcrops in the northern part of the area. The Lynn Lake-Thompson power line, trending northwest, passes within one mile of the southwest corner of the area.

Previous Work

In 1953, H. A. Quinn of the Geological Survey of Canada included the present area of study in his Nelson House map sheet, which was published at a scale of one inch = four miles. This work was revised largely by T. G. Frohlinger of the Manitoba Mines Branch in the

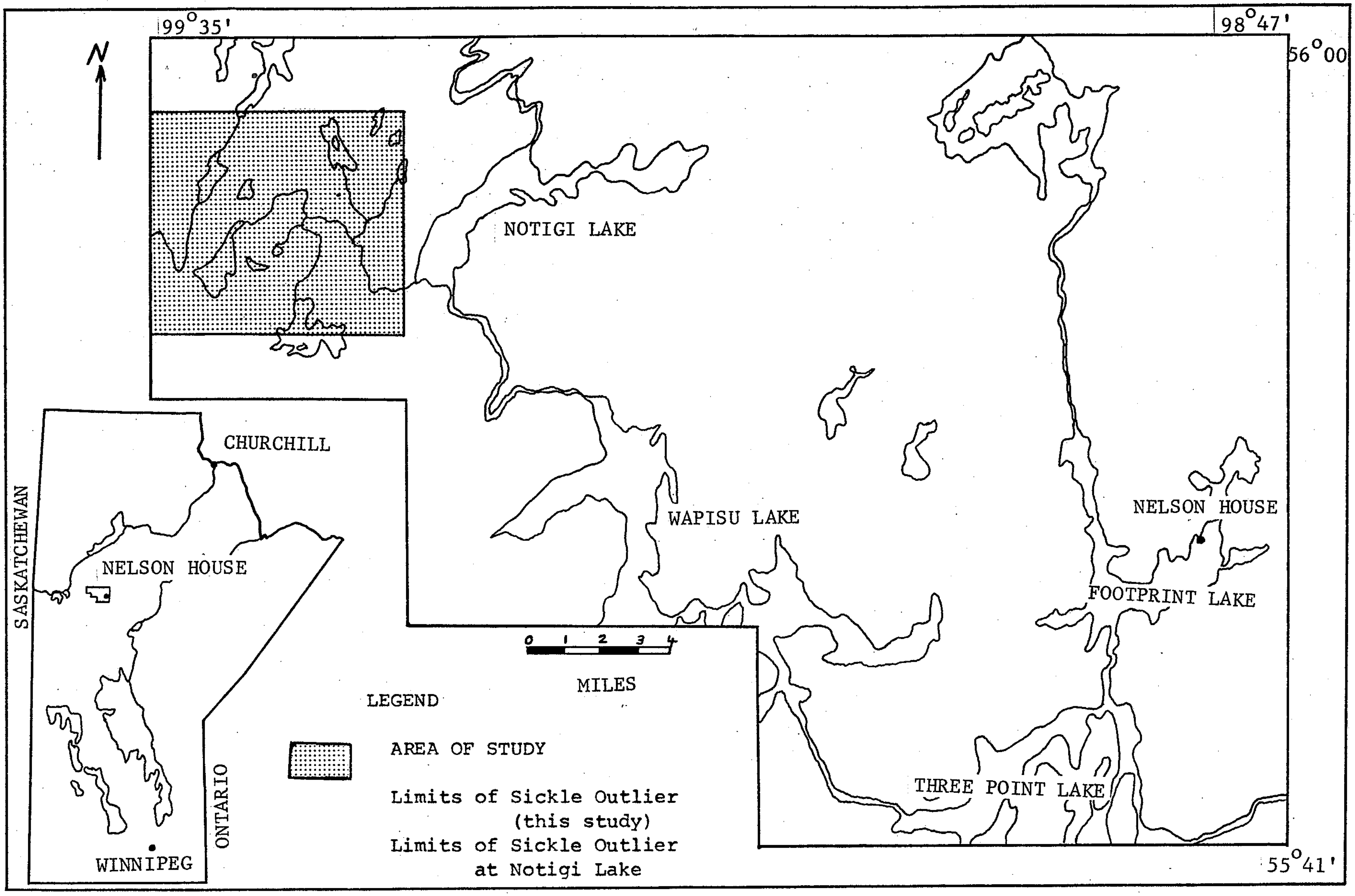


FIGURE 1 Area of Study

1971 field season, mapping at a scale of one inch = one-half mile.

Present Work

Field work in the area of study was conducted during the 1971 field season while in the employ of the Manitoba Mines Branch, working with T. G. Frohlinger. The pace and compass method of traversing was utilized, in conjunction with air-photos and air-photo mosaics. Although outcrop comprises approximately twenty per cent of the area, much of the outcrop is moss and lichen covered, restricting observations in much of the area.

Acknowledgements

The writer wishes to thank Dr. W. C. Brisbin for supervision of this work. T. G. Frohlinger was very helpful in discussing problems arising during the field mapping and in making time available for the work during a very busy field season. J. S. Roper, Director of the Mines Branch, Manitoba Department of Resources and Environmental Management, kindly released the data necessary for this study. L. Dykowski, L. Evenson and G. Smith acted as very able assistants during field mapping.

CHAPTER II

GENERAL GEOLOGY

Introduction

The area of study is composed of rocks similar in lithology and mineralogy to the Sickle Group, named by Norman (1933) from occurrences at Sickle Lake. Similar rocks were recognized and classified as Sickle-type by Schledewitz (1969) at Rat Lake to the northwest, and by Elphick (1970) in the Mynarski-Notigi Lake area to the east and north-east of the area of present study (Figure 1).

In the area of study the Sickle-type rocks are surrounded and underlain by rocks classified as belonging to the Wasekwan Group (Frohlinger, 1971, personal communication). The Sickle rocks in the area of this study are referred to as a Sickle outlier; there is some evidence to interpret that they were joined to the Sickle rocks to the north and west at Rat Lake and are now separated by erosion. Similarly, another larger body of Sickle-type rock around Notigi Lake to the east is herein called the Notigi outlier (Figure 1), for it is surrounded by Wasekwan-type rocks and separated by erosion from the large body of Sickle-type rocks to the north (Elphick, 1971, personal communication).

General Statement

The study of deformational history is restricted to the

Sickle outlier referred to above (Figure 1). This outlier is composed largely of light tan-coloured meta-arkosic paragneisses and migmatites.

Underlying the surrounding Sickle outlier is a thick sequence of pelitic gneisses. These rocks, believed to be the oldest in the area (Table 1), differ in composition and appearance from the Sickle-type rocks. They are similar in lithology and mineralogy to the Wasekwan Group (Frohlinger, 1971, personal communication), named by Bateman (1945) for rocks in the McVeigh Lake area, although no definite correlation has been made up to this time.

At the southern extent of the hook-shaped Sickle outlier (Map 1), there are two bodies of intrusive rocks. Immediately south of the Sickle rocks there is a body two miles long and one and one-half miles wide, consisting of foliated granodiorite. The composition of this unit is similar to that of the Sickle-type rocks of the outlier; however, the granodiorite is believed to be intrusive in origin.

To the south of the granodiorite there is a body of pink quartz monzonite which is in contact with the Wasekwan-type pelitic gneisses to the south.

At least two ages of intrusive pegmatite occur in the map-area. Early K-feldspar-plagioclase pegmatite occurs as an in situ metamorphic derivative of the Sickle-type arkosic gneisses. In addition, a late stage intrusive, granitic to quartz monzonitic pegmatite occurs often along the contact between the Sickle-type

TABLE I

TABLE OF FORMATIONS

Age	Group	Unit	Map Unit Number	Unit Description
PRECAMBRIAN		Pegmatite	8	coarse-grained to pegmatitic pink to white, K-feldspar-plagioclase pegmatite
	Post-Sickle Intrusives	Granodiorite	7	medium-grained, tan-coloured, hornblende-magnetite granodiorite, with penetrative foliation
		Quartz Monzonite-Granite	6	fine-to-medium-grained, light pink, biotite-magnetite bearing quartz monzonite-granite, with penetrative foliation
		Diatexite-Anatexite	5	light grey, medium-to-coarse-grained granodiorite; highly mobilized equivalent of Unit 4
		Metatexite	4	tan to grey, medium-grained equivalent of Unit 3; metamorphic layering with 20-65% leucocratic *lit-par-lit*
	Sickle Group	Meta-Arkose-Paragneiss	3	light brown to tan, fine-to-medium-grained, K-feldspar-plagioclase-quartz-magnetite-hornblende rich rock, bedded, with less than 20% *lit-par-lit* leucocratic injections
		Amphibolite	2	black to greenish black, medium to coarse-grained, hornblende-plagioclase-biotite amphibolite, with minor disseminated sulfides
	Wasekwan Group	Hybrid Gneisses and Migmatites	1	light grey, fine to medium-grained, plagioclase-K-feldspar-quartz-biotite-garnet gneisses with varying amounts of cordierite, sillimanite and diopside; rocks are bedded to highly migmatized

arkosic gneisses of the Sickle outlier and the pelitic Wasekwan-type gneisses. A large portion of the northern and central parts of the Sickle outlier is also comprised of this late stage intrusive pegmatite (Map 1).

Aeromagnetic Relationships

The aeromagnetic map of the area studied bears a close relationship to the geology (Figure 2), clearly outlining the distribution of the Sickle outlier. The Sickle-type rocks are outlined by the 2800 gammas contour and are characterized by magnetic values in excess of 2800 gammas. The underlying Wasekwan-type rocks exhibit magnetic values below 2800 gammas. This relationship is due largely to the high magnetite content of the Sickle-type rocks, as opposed to the lack of magnetite in the Wasekwan-type rocks. The granodiorite and quartz monzonite intrusions, south of the Sickle outlier, also have a high magnetic signature due largely to the presence of magnetite.

The 2800 gamma contour reveals the shape of the Sickle outlier and the fact that the Sickle outlier is clearly separated from the Notigi outlier (Figure 2).

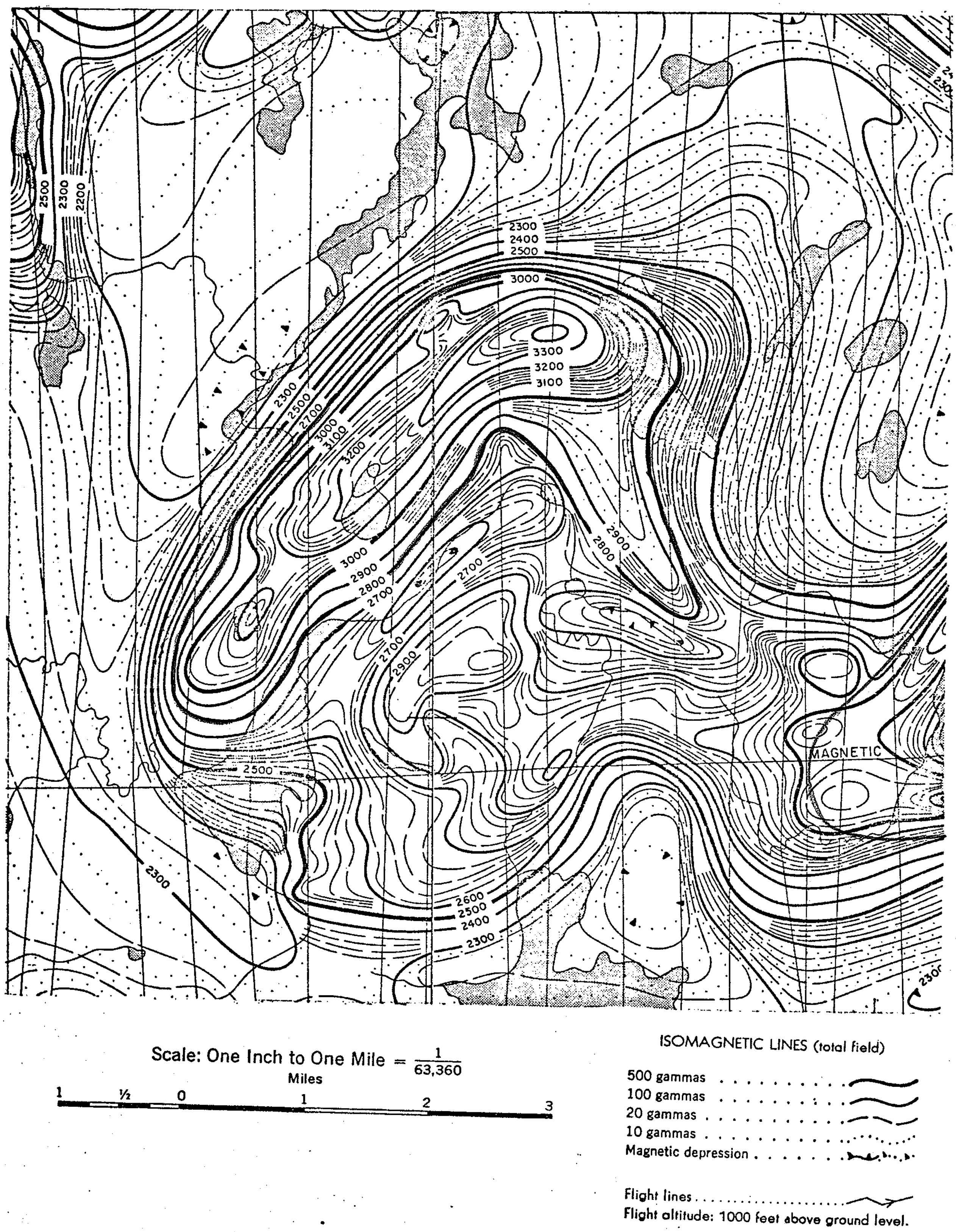


FIGURE 2 Aeromagnetic map of the area of study (2800 gamma contour outlined in red). The SW corner of the Notigi Lake outlier outlined in green

CHAPTER III

DESCRIPTIVE PETROLOGY OF ROCK TYPES

Introduction

This chapter describes the different rock types occurring in the area and their relationships to one another.

Wasekwan Group

The Sickle outlier is surrounded and underlain by light to medium grey gneisses composed predominantly of plagioclase, quartz, biotite and garnet with or without varying amounts of K-feldspar cordierite, sillimanite and diopside. These rocks vary from well bedded meta-greywackes, to interlayered paragneisses with granitic and leucocratic lit-par-lit material, to highly mobilized diatexite-anatexite migmatites with more than seventy-five per cent pegmatitic mobilizate and very little evidence of layering.

Structural evidence indicates a long and complex tectonic history within the Wasekwan Group. At least three periods of folding and at least three periods of faulting have been established by others (Frohlinger, 1971). The presence of two ages of development of cordierite, garnet and sillimanite indicates at least two stages of metamorphism of upper amphibolite grade, under high temperature and low pressure conditions (Frohlinger, 1971).

Wasekwan tectonic history will not be discussed in further detail, for this thesis deals only with deformation within the Sickle-type rocks.

Sickle Group

Distribution

The area of structural study, the Sickle outlier, is manifest on the surface by a topographic form which outlines a large hook-shaped fold (Figure 3). The outlier is visible on air-photos and measures five miles in an east-west direction from limb to limb, and two and one-half miles in a north-south direction. The rocks within the outlier are Sickle-type arkosic gneisses and migmatites, some late stage intrusive pegmatites, and minor amphibolite. The form of the outlier initially drew the attention of the author to this area as one in which studies of the deformational history of Sickle rocks within the Churchill Province might prove enlightening.

Stratigraphy

The homogeneity of what appear to have been predominantly arkosic sediments, coupled with high grade amphibolite facies metamorphism, create problems in establishing the stratigraphy within the outlier. Bedding is visible in some outcrops; however, correlation of beds between outcrops is not possible. The primary features have been obliterated by recrystallization and mobilization which accompanied regional metamorphism. The marker amphibolite, which is very continuous

FIGURE 3 Air-photo [illegible] overlay outlining the Sickle - [illegible]

and which has been used as a stratigraphic marker horizon at the base of the Sickle Group northeast of Notigi Lake (Taylor, 1971, personal communication), appears in only one locality of limited extent in the area of present study. The absence of marker horizons led to the use of structural trends and air-photo interpretation combined with petrology to outline the stratigraphy within the outlier. Excellent quality (one inch = one-quarter mile) aerial photographs were available upon which the strike of layering, wherever visible, was found to correspond closely to field measurements.

The Sickle-type rocks comprising the outlier can be divided petrologically into three units on the basis of continuity of layering and degree of mobilizate development:

(1) meta-arkose-paragneiss;

(2) metatexite;

(3) diatexite-anatexite.

These terms have been described by Mehnert (1968). Although the exact boundaries between these divisions are often difficult to map due to gradations from one unit to another, a number of definite units are identified (map 1). These units, which can be mapped, especially around the nose in the southwest limb of the Sickle outlier, probably reflect some initial distribution of orthoclase and albite-anorthite ratios in feldspars, resulting in differing degrees of mobilization due to partial anatexis. The amount of mobilizate appears dependent upon compositional variations within the original sediment rather than to extreme variations in the temperature gradient during regional metamorphism. The fact that the metatexite unit around the nose of the southwest limb of the large fold feature (Map 1) is exactly parallel to observed layering may indicate that it bears a direct relationship to this layering. The surface distribution of these units and its relationship to deformational history will be discussed in a later chapter.

A description of each of the three subdivisions is presented in the following sections.

Meta-arkose Paragneiss

These rocks consist of well bedded to interlayered meta-arkose to paragneiss (Map 1), usually light tan to grey-brown in color (Figure 4). Grain sizes range from fine- to medium-grained with a crystalline texture. Layering ranges from less than one inch to ten inches in thickness. Bedding is defined by alternating K-feldspar, plagioclase, quartz, magnetite, hornblende rich layers and thinner K-feldspar, hornblende, diopside, epidote, magnetite rich layers. Layering can be traced over one hundred feet in a number of outcrops. Occasional grain size gradations and color variations are observed in some mafic rich layers; however, these do not indicate consistent facing directions, even over several feet. These rocks have been recrystallized, as illustrated by the crystalline texture. Lit-par-lit of K-feldspar and quartzo-feldspathic material commonly comprises less than twenty per cent of these rocks.

Metatexite

The metatexite unit consists of light tan to grey colored layers of interlayered plagioclase, K-feldspar, quartz, magnetite and dark hornblende, epidote, biotite, magnetite rich layers. These layers vary in thickness from one inch to twenty-four inches. Layering is parallel to a penetrative foliation but is rarely traceable over forty feet (Figure 5). Grain size ranges from fine- to coarse-grained, with medium-grained being the most common size. Granitic and pegmatitic mobilizates comprise from twenty-five to sixty-five per cent of this rock, much in the form of *lit-par-lit*.

Diatexite-anatexite

The third subdivision of the Sickle-type rocks consists of highly mobilized, light tan to buff grey colored, medium- to coarse-grained, hornblende-magnetite bearing quartz monzonite and granodiorite. A penetrative foliation is usually present and occasionally there are relict layers visible in schlieren composed of metatexite. Mobilized granitic to granodioritic material comprises greater than seventy-five per cent of these rocks. This unit grades into a metatexite (Figure 6), depending on the degree of mobilization and the condition of the layering.

Discussion of the Sickle - Wasekwan Contact and the Marker Amphibolite

To the north-east of the area of study, in the Mynarski-Notigi Lakes area, an amphibolite unit occurs extensively between the arkosic gneisses and the older pelitic gneisses, and is believed to mark the contact between the Sickle and Wasekwan rocks (Elphick, 1970).

In the present area of study, the amphibolite, related to the contact between the Sickle - Wasekwan has been noted in only one locality, in the northwest part of the area (Map 1). Here it occurs as a thirty to one-hundred foot thick black to greenish black, medium- to coarse-grained hornblende, plagioclase, biotite, amphibolite, with minor amounts of disseminated sulfide. Although the marker amphibolite is not common in the area of study, the contact of the Sickle outlier and the underlying Wasekwan Group is identified easily by lithology changes. In other localities the Sickle and Wasekwan Groups are separated by angular and erosional unconformities (Milligan, 1957 and Campbell, 1970). In the present area of study, the nature of the contact is not understood because of poor exposure.

The position of the Sickle-Wasekwan contact (Figure 3) outlines the folding that has occurred within the Sickle outlier. The geometric form of this contact will be referred to in later chapters.

Post-Sickle Granitic Intrusive Rocks

Two distinct bodies of granitic rocks occur directly south of, and partially between the southernmost extensions of the two limbs of the large Sickle outlier (Map 1). The relative ages of these two intrusions are not understood completely but it appears that the granodiorite plug intrudes the earlier quartz monzonite. (This is evidenced by granitic and quartz monzonitic schlieren within the granodiorite). However, as much pegmatite has intruded both bodies and much mixing has occurred, it is possible that the schlieren may be related to these pegmatites. The granodiorite-quartz monzonite contact is well defined near Slit Lake (Map 1) but considerable mixing between the two bodies occurs northeast of Slit Lake.

Quartz monzonite-granite

This intrusive body extends both north and south of Slit Lake,around the granodiorite plug (Map 1). The composition of this rock ranges from fine-grained pink K-feldspar, quartz, plagioclase, biotite, magnetite granite to medium-grained light tan K-feldspar, plagioclase, quartz, biotite, magnetite quartz monzonite. K-feldspar rich pegmatite comprises from zero to more than fifty per cent of these outcrops, occurring as irregular bodies with gradational boundaries, and as well-defined aplite dykes. This body has a well-developed penetrative foliation striking slightly east of north. The relationship of the foliation to deformational history will be discussed in a later chapter.

Granodiorite

The granodiorite, a circular plug-shaped body, measures one mile in diameter and is located directly north of Slit Lake (Map 1). The body consists of a medium-grained, light tan plagioclase, quartz, biotite, K-feldspar, magnetite, hornblende granodiorite. A well-developed penetrative foliation, similar to the foliation occurring in the quartz monzonite intrusion, trends slightly east of north. Intrusive K-feldspar rich pegmatite in dykes and veins comprise up to forty per cent of some outcrops, often with poorly defined contacts. Possible schlieren of the quartz monzonite-granite intrusive body also occurs in several localities near the contact between the granodiorite and the quartz monzonite.

Pegmatites

Two types of pegmatite occur within the Sickle outlier:

(1) Various amounts of early pink pegmatite derived *in situ* occur within the gneissic Sickle rocks, largely *lit-par-lit* (where locally migrated) with layers generally less than a few inches thick, contacts of this type of pegmatite are often poorly defined. Occassional discordant stringers cut across the layering.

(2) A large amount of granitic to granodioritic massive intrusive pegmatite is present in the map-area, particularly within the northern and central portions of the Sickle outlier (Map 1). Here, bodies up to one-quarter mile across are present with only minor amounts of layered inclusions.

The large pegmatite bodies of the second type disrupt the early *in situ* pegmatite layering and are thus younger. These large late pegmatite intrusions are commonly associated with diatexite-anatexite migmatites in the northern and central part of the Sickle outlier. Large pegmatite lenses are common along the Sickle-Wasekwan contact obliterating contact relations in many areas, particularly along the northern contact between Smitty and Timber Lakes as well as south of Smitty Lake (Map 1).

CHAPTER IV

STRUCTURAL ELEMENTS

This chapter presents a description of the structural elements as they now appear within the Sickle outlier.

Layering Types

Two types of layering are recognized in the Sickle-type rocks:

(1) relict bedding,
(2) gneissic layering.

Relict bedding is recognizable remnant primary layering. Gneissic layering is defined as all layering not recognizable as primary layering. One type of layering is gradational into the other. The gradation is a result of increasing amounts of mobilized pegmatitic material in the form of lit-par-lit. Where both types of layering were observed in a single large outcrop (over 1000 ft.) they had parallel orientation, consequently, the two elements are combined and plotted simply as layering on Map 3.

Bedding

Relict bedding is interpreted in the meta-arkose-gneiss, unit 3, Map 1. This interpretation is evidenced by layering continuous over 100 ft one-half to 10 inches thick, and defined by sharp compositional and textural changes (Figure 4). Grain size changes from fine-grained to coarse-grained across layers with occasional grain size variations within a single well-defined layer. The grain size variations are believed to reflect original premetamorphic grain size variations, possibly related to graded bedding. However, it was not possible to establish any consistent facing directions.

Mobilized pegmatitic lit-par-lit material, at a minimum in the meta-arkose-gneiss unit, can be easily distinguished from essentially non-mobilized but recrystallized meta-arkose.

Gneissic Layering

The most dominant structural element in the area of study is the feature classified as gneissic layering. As the amount of mobilizate increases from paragneiss to metatexite, the features interpreted as relict primary layering become less obvious and more discontinuous; also, grain size variation becomes less distinct and no longer coincides with compositional layering. Abundant mobilizate material is often indistinguishable from non-mobilized recrystallized rock. These two inch to twelve inch poorly defined layers are classified as gneissic layering.

It is apparent that very little, if any, realignement of layering occurred during migmatization. Thus the two types of layering are apparently related - one developing from the other. Their attitudes represent a true picture of folding in the layered Sickle rocks.

Foliation

Foliation is not as dominant a fabric as gneissic layering and bedding. Linear hornblende crystals are aligned to form a foliation but the low content of biotite makes the foliation less noticeable than layering. In certain outcrops where biotite is more abundant, and in diatexite-anatexite migmatites, foliation is the dominant fabric and was recorded as such (Map 1). Within the Sickle outlier foliation is almost always parallel to layering.

In the quartz monzonite and granodiorite intrusions around Slit Lake, foliation is the dominant fabric. Throughout these rocks a largely penetrative foliation, possibly in part attributed to flow, strikes approximately 010° to 020° and dips steeply to the east. This same foliation, for the most part, ends abruptly against the Sickle outlier, but was observed in one outcrop near Mogul Lake as a weakly developed foliation cutting across layering at 018° strike, and 73° dip to the east.

Lineations

Lineations are practically non-existent in the Sickle-type rocks. Most hornblende crystals show no linear alignement. Several very localized hornblende mineral lineations were observed; however, these were erratic in orientation and could not be related to other structures.

Joints

Jointing occurs in all rock types in the area. The most common spacing is 10 cm to 100 cm with some joints spaced less than 10 cm. Some larger scale joints are visible on air-photos (Map 2). Two dominant joint sets were measured at every observational locality and the analysis of these measurements is given in Chapter VIII.

Earlier joint sets may have controlled the emplacement of pegmatite and aplite dykes. A geometric comparison between dykes and existing joint sets is given in Chapter VIII.

Faults

Although measurable small scale faults are scarce in the Sickle rocks, a large scale north-northeast trending fault, located just to the east of the Sickle outlier, shows left lateral movement by displacing earlier formed faults (Map 2).

CHAPTER V

FOLDS WITHIN THE SICKLE OUTLIER

General Statement

Folds within the Sickle outlier were identified on the basis of the following types of evidence:

(a) air-photo trends,

(b) attitudes of layering and foliation,

(c) geologic field measurement trends (trends established by extending layering and foliation attitude measurements between stations, Map 3),

(d) limited stratigraphy,

(e) aeromagnetic trends.

Conventional methods of tracing units and establishing an age sequence were precluded by the degree of metamorphism.

Folded Form of the Sickle Outlier

The surface distribution of the Sickle-Wasekwan contact in the area of study can be interpreted as an interference pattern resulting from more than a single deformational event (Figure 3 overlay). This interpretation is supported by detailed surface mapping which indicates layering (bedding and gneissic layering) parallel to the Sickle-Wasekwan contact throughout the Sickle outlier (Map 1).

Late folding about a N-S axial trace

The entire Sickle outlier appears to have been folded about an approximately north-south axial trace, with limbs extending in southeast and southwest directions (Figure 3 overlay). This fold shows up readily on air photographs (Figure 3) and is supported by the aerial photograph linear interpretation map (Map 2). The Sickle-Wasekwan contact outlines the hook-shaped fold about the north-south axial trace, and attitude measurements (Map 1), as well as geologic trend lines (Map 3) support this interpretation. The aeromagnetic map (Figure 2), on which the 2800 gamma contour is essentially parallel to the Sickle-Wasekwan contact, also indicates a major fold about the north-south axial trace. The event leading to this fold can be interpreted as the final folding event, for the north-south axial trace has not undergone subsequent folding within the study area.

Closure on the limbs of the late fold

Closure can be established very clearly on the southwest limb of the Sickle outlier just west of Timber Lake (Map 1). This closure can be documented by the position of the Sickle-Wasekwan contact (Map 1), air-photos (Figure 3), air-photo lineaments (Map 2), summary of layering and schistosity (Map 3) and by aeromagnetic trends (Figure 2). Ground geologic mapping verifies this with layering following the contact around the nose of the southwest limb of the Sickle outlier.

Closure occurs on the southeast limb of the large Sickle fold as well, however, the plunge of the hinge line is shallow in this area. Air-photo interpretation (Map 2) and geological mapping indicate that layering continues on without closure appearing on the surface towards the major north-northeast trending fault, one-quarter mile to the east. Nevertheless the presence of the Sickle-Wasekwan contact on either side of the limb indicates the presence of a recumbant synformal axis.

Thus, the form of the Sickle outlier as a whole is that of a synform which has been refolded about a north-south axial surface.

The Possibility of Multi-Phase Folding

The well documented closure on the southwest limb and the less well established closure on the southeast limb of the Sickle outlier, plus the later folding of this axis about a north-south axial trace, indicates two periods of folding.

Additional folding events can be documented by field observations from within the Sickle outlier. Evidence is presented in the following section which indicates at least one, and probably two, events which predate the two events noted above.

Field evidence of early folding events

The layering in the Sickle rocks is parallel to the trace of the Sickle-Wasekwan contact. Detailed mapping of attitudes of these layered paragneisses and migmatites reveals changes in the direction of dip across strike in the southwest limb of the outlier. In addition, an occasional closure observed in the field indicates that the sequence consists of a series of almost upright isoclinal folds, whose axial planes are dipping steeply to the northwest. The fact that these axial traces can be traced around the nose of the southwest limb indicates that they are not related to, but predate the folding event which resulted in the closure on this southwest limb. In addition, large scale hook structures have been formed on the sides of the southwest limb of the outlier as a consequence of interference between these early isoclinal folds and later axial traces which are parallel to the central axial trace of the southwest limb. The small scale isoclinal folds definitely predate all other folding events and are interpreted as the first-formed folds within the outlier.

Changes in the direction of the plunge of the axes of the small-scale upright isoclinal folds are evident in many outcrops in both the southwest and southeast limbs of the Sickle outlier. Most of the tight isoclinal folds have axes which are essentially horizontal, however, the variations in the plunge of these axes reflect minor flexures in the early isoclinal axes. These flexures with axial traces everywhere perpendicular to the Sickle-Wasekwan contact may reflect another weak folding event which post-dates the early isoclinal folding, and pre-dates the two late deformational events discussed earlier.

Summary of Folding History

Field evidence permits the interpretation of three folding event with confidence. The fourth event is also possible.

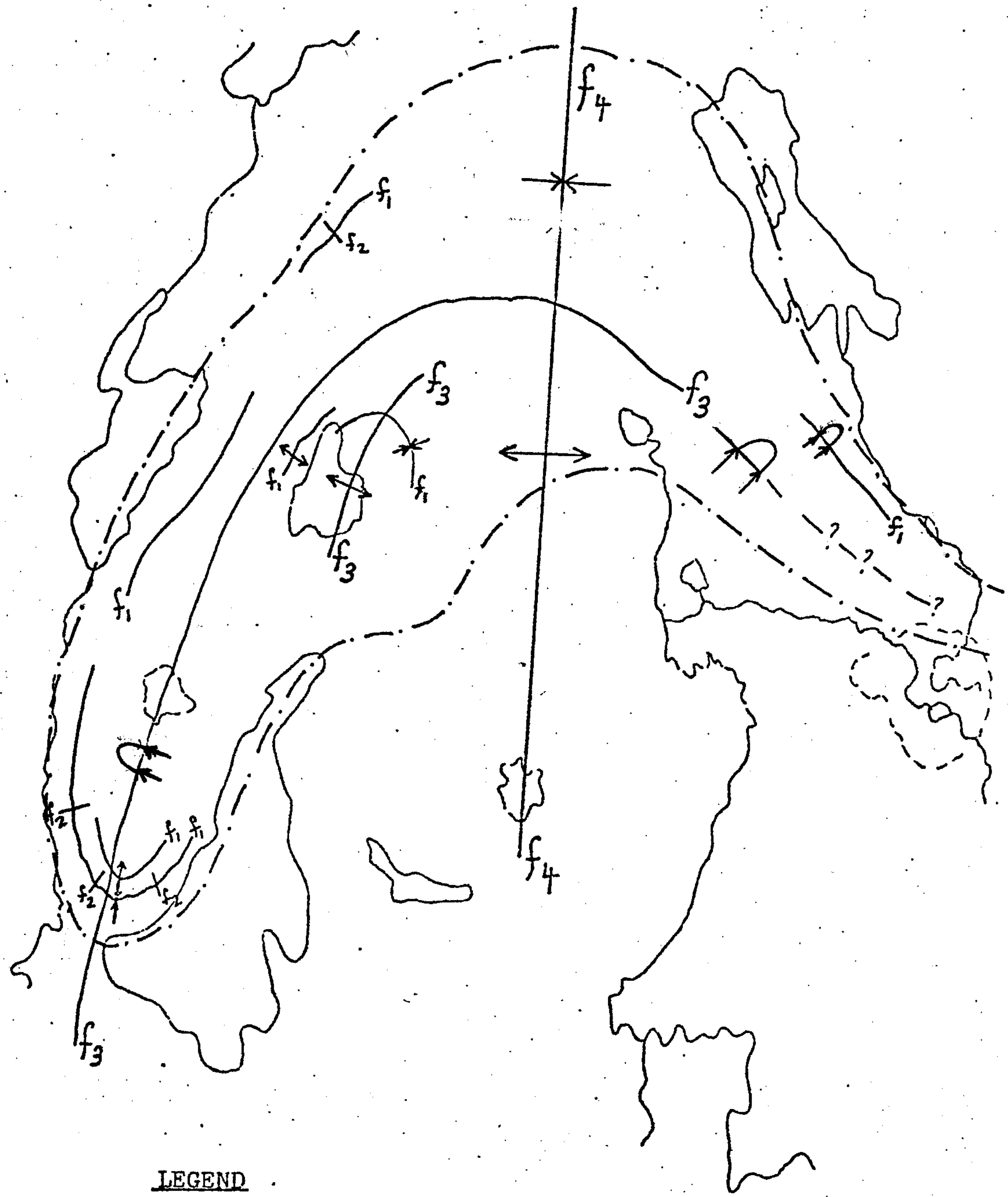
(1) f_1 - early isoclinal folds (well-documented).

(2) f_2 - weak open folding of f_1 axes (possible).

(3) f_3 - folding of f_1 and f_2 axial planes producing the interference patterns best depicted in the southwest limb of the outlier, but also in the southeast limb (well-documented).

(4) f_4 - final folding of f_1, f_2 and f_3 axes about a north-south axial plane to produce the hook-shaped large Sickle fold (Figure 7) (well-documented).

Geometric analysis of field data is presented in the next chapter and analysed with respect to these folding events. This is followed by a discussion of folding mechanisms.



LEGEND

—·—·— Sickle outlier boundary

f3———f3 Axial traces

FIGURE 7 Axial traces of folding events

CHAPTER VI

GEOMETRIC ANALYSIS OF FOLDS

Introduction

This chapter presents a geometric analysis of the data collected in the field. The objective of this analysis is to establish the geometric characteristics of the folds, which in turn will bear on deformational mechanisms during each event.

The area of study was divided into several sub-areas (Figure 8) based on field observations which indicated possible areas where the effects of separate deformational events could be isolated.

Sub-area I, the southwest limb of the outlier, was chosen to show f_1 isoclines as well as possible f_3 closure effects. Sub-area II, the Mogul Lake fold (Map 1), was selected to determine to which folding event this large fold is related. Sub-area III, on the nose of the large Sickle fold was chosen to determine the effects of f_4 in this region. Sub-area IV, the southeast limb of the Sickle outlier, was selected to determine the effect of early f_1 isoclinal folding and later f_3 folding. Sub-area V, which covers the intrusions south of the Sickle outlier, was selected as a separate sub-area so that tectonic effects within the late intrusions could be examined, with the possibility of relating the fabric in these intrusions to one or more folding events within the Sickle outlier.

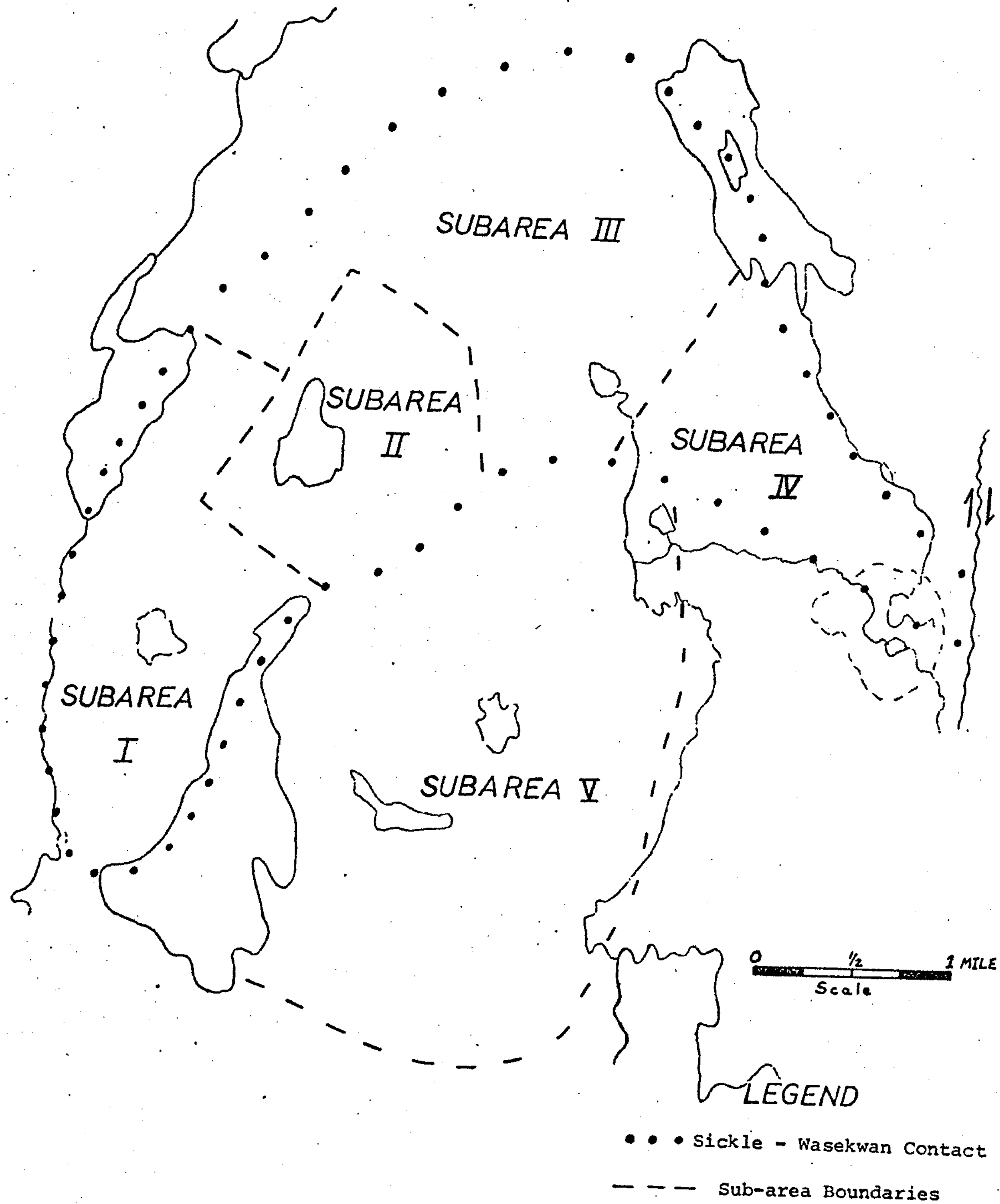


FIGURE 8 Boundaries of sub-areas of geometric analysis

The geometric analysis of folds is based on plots of poles to layering (bedding and gneissic layering combined) for all measurements in the Sickle outlier, and on poles to foliation for the intrusions south of the outlier (Sub-area V).

The data on which the stereonet plots are based do not represent a true statistical sampling. The distribution and quality of outcrop in the area of study placed definite limits on the acquisition of data on a grid basis; consequently the stereonet plots will reveal some bias towards portions of the area where more field data could be obtained (for example lack of data in Sickle rocks in the northern portion of the area as compared to abundant measurements in certain parts of the southwest limb (Map 1)). In spite of the absence of statistical validity the stereonet plots serve a useful purpose in determining the geometric properties of the folds observed in the field and in relating these folds to overall deformation in the Sickle outlier.

Each subarea is discussed separately with equal-area projections related to folding events where applicable.

The Entire Sickle Outlier

Poles to layering for the entire Sickle outlier (Figure 9) form a well-defined great circle girdle which contains two major concentrations, A and B. Concentration A represents data from the

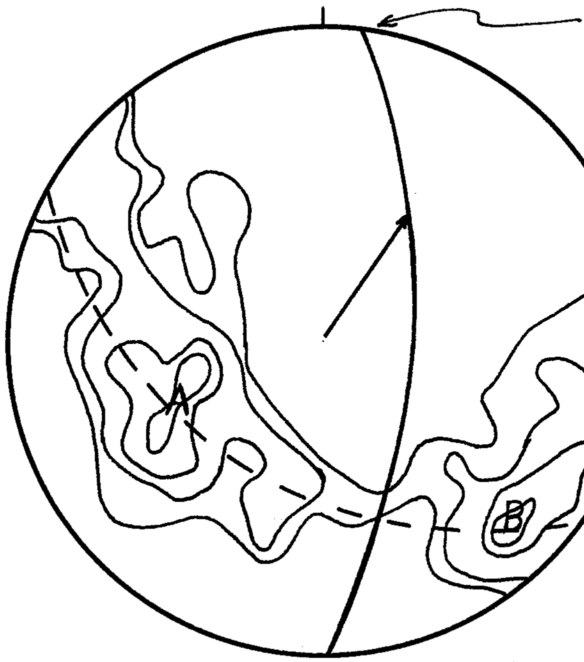


FIGURE 9 Contoured lower hemisphere stereographic projection of poles to layering for entire Sickle outlier, 222 poles.
Contours: 1%, 4%, 5%, 6%

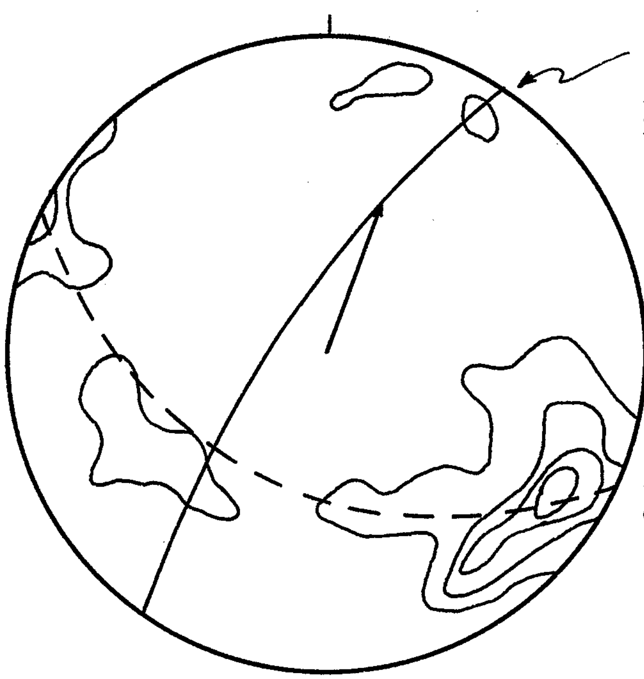


FIGURE 10 Contoured lower hemisphere stereographic projection of poles to layering for Sub-area I, 63 poles.
Contours: 5%, 9%, 12%, 14%

southeast limb of the outlier and concentration B represents data from the southwest limb of the outlier. This pattern could be interpreted as a simple cylindrical fold with well-developed limbs, however, the data presented previously indicates that the structure is complex and that a minimum of three events are included. The simple stereonet pattern implies that the earliest folds were isoclinal, and that they have been folded into a large fold with the two concentrations on the girdle being the two limbs of the Sickle outlier. The axial plane of the f_4 fold can be interpreted using the axis, a point midway between concentrations on the pole circle, and field evidence that the fold is not overturned (Map 1). The resulting axial plane strikes 008° and dips 60° west. The plunge of the fold is 40° at 034°. An interlimb angle of approximately 90° can be interpreted from the stereonet plot.

This large fold represents the last folding event, f_4, which produced the large hook-shaped Sickle fold. The axial trace based on stereonet data is similar to the axial trace interpreted from surface distribution of rocks (Figure 7). Where the f_4 axis crosses the f_3 syncline the f_4 axis changes from anticlinal on the south to synclinal on the north (Figure 7).

Sub-area I

One major concentration of poles to layering and a weak girdle suggests isoclinal cylindrical folding (Figure 10). Field observations indicate that f_1 isoclinal folds occur in this limb (Figure 7) and that they are folded about the nose of the limb of the outlier by a later event.

In this plot the best fitting axial plane strikes 213° and dips 77° W, with an axis plunging 40° at 022°. This is consistent with axial traces of f_1 and f_3 interpreted from surface mapping (Figure 7), except in the nose where f_1 axial traces are folded by f_3. F_3 and f_1 cannot be separated in the stereonet plots because both events produced isoclinal folds.

Sub-area II

Equal area stereonet plot of poles to layering northeast of Mogul Lake (Figure 11) result in a pattern indicating the presence of an asymmetric cylindrical fold. The data distribution in this sub-area (Map 1 and Figure 8) indicates that the concentration A (Figure 11) is a crestal scatter. An axial plane can be selected passing through this crestal scatter and through the axis to the pole circle, resulting in an axial plane striking 032° and dipping 66° southeast, and an axis plunging 30° at 047°.

Field trends (Maps 1 and 3) indicate that this is an axial trace parallel to the f_3 axial trace through the nose of the southwest limb of the Sickle outlier (Figure 7). The dip of the axial surface of the Mogul Lake fold differs from the dip of the f_3 axial surface through the nose of the southwest limb of the outlier, even though the strike is the same. This is not surprising considering the degree of monilization of the Sickle rocks in the Mogul Lake area (Map 1), the

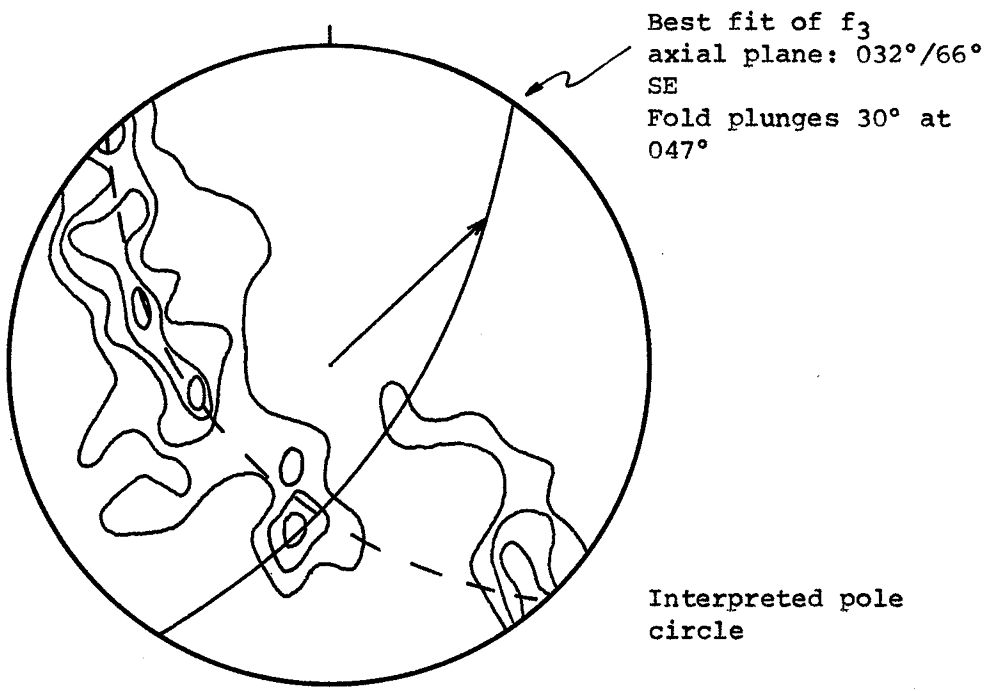


FIGURE 11 Contoured lower hemisphere stereographic projection of poles to layering for Sub-area II, 40 poles.
Contours: 2%, 7%, 10%, 13%

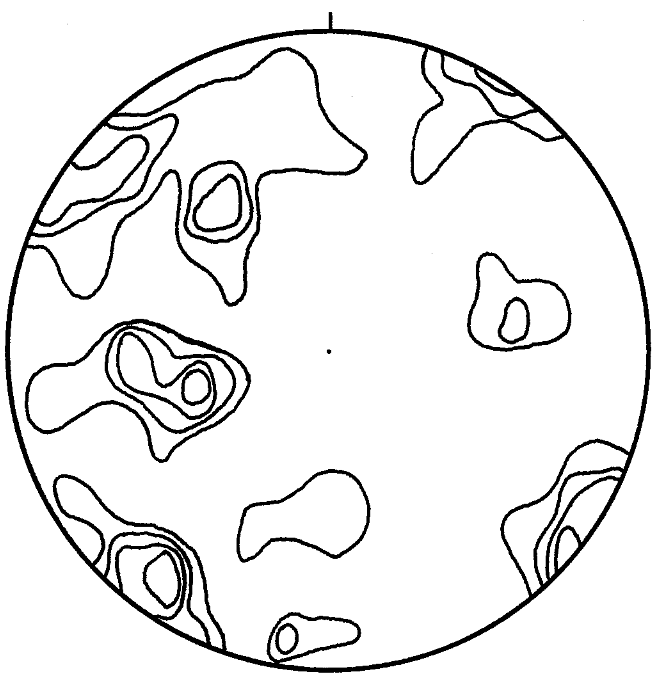


FIGURE 12 Contoured lower hemisphere stereographic projection of poles to layering for Sub-area III, 53 poles.
Contours: 2%, 5%, 7%, 9%

presence of much intrusive pegmatite near Mogul Lake, and the presence of the f_4 axial trace to the east which may have had some effect on the nearby Mogul Lake fold. In any case the Mogul Lake fold is considered to be an f_3 fold, refolding earlier f_1 and f_2 folds (Figure 7).

Sub-area III

A plot of poles to layering in the nose of the large Sickle fold (Figure 12) produced a complicated scatter pattern from which no simple or definite folds could be interpreted.

The intrusion by late stage pegmatite is believed to be disrupting the normal closure pattern resulting in a complex distribution on the stereonet.

Sub-area IV

A plot of poles to layering in the southeast limb of the large Sickle fold (Figure 13) produces a single concentration. This concentration is consistent with isoclinal folds with an axial surface striking approximately 316° and dipping 50° NE. In fact field evidence indicates two sets of isoclinal folds in this region, f_1 and f_3 (Figure 7). The surface observations suggest both sets of folds have relatively shallow plunges.

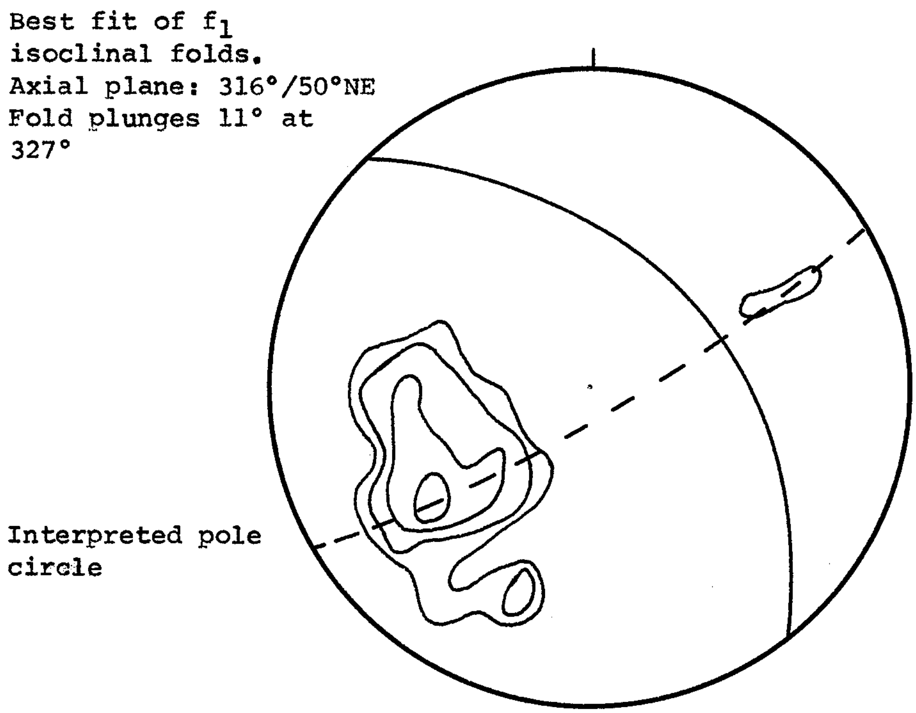


FIGURE 13 Contoured lower hemisphere stereographic projection of poles to layering for Sub-area IV, 58 poles.
Contours: 5%, 9%, 12%, 15%

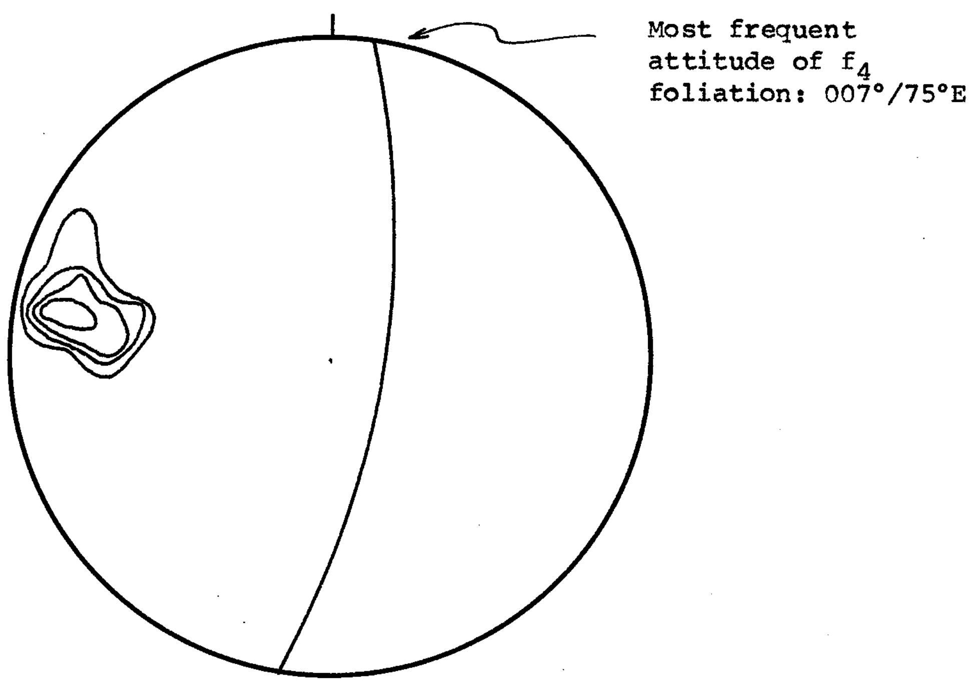


FIGURE 14 Contoured lower hemisphere stereographic projection of poles to foliation for Sub-area V, 32 poles.
Contours: 12%, 15%, 18%, 22%

Sub-area V

Poles to foliation in the two massive but well-foliated intrusive bodies south of the Sickle outlier (Figure 14) yield a single concentration with an average foliation striking 007° and dipping 75°E. This foliation is remarkably consistent throughout these two intrusions (Map 1) and is very similar to the best fit axial plane of the large Sickle fold in Figure 9. The foliation in these intrusions is interpreted therefore as being syntectonic with f_4 and the formation of the large Sickle fold.

Summary

The geometry of the folds as presented in the stereonet plots is consistent with the interpretation of folding made from field evidence (end of Chapter V). Only the f_2 folding event (weak open flexuring of f_1 axis) does not show up conclusively on stereonet plots. The presence of these flexures which have been observed in outcrops, may represent a separate event or may be local readjustments to other post f_1 folding events.

Figure 15 is a diagramatic summary of folding events showing axial traces of each event (f_1 through to f_4) and the effects of subsequent folding on earlier axial traces (Figure 15a to 15d).

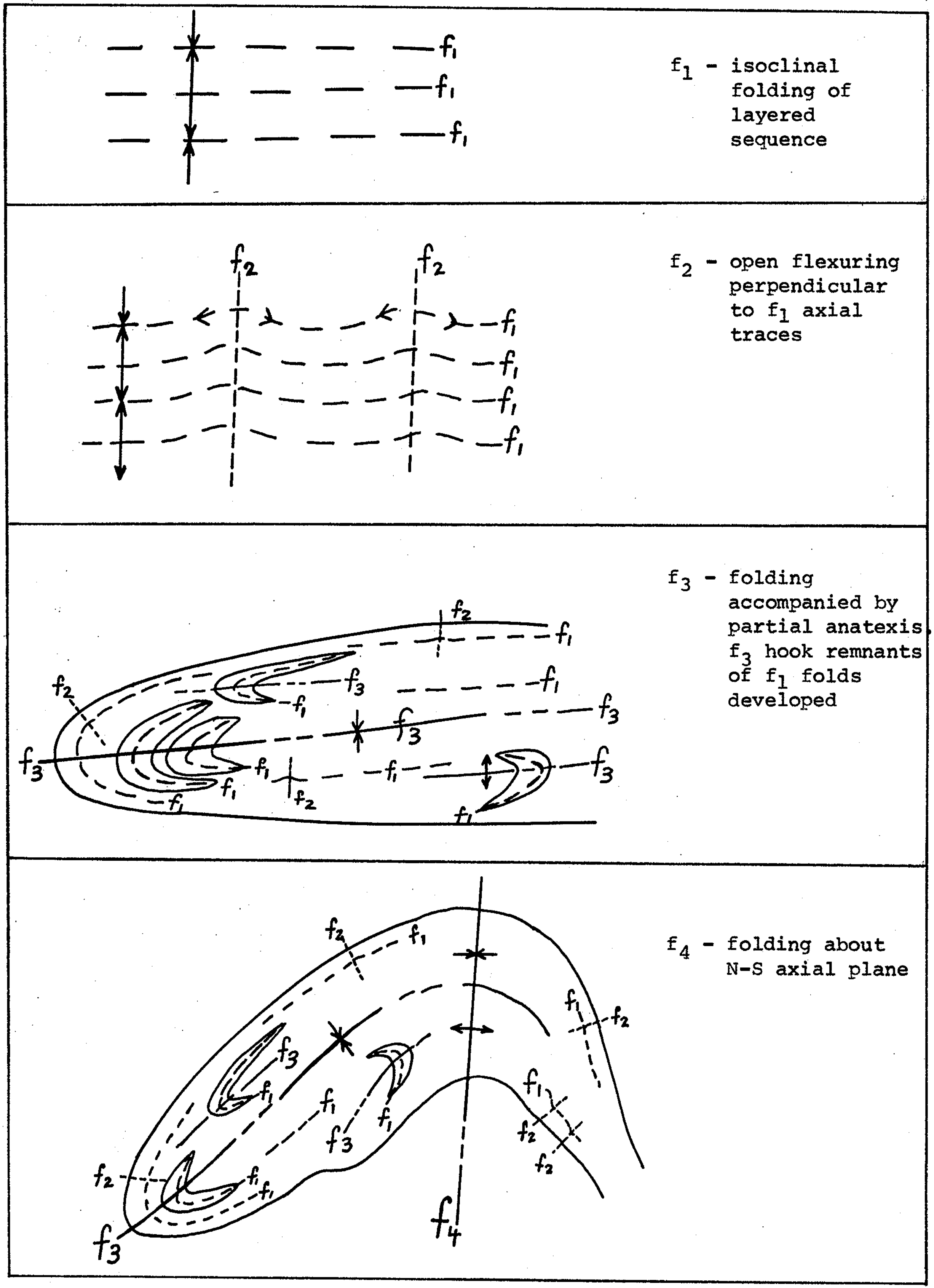


FIGURE 15 Diagrammatic interpretation of the folding events leading up to the present form of the Sickle outlier.

CHAPTER VII

FOLDING MECHANISMS

General Statement

The deformational history and folding mechanisms in complexly folded Precambrian gneissic belts, become increasingly difficult to ascertain the further back in the deformational history one projects. Although the early history of the Sickle outlier has been somewhat obliterated by the extensive recrystallization of amphibolite grade metamorphism, the present study indicates that three or possibly four folding events have occurred within the Sickle outlier (Table II). In addition, a number of late brittle deformational events have occurred and will be dealt with in the next chapter.

The folding mechanisms and the relationship of metamorphism to folding will be discussed in this chapter.

First Folding Event (D_1 f_1)

The earliest recognizable series of folds are isoclinal, with axial traces parallel to the Sickle-Wasekwan contact throughout the outlier.

The folding mechanism for the f_1 folds is difficult to assess due to subsequent recrystallization. In the f_1 fold closures observed, no thickening of the nose or shear folding was in evidence.

The fact that the layers have a constant true thickness from the limbs to the nose of f_1 folds, suggests that flexural slip was probably the main folding mechanism, however, little confidence is placed in this interpretation. No evidence of metamorphism accompanying this event was observed probably due to masking by later metamorphic effects.

Second Folding Event (D_2 f_2)

Throughout the Sickle outlier weak open folding of layering is common. These folds generally have an amplitude of less than three feet and an interlimb angle of 120° or more. They are most commonly present in meta-arkose-gneiss and metatexites. These f_2 folds produce open folding with axial planes perpendicular to f_1 axial traces.

There is little evidence to support interpretation for mechanism of f_2 folds. The folds are open and do not lend themselves to a study of the variation of axial planar or true thicknesses. No textural evidence indicating mechanism was observed. Flexural folding is probable, but not necessary. No evidence of metamorphism could be related to this gentle folding. The recrystallization observed in these folds is interpreted as post-D_2 f_2 folding.

Third Folding Event (D_3 f_3)

This event resulted in the large-scale syncline along the length of the outlier and produced the hook-shaped migmatite units (Map 1 and Figure 15c).

It is with this event that the intense regional metamorphism can be associated. Metamorphism reached well into the amphibolite grade as indicated by the abundance of metamorphic hornblende, orthoclase, and diopside.Sillimanite has also been recognized in thin-section. Complete recrystallization resulted in interlocking crystalline texture in the Sickle rocks. Partial anatexis of less resistant layers due to the intense amphibolite grade metamorphism led to conditions which resulted in asymmetrically boudinaged hook-shaped f_3 folds; while more resistant layers show little evidence of such flow.

In determining folding mechanisms of f_3 folding, it is not possible to assess variations in true thickness or axial plane thickness, or to do dip isogon analysis because of the absence of stratigraphy. However, in the nose of the south-west limb no evidence of passive slip or catalasis was observed, and layers seem to be fairly regular in apparent true thickness. Even in hook-shaped mobilizate features, where partial anatexis and flow have occurred, no disharmonic folding was in evidence.

Thus f_3 folding seems to have been a combination of flexure and flow within layers. Field relationships and fold geometry for f_3 folds are consistent with flexural flow, as described by Donath (1967).

Fourth Folding Event (D_4 f_4)

The final folding event was the folding of f_1, f_2 and f_3 axial planes about a north-south striking axial plane to produce the present configuration of the Sickle outlier (Figure 15d and Figure 7). The same tectonic event that produced this large f_4 Sickle fold produced foliation in the granitic bodies south of the outlier (Map 1). This foliation has an orientation which is parallel to the axial plane of the major f_4 fold.

The fact that this foliation generally does not penetrate the Sickle rocks may result from the fact that the granitic rocks may have been partially fluid during D_4 and readily acquired the axial planar foliation, while the less fluid Sickle rocks did not. The plutonic rocks may have been intruded syntectonically or pretectonically. In any case they were still partially liquid during the D_4 event.

Determination of the folding mechanisms for the large scale f_4 fold is hampered by the large volumes of pegmatite which intrude the central Sickle outlier, disrupting the normal fold pattern in the nose area of this fold.

In a small number of outcrops within the outlier a cross cutting biotite foliation was observed with an axial plane orientation parallel to f_4 foliation developed in the granitic plutons south of the outlier. This axial planar foliation could be attributed to a passive slip mechanism. However, in most areas, particularly the north end of the outlier near the point of maximum f_4 curvature, no passive slip was observed and layers were generally constant thickness in all outcrops. Here, no mechanism other than simple flexure appears to have operated.

The f_4 folding may be closely associated with the emplacement of the granitic rocks south of the outlier (Map 1 and Figure 3), whose foliation is parallel to the f_4 axial plane.

No metamorphic effects associated with f_4 were observed.

CHAPTER VIII

POST FOLDING TECTONISM

Introduction

The folding events within the Sickle outlier were followed by later deformation which resulted in joints, intrusion of dykes, and faulting. The field and geometric relationships of these features are presented in this chapter. Description of joints and faults have been presented earlier in Chapter IV and are not repeated here.

Joint, Dyke and Fault Relations

Joints are visible in all outcrops within the study area. The joints have a constant orientation independent of folds, and consequently, are interpreted as post-f_4 in age. Field evidence indicates that some early formed joints served as tabular conduits for intrusive pegmatite; several pegmatite dykes are parallel and appear to be joint controlled. Subsequent joints cutting across these parallel pegmatite dykes indicate the presence of post pegmatite jointing.

The dykes which are to some extent joint controlled are of the late intrusive type and are not the _in situ_ derived mobilizate pegmatite associated with f_3 partial anatexis. The distinction between f_3 _in situ_ derived pegmatite and later intrusive pegmatite has been made in Chapter III.

In addition to jointing and the intrusion of dykes, large scale north-south faulting (Map 2) offsets earlier formed northeast trending faults by apparent left lateral displacement. The age relations of these faults to joints and the intrusion of dykes could not be established in the field.

Geometric Analysis of Joints and Dykes

Joints

A lower hemisphere, equal-area projection of all poles to joints measured in the field is shown in Figure 16. This plot reveals that jointing strikes in almost all directions, with steep dips. The three dominant joint sets are:

(1) striking 018°, dipping vertically;

(2) striking 062°, dipping 84° SE;

(3) striking 132°, dipping vertically.

Dykes

An equal area stereonet plot of poles to dykes measured in the field (Figure 17) reveals two dominant attitudes of dykes:

(1) striking 060°, dipping vertically;

(2) striking 110°, dipping vertically.

The dykes plotted are all of the late intrusive pegmatite type, not the thin, *in situ* derived mobilizate pegmatite.

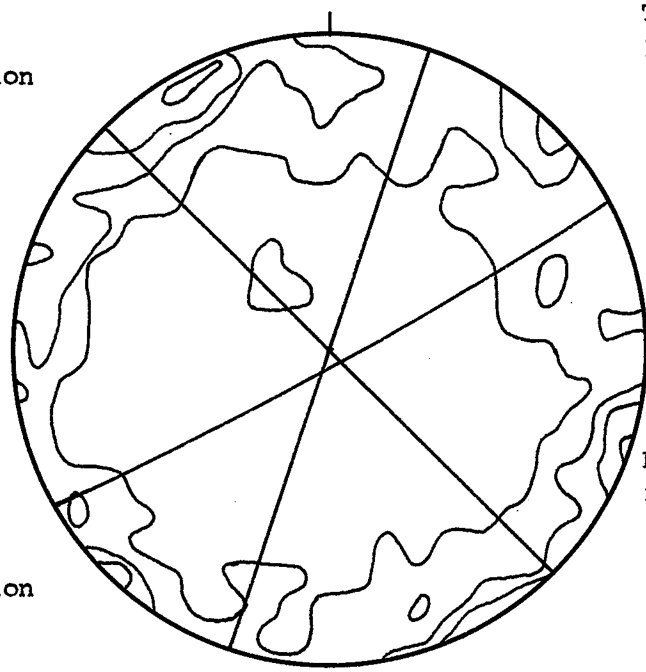


FIGURE 16 Contoured lower hemisphere stereographic projection of poles to joints, 127 poles.
Contours: 2%, 4%, 6%, 8%

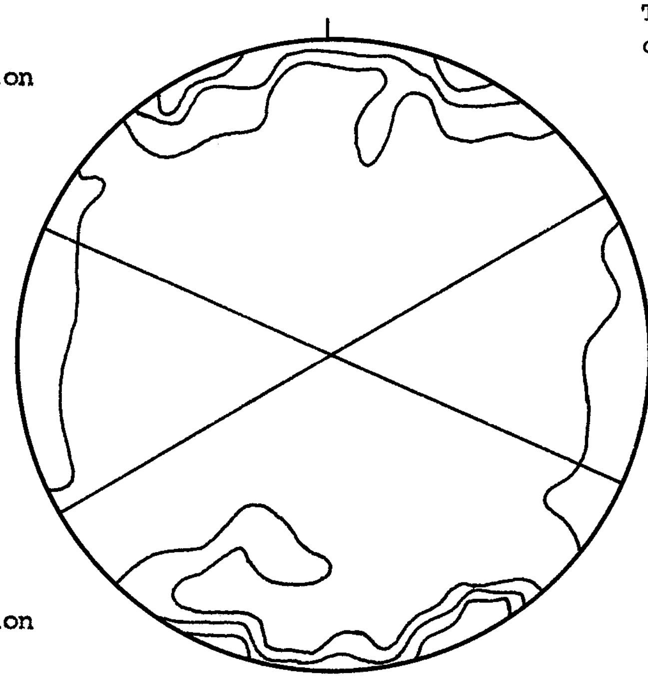


FIGURE 17 Contoured lower hemisphere stereographic projection of poles to dykes, 35 poles.
Contours: 2%, 8%, 17%

The 060° striking set of dykes corresponds closely to the joint set which strikes 062° and dips 84° SE. It is possible that this joint set may predate the pegmatite and that some of these early joints were occupied by later pegmatites. The second dyke set does not show any relationship to jointing although these dykes may fill an earlier joint-set, as well.

Summary of Post-Folding Tectonism

Late post-folding tectonism can be stated as follows:

D_5 jointing in Sickle rocks, followed by pegmatite intrusion (some of which intruded along early D_5 joint sets);

D_6 late jointing developed cutting pegmatite dykes as well as Sickle rocks.

The northeast fault (Map 1) was offset by the long north-northeast trending fault, to the east of the Sickle outlier, somewhere in the sequence, possibly associated with one of the jointing events. The relative ages of faults could not be related to dykes and joints in the field.

Table II is a summary of folding and late tectonic events.

TABLE II

SUMMARY OF FOLDING AND TECTONISM

Deformation Event	Generation of Folds	Associated Period of Metamorphism	Folding Mechanisms and Features Developed	Intrusive Events
D_1	f_1		cylindrical, isoclinal, flexural folds	
D_2	f_2		weak, open flexural folds perpendicular to f_1 axis	
D_3	f_3	major amphibolite grade regional metamorphism accompanied by partial anatexis	flexural flow folds with axis parallel to f_1 axis; exposed closure on SW limb of Sickle outlier produced	*in situ* migmatite, locally migrated, largely *lit-par-lit*
D_4	f_4		largely flexural flow, some passive mechanism, cylindrical folding of entire overlier about N-S axial trace	syntectonic emplacement of granodiorite and granite-quartz monzonite intrusions south of Sickle outlier
D_5			early jointing in Sickle rocks, possible early faulting	intrusion of pegmatite into Sickle rocks filling some early joints
D_6			late jointing in Sickle rocks, jointing in pegmatite dykes; possible late N-S faulting offsetting early faults	

CHAPTER IX

CONCLUSIONS

The Sickle outlier is composed of Sickle-type arkosic gneisses which can be divided into three units:

(1) meta-arkose-paragneiss;

(2) metatexite;

(3) diatexite-anatexite.

These rocks overlie older Wasekwan-type pelitic gneisses.

Interpretation of structural history is based on detailed field observations and on air-photo interpretation. The study reveals at least three and probably four folding events, followed by a minimum of two brittle deformation events (Table II).

The first period of deformation (D_1 f_1) folded the sediments of the Sickle outlier into isoclinal folds.

The second deformational event (D_2 f_2) resulted in open flexural folding of f_1 axial planes (Figure 15b).

The third and most intensive folding event (D_3 f_3)refolded f_1 and f_2 folds about an axis essentially parallel to f_1, resulting in exposed closure at the west end of the Sickle outlier (Figure 15c). This event was accomapnied by intense amphibolite grade metamorphism which resulted in partial anatexis within less competent units. These units suffered flexural-flow deformation resulting in the more mobilized present day appearance and the thickening of f_3 closures (Figure 15c and Map 1).

The final folding event (D_4 f_4) produced the large Sickle fold by folding f_1, f_2 and f_3 axial planes about an axial plane striking slightly east of north and dipping steeply towards the east. This event was accompanied by the development of an axial planar foliation in the granitic and granodioritic intrusions south of the outlier, whose emplacement was syntectonic or pretectonic to D_4f_4.

Following all folding events, two brittle deformation events occurred:

- D_5 the formation of an early joint pattern(followed by the intrusion of pegmatites along what was likely a D_5 joint set);
- D_6 late-stage jointing which produced joints that cross the pegmatite dykes as well as the Sickle rocks.

Two periods of faulting may be identified; one striking northeast, and a later fault offsetting the earlier faults by left lateral movement. The exact age relationship between faulting and other brittle deformation is not known.

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OF THE SICKLE OUTLIER , NEAR NOTIGI LAKE MANITOBA .

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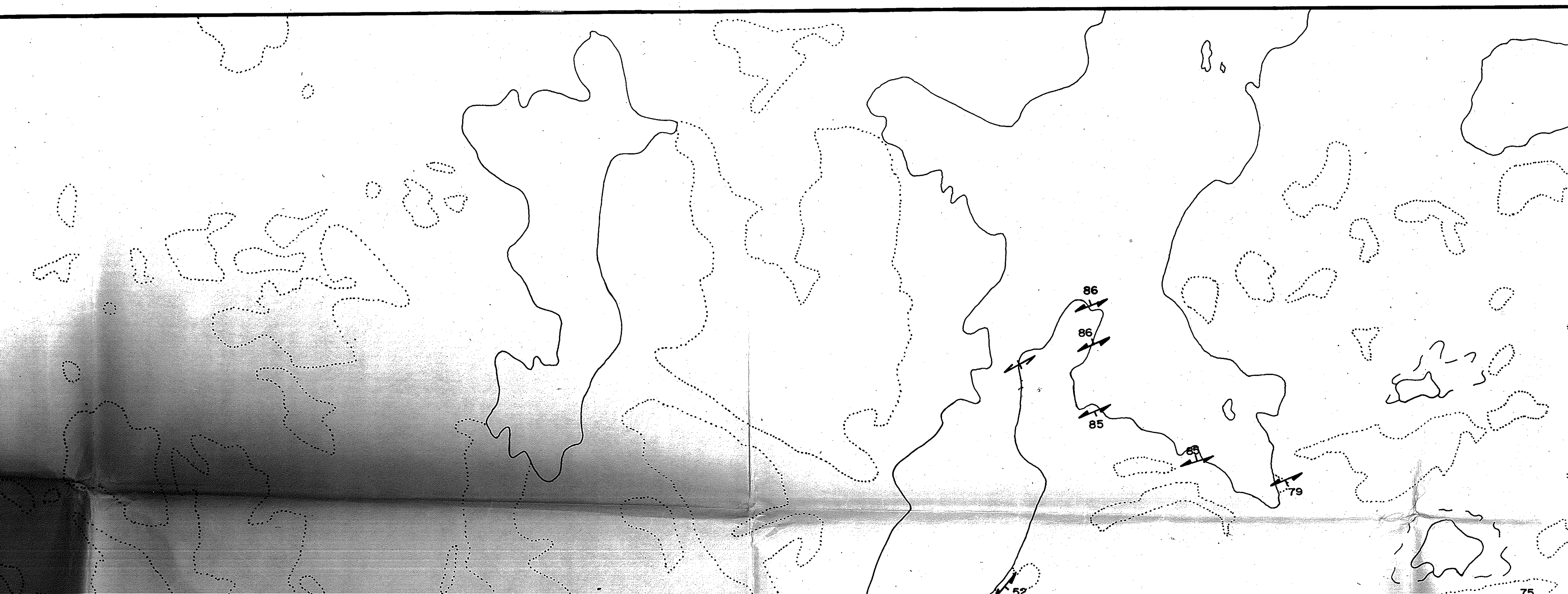
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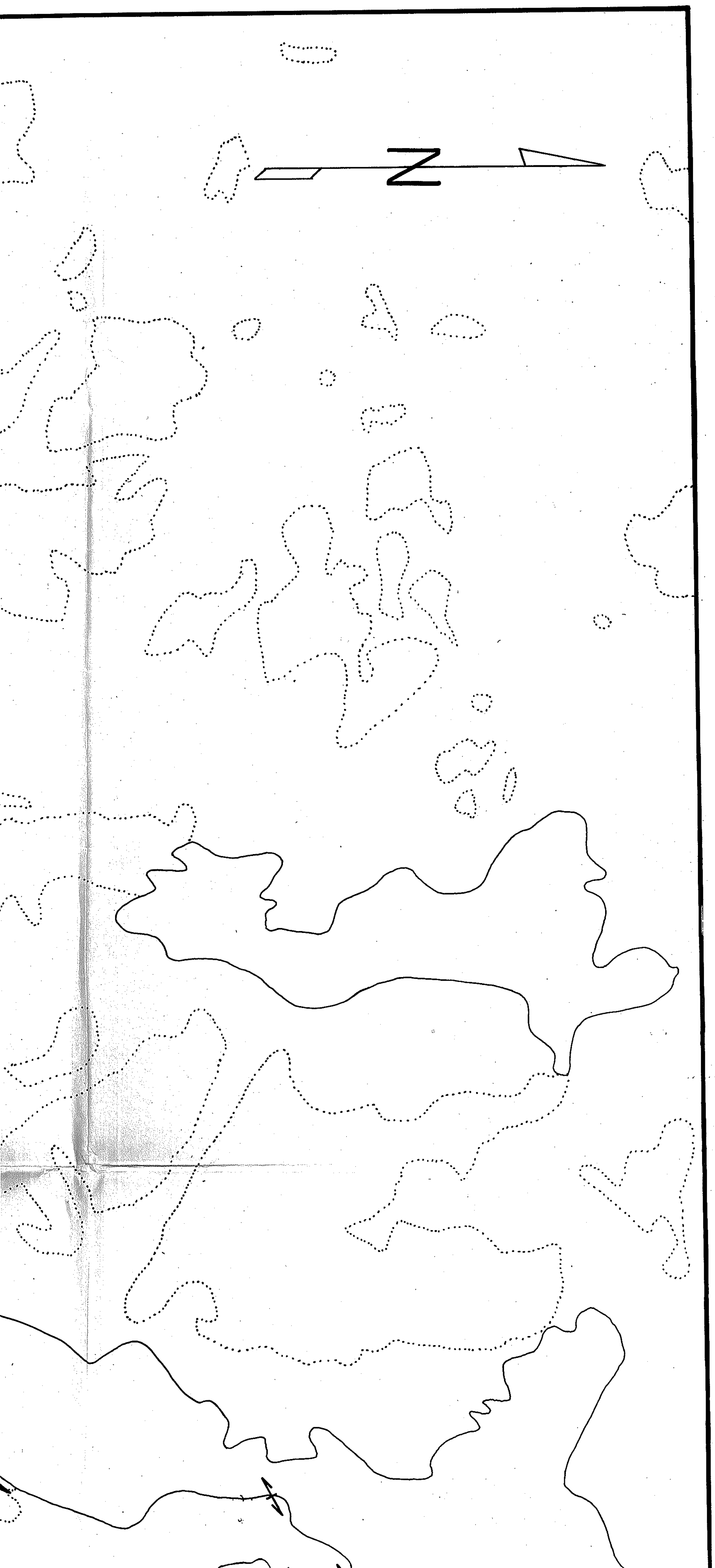
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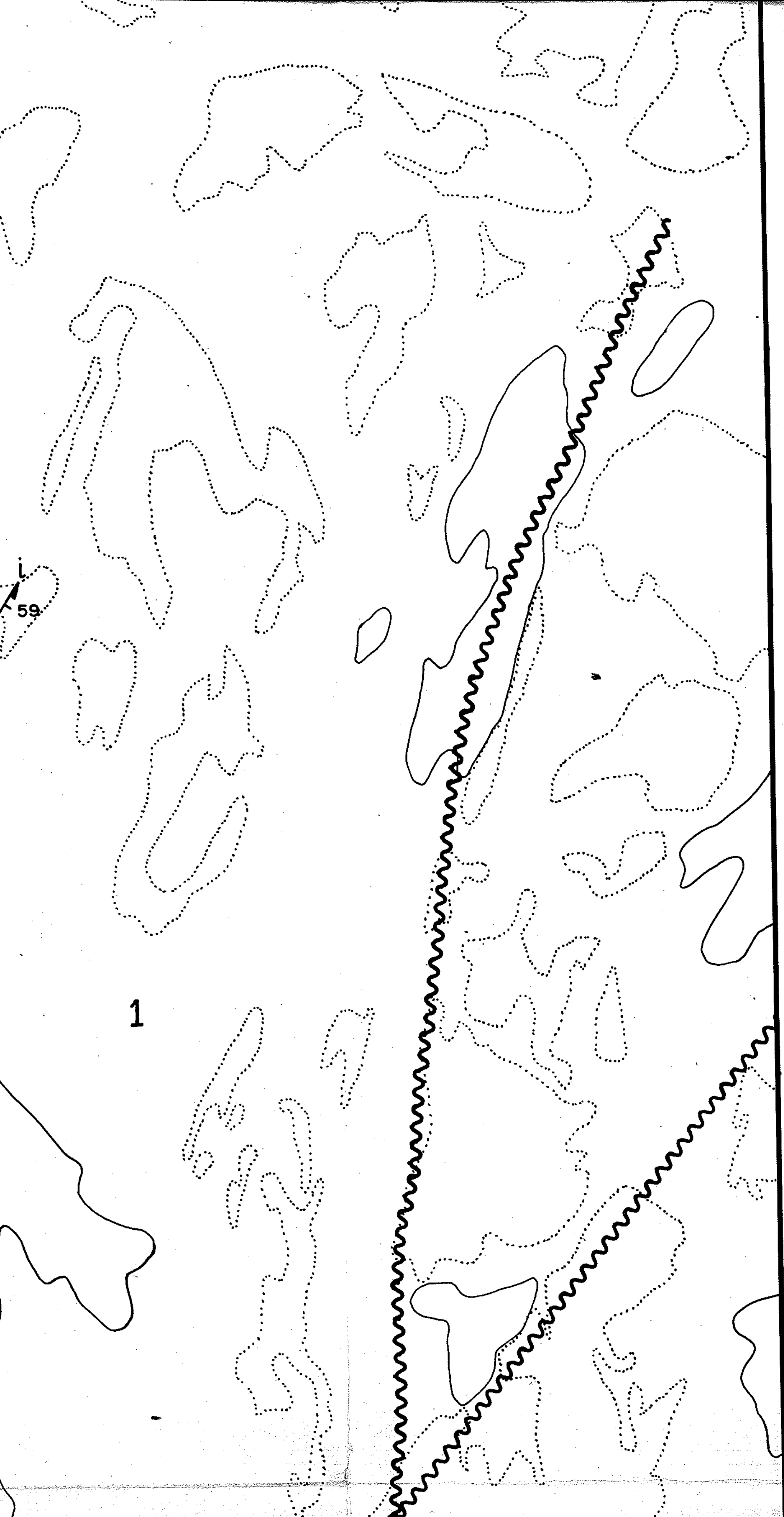

ARCHEAN

6 Quartz monzonite , grani

SICKLE GROUP

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4 Metatexite

3 Meta - arkose - gneiss

2 Amphibolite

WASEKWAN GROUP

1 Hybrid gneiss and mig
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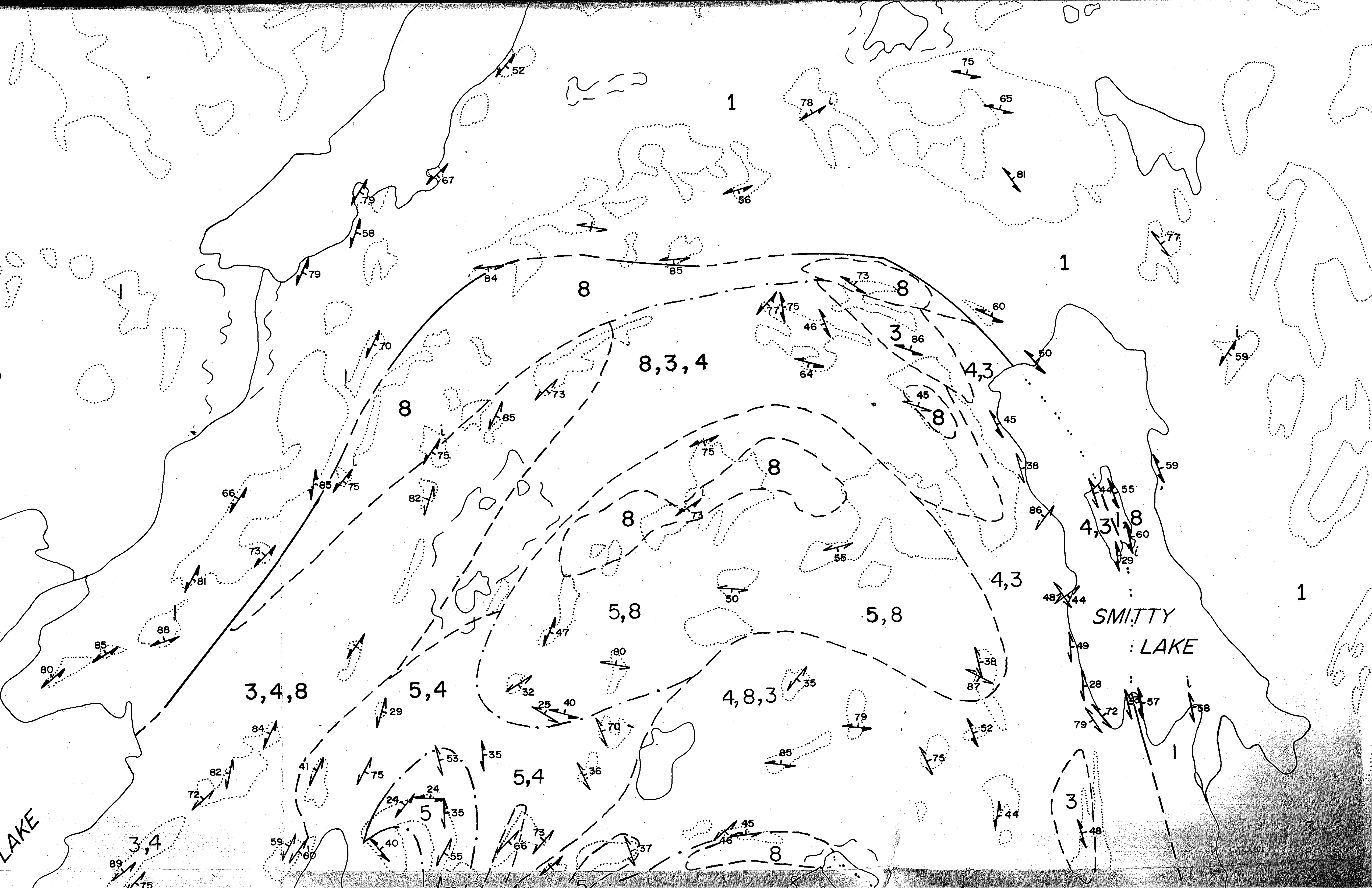

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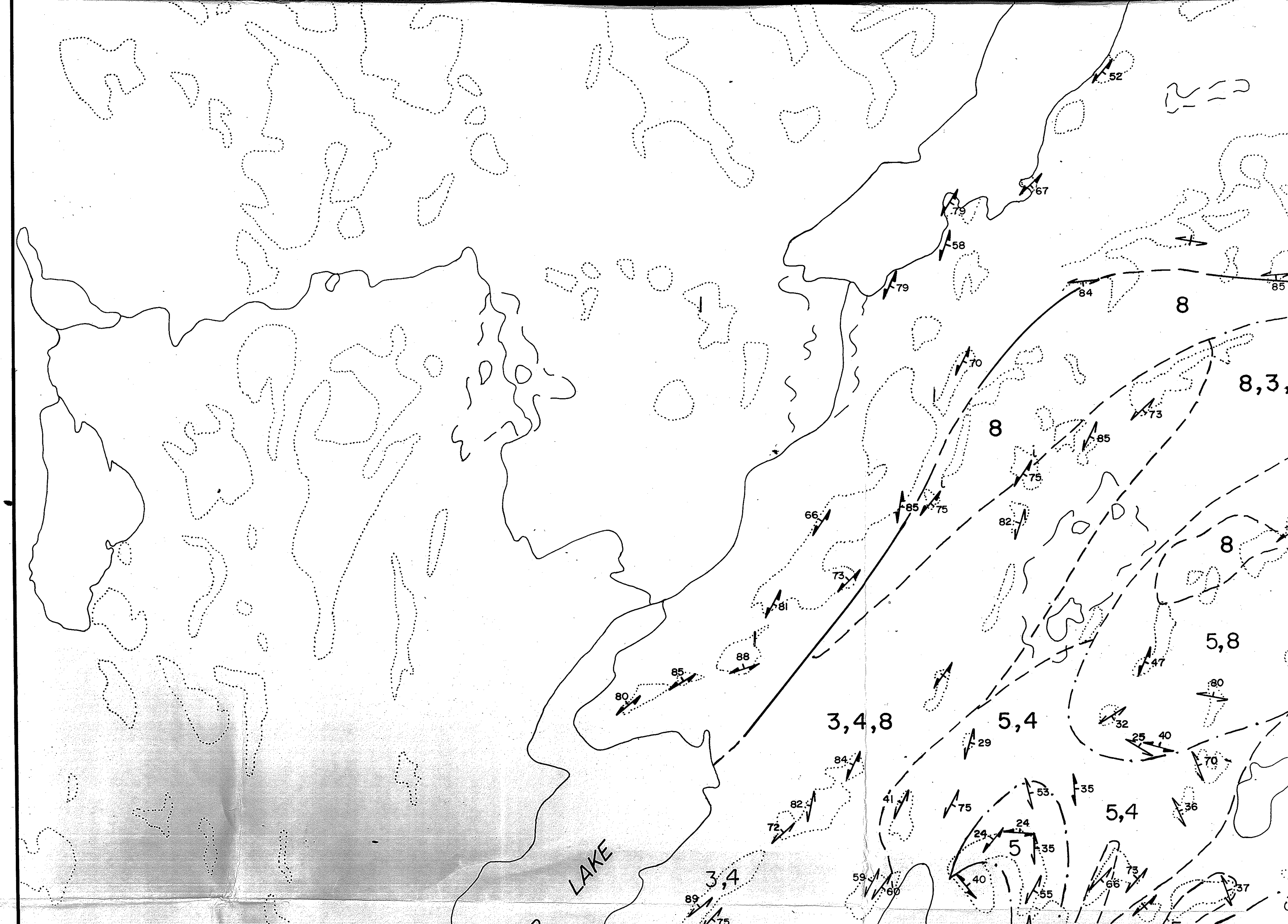
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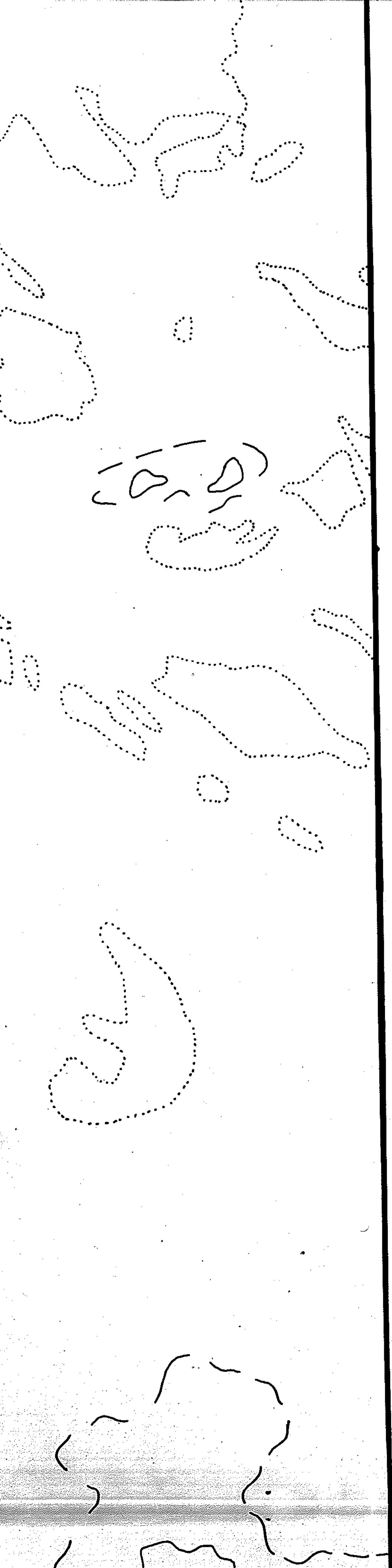


SYMBOLS

Geological boundary (defined, approx, assumed)

Gradational contact.

Schistosity

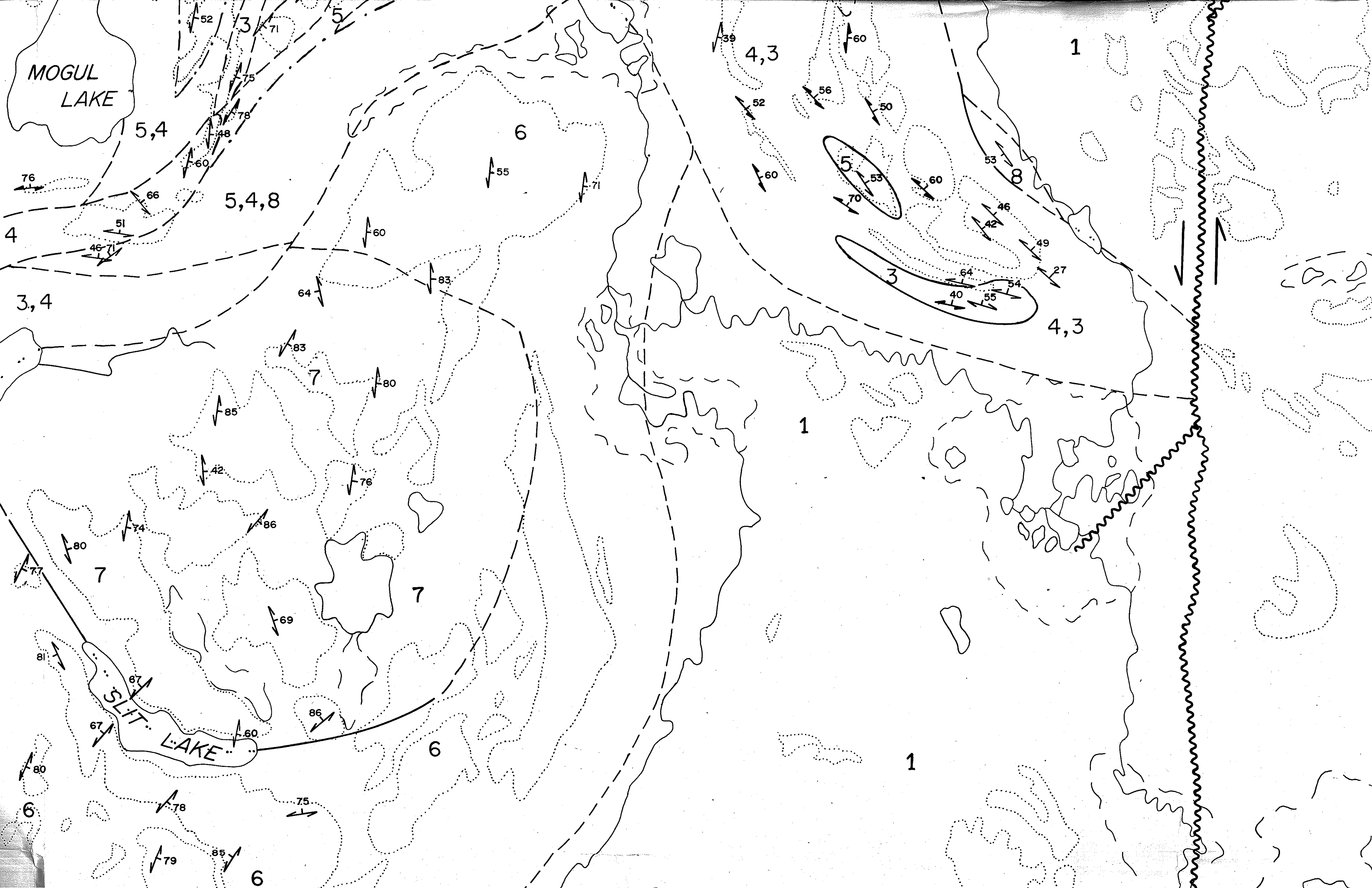
Gneissosity

Bedding

Outcrop

Faults

Powerline



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