THE STRATIGRAPHY, STRUCTURE AND METAMORPHISM
OF
ARCHEAN ROCKS
AT
RAINY LAKE, ONTARIO

By

© Knud Howard Poulsen

Submitted in partial fulfillment
of the requirements for the degree of

Master of Science

Faculty of Science
Lakehead University
Thunder Bay, Ontario, Canada

May 31, 1980

ABSTRACT

The rocks of the Rainy Lake area have been deformed during three distinctive episodes. Minor structures provide the geometry which characterizes each episode. The youngest structures include regional faults, a crenulation cleavage, kink bands and minor F_3 folds. These D_3 structures are superimposed on structures of the D_2 episode. These include dominant F_2 folds having axes lying in a penetrative cleavage which parallels the axial surfaces of the folds. Some F_2 folds have a downward structural facing which is evidence that the stratigraphic succession at Rainy Lake is overturned at a regional scale. It is proposed that this inversion took place during a D_1 deformation by the formation of large F_1 fold nappes. Minor D_1 structures are difficult to document.

The rocks of the region were metamorphosed simultaneously with much of the deformation. The distribution of index minerals defines the boundaries of the biotite, staurolite-cordierite and sillimanite-muscovite zones. The non-parallel distribution of metamorphic minerals may be explained by the non-parallelism of isotherms and isobars during medium grade metamorphism.

These new data support the view that the Coutchiching biotite schists at Rainy Lake are stratigraphically younger than metavolcanic rocks of the Keewatin Group although they presently underlie the Keewatin structurally. This observation resolves a part of the historically important "Seine-Coutchiching problem".

ACKNOWLEDGEMENTS

Dr. M. M. Kehlenbeck and Dr. G. J. Borradaile supervised this thesis. Throughout the study they provided field assistance, financial support, patient encouragement and, most importantly, a high level of scientific leadership. I am particularly grateful for their efforts.

Dr. J. M. Franklin, Geological Survey of Canada, visited the Rainy Lake area with the author in 1976 and jointly recognized the potential structural complexity. His continued encouragement to pursue the study is greatly appreciated.

The thesis has benefited from a high level of technical support which was provided by a large number of individuals. Sam Spivak drafted several diagrams and provided willing assistance with drafting problems. Bill McIlwaine and Ron Bennet prepared thin and polished sections of high quality. Dr. T. Griffith and staff cheerfully provided x-ray data and volatile analyses. Warren Clendinning, Tom Griffith and Martin Griffith provided able field assistance. Henrietta Shegelski typed the thesis in an exceptionally competent fashion. To all of these people sincere thanks are due.

Throughout the study, the author made considerable use of Ontario Division of Mines Maps 2278 and 2279 by F.R. Harris. While some of the observations presented in this thesis conflict with those shown on these maps, their importance as a starting point for further work can in no way be minimized.

Valuable discussions were held with a large number of geologists at Lakehead University and at other institutions. The thesis has benefited from these exchanges.

Dr. R. W. Ojakangas, University of Minnesota at Duluth, served as external examiner for this thesis. His constructive comments are greatly appreciated.

Finally I wish to acknowledge the quiet encouragement and support of Gwen and Jobina. They sacrificed many evenings and mealtimes so that this thesis could be written.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Figures - cont'd

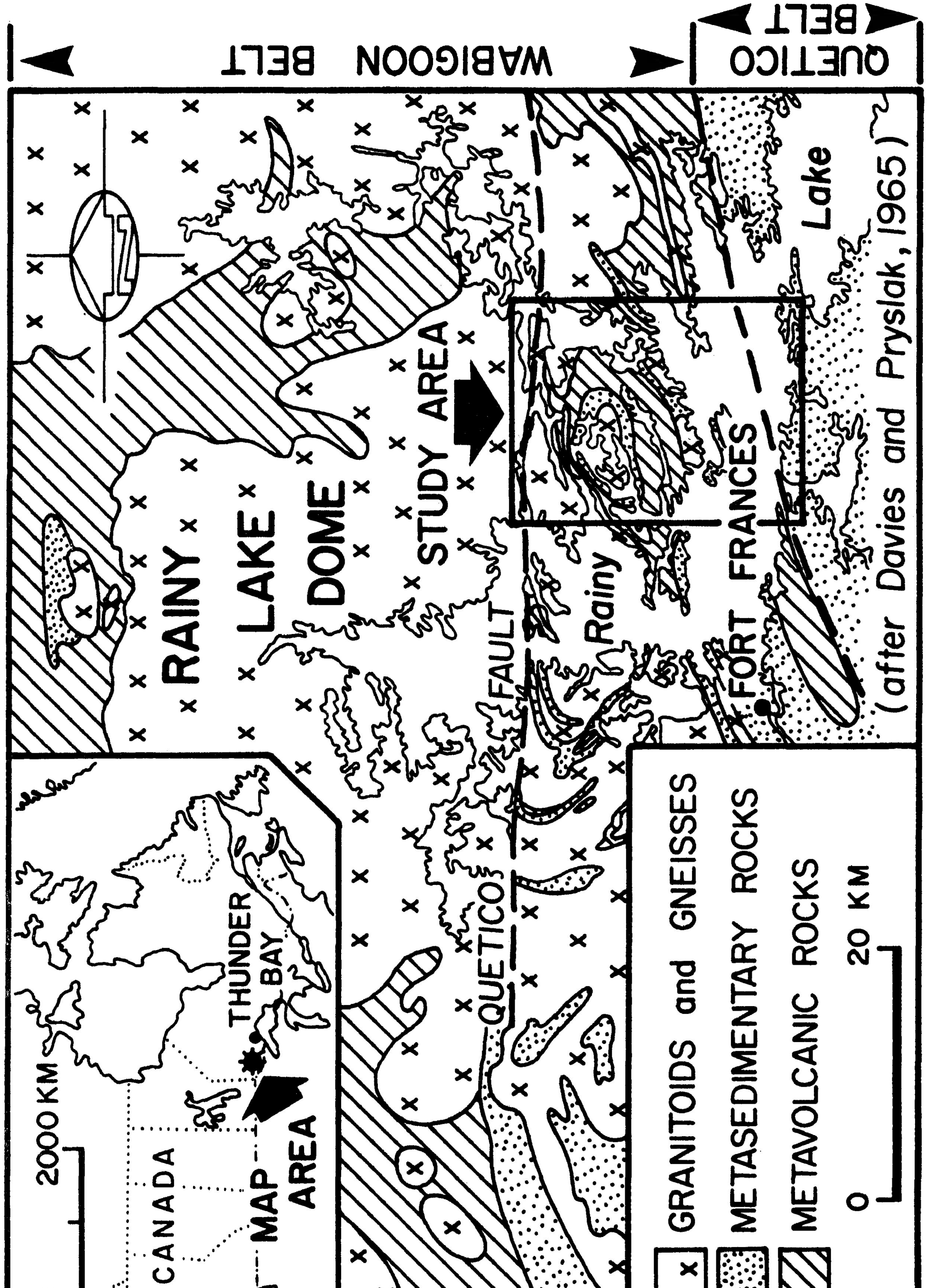
List of Plates

INTRODUCTION

The geology of the Archean rocks at Rainy Lake, Ontario has been the subject of nearly continuous study for more than 90 years. As such, the Rainy Lake region represents one of the first Canadian Archean terrains to be geologically documented. The stratigraphic sequence of lithologic units and the accompanying nomenclature, proposed for the Rainy Lake area, has been applied extensively beyond the boundaries of this region. Although recent studies have de-emphasized the practice of widespread stratigraphic correlation, the terms Coutchiching, Seine, Algoman and Laurentian still appear occasionally in the literature.

Rainy Lake is located 200 kilometers northwest of Lake Superior and includes the international boundary between Canada and the U.S.A. Archean rocks underlie most of the area and form part of the Superior structural province of the Canadian Shield. More specifically, the region encompasses portions of two structural subprovinces (Stockwell, 1970): the Wabigoon volcano-plutonic belt and the Quetico gneiss belt (Fig. 1). This study reviews the now classical stratigraphic relationships at Rainy Lake and attempts to re-evaluate them in terms of new structural and metamorphic data.

Figure 1 - Regional geological map of the Rainy Lake area. The study area includes the boundary between the Quetico and Wabigoon subprovinces as well as the Quetico Fault.


WABIGOON BELT
QUETICO BELT
RAINY LAKE DOME
STUDY AREA
QUETICO FAULT
Rainy Lake
FORT FRANCES
(after Davies and Pryslak, 1965)
N
0 2000 KM
CANADA
THUNDER BAY
MAP AREA
GRANITOIDS and GNEISSES
METASEDIMENTARY ROCKS
METAVOLCANIC ROCKS
0 20 KM

PREVIOUS STUDIES

An extensive body of literature has evolved from the activities of previous workers who have applied the principles and techniques of stratigraphy, petrology, structural geology and geochronology at Rainy Lake.

STRATIGRAPHY

The stratigraphic nomenclature for the rocks in the region was established by A.C. Lawson (1913) following a revision of his earlier mapping (Lawson, 1887). He recognized three lithostratigraphic groups:

i) the Coutchiching Group consisting of thin bedded biotite schists of sedimentary origin

ii) the Keewatin Group consisting of chlorite and amphibole schists of volcanic origin

iii) the Seine Group consisting of metasedimentary rocks which are dominantly conglomeratic.

In addition, Lawson recognized three classes of plutonic rock:

i) extensive tabular intrusions, ranging in composition from gabbro to anorthosite, cutting the Keewatin strata

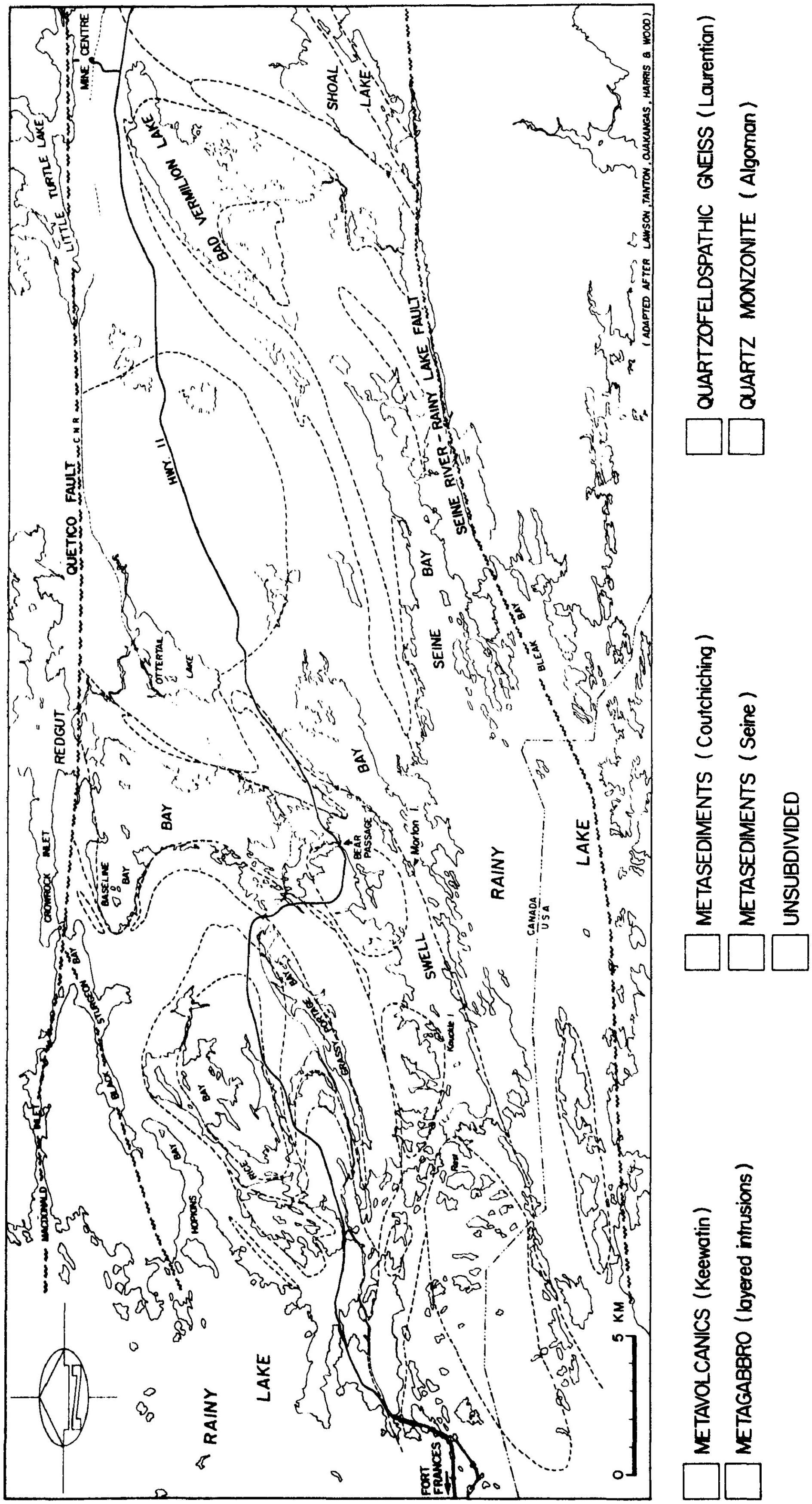
ii) Laurentian gneissic sills of trondhjemite to to granodiorite composition occurring in the cores of domal structures

iii) Algoman plutons composed of massive quartz monzonite and granodiorite.

Table 1

Lawson (1913)	Grout (1925)	Harris (1974)
Algoman Granite	Algoman Granite	Felsic and Intermediate Intrusive Rocks
--(intrusive contact)---	------(intrusive contact)------	------(contact indeterminate)-----
		Early Mafic Intrusions
		(intrusive contact)
Seine Group	Huronian Metasediments	Metasediments
----(unconformity)------	--------(unconformity)--------	----------(unconformity)----------
Laurentian Granite	Laurentian Granite Gneiss	
(intrusive contact)	(intrusive contact)	
----Keewatin Group------	----Archean Greenschist-------	--Metavolcanics & Metasediments--
Coutchiching Group		Lower Metasediments

Figure 2 - Map of A.C. Lawson (1913) with minor revision. The structures at Rice Bay, Bear Passage and Bad Vermillion Lake are antiformal. See text for discussion of stratigraphic order.



RAINY
LAKE
FORT FRANCES
0
5 KM
MACDONALD INLET
BLACK
STURGEON BAY
CROWROCK INLET
REDGUT
QUETICO FAULT
C N R
LITTLE TURTLE LAKE
MINE CENTRE
HOPKINS
BAY
RICE BAY
GRASSY PORTAGE BAY
BASE LINE BAY
BAY
BEAR PASSAGE
Morton I.
Knuckle I.
OTTERTAIL LAKE
HWY 11
BAD VERMILION LAKE
SHOAL LAKE
SWELL BAY
SEINE BAY
SEINE BAY
SEINE RIVER - RAINY LAKE FAULT
BLEAK BAY
RAINY LAKE
CANADA
U S A
(ADAPTED AFTER LAWSON, TANTON, OJAKANGAS, HARRIS & WOOD)
METAVOLCANICS (Keewatin)
METAGABBRO (layered intrusions)
METASEDIMENTS (Coutchiching)
METASEDIMENTS (Seine)
UNSUBDIVIDED
QUARTZOFELDSPATHIC GNEISS (Laurentian)
QUARTZ MONZONITE (Algoman)

Figure 2 illustrates the distribution of these units. Lawson, assuming that structural and stratigraphic succession were equivalent, used the classical concepts of structural superposition and cross-cutting relationships to establish chronological order for the units. Table 1 summarizes his interpretation.

Since Lawson, a number of geologists have commented on the stratigraphic relationships among the rocks of the area. Grout (1925) recorded the sense of younging of metasedimentary rocks using outcrops in which grain size gradations and crossbedding are preserved. Based on these data at Morton Island (Fig. 2) he concluded that the rocks of the Coutchiching Group are younger than rocks of the Keewatin Group. He argued that since the Seine and Coutchiching Groups are both post-Keewatin metasedimentary successions, they therefore should be combined into a single group which he called Huronian (Table 1). Contemporaneously, Bruce (1925) and Tanton (1927) reaffirmed that the Keewatin is structurally above the Coutchiching at Rice Bay and Bear Passage (Fig. 2). Subsequent studies (Bruce, 1927; Merrit, 1934; Pettijohn, 1937) extended the investigation beyond the Rainy Lake region with the addition of further ambiguities. The stratigraphic controversy became known as the Seine-Coutchiching problem (Merritt, 1934).

Goldich et al. (1961) refocused attention on the problem and its particular importance for the Rainy Lake region. This and a number of other studies (Alt, 1958;

Peterman et al., 1972; Ojakangas, 1972; Harris, 1974) retained much of the original stratigraphic interpretation of Lawson. Harris (1974) abandoned Lawson's nomenclature but did reconsider the relationships between the litho-stratigraphic units (Table 1). Harris (1974, p. 9) observed that at Rice Bay, metavolcanic (Keewatin) strata which host a band of iron formation are structurally underlain by metasedimentary (Coutchiching) strata, while overlain by (Seine) conglomerate containing clasts of iron formation. Presumably based on the assumption that unconformable superposition of the conglomerate across both the Keewatin and Coutchiching Groups is not likely, he concluded that: "in the Rice Bay area, it can be definitely stated that metasediments are structurally and stratigraphically over-lain by metavolcanics". Further, he reconfirmed Grout's observations of the younging relationships at Morton Island. Harris recognized, however, (1974, p. 10) that at nearby Sandpoint Island "the metasediments are tightly folded" and concluded that with respect to the Keewatin-Coutchiching contact a stratigraphic interpretation ..."is not possible until more data on the graded beds close to this contact are available." Thus, at Rainy Lake, workers have relied on either structural superposition or younging criteria near contacts to interpret the stratigraphy.

PETROLOGY

Igneous Rocks

Previous studies in igneous, sedimentary and metamorphic petrology have generally been incorporated into broader stratigraphic investigations. To date, particular attention has been paid to the nature of the plutonic rocks of the region. Cram (1932) studied the Algoman Rest Island granite (Fig. 2) and recognized a melanocratic border phase which he classified as shonkinite. Frye (1959) contrasted the petrographic details of the Algoman and Laurential granites. He found the former to be commonly quartz monzonites and granodiorites while the latter tend to be tonalites and trondhjemites. Geochemical studies (Goldich and Peterman, 1978) have emphasized this contrasting nature. The origin of magmas from which these rocks may have crystallized has variably been assigned to models involving partial melting of eclogite, amphibolite or greywacke.

Sedimentary Rocks

The history of sedimentation for rocks of the Seine and Coutchiching Groups has only recently been studied. Wood (1979) described the Seine Group as clast supported conglomerate, pebbly sandstone and crossbedded sandstone. The Coutchiching Group is characterized by massive sandstones and graded sandstones displaying Bouma cycles (see Fig. 6). Wood interpreted the Seine Group as an alluvial fan deposit which is a lateral equivalent of the Coutchiching Group, which he considers a submarine fan deposit. Ojakangas (1972) interpreted the presence of crossbedding in the Seine Group to reflect high velocity currents and proposed a fluvial origin for these rocks. He, too, recognized the turbidite association of the Coutchiching but did not directly link the two environments of sedimentation.

Metamorphic Rocks

The metamorphic history of the region has only been documented on a local scale. Lawson (1913) recognized contact metamorphic aureoles which developed in the biotite schists near the margins of the Algoman plutons. He referred to these rocks as "knotty schists" and identified cordierite porphyroblasts. Peterman (1959) contrasted the metamorphic mineral assemblages in the pelitic rocks at the western end of Rice Bay with those at Sandpoint Island (Fig. 2). At the former locality the rocks were assigned to the almandine-amphibolite facies while at the latter, greenschist facies assemblages were recognized. Harris (1974) recorded the presence of garnet and staurolite in metapelites from the eastern margin of the Rice Bay dome (Fig. 2) but did not comment on the distribution of these minerals.

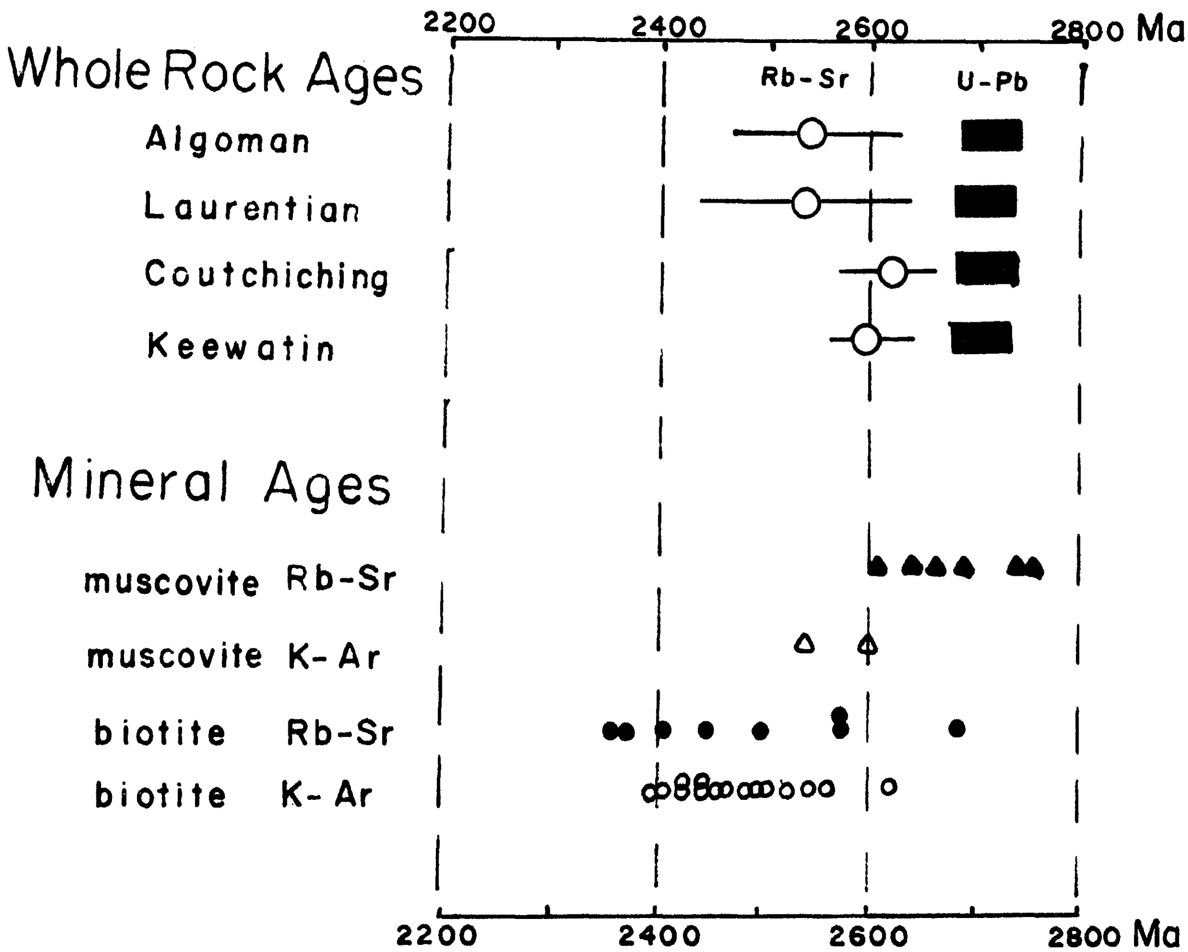
STRUCTURE

Comprehensive structural studies in the Rainy Lake area have not been documented to date. Lawson (1913) outlined major antiforms and synforms which he interpreted as anticlines and synclines respectively. He speculated that two tectonic events, the Laurentian and the Algoman, were responsible for the structures but did not relate individual structural elements directly to either of them. Bruce (1925) confirmed Lawson's interpretation of an antiformal structure at Bear Passage (Fig. 2). Grout et al. (1951) based the presence of folds near Sandpoint Island on observed reversals in younging direction. In explaining the general distribution of lithologies, Davies (1973) suggested three episodes of folding. He proposed that major domal structures resulted from the interference of north-south trending and east-west trending folds. He also mapped the Quetico Fault and the Rainy Lake-Seine River Fault (Fig. 2). Ojakangas (1972) emphasized that this fault significantly complicates the stratigraphic relationships of the area. Harris (1974) proposed two periods of folding, one resulting in folds with axial surfaces striking east-northeast and the other resulting in domal structures in response to the emplacement of the Algoman granites. Hsu (1971) studied variations in the shape and orientation of deformed pebbles in the Seine conglomerate and concluded that the bulk strain ellipsoid for these rocks is of the flattening type.

GEOCHRONOLOGY

The rocks of the Rainy Lake region have been the subject of intensive geochronological study. Goldich et al. (1961) reported biotite ages from the Rice Bay area. This pioneer study was followed by a number of investigations

Figure 3 - Summary of geochronological data from the Rainy Lake area (after Peterman et al., 1972). Ranges of Rb-Sr and U-Pb zircon ages are shown. For mineral ages, each plotted symbol represents a single determination.


2200
2400
2600
2800 Ma
Whole Rock Ages
Rb-Sr
U-Pb
Algoman
Laurentian
Coutchiching
Keewatin
Mineral Ages
muscovite Rb-Sr
muscovite K-Ar
biotite Rb-Sr
biotite K-Ar
2200
2400
2600
2800 Ma

employing potassium-argon, rubidium-strontium and uranium-lead radiometric dating methods (Tilton and Grunenfelder, 1968; Hart and Davis, 1969; Peterman et al., 1972). Figure 3 summarizes the results of these studies. These data have failed to completely clarify the stratigraphic problems because of a lack of correlation between ages determined by different methods. However, it is clear that most of the igneous and sedimentary lithologies yield zircon ages of approximately 2700 Ma. These ages probably reflect a magmatic event of short duration. The extended radiometric history, as deduced by the other methods, probably relates to the deformation, metamorphism and uplift of the rocks of the region. Hanson (1968) obtained a K-Ar age of 2100 Ma. from a diabase dyke which clearly postdates these tectonic events.

THIS STUDY

The foregoing literature review reveals that certain gaps exist in the published information for the rocks at Rainy Lake. These include:

i) The relative age of the Keewatin metavolcanic rocks and the Coutchiching and Seine metasedimentary rocks

ii) The relationships of minor geological structures to the major structures and to the deformational history of the region

iii) The distribution of metamorphic mineral assemblages and their relationship to the conditions of metamorphism and deformation.

This study presents new data in these critical areas.

After a preliminary field examination of the region in 1976, it was concluded that the Rice Bay-Bear Passage-Sandpoint Island area (Fig. 2) would prove to be the most promising for detailed study. In this area, each of the major lithostratigraphic groups and major plutonic types are exposed. Most of the historically important localities are found within this area together with some regional fold closures and domes. In addition, the greatest variation in metamorphic grade can be demonstrated here and the largest number of samples chosen for radiometric dating were collected from this area. In short, the rocks at Rice Bay, Bear Passage and Sandpoint Island are excellent representatives reflecting the regional geology.

Approximately eight weeks were devoted to field study within the project area. Exposures representative of the major lithotypes were mapped at a reconnaisance scale. Detailed mapping was carried out in important subareas in which critical structural, metamorphic and stratigraphic relationships are well exposed. In total, over four hundred outcrops were examined and one hundred and twenty specimens were collected. Laboratory study included examination and description of thin sections, whole rock chemical analysis, interpretation of x-ray diffraction data on rock and mineral powders, and graphical analysis of structural and metamorphic data. The documentation and interpretation of these results and their bearing on the stratigraphy, structure and metamorphism in the Rainy Lake region forms the main body of this thesis.

STRATIGRAPHY

In this thesis the emphasis is directed toward the structure and metamorphism of the rocks. Description of the lithostratigraphic units are therefore of a general nature. Table 2 lists the formations, their characteristics and their age relationships. Figure 4 is a generalized geological map of the study area and shows the distribution of these units. Exposures of specific importance are also represented in this figure as are outcrops from which samples were analysed chemically. Discussion of analytical methods, precision and accuracy is contained in Appendix A.

METABASITES

The metabasic rocks, the Keewatin of Lawson, are predominantly amphibolites. The preservation of pillow structures and angular clastic textures in these rocks is strong evidence for their volcanic origin.

Two distinct types of metabasite are recognized. The first of these includes black to dark green massive metabasites in which pillowed units are common (locality 1, Fig. 4). These rocks have been metamorphosed at medium grade and typically contain plagioclase, hornblende, quartz and sphene. Equivalent rocks metamorphosed at lower grade tend to be phyllitic, are more green in colour and contain plagioclase, hornblende and quartz with variable amounts of chlorite, epidote and calcite. One mappable metavolcanic unit contains abundant actinolite with some quartz, chlorite

Figure 4 - Location of outcrops examined during this study. Circled numbers refer to localities where typical features may be observed and are referred to in the text. Uncircled numbers give the locations for chemically analysed samples whose numbers are prefexed by "KHP-". Geological contacts are also shown.

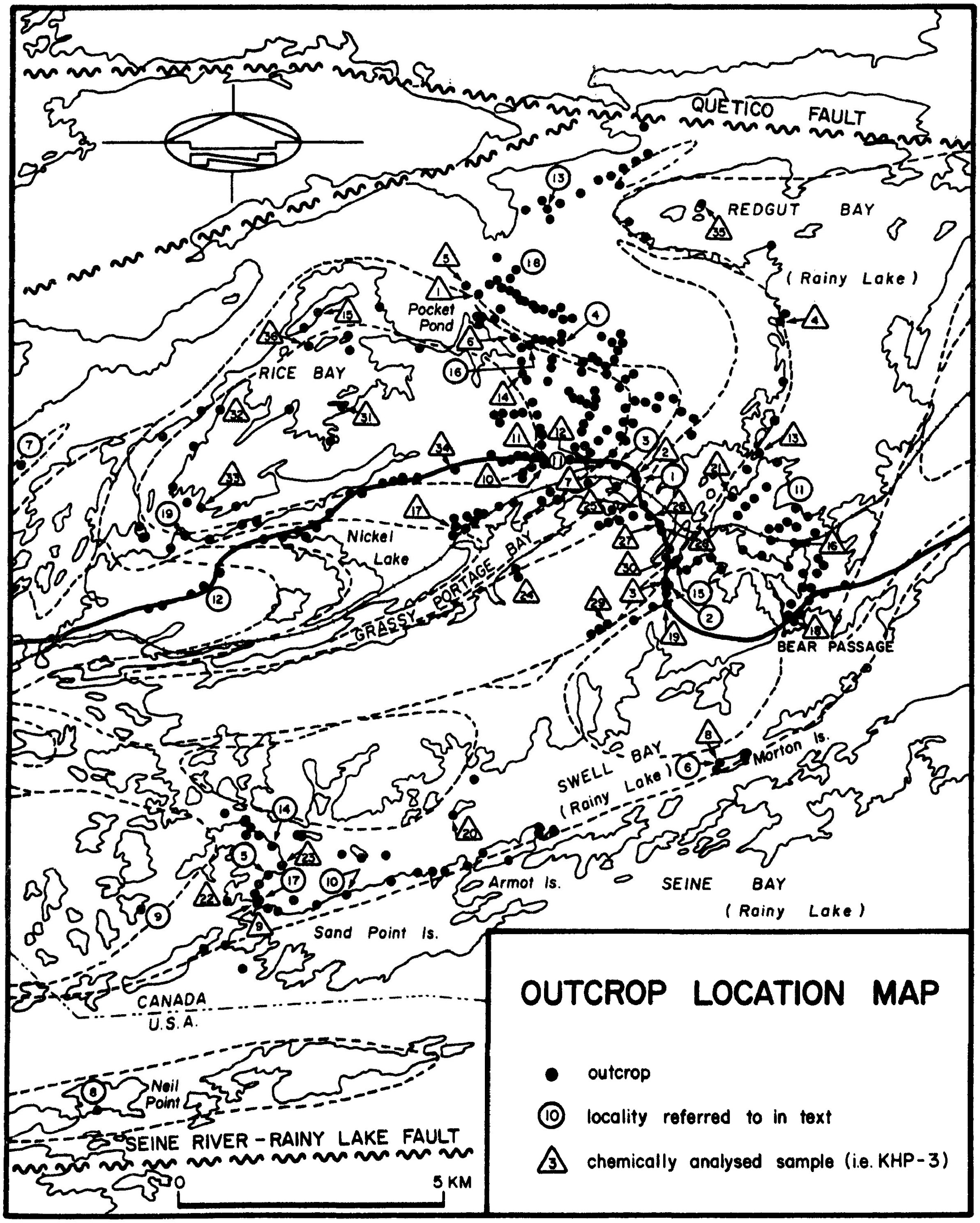

QUETICO FAULT
REDGUT BAY
(Rainy Lake)
Pocket Pond
RICE BAY
Nickel Lake
GRASSY PORTAGE BAY
BEAR PASSAGE
SWELL BAY
(Rainy Lake)
Morton Is.
Armot Is.
SEINE BAY
(Rainy Lake)
Sand Point Is.
CANADA
U.S.A.
Neil Point
SEINE RIVER - RAINY LAKE FAULT
0
5 KM
OUTCROP LOCATION MAP
outcrop
locality referred to in text
chemically analysed sample (i.e. KHP-3)

Table 2

Age	Formation* Name	Lithology
ARCHEAN	ALGOMAN GRANITES	quartz monzonite, granodiorite; minor quartz diorite
	inferred intrusive contact	
	SEINE GROUP**	conglomerate, crossbedded arenites; minor greenstone
	unconformity	
	LAURENTIAN GRANITE	paragneiss***; granodiorite; trondhjemite; tonalite
	intrusive contact (locally)	
	HORNBLENDE GABBRO	layered basic intrusions; mainly gabbro and leucogabbro; some melagabbro, anorthosite, and oxide-phosphate cumulates
	intrusive contact	
	COUTCHICHING GROUP**	metasedimentary schists; some phyllite
	KEEWATIN GROUP**	metabasites; pillowed and massive flows, fragmental ultrabasic rocks, phyllite greenstones; intercalated iron formation

* informal usage

** Group used formally to replace the term series

***Stratigraphic position uncertain

and minor biotite. This actinolite schist horizon may be traced along strike for at least 5 km near the southern margin of the Grassy Portage basic intrusion (locality 2, Fig. 4).

A second type of metabasite includes an ultrabasic fragmental rock which outcrops near the eastern margin of the Rice Bay dome (locality 3, Fig. 4). Hand specimens of this friable unit are pale to bright green in colour, strongly magnetic and commonly contain angular fragments up to 2 cm in diameter. The fragments and matrix are compositionally similar and contain a pale blue amphibole, and abundant magnetite with variable amounts of chlorite, talc, quartz and carbonate. To date, no field evidence has been found to support either a volcanic (Gélinas et al., 1977) or sedimentary (Stamatelopoulou-Seymour and Francis, 1979) origin for these clastic rocks. Harris (1974) referred to these rocks as "magnetic lapilli tuff" and mapped their extent to the north of Grassy Portage Bay (Fig. 4). In the present study this unit has been traced for an additional 2.5 km northwest to Pocket Pond (Fig. 4).

Chemical analyses of metabasites are given in Table 3. The two specimens of amphibolite yield compositions which agree closely to those of typical Archean tholeiitic basalts (Condie, 1976). The actinolite schist, though similar in most respects, is higher in magnesia. The garnetiferous metavolcanic rock contains more silica and therefore likely represents an intermediate rock composition.

Table 3

Representative Chemical Analyses

Keewatin Group - Metabasic Rocks

	KHP-1	KHP-2	KHP-3	KHP-4	Archean Tholeiitic Basalts[1]		KHP-5	KHP-6	KHP-7	Ash-Rock[2*]	Ash-Rock[3*]
SiO_2	50.70	49.65	47.30	65.00	51.4	49.7	42.24	41.53	44.24	43.0	43.8
Al_2O_3	16.18	13.14	12.62	10.87	14.8	14.9	5.96	7.19	5.80	6.8	5.5
TiO_2	.81	1.77	.52	.91	1.9	1.0	1.75	1.28	1.38	1.8	1.7
FeO	8.58	13.56	9.24	13.40	8.3	8.8	9.4	8.4	10.2	12.5	19.3**
Fe_2O_3	1.99	2.30	1.55	1.52	2.1	2.6	7.4	8.1	6.5	5.3	
MgO	6.52	5.54	14.04	3.56	6.7	6.3	20.64	19.24	24.34	17.4	21.4
CaO	11.32	8.64	9.11	.74	10.7	9.4	7.29	9.05	3.64	10.0	8.6
Na_2O	2.00	3.48	2.22	1.33	2.7	2.1	1.24	1.36	.73	.2	.01
K_2O	.19	.23	.62	.51	.18	.32	.01	.03	.01	.7	.02
P_2O_5	.13	.21	.10	.27	-	-	.12	.10	.15	.09	.14
MnO	.20	.23	.18	.27	-	-	.31	.25	.15	nd.	nd.
CO_2	.11	.03	.33	.03	-	-	-	.18	-	.06	.06
H_2O^T	1.26	1.35	2.52	1.80	-	-	3.51	3.06	2.43	3.0	3.0

KHP-1: Sample 78-Po-03 amphibolite
KHP-2: Sample 78-Po-19 pillowed amphibolite
KHP-3: Sample 78-Po-21 actinolite schist
KHP-4: Sample 78-Po-44 garnetiferous metabasite
KHP-5: Sample 78-Po-04 magnetic ultrabasic
KHP-6: Sample 78-Po-08 magnetic ultrabasic
KHP-7: Sample 78-Po-073 magnetic ultrabasic

1 from Condie (1976, p. 399)

2* Joliffe (1971) MacRae (pers. comm.)

3* renormalized to equal volatile content (see text)

** total iron

Chemically the ultrabasic unit is unique among the rocks in the area. Typical samples yield greater than 20 per cent MgO, 5 to 7 per cent Al_2O_3 and approximately 8 per cent CaO. These are chemical characteristics typical of komatiites (Jensen, 1976). It is interesting to note that rocks of similar composition have been described (Joliffe, 1971) from the Ashrock Formation of the Steeprock Group near Atikokan, Ontario. At this locality, some 100 km east of Rainy Lake, the fragmental rocks occupy a similar stratigraphic position to that described in the present study area. Appendix B lists average analyses from the ultrabasic unit at Atikokan (Joliffe, 1971; MacRae, pers. comm.). These data have been recalculated (Table 3) to equate volatile levels with those observed for the ultrabasics at Rice Bay. This is necessary because the low grade Steeprock ultrabasic contains high concentrations of calcite and dolomite. Decarbonation reactions to form equivalent medium grade rocks such as those at Rice Bay would result in the removal of CO_2 from an analysis.

Bedded iron formation is intercalated with the metabasites. Near Pocket Pond (locality 4, Fig. 4) a diamond drill hole normal to layering intersected one of these iron formation horizons. The core contains a section composed of 30 m of carbonaceous, pyritiferous shale, banded magnetite iron formation and a carbonate iron formation containing dolomite, epidote and garnet.

METASEDIMENTARY SCHISTS

Exposures of biotite schists, the Coutchiching of Lawson, are exposed as an annular zone around the Rice Bay dome, in a belt parallel to Swell Bay extending through Sandpoint Island and Bear Passage, and in the area south of the Rainy Lake-Seine River Fault (Fig. 4).

The sedimentary origin of the schists is evidenced by the preservation of features such as bedding, graded bedding, and shale rip-ups (localities 5 and 6, Fig. 4). Detrital quartz and plagioclase have also been identified in the coarse fractions of beds. Rock fragments are rare in these rocks. The effects of metamorphism is notable north of Swell Bay. Biotite schists here are coarsely crystalline and contain abundant quartz veins. Porphyroblasts constitute up to 20 per cent of the rocks and tend to be concentrated in the pelitic portions of individual beds.

Table 4 presents the results of bulk chemical analyses of metasedimentary schists. With the exception of two samples from the Rice Bay area, KHP-10 and 11, the chemical compositions are remarkably similar considering that the grade of metamorphism of these rocks is variable. The two deviant compositions are from samples of biotite phyllite which are located near the transitional contact between the Coutchiching and the core zone rocks of the Rice Bay dome. Excluding these two samples, an average composition for the Rainy Lake metasedimentary schists was calculated (Table 4). This calculated composition lies well

Table 4 - Chemical Analyses

Coutchiching Metasedimentary Rocks

	KHP-8	KHP-9	KHP-10	KHP-11	KHP-12	KHP-13	KHP-14	KHP-15	KHP-16	KHP-17
SiO_2	64.48	62.57	58.10	57.11	60.99	62.05	59.53	62.36	61.28	60.86
Al_2O_3	15.46	16.40	16.54	17.22	16.73	16.88	17.71	16.56	17.01	17.27
TiO_2	.57	.67	.45	.41	.64	.67	.67	.61	.67	.57
FeO	4.76	4.40	4.32	4.40	6.04	5.36	6.60	5.56	5.44	5.54
Fe_2O_3	1.26	2.25	1.66	1.39	1.76	2.59	1.64	1.79	1.65	1.55
MgO	3.13	3.66	6.42	6.35	3.75	3.80	3.48	3.80	3.57	3.56
CaO	2.16	1.85	4.54	4.85	1.32	1.75	2.20	1.13	2.43	1.83
Na_2O	3.95	3.21	4.15	4.28	2.48	2.92	2.60	2.36	3.25	3.12
K_2O	1.06	2.51	2.76	2.82	2.99	2.55	3.64	3.19	2.37	3.34
P_2O_5	.18	.14	.25	.25	.19	.19	.19	.18	.13	.19
MnO	.08	.10	.08	.08	.09	.08	.10	.08	.12	.07
CO_2	.15	.22	.03	-	.11	.11	-	.07	.03	.07
H_2O^t	2.79	1.89	.81	.90	3.06	1.35	1.80	2.70	2.16	2.16

KHP-8: 76-Po-16 "low" grade metasedimentary rock
KHP-9: 79-Po-26 "low" grade metasedimentary rock
KHP-10: Biotite Phyllite
KHP-11: 78-Po-36 Biotite Phyllite
KHP-12: 78-Po-13 staurolite schist
KHP-13: 78-Po-50 staurolite schist
KHP-14: 78-Po-06 sillimanite-muscovite schist
KHP-15: 78-Po-54 Sillimanite-muscovite schist
KHP-16: 78-Po-24 garnet bearing schist
KHP-17: 78-Po-31 andalusite schist

Table 4 (cont'd)

	KHP-18	KHP-19	KHP-20	KHP-21	KHP-22	KHP-23	(1)	(2)	(3)	(4)
SiO_2	61.11	61.32	60.94	60.96	61.09	58.37	61.26	66.3	61.93	58.80
Al_2O_3	17.57	17.20	17.33	17.88	17.14	17.56	17.05	13.3	15.84	19.70
TiO_2	.69	.59	.60	.64	.66	.62	.63	.56	.68	.66
FeO	5.12	5.08	6.00	6.12	5.28	6.00	5.52	4.9	5.95	5.24
Fe_2O_3	1.39	1.46	1.86	1.89	2.20	2.37	1.85	1.0	0.68	1.29
MgO	2.95	3.79	3.86	3.62	3.89	4.06	3.64	3.7	3.23	3.25
CaO	3.24	1.98	2.11	1.12	1.48	2.06	2.10	3.4	2.73	1.35
Na_2O	3.22	3.21	2.54	1.47	1.95	2.34	2.76	2.9	2.99	2.68
K_2O	2.19	1.98	2.54	3.31	2.72	3.48	2.64	2.1	1.94	2.82
P_2O_5	.18	.22	.15	.18	.16	.12	.17		.19	.13
MnO	.11	.08	.09	.07	.10	.08	.09		.19	.08
CO_2	.11	.07	.26	.03	.03	.15	.10		.98	.09
H_2O^t	1.71	2.25	1.80	2.79	3.15	2.70	2.31		2.87	3.68

KHP-18 78-Po-71 cordierite-andalusite schist
KHP-19 78-Po-22 cordierite-andalusite schist
KHP-20 79-Po-41 cordierite schist
KHP-21 79-Po-09 staurolite-andalusite schist
KHP-22 79-Po-28 knotty schist
KHP-23 79-Po-34 knotty schist
(1) average Rainy Lake meta-sedimentary rock (see text)
(2) after Condie (1976)
(3) average greywacke after Pettijohn (1972)
(4) average slate after Pettijohn (1972)

within the ranges published for slates and greywackes from other terrains (Pettijohn, 1972; Condie, 1976).

LAYERED BASIC INTRUSIONS

Tabular intrusions, ranging in composition within a single intrusion from gabbro to anorthosite, are well exposed, particularly at the southeastern margin of the Rice Bay dome. Here the Grassy Portage intrusion is in contact with pillow lavas of the Keewatin Group. Authors who have documented the geology of similar rocks (Windley, 1973; Allard, 1970) have suggested that crystallization occurred while the intrusions were nearly horizontal. As a result, mineral layering and cryptic layering produces an igneous stratigraphy (Windley, 1971) within the intrusion which can be used to determine way-up for the body as a whole at the time of crystallization. Way-up determined in this way is consistent with that determined from the observation of magmatic sedimentation structures within the intrusion studied by Windley (1973). Figure 5a gives a comparison of the stratigraphy of the Grassy Portage intrusion with two other examples from Archean terrains. The column shown for the Grassy Portage intrusion, from bottom to top in the diagram, corresponds to a traverse taken from northwest to southeast across the strike of the body (Fig. 5b). This is likely close to a true section since the dip of mineral layering is everywhere steep.

The gabbros are composed mainly of plagioclase

Table 5 - Chemical Analyses

The Grassy Portage Basic Intrusion

(K.H. Poulsen, analyst)

	KHP-24	KHP-25	KHP-26	KHP-27	KHP-28	KHP-29	KHP-30
SiO_2	45.42	50.48	43.04	46.31	64.06	25.92	50.96
Al_2O_3	12.97	15.54	19.31	24.93	11.41	6.14	14.25
TiO_2	1.93	.37	.14	.51	1.15	2.57	1.98
FeO	15.68	10.12	9.28	5.8	8.56	21.88	11.88
Fe_2O_3	3.07	.01	1.65	1.46	5.16	12.91	2.94
MgO	5.88	8.20	11.06	3.94	.86	16.22	4.49
CaO	9.02	10.43	9.56	11.36	4.85	2.75	7.71
Na_2O	2.02	2.49	2.38	2.85	2.71	.93	3.19
K_2O	.46	.04	.01	.49	.01	.01	.40
P_2O_5	.10	.08	.04	.02	.41	1.57	.43
MnO	.25	.19	.14	.09	.26	.32	.24
CO_2	.07	.51	-	.33	.22	.03	.07
H_2O^t	1.89	1.71	3.42	1.71	.54	4.23	1.26

KHP-24: melagabbro 78-Po-75
KHP-25: gabbro 78-Po-26
KHP-26: gabbro 79-Po-24
KHP-27: leucogabbro 78-Po-28
KHP-28: garnetiferous gabbro 78-Po-29
KHP-29: oxide cumulate ddh 94-145'
KHP-30: gabbro ddh B1:322'

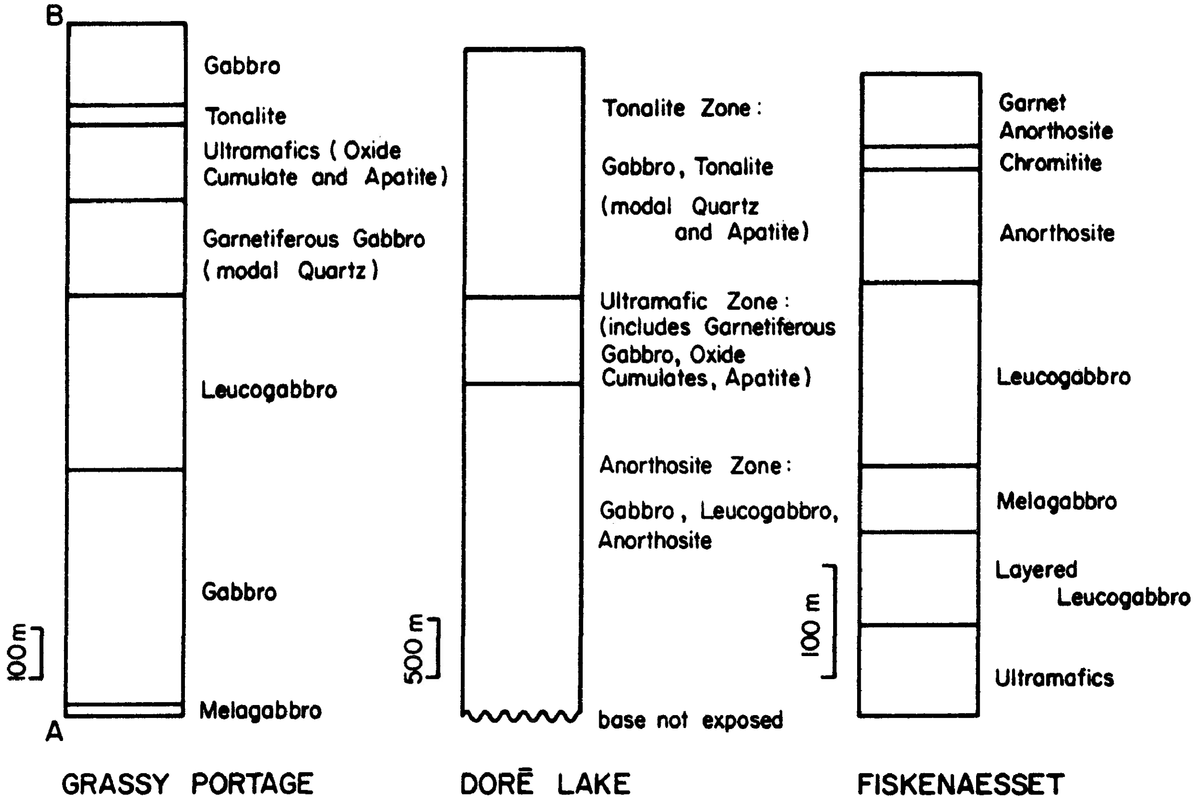
and amphibole. Apatite, oxide minerals, quartz and garnet are common accessories and increase in abundance to the southern margin of the intrusion. Copper and nickel sulphide mineralization may be found in melagabbro along the northern margin of the intrusion. Biotite is present locally in the gabbros, and commonly occurs with garnet or sulphide minerals in ductile shear zones.

In Table 5 chemical analyses of a suite of samples from the intrusion are presented. In the table, analyses are arranged from left to right to reflect the locations of samples taken along a north to south traverse across the intrusion. Al_2O_3, which indicates plagioclase abundance, shows an initial gradual increase followed by an abrupt decrease with distance from the northern margin. P_2O_5 and TiO_2 values increase towards the southern contact.

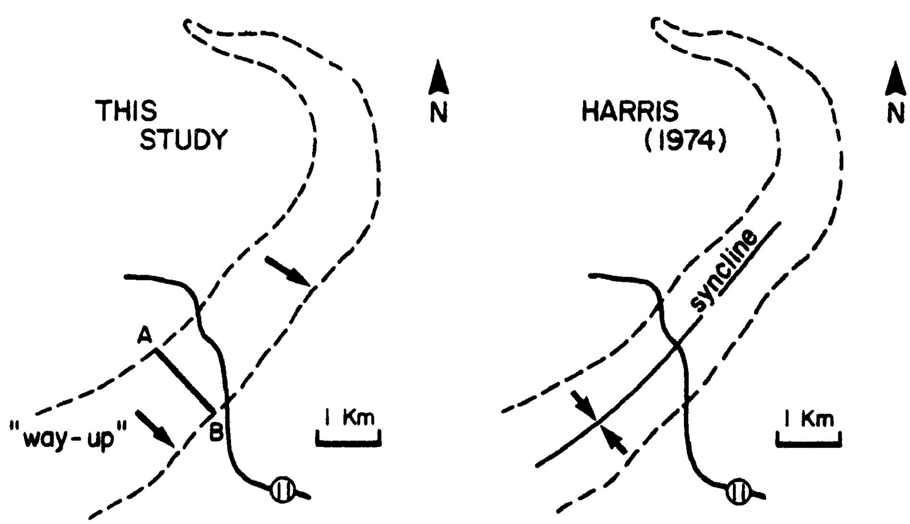
The petrographic and chemical variations demonstrated above emphasize the general similarity of the Grassy Portage intrusion to those at Doré Lake and Fiskenaesset (Fig. 5a). In these latter intrusions lithologies such as garnetiferous gabbro, oxide cumulates, and tonalite are restricted to the upper portions of the intrusion. Leucogabbros and anorthosites occupy the center and melagabbros are found near the base. The similar stratigraphy of the Grassy Portage intrusion implies that here, way-up is to the southeast. It also implies that there is no symmetrical repetition of stratigraphy on opposite margins of the

Figure 5 (a) The Grassy Portage Intrusion
Simplified "stratigraphic column" for the Grassy Portage intrusion. Published sections for the Doré Lake intrusion, Québec (Allard, 1970) and the Fiskenaesset intrusion, West Greenland (Windley, 1973) are shown for comparison.

(b) Two conflicting interpretations of the internal structure of the Grassy Portage intrusion. This study shows that, along a typical section, the intrusion is petrographically and chemically asymmetric suggestive of a southeastward primary "way-up" direction. Harris (1974) implied, on the other hand, that the intrusion is tightly folded into a syncline.


B
Gabbro
Tonalite
Ultramafics (Oxide Cumulate and Apatite)
Garnetiferous Gabbro (modal Quartz)
Leucogabbro
Gabbro
100m
Melagabbro
A
Tonalite Zone :
Gabbro, Tonalite
(modal Quartz and Apatite)
Ultramafic Zone :
(includes Garnetiferous Gabbro, Oxide Cumulates, Apatite)
Anorthosite Zone :
Gabbro , Leucogabbro, Anorthosite
500 m
base not exposed
Garnet Anorthosite
Chromitite
Anorthosite
Leucogabbro
Melagabbro
Layered Leucogabbro
Ultramafics
100 m
GRASSY PORTAGE
DORĒ LAKE
FISKENAESSET

(a)


THIS STUDY
N
A
B
"way-up"
1 Km
11
HARRIS (1974)
N
syncline
1 Km
11

(b)

intrusion. These points conflict with the interpretation of Harris (1974) who indicated that the outcrop pattern of the gabbroic rocks was controlled by a tight syncline with an axial surface passing along the centre of the intrusion (Fig. 5b).

PARAGNEISS AND RELATED INTRUSIONS

A sequence of leucocratic, compositionally layered schists and gneisses is found at the core of the Rice Bay dome. These rocks have been interpreted as paragneisses (Peterman, 1959). The dominant quartz and plagioclase commonly occurs as large mortared grains or as aggregates of small recrystallized grains. Coarse grained muscovite and biotite are present as are chlorite pseudomorphs after biotite.

Sills of coarse granitoid rock are intercalated with the paragneiss. These granitoid rocks commonly contain elongate megacrysts of quartz or plagioclase or both. In most cases the megacrysts are recrystallized or polygonized into strain-free subgrains. Microcline is present in all samples. Its distinction from plagioclase was enhanced by staining with sodium cobaltinitrite solution. Coarse biotite and muscovite are common. Based on mineralogical composition and relative abundances, these rocks range from granite to granodiorite (Streckeisen, 1976).

Collectively, the paragneiss and granitoid sills constitute the Laurentian of Lawson. Table 6 gives chemical

Table 6 - Chemical Analyses

Paragneiss & Associated Plutonic Rocks

	KHP-31	KHP-32	KHP-33	KHP-34	KHP-35	KHP-36
SiO_2	76.18	71.14	73.39	75.09	71.68	71.31
Al_2O_3	11.15	10.37	11.55	12.44	15.04	16.40
TiO_2	.22	.38	.28	.20	.29	.13
FeO	1.92	6.32	2.40	1.48	.92	.56
Fe_2O_3	1.14	2.67	1.51	1.13	.60	.47
MgO	3.47	4.02	5.05	.49	.58	.65
CaO	.11	.16	.16	.95	1.09	2.64
Na_2O	.51	.51	.19	2.86	4.52	5.06
K_2O	2.69	1.21	2.37	4.27	4.58	2.24
P_2O_5	.05	.10	.11	.06	.11	.06
MnO	.04	.11	.04	.05	.09	.02
CO_2	.15	.03	.07	.40	.15	.18
H_2O^t	2.34	3.15	2.97	.54	.36	.27

KHP-31: paragneiss 78-Po-58
KHP-32: paragneiss 78-Po-65
KHP-33: paragneiss 78-Po-68
KHP-34: granodiorite 78-Po-40
KHP-35: granodiorite 78-Po-42
KHP-36: granodiorite 78-Po-55

analyses for these rock types which show that the silica contents for both are similar. Significant differences however exist in the percentages of other oxides, notably MgO, CaO, Na_2 and K_2O. Peterman (1959) assigned the paragneisses to the Coutchiching Group. However, comparison of the paragneiss compositions with those for Coutchiching biotite schists (Table 4) indicates that these rocks are chemically distinct from one another. The paragneisses contain much more silica and potash and significantly less alumina.

CONGLOMERATE

Wood (1979) has indicated that conglomerate of the Seine Group unconformably overlies Keewatin volcanic rocks near Mine Center, some 35 km east of Rice Bay. This contact relationship has not been established in the present study area. Near Hopkins Bay (locality 7, Fig. 4) and at Neil Point, Minnesota (locality 8, Fig. 4) good exposures of the conglomerate may be found. These show that the conglomerate is clast supported with clast sizes ranging from 5 to 40 cm in maximum dimension. Clasts comprise basic volcanic rock, finegrained feldspar porphyry, granodiorite and iron formation.

ALGOMAN GRANITE

Although the study of these rocks is not a prime objective of this thesis, a few general observations are deemed appropriate. Granodiorites and quartz monzonites are confined to plutons with elliptical outcrop patterns. The rocks are generally massive and medium grained. The plutons are compositionally zoned (Goldich and Peterman, 1978) and become more basic in composition near the margins where internal fabrics are also developed. On a regional scale the schistosity and bedding of the country rocks envelopes the plutons. Enclaves of country rock are common at pluton margins (locality 9, Fig. 4). The above characteristics distinguish the Algoman rocks from the granitoid rocks which are exposed at Rice Bay. The latter rocks are gneissic and contain megacrysts, and occur as sills which have been deformed with the surrounding strata. Evidence of metamorphic recrystallization is abundant in most cases.

STRUCTURE

MINOR STRUCTURES

The attitudes of structural elements observable in outcrops were systematically recorded. These include S-surfaces, lineations, younging directions, fold asymmetry, bedding-cleavage relationships and fold structural facings.

S-Surfaces

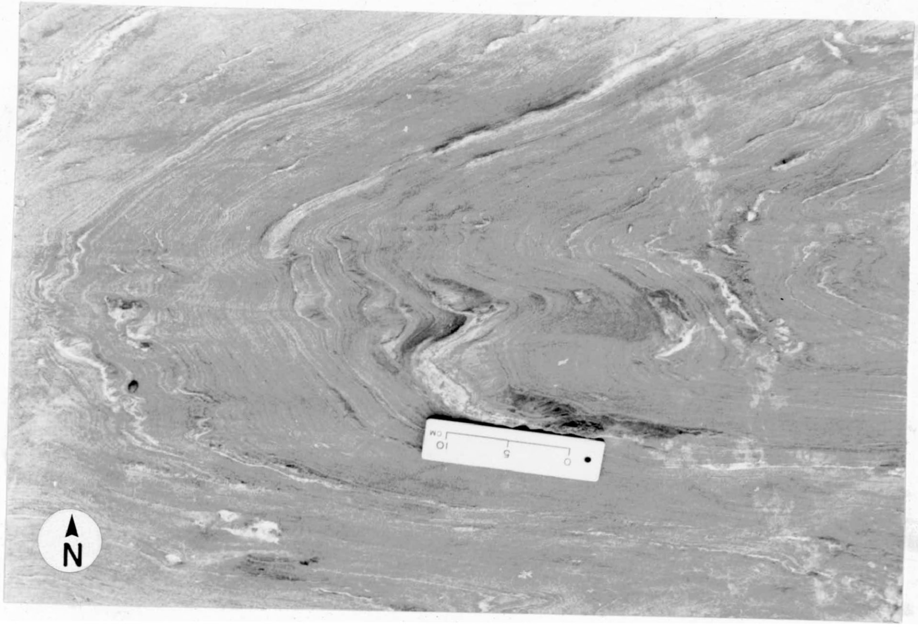
The planar fabric elements observed include a variety of types. Compositional layering in schists and gneisses and bedding in sedimentary rocks are designated So.

PLATE I

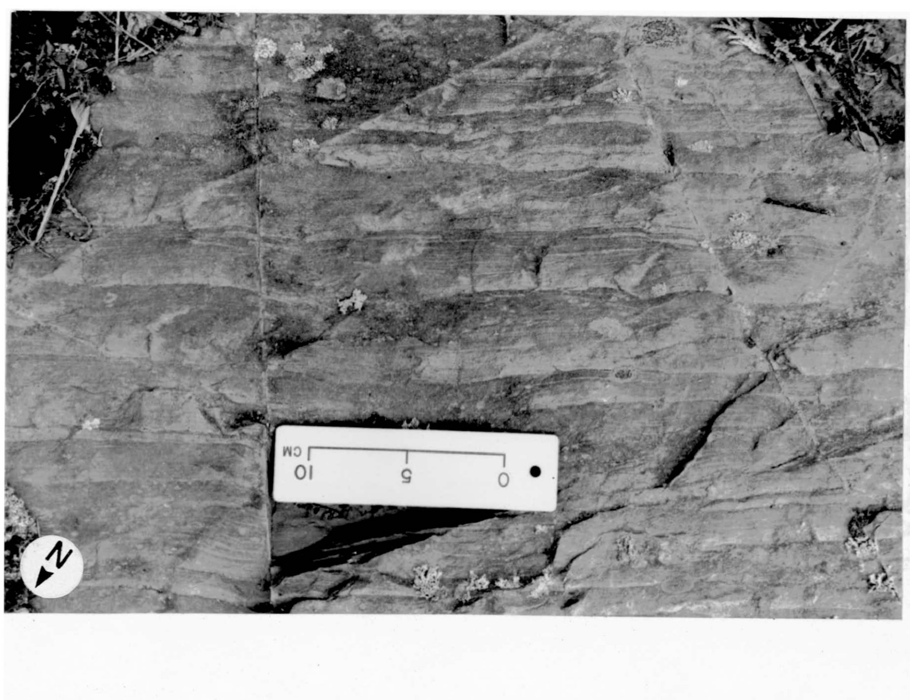
Minor Structures

(a) Minor F_2 fold in biotite schist near the intersection of Hwy. 11 and Manitou Access Road.

(b) Graded beds near the shore of Bear Passage. Here the beds young southeastward yet the beds dip 45° northwestward.



(a)



(b)

Cleavage is well developed, particularly in the low grade metasedimentary rocks. Here the cleavage is discrete and cleavage planes are commonly spaced 1 cm apart. Microscopically however, the cleavage appears to be continuous (Powell, 1979) and results from a strong fabric defined by the crystallographic orientation of phyllosilicates. In individual outcrops (locality 10, Fig. 4) this cleavage is parallel to the axial surface of minor folds. A crenulation cleavage, also present in many outcrops (locality 11, Fig. 4) generally cuts other S-surfaces at a high angle. Cleavage surfaces are commonly discrete and are spaced approximately 1 cm apart. This crenulation cleavage commonly parallels kink band axial surfaces and axial surfaces of minor folds. Schistosity is particularly well developed in medium grade rocks. Two types are distinguished: a schistosity defined mainly by the crystallographic orientation of phyllosilicates is commonly sub-parallel to bedding and is termed S_1 while schistosity defined by the preferred dimensional orientation of porphyroblasts commonly parallels the axial surfaces of minor folds.

Lineations

Linear fabric elements include a number of types. Fold axes were routinely measured in rocks possessing folded compositional layering (Plate Ia). These include mullions and axes of kink folds. Intersection lineations are commonly seen on either cleavage or bedding surfaces and are the result of the mutual intersection of these S-surfaces.

Mineral lineations in the rocks are produced by the preferred dimensional orientation of amphibole grains in metabasites and elongate quartz megacrysts in leucocratic plutonic rocks.

Younging Directions

The two primary younging criteria used extensively in this study are graded bedding in metasedimentary rocks and pillow morphology in basic volcanic rocks.

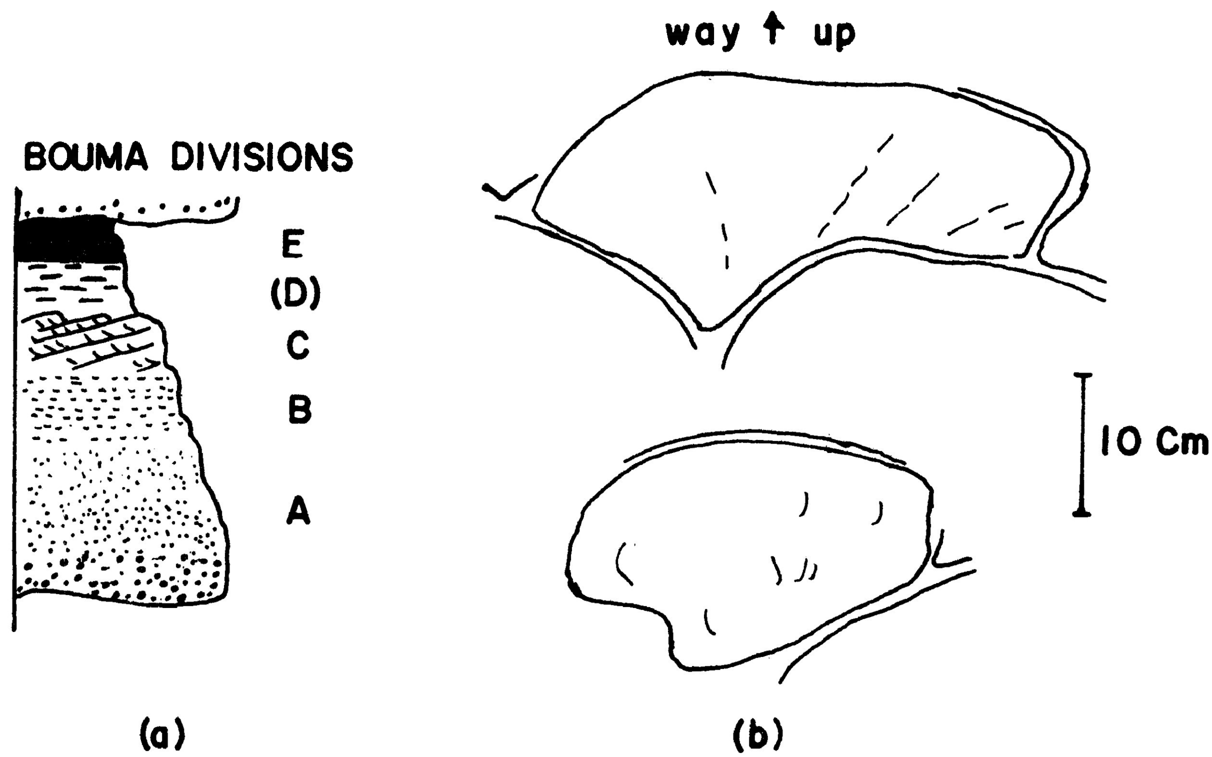
Graded bedding is present in many exposures of the Coutchiching group. These rocks have been interpreted as turbidites (Ojakangas, 1972; Wood, 1979). Figure 6a represents the divisions of the Bouma cycle of a model turbidite (Walker, 1979). This cycle of sandy A divisions through pelitic E divisions can be used to determine the direction of younging of an individual bed. Commonly, some divisions of the cycle are not represented. Thick ABE beds are exposed at Sandpoint and Morton Islands. More commonly however, five to ten consecutive AE beds, each 2 to 5 cm thick, yield a consistent polarity (Plate Ib). These "bundles" of graded beds are well exposed in both the low- and medium-grade rocks. Two common objections concerning the reliability of graded beds as indicators of younging are felt to be of minimal importance here. Reversals in polarity are common in sediments from fluviatile and shallow marine environments (Bishop and Force, 1969). Other sedimentary features such as trough crossbedding and conglomerates, however, serve to distinguish rocks of these environments

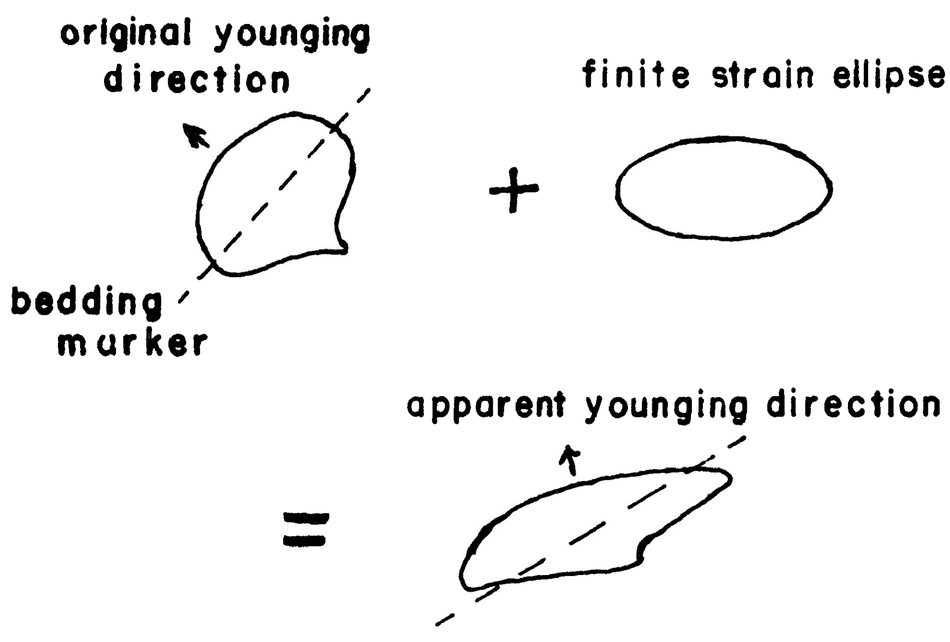
Figure 6 - Younging Criteria

(a) The idealized Bouma sequence for a turbidite from which a direction of younging may be interpreted (after Walker, 1979).

(b) Typical cuspate pillow forms from the study area show a primary direction of younging (locality 16, Fig. 4).

(c) The influence of homogeneous finite strain on the shape and orientation of an originally equant, cuspate pillow. The maximum elongation direction of the deformed pillow need not represent an attitude of "bedding".


BOUMA DIVISIONS
E
(D)
C
B
A
(a)
way ↑ up
10 Cm
(b)


original younging direction
bedding marker
finite strain ellipse
+
=
apparent younging direction

(c)

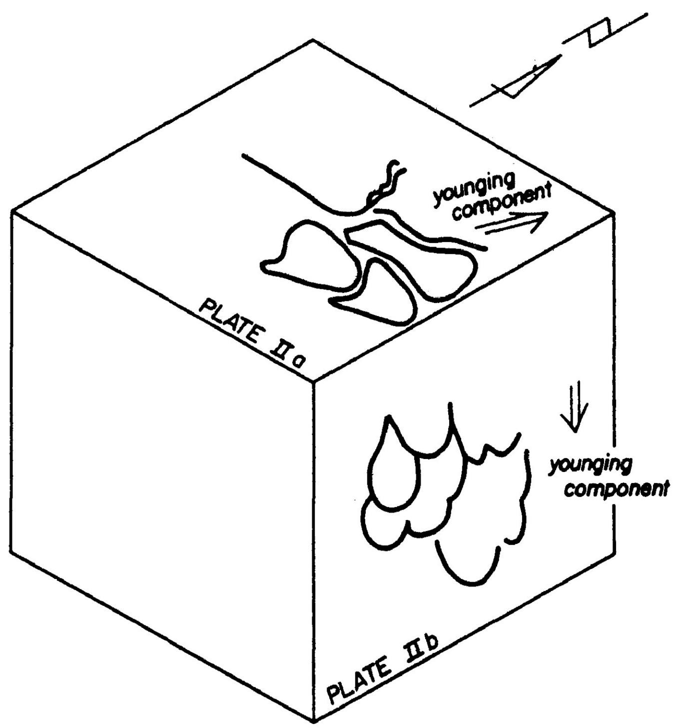
from deep water turbidites which display a more consistent polarity. The Coutchiching rocks have characteristics of the latter type. Metamorphism is often cited as a process which alters original grain sizes and causes an apparent reversal polarity of grain gradation. In the rocks of the study area, metamorphism has actually enhanced the contrast between A and E divisions of beds as porphyroblasts develop preferentially in the pelitic division. Thus younging directions from metasedimentary rocks reported here are believed to be reliable.

The use of pillow lavas is well established as a method by which younging directions in basic volcanic rocks may be determined. A variety of pillow forms may be observed in undeformed Archean basalts (Dimroth et al, 1978; Hargreaves and Ayres, 1979). The common cuspate form which is most useful in the interpretation of younging is well exposed at many localities in the study area (Fig. 6b). However, some difficulties are inherent in the use of pillow lavas from deformed terrains. In such cases, outcrops commonly lack a marker of bedding to which a younging direction may be related. It is common practice to denote the younging direction to be normal to the long axis of an elongate pillow. This may not accurately reflect the actual younging since the attitude of the long axis of a pillow is determined in part by the finite strain ellipse (Fig. 6c). The way in which homogeneous finite strain influences the shape of a pillow is discussed in Appendix C which contains the results

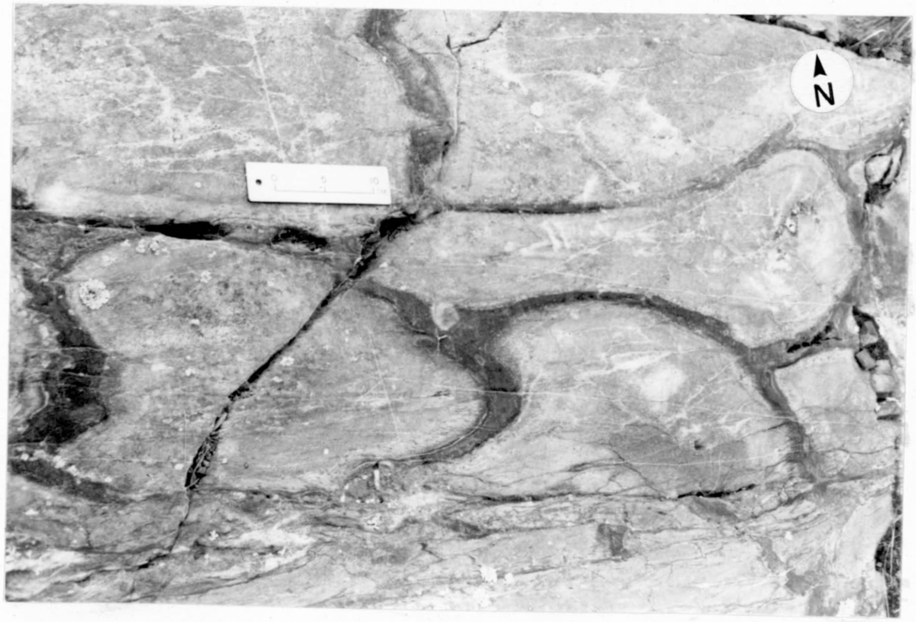
PLATE II

Deformed Pillow Lavas

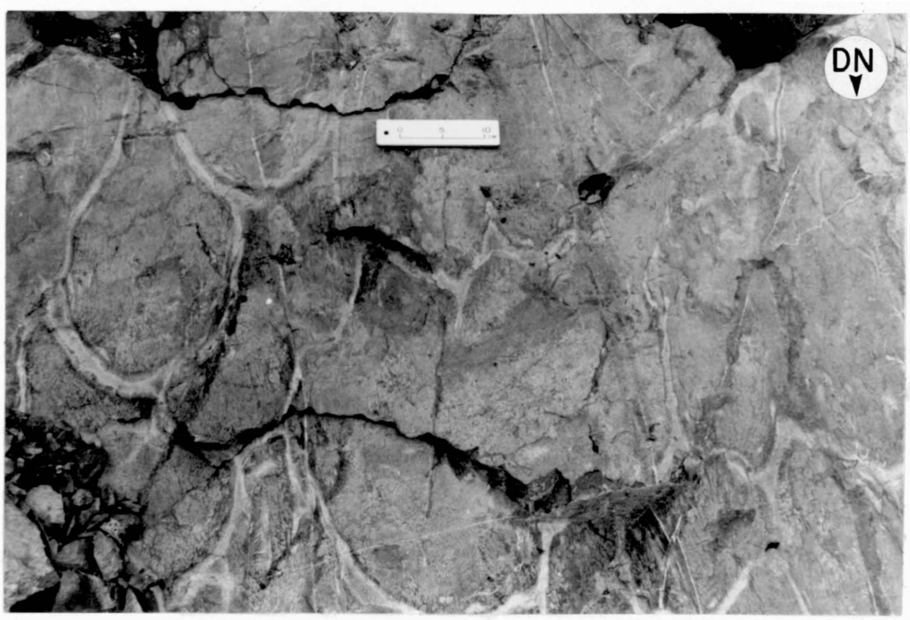
(a) Deformed pillow lavas on Hwy. 11 near Nickel Lake. Photo illustrates the shape of pillows on a shallowly inclined outcrop surface.



(b) Deformed pillow lavas on Hwy. 11 near Nickel Lake. Photo illustrates the shape of pillows on a steeply inclined outcrop surface. These shapes, combined with those shown in Plate II(a), illustrate that the pillowed unit is overturned at this location.



(a)



(b)

of some analogue experiments on these problems. These results may be applied to a specific example from the study area. West of Nickel Lake (locality 12, Fig. 4), individual pillows are tectonically elongated with aspect ratios greater than 5 to 1. No younging information can be gained on outcrop surfaces which parallel the maximum elongation direction but on surfaces normal to this direction, somewhat equant sections through pillows may be observed (Plate IIa,b). These sections reveal a component of younging eastward and downward. This example emphasizes that much care is needed to obtain reliable younging information from deformed pillow lavas.

Fold Asymmetry and Bedding-Cleavage Relationships

The type of fold asymmetry was recorded where trains of folds are developed. Where both bedding and cleavage observations are possible, the asymmetry resulting from their mutual intersection was also noted. Figure 7a illustrates these cases.

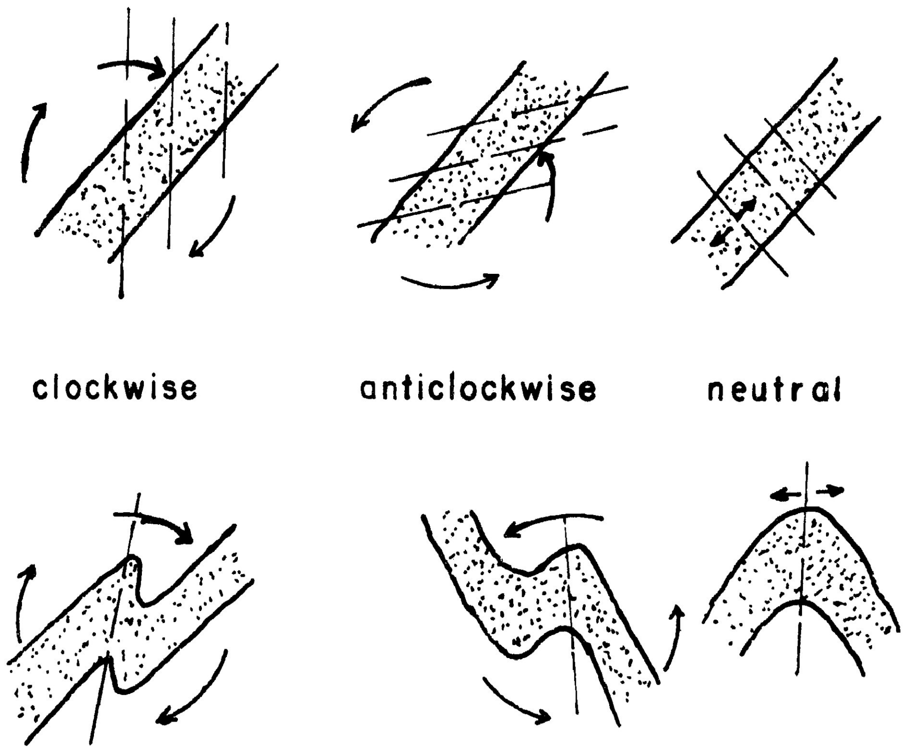
Structural Facing of Folds

At a few good exposures (locality 6, Fig. 4) both the bedding-cleavage relationships and the direction of younging may be observed. At these outcrops the structural facing of folds can be determined. The term "structural facing", which is applied to folds rather than to beds, was introduced by Shackleton (1958). Anticlines and synclines (Fig. 7b) are defined both by morphology and by the

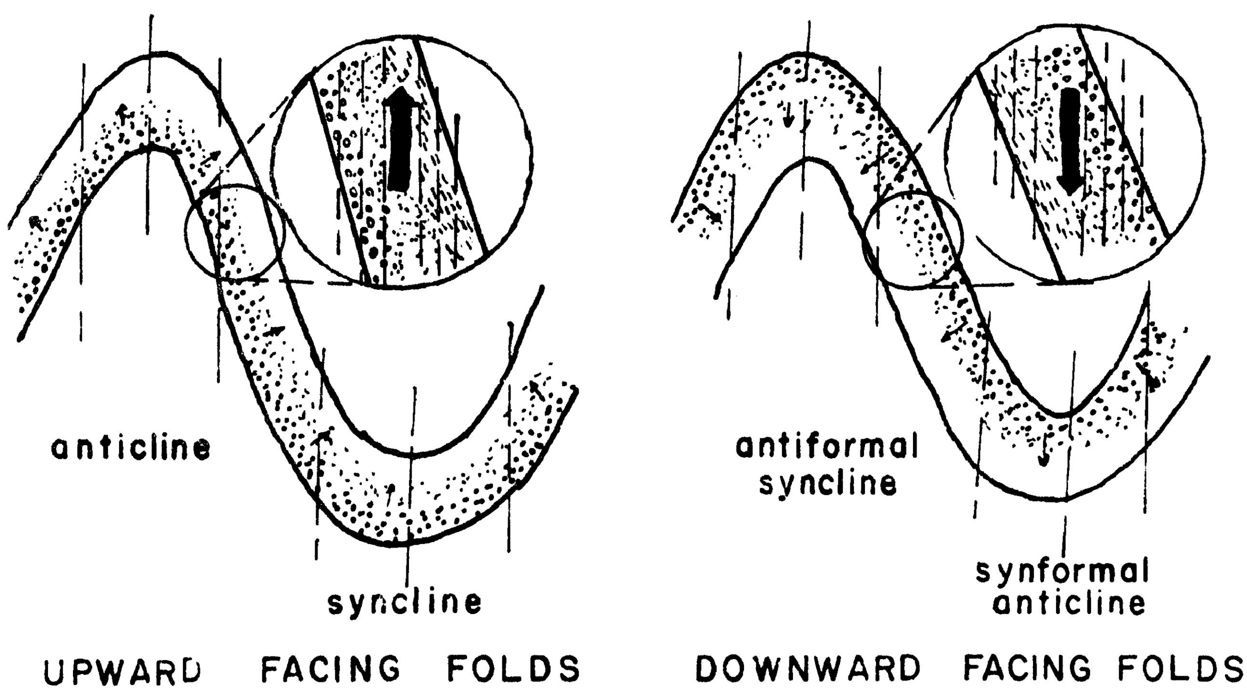
Figure 7 - Bedding-cleavage-younging relationships in folds.

(a) An illustration of the nomenclature used to describe the asymmetry of bedding-cleavage relationships and minor folds. Views are normal to intersection lineations and fold axes respectively. Rotational arrows give the asymmetry, clockwise, anticlockwise or neutral.

(b) The structural facing of folds in layers where the direction of younging is known. At any position in the folded layers the structural facing of the folds may be determined by tracing along the fold axial surface (or axial plane cleavage) in the direction of younging. The anticline and syncline face upward while the antiformal syncline and synformal anticline face downward. The views shown are normal to fold axes and bedding-cleavage intersection lineations.


clockwise
anticlockwise
neutral

(a)


anticline
syncline
antiformal
syncline
synformal
anticline
UPWARD FACING FOLDS
DOWNWARD FACING FOLDS

(b)

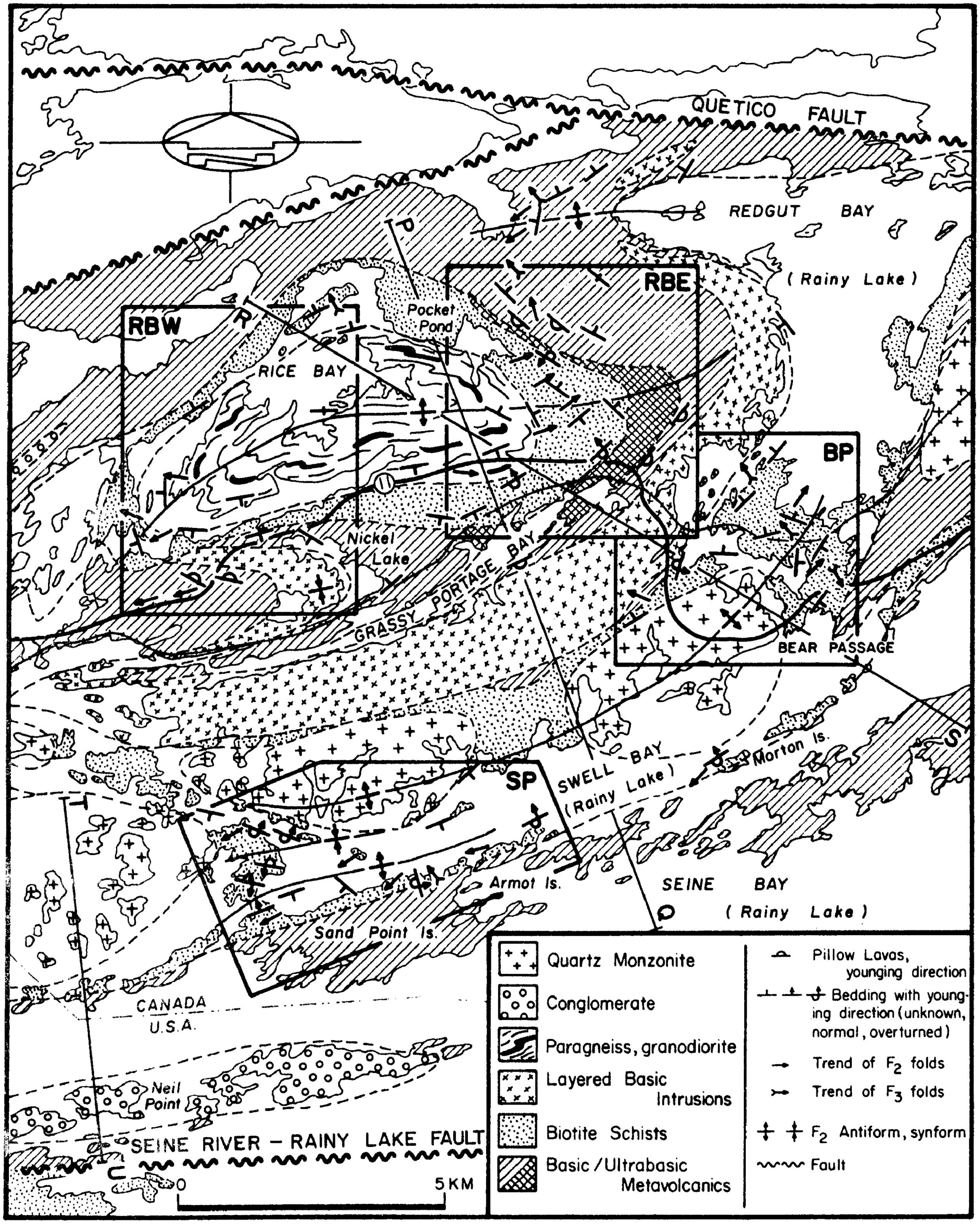
stratigraphic order of the folded layers. They have an upward structural facing. Antiformal synclines and synformal anticlines (Hobbs et al., 1976) face downwards and are developed on strata which were inverted prior to, during, or after the formation of these folds. Where an axial planar cleavage is present, the facing of folds may be determined without actually observing minor fold closures in an outcrop (Borradaile, 1976). In this case, the structural facing direction is determined by tracing the direction of younging of beds along the cleavage surface in a plane normal to the bedding-cleavage intersection lineation (Fig. 7b). As such, the direction of structural facing indicates the overall "way-up" of the folded stratigraphic sequence.

MAJOR STRUCTURES

Figure 8 shows typical attitudes of minor structural elements. There is considerable variation in the attitudes of bedding, cleavage, fold axes and mineral lineations in the study area. All younging data (Fig. 8) also show similar variability. Because of this diversity, systematic geometric analysis of planar and linear data was carried out to relate minor and major structures, to determine the number of deformational episodes, and to evaluate the affects of the deformation on the Keewatin-Coutchiching contact. All structural measurements from planar and linear elements are plotted in equal area stereographic projections.

The results of the geometric analysis led to the

Figure 8 - Summary geological map of the study area. Typical attitudes of bedding, traces of axial surfaces and younging directions are shown. The boundaries of domains from which detailed structural data were gathered are indicated (RBW: Rice Bay West, RBE: Rice Bay East, BP: Bear Passage and SP: Sandpoint Island). Locations of geological cross-sections from this (PQ) and other studies (RS,TU) are shown (see Fig. 24).



QUETICO FAULT
REDGUT BAY
(Rainy Lake)
RBE
RBW
Pocket Pond
RICE BAY
BP
Nickel Lake
GRASSY PORTAGE BAY
BEAR PASSAGE
SWELL BAY
(Rainy Lake)
Morton Is.
SP
Armot Is.
SEINE BAY
(Rainy Lake)
Sand Point Is.
CANADA
U.S.A.
Neil Point
SEINE RIVER – RAINY LAKE FAULT
0
5 KM
Quartz Monzonite
Conglomerate
Paragneiss, granodiorite
Layered Basic Intrusions
Biotite Schists
Basic / Ultrabasic Metavolcanics
Pillow Lavas, younging direction
Bedding with younging direction (unknown, normal, overturned)
Trend of F2 folds
Trend of F3 folds
F2 Antiform, synform
Fault

recognition of a sequence of three deformational episodes:

D_3 Episode: Development of a discrete crenulation cleavage (S_3) which strikes northwest-southeast. Kink bands and open folds (F_3) have axial surfaces parallel to the cleavage.

D_2 Episode: Development of tight folds (F_2) about east-west trending axes. Fold axes, mineral lineations and intersection lineations (L_2) are coplanar with a regionally developed axial plane continuous cleavage or schistosity (S_2).

D_1 Episode: Inversion of much of the stratigraphic succession, possibly by fold nappes (F_1). Minor folds are rare and a precise definition of S_1 is difficult.

D_3 Structures

In the study area many outcrops display a well developed, consistently oriented S_3 crenulation cleavage (Fig. 9). Discrete cleavage surfaces are spaced 1 cm apart (Fig. 10a). Kink bands one to two cm in amplitude and small open folds have axial surfaces parallel to the S_3 cleavage. At some localities, these minor folds are found superimposed on folds of an earlier generation (Fig. 10b). D_3 fabric elements are to some extent controlled by lithology since these structures are best developed in the sedimentary rocks. In the vicinity of Bear Passage the greatest number of D_3 structures are found and here a large F_3 fold has been mapped (Fig. 9). Orientation data from the entire study area (Fig. 10c)

Figure 9 - The distribution of D_3 fabric elements. Crenulation cleavages and parallel fold axial surfaces (S_3) and minor fold axes (L_3) are shown. The trace of the axial surface of a large F_3 antiform is shown.

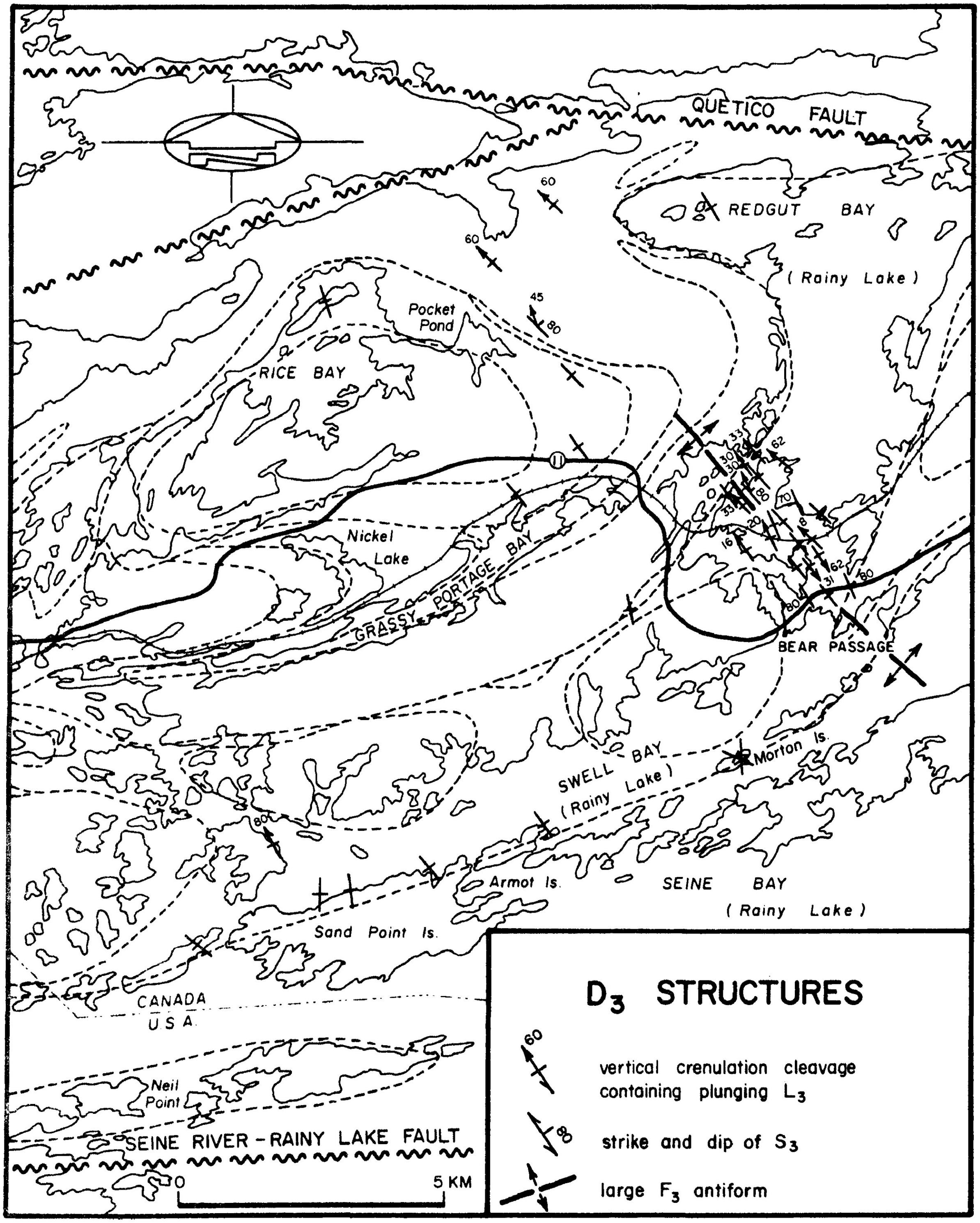

QUETICO FAULT
REDGUT BAY
(Rainy Lake)
Pocket Pond
RICE BAY
Nickel Lake
GRASSY PORTAGE BAY
BEAR PASSAGE
SWELL BAY
(Rainy Lake)
Morton Is.
Armot Is.
SEINE BAY
(Rainy Lake)
Sand Point Is.
CANADA
U S A
Neil Point
SEINE RIVER - RAINY LAKE FAULT
0
5 KM
D3 STRUCTURES
vertical crenulation cleavage containing plunging L3
strike and dip of S3
large F3 antiform

Figure 10 - D_3 structures

(a) Typical crenulation cleavage and minor F_3 folds as exposed on a sub-vertical outcrop surface viewed to the northwest (locality 11, Fig. 4). The section is approximately normal to L_3.

(b) Refolding of an earlier (F_2) fold by F_3 as exposed on a sub-horizontal outcrop surface (locality 13, Fig. 4). The F_3 synform plunges to the northwest and the earlier fold closes eastward.

(c) Lower hemisphere equal area projection of S_3 and L_3 data. A strike of 325° and a vertical dip define the mean attitude of S_3.

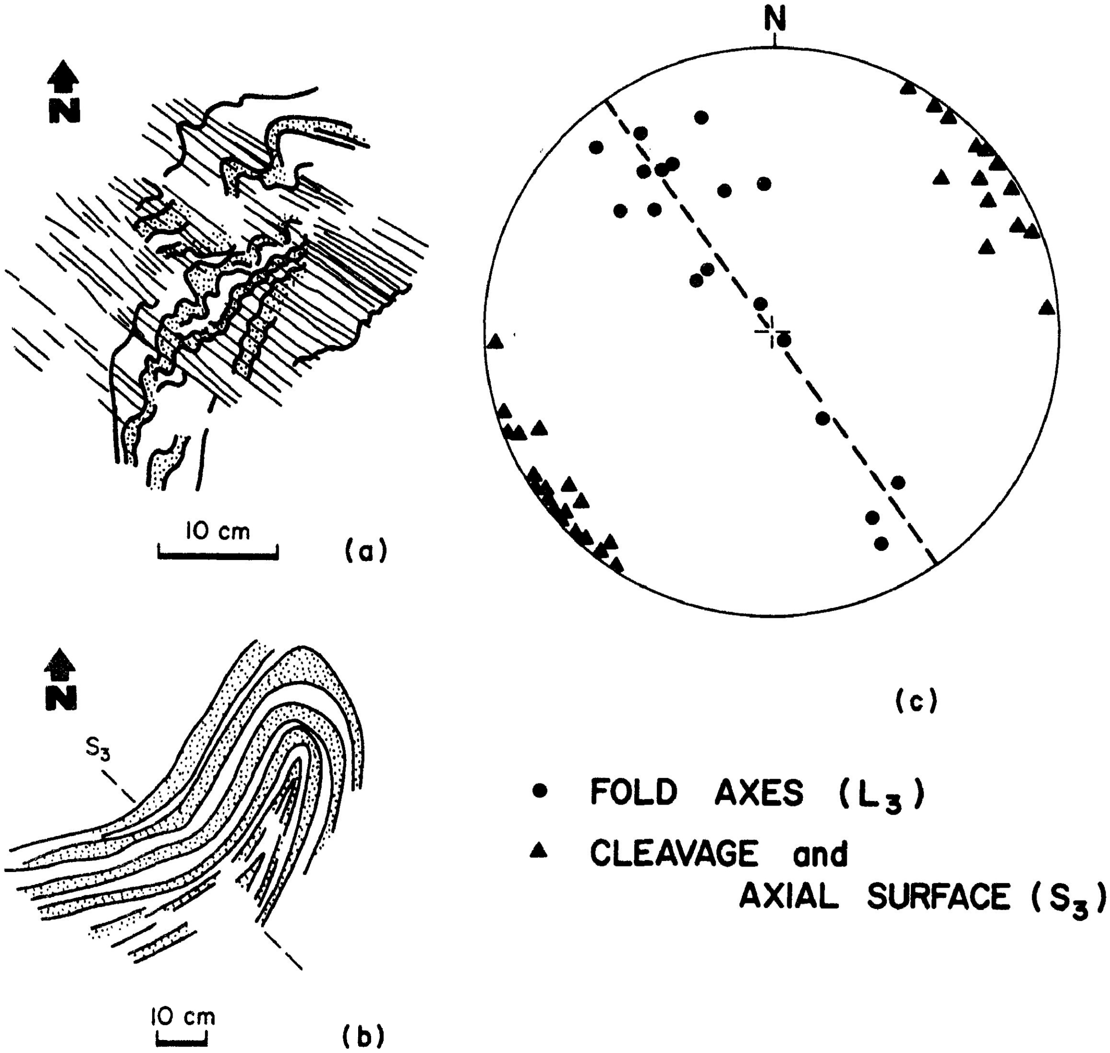
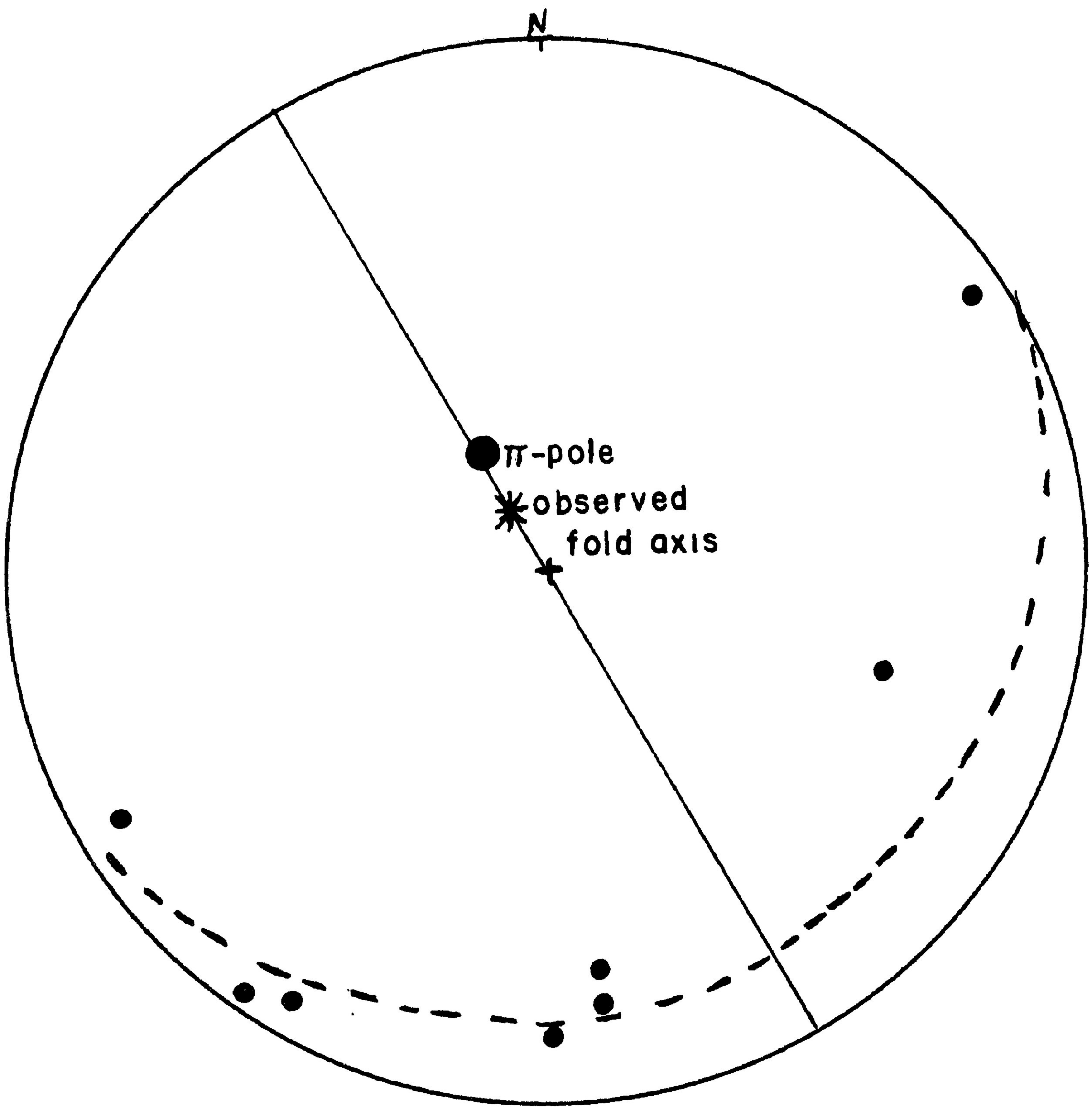

N
10 cm
(a)
N
S3
10 cm
(b)
N
(c)
● FOLD AXES (L3)
▲ CLEAVAGE and
AXIAL SURFACE (S3)

Figure 11 - Lower hemisphere equal area projection of poles to bedding from a small F_3 fold. The poles are distributed along a large radius girdle which lies at a high angle to S_3. The position of the measured fold axis is shown.


N
π-pole
observed
fold axis

indicate a mean strike of 325° for the near-vertical S_3 crenulation cleavage. The variable orientation of small F_3 folds probably reflects the diverse orientations of layers prior to folding.

Good examples of F_3 folds of approximately 1 m amplitude and 2 to 3 m wavelength are exposed on Sandpoint Island (locality 14, Fig. 4). Here, variations in the attitude of bedding were recorded at different places in the folds. Fig. 11 shows that the F_3 folds have redistributed the poles to bedding along a large radius girdle which lies at a high angle to the S_3 cleavage. A comparable pattern of redistribution may be expected for Pre-F_3 lineations. This type of redistribution is revealed by several of the stereographic projections presented in the next section.

D_2 Structures

At some localities, F_3 structures may be found superimposed on earlier minor folds (Fig. 10b). These earlier (F_2) folds, where not greatly affected by D_3, generally have axial surfaces which dip steeply to either the north or south. A spaced to continuous cleavage is axial planar to these F_2 folds and is particularly well developed in the low grade metasedimentary rocks. In medium grade rocks, a schistosity defined by a preferred dimensional orientation of porphyroblasts is well developed in some outcrops. This schistosity parallels the (S_2) axial surfaces at some localities. Mineral lineations, mullions,

Figure 12 - Distribution of D_2 fabric elements. Axial surfaces and axial plane cleavages (S_2) are shown with fold axes, intersection lineations and mineral lineations (L_2).

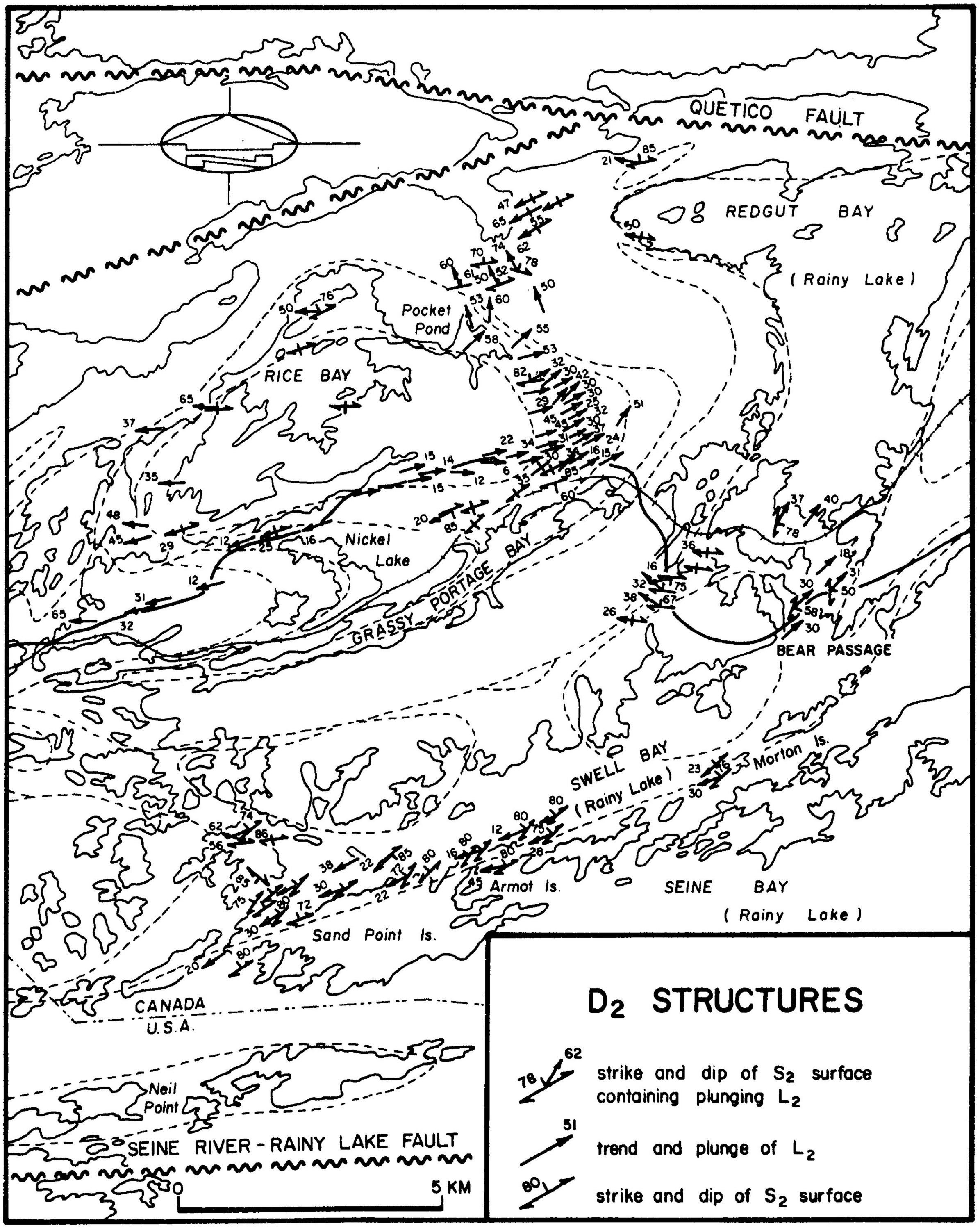

QUETICO FAULT
REDGUT BAY
(Rainy Lake)
Pocket Pond
RICE BAY
Nickel Lake
GRASSY PORTAGE BAY
BEAR PASSAGE
SWELL BAY
(Rainy Lake)
Morton Is.
Armot Is.
SEINE BAY
(Rainy Lake)
Sand Point Is.
CANADA
U.S.A.
Neil Point
SEINE RIVER - RAINY LAKE FAULT
0
5 KM
D2 STRUCTURES
strike and dip of S2 surface containing plunging L2
trend and plunge of L2
strike and dip of S2 surface

Figure 13 - Data on compositional layering. The attitudes shown are largely from metapelites.

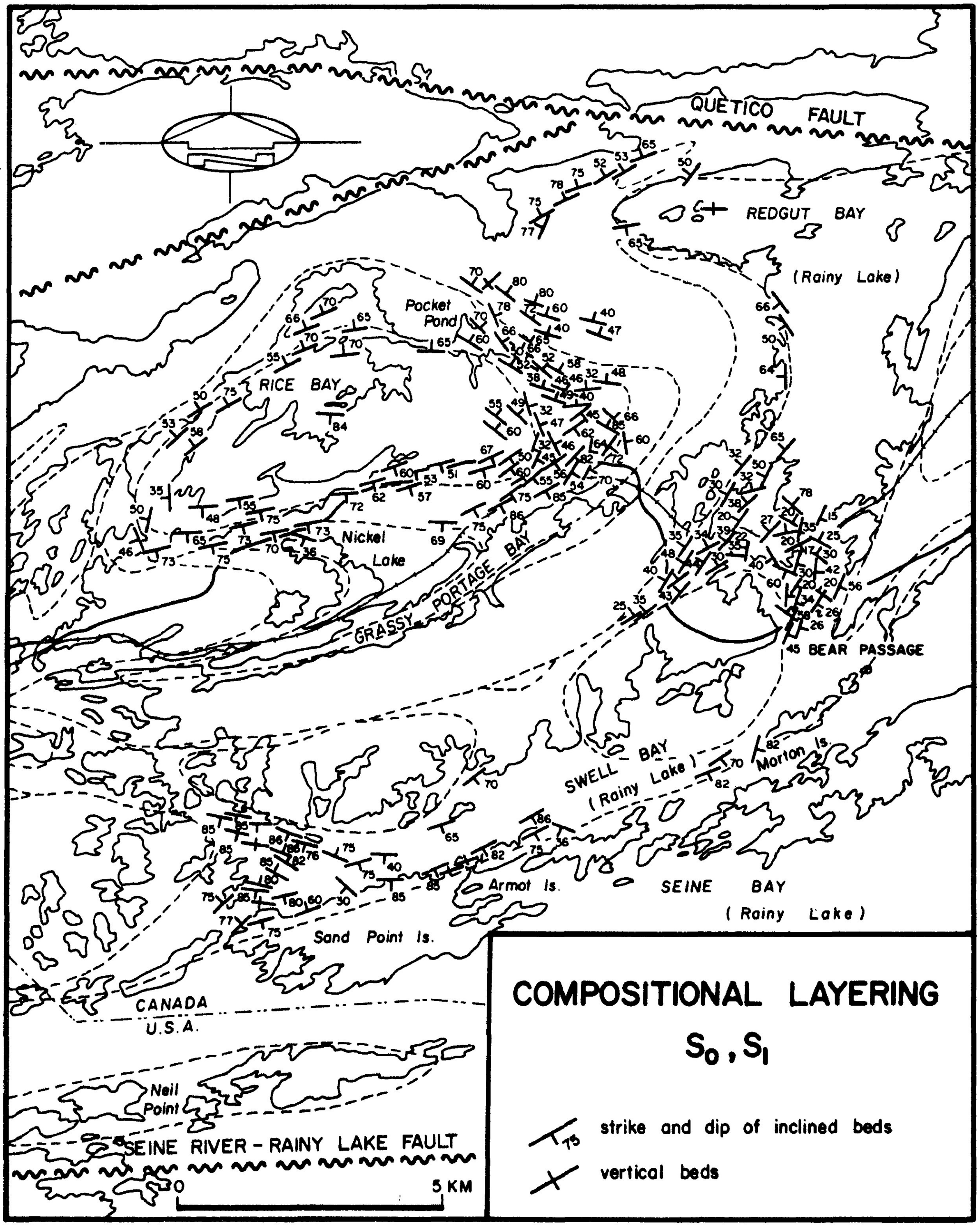
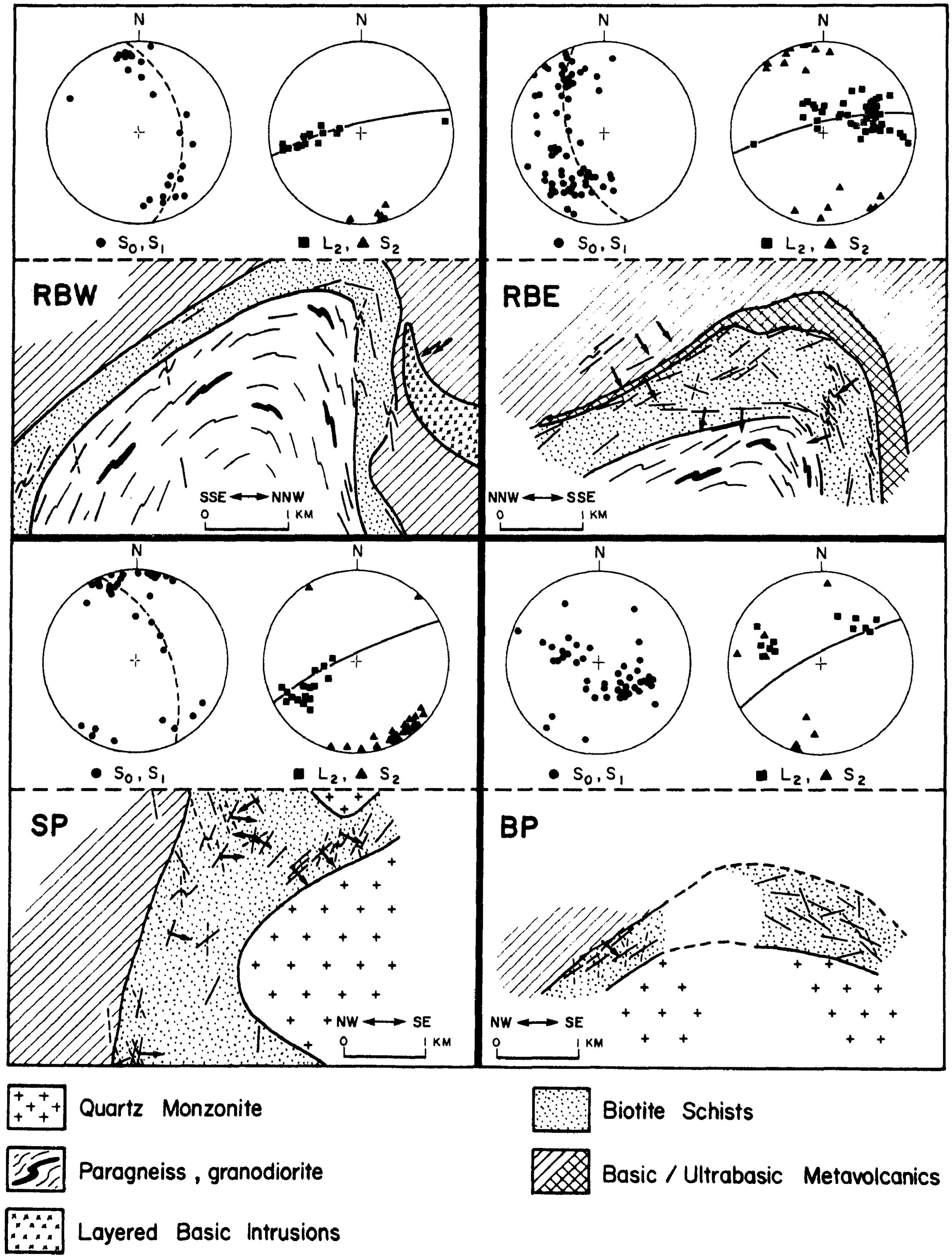

QUETICO FAULT
REDGUT BAY
(Rainy Lake)
Pocket Pond
RICE BAY
Nickel Lake
GRASSY PORTAGE BAY
BEAR PASSAGE
SWELL BAY
(Rainy Lake)
Morton Is.
Armot Is.
SEINE BAY
(Rainy Lake)
Sand Point Is.
CANADA
U.S.A.
Neil Point
SEINE RIVER - RAINY LAKE FAULT
0
5 KM
COMPOSITIONAL LAYERING
S_0, S_1
strike and dip of inclined beds
vertical beds

Figure 14 - Graphical analysis of structural data. Lower hemisphere equal area projections of S-surface and lineation data with fold profiles for large F_2 folds from four domains:

(a) Rice Bay East
(b) Rice Bay West
(c) Sandpoint Island
(d) Bear Passage

Profiles show the traces of bedding and cleavage, fold symmetries and directions of younging. See Figure 8 for the location of domains.



N
S_0, S_1
L_2, S_2
RBW
SSE NNW
0 1 KM
RBE
NNW SSE
0 1 KM
SP
NW SE
0 1 KM
BP
NW SE
0 1 KM
Quartz Monzonite
Paragneiss, granodiorite
Layered Basic Intrusions
Biotite Schists
Basic / Ultrabasic Metavolcanics

and intersection lineations (L_2) are commonly co-planar with S_2 fold axial surfaces and co-axial with minor L_2 fold axes. The orientation of D_2 fabric elements and compositional layering is variable in the study area (Fig. 12, 13). Four structural domains, each of which contains the Keewatin-Coutchiching contact, were chosen for detailed study (Fig. 8). Mean attitudes of fold axes (L_2) and axial surfaces (S_2) were statistically determined from plots of orientation data for each domain (Fig. 14). Based on this information, fold profiles were constructed. These show the traces of bedding and cleavage, the asymmetries of minor folds and the vector components of younging (Fig. 14). Pertinent comments for each domain are summarized below.

Planar and linear data from the Rice Bay East domain (Fig. 14a) are consistent with the interpretation of an easterly plunging antiform. The data from this domain confirm that the minor structures indeed reflect the major structure and that, to a first approximation, these folds may be considered cylindrical. The younging directions, however, are inconsistent with the interpretations of earlier workers who considered this structure to be an anticline. The beds here become younger towards the core of the fold so that the term antiformal syncline is much more appropriate.

Data from the Rice Bay West (Fig. 14b) domain support the interpretation of a westerly plunging antiform which is the mirror image of the Rice Bay East structure.

The two observations of younging in this domain support the interpretation that this F_2 structure is also an antiformal syncline and that the adjacent "Nickel Lake Syncline" as mapped by Lawson (1913) and Harris (1974) is in fact a synformal anticline.

At Sandpoint Island, numerous measurements of axial planar cleavage were made. The data (Fig. 14c) shows the effects of redistribution of pre-D_3 s-surfaces. The structural profile reveals that here the strata form the south limb of a westerly plunging antiform. Once again the younging data suggest a large downward facing F_2 fold.

At Bear Passage, D_3 deformation has resulted in extensive redistribution of earlier structural elements (Fig. 14d). Further the emplacement of the Algoman Bear Passage pluton during the late stages of the D_2 episode added to this redistribution. A partial cross-section has been constructed for this domain. The only reliable obser-varion of younging from this domain gives a direction towards the hinge of the antiform.

D_1 Structures

In can be demonstrated that the stratigraphic succession at Rice Bay, Bear Passage and Sandpoint Island is overturned and that structural inversion likely pre-dated the development of D_2 minor structures.

Overturned stratigraphic contacts are well exposed at three localities. Grout (1925) pointed out that graded

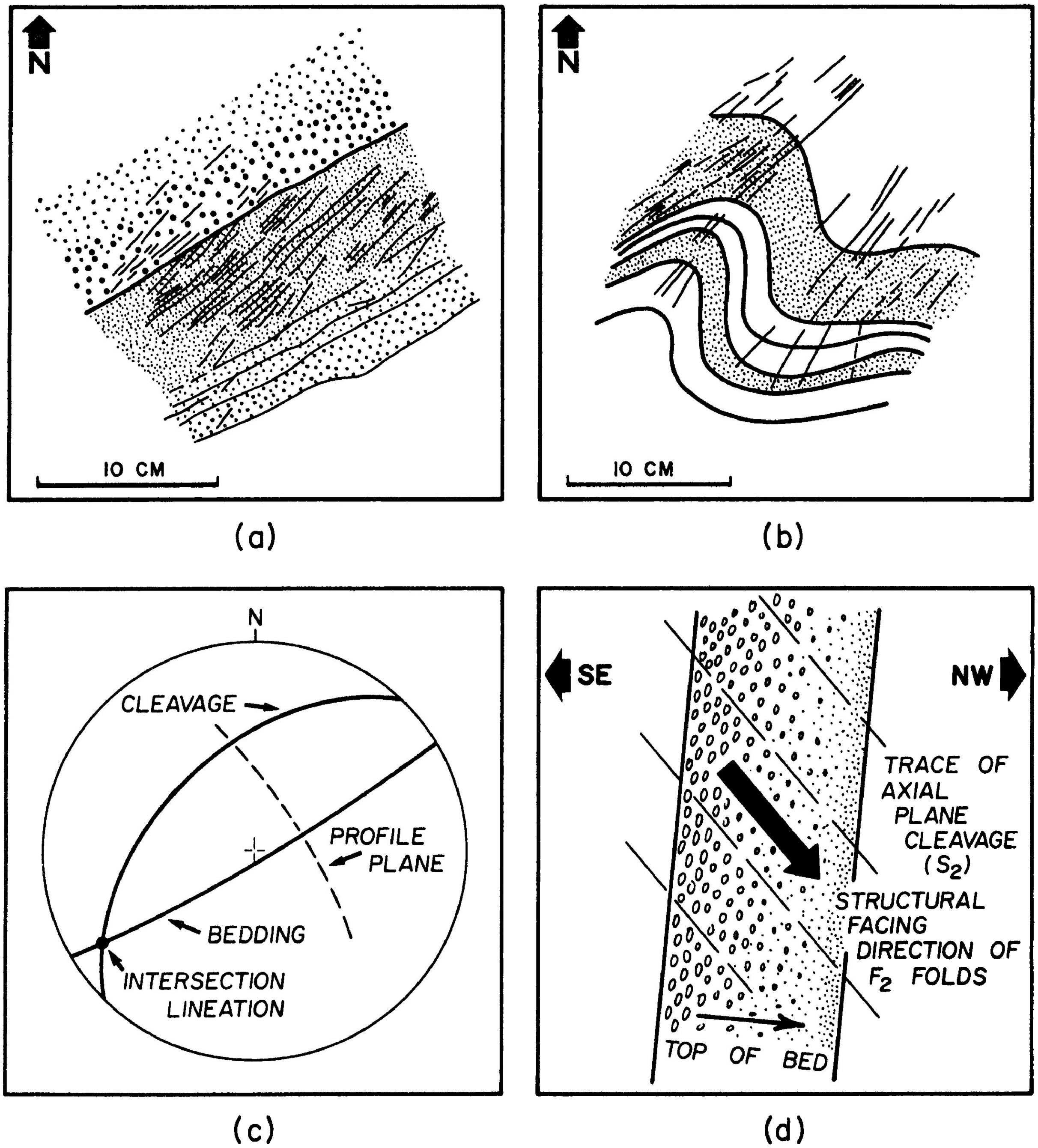
Figure 15 - Structural facing of F_2 folds.

(a) Typical bedding-cleavage-younging relationship as viewed on subhorizontal outcrop surfaces from Morton Island (locality 6, Fig. 4), Armot Island and Sandpoint Island. The measured bedding-cleavage intersection plunges southwestward.

(b) An outcrop sketch showing that the cleavage is axial planar to minor F_2 folds (locality 10, Fig. 4).

(c) Attitudes of bedding, cleavage and their mutual intersection plotted in lower hemisphere equal area projection. Data are from Morton Island.

(d) A schematic profile view, normal to the intersection lineation, of the bedding-cleavage-younging relationship. The F_2 folds to which the cleavage is axial planar, face downward.


N
10 CM
(a)
N
10 CM
(b)
N
CLEAVAGE
PROFILE
PLANE
BEDDING
INTERSECTION
LINEATION
(c)
SE
NW
TRACE OF
AXIAL
PLANE
CLEAVAGE
(S2)
STRUCTURAL
FACING
DIRECTION OF
F2 FOLDS
TOP OF BED
(d)

beds in the Coutchiching Group at Morton Island (locality 6, Fig. 4) gives a younging direction which is away from rocks of the Keewatin Group. The beds dip steeply here but are slightly overturned. During the course of this study, two additional well exposed overturned contacts were located. Near the shore of Bear Passage (locality 15, Fig. 4) the Keewatin rocks are staurolite and garnet-bearing biotite schists. Beds here dip 45^{o} northwestward yet excellent grading (Plate Ib) indicates they become younger towards the southeast. Near Pocket Pond, a northeastward traverse along a bush road (locality 16, Fig. 4) reveals a similar relationship. Coutchiching biotite schists which dip 50^{o} to the northeast are structurally overlain in turn by fragmental ultrabasic rock and metabasites of the Keewatin Group. Good pillow forms in the latter (Fig. 6b) however indicate that the direction of younging is here towards the metasedimentary rocks to the southwest.

The downward structural facing of F_2 folds may be demonstrated in outcrop at a number of locations including Morton Island, Armot Island and Sandpoint Island. Figure 15a shows typical bedding-cleavage-younging relationships as viewed on sub-horizontal outcrop surfaces. Here, the cleavage is axial planar to F_2 folds (Fig. 15b). The intersection lineation is commonly well-exposed and may be measured along with the strike of bedding and cleavage (Fig. 15c). Figure 15d gives a profile view of relationships in a plane normal to the intersection lineation. Thus

F_2 folds face downward here. Since there is no field evidence that the S_2 cleavage has been deformed other than by small F_3 folds, it can be argued that this cleavage has not likely been overturned after it formed. If this is so, the downward facing of F_2 folds implies that inversion of the strata preceded cleavage development. The above example applies to a number of exposures in the area where younging of beds is northward. In some outcrops (locality 17, Fig. 4) southward younging is encountered yet the structural facing of F_2 folds is still downward.

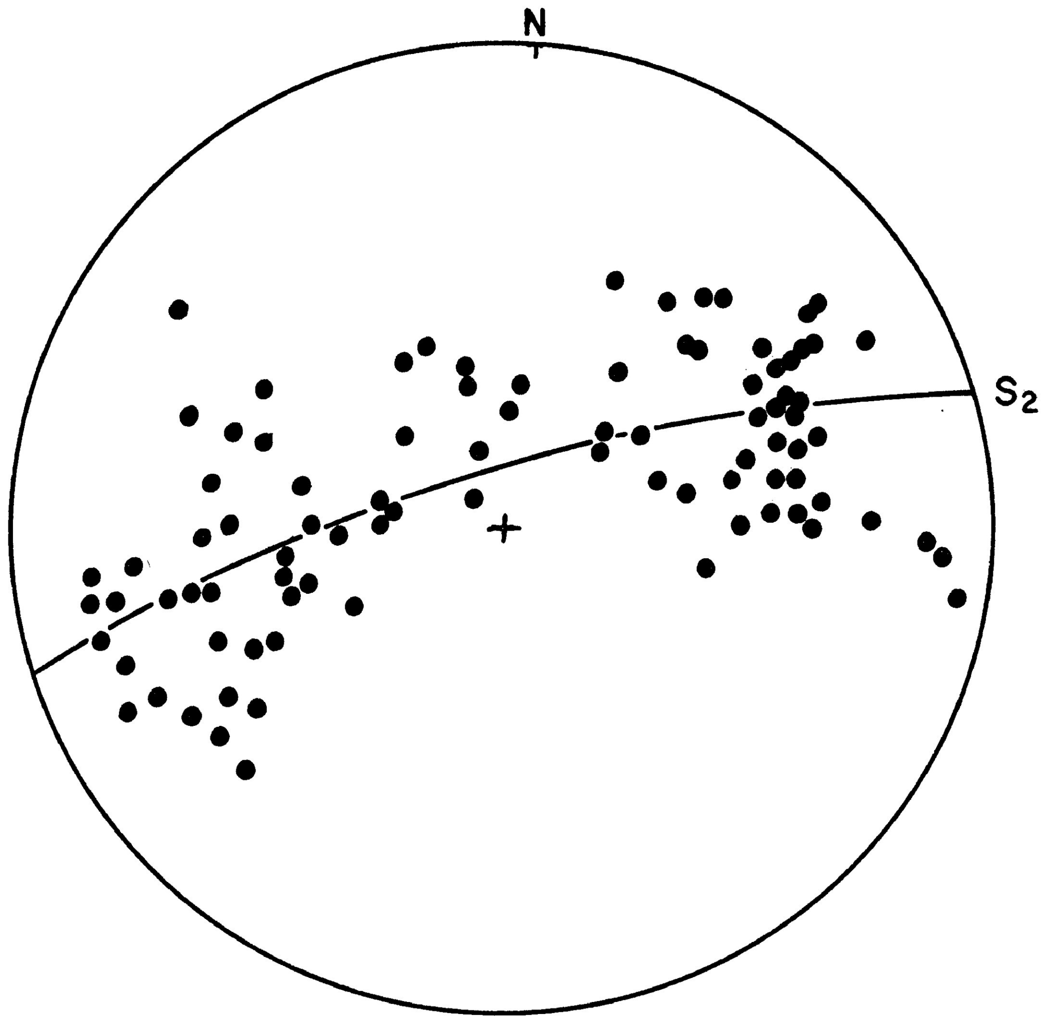
Large F_2 folds have been recognized (Fig. 14). In each case younging criteria indicate that these folds are antiformal synclines or synformal anticlines. This further confirms the existence of an overturned succession at a large scale.

The deformation which resulted in the inversion of such an extensive stratigraphic sequence, at least 20 km long and 1.5 km thick, is assigned to D_1 episode. The precise nature of this deformation is not clear from the above observations but it is possible that fold nappes (F_1) possibly played a major role in this deformation. Evidence for the existence of F_1 folds comes indirectly. Axes of F_2 folds are variably oriented within a great circle which is subparallel to the mean value of S_2 for the study area (Fig. 16a). These orientations may be explained by the superposition of small F_2 folds on the limbs of such large F_1 folds. Rarely, small isoclinal intrafolial folds have

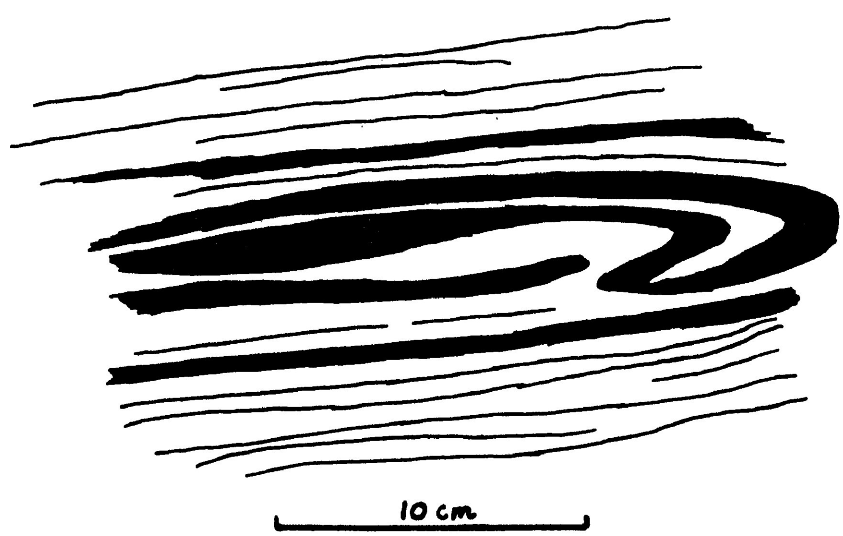
Figure 16 - Evidence for D_1 Deformation.

(a) Lower hemisphere equal area projection of all L_2 data from the study area. The points are scattered about a great circle girdle which represents the mean attitude of S_2 for the area.

(b) Illustration of a refolded minor isoclinal intrafolial fold possibly of F_1 generation (locality 19, Fig. 4).



(a)



(b)

been observed (Fig. 16b) and these are interpreted as minor F_1 structures. The nature of S_1 and its relationship to D_1 is also not clear. However in a few exposures northeast of Pocket Pond (locality 18, Fig. 4), pillow structures are extremely flat in shape even if extreme original shapes are allowed. Aspect ratios commonly exceed 30 to 1 and the pillows are folded by minor F_2 structures. It is therefore conceivable that the elongate pillow forms, at least in part, result from D_1 deformation. Thus, while many details of the complete nature of the deformation remain to be documented, the available evidence points to a pre-F_2 deformation which resulted in large scale inversion of the Archean succession at Rainy Lake. This involved at least a few hundred cubic kilometers of rock.

METAMORPHISM

The rocks in the area have undergone regional metamorphism. Rocks of pelitic and basic composition were studied to determine the conditions and timing of metamorphism.

PELITIC ROCKS

The Coutchiching biotite schists display spatial variations in mineralogical compositions. These rocks were chosen for metamorphic study because this variation does not reflect diversities in bulk chemical composition (Table 4). The metamorphic assemblages, spatial distribution of minerals and chemical controls on metamorphism in these rocks are described below.

Mineralogy

Garnet porphyroblasts ranging from 1 to 3 mm in diameter are ubiquitous in these rocks. They range from fresh idioblastic grains (Fig. 17a), to grains rimmed by chlorite to pseudomorphic aggregates of chlorite after garnet. Some grains show evidence of helicitic inclusion trails (Fig. 17b). The textural variations indicate that garnet growth ranged from being pre-kinematic to post-kinematic (Zwart, 1960). At Bear Passage, garnet is found to overgrow all other mineral species as well as F_3 micro-folds.

Staurolite porphyroblasts, 1 to 10 mm in diameter, exhibit varying degrees of alteration. Fresh, idioblastic grains with diamond-shaped cross-sections (Fig. 17c) as well as irregularly shaped grains with inclusion trails (Fig. 17d) are present in many samples. More typical, however, is the occurrence of white mica after staurolite. In severely altered grains, identification is based on the relict habit and outlines of twinned staurolite. Staurolite grains show either random orientations or show preferred dimensional orientation parallel to schistosities which parallel axial surfaces of F_2 and F_3 folds.

Andalusite grains, 5 to 10 mm in diameter, are commonly completely altered to white mica. Their shapes are

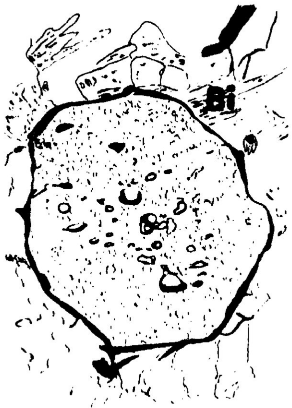
Figure 17 - Textures of metamorphic minerals in pelites.

(a) Idioblastic garnet overgrowing schistosity defined by the crystallographic orientation of biotite (Bi).

(b) Helicitic garnet wrapped by an external schistosity defined by phyllosilicates. Coarse muscovite (M) blades lie at a high angle to this (S_2?) schistosity and elsewhere may be seen to parallel S_3.

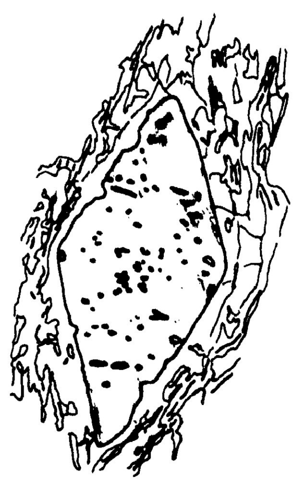
(c) Idioblastic grain of fresh staurolite.

(d) Large staurolite grain with well-defined inclusion trails at a high angle to an external schistosity defined by the preferred crystallographic orientation of muscovite and retrograde chlorite.



(a)

(b)



(c)

(d)

1 mm

typically ovoidal to equant and lack the characteristic habit of staurolite. In hand specimen they appear as grey porphyroblasts and at two localities unaltered andalusite has been found. In many outcrops altered andalusite grains show a sigmoidal texture characteristic of synkinematic crystallization (Zwart, 1960).

Cordierite was reported by Lawson (1913) but has not been positively identified in the course of the present study. Near the margins of the Algoman plutons, the metasedimentary schists contain ovoidal to rectangular shaped porphyroblasts up to 25 mm in size. They are altered to a mixture of white mica and chlorite and are interpreted as pinnitized "cordierite" grains. In some cases, large altered grains contain garnet and altered andalusite in addition to chlorite and white mica. These grains are commonly elongated parallel to F_2 axial surfaces. In many instances, they are cut by S_3 cleavage.

Muscovite is present in most rocks as fresh independent grains or as an alteration product of other minerals. Fresh white mica occurs with chlorite and biotite in low grade rocks and as coarse aggregates and porphyroblasts in medium grade rocks. Here, the muscovite commonly shows a preferred crystallographic orientation parralel to S_3.

Sillimanite occurs as fibrous mats. Most commonly it forms intergrowths with muscovite. This intimate association is interpreted to represent epitaxial growth of sillimanite on muscovite or the growth of muscovite after fibrous sillimanite aggregates. Samples from the vicinity of Bear Passage contain sillimanite aggregates and no muscovite. The sillimanite here appears epitaxially on quartz and biotite.

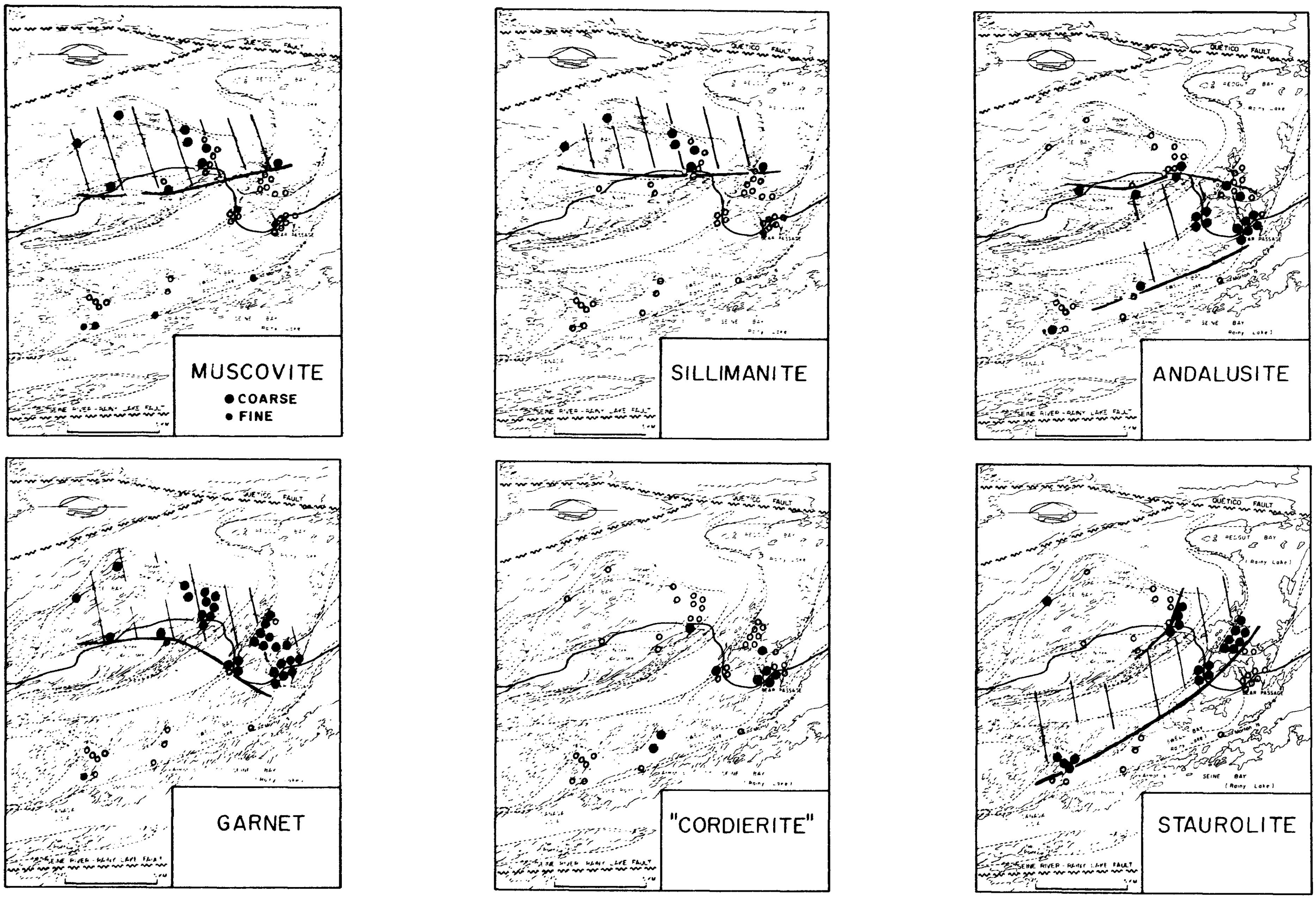
Chlorite is ubiquitous in these rocks. At Bear Passage, it occurs as fresh, colourless blades with staurolite and garnet or sillimanite. The chlorite exhibits an anomalous olive interference colour and because it persists in medium grade rocks, is thought to be magnesian in chemistry. More commonly, light green, pleochroic chlorite is present. This chlorite has anomalous blue interference colours and is found in association with altered iron-rich minerals such as garnet.

In addition to the above minerals, the pelitic schists contain variable amounts of biotite, plagioclase, quartz and opaque minerals. The latter have been identified by x-ray diffraction methods as magnetite and ilmenite. Rutile and hematite are present in some samples.

Distribution of Metamorphic Minerals

The regional distribution of the major metamorphic minerals is given in figure 18. Open circles indicate the absence of a particular mineral while closed circles indicate its presence. Based on this distribution, index mineral lines may be drawn to delineate the occurrence of each mineral. The presence of staurolite is marked by a well-defined line which parallels the attitude of the mean

Figure 18 - Distribution of metamorphic minerals in pelites. Closed circles indicate the presence of the mineral type, open circles indicate its absence. In the hatchured areas pelitic rocks of suitable composition will contain the particular mineral indicated.


MUSCOVITE
COARSE
FINE
SILLIMANITE
ANDALUSITE
GARNET
"CORDIERITE"
STAUROLITE
QUETICO FAULT
SEINE RIVER - RAINY LAKE FAULT
BEAR PASSAGE
SEINE BAY
(Rainy Lake)

S_2 for the area. "Cordierite" and andalusite occur mainly near pluton margins. There is a strong correlation between the presence of sillimanite and muscovite. Muscovite and staurolite appear to be mutually exclusive. Part of the garnet index mineral line corresponds generally with those for muscovite and sillimanite. The index mineral lines defining boundaries for the presence of staurolite, garnet and sillimanite are non-parallel.

The mineral distributions in the Rice Bay area are those typical of the transition from low to medium grade metamorphism. Winkler (1974) emphasized that the first appearance of staurolite or cordierite in pelites is a good indicator of this transition. He further stated that metamorphic zone boundaries or isograds should be defined by recognizable metamorphic reactions and not merely by the first appearance of an index mineral. Following this criterion, it is possible to define three metamorphic zones within the study area based on two isograds (Fig. 19).

The "knotty schist" isograd corresponds to the first appearance of porphyroblasts of staurolite or corcierite. The disappearance of fresh muscovite at this isograd may be analagous with experimental reactions such as:

chlorite + muscovite $\rightarrow$ staurolite + biotite + quartz + H_2O
(Hoschek, 1969)

chlorite + muscovite $\rightarrow$ cordierite + andalusite + biotite + H_2O
(Hirschberg and Winkler, 1968).

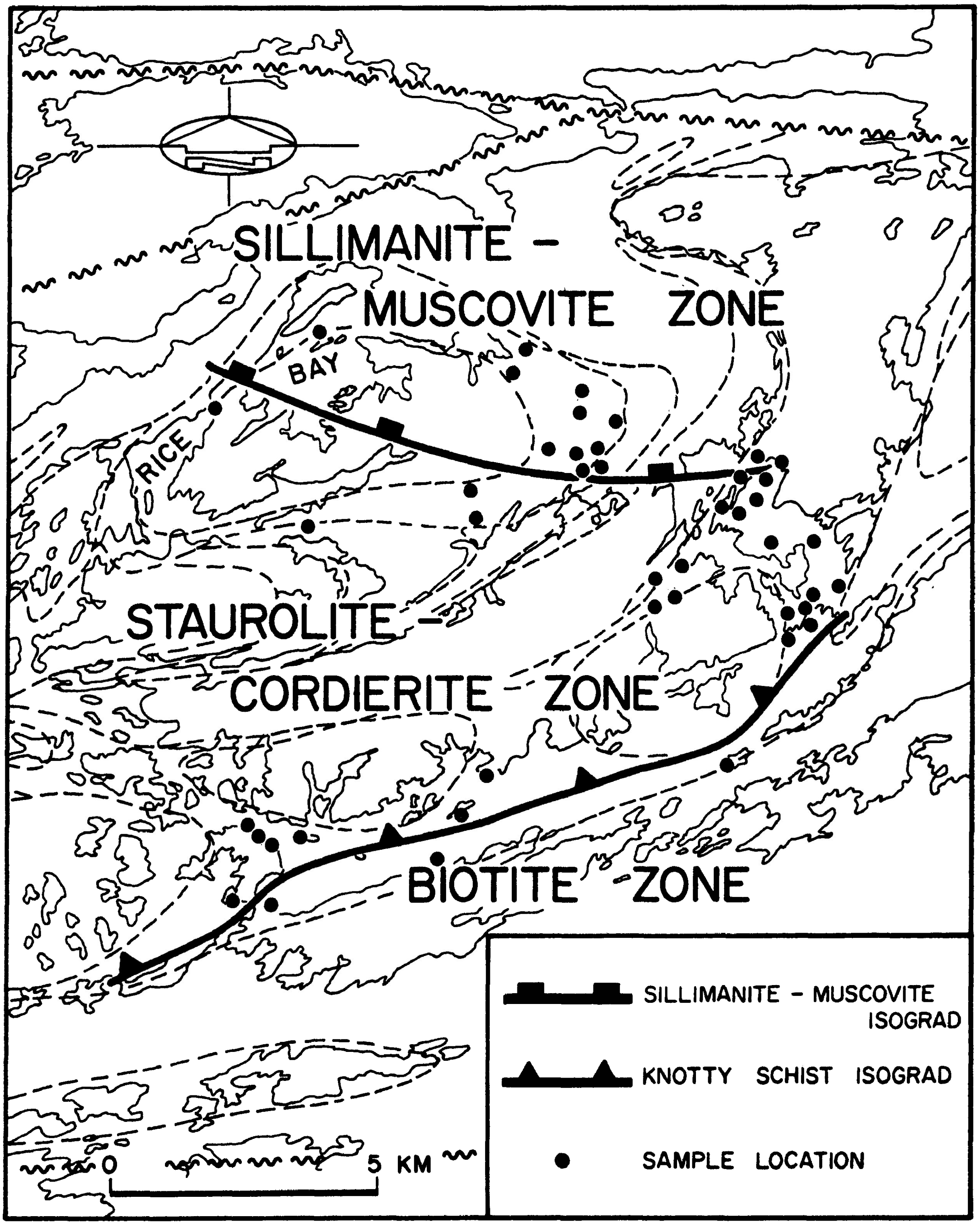
This isograd then separates the biotite zone from the staurolite-cordierite zone.

Table 7

Metamorphic Mineral Assemblages

	METAPELITES	METABASITES
BIOTITE ZONE	biotite + muscovite ± chlorite	hornblende + chlorite + plagioclase + quartz
		hornblende + epidote + quartz ± plagioclase
STAUROLITE-CORDIERITE ZONE	staurolite + chlorite + biotite	actinolite + mg - chlorite + plagioclase
	staurolite + garnet + biotite ± chlorite	hornblende + plagioclase
	staurolite + andalusite + garnet + biotite	tremolite(?) + magnetite + mg - chlorite ± talc ± carbonate
	cordierite + andalusite + garnet + biotite	
	cordierite + biotite	
SILLIMANITE-MUSCOVITE ZONE	staurolite + garnet + biotite	hornblende + plagioclase + quartz + sphene
	staurolite + sillimanite + biotite	tremolite(?) + magnetite + mg - chlorite + talc
	muscovite + sillimanite + biotite	
	muscovite ± sillimanite + garnet + biotite	chlorite + garnet + quartz + biotite

Figure 19 - Map of the inferred extent of the metamorphic zones.


SILLIMANITE -
MUSCOVITE ZONE
RICE
BAY
STAUROLITE -
CORDIERITE ZONE
BIOTITE ZONE
0
5 KM
SILLIMANITE - MUSCOVITE ISOGRAD
KNOTTY SCHIST ISOGRAD
SAMPLE LOCATION

The sillimanite isograd marks the first appearance of that mineral in pelites. The data of figure 18 show that this may result from the breakdown of staurolite accompanied by the growth of muscovite and possibly garnet. Pseudomorphic growth of muscovite after staurolite in this way is characteristic of the transition into silliminite zones in general (Guidotti, 1968). Possible reactions include:

Staurolite + Na-muscovite + quartz $\rightarrow$ sillimanite + K-muscovite + garnet + albite + H_2O (Guidotti, 1970)

Staurolite + muscovite + quartz $\rightarrow$ sillimanite + biotite + H_2O (Hoschek, 1969).

It is also possible that some aggregates of muscovite and sillimanite are pseudomorphs after andalusite. In this case, the distribution of sillimanite will be controlled by a reaction such as:

andalusite + K^+ $\rightarrow$ muscovite + sillimanite (Carmichael, 1969; Glen, 1979).

The sillimanite isograd separates the staurolite-cordierite zone from the sillimanite-muscovite zone.

Table 7 presents typical assemblages observed in pelitic rocks from these zones. In all cases quartz and plagioclase are additional minerals.

Chemical Controls

The data of Table 3 were studied to ascertain if rock compositions played a role in the distribution of metamorphic assemblages in the zones. Ternary AFM diagrams (Thompson, 1957; Renhardt, 1970) were constructed according

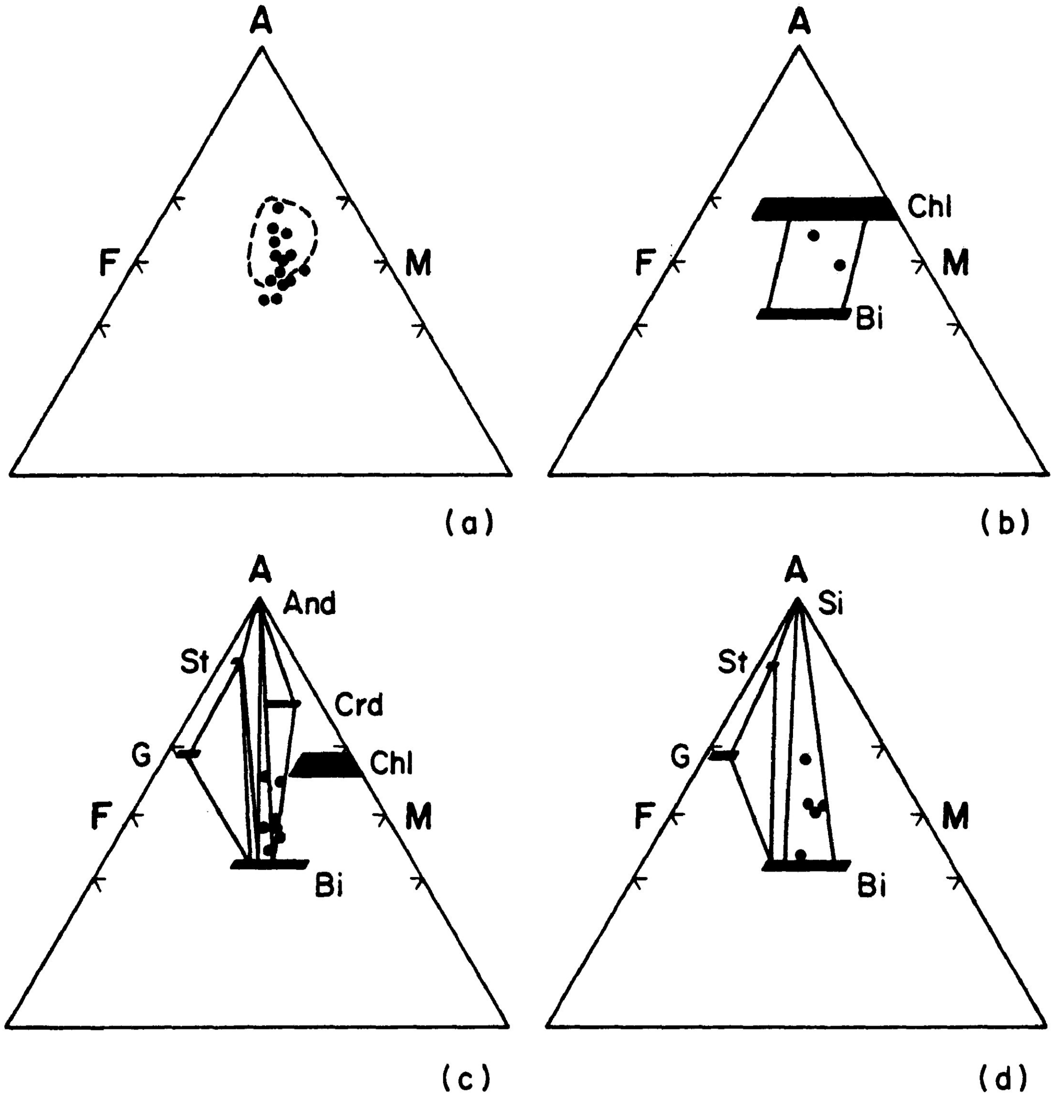
Figure 20 - Thompson type AFM diagrams.

(a) A plot of all data for pelites from the study area. The dashed line defines the field for the range of compositions in similar rocks from the Slave Province (Thompson, 1978).

(b) Compositions of samples from the biotite zone.

(c) Compositions for the staurolite-cordierite zone. Tie lines represent mineral assemblages which have been observed in this zone.

(d) Compositions for the sillimanite-muscovite zone. Tie lines represent mineral assemblages which have been observed in this zone.



And – Andalusite G – Garnet Crd – Corderite
St – Staurolite Si – Sillimanite Chl – Chlorite
Bi – Biotite

to procedures outlined by Winkler (1974, Ch. 5). Figure 20a presents data from all zones and shows that they occupy a position in the diagram similar to that reported from the Slave Province (Thompson, 1978).

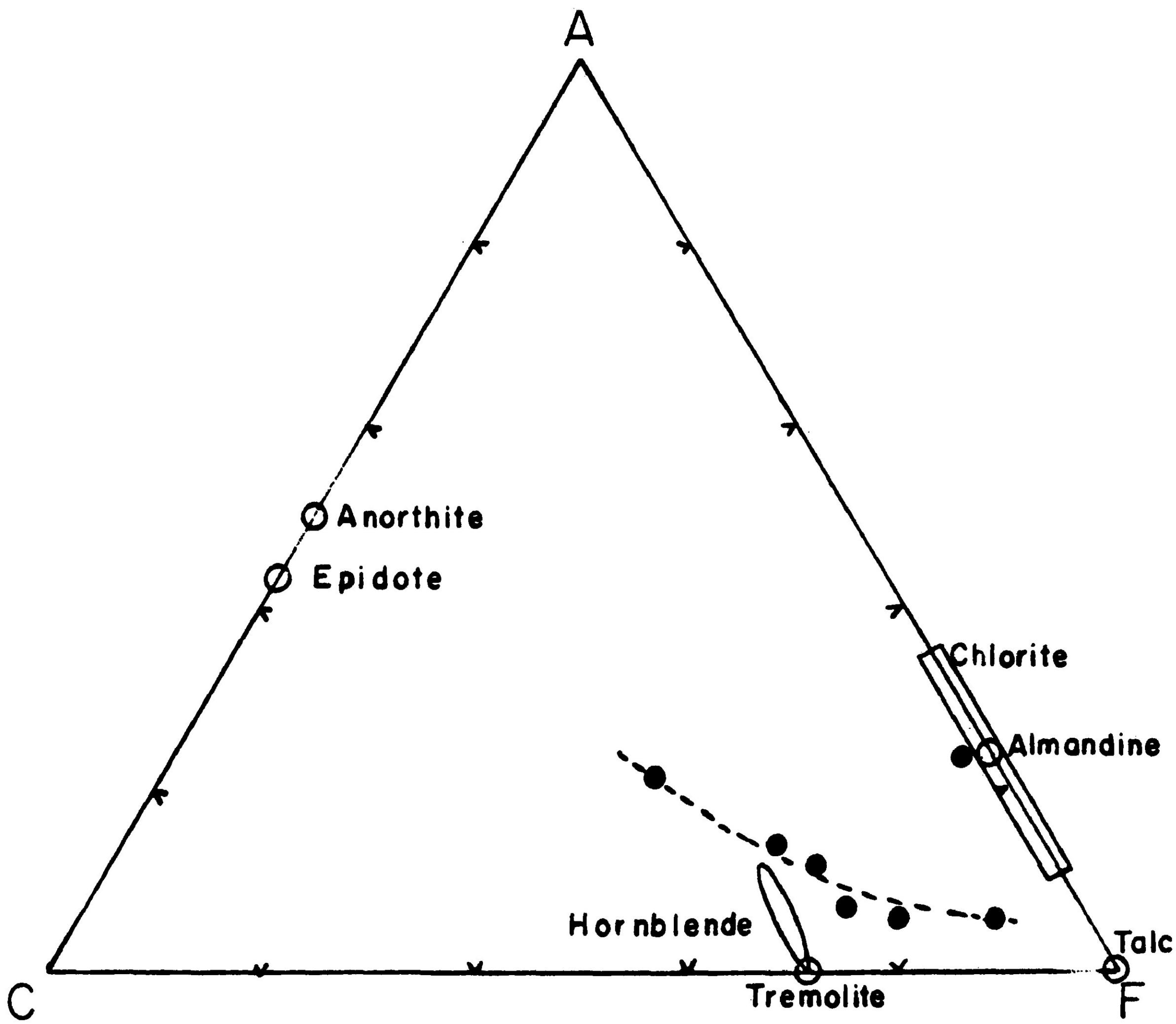
Figure 20 b,c,d gives data from individual zones. The tie-lines show common combinations of coexisting minerals observed in the zones. Because a fourth phase is often present, these observed mineral "assemblages" conflict with those predicted by the bulk chemical composition. Thus, theoretically, stable assemblages such as staurolite-garnet-biotite should not appear in muscovite-bearing rocks of this composition. The data (Fig. 20) also show that compositional variability between zones is no greater than that within a single zone. Thus, it may be concluded that the zones, as mapped, are a result of variation in intensive variables such as temperature and pressure.

BASIC ROCKS

Typical specimens contain variable quantities of hornblende, actinolite, chlorite, talc, epidote, sphene, plagioclase, garnet and quartz. No systematic patterns of mineral occurrence have been documented. It should be noted that the bulk chemical composition (Table 3) is likely to influence the metamorphic assemblages presented in Table 7.

Figure 21 shows the variation in bulk chemical composition for some mineral assemblages in basic rocks. Values for A, C and F have been calculated in accordance

Figure 21 - ACF diagram for basic rocks from the study area. The data of Table 3 are plotted along with estimated compositions for those phases which have been identified. The dashed line may represent a primary trend of compositional differentiation for the parent volcanic rocks.


A
Anorthite
Epidote
Chlorite
Almandine
Hornblende
Talc
C
Tremolite
F

with procedures outlined by Winkler (1974, Ch. 5). The dashed line (Fig. 21), along which most of the data points are distributed, probably reflects an igneous differentiation trend for the parental volcanic rocks. The one deviant point which represents a garnetiferous metabasite clearly shows a strong chemical influence on this mineral assemblage. Based on the above data, it is obvious that the metabasic rocks from this area are not as useful as metapelites in determining variations in metamorphic grade. However, the coexistence of chlorite and hornblende in metabasic rocks from the biotite zone is consistent with low grade metamorphism. The absence of chlorite with hornblende, as seen in the sillimanite zone, is indicative of medium grade metamorphism (Winkler, 1974, p. 170).

DISCUSSION

METAMORPHISM

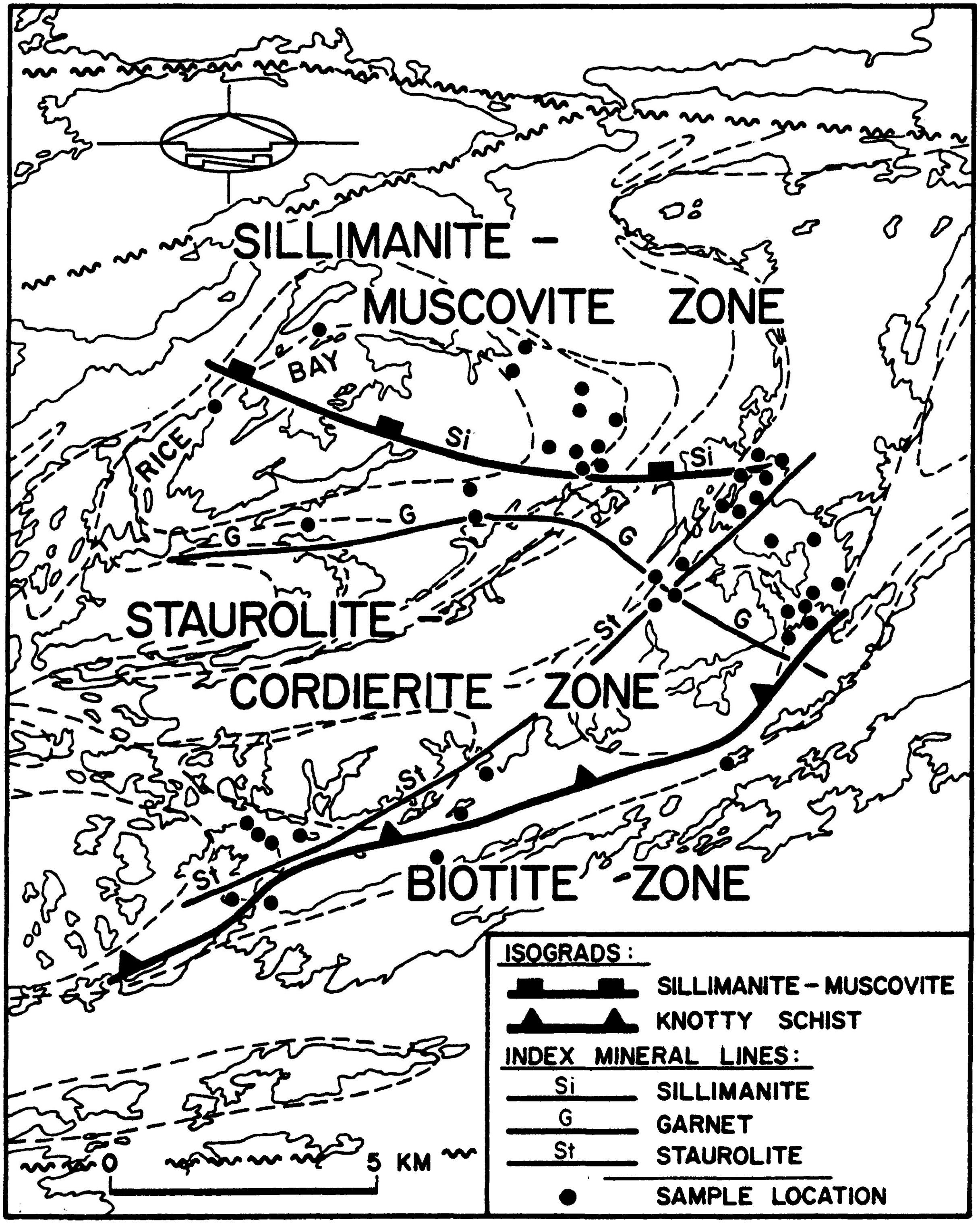
Figure 22 summarizes the distribution of the key index minerals within the metamorphic zones. Discussion of these minerals and their distribution is given below.

Conditions of Metamorphism

The variations in observed metamorphic mineral assemblages are consistent with the transition from low to medium grade metamorphism (Winkler, 1974). The experimental data of Hoschek (1969) on the formation and breakdown of staurolite (Fig. 23a) provide good estimates of temperature ranges which likely prevailed during metamorphism. The presence of andalusite with staurolite at some localities suggests that pressures were low. The presence of cordierite and garnet without staurolite at Bear Passage may be indicative of pressures around 3 Kb (Hess, 1969). This stability field is also illustrated in Figure 23a. It is estimated therefore, that metamorphism likely occurred at load pressures of 2.5 to 3.5 Kb with temperatures between 500° and 650° C.

Thompson (1978) attributed the ubiquitous occurrence of cordierite, in place of staurolite, in pelitic schists of the Slave Province to unique rock compositions rather than to such low pressures. The data presented here show that the Rainy Lake pelitic rocks are compositionally

Figure 22 - Summary map of the metamorphic zones showing some key index mineral lines.


SILLIMANITE -
MUSCOVITE ZONE
BAY
RICE
Si
Si
G
G
G
G
St
STAUROLITE -
CORDIERITE ZONE
St
St
BIOTITE ZONE
ISOGRADS:
SILLIMANITE - MUSCOVITE
KNOTTY SCHIST
INDEX MINERAL LINES:
Si SILLIMANITE
G GARNET
St STAUROLITE
SAMPLE LOCATION
0 5 KM

similar (Fig. 20a), yet staurolite is prevalent. The reason for this discrepancy probably stems from the failure of the AFM projection to correctly predict the mineral assemblages expected for a rock of a given bulk composition. It has been shown here that observed assemblages such as staurolite-garnet-biotite should not be present in rocks of this bulk composition (Fig. 20c). This assemblage does occur however, but usually in the presence of magnesian chlorite rather than muscovite. One of the underlying assumptions for the use of the AFM projection is the presence of muscovite. While some muscovite is present in the pelites from the staurolite-cordierite zone, it may be interpreted as an alteration product of other minerals. If this is so, then the AFM projection is not applicable to pelitic rocks in this zone and additional mineral phases are permitted. Thus, the compositional dependence of cordierite in favour of staurolite, as proposed by Thompson (1978), is open to question. Their presence or absence in rocks of a given composition will then largely be controlled by the baric type of metamorphism.

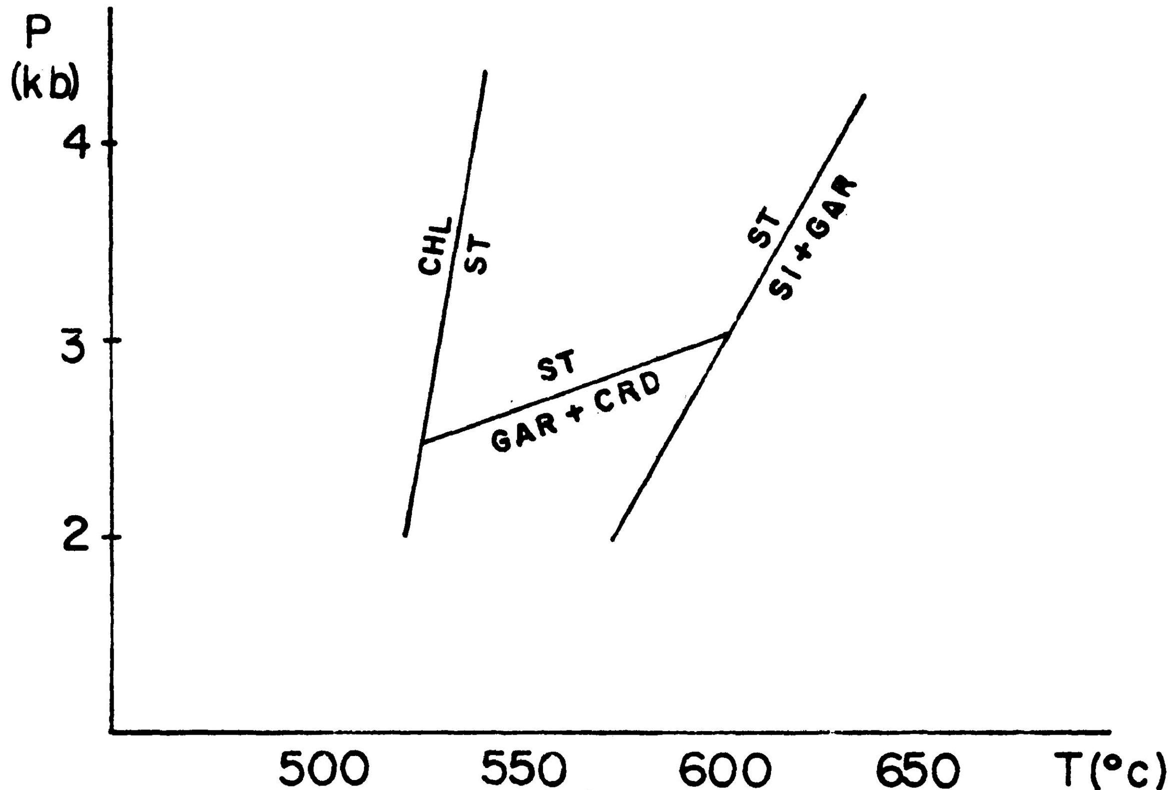
Metamorphic Distribution

One of the most striking features displayed by the index mineral lines is their lack of parallelism. This may be explained by post-metamorphic deformation or by the superposition of contact metamorphism on pre-existing regional metamorphic patterns. Also, lateral variations in

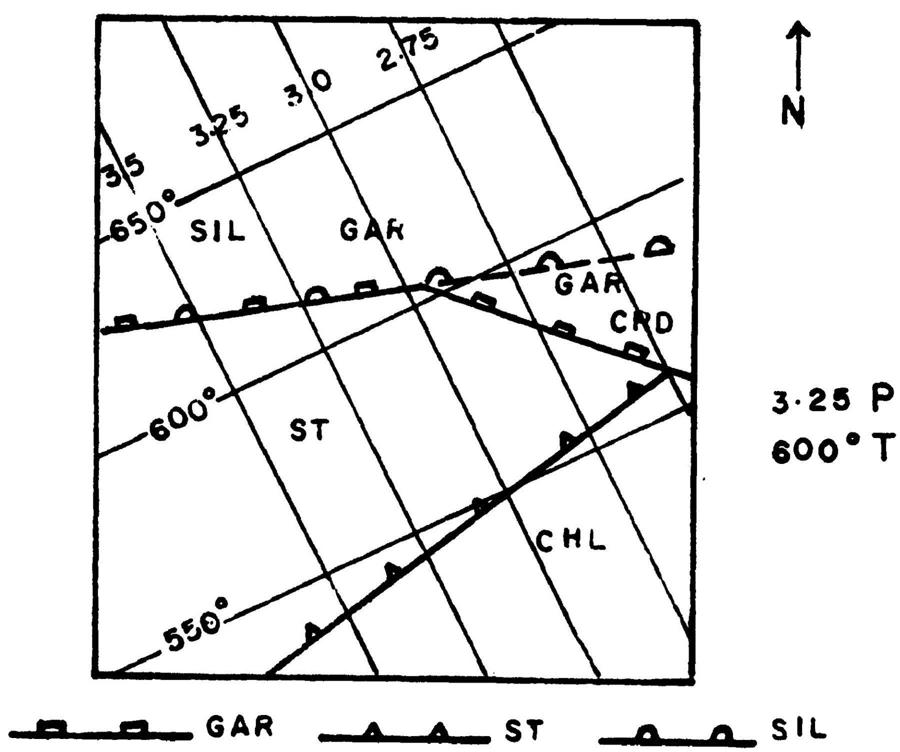
Figure 23 - Intersecting index mineral lines.

(a) Pressure-temperature diagram showing the stability of staurolite. The staurolite-forming and staurolite-breakdown reactions are from the experimental data of Hoschek (1969) and the staurolite-cordierite transition is estimated from the data of Hess (1969).

(b) Schematic map of possible temperature and pressure distributions on the present erosional surface at the time of metamorphism. This distribution is hypothetical yet satisfies the data of Figure 22 reasonably well.


P
(kb)
4
3
2
CHL
ST
ST
GAR + CRD
ST
SI + GAR
500
550
600
650
T(°c)

(a)


N
3.5
3.25
3.0
2.75
650°
600°
550°
SIL
GAR
GAR
CRD
ST
CHL
3·25 P
600° T
GAR
ST
SIL

(b)

fluid phase pressures or compositions might lead to similar patterns. A forthright explanation for this distribution, however, may be found using the hypothesis that isotherms and isobars need not be parallel during metamorphism. Intersecting isograds from other terrains have been explained successfully using this explanation (Thompson, 1976, 1978). Solutions for possible pressure-temperature distributions were made using a "trial and error" method. Mineral index lines in map view were drawn to satisfy hypothetical pressure-temperature conditions. The position of each line was determined from a P-T representation of the mineral's stability boundary (Fig. 23a). Figure 23b is a schematic map of the study area which shows a particular solution which strongly resembles the observed distributions of metamorphic minerals. Discounting the possibility of overturned isotherms, this solution would suggest that they were tilted southward during metamorphism.

Relationship Between Metamorphism and Deformation

Staurolite, garnet and andalusite display textures of synkinematic to postkinematic growth. Preferred dimensional orientation of porphyroblasts parallel to S_2 at some locations suggests mineral growth related to deformation. At other locations random orientations of porphyroblasts and the overprinting of garnets on S_3 cleavage domains suggests that metamorphism outlasted deformation. It is likely that the metamorphic patterns which are observed have been minimally affected by post-metamorphic deformation except for faulting and uplift.

Regional Significance of Metamorphic Patterns

Based on the occurrence and distribution of minerals and mineral assemblages, two contrasting patterns of metamorphism have generally been documented in Archean terrains on a world-wide basis. In the first of these, isograds are more or less parallel to the boundaries of the gneissic belts with an increase in metamorphic grade towards the centre of the gneissic belt. Such patterns have been observed in portions of the Quetico belt to the south (Kehlenbeck, 1977; Pirie and MacKasey, 1978; D. Southwick, pers. comm.). The second pattern, typical of volcano-plutonic belts (Ayres, 1978; Thompson, 1978; Saggerson and Turner, 1976), are somewhat more irregular with a zonal distribution relative to large batholiths. Patterns of this type are well documented in parts of the Wabigoon belt to the north (GSC Map 1475A). The possible southward tilting of isotherms indicated for the study area suggests that here metamorphism is related to the latter type of regional pattern.

STRUCTURE

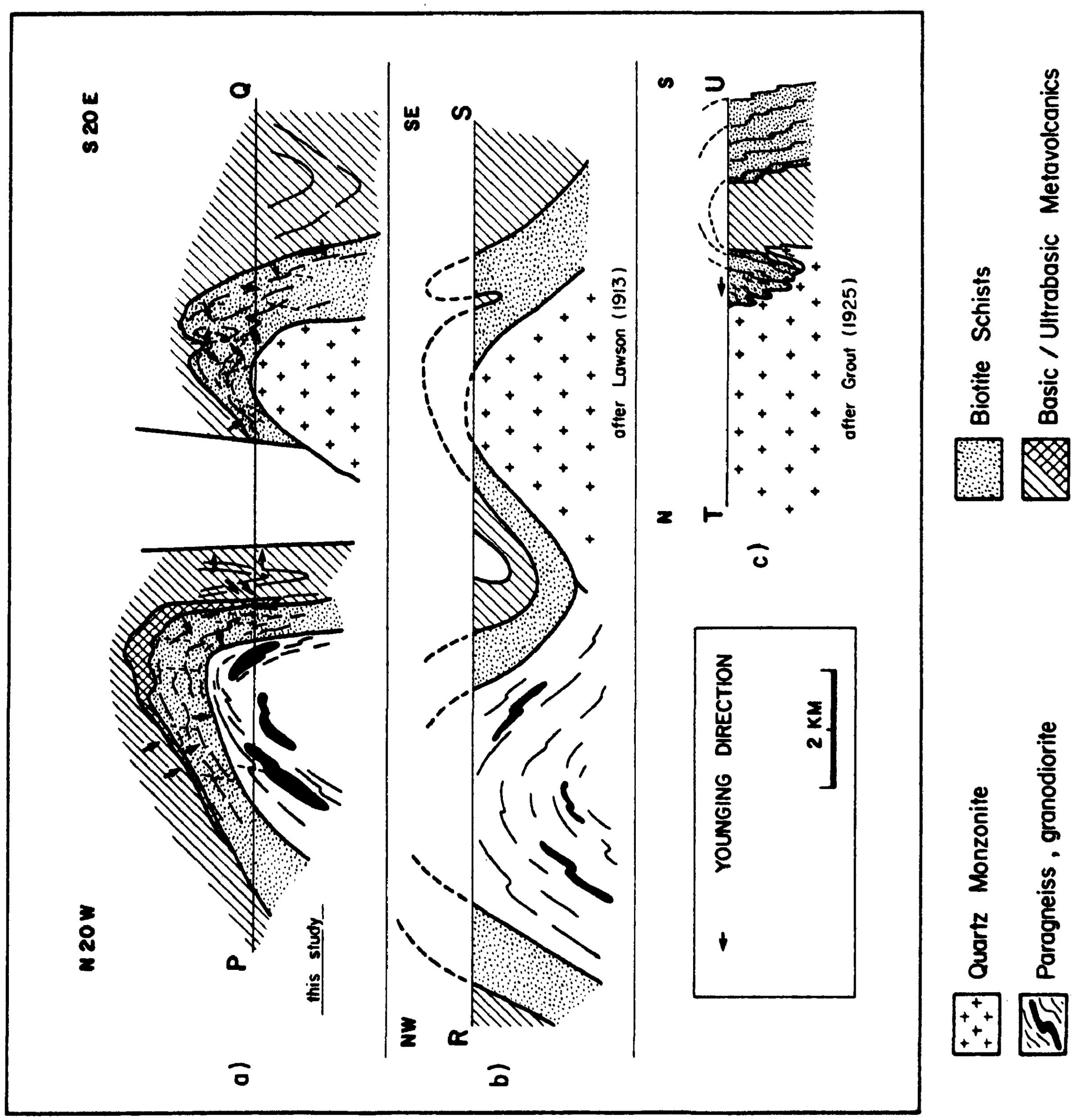
Figure 24 illustrates a number of structural cross-sections. Positions of these sections are indicated in Figure 8. The geological relationships shown in Figure

Figure 24 - Geological cross-sections (see Fig. 8 for locations)

(a) A composite cross-section for the study area. The section is based to a great extent on the data of Fig. 14.

(b) Cross-section of Lawson (1913).

(c) Cross-section of Grout (1925).


a)
N 20 W
S 20 E
P
Q
this study
b)
NW
SE
R
S
after Lawson (1913)
c)
N
S
T
U
after Grout (1925)
YOUNGING DIRECTION
2 KM
Quartz Monzonite
Biotite Schists
Paragneiss , granodiorite
Basic / Ultrabasic Metavolcanics

24a represent a compilation of the structural data from this study. The sections previously published by Lawson (Fig. 24b) and Grout (Fig. 24c) are shown for comparison.

Deformational History

It is clear from the cross-sections (Fig. 24) that Lawson and Grout recognized the existence of the kilometer size upright folds, F_2 of this study. It should be noted that Grout's interpretation of folds conflicts with the data of this study. Harris (1974) generally recognized the same folds which are termed F_2 in this study (Fig. 24a) and suggested that they represent the bulk of deformation in the area. The cross-section (Fig. 24a) however emphasizes that these F_2 folds were most likely superimposed on inverted strata, possibly on the lowermost limits of a large recumbent F_1 fold. In addition, it has been shown (Fig. 10) that minor F_3 folds associated with a crenulation cleavage are superimposed on the F_2 folds. Based on the data of this study, a three phase deformational history is therefore indicated.

A number of well documented examples of polyphase deformation involving Archean rocks have been published. These studies present data similar to those from Rainy Lake. Invariably, F_1 folds of large amplitude and wavelength are superimposed by F_2 folds of lesser size. The F_2 event is accompanied by development of a penetrative axial planar cleavage. A crenulation cleavage and axial surfaces of F_3 folds transect the early structures at a high angle. In most documented cases, F_1 folds are upright (Hooper and Ojakangas, 1971; Hudleston, 1976; Fyson et al., 1979) but in some cases recumbent folds have been observed; for example, in Southern Africa (Stowe, 1974; Coward et al., 1976; Key et al., 1976), in Greenland (Bridgewater et al., 1974; Myers, 1976), and in Australia (Archibald et al., 1978). Until now, only one other example of recumbent F_1 structures has been reported from North America (Thurston and Breaks, 1978).

Regional Significance of Structural Overturning at Rainy Lake

Based on studies from other Archean terrains, various explanations for early large recumbent folds have been suggested. Each of these may be reviewed in relationship to the structural history of the Rainy Lake region.

Myers (1976) has proposed that compressional tectonics of the Tibetan type operated in Archean times. Horizontal tectonics of this type are commonly thought to be linked to continental collision and the closing of ocean basins with the result that obducted oceanic crust is emplaced allochthonously upon cratonic masses marginal to the basins (Williams, 1977). Goodwin (1977) has proposed that in Archean times a major volcanic basin occupied much of the area to the north of the study area. He has suggested that the Quetico and English River gneissic belts represent a cratonic infrastructure which was marginal to the volcanic basin. At Rainy Lake, closure of such a basin would require emplacement of nappes from the north to the south. These southward closing nappes might also be accompanied by thrusts. Further, such a model would suggest that nappe development, D_1, was independent of later deformation and constitutes a distinct deformational event.

Thurston and Breaks (1978) have proposed that crustal instability at an initially inclined interface between subprovinces would result in the generation of pleurotoid nappes. Based on the model studies of Talbot (1974), they have suggested that large recumbent structures near the boundary between the English River and Uchi subprovinces may be explained in terms of gravitational tectonics. They have postulated that nappes advanced from the English River gneissic terrain and were transported northward onto the volcano-plutonic rocks of the Uchi subprovince. The Rainy Lake area also lies between two structural subprovinces, the Quetico gneissic belt and the Wabigoon volcano plutonic belt (Stockwell, 1970). Application of the above model to the Rainy Lake area would require northward emplacement of nappes from the Quetico subprovince onto the rocks of the Wabigoon belt.

Gorman et al. (1978) have proposed that recumbent structures should develop near the margins of large crustal diapirs. They have postulated that the diapirs represent remobilization of buoyant gneissic rocks which once formed part of the basement for volcanic and sedimentary supracrustal strata. They have pointed out that compressional features such as thrusts and recumbent folds should be generated in the supracrustal rocks near the margins of the upper surface of a basement derived diapir. First order gneissic diapirs of this type are present immediately to north of the study area (Sutcliffe, 1977; Schwerdtner et al., 1979). The rocks of the study area are presently separated from these diapirs by the Quetico Fault (MacKasey et al., 1974). However, it is likely that they were marginal to one of the diapirs at the time of its emplacement. Application of the diapiric model to the Rainy Lake area would require southward advance of nappes. This model would also imply that all three phases of deformation might merely represent progressive episodes in a single deformational event.

Because the size of the study area is small compared to the scale of the phenomena described above, further documentation of the nature of D_1 deformation at the regional scale is required before a critical assessment may be made of the application of these models to the observed structures.

STRATIGRAPHY

The structural data of this study support the view that a reappraisal of the long-standing stratigraphic controversies at Rainy Lake is required.

The Seine-Coutchiching Problem

One of the important results of this study is the apparent resolution of one aspect of the Seine-Coutchiching problem. The stratigraphic superposition of the Coutchiching rocks upon the Keewatin is clearly indicated (Fig. 24a). It follows that neither of the two previous structural and stratigraphic interpretations for this area were correct. Lawson, and those who supported his interpretation, correctly outlined some folds, here designated F_2, but based their stratigraphic interpretation on the fact that the Coutchiching rocks occupied the cores of antiforms which they assumed to be anticlines. Grout and his supporters, on the other hand, emphasized the directions of younging indicated by graded beds near the contact on Morton Island. Grout, however, used these younging relationships to determine not only the stratigraphic succession but also the structure. His structural interpretation (Fig. 24c) is inconsistent with observed minor structures and differs from that presented here.

The results of this study indicate that the controversy has arisen, not because of observational errors by previous workers, but due to the lack of integration of younging observations with other minor structures. It is indeed unfortunate that Lawson chose Rainy Lake as the area in which to construct a system for Archean stratigraphic nomenclature.

The Laurentian Problem

An added stratigraphic difficulty which results from the present structural interpretation involves the rocks exposed in the core of the Rice Bay dome. Recent investigations (Peterman et al., 1972; Harris, 1974) have included the paragneisses exposed here with the Coutchiching on the premise that they represented the highly metamorphosed "root" of the sedimentary sequence. From the data presented here, it is suggested that these rocks are petrographically and chemically distinctive and that the Coutchiching rocks become younger towards the contact with the paragneisses of the dome. Two explanations are possible: either the paragneisses represent a sequence which is stratigraphically younger than the Coutchiching or the Coutchiching rocks have been allochthonously emplaced upon the paragneisses. Thus, at best, the stratigraphic position of the paragneisses is uncertain.

CONCLUSIONS

Based on the new data presented in this thesis for the Rice Bay-Bear Passage area, the following conclusions may be drawn:

1. Coutchiching metasedimentary rocks are younger than Keewatin metavolcanic rocks.
2. Layered rocks at the core of the Rice Bay dome have an uncertain stratigraphic position.
3. The rocks of the area record a polyphase deformational history.
4. The structural "grain" of the rocks of the area is dominated by F_2 folds and domes. Granitoid rocks in the core of the Rice Bay dome are folded by F_2 while the Algoman plutons postdate F_2.
5. The stratigraphic succession was inverted, most probably prior to F_2 folding, presumably by large fold nappes. Thrust nappes may also have formed.
6. Based on the study of pelitic rocks of the Coutchiching Group, it may be concluded that metamorphism took place simultaneously with deformation at moderate pressures and temperatures indicative of low and medium grade metamorphism.
7. Metamorphic isograds and index mineral lines are non-parallel. Their distribution indicates a northward doming of isotherms at the time of metamorphism.

The above conclusions indicate that the geological history of the rocks at Rainy Lake is much more complex than that envisaged by Lawson, some 90 years ago. Nonetheless, they fail to refute many of Lawson's sound field observations but merely serve as a refinement of his early mapping. Many problems remain unresolved in Rainy Lake geology: the lateral geographic extent of structurally overturned strata and the relationship of the Seine conglomerate to the other stratigraphic units are two particular examples.

APPENDIX

A: WHOLE ROCK CHEMICAL ANALYSIS

Methods

SiO_2, Al_2O_3, total Fe_2O_3, CaO, K_2O, MgO and TiO_2 were determined by x-ray fluorescence measurements made on glass discs composed of rock powder fused with a borate-lanthanum flux. Na_2O and MnO were determined by atomic absorption spectrophotometry on solutions prepared by the digestion of rock powders in a mixture of hydrofluoric and nitric acids. P_2O_5 was determined by a "molybdenum blue" colorimetric method. FeO was determined by potassium dichromate titration and Fe_2O_3 was calculated by difference from the FeO and total Fe_2O_3 determinations. Total water and carbon dioxide were determined instrumentally on a Perkin-Elmer CHN analyser.

Precision

Sample KHP-17, a pelitic rock, was routinely analysed four times. Table 8 gives the replicate analyses for this sample. The variations shown reflect that to be expected for a typical chemical analysis. The analysis of KHP-17 reported in Table 4 represents a mean of the data in Table 8.

Accuracy

Fused discs and solutions were prepared from USGS

Table 8

Precision of Whole-rock Chemical Analyses

Sample KHP-17

Oxide	Analysis 1	Analysis 2	Analysis 3	Analysis 4
SiO_2	60.85	60.80	60.99	60.80
Al_2O_3	17.02	17.32	17.29	17.43
TiO_2	.56	.57	.57	.56
FeO^*	5.48	5.60	5.54	5.54
Fe_2O_3	1.70	1.49	1.65	1.36
MgO	3.61	3.53	3.40	3.70
CaO	1.81	1.84	1.84	1.83
Na_2O	3.26	3.14	3.10	2.97
K_2O	3.31	3.36	3.33	3.37
P_2O_5	.19	.19	.17	.19
MnO	.07	.07	.07	.07
CO_2^{**}	.07	.07	.07	.07
$H_2O^{**}_{total}$	2.16	2.16	2.16	2.16

* duplicated only

** not replicated

Table 9

Oxide	Joliffe (6 samples	MacRae (4 samples)
SiO_2	38.7	40.1
Al_2O_3	6.1	5.0
TiO_2	1.6	1.5
FeO	11.2	17.5 total Fe_2O_3
Fe_2O_3	4.7	
MgO	15.5	19.4
CaO	9.0	7.8
Na_2O	.2	.01
K_2O	.6	.02
P_2O_5	.08	.13
CO_2	6.7	3.7
H_2O total	6.6	8.2

standard rocks G-2, GSP-1, AGV-1 and BCR1. Recommended values for these international reference standards were used to establish calibration curves in all analytical methods.

B: CHEMISTRY OF THE STEEPROCK ASHROCK

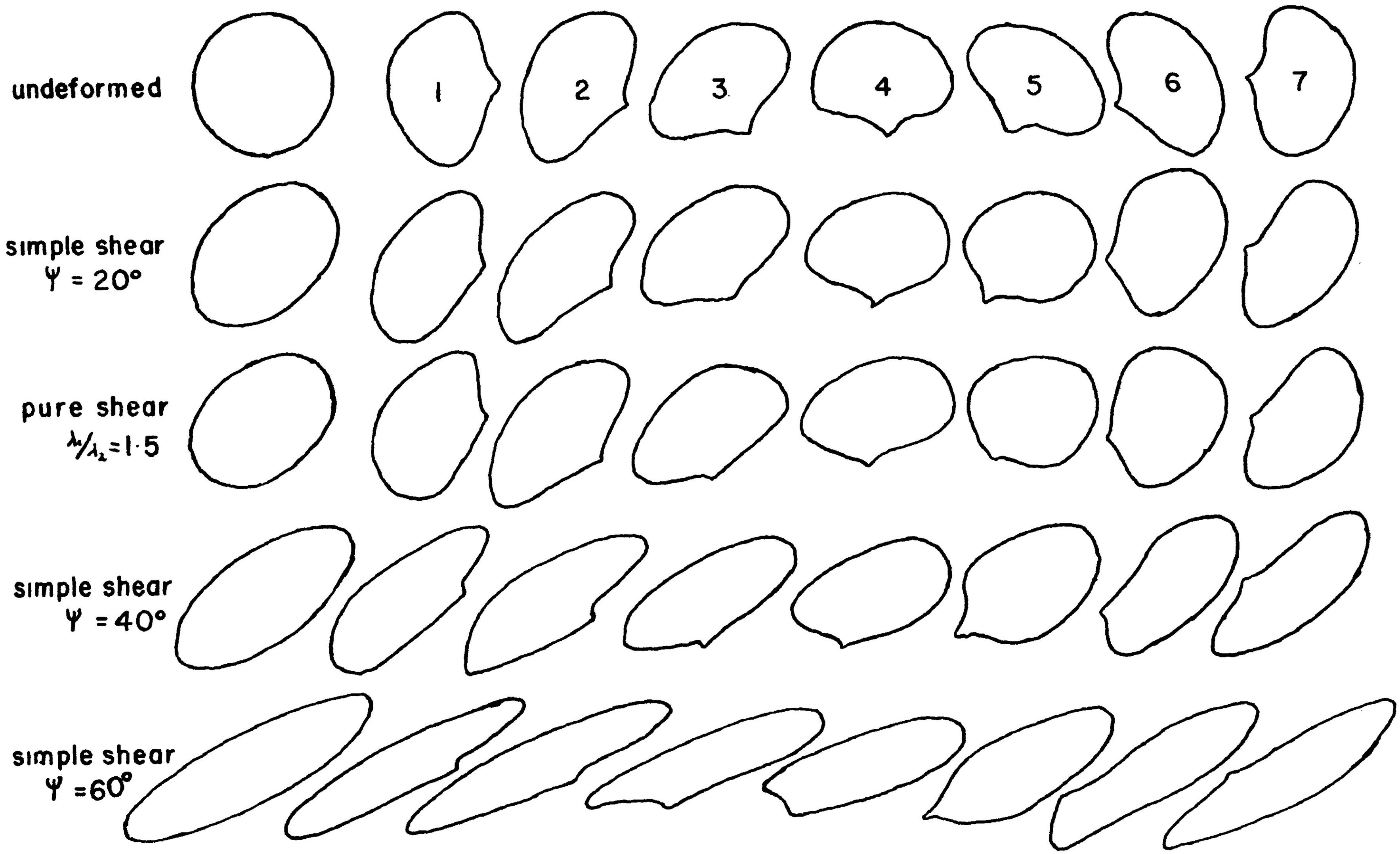
The data of Table 9 (Joliffe, 1971; W. MacRae, pers. comm.) were used to calculate the renormalized values presented in Table 3.

C: EXPERIMENTS IN PILLOW DEFORMATION

Simple experiments were devised to investigate the effects of rotational and irrotational homogeneous deformation on undeformed pillow shapes having variable orientations. Card deck models produced a rotational strain by simple shear and the relaxation of a stretched rubber sheet produced an irrotational deformation, by pure shear in 2-dimensions. The results are presented in Figure 25. Values of angular shear for the simple shear model and ratios of the principal axes of the strain ellipse in the pure shear model are also shown.

As Figure 25 shows, the directional properties of pillows are well preserved for moderate magnitudes of finite strain. The shape of deformed pillows is somewhat dependent on the strain history (compare pillow number 4 for simple shear versus pure shear). In any undeformed pillow, a single material line corresponds to the longest axis of the

Figure 25 - Experimentally deformed pillows. Results of 2-dimensional experimental deformation of pillows with simple initial shape but variable initial orientation. The shapes of the finite strain ellipse is shown for each stage of deformation. Values of angular shear (ψ) for simple shear and of axial ratios ($\lambda 1/\lambda 2$) for pure shear are given.


undeformed
1
2
3
4
5
6
7
simple shear
Ψ = 20°
pure shear
λ1/λ2 = 1·5
simple shear
Ψ = 40°
simple shear
Ψ = 60°

structure. This likely represents an undeformed marker of bedding. In the deformed state, however, this marker does not in general correspond to the longest axis of the pillow. Further, the longest axis of the deformed pillow does not coincide with the major principal axis of the finite strain ellipse. The pillow shapes shown in Figure 25 are attributed to tectonic deformation. They are similar to those shown by Coté and Dimroth (1976), although in their case they attributed such shapes as having been acquired in the molten state by overriding volcanic flows. They have used these shapes to interpret flow directions, a procedure which is certainly not applicable in tectonically deformed terrains. In summary, it should be emphasized that the shape of a deformed pillow and the orientation of its longest axis as viewed on a 2-dimensional outcrop surface, are controlled by initial pillow shape, by the finite strain ellipse and by the strain history.

References

1978: Metamorphic map of the Canadian Shield; Geol. Surv. Can., Map 1475A.

Allard, G.O.
1970: The Doré Lake complex, Chibougamau, Quebec - a metamorphosed Bushveld-type layered intrusion; Geol. Soc. S. Afr., Spec. Publ., 1, p. 477-491.

Alt, D.D.
1958: A review of the geology of Rainy Lake; unpubl. MS thesis, University of Minnesota, 73 p.

Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I. and Gunthorpe, R.J.
1978: The evolution of Archean greenstone terrains, Eastern Goldfields Province, Western Australia; Prec. Res., v. 6, p. 103-132.

Ayres, L.D.
1978: Metamorphism in the Superior province of northwestern Ontario and its relationship to crustal development; in Metamorphism in the Canadian Shield, ed. J.A. Fraser and W.W. Heywood; Geol. Surv. Can., Paper 78-10, p. 25-36.

Bishop, D.G. and Force, E.R.
1969: The reliability of graded bedding as an indicator of the order of superposition; J. Geol., v. 77, p. 346-352.

Borradaile, G.J.
1976: "Structural Facing" (Shackleton's Rule) and the Paleozoic rocks of the Malaguide Complex near Vélez Rubio, SE Spain; Proc. Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam, ser. B, v. 79, p. 330-336.

Bridgewater, D., McGregor, V.R., and Myers, J.S.
1974: A horizontal tectonic regime in the Archean of Greenland and its implications for early crustal thickening; Prec. Res., v. 1, p. 179-197.

Bruce, E.L.
1925: The Coutchiching rocks of the Bear's Pass section, Rainy Lake; Roy. Soc. Can., Proc. and Trans., 3rd Ser., v. 19, sec. 4, p. 43-46.

1927: Coutchiching delta; Geol. Soc. Am Bull., v. 38, p. 771-782.

Carmichael, D.M.
1969: On the mechanism of prograde metamorphic reactions in quartz-bearing pelitic rocks; Cont. Mineral. Petrol., v. 20, p. 244-267.

Condie, K.C.
1976: Trace element geochemistry of greenstone belts; Earth Sci. Rev., v. 12, no. 4, p. 393-417.

Coté, J. and Dimroth, E.
1976: Flow directions of Archean basalts determined from imbricated pillow breccias; N.Jb. Miner. Mh., p. 97-109.

Coward, M.P., James, P.R. and Wright, L.
1976: Northern margin of the Limpopo mobile belt, Southern Africa; Geol. Soc. Am. Bull., v. 87, p. 601-611.

Cram, I.H.
1932: The Rest Island granite of Minnesota and Ontario; Geol., v. 40, p. 270- 278.

Davies, J.C.
1973: Geology of the Fort Frances Area, District of Rainy River; Ontario Div. Mines, GR107, 35 p. Accompanied by Map 2263, scale 1 inch to 1 mile.

Davies, J.C. and Pryslak, A.P.
1967: Kenora-Fort Frances Sheet, Kenora and Rainy River Districts; Ont. Dept. Mines, Geol. Comp. Series Map 2115, 1 inch to 4 miles.

Dimroth, E., Cousineau, P. Leduc, M. and Sanschagrin, Y.
1978: Structure and organization of Archean subaqueous basalt flows, Rouyn-Noranda area, Que., Canada; Can. J. Earth Sci., v. 15, p. 902-918.

Frye, J.K.
1959: Petrography of the ancient granites of the Minnesota -Ontario boundary region; unpubl. MS thesis, University of Minnesota, 55 p.

Fyson, W.K. and Frith, R.A.
1979: Regional deformations and emplacement of granitoid plutons in the Hackett River greenstone belt, Slave Province, Northwest Territories; Can. J. Earth Sci., v. 16, p. 1187-1195.

Gélinas, L., Lajoie, J., and Brooks, C.
1977: The origin and significance of Archean ultramafic volcaniclastics from Spinifex Ridge, LaMotte Township, Québec; in Volcanic Regimes in Canada, ed. W.R.A. Baragar, L.C. Coleman, and J.M. Hall; Geol. Assoc. Can., Sp. Paper No. 16, p. 297-309.

Glen, R.A.
1979: Evidence for cyclic reactions between andalusite, "sericite" and sillimanite, Mount Franks area, Willyama Complex N.S.W.; in Microstructural Processes during Deformation and Metamorphism, ed. T.H. Bell and R.H. Vernon; Tectonophysics, v. 58, p. 97-112.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W.
1961: The Precambrian geology and geochronology of Minnesota; Minn. Geol. Surv. Bull. 41, 193 p.

Goldich, S.S. and Peterman, Z.E.
1978: Geology and geochemistry of the Rainy Lake Area; in Proceedings of the 1978 Archean Geochemistry Conference, ed. I.E.M. Smith and J.G. Williams, University of Toronto; p. 209-234.

Goodwin, A.M.
1977: Archean basin-craton complexes and the growth of Precambrian Shields; Can. J. Earth Sci., v. 14, p. 2737-2759.

Gorman, B.E., Pearce, T.H., and Birkett, T.C.
1978: On the structure of Archean greenstone belts; Prec. Res., v. 6, p. 23-41.

Grout, F.F.
1925: Coutchiching problem; Geol. Soc. Am. Bull., v. 36, p. 351-364.

Grout, F.F., Gruner, J.W., Schwartz, G.M., and Thiel, G.A.
1951: Precambrian stratigraphy of Minnesota; Geol. Soc. Am. Bull., v. 62, p. 1017-1078.

Guidotti, C.V.
1968: Prograde muscovite pseudomorphs after staurolite in the Rangeley-Oquossoc areas, Maine; Am. Mineral., v. 53, p. 1368-1376.

1970: The mineralogy and petrology of the transition from lower sillimanite zone in the Oquossoc area, Maine; J. Petrol, v. 11, pt. 2, p. 277-336.

Hanson, G.N.
1968: K-Ar ages for hornblende from granites and gneisses and for basaltic intrusives in Minnesota; Minn. Geol. Surv. Rept. Inv. 8, 20 p.

Hargreaves, R. and Ayres, L.D.
1979: Morphology of Archean metabasalt flows, Utik Lake, Manitoba; Can. J. Earth Sci., v. 16, p. 1452-1466.

Harris, F.R.
1974: Geology of the Rainy Lake Area, District of Rainy River; Ontario Div. Mines, GR 115, 94 p. Accompanied by Maps 2278 and 2279, scale 1 inch to ½ mi.

Hart, S.R. and Davis, G.L.
1969: Zircon U-Pb and whole-rock Rb-Sr ages and early crustal development near Rainy Lake, Ontario; Geol. Soc. Am. Bull., v. 80, p. 595-616.

Hess, P.C.
1969: The metamorphic paragenesis of cordierite in pelitic rocks; Contr. Mineral. Petrol., v. 24, p. 191-207.

Hirschberg, A. and Winkler, H.G.F.
1968: Stabilitatsbeziehumgen Zwischen Chlorit, Cordiesit und Almandin bei der Metamorphose; Contrib. Mineral. Petrol., v. 18, p. 17-42.

Jensen, L.
1976: A new cation plot for classifying subalkalic volcanic rocks; Ontario Div. Mines, MP66, 22 p.

Hudleston, P.J.
1976: Early deformational history of Archean rocks in the Vermillion district, northeastern Minnesota; Can. J. Earth Sci., v. 13, p. 579-592.

Hsu, M.Y.
1971: Analysis of strain, shape, and orientation of the deformed pebbles in the Seine River area, Ontario; unpubl. PhD thesis, McMaster University, 167 p.

Hoschek, G.
1969: The stability of Staurolite and Chloritoid and their significance in metamorphism of pelitic rocks; Contr. Mineral. Petrol., v. 22, p. 208-232.

Hooper, P.R. and Ojakangas, R.W.
1971: Multiple deformation in Archean rocks of the Vermillion district, northeastern Minnesota; Can. J. Earch Sci., v. 8, p. 423-434.

Hobbs, B.E., Means, W.D., and Williams, P.F.
1976: An outline of structural geology; J. Wiley and Sons, 571 p.

Joliffe, T.S.
1971: The character of the Steeprock Ashrock; unpubl. BSc thesis, Queen's University, Kingston, 57 p.

Kehlenbeck, M.M.
1976: Nature of the Quetico-Wabigoon boundary in the deCourcey-Smiley Lakes area, northwestern Ontario; Can. J. Earth Sci., v. 13, p. 737-748.

Key, R.M., Litherland, M., and Hepworth, J.V.
1976: The evolution of the Archean crust of NE Botswana; Prec. Res., v. 3, p. 375-413.

Lawson, A.C.
1887: Report on the geology of the Rainy Lake region; Geol. and Nat. Hist. Surv. Can., Ann. Rept., N.S., v. III, Pt. I, 1887-88.

Lawson, A.C.
1913: The Archaean geology of Rainy Lake re-studied; Can. Geol. Surv., Mem. 40, 111 p.

MacKasey, W.D., Blackburn, C.E., and Trowell, N.F.
1974: A regional approach to the Wabigoon-Quetico belts and its bearing on exploration in northwestern Ontario; Ontario Div. Mines, MP 58, 30 p.

Merritt, P.L.
1934: Seine-Coutchiching problem; Geol. Soc. Am. Bull., v. 45, p. 333-374.

Myers, J.
1976: Granitoid sheets, thrusting and Archean crustal thickening in West Greenland; Geology, v. 4, p. 265-268.

Ojakangas, R.W.
1972: Rainy Lake area; in Geology of Minnesota: a centennial volume, ed. P.K. Sims and G.B. Morey; Minn. Geol. Surv., p. 163-171.

Peterman, Z.E.
1959: Petrology of the metasediments of the Rainy Lake region; unpubl. MS thesis, University of Minnesota, 62 p.

Peterman, Z.E., Goldich, S.S., Hedge, C.E., and Yardley, D.H.
1972: Geochronology of the Rainy Lake region, Minnesota-Ontario; in Studies in Mineralogy and Precambrian Geology, ed. B.R. Doe and D.K. Smith; Geol. Soc. Am., Mem. 135, p. 193-215.

Pettijohn, F.J.
1937: Early precambrian geology and correlational problems of the northern subprovince of the Lake Superior region; Geol. Soc. Am Bull., v. 48, p. 153-202.

Pettijohn, F.J.
1972: The Archean of the Canadian Shield: a resumé; in Studies in Mineralogy and Precambrian Geology, ed. B.R. Doe and D.K. Smith; Geol. Soc. Am., Mem. 135, p. 131-149.

Pirie, J., and MacKasey, W.O.
1978: Preliminary examination of regional metamorphism in parts of Quetico metasedimentary belt, Superior province, Ontario; in Metamorphism in the Canadian Shield, ed. J.A. Fraser and W.W. Heywood; Geol. Surv. Can., Paper 78-10, p. 37-48.

Powell, C.McA.
1979: A morphological classification of rock cleavage; in Microstructural Processes during Deformation and Metamorphism, ed. T.H. Bell and R.H. Vernon; Tectonophysics, v. 58, p. 21-31.

Reinhardt, E.W.
1968: Phase relations in cordierite-bearing gneisses from the Gananoque area, Ontario; Can. J. Earth Sci., v. 5, p. 455-482.

Saggerson, E.P. and Turner, L.M.
1976: A review of the distribution of metamorphism in the ancient Rhodesian craton; Prec. Res., v. 3, p. 1-53.

Schwerdtner, W.M., Stone, D., Osadetz, K., Morgan, J., and Stott, G.M.
1979: Granitoid complexes and the Archean tectonic record in the southern part of northwestern Ontario; Can. J. Earth Sci., v. 16, p. 1965-1977.

Shackleton, R.M.
1958: Downward facing structures of the Highland Border; J. Geol. Soc. Lond., v. 113, p. 361-392.

Stamatelopoulou-Seymour, K. and Francis, D.M.
1979: An ultramafic turbidite; Geol. Assoc. Can., program with abstr., v. 4, p. 80.

Stockwell, C.H.
1970: Geology of the Canadian Shield - introduction; in Geology and Economic Minerals of Canada, ed. R.J.W. Douglas; Can. Geol. Surv., Econ. Geol. Report No. 1, p. 44-54.

Stowe, C.W.
1974: Alpine-type structures in the Rhodesian basement complex at Selukwe; J. Geol. Soc. Lond., v. 130, p. 411-425.

Streckeisen, A.L.
1976: To each plutonic rock its proper name; Earth Sci. Rev., v. 12, p. 1-33.

Sutcliffe, R.H.
1978: Geology of the Rainy Lake granitoid complex; in Proceedings of the 1978 Archean Geochemistry Conference, ed. I.E.M. Smith and J.G. Williams, University of Toronto, p. 235-244.

Talbot, C.J.
1974: Fold nappes as asymmetric mantled gneiss domes and ensialic orogeny; Tectonophysics, v. 24, p. 259-276.

Tanton, T.L.
1927: Stratigraphy of the northern subprovince of the Lake Superior Region; Geol. Soc. Am. Bull., v. 38, p. 731-748.

Thompson, J.B. Jr.
1957: The graphical analysis of mineral assemblages in pelitic schists; Am. Mineral., v. 42, p. 842-858.

Thompson, P.H.
1976: Isograd patterns and pressure-temperature distributions during regional metamorphism; Contrib. Mineral. Petrol., v. 57, p. 277-295.

1978: Archean regional metamorphism in the Slave structural province - a new perspective on some old rocks; in Metamorphism in the Canadian Shield, ed. J.A. Fraser and W.W. Heywood; Geol. Surv. Can., Paper 78-10, p. 85-102.

Thurston, P.C., and Breaks, F.W.
1978: Metamorphic and tectonic evolution of the Uchi-English River subprovince; in Metamorphism in the Canadian Shield, ed. J.A. Fraser and W.W. Heywood; Geol. Surv. Can., Paper 78-10, p. 49-62.

Tilton, G.R. and Grunenfelder, M.H.
1968: Sphene: Uranium-lead ages; Science, v. 159, p. 1458-1461.

Walker, R.G.
1979: Turbidites and associated coarse clastic deposits; in Facies Models, ed. R.G. Walker; Geosci. Can. Repr. Ser. 1, p. 91-103.

Williams, H.
1977: Ophiolitic Mélange and its significance in the Fleur de Lys Supergroup, northern Appalachians; Can. J. Earth Sci., v. 14, p. 987-1003.

Windley, B.F.
1971: The stratigraphy of the Fiskenaesset anorthosite complex; Groenlands Geol. Under., Rapp. Nr. 35, p. 19-21.

1973: The Chemistry of the Fiskenaesset Complex on Qequertarssuatseq; Groenlands Geol. Under., Rapp. Nr. 51, p. 41-46.

Winkler, H.G.F.
1974: Petrogenesis of Metamorphic Rocks; Springer-Verlag, New York, 334 p.

Wood, J.
1979: Archean epiclastic sedimentation in the North Spirit Lake and Rainy Lake areas: a comparison; Geol. Assoc. Can., program with abstr., v. 4, p. 86.

Zwart, H.J.
1960: Relations between folding and metamorphism in the Pyrenees and their chronological succession, Geol. Mijnbouw, v. 39, p. 163-180.