DEFORMATION OF LAYERED ROCKS NEAR THE WAWA-QUETICO SUBPROVINCE BOUNDARY

by

David Lawrence Nicol©

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Faculty of Arts and Science
Lakehead University
Thunder Bay, Ontario
Canada

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ABSTRACT

A supracrustal sequence of rocks near Manitouwadge, Ontario consists of metavolcanic rocks, including pillow lavas, banded iron formation, amphibolite, and a quartzofeldspathic hornblende-biotite gneiss. This rock has been given the name bladed gneiss to reflect the blade-like appearance of its mafic components. Results of a detailed geological investigation of the entire supracrustal sequence suggests that the apparent fragmental appearance of the gneiss, and to a lesser degree the other rock types, is not a primary feature, but rather, the product of deformation. The rocks were initially part of a layered sequence which became variably fragmented. The blades are in part the result of the transposition of layers and the variations in blade morphology are attributable to the response of the layers to strain during folding. Individual layers deform by the development of cuspate-lobate folds, buckle folds, and boudinage. The extent of fragmentation during deformation is controlled by competency contrasts between adjacent layers, absolute and relative layer thickness, and layer orientation with respect to principal finite strain directions.

Planar and linear structural elements in the metasedimentary and metavolcanic rocks suggest a defomational history which includes two episodes of folding accompanied by medium grade metamorphism and recrystallization. Similarities in lithology and structural elements between the rocks of the study area and those of the nearby Manitouwadge synform suggest that parent rock assemblages were closely related and that structures present in

both locations developed contemporaneously in response to regional tectonic activity. "Mobilist" tectonic models for the development of the Superior Province entail northward directed subduction and accretion, and are popular with many workers. The recumbent nature of F_1 folds, the shallow plunging hinge lines of F_2 folds, and their coaxial relationship may be related to low angle thrust faults and nappe structures which would be likely consequences in the proposed subduction model.

Many workers have attempted to map subprovince boundaries. In the region of the present study, the boundary between the Wawa and Quetico Subprovinces is traditionally placed a few miles north of Manitouwadge. If this is correct, the rocks studied form part of the Wawa Subprovince. Results of this investigation suggest that, on the basis of lithology and structure, such a placement of the boundary is inappropriate. It appears more appropriate to suggest that the terrain discussed in this thesis, as well as the rocks of the Manitouwadge synform, is best considered to form a zone of transition between the two subprovinces.

ACKNOWLEDGEMENTS

Many people are deserving of special recognition for their assistance in completing this study. Special thanks go to Dr. Manfred Kehlenbeck for his patience, guidence, and expertise in supervising this investigation. Thanks go to Sam Spivak for his advice and assistance in drafting, and to Anne Hammond for the many thin sections which were prepared. Thanks are also extended to other members of the LU Geology Department for their many consultations. Special thanks is also extended to Dr. Peter Hudleston (University of MN, Minneapolis) who acted as external examiner. His suggestions and constructive criticisms were well appreciated. I also wish to acknowledge Noranda Minerals Inc. - Geco Division for permitting this accademic study and their employees for their hospitality and assistance during field studies.

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INTRODUCTION

Precambrian bedrock discussed in this thesis is part of the Canadian Shield. Periodic attempts have been made to subdivide the Shield into meaningful units based primarily on overall lithological similarities and the attitude of linear structures. Today, these subdivisions are commonly known as provinces and subprovinces.

M.E. Wilson (1939) made one of the first attempts to subdivide the Shield. Although his subdivisions, outlined in Figure 1, were based primarily on geography, he did emphasize the fact that the Shield comprises several geologically distinctive domains.

In 1949 J.E. Gill proposed Shield subdivisions based mainly on structural trends (Fig. 2). Gill further subdivided these structural provinces into subprovinces based on their inferred structural character. At about the same time, J. Tuzo Wilson (1949) proposed Shield subdivisions based not only on structural trends but also on lithological and isotopic age characteristics (Fig. 3).

C.H. Stockwell's (1964, 1982) attempts to subdivide the Shield were based on differences in overall structural trends and style of folding. As Figure 4 shows, province and subprovince boundaries were placed along structural fronts where older structures are truncated by younger ones, along major regional unconformities, and at changes in degree of regional metamorphism. Stockwell's work emphasized his opinion that subdivisions of the Shield should not be based on rock lithology or age as each domain contains a variety

Figure 1. Subdivisions of the Canadian Shield; after Wilson (1939).

Figure 2. Subdivisions of the southern Canadian Shield; after Gill (1949).

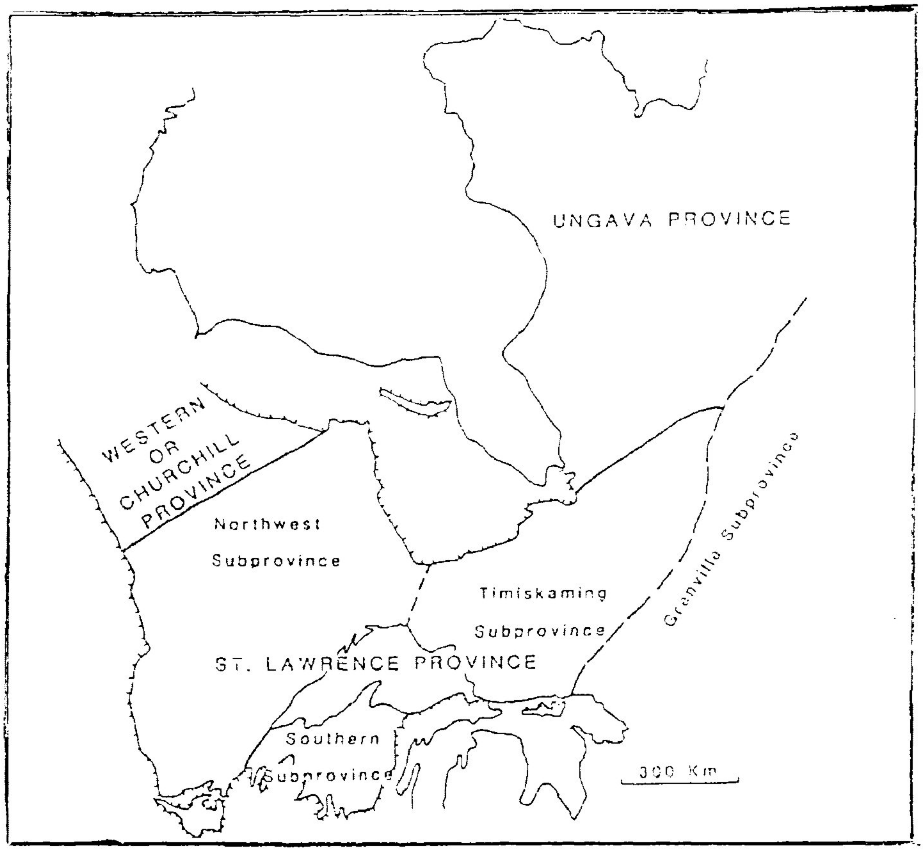

UNGAVA PROVINCE
WESTERN OR CHURCHILL PROVINCE
Northwest Subprovince
Timiskaming Subprovince
Grenville Subprovince
ST. LAWRENCE PROVINCE
Southern Subprovince
300 Km

Fig. 1

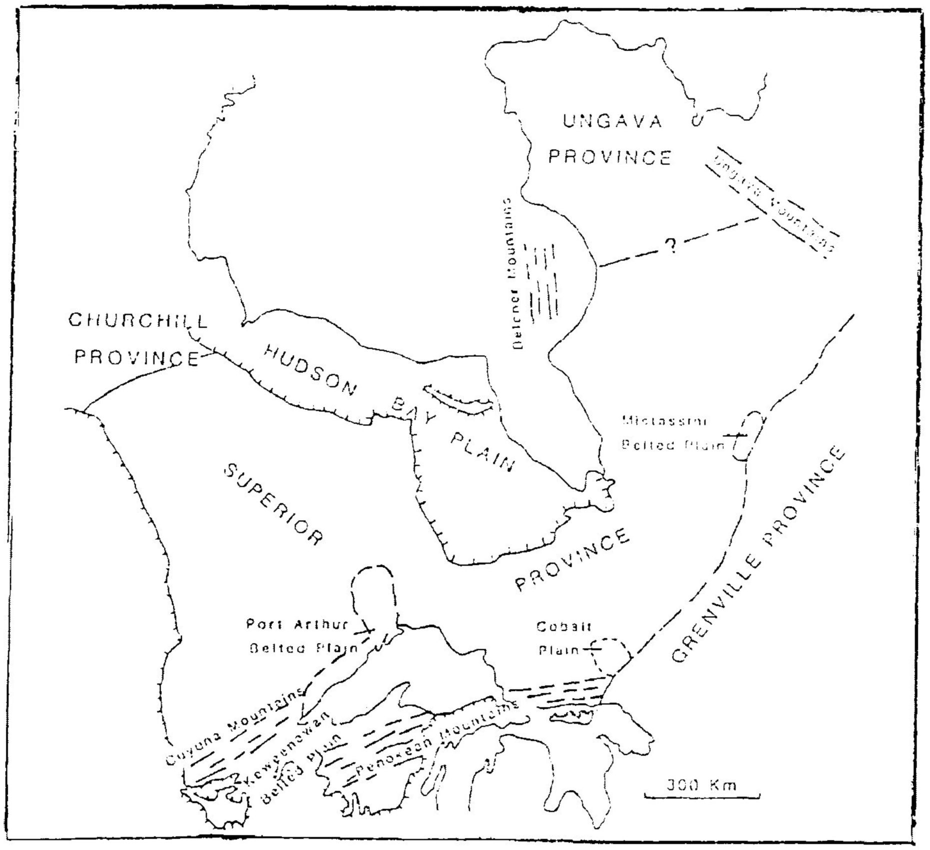

UNGAVA PROVINCE
Ungava Mountains
Belcher Mountains
?
CHURCHILL PROVINCE
HUDSON BAY PLAIN
Mistassini Belted Plain
SUPERIOR PROVINCE
GRENVILLE PROVINCE
Port Arthur Belted Plain
Cobalt Plain
Cuyuna Mountains
Keweenawan Belted Plain
Penokean Mountains
300 Km

Fig. 2

Figure 3. Subdivisions of the southern Canadian Shield; after Wilson (1949).

Figure 4. Subdivisions of the southern Canadian Shield; after Stockwell (1964, 1982).

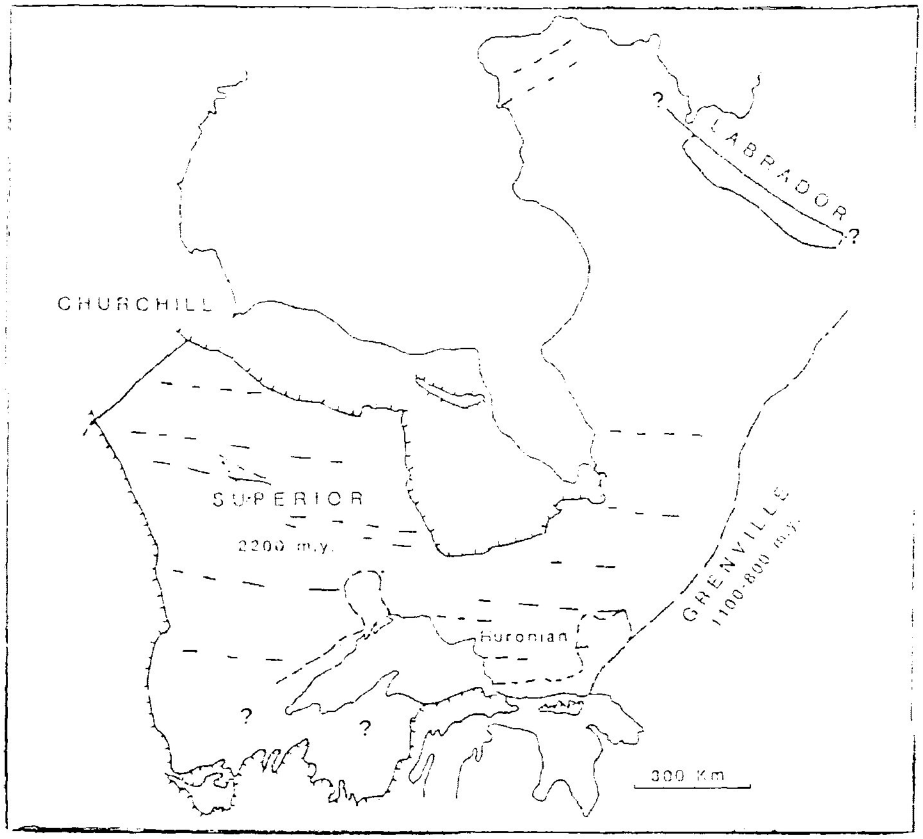

LABRADOR
?
?
CHURCHILL
SUPERIOR
2200 m.y.
GRENVILLE
1100-800 m.y.
Huronian
?
?
300 Km

Fig. 3

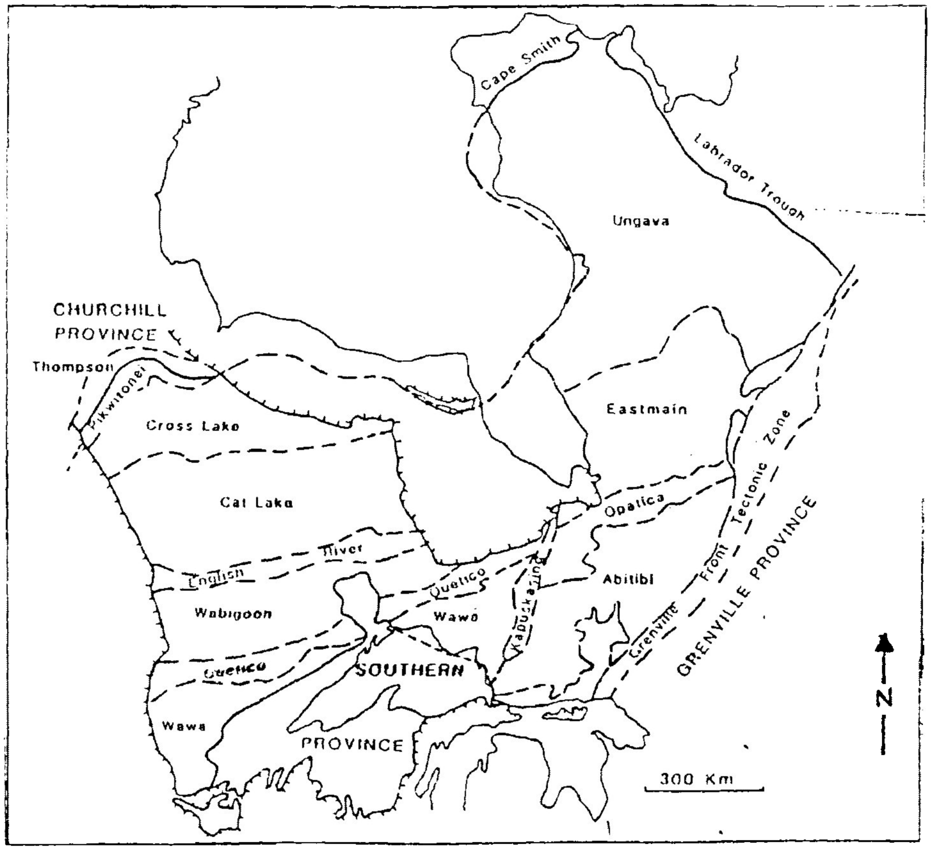

Cape Smith
Labrador Trough
Ungava
CHURCHILL
PROVINCE
Thompson
Pikwitonei
Cross Lake
Eastmain
Cat Lake
Opatica
English River
Quetico
Abitibi
Kapuskasing
Wabigoon
Wawa
Grenville Front Tectonic Zone
GRENVILLE PROVINCE
Quetico
SOUTHERN
Wawa
PROVINCE
N
300 Km

Fig. 4

of rock types of diverse ages.

Similar Shield subdivisions based in large part on dominant structural trends were proposed by R.J. Douglas (1973). It is apparent from the names given to many of the subprovinces (Fig. 5) that Douglas emphasized the dominant lithology of a particular belt.

More recent attempts to subdivide the Shield are based on lithological similarities within the proposed subregions. A.M. Goodwin (1978) noted that, in northwestern Ontario, the system of metasedimentary gneiss belts alternating with volcano-plutonic belts provides a basis for subdivision into "superbelts".

The most recent attempt to subdivide the Superior Province is that of Card and Ciesielski (1986). Their subdivisions, based on structural, lithologic, metamorphic, age, and geophysical characteristics, are similar to those proposed by Douglas (1973) and are presented in Figure 6. Minor differences in location of subprovince boundaries are attributable mainly to new mapping information. More radical departures occur in the west, where the English River Subprovince of Douglas, Stockwell, and other workers, is further subdivided. The area of this investigation lies within the Superior Province, close to the boundary between the Wawa and Quetico Subprovinces as proposed by Stockwell (1969), Douglas (1973), and Card and Cieseleski (1986) (Figure 7).

Card and Cieseleski (1986) summarize the accepted geological characteristics of the various subprovinces. They describe metasedimentary subprovinces, such as the Quetico, which are characterized by sedimentary supracrustal rocks, mainly turbiditic

Figure 5. Subdivisions of the southern Canadian Shield; after Douglas (1973).

Figure 6. Subdivisions of the Superior Province; after Card and Cieseleski (1986),

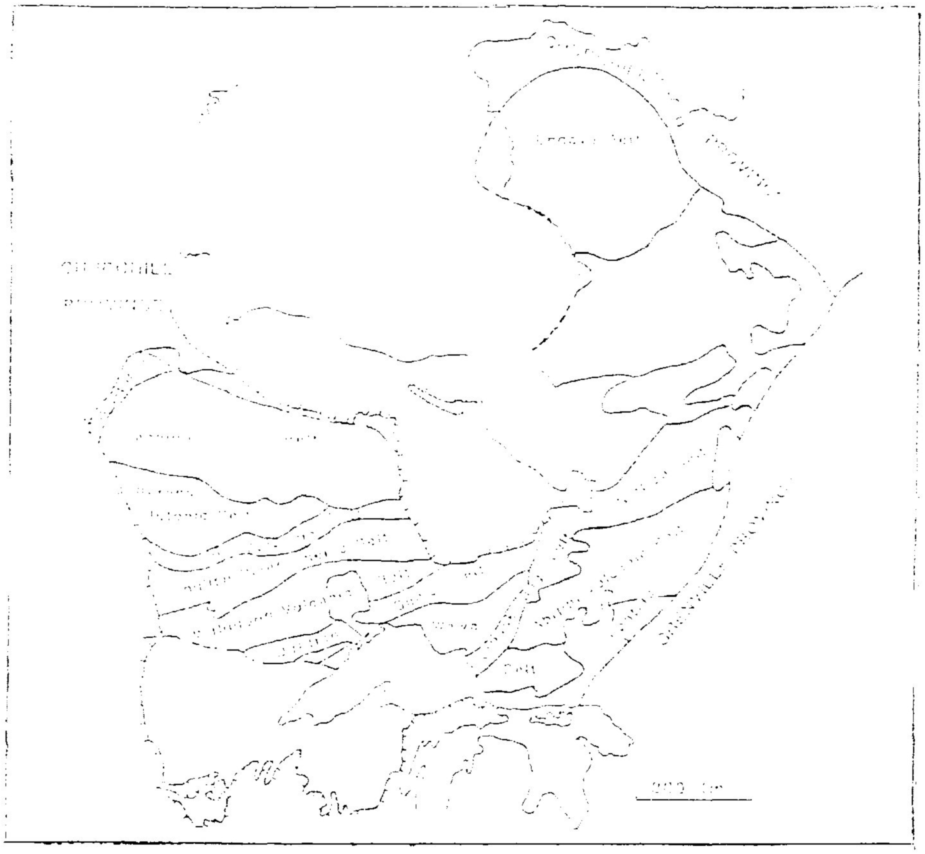

CHURCHILL
PROVINCE
Wawa
Belt

Fig. 5

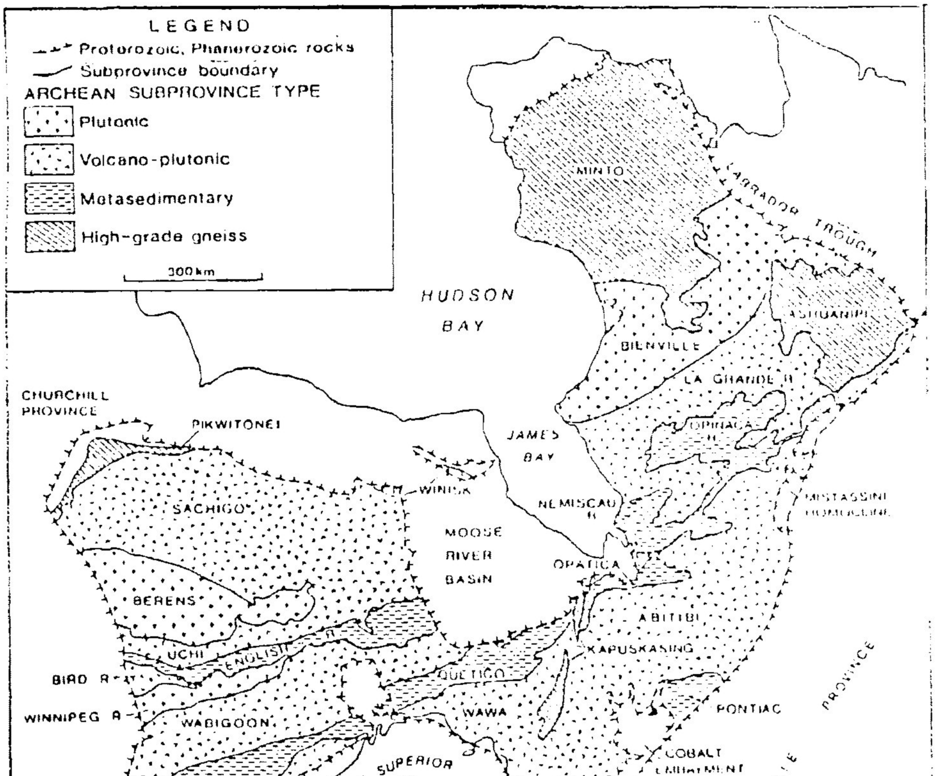

LEGEND
Proterozoic, Phanerozoic rocks
Subprovince boundary
ARCHEAN SUBPROVINCE TYPE
Plutonic
Volcano-plutonic
Metasedimentary
High-grade gneiss
300 km
HUDSON
BAY
MINTO
LABRADOR TROUGH
ASHUANIPI
BIENVILLE
LA GRANDE R
OPINACA R
JAMES
BAY
NEMISCAU R
MISTASSINI
HOMOCLINE
CHURCHILL
PROVINCE
PIKWITONEI
WINISK
SACHIGO
MOOSE
RIVER
BASIN
OPATICA
BERENS
ABITIBI
UCHI
ENGLISH R
KAPUSKASING
BIRD R
QUETICO
WINNIPEG R
WABIGOON
WAWA
PONTIAC
GRENVILLE PROVINCE
COBALT
EMBAYMENT
LAKE SUPERIOR
INTERIOR
PLAINS
SOUTHERN
PROVINCE
MINNESOTA
R. VALLEY
N

Fig. 6

Figure 7. Study area location with respect to subprovince boundaries; after Card and Cieseleski (1986).

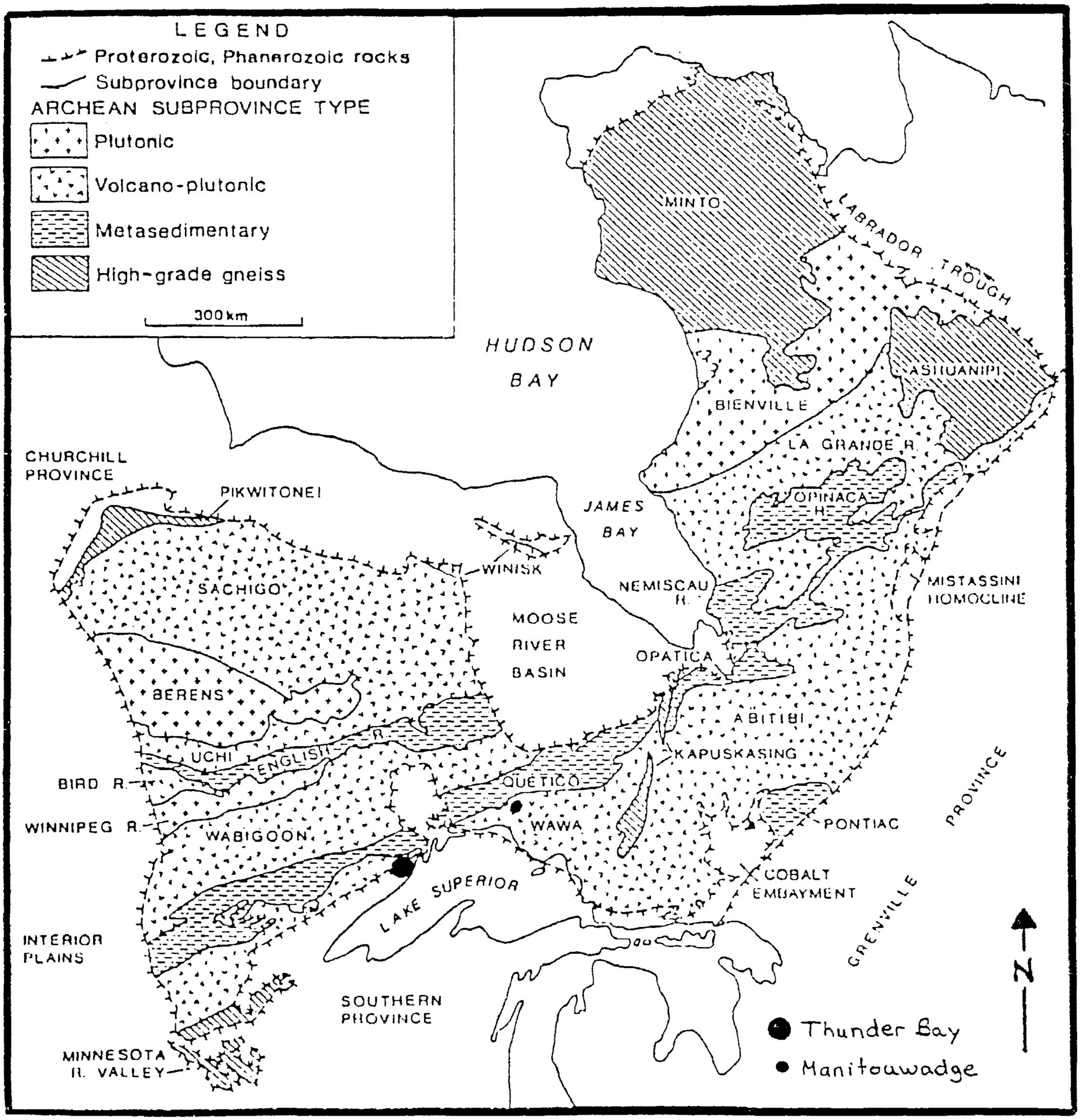

LEGEND
Proterozoic, Phanerozoic rocks
Subprovince boundary
ARCHEAN SUBPROVINCE TYPE
Plutonic
Volcano-plutonic
Metasedimentary
High-grade gneiss
300 km
HUDSON BAY
JAMES BAY
MOOSE RIVER BASIN
MINTO
LABRADOR TROUGH
ASHUANIPI
BIENVILLE
LA GRANDE R.
OPINACA R.
NEMISCAU R.
MISTASSINI HOMOCLINE
OPATICA
ABITIBI
KAPUSKASING
PONTIAC
COBALT EMBAYMENT
GRENVILLE PROVINCE
CHURCHILL PROVINCE
PIKWITONEI
WINISK
SACHIGO
BERENS
UCHI
ENGLISH R.
BIRD R.
WINNIPEG R.
WABIGOON
QUETICO
WAWA
LAKE SUPERIOR
INTERIOR PLAINS
SOUTHERN PROVINCE
MINNESOTA R. VALLEY
Thunder Bay
Manitouwadge
N

Fig. 7

wacke and pelite, metamorphosed to schist, paragneiss, and migmatite, and by the symmetrical metamorphic zonation across the subprovince from marginal low-grade to central high-grade assemblages. Intrusive rocks include abundant granites and pegmatites with the chemical and mineralogical attributes of S-type granites generated by anatexis of sedimentary rocks. Percival (1988) adds that the most prominent structural feature of the Quetico Subprovince is steep, east-striking bedding and cleavage in marginal schists. Gentler bedding and cleavage dips predominate in central regions. A gently east-plunging stretching lineation is a subtle to prominent characteristic of the higher grade parts of the belt. In some locations sedimentary facing directions and dips are consistently north (Pirie and Mackasey 1978; Percival and Stern 1984), yet in other locations a simple interpretation of regional structure is precluded by complex refolded-folds and strike-slip faulting (Borradaile 1982; Kehlenbeck 1984).

The Wawa Subprovince is characterized by metavolcanic supracrustal sequences (greenstone) in contact with felsic plutonic rocks (Card and Cieseleski, 1986). Structural patterns are typically irregular, the product of polyphase deformation that formed sinuous, commonly synformal metavolcanic belts and intervening domal, gneissic-plutonic domains. Metamorphic patterns in the Wawa Subprovince is typical of that of volcano-plutonic subprovinces, with greenschist or sub-greenschist grades predominating in central regions and grade increasing outward to low-pressure amphibolite facies in the margins (Card and Cieseleski, 1986).

The contact between the Quetico and Wawa belts varies in character along its length, marked locally by contrasting lithologies and metamorphic grade, and elsewhere by oblique faults. In the vicinity of the study area the contact between the two subprovinces has been placed just north of Manitouwadge. Based on this information rocks of the study area, and those which host the Geco ore deposit, form portions of the Wawa subprovince.

Area of Investigation

The study area is located in Cecil Township, approximately twenty kilometres southeast of Manitouwadge (Fig. 8). Access to the area is by means of an all-weather road from Manitouwadge on Geco Mine property. Except for the region which includes the Manitouwadge synform, the geology of the study area and surrounding region is known only on a reconaissance scale. Detailed geology is the result of exploration activities carried out by Noranda Minerals Incorporated since the opening of the Geco Mine. Government sponsored investigations in the Manitouwadge area include work by Pye (1960) and Milne (1974). Geological mapping of a more regional nature, including the current study area, was carried out by Milne (1968), Coates (1968, 1970) and Giguere (1972). Recent geological mapping by Williams and Breaks (1989) in the Manitouwadge-Hornpayne area includes the current study area.

Consolidated rocks in the vicinity of Manitouwadge are of Precambrian age and consist of a highly strained volcano-sedimentary sequence of unknown facing which occurs in an east-northeasterly trending regional synform (Fig. 9). Stratigraphic

Figure 8. Map of the study area. Insert shows location relative to Manitouwadge.

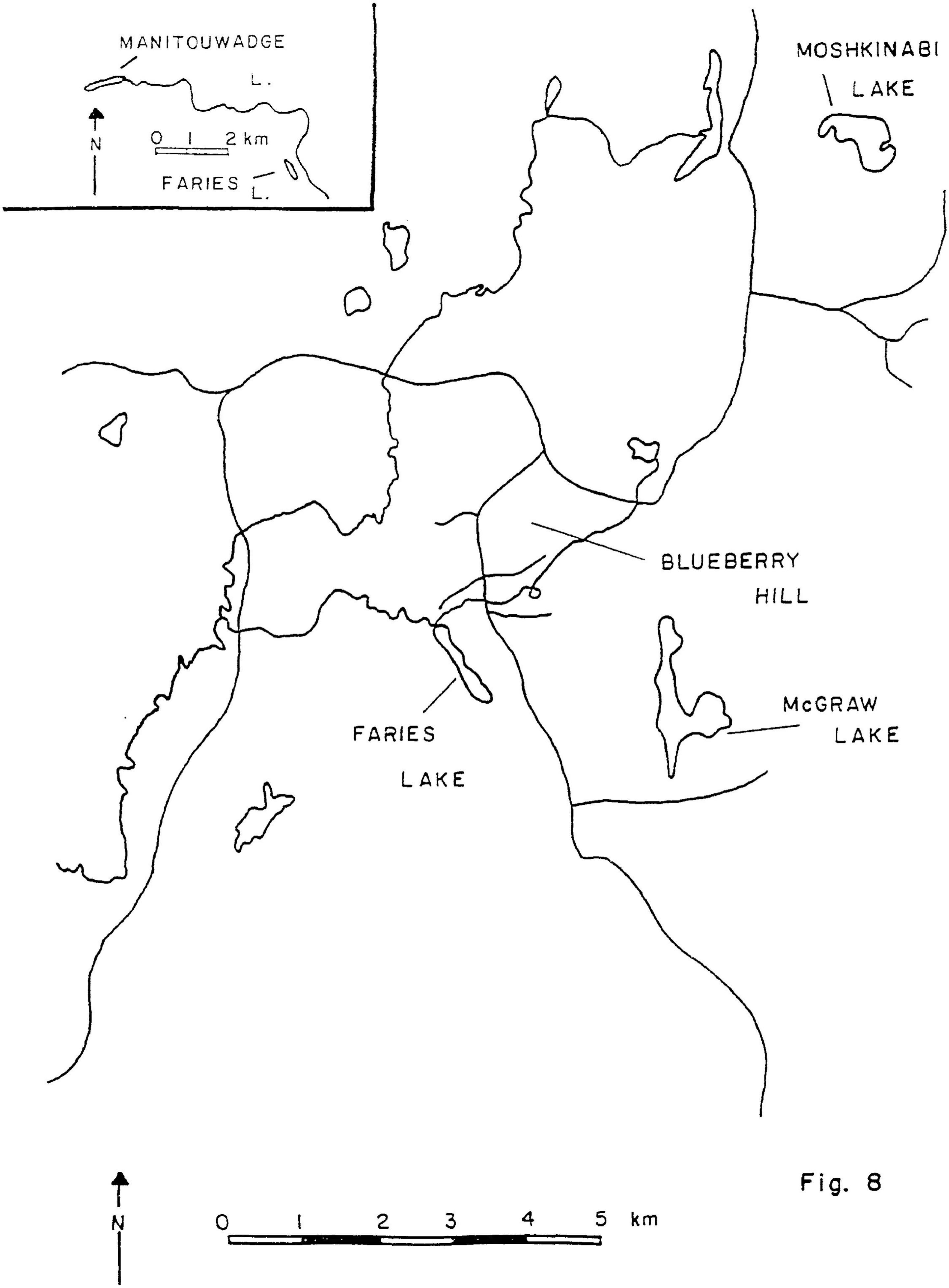

MANITOUWADGE
L.
N
0 1 2 km
FARIES
L.
MOSHKINABI
LAKE
BLUEBERRY
HILL
McGRAW
LAKE
FARIES
LAKE
N
0 1 2 3 4 5 km

Fig. 8

Figure 9.

(a) Geological map of the Manitouwadge-Hornpayne area; after Williams and Breaks (1989).

A- Moshkinabi Lake
D-Faries Lake

Note other leters on map refer to authors' sample locations and are not relevant to this study.

(b) Detailed geological map of the Manitouwadge synform; after Friesen, Pierce, and Weeks (1978).

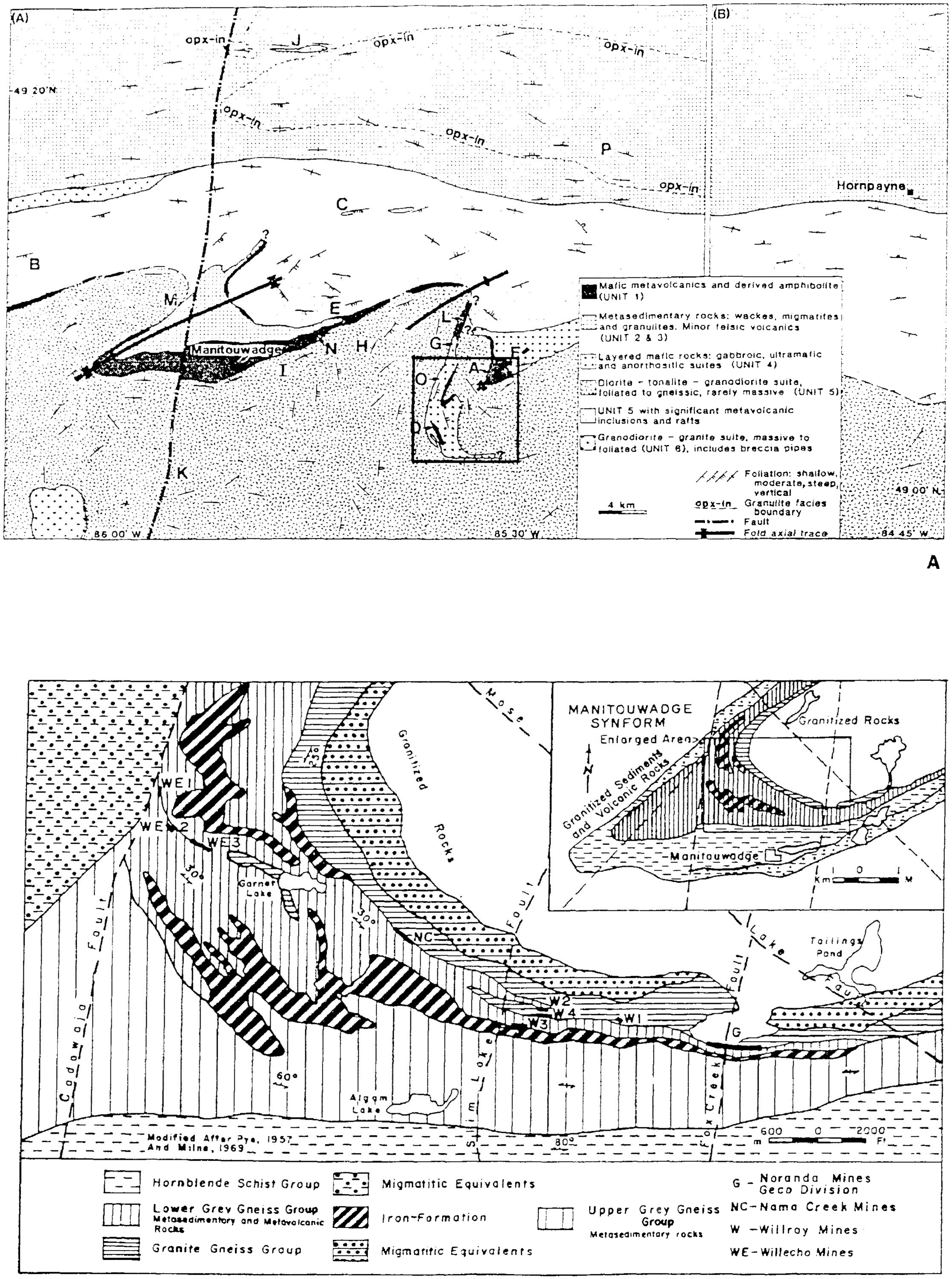

(A)
(B)
opx-in
J
49 20'N
P
Hornpayne
C
B
M
E
L
G
F
A
O
D
Manitouwadge
N
H
I
K
?
86 00' W
85 30' W
84 45' W
49 00' N
Mafic metavolcanics and derived amphibolite (UNIT 1)
Metasedimentary rocks: wackes, migmatites and granulites. Minor felsic volcanics (UNIT 2 & 3)
Layered mafic rocks: gabbroic, ultramafic and anorthositic suites (UNIT 4)
Diorite - tonalite - granodiorite suite, foliated to gneissic, rarely massive (UNIT 5)
UNIT 5 with significant metavolcanic inclusions and rafts
Granodiorite - granite suite, massive to foliated (UNIT 6), includes breccia pipes
Foliation: shallow, moderate, steep, vertical
opx-in Granulite facies boundary
Fault
Fold axial trace
4 km
A
MANITOUWADGE SYNFORM
Enlarged Area
N
Granitized Rocks
Granitized Sediments and Volcanic Rocks
Manitouwadge
Km 1 0 1 M
Granitized Rocks
Mose Fault
Lake
WE1
WE2
WE3
30°
25°
30°
Garnet Lake
NC
W2
W4
W1
W3
G
Tailings Pond
Lake Fault
Fox Creek Fault
Slim Lake Fault
Cadawaja Fault
60°
80°
Algom Lake
Modified After Pye, 1957 And Milne, 1969
600 0 2000
m Ft
Hornblende Schist Group
Lower Grey Gneiss Group Metasedimentary and Metavolcanic Rocks
Granite Gneiss Group
Migmatitic Equivalents
Iron-Formation
Migmatitic Equivalents
Upper Grey Gneiss Group Metasedimentary rocks
G - Noranda Mines Geco Division
NC - Nama Creek Mines
W - Willroy Mines
WE - Willecho Mines
B

Fig. 9

thickness is in the order of one-to-two kilometers. Rock types present include mafic, intermediate, and felsic volcanic rocks along with metasedimentary rocks and banded iron formation. The sequence is intruded by several generations of intermediate to felsic rocks including diorite, tonalite, granodiorite and granite. Emplacement of diabase dykes and local fault movement post-dates the felsic intrusions (Pye 1960; Williams and Breaks 1989). Metamorphism of the deformed rock sequence is of the amphibolite-facies (Friesen, Pearce, and Weaks, 1978). Associated mineralization consists of massive sulphides spatially associated with banded iron formations; the sulphides are considered by many workers to be of volcanic hydro-thermal origin (Pye 1960, Williams and Breaks 1989).

The most important structural feature in the Manitouwadge area is the Manitouwadge synform. In western portions of the map (Fig. 9) the structure is expressed by the attitude of the metavolcanic-metasedimentary rock contact. This contact trace is roughly V-shaped and delineates a northeast-plunging trough or synform. The geological map of the Manitouwadge area (Pye, 1960) shows the Manitouwadge synform as well as the orientation of a number of foliations. Analysis of the structural data presented in this map suggests that deformation of the metavolcanic-metasedimentary sequence included more than one episode of folding. The refolded nature of the banded iron formations, as seen in the map, supports this interpretation. In addition to the Manitouwadge synform a number of minor folds are exposed in the surrounding area. The axial planes of these minor folds are parallel or subparallel to that of the Manitouwadge synform and the folds are interpreted as large, incipient parasitic drag folds accompanying the period of regional deformation (Pye, 1960).

The metasedimentary and metavolcanic rocks are distinctly foliated due to the parallel alignment of platy minerals such as biotite and muscovite or prismatic minerals such as hornblende. The foliation appears to be nearly coplanar with relict stratification in the deformed metasedimentary rocks. In many locations the foliated rocks also exhibit a well developed rodding and/or mineral lineation (Pye, 1960; Williams and Breaks, 1989).

The current study area was mapped on a reconaissance scale by Milne (1968) and Giguere (1972). Rock types identified by these workers are shown on the maps which accompany their reports. Bedrock exposed in the vicinity of Faries Lake was identified as mafic intrusive rocks including anorthositic gneiss along with various plutonic rocks. Additional exposures of plutonic gneisses were mapped to the southeast, at McGraw Lake, and to the northwest, along Macutagon Creek. Northeast of Faries Lake, at Moshkinabi Lake, exposures of quartzites and assorted mafic gneisses were mapped along with additional plutonic rocks.

Local detail of geology and structure is available from investigations carried out by Noranda's exploration crews. Their findings are summarized in unpublished compilation maps constructed from several field seasons of detailed mapping (1986-1989) and in drill logs from exploratory holes drilled in 1987. An airborne magnetic survey carried by Noranda in 1989 also includes the current study area. Government sponsored investigations in the area were completed at the same time as this thesis study. Readers are referred to the work of Williams and Breaks (1989) for a summary of their findings.

Purpose and Method of Investigation

The main objective of this thesis is to investigate and describe the rock types and structures in the Faries Lake area and to offer a reasoned explanation for their present geometric and spatial relationships. In many parts of the study area the geology was mapped in great detail. Consequently, much of the data gathered are centered in locations where exposures were abundant and where the detailed studies were most likely to yield results.

Of particular interest is the rock type identified as the "bladed gneiss". This name was a field term used during mapping, however it still appears most appropriate at this time. At first inspection the bladed gneiss appears to be a clastic rock but careful examination of the exposures suggests that it is a product of deformation. Outcrops of the bladed gneiss and the associated amphibolite and iron formation were studied in detail in an attempt to gain information regarding the protoliths and deformational history of these rocks. Interpretations are presented to describe the nature and regional extent of existing structures. Finally, a model is proposed to explain the structural evolution for this part of the Superior Province and to better define the location and nature of the Wawa-Quetico Subprovince boundary.

Field work for this thesis took place during the summers of 1989 and 1990. Observed structures were recorded in detail and many of the subsequent interpretations are based on these field observations. Structural data were plotted in stereographic projection and analized. Mapping was concentrated in areas where exposures are best, particularly at the Faries Lake trench and at Blueberry Hill. Microscopic analysis of representative samples led to the documentation of fabrics, structures, and mineral assemblages. In some instances mineral compositions were determined by use of semi-quatitative analysis with the scanning electron microscope. Thin sections were examined in an attempt to isolate kinematic and strain indicators.

DATA AND OBSERVATIONS

Stratigraphy:

In this thesis emphasis is placed on the identification and interpretation of structures. Consequently, descriptions of the lithostratigraphic units are of a general nature. Figure 10 is a generalized geological map of the study area and shows the distribution of the various rock types. Since no way-up indicators could be identified it is not possible to construct a true stratigraphic succession for the area. However, it is possible to determine relative positions of the various rock types based on overall structural positions and orientations. The profile shown in Figure 11 illustrates the structural positions of the units. Detailed mapping at metre scale was undertaken on the stripped ground east of Faries Lake where the metasedimentary rocks are particularly well exposed. Observed lithologies are presented in Figures 12 and 13 while observed structures are discussed and illustrated throughout this thesis. Outcrop locations from which samples were collected, or photographs taken, are given in Figure 14.

Metasedimentary Rocks

Metasedimentary rocks present comprise a gneissic sequence which includes banded iron formation, amphibolite, and the bladed gneiss. The development of hornblende and biotite during

Figure 10. Generalized geological map of the study area in the vicinity of Faries Lake where most of the observations were made.

Note: dashed line is the inferred contact (S_o) between the metavolcanic rocks and the metasedimentary rocks.

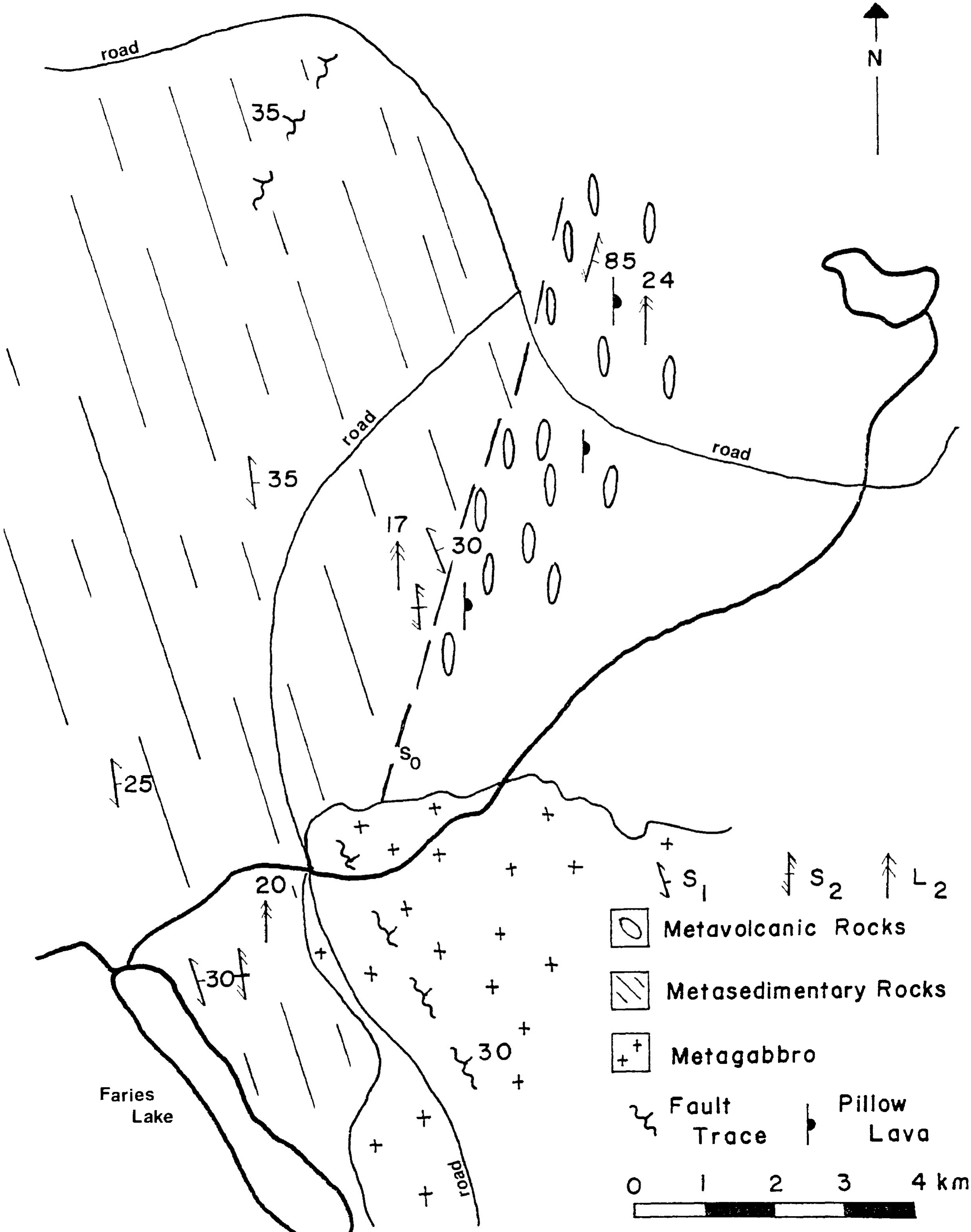

N
road
road
road
road
35
35
85
24
17
30
S0
25
20
30
30
Faries Lake
S1
S2
L2
Metavolcanic Rocks
Metasedimentary Rocks
Metagabbro
Fault Trace
Pillow Lava
0
1
2
3
4 km

Fig. 10

Figure 11. Structural Profile (down plunge) of areaa in Figure 10.

S- Metasedimentary Rocks
V- Metavolcanic Rocks
G- Metagabbro

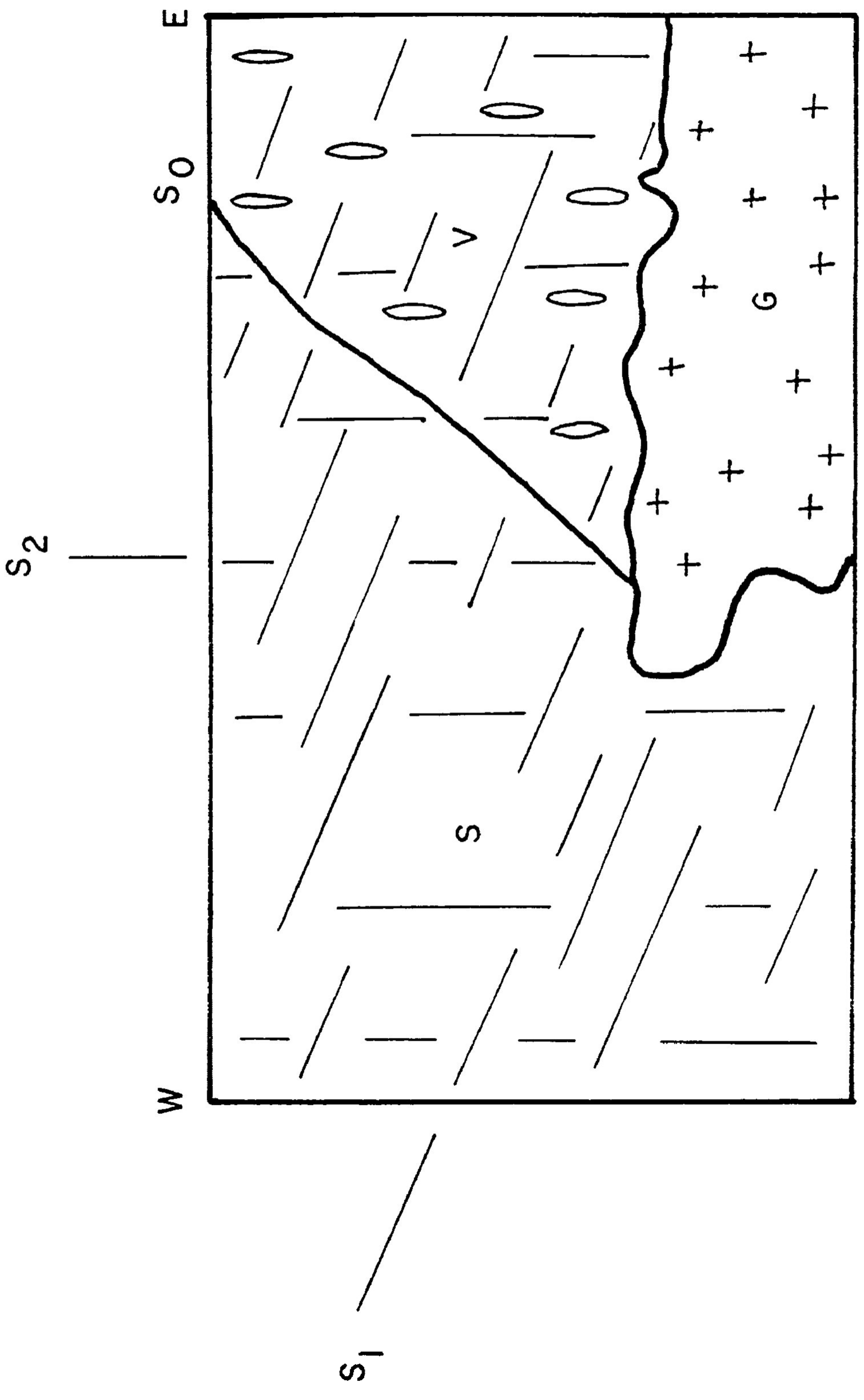


Fig. 11

Figure 12. Geological map of a portion of the Faries Lake trench.

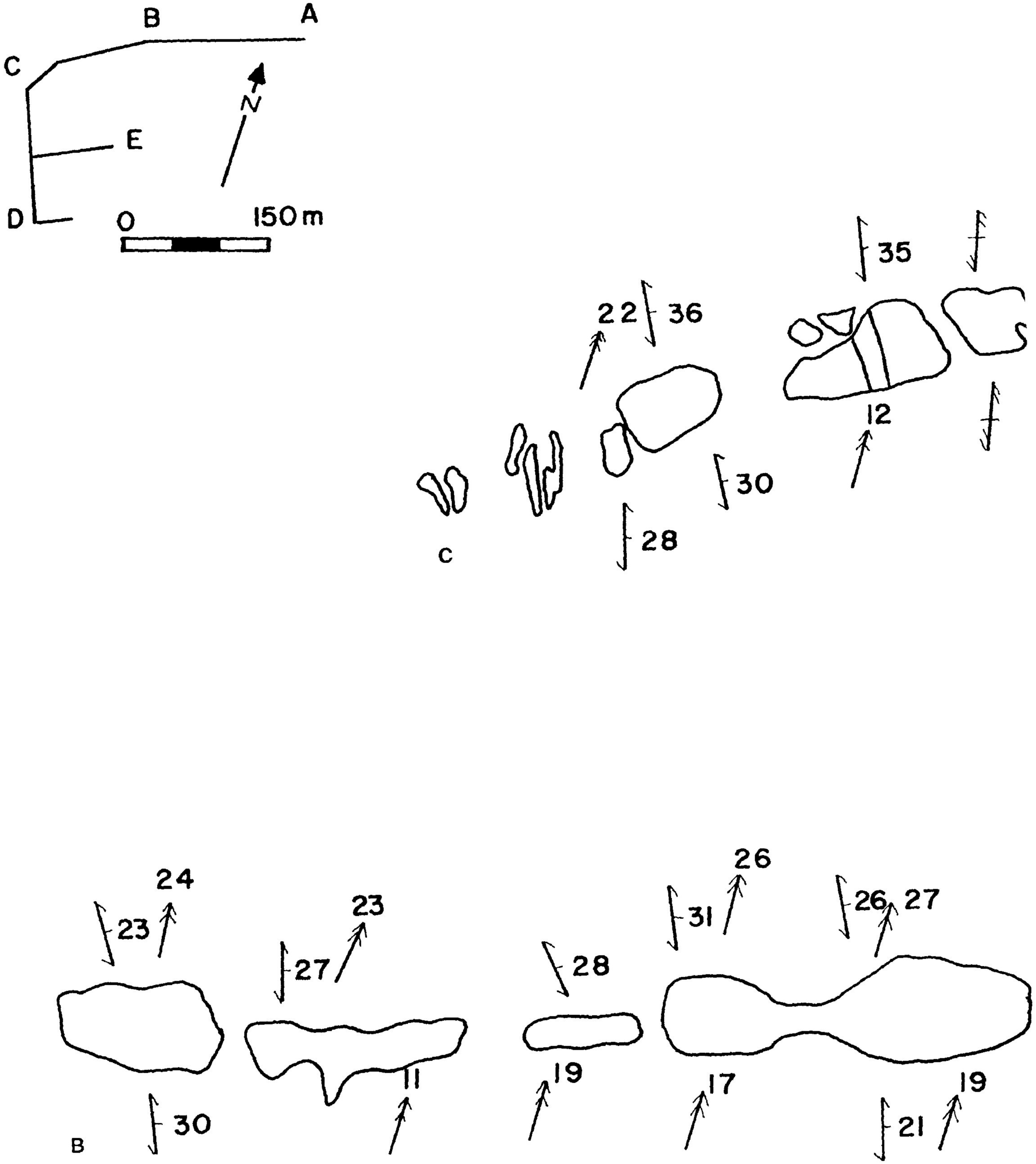

B
A
C
E
D
N
0
150m
22
36
35
12
30
28
c
24
23
23
27
28
31
26
26
27
30
11
19
17
19
21
B

Figure 13. Geological map of a portion of the Faries Lake trench.

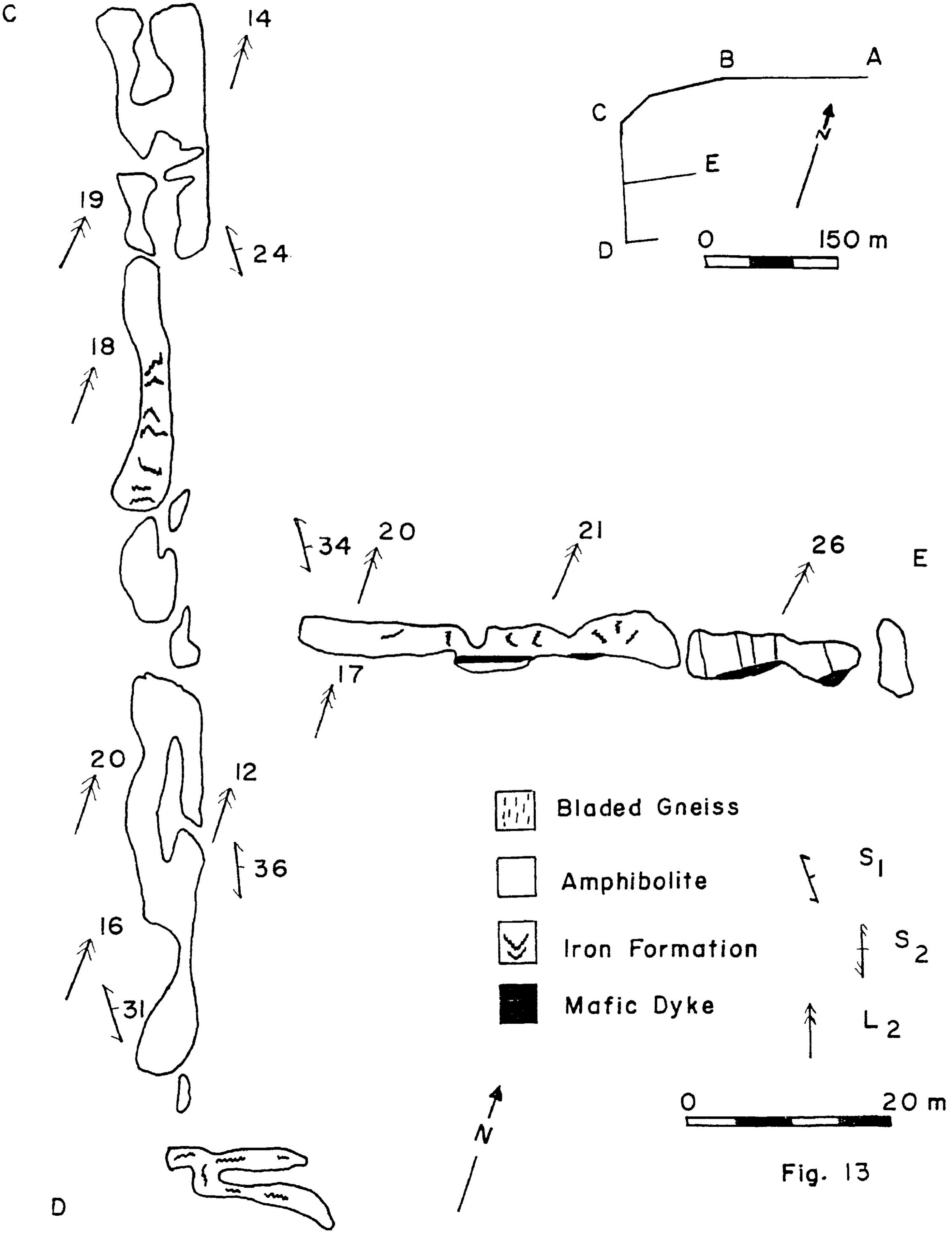

C
14
B
A
C
N
E
D
0
150 m
19
24
18
34
20
21
26
E
17
20
12
36
16
31
D
N
Bladed Gneiss
Amphibolite
Iron Formation
Mafic Dyke
S_1
S_2
L_2
0
20 m

Fig. 13

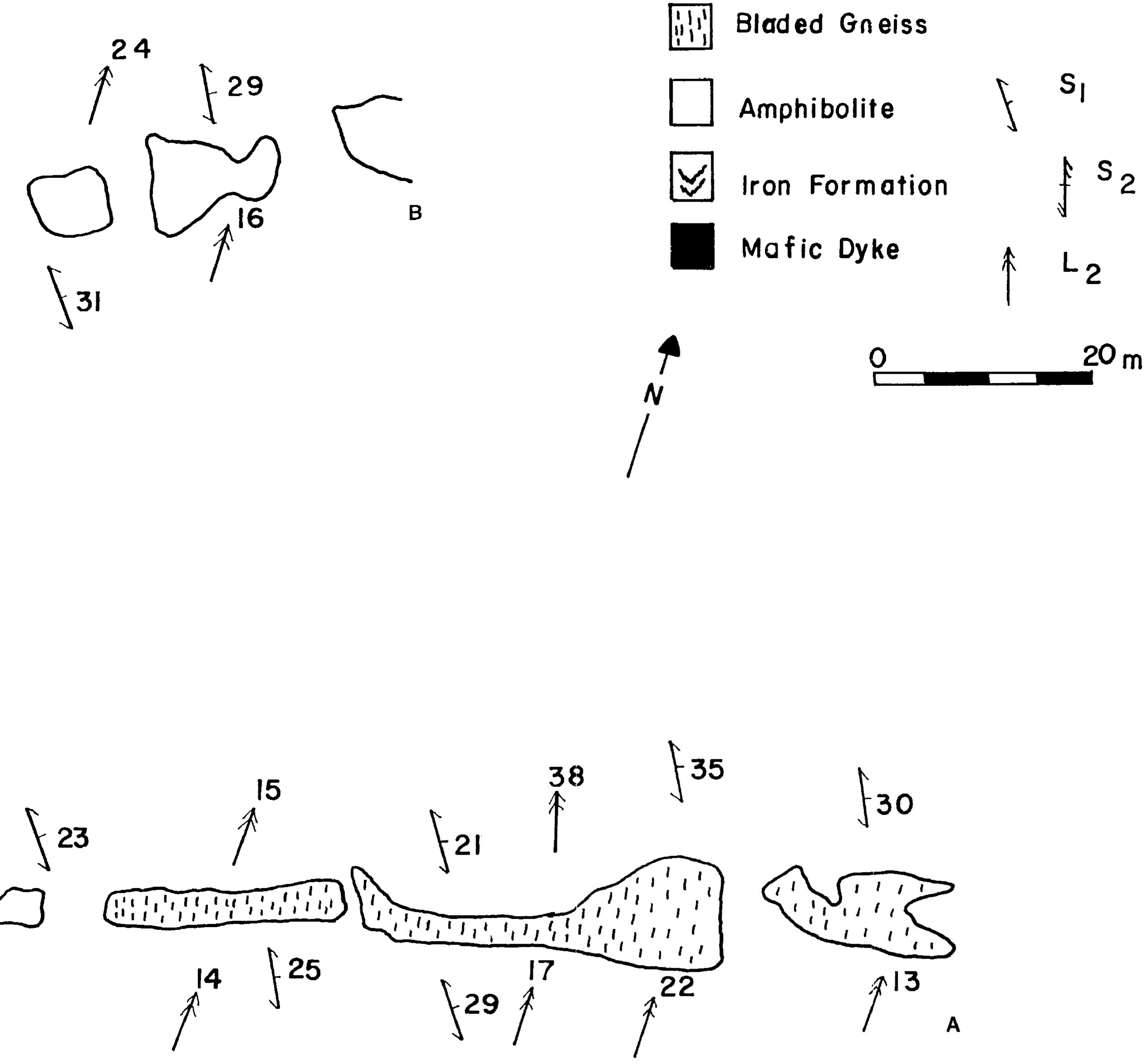

Bladed Gneiss
Amphibolite
Iron Formation
Mafic Dyke
S_1
S_2
L_2
0
20 m
N
24
29
16
31
B
23
15
21
38
35
30
14
25
29
17
22
13
A

Figure 14. Outcrop and photograph location map.

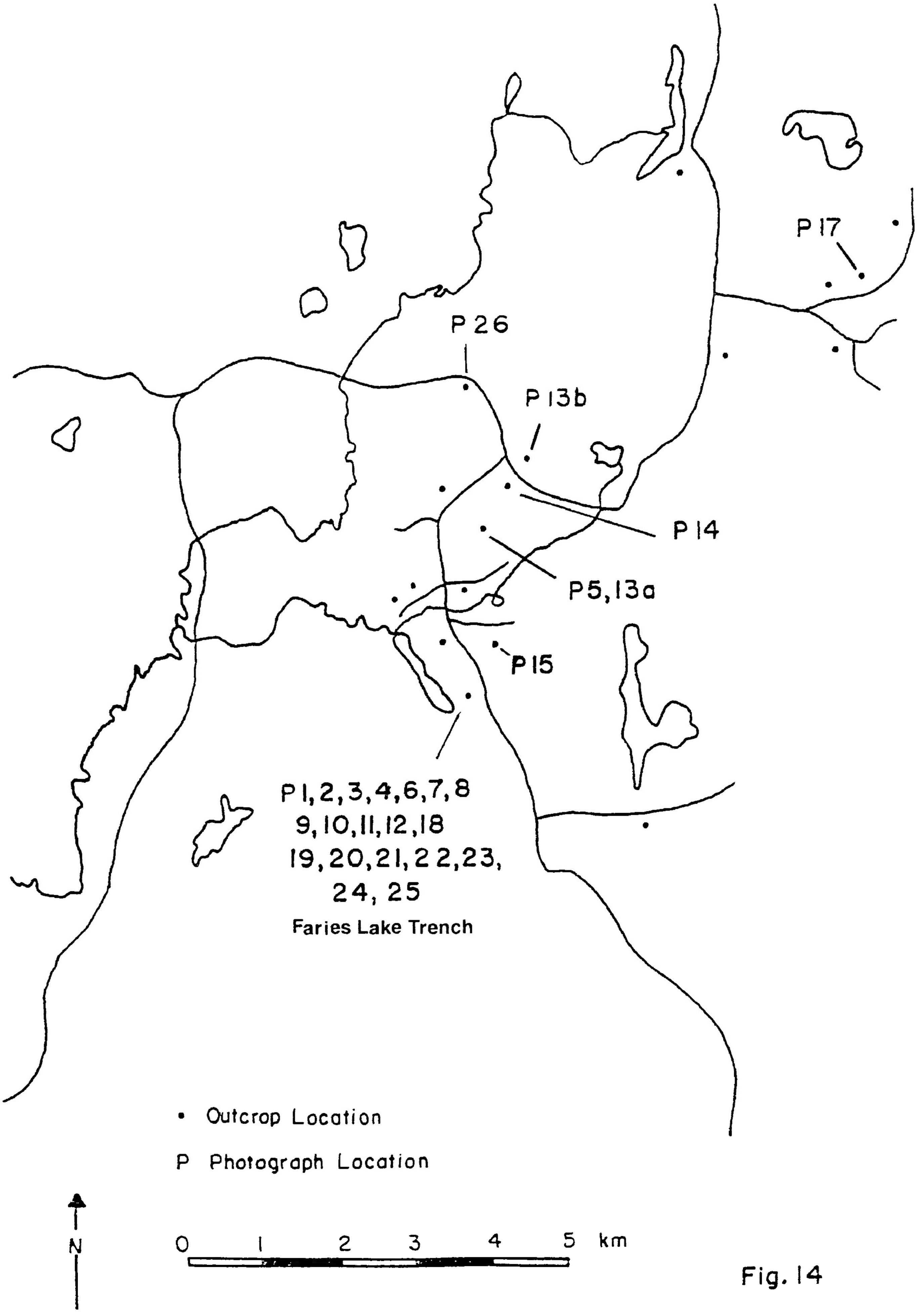

P 17
P 26
P 13b
P 14
P 5, 13a
P 15
P 1, 2, 3, 4, 6, 7, 8
9, 10, 11, 12, 18
19, 20, 21, 22, 23,
24, 25
Faries Lake Trench
• Outcrop Location
P Photograph Location
N
0 1 2 3 4 5 km

Fig. 14

recrystallization suggests that metamorphism was of the amphibolite facies (medium pressure type). Grayish-white feldspar "eyes" up to 5mm in diameter are pervasive throughout the gneissic sequence. In thin section these megacrysts are seen to be recrystallized plagioclase grains, with mortar textures commonly developed (Plate 1).

The gneissic sequence is locally crosscut by a series of dykes. These dykes have distinct chill margins and a well developed cooling texture. As seen in thin section dyke mineralogy consists of differentiated zones of quartz surrounding intergrown masses of hornblende, biotite, chlorite, and plagioclase. Minor amounts of magnetite and accessory apatite and sphene are also present. Quartz comprises approximately 25% of the rock, while hornblende comprises roughly 50%. The balance of the rock is composed of equal amounts of biotite, chlorite, and plagioclase. A weak foliation in the dykes is defined by the planar alignment of biotite and hornblende.

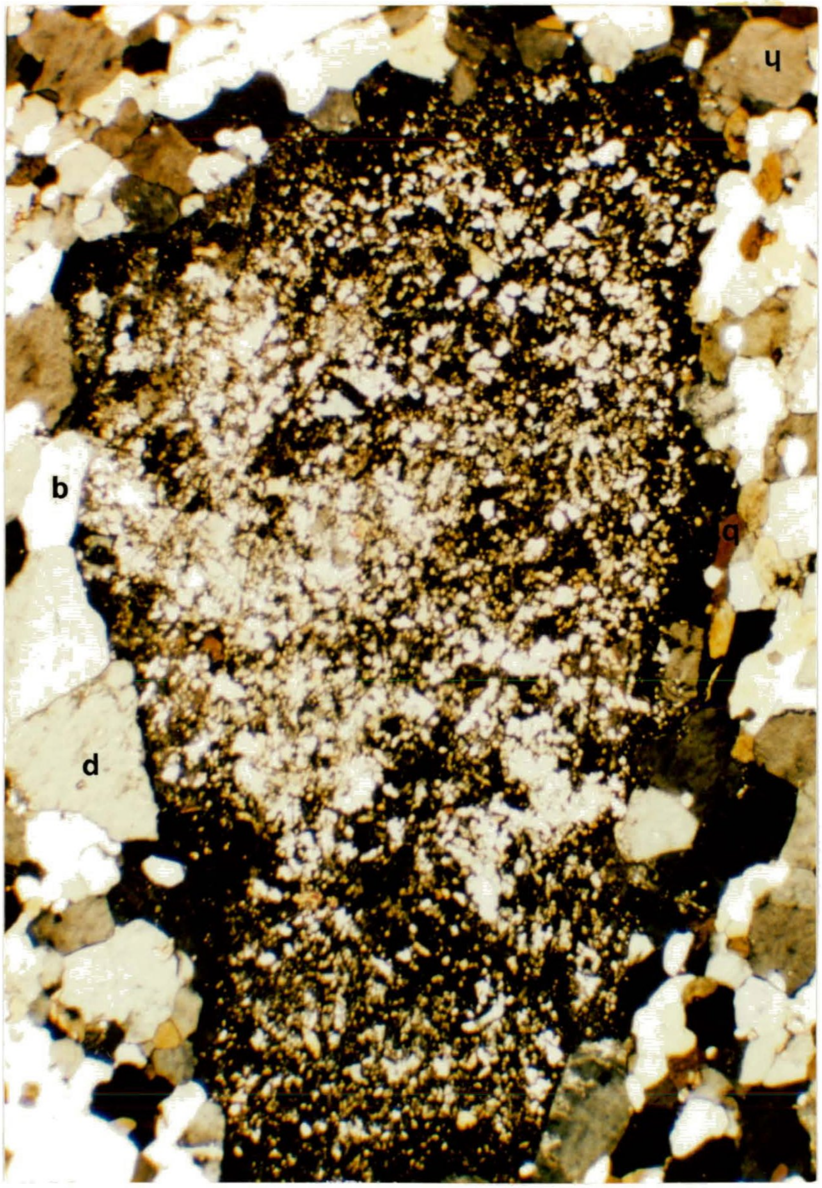
Bladed Gneiss:

In exposures east of Faries Lake the bladed gneiss has a clastic appearance and consists of mafic "fragments" in a quartzofeldspathic matrix. Fragments have been given the name blades to reflect their knife-like geometry. Blades occur in a wide variety of sizes and their appearance varies greatly depending upon the orientation of the surface of view. On surfaces where long dimensions of the blades dominate, blade lengths are generally

Plate 1. Photomicrograph of the bladed gneiss showing the subgrain development which commonly accompanies the recrystallization of feldspar megacrysts.

P = plagioclase
Q = quartz
H = hornblende
B = biotite

Note: scale bar is 2.5mm.


q
b
q
d

many times their width or thickness. Viewed in cross-section the blades appear as flattened objects, somewhat similar to flattened pebbles in a conglomerate (Plate 2a). End-on views of the blades also reveal the corona-like rims of amphibole and biotite which commonly envelop the blades (Plate 2b).

The bladed gneiss is a strongly foliated and lineated rock. Observed foliations are defined by the prefered dimensional orientation of hornblende and biotite. Blades have a strong preferred linear dimensional orientation within the bulk of the gneiss. This orientation is identical to that of the intersection lineation.

The bladed gneiss is principally composed of hornblende, plagioclase, and quartz. Blades are mainly composed of amphibole with lesser proportions of plagioclase and quartz. The bulk of the gneiss is composed of approximately 45% plagioclase, 45% quartz, and 8% hornblende. Biotite is present in minor amounts along with accessory apatite, zircon, sphene, magnetite, and ilmenite (Plate 3).

Variations in the blade-matrix relationship have been noted and in some exposures the bladed gneiss contains felsic blades set in a matrix rich in amphibole. Examples of thess variations are shown in Plate 4. In all varieties of bladed gneiss structural elements are the same.

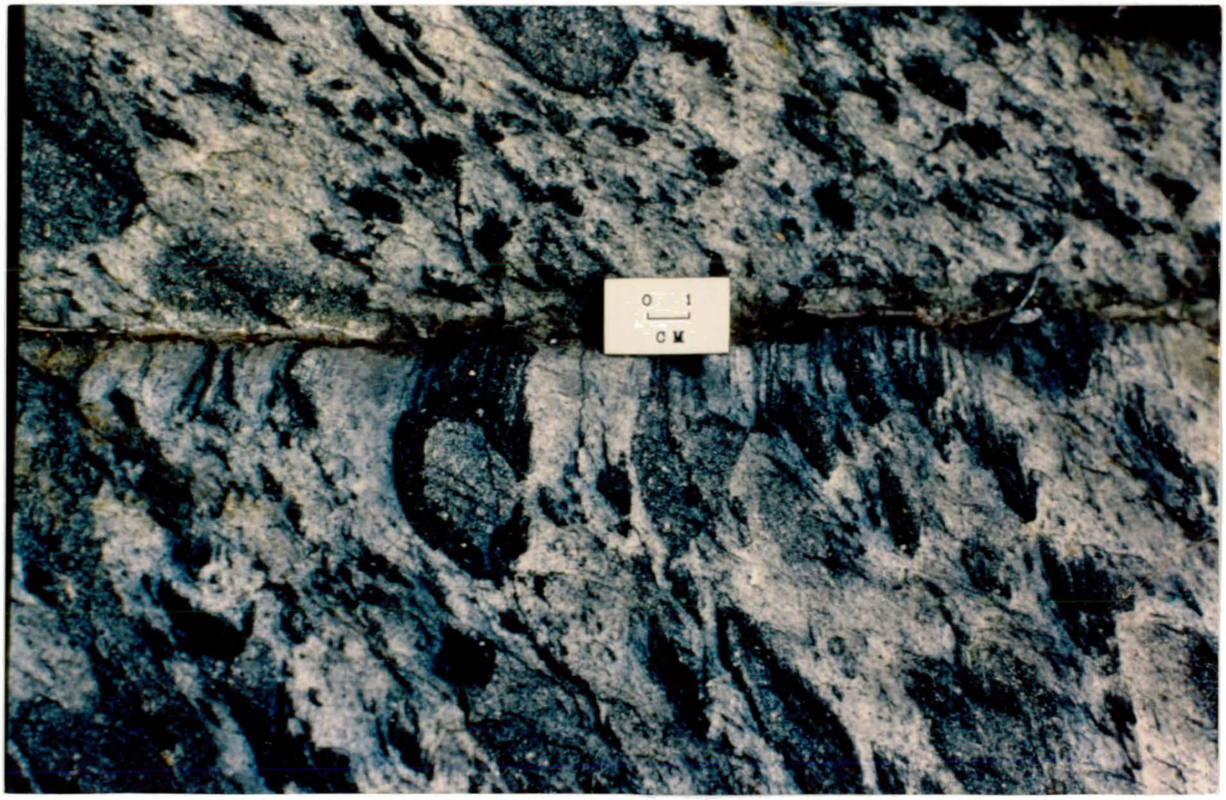
A second area where exposures of bladed gneiss are abundant is at Blueberry Hill (Fig. 8). Some of the exposures are very similar to those seen at Faries Lake while others clearly display identifiable layers (Plate 5a,b). Layers are transposed along

Plate 2. Photograph of the bladed gneiss showing

(a) blade morphology in various sections of view

(b) the corona-like rims of amphibole and biotite which commonly envelop the blades.

A



B

Plate 3. Photomicrograph of the bladed gneiss showing larger hornblende and biotite grains in a quartzofeldspathic matrix.

P = plagioclase
Q = quartz
H = hornblende
B = biotite

Note: scale bar is 2.5mm.

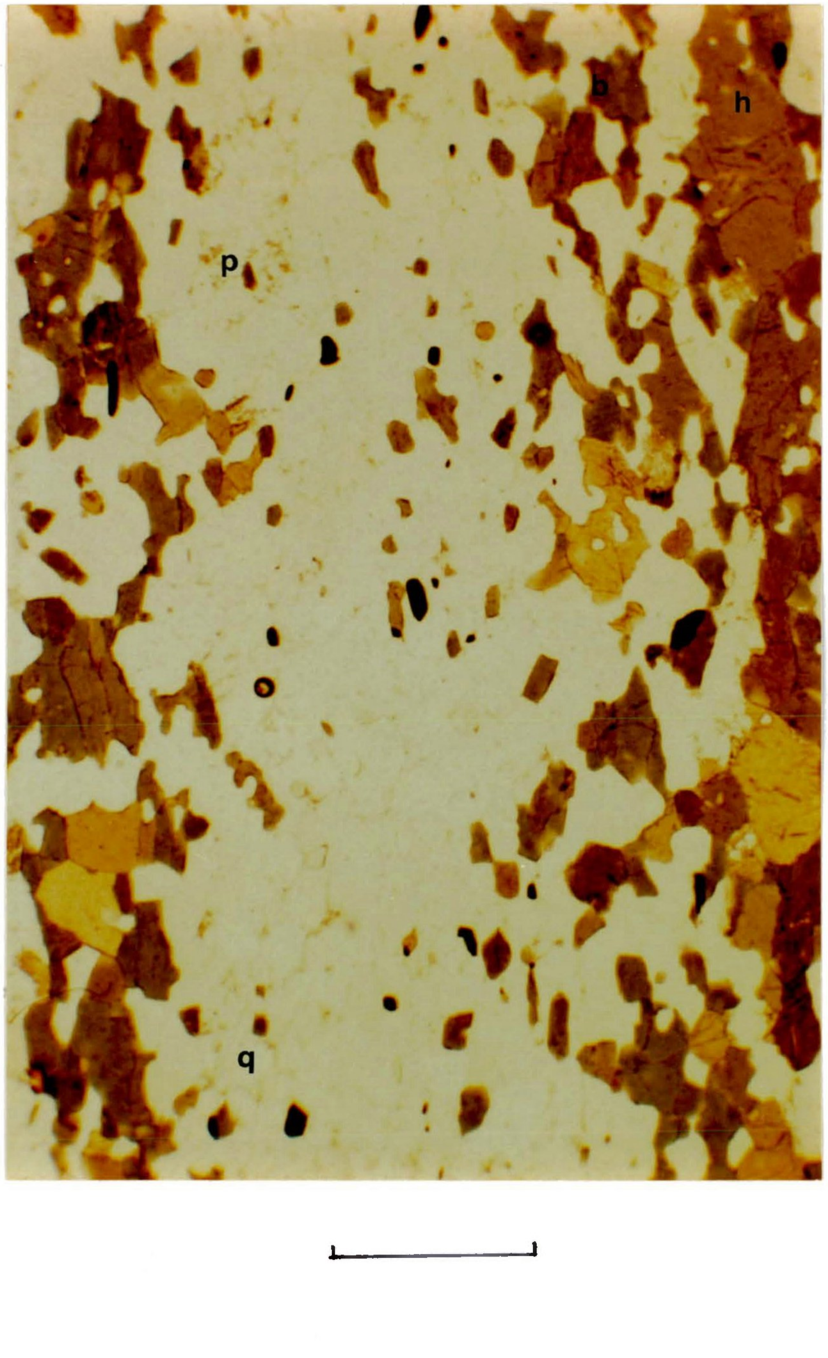

b
h
p
q

Plate 4. Examples of the less common varieties of bladed gneiss in which

(a) felsic components form blades in a mafic matrix

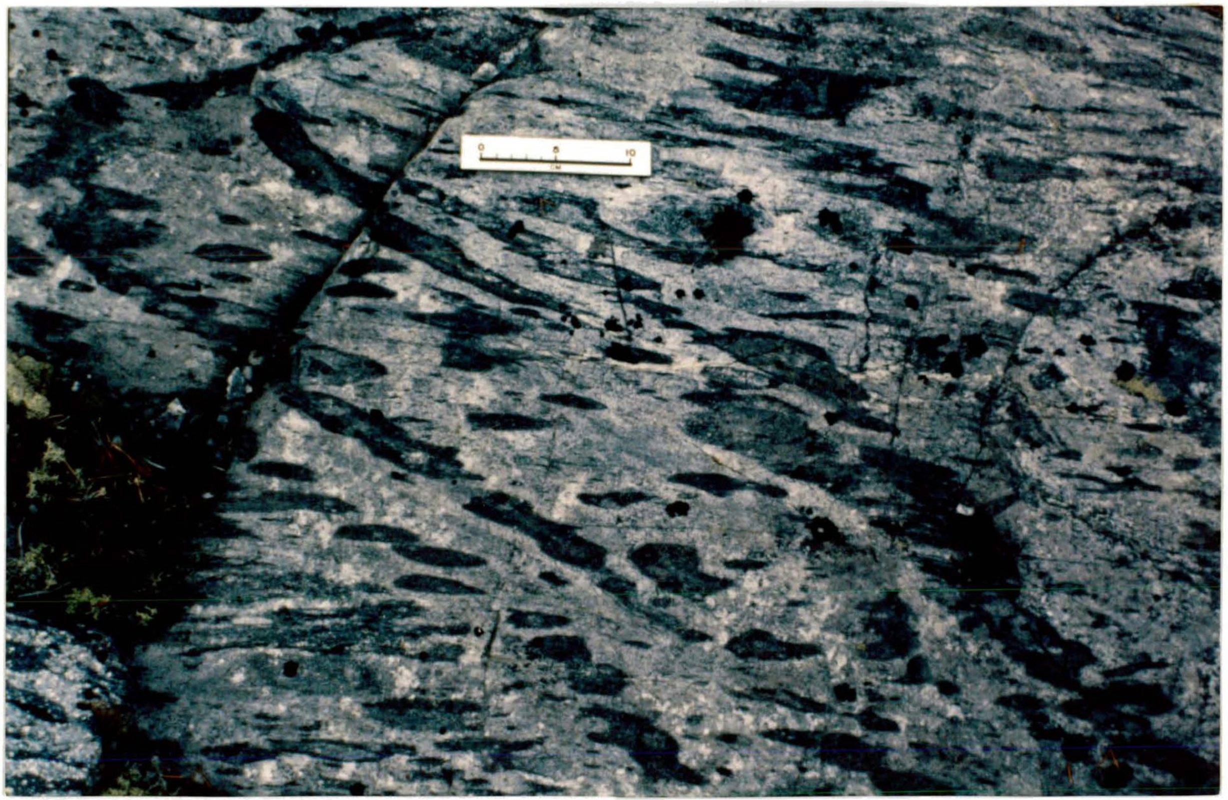
(b) matrix-blade relationships alternate in a continuous exposure.

A

B

Plate 5a,b Exposures of the bladed gneiss at Blueberry Hill in which clearly identifiable layers persist.

A



B

cleavage planes resulting in varying degrees of layer disruption along discontinuities (Plate 5c). Where transposition is extensive, layers separate into blades. In one location this transposition has resulted in a rock which, on first inspection, strongly resembles a conglomerate (Plate 5d). Some of the preserved layers show folds, while elsewhere transposition of these structures has produced intrafolial folds.

Ampbibolite and Banded Iron Formation::

The ampbibolites and banded iron formation are best exposed east of Faries Lake where they are intimately interlayered and structurally underlie the bladed gneiss. The amphibolite is exposed at Blueberry Hill, but exposures of banded iron formation have not been found here. The amphibolite is a medium- to coarse-grained dark green rock which is typically well foliated and in which a mineral lineation is strongly developed (Plate 6). The typical amphibolite contains 50% hornblende, 20% plagioclase (An_{30}) which is commonly sausseritized, 15-20% quartz, and 10% biotite. Apatite, chlorite, sphene, and opaques form the accessory minerals (Plate 7). Locally, increased magnetite concentrations give the rock a weakly magnetic character. Ductile shear zones are present in the amphibolite north of Faries Lake. The mylonite fabric is characterized by quartz ribbons and a strong lineation.

Banded iron formation is abundant and consists of fine grained quartz and magnetite (Plate 8). The outermost layers within an iron rich sequence are commonly gradational to magnetite bearing

Plate 5c,d

Photographs of the bladed gneiss at Blueberry Hillin which

(c) layer is transposed along cleavage planes

(d) layer transposition has modified the rock's appearance so extensively that it strongly resembles a conglomerate.

C

D

Plate 6. Example of amphibolite in the Faries Lake trench. The thin mafic layers reveal the attitude of the nearly recumbent F_1 folds.

Plate 7. Photomicrograph of the amphibolite taken in crossed nicols and showing the preferred dimensional orientation of hornblende and biotite in the quartzofeldspathic matrix.

P = plagioclase
Q = quartz
H = hornblende
B = biotite

Note: scale bar is 2.5mm.


0
1
CM

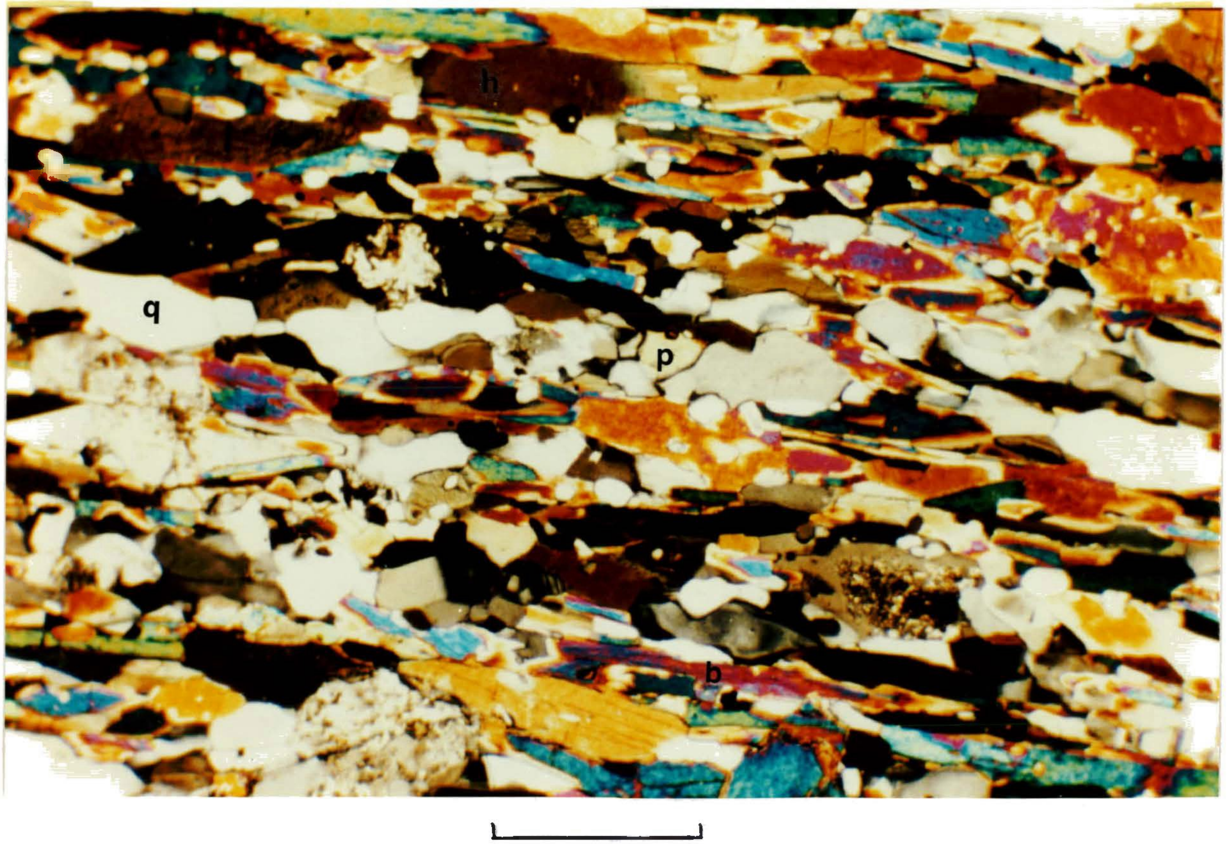
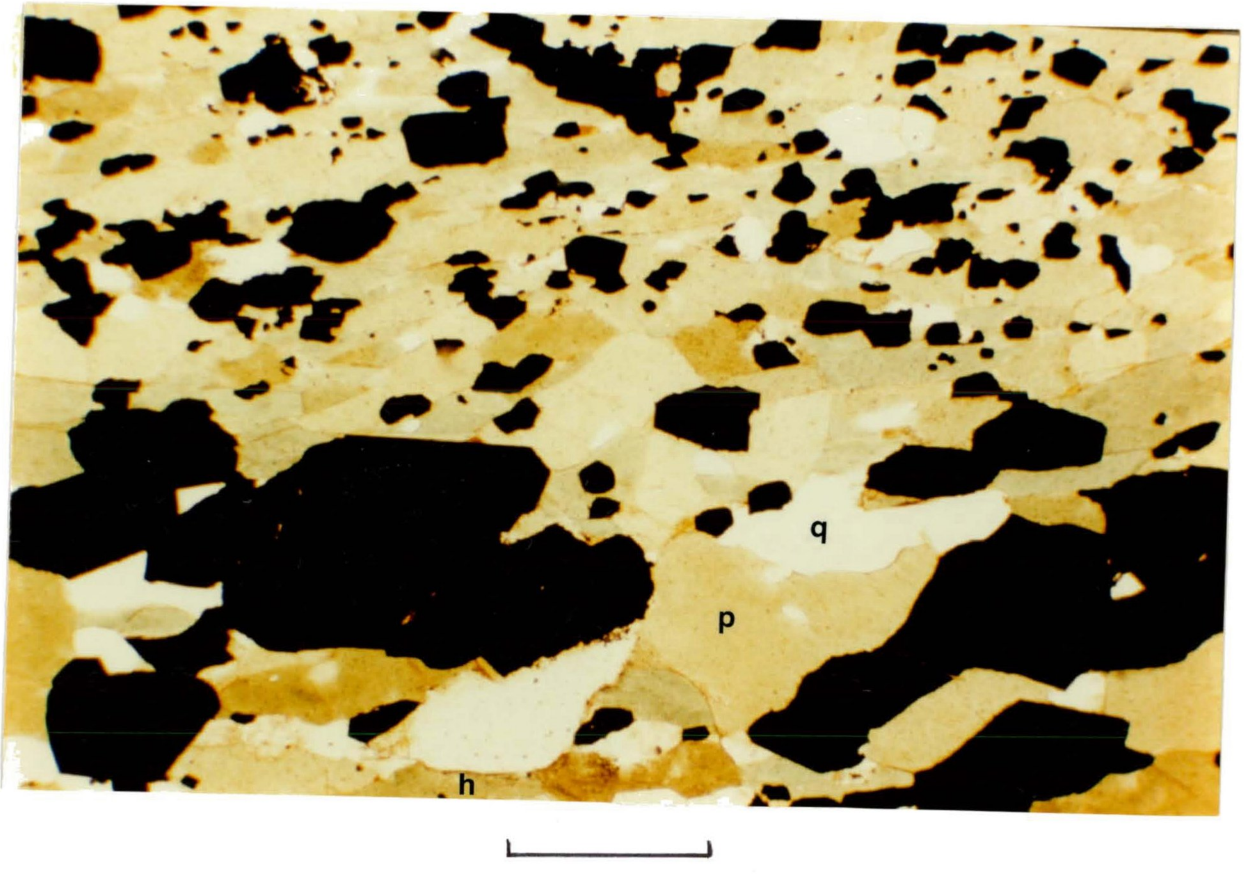

h
q
p
b

Plate 8. Interlayered amphibolite and iron formation as seen in the Faries Lake trench. Folding nature of the gneissic sequence is clearly apparent.

Plate 9. Photomicrograph of the banded iron formation which, at its margins, typically grades to magnetite rich amphibolite.

P = plagioclase
Q = quartz
H = hornblende
B = biotite
Opaque mineral grains are magnetite

Note: scale bar is 2.5mm.


q
p
h

amphibolite. Here, amphibole and magnetite comprise roughly equal proportions of the rock, with lesser amounts of plagioclase and quartz (Plate 9). Exposed iron formations are generally barren with respect to sulphides, but minor amounts of pyrite and trace amounts of chalcopyrite are observed in core samples. Lamination thickness varies from 3-5mm while unit thicknesses range from a few decimetres to tens of metres.

Evidence of deformation is well preserved in the fabric of the amphibolite and banded iron formation. A number of planar structures are present and refraction of these structures is common where they transect layers of varying composition. Observed lineations are consistent with those of the bladed gneiss. Refolded folds are exposed in several locations (Plate 8).

Particularly well developed in these rocks are cuspate-lobate folds. These are widespread throughout much of the sequence, and are best seen when viewed in a down plunge direction. Several examples are shown in Plate 10. As these plates show, in some layers cuspate-lobate folds formed on opposing layer boundaries and in some places the folded layers are offset along shear discontinuities. Included in the folded sequence are layers which are comprised of issolated mafic fragments in a felsic matrix. Some of theses fragments have ovoid shapes (Plate 11) and others are strongly flattened (Plate 12).

Metavolcanic Rocks:

Rocks of volcanic origin are exposed in the study area. At

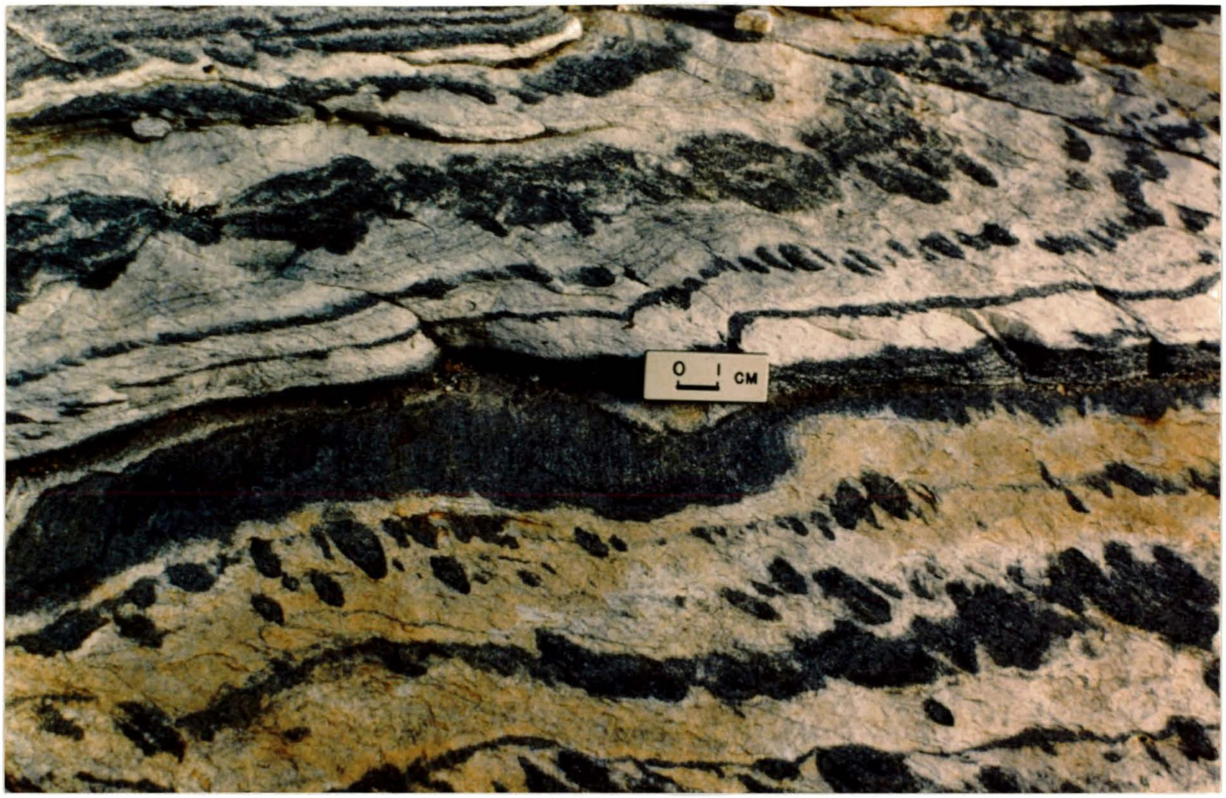
Plate 10. Examples of cuspate-lobate folds in the gneissic sequence where amphibolite and iron formation are interlayered.

A

B

Plate 11. Cross-section of ovoid mullions.

Plate 12. Cross section of flattened mullions.



A

B

Blueberry Hill pillow lavas and basalts, metamorphosed to amphibolite, form a narrow zone which can be traced northward for about 1km to exposures along a logging road. These volcanic rocks structurally overlie the metasedimentary sequence. Although it was not possible to obtain hand specimens from these exposures examination in the field suggests that hornblende and feldspar are the main mineral components. Observed planar and linear fabric elements in these rocks are consistent with those recorded in the metasedimentary rocks. Additional evidence of deformation stems from the folded nature of the inter-pillow material. In horizontal outcrop surfaces the pillows appear strongly elongated parallel to the stretching lineation direction (Plate 13). In these outcrops, pillow lengths range from less than a metre to more than three metres. One exposure of pillows is suitably oriented to provide a profile view of the pillows (Plate 14). Here selvages thicknesses are appreciably thickened at the pillow ends (thickness ratios on order of 7:1).

Meta-Intrusive Rocks

Regionally metamorphosed intrusive rocks are exposed in numerous locations throughout the study area. The exposures are situated east of Faries Lake and just south of Moshkinabi Lake. These exposures are confined to areas bounded by circular magnetic anomalies which are well defined on regional airborne electromagnetic survey maps.

At Faries Lake, rocks exposed at the surface include gabbro

Plate 13. Exposures of metavolcanic rocks including pillows which are strongly elongate parallel to the local stretching direction.

A

B

Plate 14. Near-profile view of the pillow lavas. Interpillow material is dark grey.

Note: scale bar is 10cm.

and anorthositic gabbro, while in drill core, more siliceous rock types occur. These include varieties of hornblende, biotite, and magnetite rich schists and gneisses. Examination of Noranda drill logs suggests that the intrusive rocks underlie the metasedimentary rocks at depth. The magnetite rich units, which are typically well layered and commonly mineralized in minor amounts with copper and iron sulphides, have stratigraphic thicknesses up to a few metres.

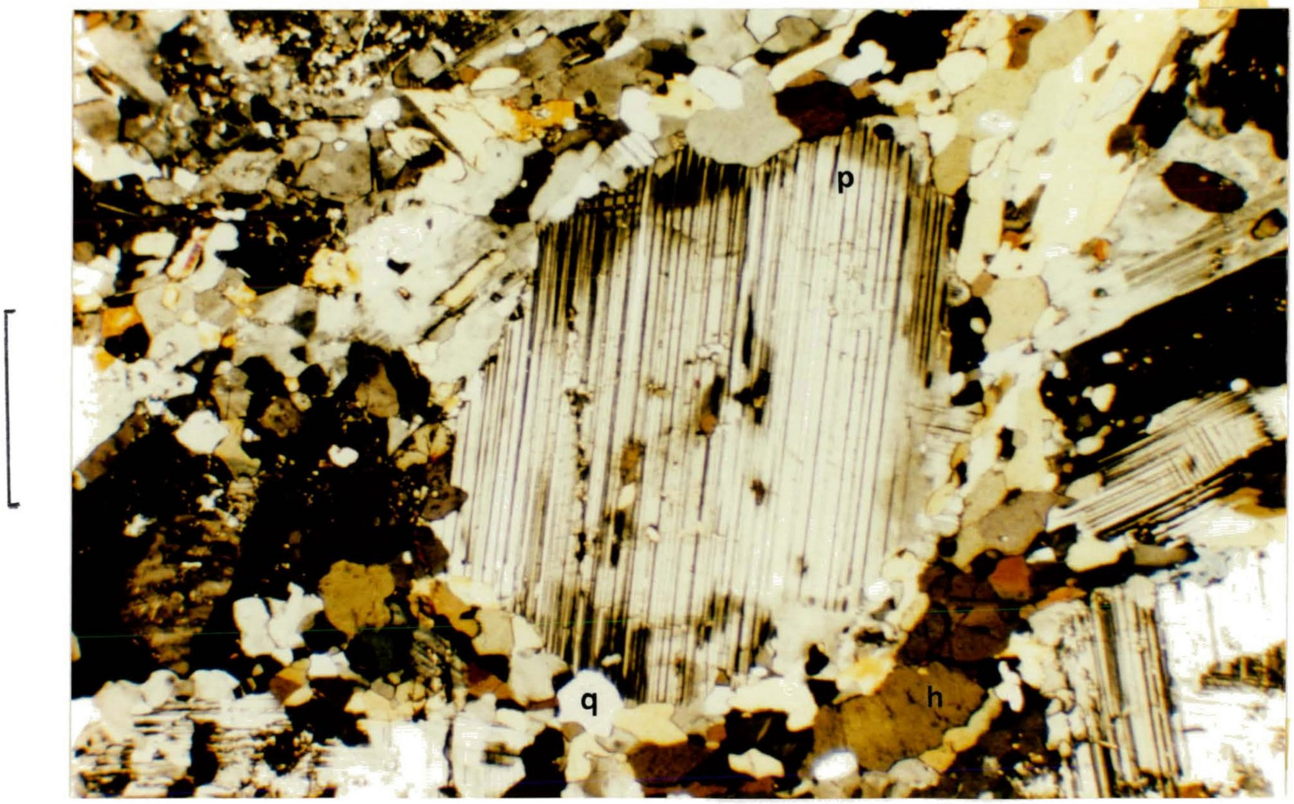
The gabbro is a coarse grained, dark green rock which is extensively exposed east of Faries Lake. Both massive and sheared varieties occur. Mineralogically the typical gabbro consists of 45% hornblende and 45% plagioclase, which is typically sausseritized. Chlorite, biotite and quartz, compose less than 10% of the rock. Opaque mineral grains are present in accessory quantities along with rare epidote and apatite.

East of Faries Lake a number of exposures of brecciated gabbro occur in which angular fragments are supported in a quartz-plagioclase matrix (Plate 15). Fragment mineralogy is extensively altered, with abundant chlorite, biotite and saussérite occuring as alteration minerals.

Rocks with compositions approximating those of anorthosite outcrop in one location east of Faries Lake and is commonly present in drill core. This coarse grained and massive rock is characterized by its cumulus texture (Plate 16). The rock consists chiefly of plagioclase (85%), some of which is altered to sausserite, and biotite (10-15%) with trace amounts of sphene. Since mafic proportions constitute more than 10% of the rock it is not a true anorthosite, but rather a gabbroic anorthosite, based on

Plate 15. An exposure of brecciated gabbro in which angular fragments are supported in a quartz-feldspar matrix.

Plate 16. Photomicrograph of the cumulus texture which is characteristic of the gabbroic anorthosite. Note the extensive subgrain development which accompanied recrystallization.


p
q
h

classifications of anorthositic rocks by Buddington (1939). It is likely that this anorthositic gabbro is a part of a differentiated mafic intrusion and not a representative of the anorthosite massifs so typical of the Grenville and Nain Provinces.

Various igneous rocks outcrop just south of Moshkinabi Lake. Plate 17 shows the marked layered nature of these rocks. Layer compositions vary significantly and include ultramafic units, sometimes containing garnet, and plagioclase dominated units. The dark green, massive unit shown in Plate 17 consists of 90% actinolite and 10% sausseritized plagioclase. Trace amounts of biotite and muscovite are also noted. The lighter green unit shown in the same plate is dominated by massive, fine grained chlorite, which constitutes roughly 60% of the rock. Magnetite is present in concentrations up to 10% and accounts for the units strongly magnetic character. The balance of the rock consists of roughly equal proportions of coarse grained chlorite, hornblende, and plagioclase while muscovite is present in accessory amounts. The light coloured unit shown in the central portion of Plate 17 is dominated by extensively sausseritized plagioclase and by fine grained chlorite and muscovite. Mafic components (hornblende-actinolite) comprise only about 25% of the rock.

The boundaries of the study area are dominated by extensive exposures of orthogneisses. These pinkish-grey, foliated to massive gneisses have a mineralogical composition which closely approximates that of a tonalite. The typical medium- to coarse grained tonalitic gneiss consists of 60% plagioclase, 25% quartz, 10% biotite, 5% muscovite, and trace amounts of opaque mineral

Plate 17. Photograph of the intrusive rocks which outcrop just south of Moshkinabi Lake. These rocks are characterized by their marked layered nature. See text for details.

grains. The more mafic varieties contain up to 25% biotite and a few percent magnetite and are typically foliated.

Structure:

Structural elements observed in outcrops include S-surfaces, lineations and linear structures, and minor folds. C-S fabric is present in some rocks and has been observed at both outcrop and microscopic scales.

S-Surfaces:

Planar fabric elements present are of two types, compositional layering and foliations. The s-surface denoted S_0 refers to compositional layering in the metasedimentary rocks. Layering is attributed to the relative abundance of component minerals in a given layer. The compositional layering likely represents primary layering in the sedimentary succession, although it may have been somewhat altered or enhanced by metamorphic segregation.

Three penetrative cleavages can be identified in most outcrops and reflect different periods of development. These are identified as S_1, S_2, and S_3, in progressive order of development in the deformational history of these layered gneisses. The relative orientations of planar elements are shown in Figure 15. S_1 and S_2 are north-south striking cleavages which are axial planar to minor folds (F_1 and F_2, respectively). S_3 is an east-west striking, subvertical crenulation cleavage. S_1, shown in Plate 18, is a

Figure 15. Schematic diagram illustrating the relative orientations of planar fabric elements. Note that modification of earlier-formed fabrics by later fabric development is not shown.

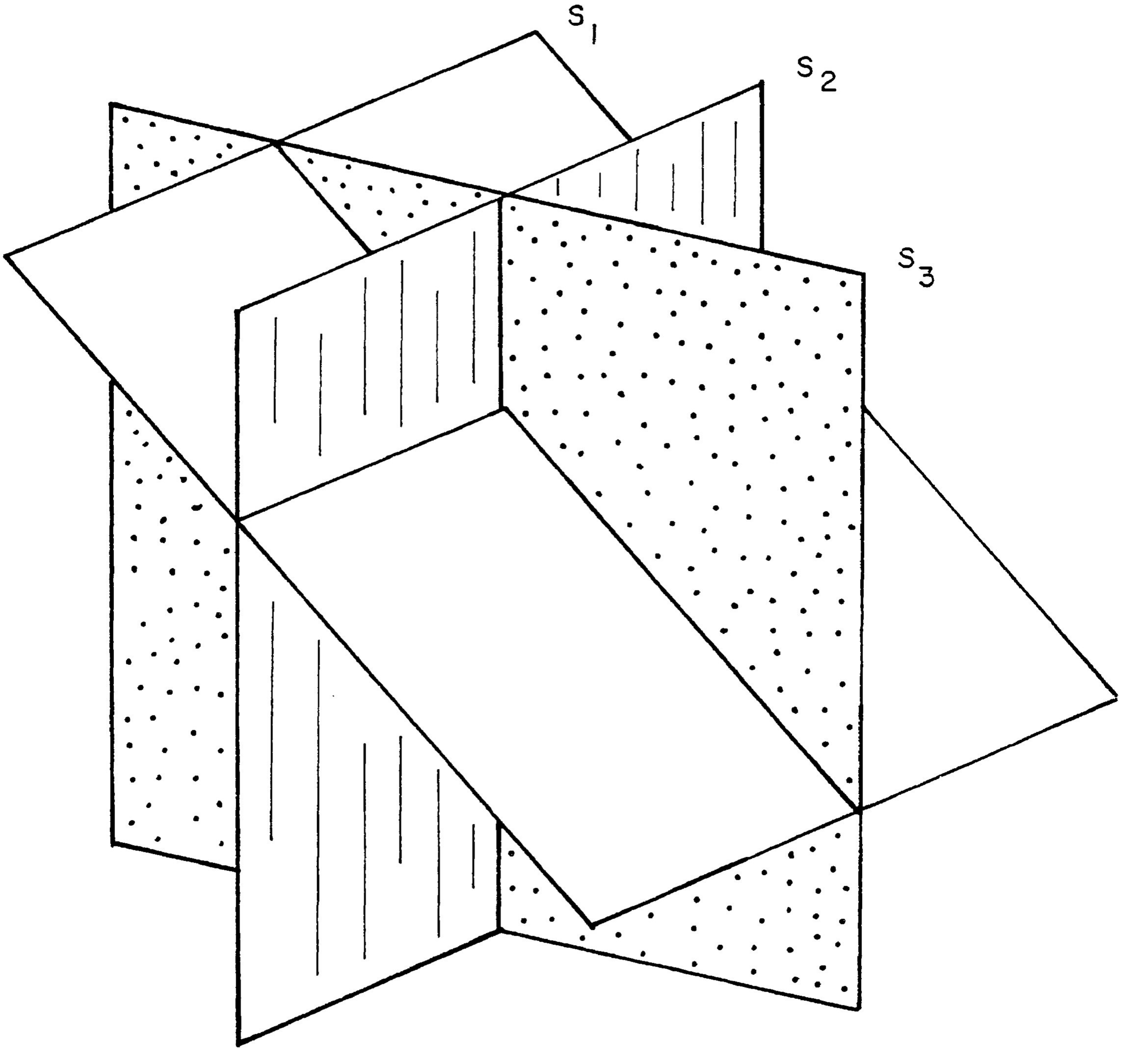


Fig. 15

Plate 18. Example of the bladed gneiss in which S_1 is well developed. Scale marker is resting on the foliation plane.

Plate 19. Spaced cleavage (S_2) in amphibolite. Cleavage planes are discrete and spaced at roughly 1cm intervals.

Plate 20. An exposure of bladed gneiss in which a crenulation cleavage (S_3) is well developed. S_3 is best expressed by the crenulation of S_2.

Plate 21. The lineation direction (L_2) as defined by the orientation of buckled layers and mullions.

Figure 16. Stereograms of (a) planar, and (b) linear fabric elements.

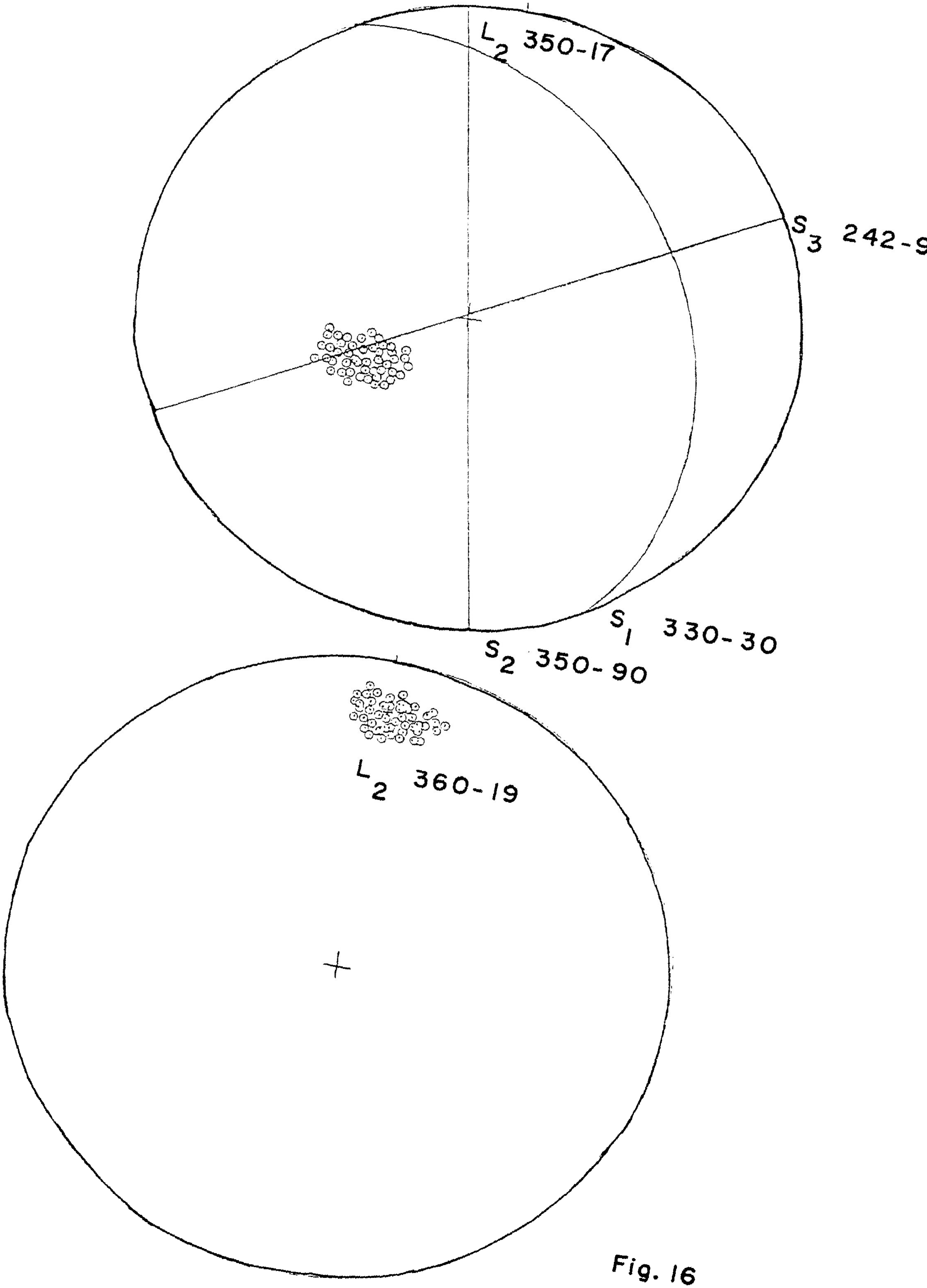


Fig. 16

pervasive foliation and its orientation is readily measured in outcrop. Plate 19 shows an exposure of amphibolite in the Faries Lake trench in which S_2 is well developed. Here the cleavage is discrete and cleavage planes are spaced at roughly 1 cm intervals. S_3 is best developed in the bladed gneiss and is expressed by the crenulation of S_2 planes. Plate 20 shows an example from the Faries Lake trench. Microscopically the cleavages result from a strong fabric defined by the dimensionally preferred orientation of hornblende and biotite.

The stereogram shown in Figure 16a summarizes the planar data. Poles to S_1 plot as a tight cluster and yield an average S_1 orientation of 330-36. S_2, also plotted in the stereogram, is a subvertical cleavage with an average strike of 350 degrees. The intersection of the two foliations defines a lineation (L_2) with an orientation of 350-17.

Lineations:

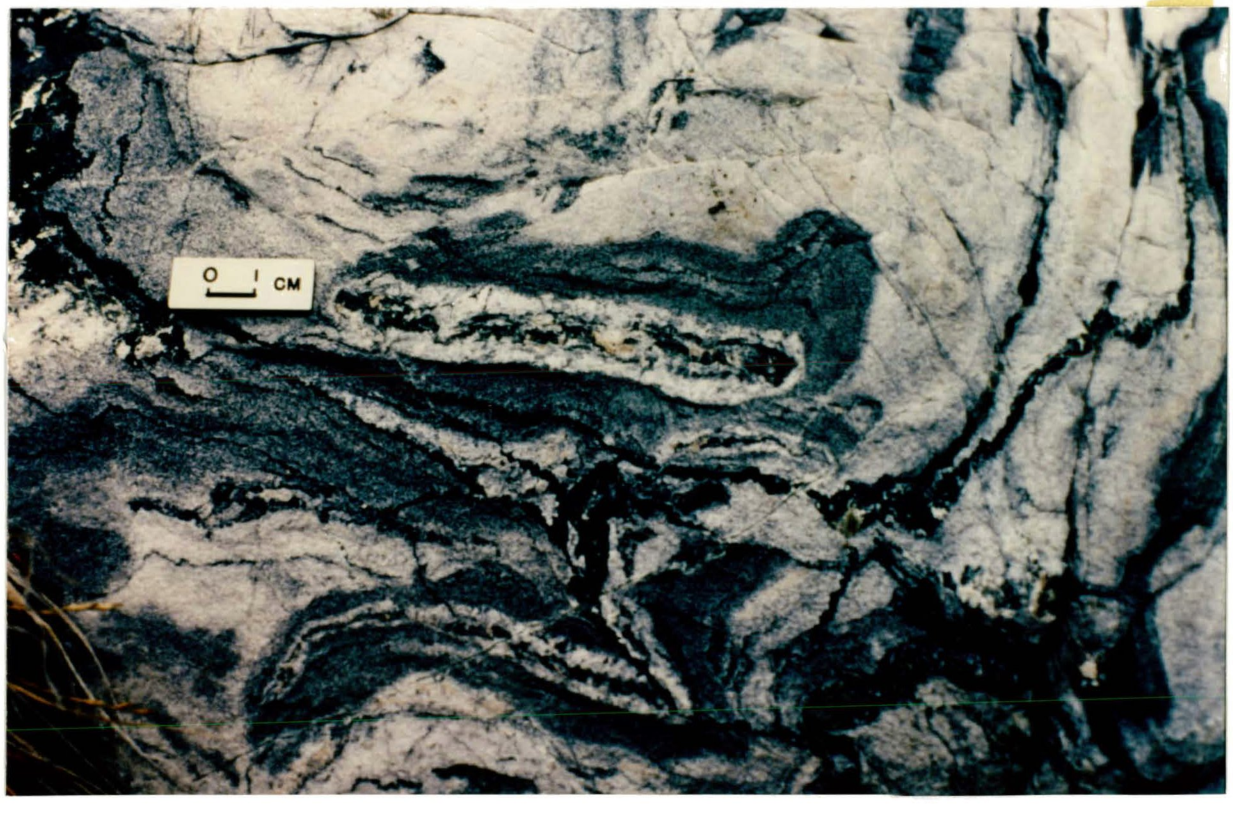
All rocks in the sequence of layered gneisses share a common lineation which is readily measured in most outcrops. Linear data are plotted in a stereogram (Fig. 16b). The lineations plot as a tight cluster and have an average orientation of 360-19. The lineation direction measured in the field (Plate 21) is nearly coincident with that generated by the intersection of S_1 and S_2 (as seen in Figure 16b). Thus this lineation (L_2) is the result of the mutual intersection of S_2 and S_1. Linear structures are also present in the form of blades, and their trend and plunge is

Plate 22. Macrofolds in the gneissic sequence.

(a) Profile view of an F_2 hinge with axial planar cleavage (S_2).

(b) Close-up view of F_1 hinge as seen in upper right hand corner of (a).

A



B

Plate 23. Example of the complex fold interference patterns which are commonly seen in outcrops of the gneissic sequence.

Plate 24. Photograph showing the wide variety of scales on which cuspate-lobate folding has occurred.

Plate 25. Example of the intrafolial folds which develop as a product of layer transposition.


0 1 cm

Plate 26a,b. Photograph of c-s fabric as seen in an exposure of metasedimentary rocks. Sense of shear is sinistral.

A

B

identical to that of L_2. Several other intersection lineations are geometrically possible, but have not been observed in the rocks.

Folds:

Two generations of folds have been identified in the study area. First generation folds (F_1) are recumbent with both limbs dipping eastward at shallow to moderate angles. Hinge lines of these folds are horizontal. Second generation folds (F_2) are low amplitude, upright folds with shallowly plunging hinge lines. Plate 22 shows examples of these folds as seen in the Faries Lake trench. The two generations of folds are coaxial and fold interference patterns are often complex (Plate 23). In addition to macrofolds individual layers within the gneissic sequence have undergone cuspate-lobate folding (Plate 24) and layer transposition has resulted in intrafolial folds (Plate 25).

C-S Fabric:

C-S fabric has been identified in several locations, both at outcrop and at microscopic scales. Plate 26 shows c-s fabric as seen in outcrop. Both s- and c-planes are defined by an alignment of amphibole. Similar features have been described by numerous authors (eg. Berthe et. al., 1979). They recognized two types of foliation: S-surfaces related to the accumulation of finite strain, and C-surfaces related to local high shear strains. C-S fabric is a kinematic indicator and permits the determination of sense of shear. In plate 26 the sense of shear is sinistral. Examples of bladed gneiss are known in which c-s fabric exists. Unfortunately the samples were not oriented and consequently the in situ sense of shear can not be determined.

DISCUSSION

The strongly layered nature of the gneissic sequence reflects initial compositional and textural characteristics of the parental rocks. Based on the compositions represented, the metamorphic rocks were derived from a sequence of feldspathic greywackes and interbedded mudstones. It is also likely that a part of this sequence included tuffaceous units of limited extent. Petrographic evidence shows that the rocks are recrystallized. Quartz and feldspar grains form a granoblastic background to larger grains of hornblende and biotite. The latter shows a strong preferred dimensional orientation. It is not possible to identify the sediment source region, however, it is worth noting that these sedimentary rocks are lithologically typical of those of the nearby Quetico subprovince.

Throughout the metasedimentary rocks feldspar megacrysts (An_{30}) occur. These are typically enveloped by finer grained plagioclase in a mortar texture. Petrographic evidence indicates that the megacrystic plagioclase may represent an earlier porphyroblastic plagioclase which become commuted during deformation. This would imply that metamorphism and recrystallization preceded deformation by some time and continued during folding and shearing. An alternative explanation is that the megacrysts are remnant clastic grains which were part of the parental rock. The widespread nature and relative abundance in the quartzofeldspathic gneisses appears to give some strength to this idea. However, presence of similar plagioclases in the amphibolitic rocks suggests that they are a product of metamorphism.

Known exposures of iron formation are confined to the vicinity of Faries Lake. The absence of iron formation at Blueberry Hill might be explained by a lateral variation in sediment deposition within the sedimentary succession. Alternatively, iron formation may be present, but is not exposed. The presence of banded iron formation provides convincing evidence that these rocks are of sedimentary origin and might suggest deposition in a shallow-water, near-shore enviornment, as is typical of Archean iron formations. In several drill holes banded iron formation is intersected at different depths. It is likely that these repeated intersections are caused by the extensive folding of the layered sequence.

Metavolcanic rocks including basalt, metamorphosed to amphibolite, and pillow lavas are exposed in the northern part of the area. Outcrop exposures suggest that pillow lavas are confined to a narrow zone less than 10 metres in width within thicker basalt flows. The presence of pillow lavas implies that the basaltic flows were in part subaqeous. The pillows are not of the classic "bun-shaped" variety, rather they are extremely elongate parallel to the local stretching lineation. Some estimate of the total strain can be obtained by measuring the maximum and minimum selvage thicknesses which yield ratios of an order of 7:1. Strains greater than 4.5:1 are generally acknowledged to be an overestimate of the actual strain (Borradaile, 1982). Strains of this magnitude are insufficient to explain the extreme elongation of the pillows. Consequently, their atypical shape may reflect the nature of the depositional surface, or perhaps, the composition or viscosity of the extruded magma, or the combination of these factors.

The development of structures in the metasedimentary rocks was strongly controlled by their layered nature and by the competency contrasts between adjacent layers. The term competence is used to describe differences in rock properties which lead to mechanical instability (Ramsay and Huber, 1983, p. 7). Rocks which "flow" easily are described as the least competent members, whereas those which are resistant to "flow" are the most competent rocks. In a layered sequence, layers which are competent will commonly reflect layer parallel shortening by the development of buckle folds. Where the layers are extended, boudins result. In either case the incompetent material moves to accommodate low pressure regions in the developing structures. The extent to which structures develop depends on a number of factors which include viscosity contrasts between the competent and incompetent layers, layer thickness, and the proportion of competent to incompetent material within the layered sequence.

Boudinage is a structure produced during the extension of competent layers enclosed in an incompetent matrix (Ramsay and Huber, 1983, p. 11). As Fig. 17 shows the competent layer is preferentially stretched and thinned, and where competency contrasts are high, layer failure ultimately results. Further extension results in separation of the isolated fragments of the competent layer, which are termed boudins, and the surrounding less competent material flows into the voids between the boudins. As the surrounding ductile material flows around the edges of the

Figure 17. The progressive development of boudinage. The competent bands 1, 2, 3, and 4 are arranged in decreasing order of competence, and band 4 has the same properties as the matrix; after Ramsay, 1967, p. 106.

Figure 18. Chocolate-tablet structure; after Ramsay, 1967, p. 112.

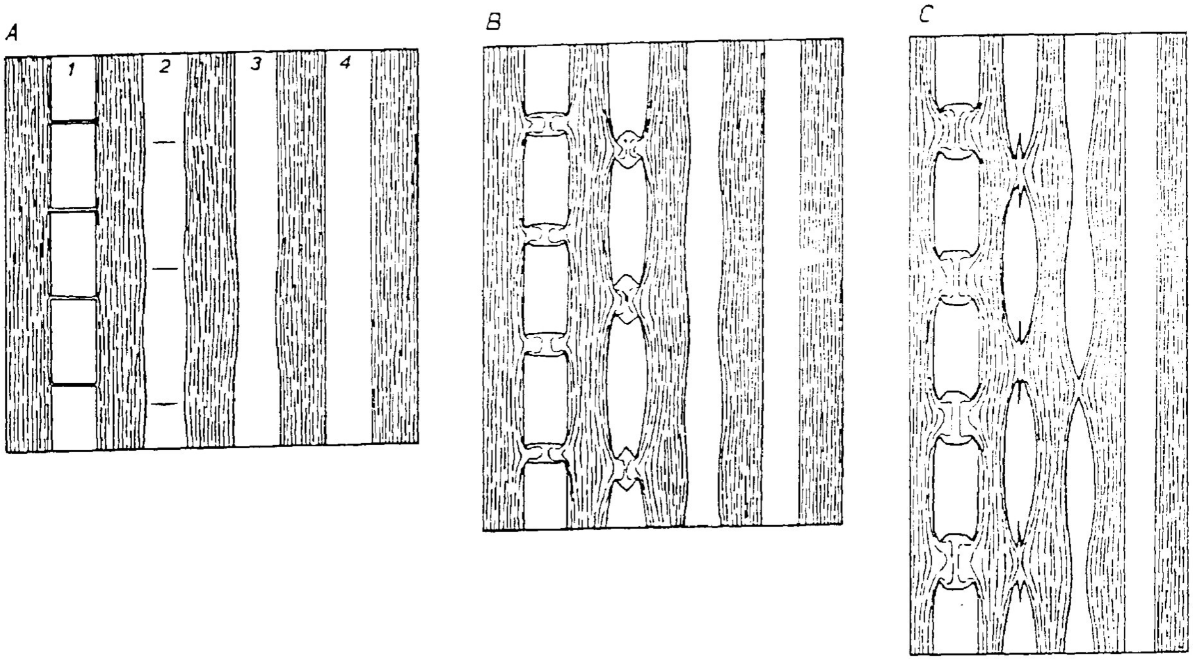


Fig. 17

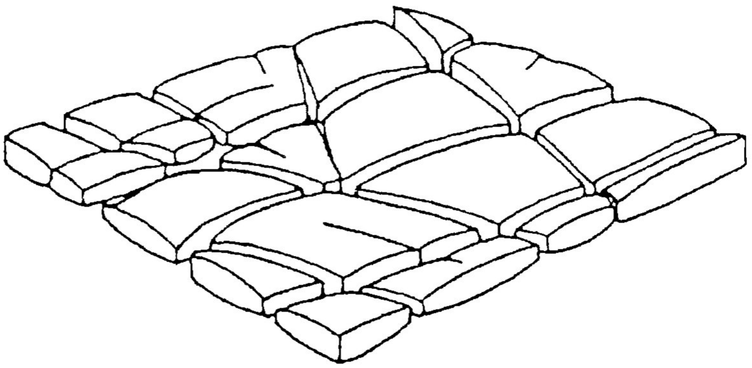


Fig. 18

boudins differential shear along the competent-incompetent rock interface modifies their block-like profiles. The boudins develop a characteristic barrel-shaped cross section, and, where the separation is large, the strong flow of the ductile material produces boudins with a fish-mouth form (Figure 17c). Where layer competency contrasts are low the more competent layer undergoes steady thinning, and perhaps necking, without ultimate layer failure.

Where a competent layer is stretched in all directions a complex of crossing boudins is produced and is known as chocolate tablet structure (Figure 18). If the strain is confined to a single deformation the boudin necks will be generally rather irregular. Structures arising from the superposition of several deformations or several phases of a single deformation show periodic or sequential development, and the boudins often intersect at angles other than 90°.

When a competent layer embedded in a less competent matrix is shortened parallel to the layer boundaries fold forming buckling instabilties are inhibited. If the competent layer is isolated and separated from other competent layers by a considerable thickness of incompetent rock, then the fold wavelength is a function of competent layer thickness and of layer competence contrasts. An increase in the thickness of the competent layer and an increase in the competence contrast both lead to an increase in fold wavelength. In multilayered sequences where competent layers are relatively closely spaced, the folding of the competent layers will be geometricly related. If the competent layers are of about the same thickness and if the ductility contrasts are similar, harmonic folds form, whereas polyharmonic folds form if thickness or ductility contrasts are markedly disimilar (Ramsay and Huber, 1987, pp. 412-424).

Figure 19 shows the different fold forms which result from layer shortening in a multilayered sequence. These include ptygmatic folds, or elasticas, buckle folds, and cuspate-lobate folds. Ptygmatic folds form where single, isolated layers of relatively highly competent material enclosed in a matrix of low competence ($\mu_o/\mu_1 > 50$) are strongly shortened. Ptygmatic folds have a large initial wavelength relative to layer thickness, which is constant throughout the fold. At lower competence contrasts buckle folds develop. At low competence contrasts ($\mu_o/\mu_1 < 10$) cuspate-lobate fold formation is the characteristic structure developed along interfaces between competent and incompetent materials where the interface lies along a direction of shortening. These folds show systematic shape variations between adjacent antiforms and synforms. The lobate folds have cores of competent material and the cuspate folds have cores of less competent material. In three dimensions the cuspate lobate folds give rise to linear features parallel to the hinges of the folds. These structures have been given the name fold mullions (Ramsay and Huber, 1987, p. 397) and resemble the exposed wood surfaces in a pile of wooden logs.

Sedimentary structures which are similar to cuspate-lobate folds are well known. In many unconsolidated sediments, complex structures often develop at the contacts of rocks of different

Figure 19. Fold shapes produced by buckling of a competent layer in a less competent host material. The upper ptygmatic fold shows the maximum viscosity contrast μ_1 / μ_5, the lowest cuspate-lobate fold the minimum contrast μ_4 / μ_5. The middle folds have intermediate viscosity ratios; after Ramsay and Huber, 1987, p. 394.

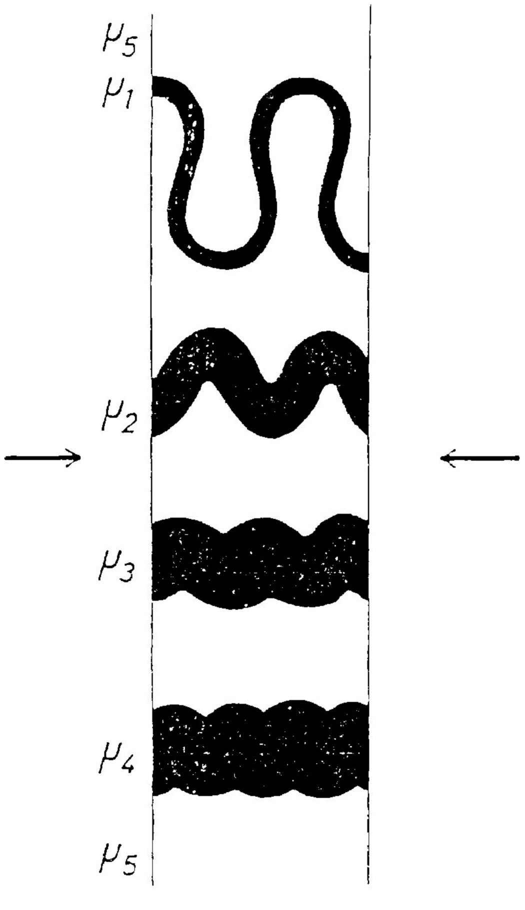


Fig. 19

composition. Although many of these are undoubtably the result of erosion and sediment sculpting, others, such as load casts and flame structures, may be the result of shortening of the layer contacts (Ramsay, 1967, p. 386). Since the sedimentary succession consists of layers of alternating lithology it is conceivable that these structures may have developed locally, however, the vast majority of the observed cuspate-lobate structures formed by deformation.

Where viscosities are equal throughout a layered sequence layer parallel shortening reduces layer length and increases layer thickness. For example, in many high grade metamorphic terranes gneisses abound in which parallel unfolded layers of different mineral composition occur. In these cases viscosities of the layers were nearly equal.

Variations in layer orientation with respect to pincipal strain directions are reflected in a variety of structures. Where oriented obliquely, extensional strains in layers result in en echelon arangements of boudins, and compressive strains result in asymmetric folds.

A possible model for the deformation of the metasedimentary rocks is presented below. The proposed model is based on silmilarities of existing structures with those described by Ramsay and Huber (1983 and 1987) in deformed layered rock sequences (summarized above). Although macrofolding and the development of accompanying axial planar cleavages is consistent throughout the metasedimentary succession, layer response to strain varies locally and is attributable to varying layer neighbor relationships.

In the early stages of deformation nearly recumbent folds (F_1) were produced (Fig. 20a). In the hinge zones of these folds layers were shortened and cuspate-lobate folds developed where competency contrasts were small, and sinuous buckle folds developed where competency contrasts were great (Fig. 20b). Where shortening strains acted along layer boundaries across which there was no appreciable competency contrast, layers were shortened and appreciably thickened. This latter process dominated in the more massive amphibolite units. Where layer competency contasts were small the resultant features would have resembled mullion structures if exposed to show the three dimensional shapes (Fig. 20c). However, layers were also subject to extension parallel to the hinge lines of the F_1 folds. Where conditions were suitable this would generate boudins in the buckled layers and also separate the mullions along their length. The development of an axial planar cleavage (S_1) accompanied the first fold episode and acted to segment the mullions into distinct rods and the buckled layers into microlithons (Fig. 20d). The mutual intersection of S_o and S_1 generates an intersection lineation (L_1). which is not discernible in outcrop.

Extensional strains in F_1 fold limbs resulted in boudinage. Boudins resulted where layer competency contrasts were large, and where lesser competency contrasts existed, layers underwent thinning and necking (Fig. 20e). Units comprised of mudstone would have been markedly thinned, but boudins would not have resulted, since viscosity contrast between adjacent layers was negligible. The corona-like rims seen in many blades are in part a product of

Figure 20. Model for the development of the bladed gneiss through the processes of cuspate-lobate folding, buckle folding, and boudinage of layers.

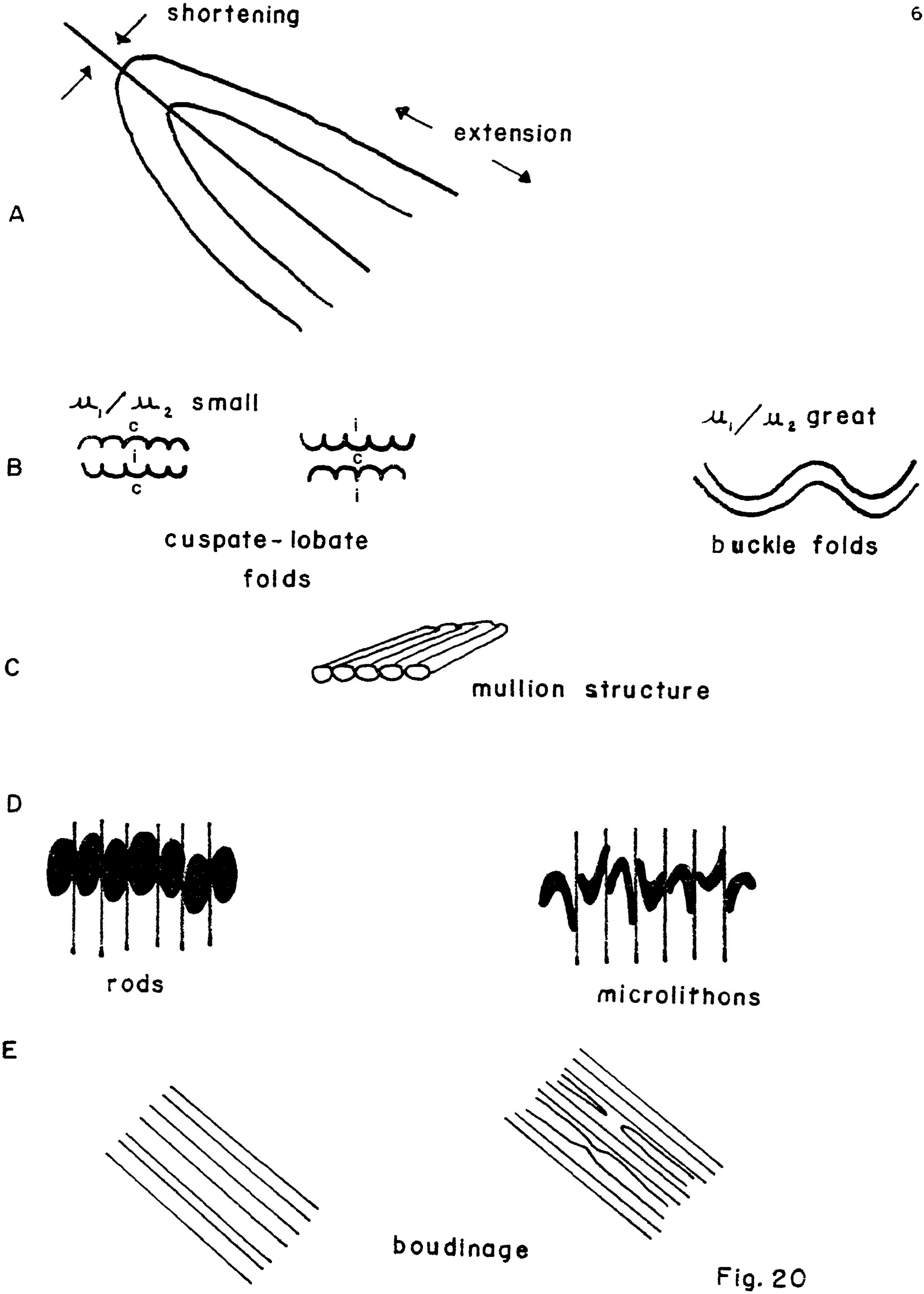

shortening
extension
A
μ_1/μ_2 small
c
i
c
i
c
i
B
cuspate-lobate folds
μ_1/μ_2 great
buckle folds
C
mullion structure
D
rods
microlithons
E
boudinage

Fig. 20

layer extension. As the competent layers were boudined, the less competent surrounding material flowed into the gaps between the individual boudins, effectively enveloping them, thus producing the corona-like rims. The formation of blades with corona-like rims also accompanies cuspate-lobate folding. The less competent material flows into the regions between adjacent lobes and subsequent offsetting due to shearing results in an incomplete enveloping layer.

During the development of folds, layer orientation with respect to the finite extensional and compressive strain direcctions will vary. This can lead to unfolding of previously folded layers, to the development of boudinage, or to intrafolial folds. Undoubtedly, many of the structures seen in the gneissic sequence developed in this manner.

Subsequent deformation of the metasedimentary rocks includes a second fold episode wherein the earlier formed recumbent folds (F_1) are refolded to produce upright, low amplitude folds whose hinge lines plunge shallowly to the north (F_2). F_1 and F_2 are coaxial. During the second folding event S_1 is folded along with the layering and is subsequently coplanar with S_0, except in F_1 hinges. The development of an axial planar cleavage (S_2) accompanies the second fold event and the intersection of S_2 with S_0 and S_1 defines L_2.

Superposed folding also acts to modify the earlier developed structures. Layers which initially buckled were refolded or subsequently boudinaged, while initially thinned or boudined layers underwent further extensional strain or were subsequently folded.

For layers in which cuspate-lobate folds initially developed, extensional strain would act to further separate the mullions, thus creating a rock which has a strongly clastic appearance (Plate 11). If the layers were subsequently subjected to shortening strains, the individual rods would have been strongly flattened, and offsetting of the rods would result from motion along the cleavage planes (Plate 12).

During the latest stages of deformation a cleavage developed which crenulated all suitably oriented planar fabrics. Crenulation cleavage is a structure formed by the development of regular microfolds in some pre-existing, fine sedimentary or tectonic lamination, or more commonly in a pre-existing tectonic fabric such as a cleavage or schistosity (Ramsay and Huber, 1987, p. 436). Because of their orthogonal orientations, the presence of S_3 is best expressed by the crenulation of S_2.

Discussion thus far has concentrated principally on layer competency contrasts as the controlling factor for deformational structures. Layer thickness unquestionably also plays a governing role in the development of these structures. For example, variation in blade thickness in the bladed gneiss is attributable to variations in primary layer thickness. Relative layer thicknesses are also a controlling factor. Examples of bladed gneiss in which mafic minerals comprise the blades and felsic minerals comprise the matrix are known as well as the reverse situation, where felsic blades occur in a mafic matrix (Plates 3 and 4, respectively). When the proportion of mafic layers to felsic layers is low, the blades will have a felsic composition.

In the more typical case, the mafic layers give rise to blades and the felsic layers form the bulk of the gneiss, which reflects a relatively high proportion of mafic to felsic layers.

In summary, the development of the bladed gneiss and associated rocks is attributable to the combined processes of buckle folding, cuspate-lobate folding, and boudinage. The three processes were simmultaneously active during deformation of the layered sedimentary sequence and the structures produced by any one process in early stages of deformation were commonly reshaped by the others at a later stage in the deformation. Layer neighbor relationships, including relative competency contrasts and thicknesses, dictated the response of individual layers to the strains which accompanied regional folding. Folding (F_1 and F_2) is accompanied by the development of axial planar cleavages (S_1 and S_2). At more advanced stages in the deformation layer transposition occurred along shear discontinuities which developed parallel to the axial planar cleavages.

It is not possible to determine the elapsed duration of deformation, nor is it possible to determine whether deformation was a single continuous event, or a series of distinct episodes of deformation separated by significant time intervals. The metamorphic history of these rocks is similarly unclear. It has been established that each episode of folding was accompanied by the development of an axial planar cleavage. S_1 and S_2 are defined by the growth of platy minerals, specifically biotite and hornblende, and this neomineralization might suggest multiple periods of metamorphism. However, since the same minerals define

S_1 and S_2 it is possible that only one prolonged period of metamorphism occurred. Alternatively, multiple metamorphic events may have occurred, with metamorphic grade nearly equal during each phase of deformation.

During progressive metamorphism the growth of new minerals in the deforming sedimentary succession would have affected the viscosity of individual layers. Therefore, competency contrasts between adjacent layers may have been variable throughout deformation. Consequently, the response of a given layer boundary to finite strain may not have been constant throughout the course of deformation, and this would be reflected in the resultant structures.

All supracrustal rocks in the study area share common structural elements, which implies that the metasedimentary and metavolcanic rocks have a common deformational history. The metavolcanic rocks resemble the amphibolites which are interpreted to reflect the unlayered nature of the basalts. The relationship between the metavolcanic and metasedimentary rocks becomes evident when interpreted in light of regional structures. Figure 21 illustrates the relationship between the regional and local structures. S_0 and S_1 are everywhere co-planar, except in F_1 hinge zones where they have an orthoganal relationship. In the geologic profile (Fig. 11) S_0 marks the contact between the metasedimentary and metavolcanic rocks. Supracrustal rocks in the study area are in a position structurally above the axial plane of the F_1 folds. Post-folding intrusion of the supracrustal rocks by gabbro has obliterated those rocks which were structurally below the axial

Figure 21a, b. Relationship of minor structures to regional structure.

S- Metasedimentary Rocks
V- Metavolcanic Rocks
G- Metagabbro

Note: a and b are schematic sketches and are not related in scale to Figures 10 and 11.

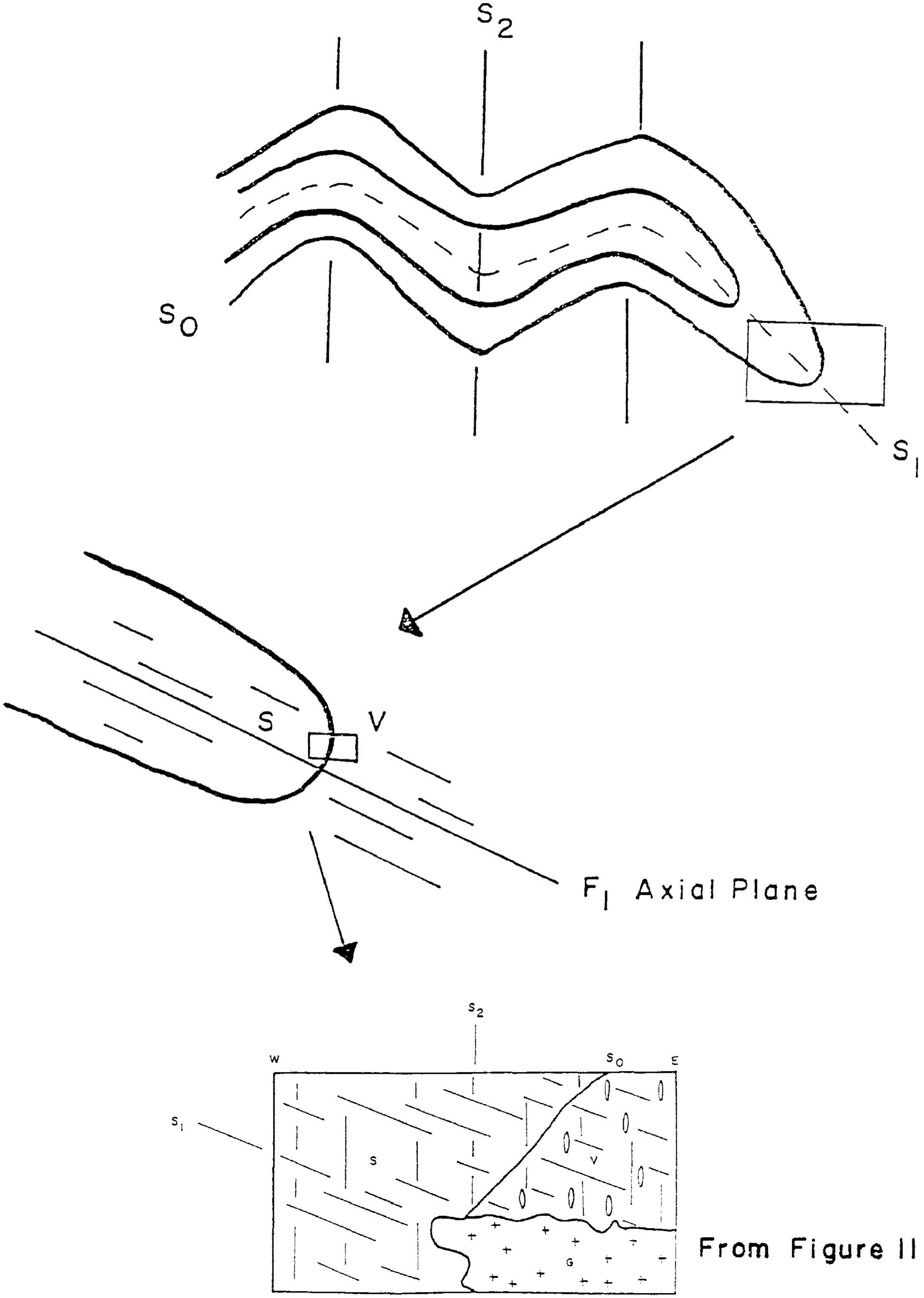


Fig. 21

plane of the F_1 folds, and consequently no exposures exist in which metavolcanic rocks underlie metasedimentary rocks.

Numerous workers have proposed tectonic models for the Superior Province. Card (1990) provides a review of these models, which include "fixist" and "mobilist" models, depending on whether the rock units are considered to have been brought together principally by vertical or horizontal mechanisms of assembly. Most fixist models assume a preexisting sialic crust with formation of supracrustal sequences in rifts or linear downwarps initiated in the crust by mantle processes. Continued downwarping and partial melting followed by plutonism, diapirism, deformation, metamorphism, thickening and uplift resulted in the formation of an Archean craton rich in plutonic rocks and greenstones (Card, 1990). Examples include those of Goodwin (1977), Young (1978), and Ayres and Thurston (1985). Mobilist models differ in that they assume mobile, mainly oceanic crust within a plate textonic framework involving subduction and horizontal accretion (Talbot, 1973), mainly in convergent plate boundary settings (Card, 1990). Examples include those of Goodwin and Ridler (1970), Langford and Morin (1976), Dimroth et al. (1983), Ludden et al. (1986), and Sylvester (1987). Card (1990) also proposes a tectonic model for the Superior Province (Fig. 22). This is considered a mobilist model and involves subduction driven accretion of Archean crustal elements, most of which range in age from 3.1 to 2.6 Ga.

In light of these tectonic models for the Superior Province, a model for regional deformation is proposed to explain the development of the structures mapped in the thesis area. Assorted

Figure 22. Model for the tectonic evolution of the Superior Province involving southward oblique acretion of island arcs, acretionary prisms, and microcontinents; after Card (1990).

AW- Abitibi-Wawa terrane
ER- English River acretionary prism
MRV- Minnesota River Valley foreland
P- Pontiac acretionary prism
Q- Quetico acretionary prism
US- Uchi-Sachio island arc terranes
W- Wabigoon island arc and microcontinent
WR- Winnipeg River microcontinent

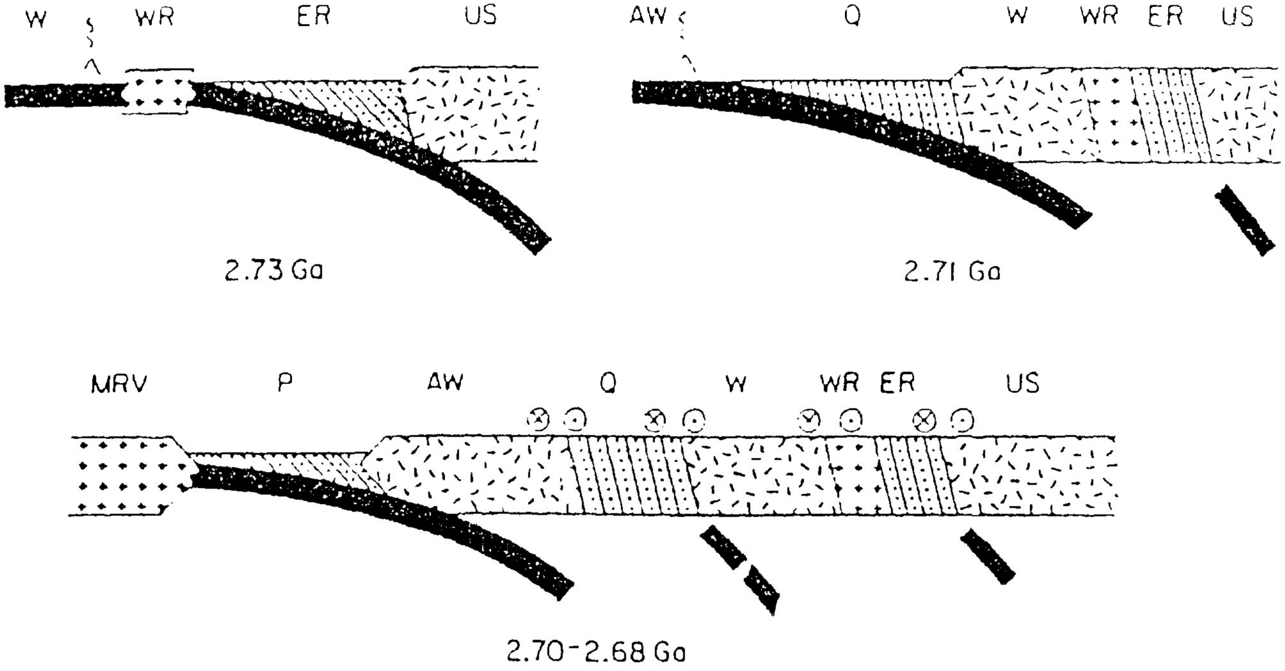


Fig. 22

sediments, including iron rich varieties, were deposited in a basin of unknown magnitude. This basin likely formed part of the developing Quetico Subprovince. Volcanic activity subsequently deposited massive and pillowed basalts. As volcanic terrane (Wawa) moved northward in response to northward-directed shallow subduction, basin sediments and volcanics were deformed as low angle thrust faults and nappe developed. The presence of recumbent folds (F_1), the shallow plunge of F_2 hinge lines, and the coaxial nature of F_1 and F_2 are consistent with this model.

Close examination of the rock sequence in the Manitouwadge synform reveals a number of striking similarities with the rocks of the study area. Equivalant lithologies exist in both locations, with abundant metasedimentary rocks which include iron formation, along with metavolcanic rocks. Metamorphic grade of bedrock in both locations is also equivelant. Further, from the map of the synform produced by Pye (1960) it is clear from the banded iron formations that the rock sequence has been doubly-folded and at least two distinct foliations are present. The main structure, ie. the synform, plunges shallowly to the northeast, not vastly dissimilar to F_2 structures at Faries Lake. Based on these observations it is suggested that the regional tectonic events responsible for the development of the Manitouwadge synform are also responsible for the structures developed in the supracrustal rocks at Faries Lake. Given their proximity and similar lithological nature the parental rocks at these locations were likely closely related.

Aeromagnetic maps of Manitouwadge and the surrounding region show a marked change in the magnetic character of the rocks along a zone which includes the Manitouwadge synform and those at Faries Lake. Although well defined magnetically, the zone is lithologically transitional, wherein supracrustal rocks of the Quetico and Wawa subprovince are tectonically inter-related and intruded by an assortment of plutonic rocks. Many workers have tried to assign positions to subprovince boundaries, which are usually drawn on maps as distinct lines, falsely giving the impression that the boundaries are well defined. In the region surrounding the study area the contact between the Wawa and Quetico Subprovinces is best described as a zone of transition. Only where contacts are marked by distinct lithological changes and supported by structural features (eg. the Quetico Fault) should subprovince boundaries be considered anything but transitional.

SUMMARY

Supracrustal rocks in the vicinty of Faries Lake include metasedimentary rocks with lesser metavolcanic rocks. Assorted igneous rocks intrude the supracrustal sequence. Recrystallization and amphibolite facies metamorphism accompanied the deformation of the metasedimentary rocks. Two fold generations, each with an accompanying axial planar cleavage, have been identified and are thought to have developed in response to regional low angle thrusting and nappe development.

The bladed gneiss formed from a layered sedimentary succession. During regional folding the processes of cuspate-lobate folding, buckle folding, and boudinage acted simultaneously to develop blades from the primary layers. Layer response to finite strain during folding of the layered sequence was controlled by several factors including layer competency contrasts, absolute and relative layer thicknesses, and layer orientation with respect to principal strain directions. Foliations developed during folding and subsequently developed co-planar shear discontinuities facilitated layer transposition.

Rocks in the study are structurally and lithologically similar to those of the Manitouwadge synform. Together these rocks form portions of a zone of transition which marks the boundary between the Wawa and Quetico Subprovinces.

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