SEDIMENTOLOGY AND RELATIONSHIP TO VOLCANOLOGY OF FORMATION K, FAVOURABLE LAKE METAVOLCANIC - METASEDIMENTARY BELT, NORTHWESTERN ONTARIO

by

Wayne Derek Gordanier
Department of Earth Sciences

Submitted in partial fulfillment of the requirement for the degree of Master of Science

Faculty of Graduate Studies
University of Manitoba
Winnipeg, Manitoba

May, 1982

SEDIMENTOLOGY AND RELATIONSHIP TO VOLCANOLOGY

OF FORMATION K, FAVOURABLE LAKE

METAVOLCANIC - METASEDIMENTARY BELT,

NORTHWESTERN ONTARIO

BY

WAYNE DEREK GORDANIER

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

Many Archean volcano-tectonic models that have been proposed for the evolution of greenstone belts utilized incomplete and inconclusive sedimentological data. In many areas, sedimentary basins are the only preserved record of changes in tectonism and composition of the provenance terrain. Quantitative rather than qualitative sedimentology applied to Archean sedimentary basins is essential in clarifying existing ambiguities in these models. Quantitative and semi-quantitative sedimentology was applied to Formation K, a conglomerate-greywacke unit, in the Favourable Lake metavolcanic-metasedimentary belt of northwestern Ontario.

The Favourable Lake belt is composed of 5 cycles of volcanism and sedimentation that are progressively displaced to the northwest. Formation K forms the upper part of Cycle 3 and was deposited, apparently conformably, upon the flanks of a subaqueous basaltic shield volcano (Formation J). Formation K is superceded by subaerial basalt flows of Cycle 4 volcanism (Formation M). The contact between Formation K and Formation M is a bedding plane thrust fault.

At its maximum extent and thickness Formation K is 15 km long and 2 km thick and comprises two members, a lower Conglomerate Member (0.3 km thick) and an upper Sandstone Member (1.7 km thick). The Conglomerate Member is a wedge-shaped unit of interbedded conglomerate and lithic

greywacke and was deposited subaerially as two or more coalescing alluvial fans. Detritus for the member was derived from the east and west of the member. The Sandstone Member is a wedge-shaped unit of interbedded feldspathic greywacke, conglomerate, felsic tuff, siltstone and shale and was deposited as a submarine fan with its apex to the east.

Sandstones of the Sandstone Member have unusually high contents of sand-size quartz forming up to 90 percent of the framework grains and averaging 68 percent. The remainder of the framework grains is composed of plagioclase and lithic fragments. The high content of quartz sand in the Sandstone Member coincides with the increase in importance of felsic volcanic clasts relative to the Conglomerate Member and the presence of interbedded felsic tuffs. The high quartz sand content was derived by the erosion and transportation of tuffs related to a pre-existing felsic volcanic sequence in the source terrain to the east. The presence of a possible orthoquartzite pebble in the member suggests that some of the quartz may have been derived from erosion of a pre-existing sedimentary terrain. In addition, associated felsic plutonic, subvolcanic and quartz vein clasts in the member suggests that some of the quartz was derived from the erosion of felsic plutons and felsic subvolcanic plutons with quartz veins.

The Sandstone Member is a sedimentary record of concomitant felsic volcanism that is presently not exposed in the Favourable Lake belt and thus is an integral part of the volcanic record. In addition, Formation K documents the possible existence of a pre-existing orthoquartzite sedimentary terrain possibly related to a relatively stable cratonic terrain represented today by crustal enclaves such as that exposed 3 km north of Formation K. The similarities between Formation K and sedimentary rocks at North Spirit Lake, 65 km to the southeast suggests a similar mode of occurrence. The existence of orthoquartzite pebbles at North Spirit Lake indicates that the area of tectonic stability, where such sediments can occur, may be more extensive than previously considered. The area of tectonic stability may be an original early Archean sialic crust of regional proportions represented today by crustal enclaves.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF TABLES

INTRODUCTION

General Statement

Archean sedimentary basins are poorly documented. In part this reflects a lack of detailed study, in conjunction with the fact that many volcano-tectonic models proposed for the evolution of the greenstone belts (eg. Goodwin and Shlanka, 1967; Goodwin and Ridler, 1970) utilized incomplete and inconclusive sedimentologic information (eg. Turner and Walker, 1973; Walker, 1978a).

In many regions sedimentary basins are the only preserved record of changes in tectonism and composition of the provenance terrain. The nature of the tectonic regime can be deduced from the developmental history of the sedimentary basin as recorded by the nature and frequency of the transition from one sedimentary environment to another. The presence or absence of a sialic hinterland and changes in composition and type of volcanism in the provenance area will be recorded by the clastic input into the basin.

Quantitative rather than qualitative sedimentology applied to Archean sedimentary basins is essential in clarifying existing ambiguities in Archean volcano-tectonic models. Until recently, modern sedimentological methods were largely neglected in the Archean because of structural and metamorphic complications that hindered their application. In spite of these complications modified sedimentological techniques have been applied successfully to several Archean basins (Walker and Pettijohn, 1971; Turner and Walker, 1973; Henderson, 1972; Ojakangas, 1972 (a,b); Donaldson and Jackson, 1965; Bouttcher et al, 1966).

Compositionally and texturally mature Archean sandstones have volcano-tectonic implications for the evolution of greenstone belts. There are three main hypotheses for the evolution of greenstone belts (Glikson, 1978). In the first model, greenstone belts evolved as intrasialic basins. In this model sediments would be derived from both the sialic margins of the basins and volcanic rocks within the basins. In the second model greenstone belts evolved above oceanic crust in ensialic rift zones. In this model sediments would be derived from the rift margins and volcanic rocks within the rift zone. In the third model greenstone belts evolved by rifting or downbuckling of a simatic crust. Partial melting of the crustal root zones result in granite diapirism and ultimately cratonization. In this model the sediments would be derived from the erosion of the volcanic pile and adjacent cratons.

Archean sandstones that are unusually rich in clastic quartz have been reported from several localities in northwestern Ontario by Donaldson and Jackson (1965). At the North Spirit Lake locality (Figure 1) the high quartz content was attributed by Donaldson and Jackson (1965) to intense mechanical weathering of a combined granitic and sedimentary source terrain. This has since been corroborated by the discovery of orthoquartzite pebbles in the sandstone (Donaldson and Ojakangas, 1977). In the North Spirit Lake area the presence of orthoquartzite pebbles in sedimentary rocks derived from a combined sedimentary and granitoid terrain implies relative tectonic stability for long periods of time with intense chemical and mechanical weathering followed by redeposition in flanking, relatively unstable volcanic terrains. This would be consistent with the first two models of greenstone evolution but not necessarily the third. Isotopic age dates from the North Spirit Lake area (Nunes and Wood, 1979) indicate a 300 Ma hiatus between the extrusion of the volcanics and deposition of the sediments. It is possible that the high clastic quartz content of the sandstones is the result of upgrading by cyclic erosion and redeposition, during this period of sediment derived from felsic volcanics in addition to sediment derived from a granitoid and sedimentary terrain.

Controversy exists in the literature as to the relative importance of felsic volcanics in the provenance terrain. Some workers have discounted the importance of felsic volcanics as a source of clastic quartz (Donaldson and Jackson, 1965) while other workers have stressed the importance of clastic quartz derived from felsic volcanic terrains (Ayres, manuscript). The relative importance of felsic volcanics as a source terrain could be significant and would be consistent with all three models of greenstone belt evolution.

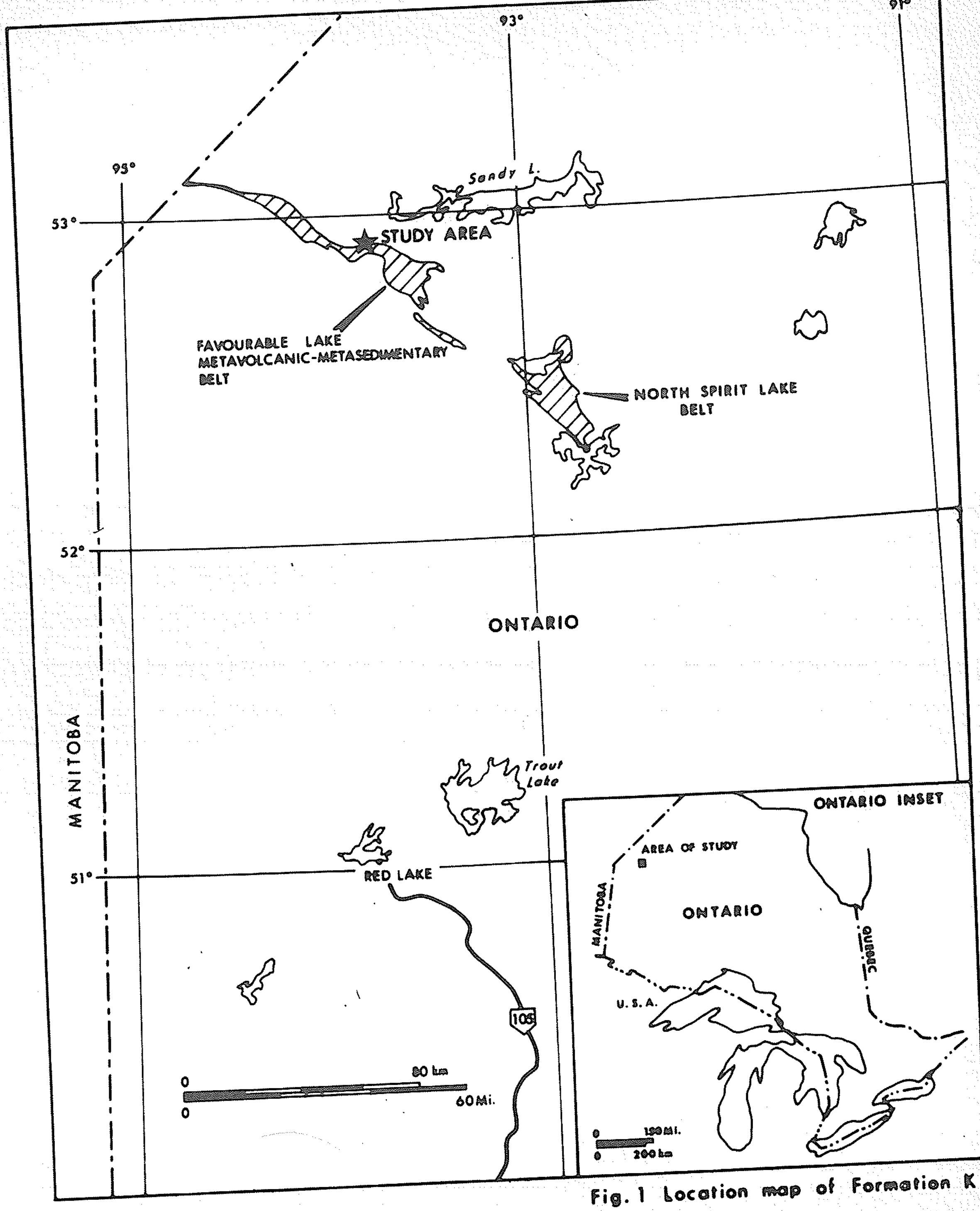


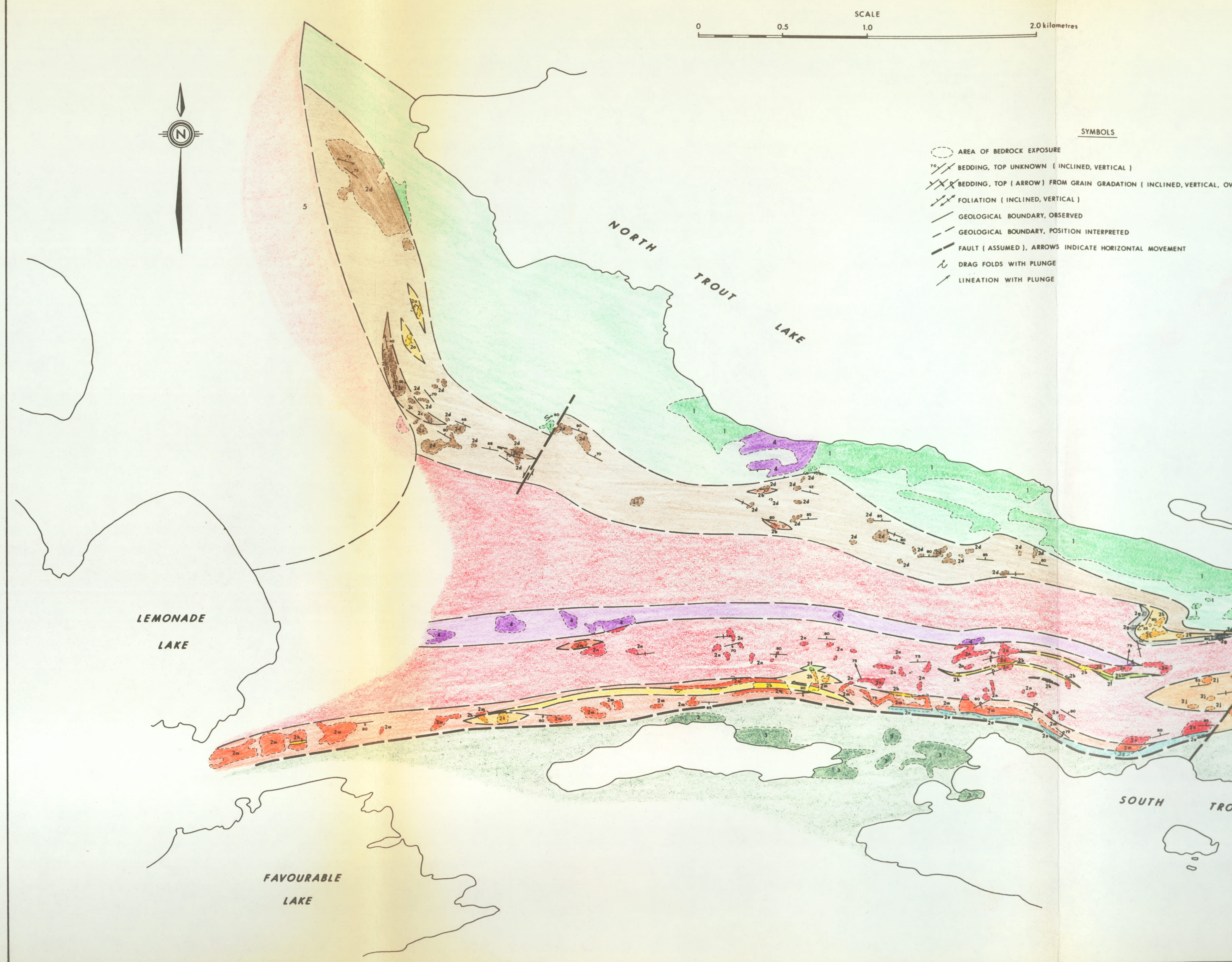
Fig. 1 Location map of Formation K

A new and less deformed quartz-rich sandstone unit (Formation K) has been examined in this study to determine the environment of deposition of the unit and its possible relationship to volcanism. The quartz-rich sandstone unit is within the Favourable Lake greenstone belt 65 km northwest of the North Spirit Lake metasediments (Figure 1). In addition to determining the environment of deposition of the unit an attempt is made to explain the high quartz content of these sandstones.

Location, Access and Previous Work

The study is in the Favourable Lake greenstone belt at latitude 93°44' West and longitude 52°50' North about 200 km north of Red Lake, Ontario (Figure 1). The only access to the area is by float-equipped airplane. The quartz-rich metasediments form a lenticular unit 10 km long and 2 km thick between North and South Trout Lakes. It was termed Formation K by Ayres (1974) and was subdivided into a basal conglomerate member and an upper sandstone member. The conglomerate member was later described (Ayres, 1977) as having been deposited "in a shallow water to alluvial basin on the flank of the volcano", with the sandstone member being deposited in somewhat deeper water indicating progressive subsidence of the basin.

GEOLOGY OF FORMATION K, FAVOURABLE LAKE METAVOLCANIC-METASEDIMENTARY BELT, NORTHWESTERN ONTARIO



4a

GEOLOGY OF FORMATION K, FAVOURABLE LAKE METAVOLCANIC - METASEDIMENTARY BELT, NORTHWESTERN ONTARIO

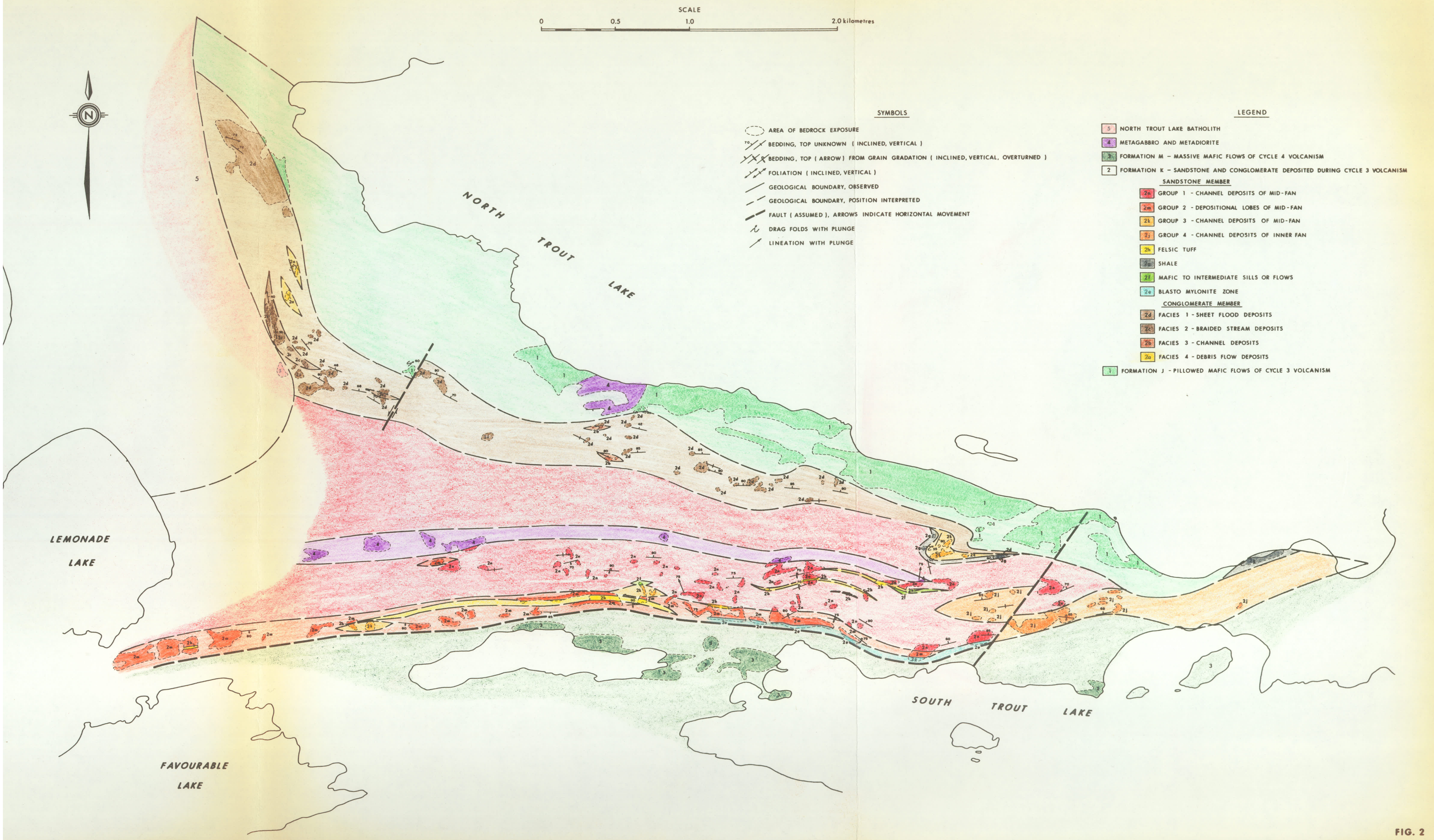


FIG. 2

Methods of Study

The eastern half of Formation K was mapped on a scale of 1:15,840 using air photographs with acetate overlays (Figure 2).

The western half was not mapped due to time restrictions and difficulty of access. All outcrops in the eastern half were visited and stripped of moss and light overburden to facilitate examination.

A general examination of the eastern half of the formation was followed by detailed stratigraphic measurements at selected localities. In the Conglomerate Member the following parameters were noted in outcrop:

a) range and average bedding thickness of conglomerate and sandstone beds;

b) bedding character (horizontal, lenticular, etc.) and presence or absence of channeling, scour and fill, cross-bedding and any other sedimentary structures;

c) presence or absence of grading in the sandstone and conglomerate beds;

d) intrabed distribution of clasts in the conglomerate and pebbly sandstone beds (i.e. pebbles only at base of bed, irregularly distributed, etc.);

e) the nature of the contact between sandstone and conglomerate beds.

In addition, 17 outcrops were selected for detailed analysis of clast populations. The method used consisted of two tape measures placed on a conglomerate bed parallel to bedding with a string marked in 1 cm segments placed perpendicular to the tape measures. The clast lithology under the string was noted at 1 cm intervals and the string was then moved in 10 cm intervals along the tape measure. Between 200 and 500 counts were made over 1 linear metre of conglomerate at each locality. The size range, average size and angularity of each clast type was noted.

In the Sandstone Member the following parameters were noted:

a) types of beds, and the average thickness and thickness range of each bed type;

b) presence or absence of graded bedding, and the nature of the grading;

c) presence or absence of pebbles, and their distribution and lithology;

d) sedimentary structures in addition to grading and their size and distribution;

e) presence or absence of shale, conglomerate, tuffaceous horizons, flows and brecciated units.

In addition, detailed stratigraphic measurements were made at 20 outcrops over thicknesses of 5-8 m. In these sections each bed was measured to the nearest centimetre and its grain size distribution, sedimentary structures and the presence or absence of lamination was noted. Grain size distribution was determined by comparison on outcrops with a grain size card produced by the Geological Speciality Company.

About 250 samples were examined in thin section and modal analyses were made on 40 of these from Formation K. The boundary between framework grains and matrix was placed at 0.06 mm and was determined using a micrometer eyepiece. Chemical analyses of 32 samples were made using a combination of atomic absorption, X-ray fluorecence and Leko induction furnace by the chemical laboratory of the Department of Earth Sciences, University of Manitoba.

Rock Nomenclature

The classification of the sandstones follows that proposed by Pettijohn (1954) and modified by Dott (1964). This classification uses 15% matrix as the boundary between arenites and wackes with further subdivisions based on the relative percentages of quartz, feldspar and rock fragments. The scale of stratification thickness described by Ingram (1954) is used where bedding thickness is described semi-quantitatively. The grain size limits are those proposed by Wentworth (1922) and modified by Lane (1947). Terms defining roundness and sorting follows that described by Pettijohn (1972). Granitic rock nomenclature follows that of Ayres (1972).

Without exception all sedimentary rocks in the study area are metamorphosed and should carry the prefix meta. However, for convenience and clarity, the prefix is omitted and terms such as greywacke are used when the proper reference should be metagreywacke.

Acknowledgements

I would like to acknowledge the aid and supervision of Dr. Lorne Ayres of the University of Manitoba in the completion of this thesis. Also I would like to thank Mr. K. Ramlal at the University of Manitoba for the geochemical analyses. I would also like to acknowledge the readers of this thesis, Dr. William Last of the Department of Earth Sciences, University of Manitoba and Dr. A.E. Davison of the Department of Physics, University of Manitoba. Thanks should also be given to the staff of Zelon Enterprises for their assistance in the drafting of some of the figures and typing of the thesis. Thanks is also given to M. Friis of Mobil Energy Minerals and S. Claydon of AGIP Canada Ltd. in the typing of this thesis. I would also like to thank my wife Shelly for her understanding and the proofreading of this thesis.

GEOLOGICAL SETTING

Formation K is in the east part of the 7.5 km thick Favourable Lake metavolcanic - metasedimentary sequence in northwestern Ontario (Figure 3). The sequence comprises 5 cycles (Ayres, 1977) that represent a subaerial, andesitic to dacitic stratovolcano (cycle 1) with three successive, predominantly subaqueous, basaltic shields (cycles 2, 3, and 4) developed on its northwestern flank (Figure 4). The upper part of cycle 2 is a subaerial, dacitic caldera complex. The shields represent continued growth of the volcanic complex northwest and upward (Ayres, 1977). Cycle 5 unconformably overlies cycles 2, 3, and 4 and represents subaerial to shallow water, andesitic to dacitic volcanism.

Formation K forms the upper part of cycle 3 and overlies pillowed tholeitic basalt flows of Formation J which represents a subaqueous shield volcano (Figure 2) (Ayres, 1977). The contact between Formation K and overlying basalt flows of Formation M, the basal part of cycle 4, is a fault. The overlying flows lack pillows and may be subaerial (Ayres, 1977).

Formation K is on the north limb of an east trending, upright, isoclinal syncline and the sequence faces south. The exposure is thus a near-vertical cross-section through the formation. The metamorphic grade in the eastern part of the Favourable Lake belt ranges from mid-greenschist facies in the centre of the belt to amphibolite and hornblende

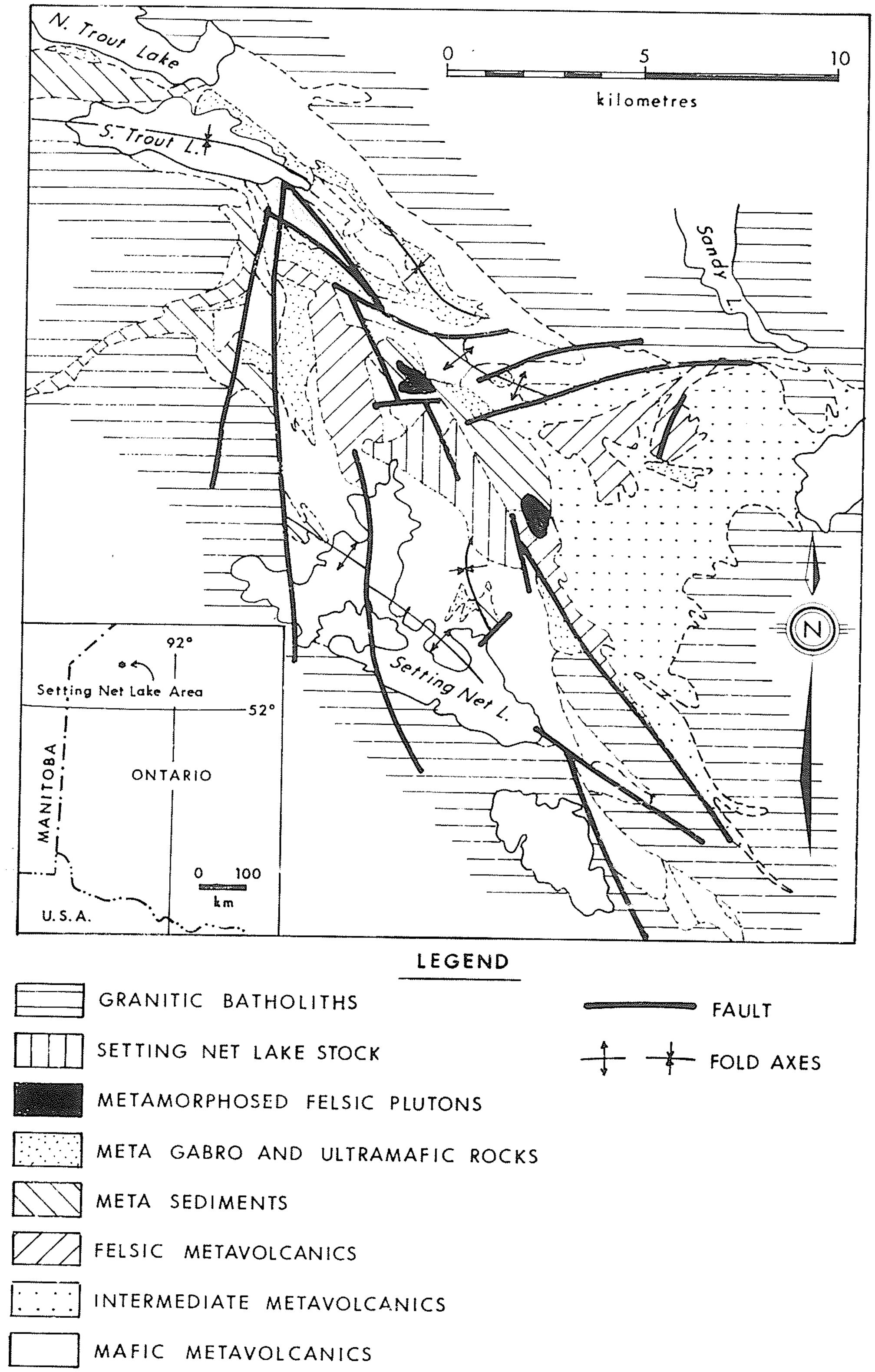


Fig. 3 Distribution of major lithofacies, eastern part of the Favourable Lake metavolcanic-metasedimentary sequence. (Ayres, 1977)

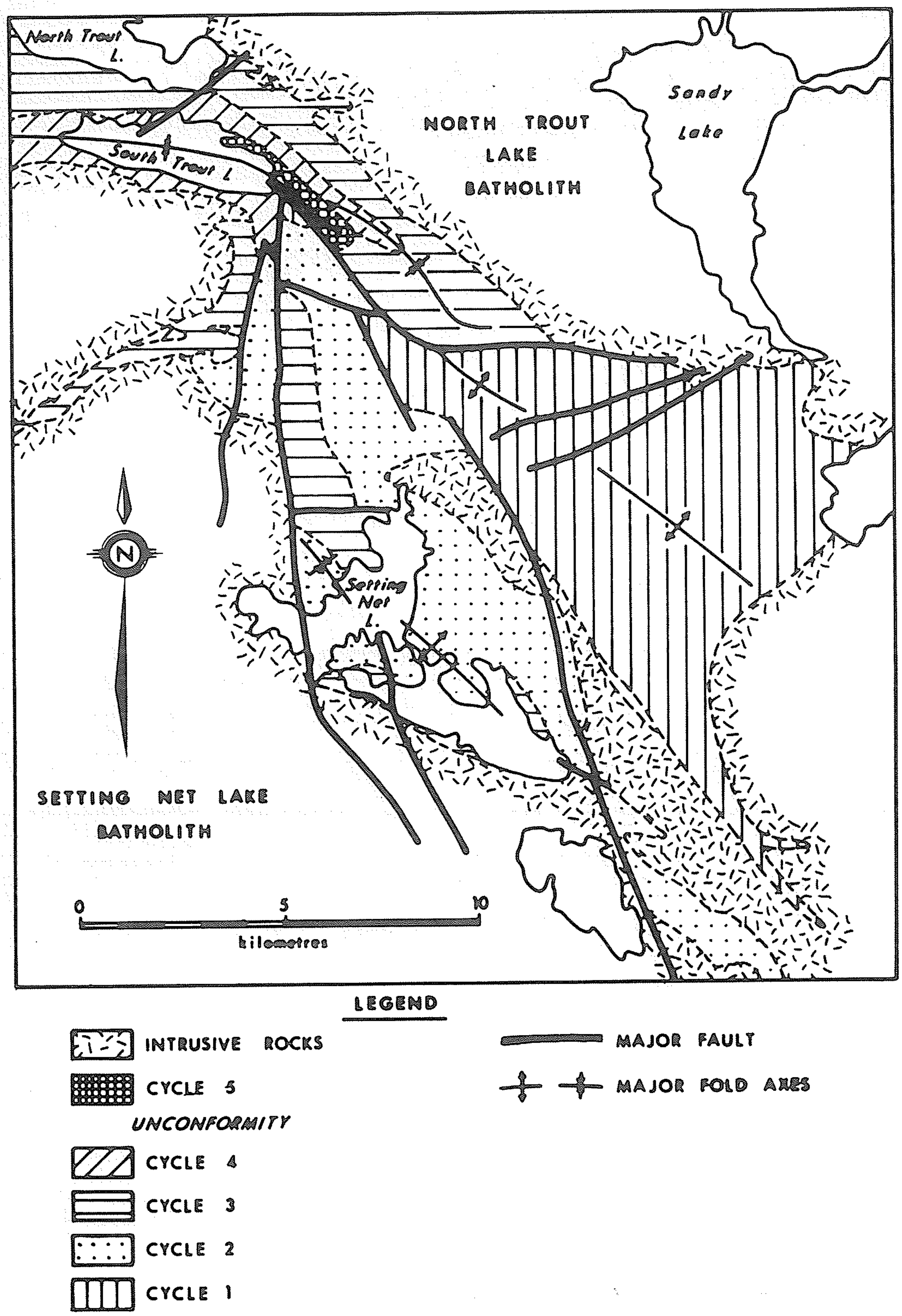


Fig. 4 Distribution of volcanic cycles, eastern part of the Favourable Lake metavolcanic-metasedimentary sequence. (Ayres, 1977).

hornfels facies at the margins (Ayres, 1977). The higher grade of metamorphism at the margins may be due to the proximity of granitic batholiths. The metamorphic grade of Formation K varies from mid-greenschist facies in the Sandstone Member to lower amphibolite facies in the Conglomerate Member. The change in metamorphic grade reflects the proximity of Formation K to the North Trout Lake batholith.

The North Trout Lake batholith separates Formation K from a 2927 Ma (Corfu et al, 1981) trondhjemitic basement enclave described by Hillary and Ayres (1980). The basement enclave is 3 km north of Formation K and was suggested by Hillary and Ayres (1980) to be a provenance terrain for the sediments of Formation K. Tuff interbeds in Formation K are 2718 Ma (Corfu et al, 1981).

The quartz-rich sedimentary rocks described by Donaldson and Jackson (1965) in the North Spirit Lake area are 65 km to the southeast (Figure 1). The stratigraphic relationship between this unit and Formation K is unknown. The high quartz content makes these two units unique and implies a somewhat similar genesis.

STATIGRAPHY OF FORMATION K

Introduction

At its maximum extent and thickness, Formation K is 2.0 km thick and 15 km long (Ayres et al, 1973) and comprises two members, a lower Conglomerate Member and an upper Sandstone Member. The eastern 7.4 km of Formation K was examined in this study and the maximum thickness of 2.0 km is in the western part of the examined area (Figure 2). The Conglomerate Member is a wedge-shaped unit of interbedded conglomerate and greywacke approximately 0.3 km thick and 7.4 km long (Figure 2). The member wedges out to the east and is intruded and truncated to the west by the North Trout Lake batholith. The Sandstone Member is also a wedge-shaped unit composed predominantly of sandstone with minor interbedded conglomerate, tuff, shale and siltstone. It is approximately 1.7 km thick and 7.4 km long in the study area. The contact between the two members is covered by a large swamp (Figure 5), and the contact has been placed arbitrarily at the top of the last exposed conglomerate bed in the Conglomerate Member. The contact between the Conglomerate Member and the underlying basalt flows of Formation J is also not exposed, but in places it can be confined to a 1-5 m covered interval between basalt and conglomerate outcrops. The contact is arbitrarily placed at the base of the lowest conglomerate bed of the Conglomerate Member. The top of the Sandstone Member

Figure 5 Sample Location Map of Formation K

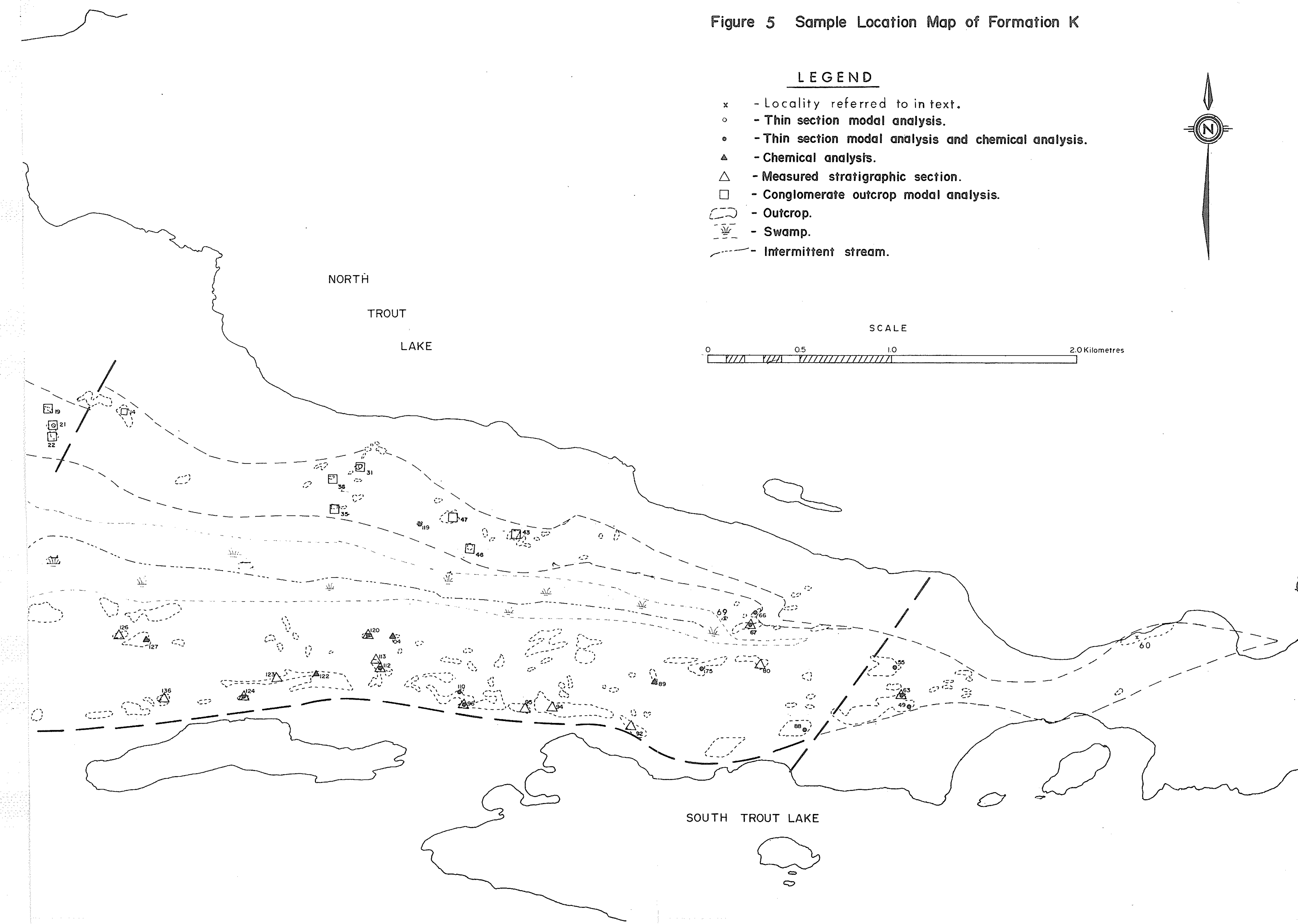
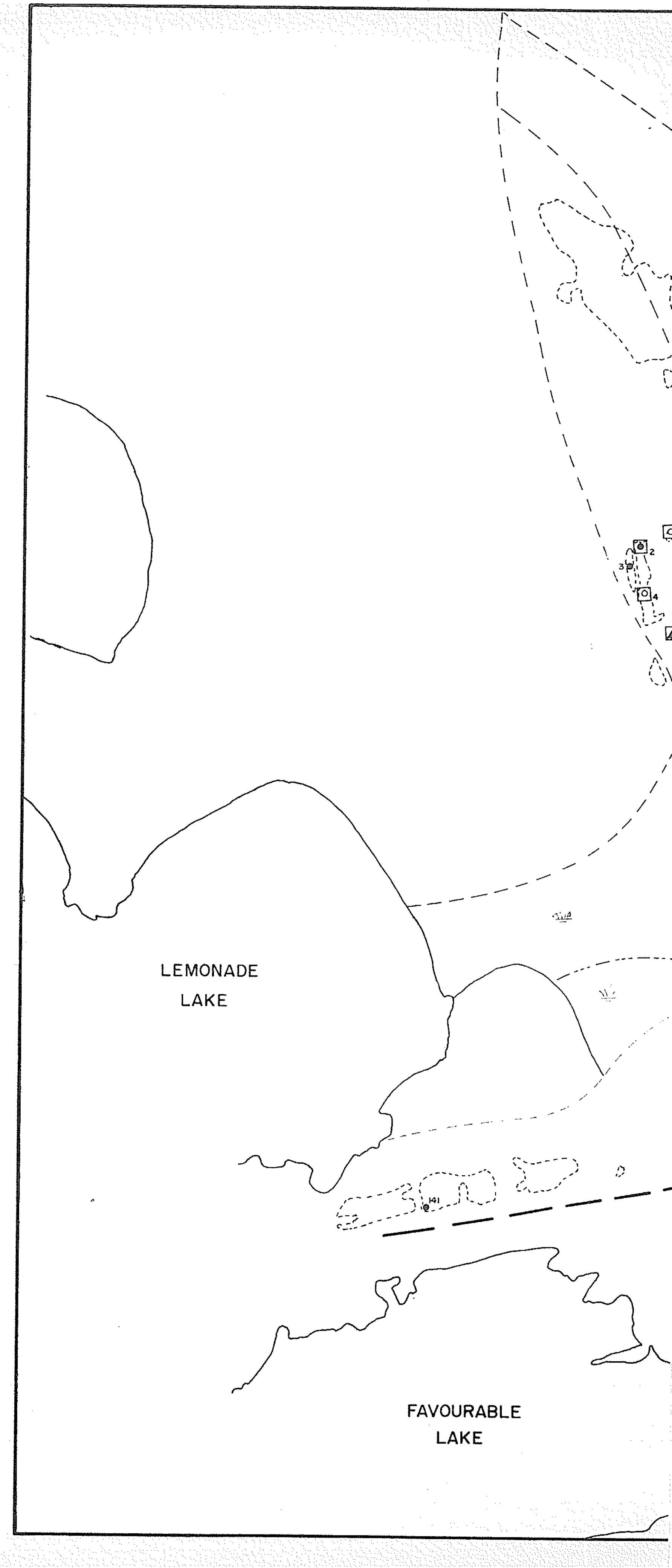


FIG. 5


LEMONADE
LAKE
FAVOURABLE
LAKE

is a bedding plane thrust fault. This fault is marked by a cataclastic zone up to 20 m wide and a prominent cliff up to 10 m high (Figure 2).

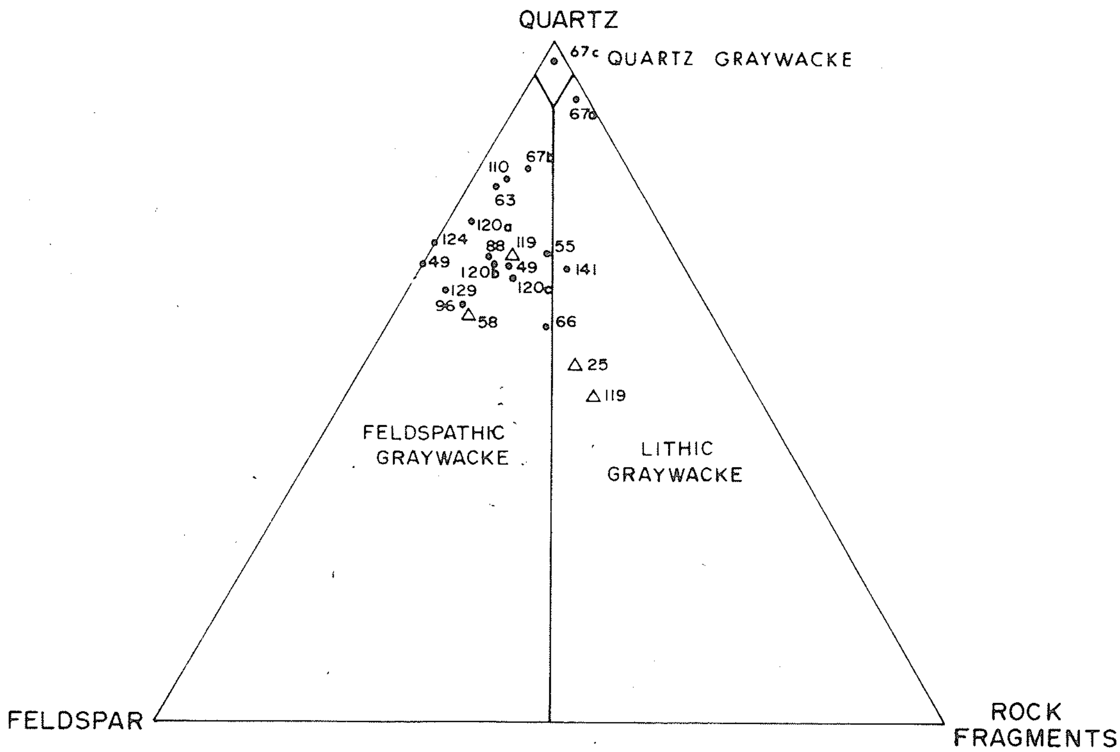
The foliation is moderately well developed and is parallel to bedding except in the northwest where Formation K is truncated by the North Trout Lake batholith.

Bedding attitudes indicate gentle flexural folding of this northern limb with axial planes trending northeast and fold axes plunging steeply to the northeast. Near the northeast trending fault at the east end of the formation, however, folding is more intense with the development of a steeply plunging tight fold at locality 67 (Figures 2 and 5) with the axial plane trending northeast. Folding and deformation appear to be more intense in the Conglomerate Member, particularly in the northwest part, and this may reflect the proximity of the North Trout Lake batholith. In the west part of the Conglomerate Member numerous granite and pegmatite dikes are present. The intrusion of the North Trout Lake batholith may explain the warping of the Conglomerate Member to the northwest.

Conglomerate Member

Introduction

A detailed sedimentological description of the Conglomerate Member is hampered by medium-grade metamorphism,



NOTE : MATRIX CONTAINS QUARTZ + FELDSPAR + BIOTITE + MUSCOVITE

LEGEND

96 ∘ – SAMPLE LOCALITY FROM THE SANDSTONE MEMBER

119 △ – SAMPLE LOCALITY FROM THE CONGLOMERATE MEMBER

Figure 6 -Classification of Sandstones with Matrix $>15\%$ (After Dott 1964).

extensive calc-silicate alteration and deformation. The sandstones and conglomerates of this member are well foliated with foliation defined by aligned biotite and hornblende, and by clast elongation.

The Conglomerate Member is predominantly moderately sorted, generally horizontally bedded pebble and cobble paraconglomerate. In addition to horizontal bedding, poorly sorted, large scale cross-beds with cobble conglomerate lag deposits are also present.

Pebbly, coarse-grained lithic and feldspathic greywacke (Figure 6) forms 20-50 percent of the member. The sandstone is horizontally bedded with local small scale scour and fill structures, and amalgamation of beds. No internal sedimentary structures are recognizable because of the metamorphic grade and pervasive calc-silicate alteration. The sandstone is compositionally similar to the conglomerate matrix.

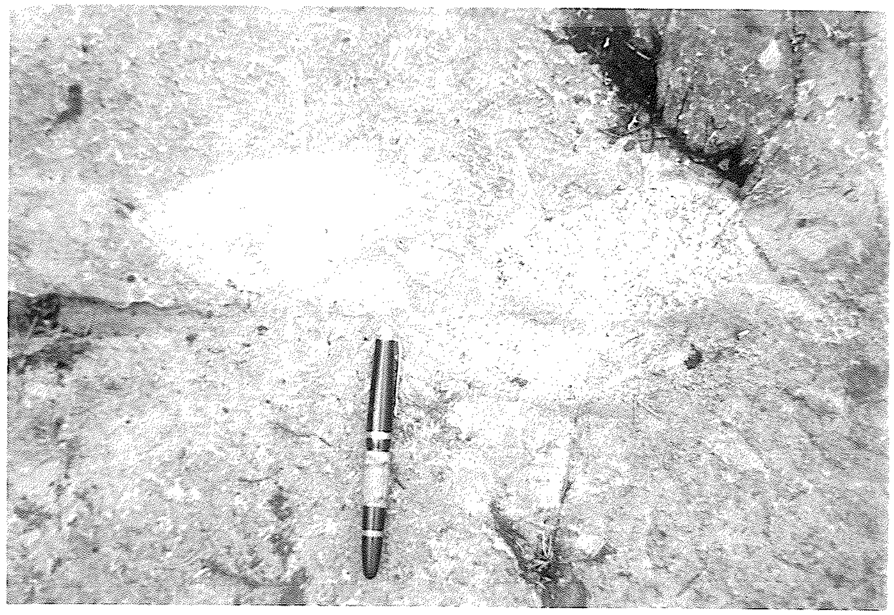
Lithology and Petrography

Conglomerate

1) Clast Types

The conglomerate is polymictic and contains pebbles, cobbles, and sparse boulders in a coarse, mafic, lithic sandstone matrix. Pebble conglomerate is the most common and

a)



b)

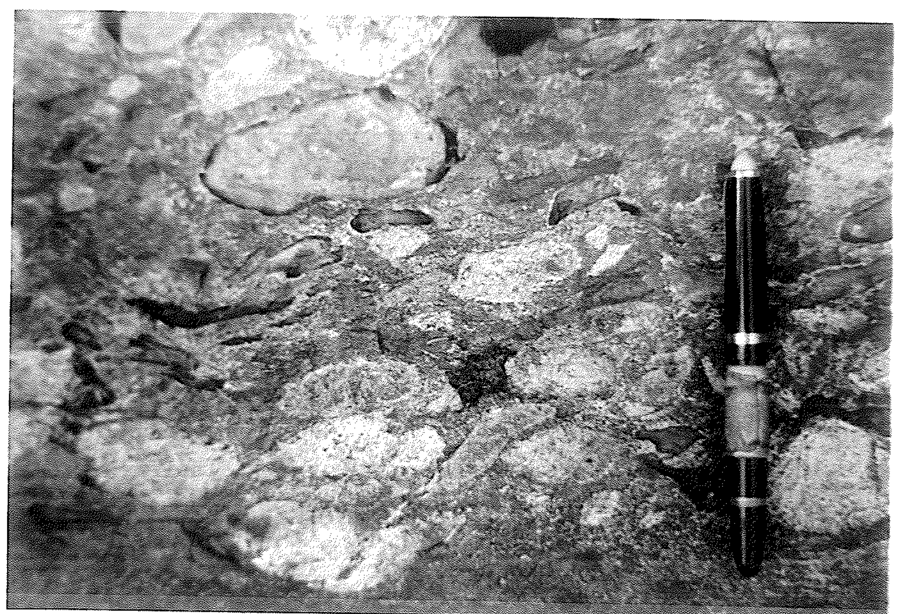


Figure 7: Clast Types in the Conglomerate Member.

a) Felsic subvolcanic (large clast left and above pen) and felsic plutonic clasts (large clast right of pen) in completely altered matrix from locality 29. Pen top points to stratigraphic tops. Pen is 12 cm long.

b) Clasts of an unknown type (weathering with negative relief) felsic subvolcanic (right of bottom of the pen) and intermediate volcanic (light gray) clasts from locality 35. Pen top points to stratigraphic tops. Pen is 12 cm long.

forms 80 percent of the exposed conglomerate. Cobble and boulder conglomerates are confined to the western end of the member and occur as lag deposits at the base of local scour channels.

Clast types, in order of decreasing relative abundance are intermediate volcanic, felsic subvolcanic, felsic plutonic, and vein quartz which occur in most beds, and more restricted mafic volcanic, chert, and iron formation (Table 1, Figures 7 and 8). Clast types are described in Table 2. Unknown clasts are those in which primary lithology could not be identified because of weathering characteristics, small size or lack of a sample for thin section study. The average size of most clasts is 5 cm and the largest observed clasts, which are felsic plutonic, are 40 cm in diameter (Table 2). The felsic plutonic, felsic subvolcanic, felsic volcanic and vein quartz are rounded to subrounded and the mafic volcanic and intermediate volcanic clasts are angular to subangular in shape. Iron formation clasts are tabular, subangular to subrounded in shape. The clasts classified as unknown are well rounded. Original clast shapes have been distorted by deformation with intermediate and mafic volcanic clasts being affected most by deformational flattening. All clasts were measured along their long axes in the plane of the outcrop exposure. Petrographically and compostionally the felsic plutonic and felsic subvolcanic clasts are very similar but can be distinguished by the finer grain size and lower abundance of phenocrysts in the felsic subvolcanic clasts (Table 2, Figure 9).

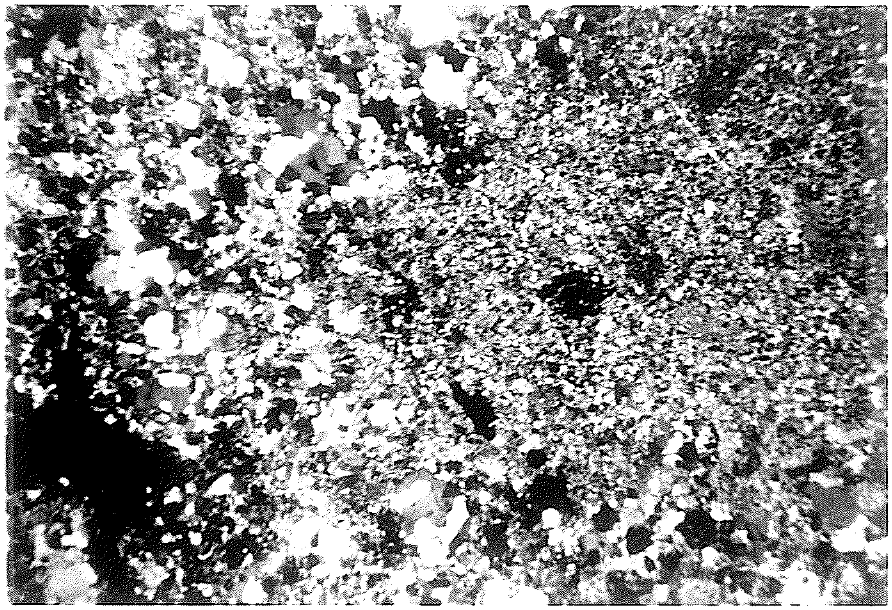
TABLE 1 Pebble Modes from Conglomerates of the Conglomerate Member

Location[1]	Felsic Plutonic	Felsic Subvolcanic	Vein Quartz	Intermediate Volcanic	Felsic Volcanic	Mafic Volcanic	Chert + Iron Fm	Unknown	Total Clast %	Matrix %	% Interbedded Sandstone
1	15.0	9.5	1.7	29.2					55.0	45.0	20
2	15.2	18.1	2.7						36.5	63.5	20
4	9.4	27.7	4.3						41.4	58.6	40
5	17.8	31.7	6.0						55.5	44.5	40
6a)[2]	6.7	16.1	1.4	2.8					27.0	73.0	50
6b)[2]	8.0	40.6	13.7						62.5	37.5	50
25a)[2]	10.4	32.6	11.2	10.4					32.6	67.4	40
25b)[2]	11.2	15.6	2.2	26.2					55.2	44.8	40
22	11.6	11.0	6.7	13.0					42.3	57.7	25
21	4.9	17.4	11.5	39.2					73.0	27.0	20
14	21.9	18.5	15.6	10.8					66.0	34.0	40
31	20.9	32.6	5.2	25.4					84.1	15.9	30
36	9.6	19.6	3.8	39.8	7.1				80.2	19.8	50
35	6.5	16.8	3.6	26.2		7.0	7.0	4.1	70.7	29.3	50
47	2.5	8.0	.9	23.0		2.4		3.0	39.8	60.2	50
46	1.6	7.5	.3	9.9	2.5	10.8	.6	.9	34.1	65.9	40
43	7.6	11.2	1.0	25.0	4.4	.8		1.6	51.6	48.4	50

NOTE: 1. Locations (Figure 5) presented in relative lateral position in member from west to east.

2. Duplicate modes at locality 6 and 25 represent different conglomerate beds at same locality .

a)



Scale
1 mm

b)

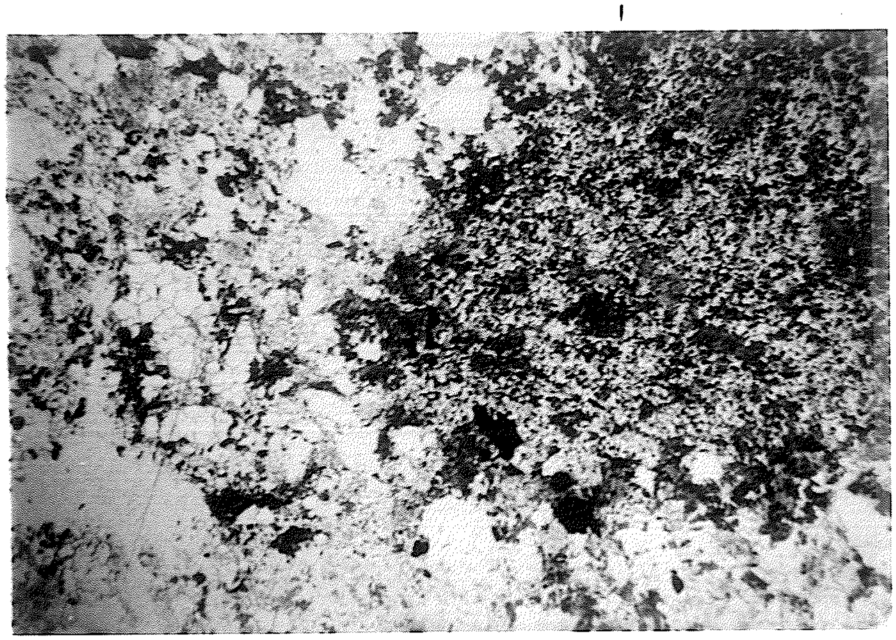
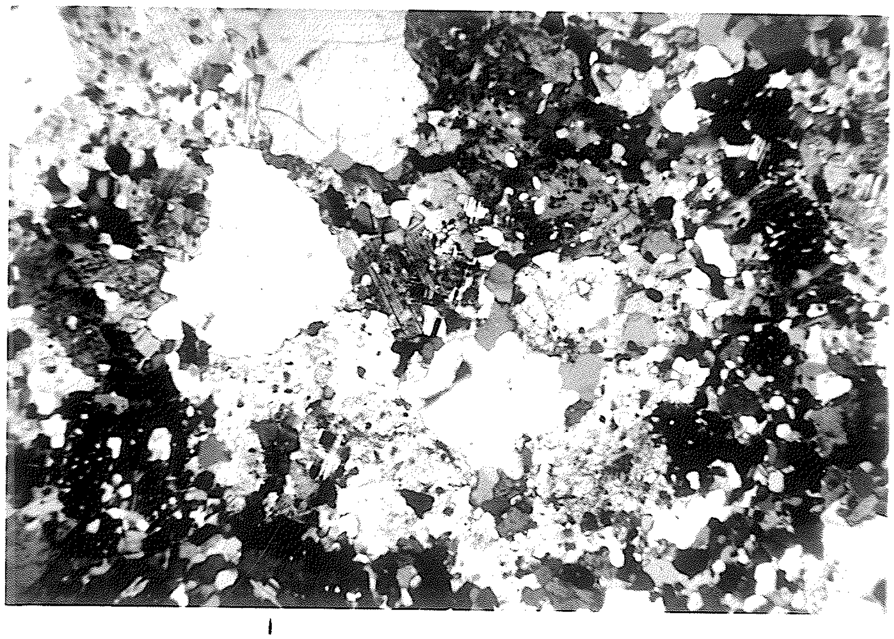


Figure 8: Photomicrograph of an intermediate volcanic clast showing the development of hornblende porphyroblasts. Nicols crossed (a) and uncrossed (b). Section from locality 119.

a)



Scale
1 mm

b)

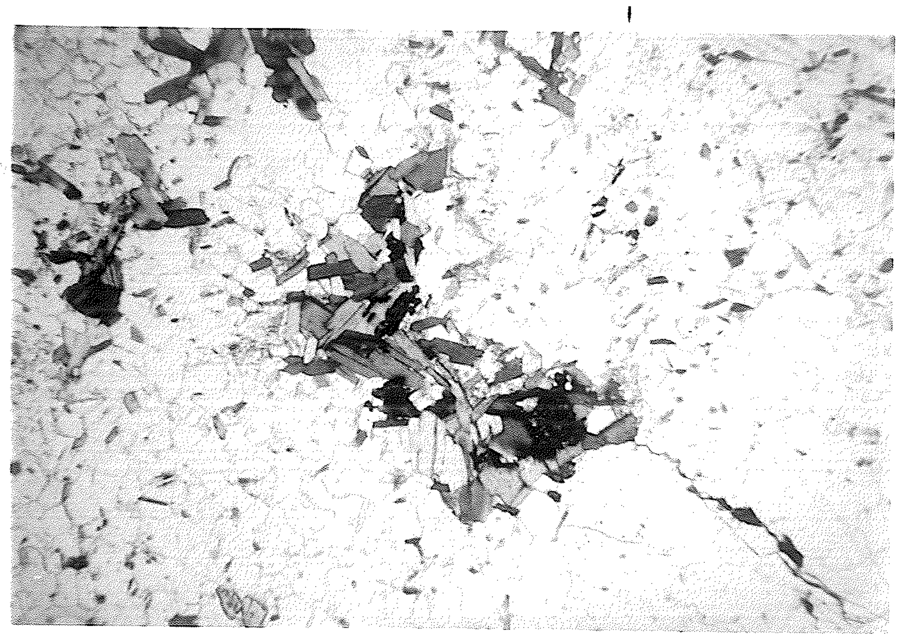


Figure 9: a) Photomicrograph of felsic subvolcanic clast (nicols crossed) showing plagioclase alteration and lack of phenocrysts; b) felsic plutonic clast (nicols uncrossed) showing biotite clots with sphene and a portion of a quartz phenocryst (bottom right hand corner). Both samples are from locality 1.

TABLE 2 Description of Clast Types in Conglomerate Member

TYPE	SHAPE	SIZE	COLOR & TEXTURE	PETROGRAPHY
Felsic Plutonic (quartz diorite)	rounded	range 1-40 cm.; average 5 cm	white, medium to coarse-grained with 20-30% quartz phenocrysts weathering in positive relief	- porphyritic with 5 mm quartz phenocrysts in a 0.5-3 mm quartz + plagioclase + potassium feldspar groundmass. - plagioclase in altered to sericite and replaced in part by a patchy network of albite, quartz and microcline but some original andesine An_{31-40} is preserved. - biotite forms 5-10% of rock and occurs in clots with intergranular sphene which causes a darkened halo in the surrounding biotite.
Felsic Subvolcanic (quartz diorite to quartz monzonite)	rounded to subrounded	range 1-20 cm; average 5 cm.	white, fine to medium grained with 0-5% quartz phenocrysts	- most clasts are equigranular with average grain size 0.1-2 mm; some clasts are porphyritic with quartz phenocrysts up to 4 mm. - plagioclase is strongly sericitized and replaced by a patchy network of quartz, albite and microcline. - biotite is homogeneously distributed with intergranular sphene causing darkened halos in surrounding biotite. - similar to felsic plutonic but finer grained and fewer phenocrysts.
Vein Quartz	rounded	range 1-15 cm; average 5 cm.	white to opaque grey, coarse-grained	- individual quartz crystals show undulatory extinction. - crystal boundaries are sutured.
Intermediate Volcanic	angular to subangular	range 1-10 cm; average 4 cm.	light grey, very fine grained and weathers recessive	- equigranular with granoblastic textures; average grain size 0.05-0.1 cm - biotite is homogenously distributed with minor sericite alteration - euhedral poilidític hornblende porphyroblasts surrounded by biotite deficient halos. (Fig. 8). -outside edge of clast is commonly enriched in hornblende. -sphene occurs as anhedral aggregates surrounding Fe-Ti oxides.
Mafic Volcanic	angular to subangular	range 1-8 cm; average 5 cm.	dark grey, fine grained and weathers recessive.	- clast is equigranular composed of interlocking euhedral hornblende and plagioclase crystals (0.05 - 0.1 mm) - plagioclase An_{30-35} is strongly altered to sericite; albite twins.
Felsic Volcanic	rounded	range 1-10 cm; average 5 cm.	white & fine grained with 1-5% biotite.	- equigranular quartz and untwinned plagioclase; average grain size 0.05-0.1 mm. - biotite is homogeneously distributed forming 1-5% of rock - plagioclase is partially altered to sericite - euhedral hornblende is found in trace amount
Chert	rounded	range 1-4 cm; average 3 cm.	white, very fine grained and weathers with positive relief.	- equigranular quartz; average grain size 0.06 mm.
Iron Formation	subangular to subrounded	range 4-10 cm., average 5 cm.	clasts bedded and rusty weathering; magnetic	- no sample for thin section
Unknown	rounded	range 1-5 cm. average 3 m	light grey, very fine grained and weathers recessive.	- no sample for thin section

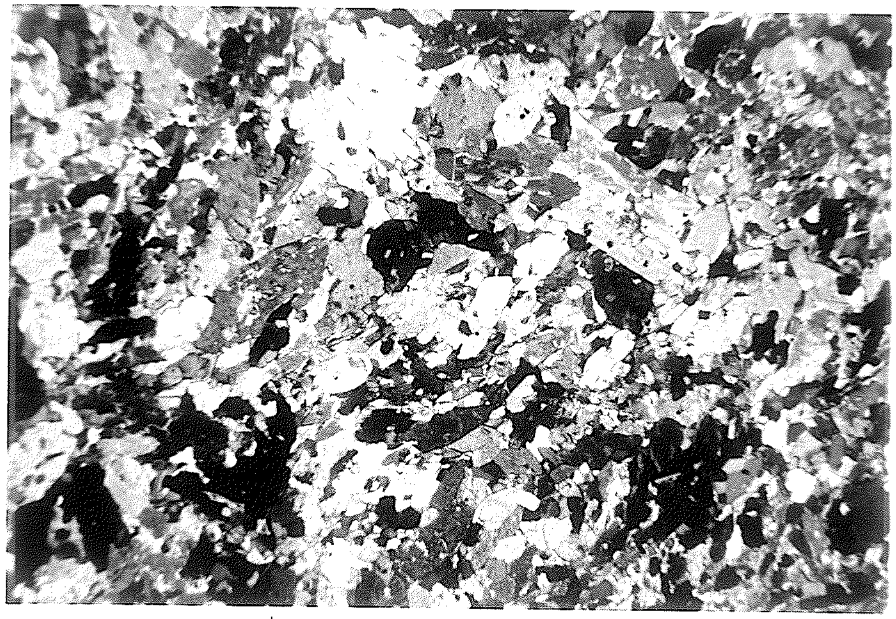
2) Matrix

The matrix varies in abundance from 15 - 73 percent (Table 1). It is a mafic, coarse-grained, lithic greywacke composed of, in decreasing order of abundance, hornblende and/or diopside, quartz, lithic fragments, and plagioclase (Figure 10, Table 3). The matrix is always partly altered and this alteration combined with the moderate metamorphic grade make the identification of most original textures difficult. The lithic fragments identified are invariably intermediate volcanic and are highly deformed and flattened parallel to the foliation. Subhedral metamorphic hornblende locally forms aggregates that may represent recrystallized mafic volcanic fragments. The original subangular to subrounded quartz and plagioclase grains are strongly recrystallized and some of the rounding may be the result of deformation. The alteration which can be recognized by the presence of diopside will be discussed in a subsequent section (see Calc-Silicate Alteration).

Sandstone

Except for relict bedding (Figure 11), primary textures and structures in the interbedded sandstones have been partially to completely destroyed by calc-silicate alteration and metamorphism. Where primary textures are preserved the sandstones are similar to the conglomerate matrix and are

a)



Scale
1 mm

b)

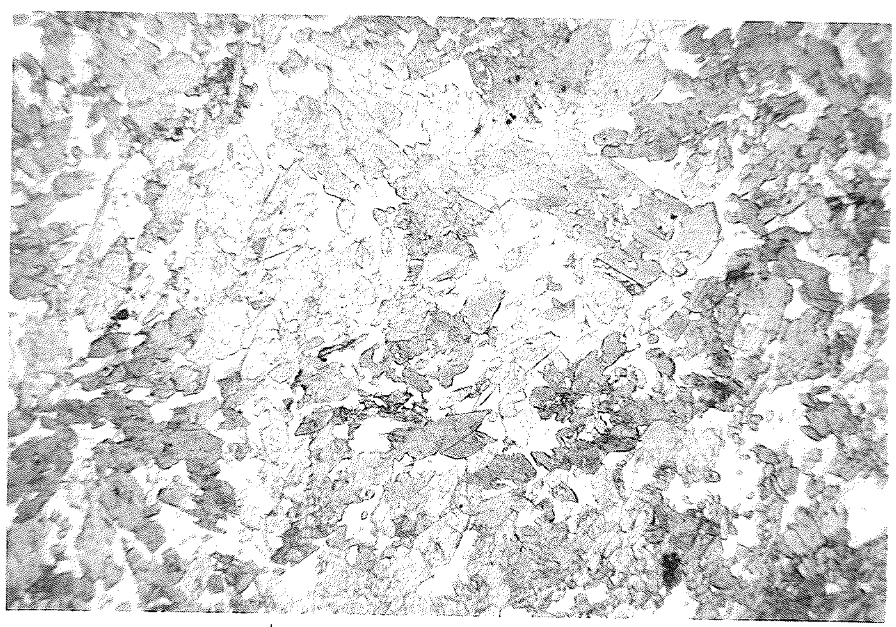


Figure 10: Photomicrograph of conglomerate matrix from locality 5, showing high content of euhedral to subhedral hornblende a) nicols crossed and b) nicols uncrossed.

TABLE 3 Modal Analyses of Samples From the Conglomerate Member

	Felsic Plutonic Clasts			Felsic Sub-Volcanic Clasts					Intermediate Volcanic Clasts		Felsic Volcanic Clasts	Partly Altered Conglomerate Matrix			Partly Altered Sandstone			Altered Sandstone			Sandstone Mean[1]
Locality	1	2	25	1	6	21	25	119	31	1	25	119	25	58	119	3	19	3	1	4	
Quartz	52.3	30.9	51.4	33.8	40.5	27.1	45.4	25.2		26.4	39.9	36.1	29.5	28.9	32.2	34.9	39.0	1.5	tr	15.5	35.4
Plagioclase	31.7	46.0	23.5	35.8	46.2	29.1	29.8	44.4	52.5	22.9	53.7	14.9	10.7	14.8	14.2	14.0	9.5	15.9	15.7	14.7	12.6
K-Feldspar	7.3	18.2	14.0	26.2	tr	31.0	15.1	12.0		33.4	5.7	3.0	1.0		tr	2.0	6.2	1.1	7.2	2.0	2.7
Biotite	6.9	4.4	10.5	4.2	5.5	8.8		16.7	30.6	11.7		18.9		1.0	19.7						6.5
Hornblende	tr				5.9	4.0	9.6			5.64	tr		40.5	44.6	10.5	37.1	19.2	11.0	tr	20.3	24.3
Diopside												8.1	3.1		tr	4.5	11.6	62.9	73.7	41.1	5.4
Sphene	tr	tr	tr			tr		tr	11.1			tr		tr	tr	1.9	tr	1.7	1.6	1.0	.6
Fe-Ti Oxides	tr	tr	tr			1.3			6.5			tr		1.5	1.1				tr	tr	.4
Rock Fragments												18.9	15.0	4.5	21.5	tr	2.2		tr	tr	7.9
Carbonate														4.7							
Epidote																5.4	4.6	5.5		4.4	3.3
Plagioclase An Content	40	35	31	30	35	31	45	32								30–37		20–35	30–34		

NOTE: Localities found on Figure 5.

1. Mean calculated from Partly Altered sandstone samples 119, 3 and 19.

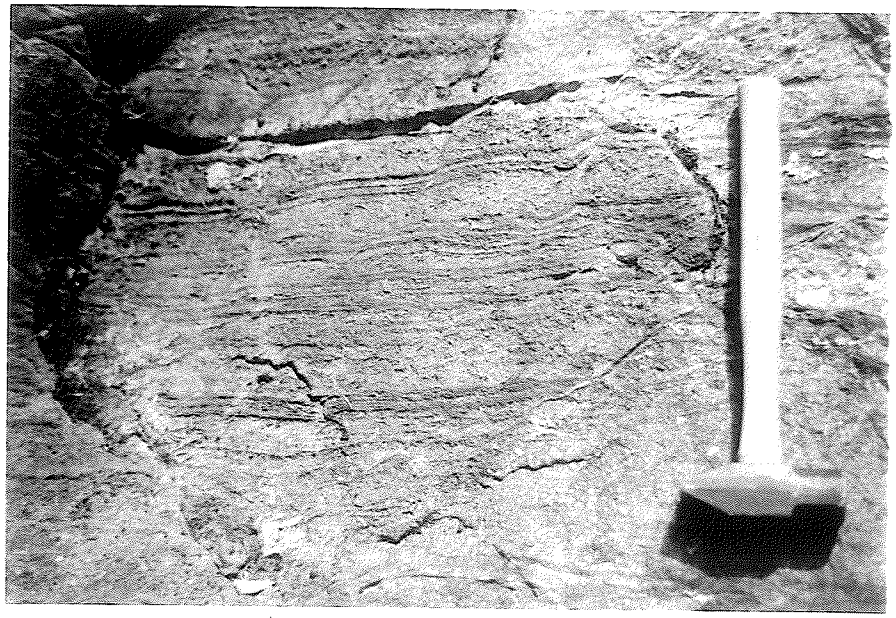


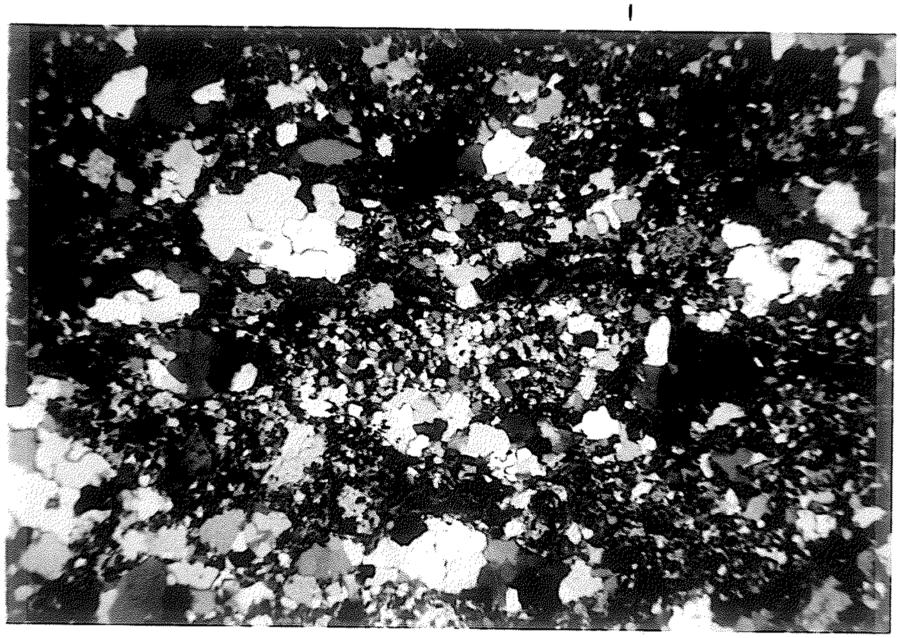
Figure 11: Laminations in completely altered sandstone at locality 25. The lamination may reflect bedding features of the sandstone. Hammer handle is 30 cm long and points to stratigraphic tops.

coarse-grained lithic greywacke to feldspathic greywacke (Figures 6, 12 and 13). Pebbles similar to those found in the conglomerate are ubiquitous and form 5 - 15 percent of the sandstone. The pebbles range in size from 3 - 15 cm and have an average size of 5 cm. The pebbles are distributed irregularly thoughout the sandstone. Textural variations and differences in degree of alteration define parallel layers in the sandstone that may reflect an original, primary bedding. Bedding defined in this way varies from 1 to 15 cm thick (Figures 11 and 15).

Calc-Silicate Alteration

Calc-silicate alteration is widespread but patchily developed in the Conglomerate Member, particularly in the lower part, but was not observed in underlying mafic flows or overlying sandstones of the Sandstone Member. It occurs both in the sandy matrix of the conglomerate and the interbedded sandstones, but is most noticeable in the sandstones. Nowhere has totally unaltered conglomerate matrix or interbedded sanstone been observed. The altered sandstone is pale green rather than the normal dark green in colour. The alteration forms crudely spherical patches that range in diameter from 0.5 - 5 cm, and locally have a quartz rim up to 4 mm thick (Figures 14 and 15). In some sandstone units the alteration spheres are confined to certain beds and, where numerous, spheres have coalesced to give an appearance of

a)



Scale
1 mm

b)

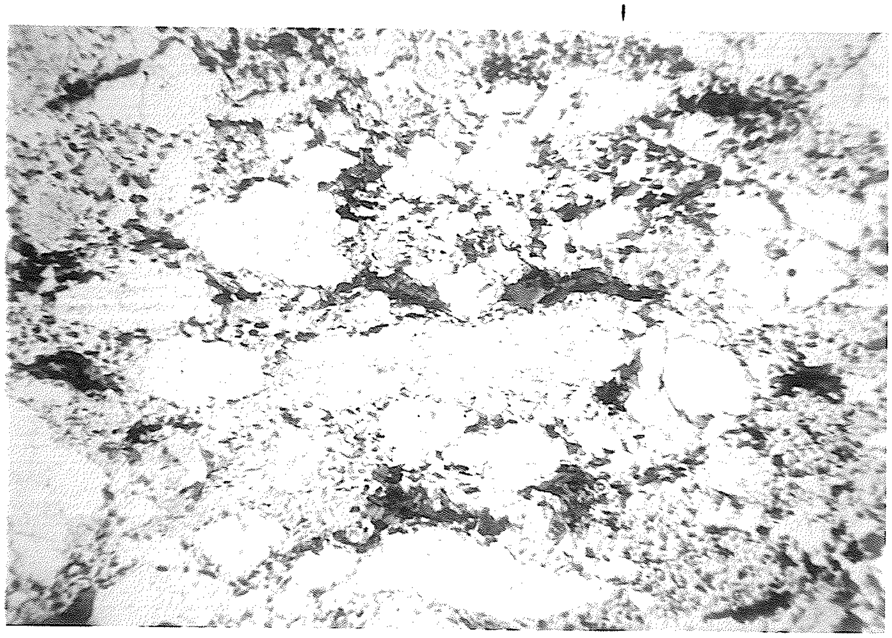
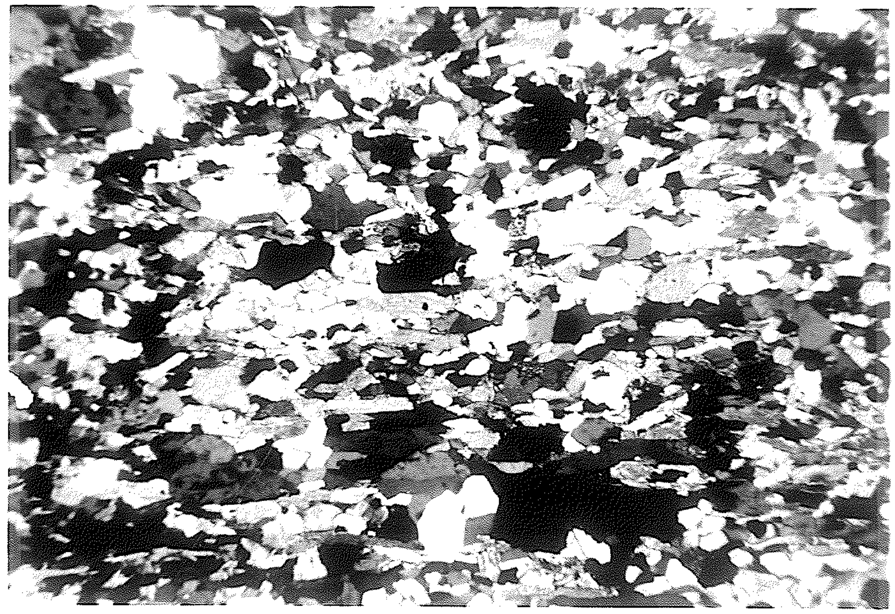


Figure 12: Photomicrograph of lithic greywacke from locality 119 showing tabular felsic volcanic clast (center photo) and mafic volcanic clasts (biotite clots that wrap around other framework grains).
a) nicols crossed; b) nicols uncrossed

a)



Scale
1 mm

b)

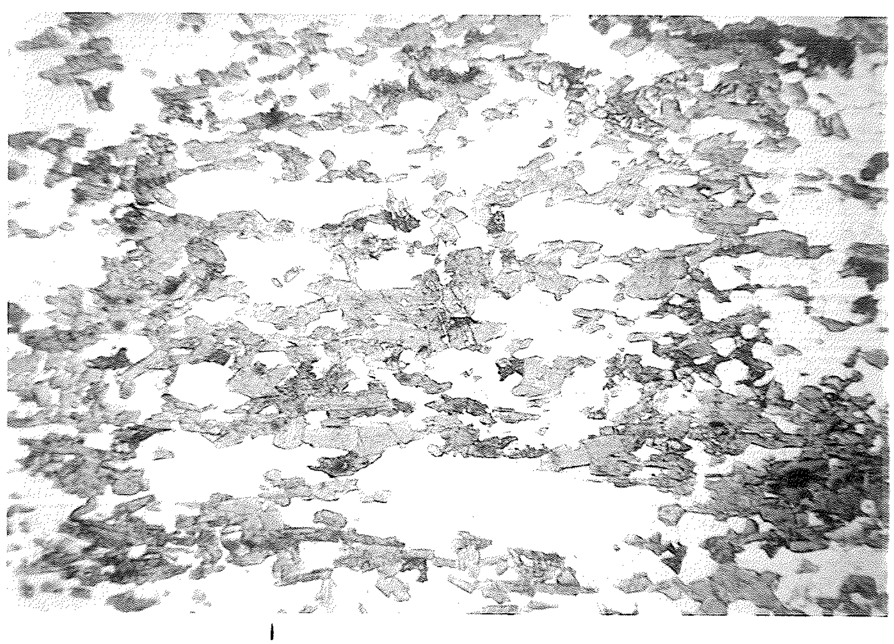


Figure 13: Feldspathic graywacke or possibly recrystallized lithic graywacke from locality 119. Strong development of hornblende may reflect recrystallized mafic volcanic fragments. a) nicols crossed; b) nicols uncrossed.

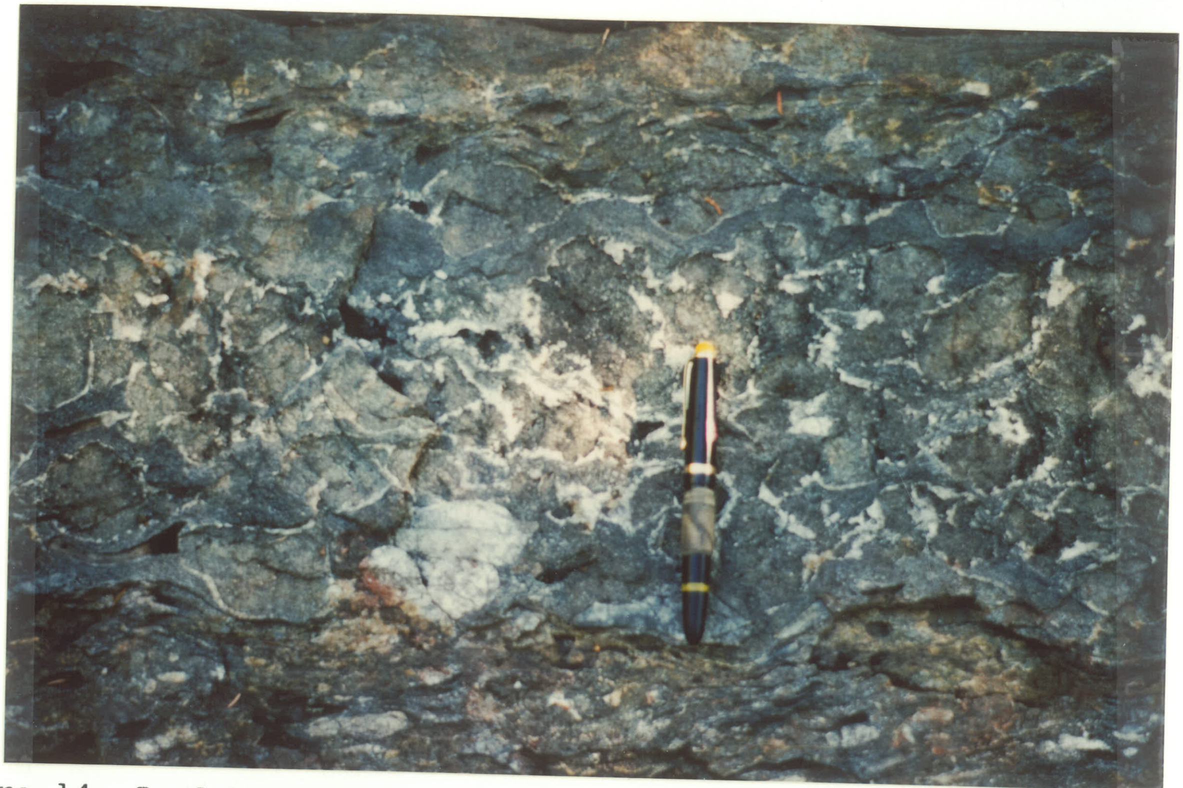


Figure 14: Crudely spheroid alteration patches (light green) in sandstone bed between 2 pebble conglomerate beds. Pen is 12 cm long and top points to stratigraphic tops. Photo from locality 42.

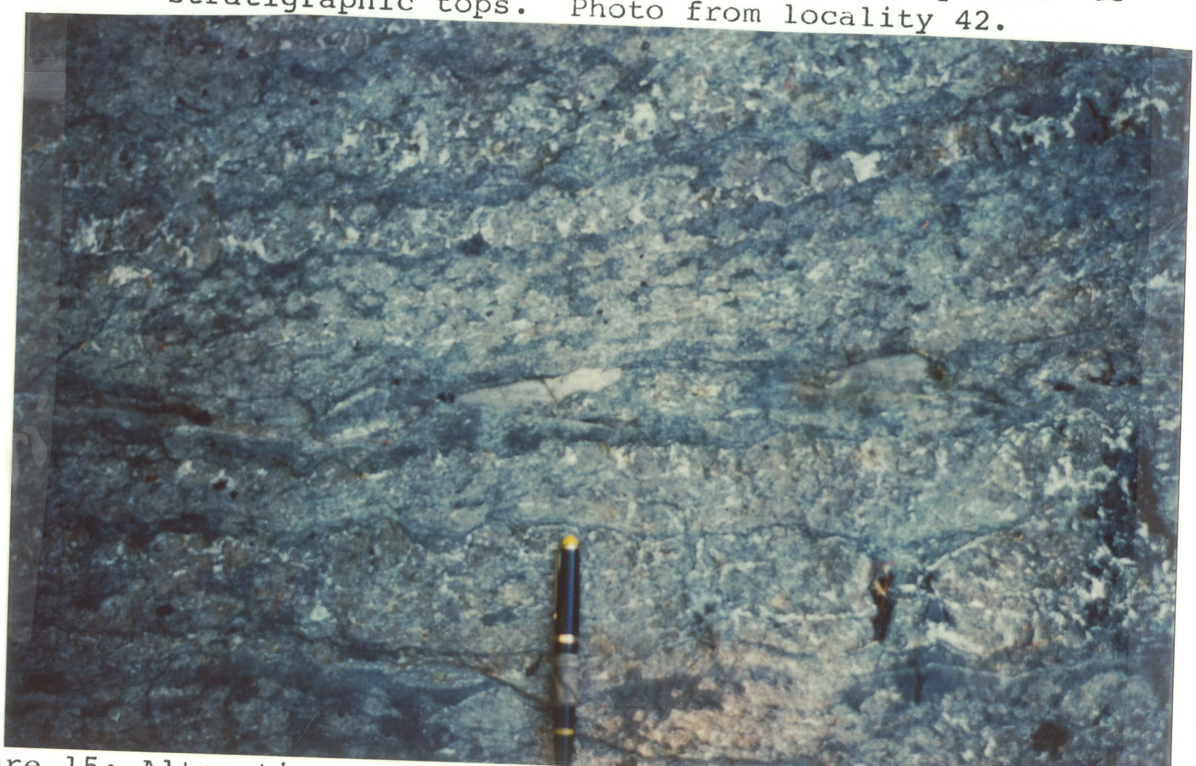


Figure 15: Alteration spheres coalesced to form layers parallel to bedding. Pen is 12 cm long and top points to stratigraphic tops. Photo from locality 39.

total alteration. Upon close inspection, however, individual alteration spheres can still be defined by the quartz rims. In the conglomerate matrix the alteration does not appear to be confined to specific beds but rather forms irregular masses. The crudely spherical habit of the alteration in the sandstones was not observed in the conglomerate matrix. Clasts in the conglomerate do not appear to be affected by the alteration.

The altered patches are composed of 3 to 75 percent diopside which forms granular aggregates and large crystals up to 1 cm in diameter that poikilitically enclose plagioclase, quartz, hornblende and minor sphene in grains up to 0.5 mm (Table 3, Figures 16 and 17). Modal analyses (Locality 3, Table 3) of altered and partly altered portions of the same bed show a marked increase in diopside and a decrease in quartz and hornblende in the altered part. There is no change in the other constituents except for a slight reduction in the An content of the plagioclase in the altered part. Chemically (Table 4) there is a significant reduction in SiO_2, Al_2O_3, and H_2O, and slight reduction in Na_2O, and a significant increase in MgO, CaO, and MnO in the altered part compared to the partly altered portion.

The mineralogical and chemical differences between the altered and partly altered samples is consistent with the introduction of dolomite into the sandstones and conglomerate matrix. During metamorphism the dolomite reacted with quartz and plagioclase to produce diopside. The presence of quartz

Scale

1 mm

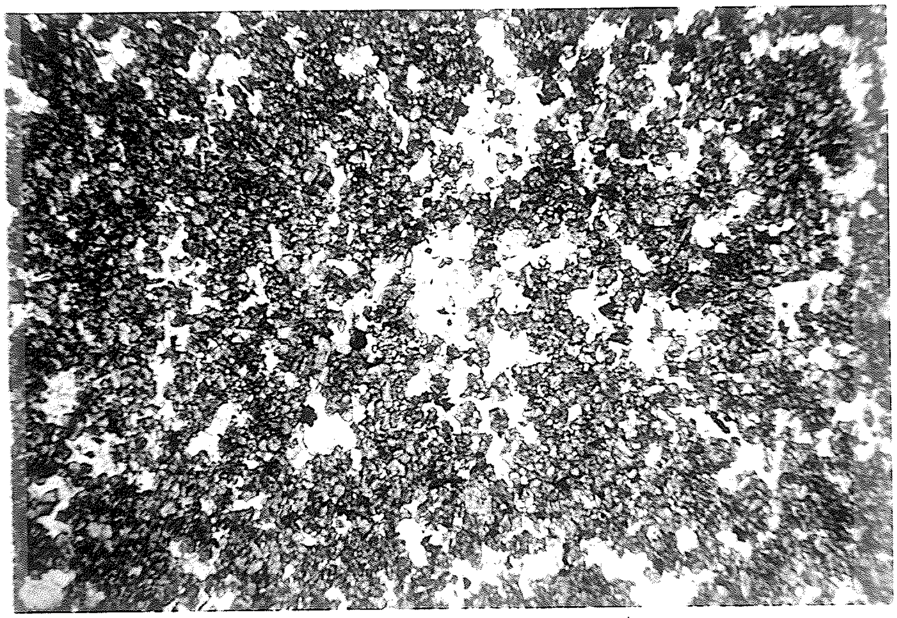


Figure 16: Photomicrograph of granular aggregates of diopside in strongly altered sandstone at locality 5 (nicols uncrossed).

Scale

1 mm

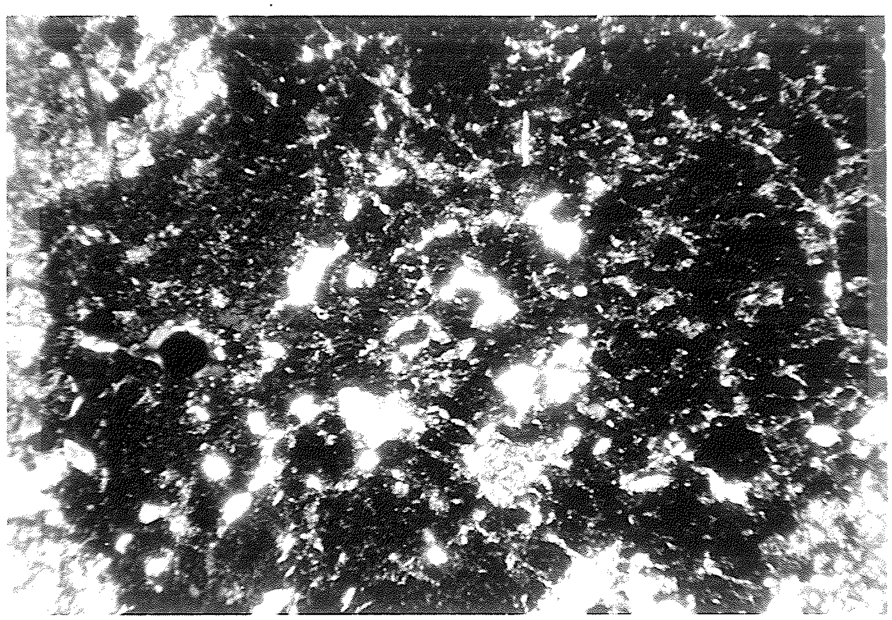


Figure 17: Photomicrograph of single large crystal of diopside that poikilitically encloses grains of quartz and plagioclase at locality 2 (nicols crossed).

TABLE 4 Major Oxide (percent) Chemical Analyses of samples from the Conglomerate Member

Lithology	Felsic Sub-Volcanic Clast	Altered Sandstones		Partly Altered Sandstones			Sandstone Mean [5]
Locality	2	2	3*	3*	5	5	
SiO_2	75.85	55.75	58.55	65.95	69.55	50.00	61.5
Al_2O_3	13.44	7.26	7.51	10.05	8.03	15.62	11.23
Fe_2O_3	.24	.84	1.48	1.37	1.9	1.21	1.50
FeO	.48	5.82	6.3	5.86	6.04	8.0	6.63
MgO	.55	8.8	7.55	4.95	4.5	7.50	5.65
CaO	3.35	17.9	15.0	7.0	6.3	8.70	7.33
Na_2O	4.0	1.64	1.52	2.16	1.26	2.6	2.01
K_2O	1.77	.86	.98	.62	.68	1.88	1.06
H_2O	.26	.30	.69	1.07	1.06	1.85	1.32
CO_2	.07	.12	.24	.22	.01	.02	.08
TiO_2	.11	.18	.15	.26	.21	.59	.35
P_2O_5	.04	.06	.05	.06	.05	.12	.07
MnO	.04	.54	.53	.24	.33	.21	.26
Ni (ppm)	21	103	104	140	129	190	133
S	ND	ND	.008	.003	ND	low	.002
Total:	100.2	100.07	100.55	99.81	99.92	98.3	99.29

NOTE:
1) Sandstone localities numbered in relative lateral position from west to east.
2) Duplicate analyses from locality 3 represent samples from the same bed.
3) Duplicate analyses from locality 5 represent samples from different beds.
4) Localities denoted by * have modal analyses in Table 3.
5) Average of 3 partly altered sandstones.

rims at the contact between altered and relatively unaltered material implies local movement of Si and possibly other elements.

The calc-silicate alteration in the Conglomerate Member could be early diagenetic in origin or due to fumarolic or hot spring activity related to volcanism. The restriction of the alteration to the Conglomerate Member and its shape and distribution suggests an early diagenetic origin. The alteration is more intense at the base of the member and this could imply that alteration moved upward from the base of the member and was possibly due to fumarolic or hot spring activity related to volcanism. Alternatively Bull (1972) indicated that alluvial fan deposits commonly contain salts such as gypsum and calcite. The salts form as a result of weathering of the surficial layers of the fan and form caliche layers. The extent of caliche development would depend, predominantly, on the length of exposure before burial of the fan surface by younger fan deposits and in part by post burial diagenesis of caliche formation. This type is the more likely origin of the alteration and could explain why some parts of the member are more altered than others. Caliche formation would also explain the apparent relationship between alteration and bedding in the member. Fumarolic or hot spring activity from the base of the member would not explain the apparent relationship to bedding of the alteration. Also, alteration as a result of fumarolic or hot spring activity would probably be restricted to specific localities and would not affect the entire member.

Lateral Distribution of Conglomerate Clast Types and Interbedded Sandstones

In order to examine lateral variations in matrix content, clast size and clast population in the conglomerate and the relative proportion of interbedded sandstone, the member was divided into three arbitrarily defined stratigraphic intervals, each about 100 m thick. Outcrop modes of the clast types, percent matrix and the conglomerate/sandstone ratio in each interval were plotted in correct lateral position (Figure 18, 19, 20), but the stratigraphic position within each interval was not considered. The outcrop modes presented (Figure 18, 19, 20) represent modal analyses of single beds at the locality and may not be representative of the entire interval. Sample locations in these intervals was limited by outcrop distribution and because of this, the lateral clast distributions were sometimes limited, particularly in the lower part of the member, to only a few localities. With these limitations, the following discussion of trends in these intervals should be considered interpretative only.

In the lower part of the member there is no lateral change in clast size of the prominent clast types (Figure 18). The relative abundances of vein quartz and felsic plutonic clasts decrease eastward whereas intermediate volcanic clasts increase eastward. Felsic subvolcanic clasts show no consistent lateral change. Felsic volcanic, mafic

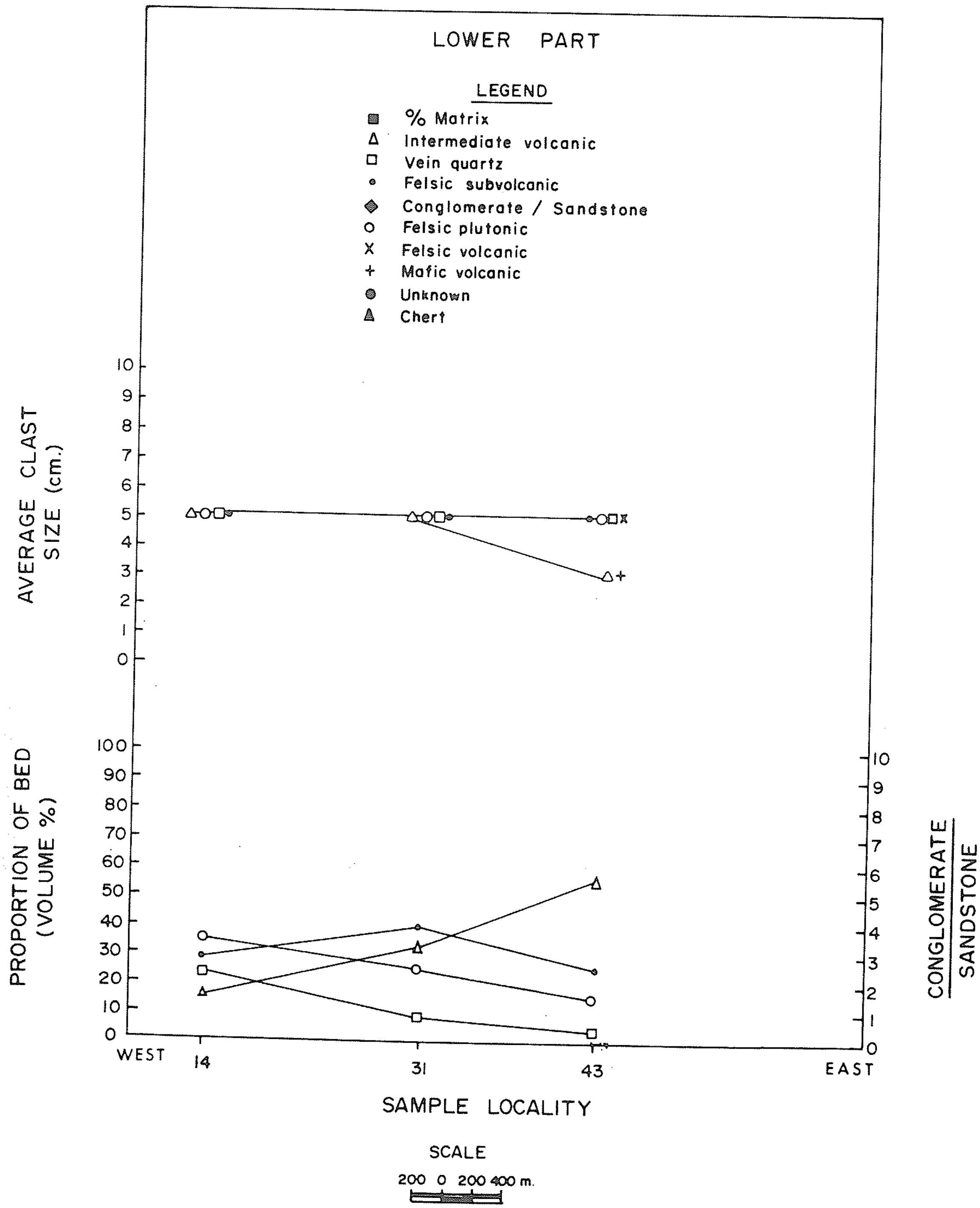


Figure 18: Lateral clast distribution from west to east in the lower part of the Conglomerate Member. Sample localities are shown on Figure 5.

Volume percent is calculated on a matrix free basis.

volcanic and unknown clasts were found only at the east end where the matrix content also increases. The relative proportion of interbedded sandstone within the conglomerate remains relatively constant.

In the middle part of the member, clast sizes decrease gradually westward, but there is a sudden increase at the west end (Figure 19). There are no consistent lateral changes in the clast abundances except for a slight decrease eastward of felsic plutonic clasts and a coincident sudden increase at the west end of felsic subvolcanic clasts and a sudden decrease of intermediate volcanic clasts. Mafic volcanic, felsic volcanic and unknown clasts are restricted to the east and the matrix content shows no consistent change across the member but does show a sudden increase at both the east and west ends. The relative proportion of interbedded sandstone increases eastward.

In the upper part of the member, clast sizes are relatively constant except at the west end where there is a sudden decrease (Figure 20). The relative abundance of felsic plutonic and vein quartz clasts decreases slightly eastward. Felsic subvolcanic clasts show no consistent lateral change. Intermediate volcanic clasts were not observed in the west end but are the dominent clast type elsewhere. As in other stratigraphic intervals felsic volcanic, mafic volcanic and clasts of unknown origin are restricted to the east end.

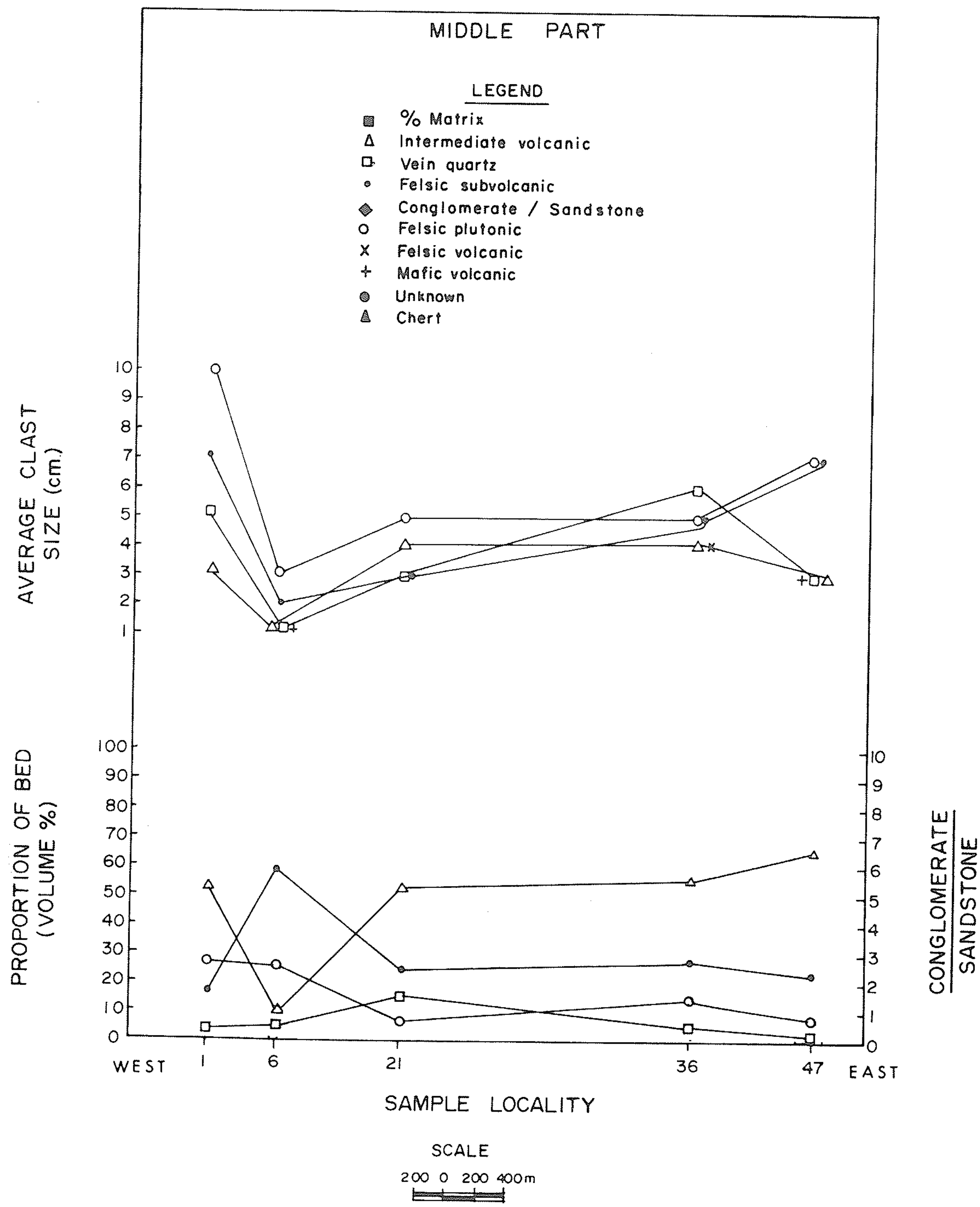


Figure 19: Lateral clast distribution in the middle part of the Conglomerate Member. Sample localities are shown on Figure 5. Volume percent is calculated on a matrix free basis.

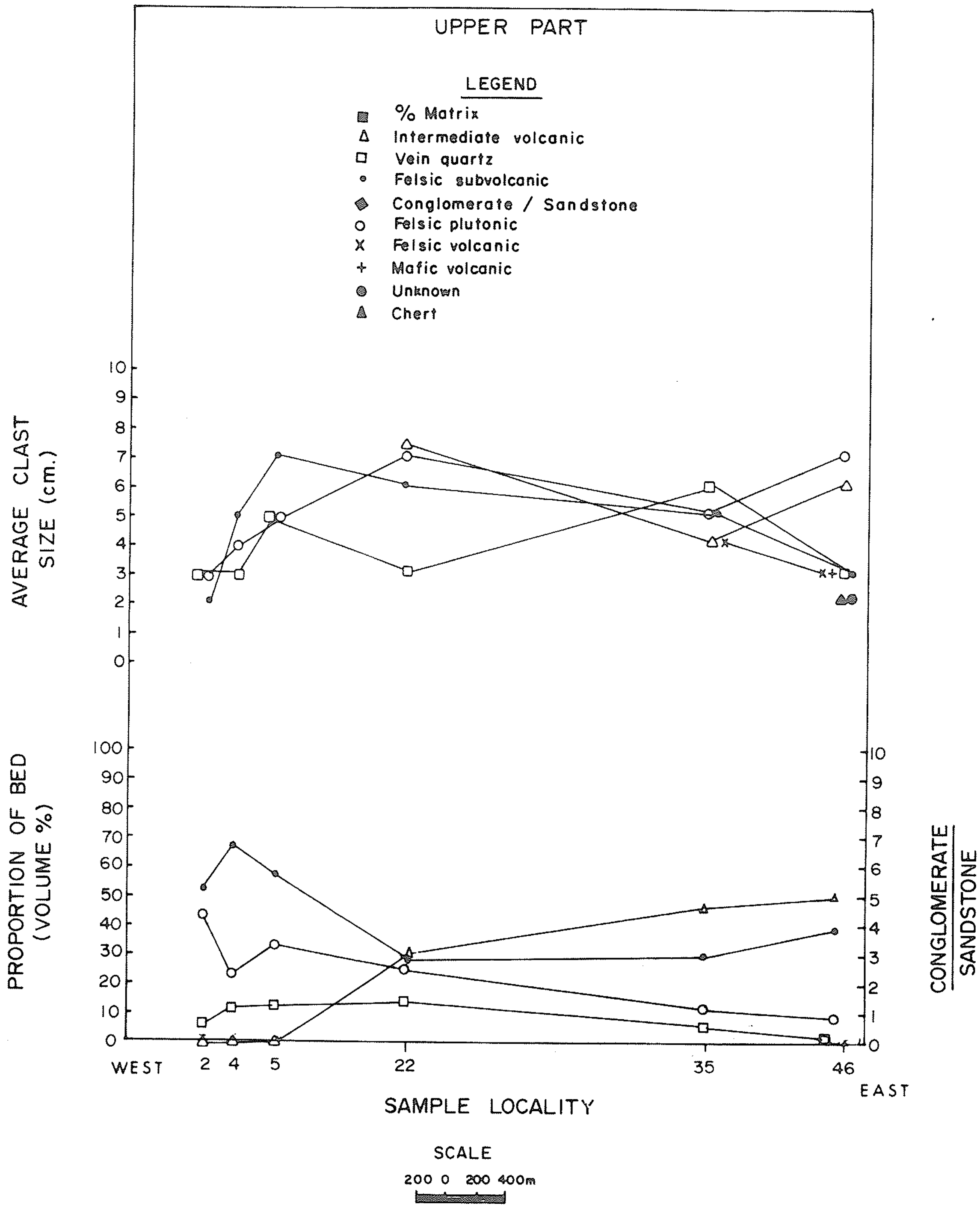


Figure 20: Lateral clast distribution in the upper part of the Conglomerate Member. Sample localities are shown on Figure 5. Volume percent is calculated on a matrix free basis.

Iron formation and chert clasts were found only at the east end of this stratigraphic interval. The matrix content is relatively constant but the relative proportion of interbedded sandstone increases eastward.

Bedding Types

Three basic bedding types can be defined from large scale bedding morphology and associated sedimentary structures (Table 5):

a) Horizontal Bedding - This is defined by even, horizontal beds of conglomerate alternating with greywacke beds, both of which are continuous on outcrop scale. There are two types of horizontal bedding within the member;

1) Moderately well sorted pebble conglomerate beds alternating with greywacke beds. Individual beds of conglomerate and greywacke average 40 cm in thickness and show local cut-and-fill structures, amalgamation of beds and, in the conglomerate beds, cobble conglomerate lenses. No internal grading was found in the conglomerate or greywacke (Figure 21).

2) Very poorly sorted, chaotic pebble to cobble conglomerate interbedded with greywacke in beds that average 1.5 m thick and show local cut-and-fill structures. This type is interbedded with the type one horizontal bedding (Figure 22).

TABLE 5 Description of facies in conglomerate member and their mode of deposition

Facies	Sorting	Lithology	Type of bedding	Bedding thickness	Other structures	Mode of deposition
1	moderate	interbedded pebble conglomerate and grey-wacke	horizontal and con-tinuous on outcrop scale	10 cm-50 cm; average 40 cm	a) local cut and fill structures 50 cm wide and 10 cm thick b) local cobble conglomerate lenses 1-2 m wide and 50 cm thick c) local pinching out of sandstone or conglomerate beds resulting in amalga-mation of overlying and underlying beds	deposition by sheet flood mechanisms resulting in lobate blanket deposits; structure (a) represents shallow distributary channels; structure (b) represents channel lag deposits; structure (c) represents the edge of a single sheet flood lobe
2	poor	interbedded pebble to cobble conglomerate and greywacke	large scale, trough-shaped, cross-bedding defined by pebble trains in greywacke	cross-bed sets about 2 m thick	a) local boulder to cobble conglomerate lenses 1-2 m wide and 50 cm thick	deposition by lateral migration in braided streams; structure (a) represents a lag deposit
3	very poor	interbedded greywacke and chaotic pebble to cobble conglomerate	channel fill cross-bedding	cut and fill structures 10-15 m wide and 3-4 m thick		channel deposits formed by scouring of facies 1 by debris flows and grain flows
4	very poor	interbedded greywacke and pebble to cobble conglomerate	horizontal and contin-uous on outcrop scale	1-2 m; average 1.5 m	a) local cut and fill structures 50 cm wide and about 20 cm thick in underlying beds	deposition as debris flows; commonly interbedded with facies 1; a) represents local channel in facies 1.

Figure 21: Horizontally bedded pebble conglomerate and sandstone. Hammer handle is 30 cm long and points to stratigraphic tops. Photo is from locality 34.

Figure 22: Chaotic pebble to cobble conglomerate (bed in upper third of photo). Hammer handle is 30 cm long and points to stratigraphic tops. Photo is from locality 36.

b) Trough-shaped Cross-bedding - This is defined by pebble trains in poorly sorted greywacke. The cross-bed sets are about 2 m thick with local cobble conglomerate lenses at the base of cross-bed sets. Coarse normal grading occurs locally within individual cross-bed sets (Figure 23).

c) Channel-fill Cross-bedding - This is defined by very poorly sorted, pebble to cobble conglomerate beds and massive greywacke in cross-bed sets 10 to 15 m wide and 3 to 4 m thick (Figure 24).

Four facies have been defined on the basis of bedding type and thickness, and large scale sedimentary structures (Figure 2, Table 5). Facies 1 includes type one horizontally bedded conglomerate and greywacke, and volumetrically is the most important facies. It is found throughout the member. Facies 2 includes trough-shaped cross-bedding, and is restricted to the west end of the member. Facies 3 includes channel-fill cross-bedding. It is locally developed only in the center of the member. Facies 4 includes thick horizontally bedded chaotic conglomerate and greywacke and is restricted to the west end of the member.

Depositional Environment

Sedimentary environments in which coarse clastic sediments such as those in the Conglomerate Member normally accumulate are restricted to stream channels, shorelines, submarine fans and alluvial fans.

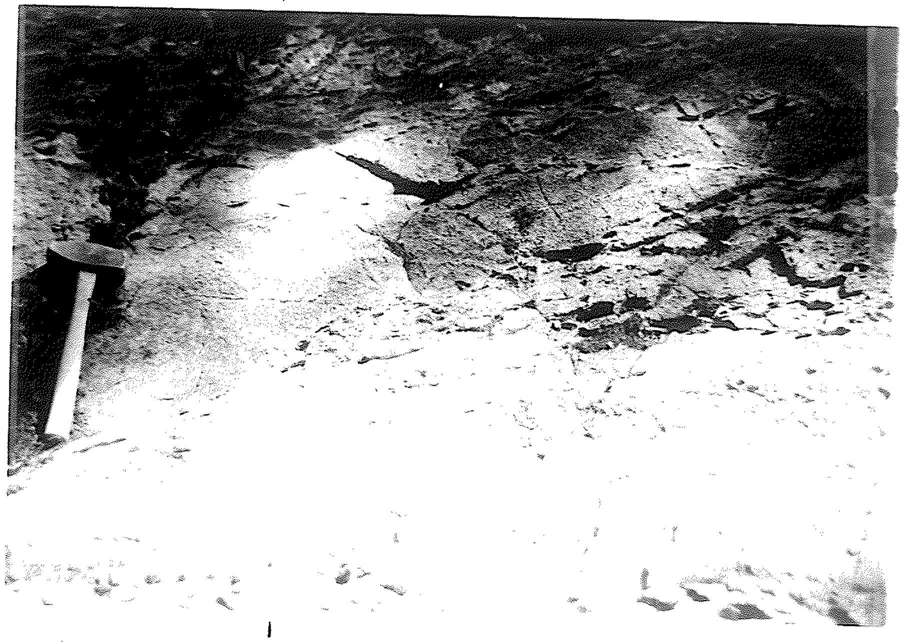


Figure 23: Trough-shaped cross-bedding at locality 4. End of hammer handle rests on pebble train defining cross-bedding. Hammer handle is 30 cm long and head of hammer points to stratigraphic tops.

Figure 24: Channel-fill cross-bedding with massive sandstone scouring horizontally bedded sandstone and conglomerate and in turn scoured by chaotic conglomerate (bottom of photo). Hammer handle is 30 cm long (top of photo) and head of hammer points to stratigraphic tops. Photo taken at locality 37.

In stream channel and associated flood plain environments, point bars and channel-fill constitute the bulk of the deposits and in braided stream environments deposits formed by lateral accretion are common. Facies 2 of the Conglomerate Member could be typical of a braided stream environment (Reineck and Singh 1975) but is only a small part of the member. The even, horizontal bedding, lacking internal cross stratification, of Facies 1 and the thick bedded, chaotic conglomerates of Facies 4 are uncommon in stream environments.

Shoreline conglomerates are characterized by well rounded, well sorted accumulations of gravel size detritus (Pettijohn, 1975, p. 155). Conglomerates of the Conglomerate Member are neither well sorted nor uniformly well rounded. Shoreline conglomerates are generally of small volume and are confined to narrow, linear belts. In a transgressive sea these conglomerates can form thin sheet-like deposits superimposed unconformably on older rocks (Pettijohn 1975, p. 156). Although the even horizontal bedding of Facies 1 is sheet-like, the generally poorly sorted nature of the conglomerate beds and the evidence of current activity in local cut-and-fill structures, amalgamation of beds and cobble conglomerate lenses in the conglomerate beds is not consistent with the shoreline environment.

"Resedimented" conglomerates of a turbidite association (Walker, 1975) can develop in submarine fans. These deposits are characterized by the presence of graded bedding in the conglomerate. Three basic types of conglomerate bedding were recognized by Walker (1975);

1) Inverse to Normally Graded Conglomerate - The conglomerate beds have inverse grading at the base and normal grading or massive conglomerates at the top. This style of grading has not been recognized in the Conglomerate Member.

2) Graded - Stratified Conglomerates - This type is characterized by normal grading at the base of the bed followed by crude oblique stratification, followed in turn, by alternating sand and pebble layers. The oblique stratification is not present in all beds. Normal grading has not been recognized in the Conglomerate Member although alternating thin sand and pebble layers are present. Walker (1975) also indicated a compositional similarity between the conglomerate matrix and associated sand layers. This is characteristic of the Conglomerate Member.

3) Disorganized Conglomerates - This type is characterized by poorly sorted, massive beds that lack grading. It is similar to Facies 4 in the Conglomerate Member. Although there are similarities between the Conglomerate Member and resedimented conglomerates, the absence of normal or inverse grading in the conglomerate beds suggests that the Conglomerate Member was not deposited on a submarine fan.

In alluvial fan environments, individual fans consist of water-laid sediments and/or debris-flow deposits (Bull, 1972). Water-laid deposits include sheet-flood deposits, stream-channel deposits and sieve deposits. Sheet-flood deposits are continuous on outcrop scale with moderate to well sorted gravels and sandstsone. The beds may be cross-bedded, laminated or massive. Bedding of this nature is similar to Facies 1 of the Conglomerate Member. Stream-channel deposits are found incised into the sheet-flood deposits and consist of more poorly sorted conglomerates and sandstones with channel-fill cross-bedding. This type of deposit is similar to Facies 3 of the Conglomerate Member. Sieve deposits consist of subangular boulders that lack significant matrix and contain void spaces (Reineck and Singh,1975). Bedding definition is poor. This type of deposit was not found in the Conglomerate Member.

Debris-flow deposits consist of massive, poorly-sorted, chaotic conglomerate or massive, structureless sandstone. This type of deposit is similar to Facies 4 of the Conglomerate Member.

Of the possible environments, the Conglomerate Member thus corresponds most closely to alluvial fan deposits. Facies 1, 3 and 4 of the Conglomerate Member are similar to sediments typical of an alluvial fan. Facies 2, although similar to sediments found in braided stream environments, is not inconsistent with an alluvial fan environment.

Alluvial fans form at the base of highland pediments where streams descending from the highland areas encounter lowland areas of reduced gradient. The surface of an alluvial fan deposit is a segment of a cone that widens downslope from the point where the stream leaves the highland area (Figure 25; Bull,1972). Contours on the fan are bowed downslope from the fan apex. In radial cross-section an alluvial fan is generally wedge-shaped, thickening towards the apex. Because of the decreasing energy regime going from the apex to the toe of the fan, the relative proportion of interbedded sand increases and the clast size in the conglomerate decreases towards the toe of the fan (McGowen and Groat, 1971). Morphologically and stratigraphically an alluvial fan can be divided into three major gradational facies and can be distinguished by differences in lithology, bedding types, and sedimentary structures. These three facies are the proximal fan, mid-fan, and distal fan (Figure 25).

The westward thickening wedge-shape of the Conglomerate Member suggests that the relative apex or the base of the highland terrain may be to the west. The wedge shape is well defined at the east end by overlying sandstone but in the center and west, lack of outcrop hampers precise location of the upper boundary (Figure 5). Consequently the Conglomerate Member as shown on Figure 2 is the minimum thickness. Shifting of the upper boundary southward would greatly emphasize the wedge shape of the member. Facies 1, which is the dominant facies and represents a sheet flood mode of deposition, is characteristic of the outer mid-fan area of an alluvial fan. The association of Facies 3 with Facies 1, and the restriction of Facies 3 to the center of the member indicates incising of the mid-fan area by larger than average

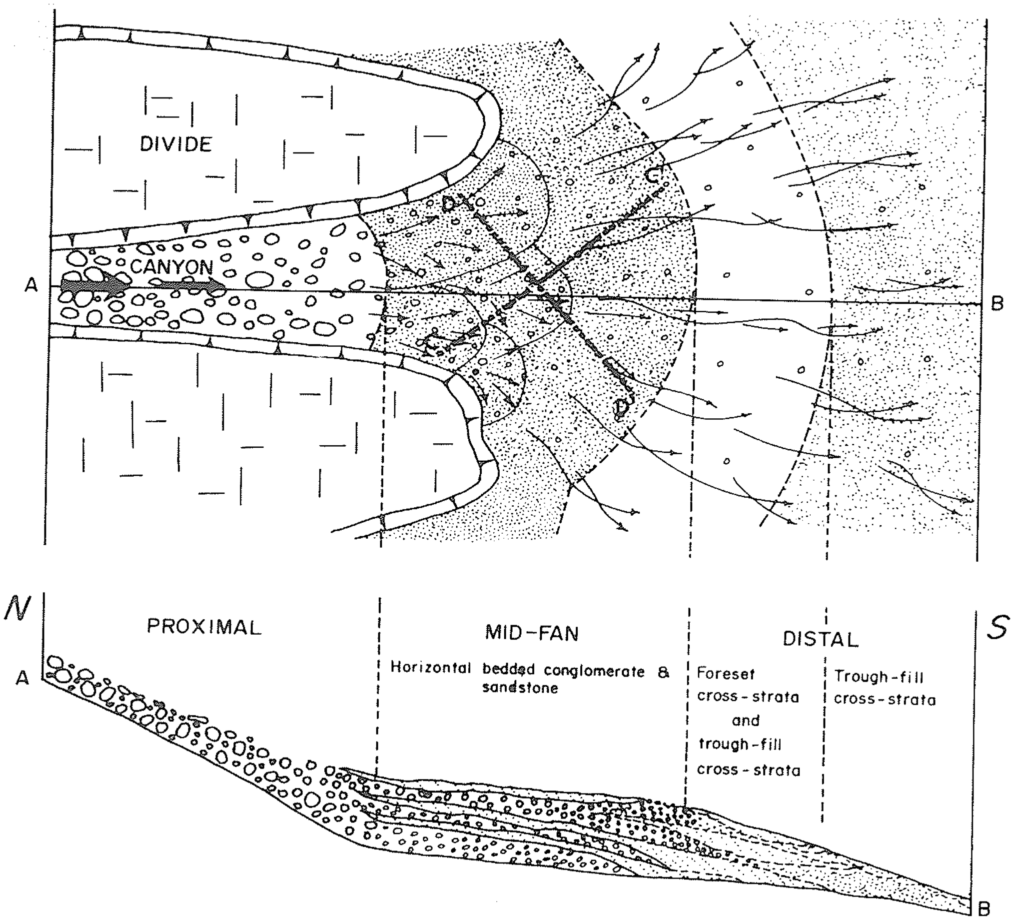


Figure 25: Plan and radial cross section of a single canyon and fan; Cambrian age, Van Horn Sandstone. Width of arrows, in plan view, indicates relative intensity of fluvial processes. Cross section shows downfan decrease in slope and grain size and the following general north-south succession of stratification types: (1) proximal: massive gravel, 2) mid-fan: alternating gravel and trough-and foreset-cross-bedded sand, and 3) distal: trough-and foreset cross-bedded sand (after McGowen and Groat, 1971). Sections C-C' and D-D', represent the possible position, in an idealized fan, of the exposed portion of the Conglomerate Member.

distributary channels and their eventual abandonment. Facies 2 and 4 are restricted to the west end of the member, and are typical of the inner mid-fan area of an alluvial fan (McGowen and Groat, 1971). A thick sequence of massive conglomerate with poorly defined bedding typical of the proximal fan and trough and foreset cross-bedded sandstone characteristic of the distal fan were not found in the exposed section of the Conglomerate Member.

As it is presently exposed, the Conglomerate Member represents an oblique section, although dominantly longitudinal, through the mid-fan area of an alluvial fan (Figure 25) with deposits of the inner mid-fan in the west represented by Facies 2 and 4 and deposits of the outer mid-fan in the east represented by Facies 1 and 3. In this interpretation the dominant stream flow would be from the northwest or southwest.

Lateral distribution of clast sizes do not have the expected trends for a simple alluvial fan with its relative apex to the west. Average clast size should decrease progressively eastward. Instead, the average clast size is constant in the lower and upper parts of the member and in the middle part there is a gradual eastward increase rather than decrease in clast size. Furthermore, in both the middle and upper parts there is a decrease in average clast size at the west end. In the middle part there is sudden increase at the west end. There is a sudden decrease at the west end of the upper part.

For a single fan the relative proportion of interbedded sandstone should increase eastward. This was observed in the middle and upper parts of the member but in the lower part of the member the proportion of sandstone is constant.

In a simple fan the matrix content should increase eastward. The matrix content of the conglomerates is erratic in the lower and middle parts of the member but is constant in the upper part.

In a simple alluvial fan model, clasts of the principal rock types would be expected to occur throughout the fan at all stratigraphic levels. However, in the Conglomerate Member clasts of felsic volcanic, mafic volcanic, iron formation and clasts of an unknown type were found only at the east end. The proportion of intermediate volcanic clasts increased to the east in the lower part but showed a sudden decrease to the west in the middle part with none found in the upper part at the west end. The felsic subvolcanic clasts show no change in the lower and upper parts and an increase to the west in the middle part. Felsic plutonic and vein quartz clasts show a general decrease to the east at all stratigraphic levels.

The Conglomerate Member does not represent a single, simple alluvial fan but at least two coalescing fans. The distribution of clast types suggests the influx of another alluvial fan with its relative apex to the east during the deposition of an alluvial fan with its relative apex to the west. This is supported by the distribution of average clast sizes, matrix contents and the proportion of interbedded sandstone which do not show the expected trends for a simple alluvial fan with its relative apex to the west but, instead, show the effects of the influx of detritus from another alluvial fan to the east. Detritus from the second alluvial fan with its relative apex to the east is found at all stratigraphic levels in the member.

Provenance

The source area of the Conglomerate Member was characterized by a variety of rock types. Reconstruction of the depositional environment suggests stream flow directions from the northwest or southwest, relative to the present geography, for the alluvial fan at the west end of the member.

The competent nature and high degree of rounding of the ubiquitous felsic plutonic and vein quartz clasts indicates a relatively distal source compared to the more angular volcanic clasts. There is a general easterly decrease in abundance of the plutonic and quartz clasts at all stratigraphic levels and this suggests a source terrain related to the western fan, or, more precisely, a source to the northwest or southwest of the Conglomerate Member. A possible source in the preserved stratigraphy of the Favourable Lake belt is a trondjhemite crustal remnant north of North Trout Lake and presently exposed 2 km from Formation K (Hillary and Ayres, 1980; Figure 3). Rock units described from this remnant are texturally similar to plutonic clasts in the Conglomerate Member but most of the clasts have a higher potash feldspar content. Hillary and Ayres (1980) suggest that the crustal remnant represents a deeper level 2927 Ma granitoid pluton, heated and elevated to its present level by the emplacement of successive phases of the 2710-2730 Ma North Trout Lake batholith (Corfu et al, 1981). The plutonic clasts could have been derived from a more potassic phase of the granitoid crustal remnant that is not exposed at the present erosional level. Plutonic clasts from Formation K have been dated at 2901 Ma (Corfu et al, 1981) and supports this conclusion.

Felsic subvolcanic clasts show no consistent lateral changes and possibly indicates the source terrain was from the west and east. The competent nature of these clasts and their high degree of rounding suggests a relatively distal source. There are no equivalent lithologies in the Favourable Lake belt.

Intermediate volcanic clasts are subangular to angular and their distribution suggests a source related to the eastern fan and possibly the western fan in the middle part of the member. These clasts are less competent than the felsic plutonic or vein quartz clasts, but are poorly rounded, and were probably derived from a more proximal source. Intermediate volcanic rocks occur east of Formation K in the Favourable Lake belt but there are no known preserved intermediate volcanics west of the Conglomerate

Member.

Mafic volcanic clasts are angular to subangular and their distribution suggests an easterly source. The poor degree of rounding and the relatively incompetent nature of the clasts compared to the felsic plutonic and vein quartz clasts suggests a more proximal source. The Conglomerate Member conformably overlies mafic volcanics of Formation J in the Favourable Lake Belt and this is a possible source of these clasts.

Felsic volcanic, iron formation, chert and clasts of an unknown type are all rounded and their distribution suggests an easterly and relatively distal source for these clasts. Ferruginous cherts and iron formation are found in the Favourable Lake belt east of the Conglomerate Member.

In summary, the conglomerates and sandstones of the Conglomerate Member were deposited as, at least, two coalescing alluvial fans. The relative apices of the fans and the source of the sediment is to the west, and, to the east of the present outcrop area. Reconstruction of the stratigraphy suggests stream flow directions from the northwest or southwest for the western fan. Stream flow directions for the eastern fan are unknown. The source terrain for the fan with its relative apex to the west was composed dominantly of distal felsic plutons, and possibly felsic subvolcanic plutons with quartz veins, with a possible intermediate volcanic terrain more proximally. Detritus derived from the east was from a mixed terrain composed of felsic volcanic units and subvolcanic plutons, iron formation

a)

1 mm

b)

Figure 26: Tectonic microbreccia in outcrop (photo a) and in thin section (photo b). Lens cap in photo a) is 5 cm in diameter. Stratigraphic tops are to the top of the photo. Photo a) is from locality 124 and photo b) is from locality 87. Note tectonic stretching of grains below the microbreccia in photo b) and the development of ultramylonite (black).

and chert distally and intermediate and mafic volcanic rocks more proximally.

Sandstone Member

Introduction

As exposed, the sandstone member is a dominantly tabular body 10 km long and 0.6 km wide, wedging out to the east, and is composed of sandstones with minor interbedded siltstone, shale and conglomerate, and rare felsic tuffs and mafic flows or dikes (Figure 2). Cataclasis extends up to 30 m below the bedding plane thrust fault at the top of the member and hinders petrographic examination in the area (Figure 26).

Sandstones form 80 percent of the member and are feldspathic to locally lithic greywackes (Figure 6) that are unusually rich in sand-size quartz compared to the average Archean greywacke. They contain 30 to 63 percent modal sand-size quartz grains (Table 6) and have silica contents ranging from 62 to 82 percent (Table 7). Felsic tuffs are interbedded with siltstone and shale and these lithologies form 8 percent of the member. Pebble conglomerate beds form 8 percent of the member but are restricted to the east end. Mafic flows or dikes are found interbedded with other lithologies and forms 4 percent of the member.

Individual beds in the Sandstone Member are horizontal and continuous on outcrop scale, but eight bedding types can

TABLE 6 Modal Analyses of the Sandstone Member

LITHOLOGY	SANDSTONE															QUARTZ GREYWACKE	CONGLOMERATE MATRIX	AVERAGE SANDSTONE	STANDARD DEVIATION
LOCALITY	141	129	124	120a 2	120b 2	120c 2	110	96	75	67a 2	67b 2	88	55	63	49	67c	66		
Sand-size quartz	36.8	32.4	37.9	51.2	47.8	35.7	49.3	28.9	33.0	63.7	43.3	46.6	42.9	48.9	32.5	59.7	41.8	40.1	9.81
Sand-size plagioclase	8.5	16.8	16.2	17.4	17.1	12.8	10.5	14.4	17.7	1.9	7.3	18.6	17.1	11.4	16.4	2.0	16.0	13.5	8.79
Quartzo-feldspathic matrix	16.9	16.4	15.6	5.0	8.9	11.2	13.8	18.1	15.8	11.4	12.9	6.1	1C.2	6.6	20.5	4.3	7.0	12.2	4.66
Rock fragments	10.0	2.1		1.7	6.4	6.3	2.7	3.9	1.6	4.0	2.9	3.3	3.1	1.6	tr	tr	15.2	4.7	2.24
Biotite	26.1	31.7	24.3	24.2	18.2	21.7	18.1	32.1	27.0	6.9	31.2	22.6	25.4	17.5	29.5	tr	13.6	23.5	6.71
Muscovite										10.0						32.2		tr	2.58
Hornblende	tr			tr		10.8	1.8	tr			1.0	tr					1.12	tr	2.71
Sphene	tr				tr	tr	tr			tr	tr	tr		tr				tr	0.05
Fe-Ti Oxide	tr	tr	tr		1.6	tr	1.9	2.1	tr	1.1	tr	1.6	tr	tr	tr	tr	1.7	tr	0.79
Epidote	tr								3.6					9.6				tr	2.58
Zircon			tr			tr			tr			tr						tr	0.04
Carbonate	tr		4.6				1.2		tr									tr	1.19
Apatite			tr											2.2				tr	0.04
Chorite			tr															tr	0.56

NOTE: 1) Sandstone locality numbered in relative lateral position from west to east.

2) Duplicate modes at locality 67 represent different sandstone beds at that locality. Triplicate modes at locality 120 represent 3 samples from the same beds; 120a - fine grained sandstone (top of bed)

120b - medium grained sandstone (middle of bed)

120c - coarse grained sandstone (bottom of bed)

TABLE 7: Major Oxide (Percent) Chemical Analyses of the Sandstone Member

Lithology	Locality	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	CO_2	TiO_2	P_2O_5	MnO	Ni (ppm)	S	TOTAL
SANDSTONE	141[*3]	77.80	9.48	0.79	2.12	2.65	1.73	2.60	1.68	0.75	0.12	0.25	0.04	0.07	143	.058	100.87
	129a[2]	66.95	16.38	1.04	2.14	1.43	1.90	4.24	3.64	1.21	0.42	0.33	0.24	0.05	24	.119	99.97
	129b[*2,3]	62.9	16.46	1.03	3.92	3.80	1.50	5.62	2.46	1.28	0.21	0.54	0.13	0.07	295	.086	99.89
	127	74.40	10.75	0.71	2.02	3.00	1.20	3.98	1.86	1.02	0.53	0.24	0.06	0.07	191	.012	99.84
	124[*3]	75.15	9.56	0.89	2.32	3.08	2.70	2.36	1.63	1.11	1.20	0.18	0.05	0.07	144	.041	100.30
	122	76.05	9.56	0.58	2.96	3.38	1.98	2.36	1.24	1.29	0.31	0.29	0.04	0.08	200	.134	100.02
	112	76.10	9.58	0.70	2.42	3.58	1.08	2.86	1.75	1.08	0.14	0.22	0.05	0.06	164	.014	99.62
	120a[*2,3]	78.45	10.16	0.92	1.62	1.98	1.92	2.32	1.32	0.77	0.13	0.16	0.02	0.08	92	.039	99.85
	120b[*2,3]	75.10	10.58	0.78	2.24	3.08	2.12	3.26	1.40	0.81	0.16	0.23	0.03	0.09	150	.021	99.90
	120c[*]	70.00	11.14	1.25	2.90	3.72	0.78	4.32	2.28	1.24	0.09	0.28	0.02	0.06	185	.013	98.08
	104	77.10	10.84	0.78	1.84	2.00	1.75	3.16	1.20	0.77	0.07	0.15	0.06	0.10	99	ND	99.77
	110[*3]	74.55	11.06	0.83	2.52	2.58	2.68	2.64	1.42	0.95	0.29	0.28	0.05	0.07	213	ND	99.92
	96[*3]	71.80	12.48	0.94	2.78	3.10	1.85	3.06	2.10	1.06	0.22	0.34	0.01	0.07	212	.154	99.81
	89	73.50	11.80	0.61	2.72	3.03	0.90	4.10	1.84	1.10	0.04	0.24	0.05	0.05	185	ND	99.98
	67a[*2,3]	82.00	9.34	1.06	1.42	0.72	0.46	0.88	2.14	1.04	0.19	0.66	0.04	0.10	48	.012	100.05
	67b[*2,3]	73.15	10.90	1.06	4.24	2.36	1.33	2.22	2.32	1.16	0.10	0.45	0.06	0.13	71	ND	99.42
	88[*3]	78.40	9.38	0.76	2.04	2.15	1.08	3.16	1.51	0.78	0.24	0.31	0.05	0.04	134	.071	99.90
	63[*]	77.50	9.38	1.13	2.34	2.98	2.15	1.60	1.29	0.99	0.15	0.24	0.02	0.11	185	.005	99.88
	55[*3]	74.80	10.63	0.74	1.98	2.98	2.23	3.10	1.56	1.11	0.76	0.23	0.05	0.07	152	.010	100.24
	49[*]	71.80	11.79	1.11	3.50	3.88	0.95	3.32	1.21	1.93	0.22	0.37	0.03	0.10	256	.083	100.21
	87[*4]	68.10	16.24	1.58	1.00	1.18	2.38	4.40	2.56	1.05	0.74	0.40	0.12	0.04	30	.047	99.79
ORTHOQUARTZITE	67c[*2,3]	84.10	10.04	0.27	0.28	0.27	0.13	0.51	2.78	1.21	0.12	0.22	0.02	0.01	10	ND	100.02
CONGLOMERATE MATRIX	66[*3]	74.80	7.36	0.68	3.60	2.75	3.75	1.68	1.62	1.03	2.25	0.17	0.12	0.16	356	ND	100.02
SILTSTONE	124	56.75	18.56	1.71	5.70	4.65	1.88	4.16	3.48	2.02	0.48	0.64	0.03	0.11	352	.102	100.17
TUFF	129	72.25	12.27	0.74	2.60	3.24	0.95	4.82	1.66	1.06	0.14	0.28	0.04	0.04	193	.055	99.50
SANDSTONE MEAN		73.96	11.15	0.93	2.55	2.91	1.67	3.17	1.77	1.07	0.28	0.28	0.06	0.08	163	.045	
STANDARD DEVIATION		4.39	2.31	0.24	0.80	0.87	1.20	1.07	0.59	0.26	0.29	0.13	0.05	0.03	71.2	.047	

Note:

1) Sandstone localities (Figure 5) numbered in relative lateral position from west to east.

2) Duplicate analyses at locality 129 and 67 represent different sandstone beds at that locality: Triplicate analyses at locality 120 represent 3 samples from the same bed; 120a -- fine-grained sandstone (top of bed)
120b -- medium-grained sandstone (middle of bed)
120c -- coarse-grained sandstone (bottom of bed)

3) All sandstone localities denoted by * have corresponding modal analyses in Table 7. Modal analyses were not performed on other samples because of a high degree of metamorphic recrystallization.

ND -- not detected

be recognized from variations in the type and distribution of internal sedimentary structures such as graded bedding, scour-and-fill structures, rip-up structures and bedding morphology. These include non-graded, chaotic, granule to cobble conglomerate; normally graded granule to pebble conglomerate; massive pebbly sandstones; massive sandstone graded only in the upper 10 percent of the bed; massive sandstone with grading and laminations in the upper 10 percent of the bed; graded beds that can be described using the Bouma (1962) model; interbedded silty shale and felsic tuff; and thinly laminated siltstone and very fine sandstone.

Lithology and Petrography

Conglomerate

Conglomerate in the Sandstone Member is predominantly pebbly conglomerate with a matrix content of 30-40 percent. It differs from that of the Conglomerate Member in the unusually high quartz content of the matrix (Table 6), and the higher percentage of felsic volcanic clasts.

1) Clast Types

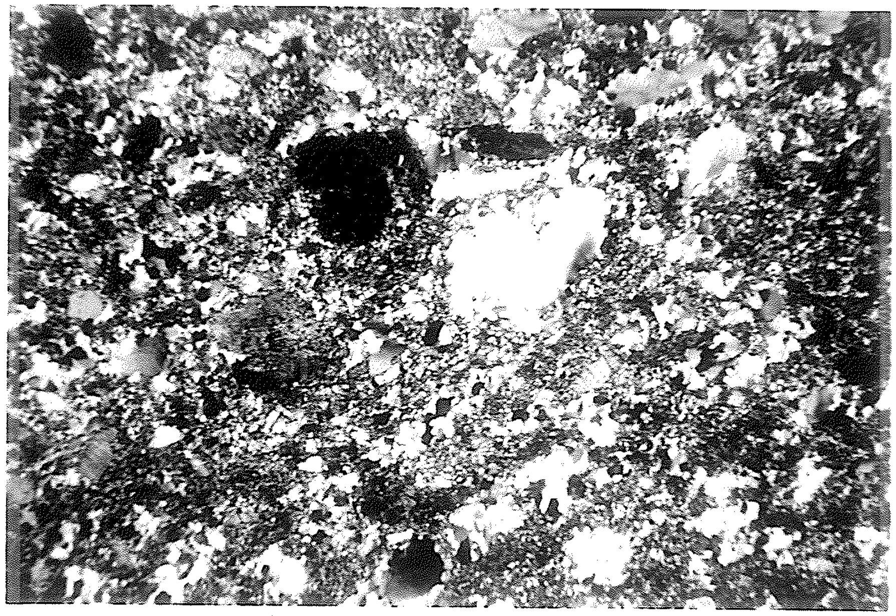
Clasts in the conglomerate, in order of importance are intermediate volcanic (20 percent), felsic volcanic (20 percent), felsic plutonic (15 percent), vein quartz (10 percent) and felsic subvolcanic (5 percent). The clast types are similar to those found in the Conglomerate Member and differ only in their relative proportions (Table 2).

2) Matrix

The conglomerate matrix is a coarse-grained lithic greywacke with a higher abundance of lithic fragments than the sandstones. The framework grains in the greywacke consist of quartz (approximately 10 percent), plagioclase (approximately 15 percent) and lithic fragments (approximately 15 percent). Potassium feldspar occurs only as an exsolved patchwork of poikilitically enclosed grains in plagioclase. The matrix forms approximately 30 percent of the greywacke.

The dominant framework constituent is subrounded quartz that ranges in diameter from 0.06-2.5 mm. The quartz grains have undulating extinction and consist of both monocrystalline grains and polycrystalline grains. Because the polycrystalline grains are associated with moderately undeformed monocrystalline grains, the polycrystalline grains presumably formed prior to incorporation in the greywacke and are not the result of in situ recrystallization. The polycrystalline grains are composed of quartz crystals from 0.5-1.0 mm in diameter. The effects of recrystallization on the conglomerate matrix are most noticeable in framework quartz grains. Original monocrystalline grains have been partly to completely recrystallized to a mosaic of similar grains. Similar framework grains have been completely recrystallized whereas the larger grains have marginal recrystallization (Figure 27). Recrystallization of monocrystalline grains can be distinguished from polycrystalline grains by the smaller grain size and equigranular texture of the recrystallized grains. The result of recrystallization of the framework quartz grains is an equigranular mosaic of quartz grains approximately 0.06 mm in diameter, which, under uncrossed polars, still retain the original grain shapes (Figure 27). Plagioclase grains are similar in size and shape to the quartz grains. The plagioclase is untwinned and ranges in composition from An_{12} to An_{28}. Lithic fragments are subangular to subrounded intermediate volcanic and subordinate felsic volcanic (Table 6, Figure 28). The intermediate volcanic fragments are deformed and recrystallized (Figure 28). The matrix is an equigranular mosaic of quartz and plagioclase with about 15 percent biotite and hornblende.

a)



Scale
1 mm

b)

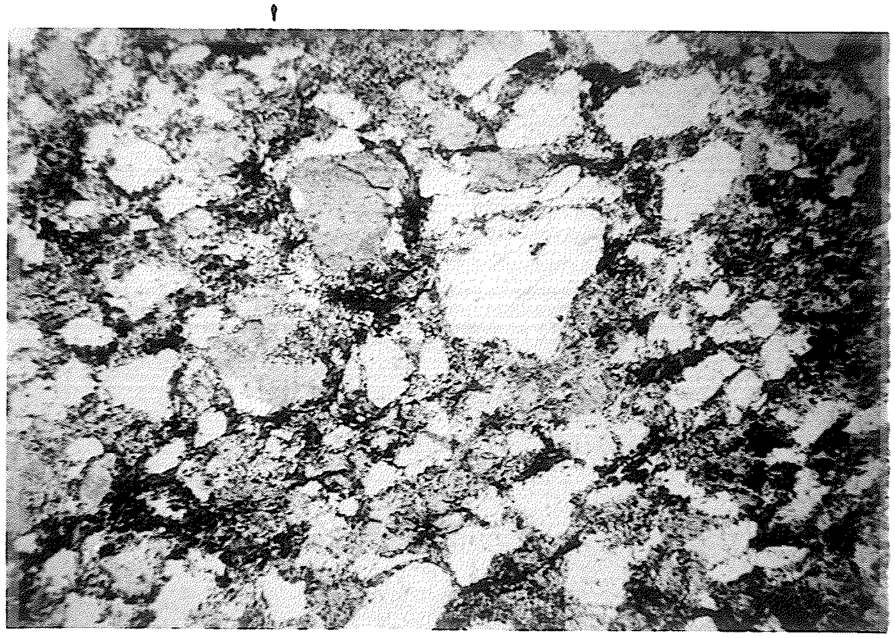
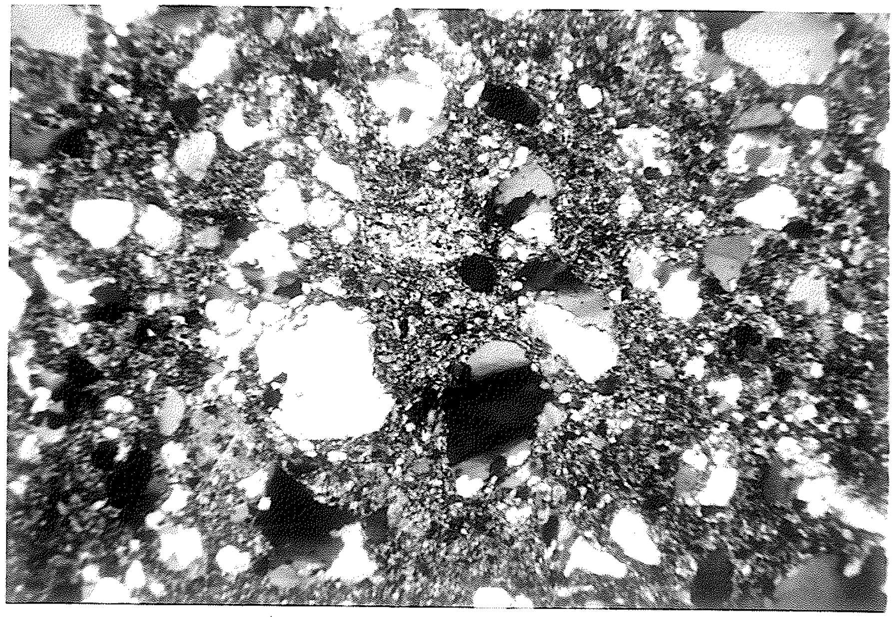


Figure 27: Partly recrystallized conglomerate matrix in sandstone member from locality 66. Some of the biotite clots that wrap around framework quartz and feldspar grains could be intermediate volcanic clasts. Nicols crossed in photo a) and uncrossed in photo b).



Scale
1 mm

Figure 28: Photomicrograph of sandstone from locality 144 showing possible embayed margins of some quartz grains in bottom third of photograph indicating a possible volcanic origin for these grains (nicols crossed).

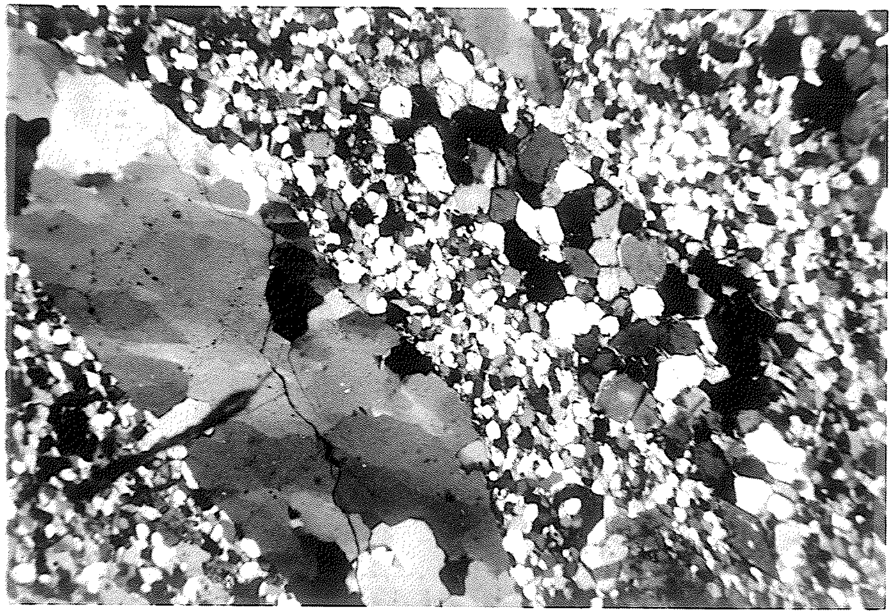
Sandstone

Sandstones are light grey to buff coloured in outcrop and are feldspathic greywacke and minor lithic greywacke (Table 6, Figure 6). The sandstones are moderately well sorted and have a bimodal texture with subangular to subrounded, 0.12-2.0 mm, framework grains of quartz (40 percent), plagioclase (13 percent) and lithic fragments (5 percent) in a matrix comprising 42 percent of the rock. About 30 percent of the sandstone is pebbly with rounded pebbles and granules either at the base of individual beds or irregularly distributed throughout the bed. Pebbles and granules include felsic volcanic (70 percent), vein quartz (20 percent) and felsic plutonic (10 percent) rock types.

The sandstone is characterized by a high quartz content. Subangular to rounded sand-size quartz forms up to 90 percent of the framework and averages 68 percent. The quartz grains include both polycrystalline aggregates (60 percent) of possible metamorphic origin and monocrystalline grains (40 percent) and 75 percent of both types have undulatory extinction. In areas of more intense recrystallization smaller grains have developed around the margins of primary grains although the original grain shape remains. Some monocrystalline grains (2-5 percent) lack wavy extinction and have emybayed outlines suggestive of a possible volcanic origin (Figure 28).

Framework plagioclase occurs as subangular to subrounded grains that lack twinning and are not zoned. The grains are invariably partly altered to fine-grained sericite, but primary compositions are preserved in the less recrystallized samples; the range in primary composition is An_{20} to An_{35}. In areas of more intensive recrystallization, the plagioclase is recrystallized to a mosaic of unaltered albite with albite twinning and rare exsolved potassium feldspar that pseudomorph the original grains.

Rock fragments are felsic volcanic (80 percent), vein quartz (15 percent), possible intermediate to mafic volcanic fragments (5 percent) and one possible orthoquartzite pebble. The felsic volcanic fragments are rounded and consist of a very fine-grained, recrystallized, equigranular mosaic of quartz and untwinned plagioclase, with about 2 percent biotite. The vein quartz fragments are rounded and consist of polycrystalline quartz with grains up to 3 mm in diameter with sutured grain boundaries and undulatory extinction (Figure 29). Intermediate volcanic fragments are an equigranular mosaic of fine-grained quartz, plagioclase and biotite (15 percent) (Figure 3). Possible mafic volcanic fragments are represented by concentrations of biotite (Figure 30). One possible fragment of orthoquartzite was found at locality 127 (Figure 5 and 29) and consists of 0.1-0.2 mm quartz grains that have straight grain boundaries with an equigranular texture (Figure 29). This fragment could also be recrystallized chert.



Scale
1 mm

Figure 29: Photomicrograph of fine-grained sandstone with a deformed vein quartz granule (left) and a clast composed of 100% polycrystalline quartz that may be an orthoquartzite fragment or recrystallized chert fragment. Locality 127 (nicols crossed).

a)

Scale
1 mm

b)

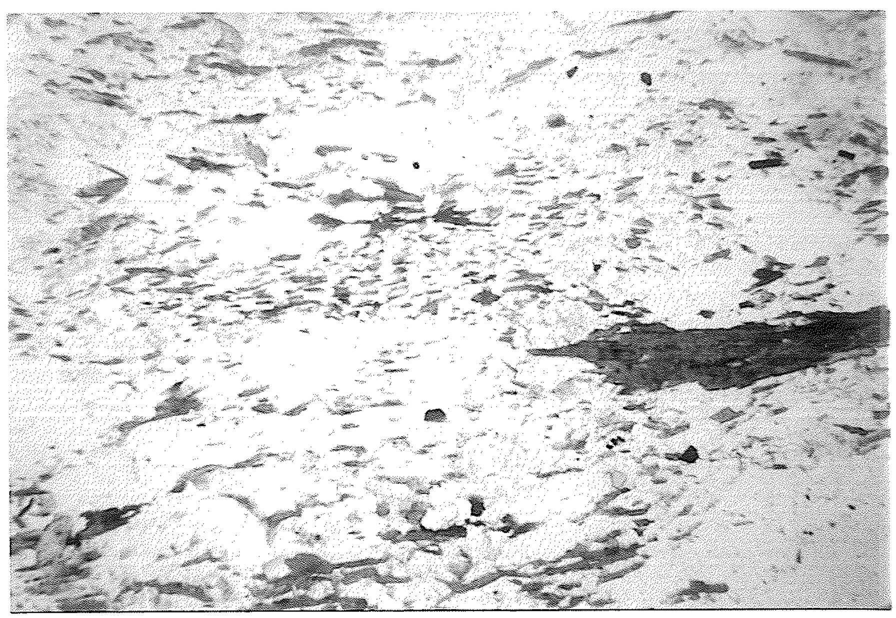


Figure 30: Photomicrograph of deformed sandstone from locality 120b showing biotite aggregate that might be a volcanic fragment (right center of photo) and intermediate volcanic fragment (center of photo). Nicols crossed in photo a) and uncrossed in photo b).

The matrix is an equigranular mosaic of 0.01-0.06 mm quartz and plagioclase with about 24 percent biotite. The biotite might be the metamorphic equivalent of an original clay constituent in the matrix. At the east end of the member chlorite and epidote locally replace biotite. Detrital zircon, apatite, sphene and Fe-Ti oxides are found in trace amounts. Calcite is found in trace amounts but at locality 124 (Figure 5), the sandstone contains 5 percent calcite as coarse anhedral grains in the matrix adjacent to sand-size rock fragments. Trace amounts of hornblende occurs locally as subhedral grains but at locality 120 (Figure 5), 11 percent hornblende is present and possibly represents recrystallized mafic fragments. Muscovite was identified only at locality 67 (Figure 5, 31) at the base of the member where 32 percent subhedral muscovite, defining a foliation, is present. The sandstone at this locality is pale green in color, and approximately 1.5 m thick and is classified as quartz greywacke.

In some sandstone beds there is a gradation upwards to siltstone. The siltstone is compositionally similar to the sandstones. Invariably the siltstone is recrystallized with an equigranular texture.

Siltstone and Shale

In addition to forming the upper parts of some graded sandstone beds, siltstone and shale form discrete beds

Figure 32: Highly deformed, laminated, silty shale at locality 69. Hammer handle is 3 cm wide and points to stratigraphic tops.

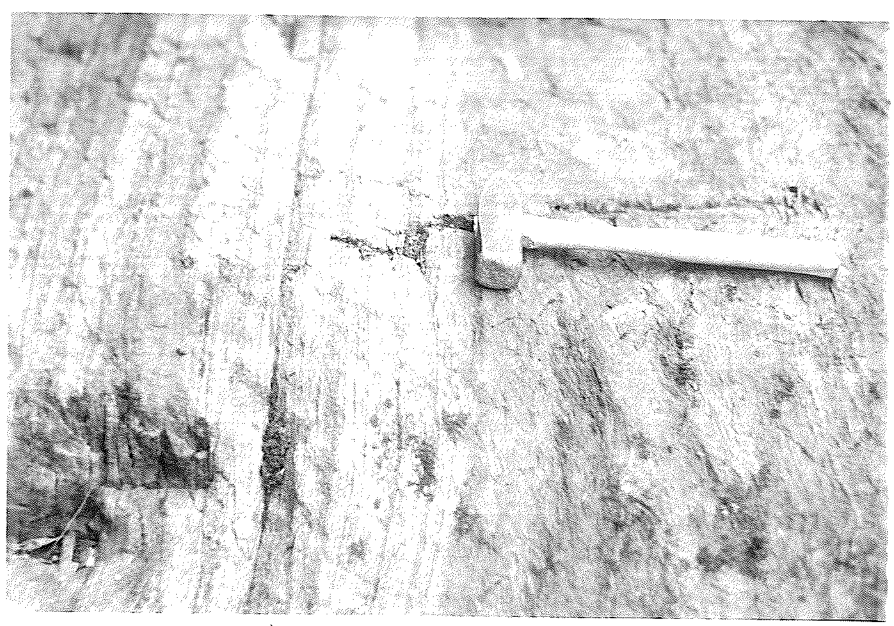


Figure 33: Interbedded felsic tuff (white) and shale (grey) from locality 67. Hammer handle is 30 cm long and points to stratigraphic tops.

interbedded with sandstone. Discrete siltstone beds are up to 2 cm thick and are interbedded with very fine sandstone and occasionally thinly laminated shale.

Shale is commonly associated with felsic tuff within the Sandstone Member where it forms 10 cm to 1 m thick units interbedded with the tuff. Shale forms a distinct unit near the base of the member at locality 69 and locality 60 at the far east end of the member (Figure 32). Shale at these localities forms a unit up to 10 m thick. In this section the shale is recrystallized and is composed almost entirely of biotite with 5 percent quartz plagioclase. Al locality 69 the shale contains 20 percent euhedral staurolite crystals up to 1 cm in diameter.

Felsic Tuff

Felsic tuffs and interbedded shale form 1-3 m thick units in the Sandstone Member (Figure 33). Tuff beds are 2-20 cm thick, weather white, and are distinguished from the sandstones by their relative lack of quartz and high content of plagioclase. Although no modal analyses were completed on the tuff, qualitatively, the tuff is composed of sand-size plagioclase (45 percent), quartz (15 percent) and felsic volcanic fragments (10 percent) in a matrix composed of quartz and plagioclase, which together occupy 20 percent, and muscovite (10 percent). The framework quartz grains are subangular and are monocrystalline grains. The framework plagioclase grains are subangular and partly altered to

Figure 32: Highly deformed, laminated, silty shale at locality 69. Hammer handle is 3 cm wide and points to stratigraphic tops.

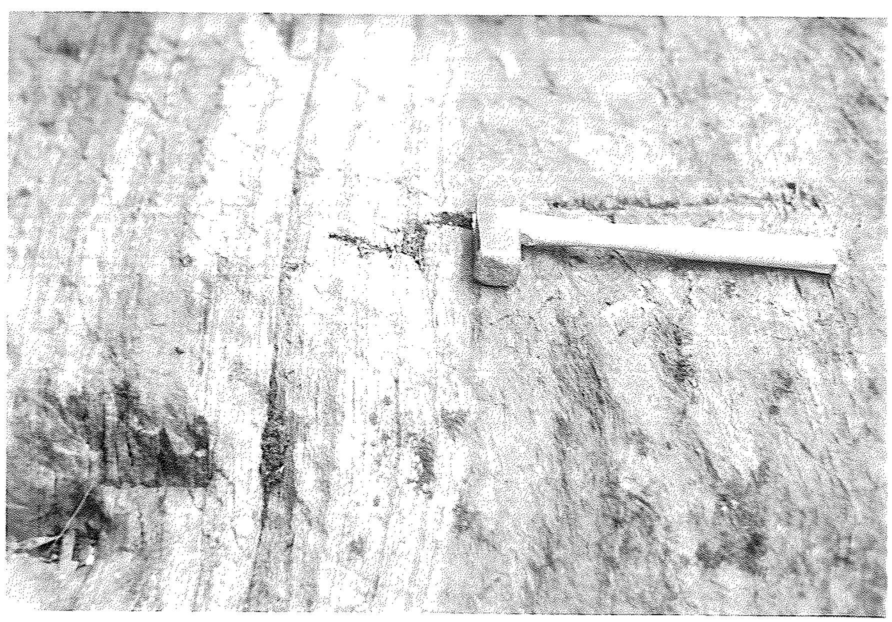


Figure 33: Interbedded felsic tuff (white) and shale (grey) from locality 67. Hammer handle is 30 cm long and points to stratigraphic tops.

sericite. The plagioclase is not zoned. The felsic volcanic fragments are fine-grained and subrounded.

Mafic Volcanics and Dikes

A medium to coarse-grained gabbro sill at least 4 km long and up to 175 m thick is found in the central part of the member (Figure 2). Stratigraphically above this sill in the sandstone are several thin concordant mafic units of uncertain origin that may be related to the larger gabbroic sill.

Description and Distribution of Bedding Types

Eight general bedding types could be recognized from the measured stratigraphic sections in the member.

1) Non-graded, chaotic, granule to cobble conglomerate beds that range in thickness from 10 cm to 1 m with an average thickness of 60 cm. They are restricted to the east end and form 4 percent of the member.

2) Normally graded granule to pebbly conglomerate beds that have laminations in the upper portion are 40-60 cm thick, and average 50 cm. These beds are also restricted to the east end and form 4 percent of the member.

3) Massive, pebbly sandstone beds that have pebbles distributed irregularly throughout, or restricted to the base of the bed (Figure 34), range in thickness from 70 cm to 2 m and average 1.5 m. The upper 10 percent of the bed is graded

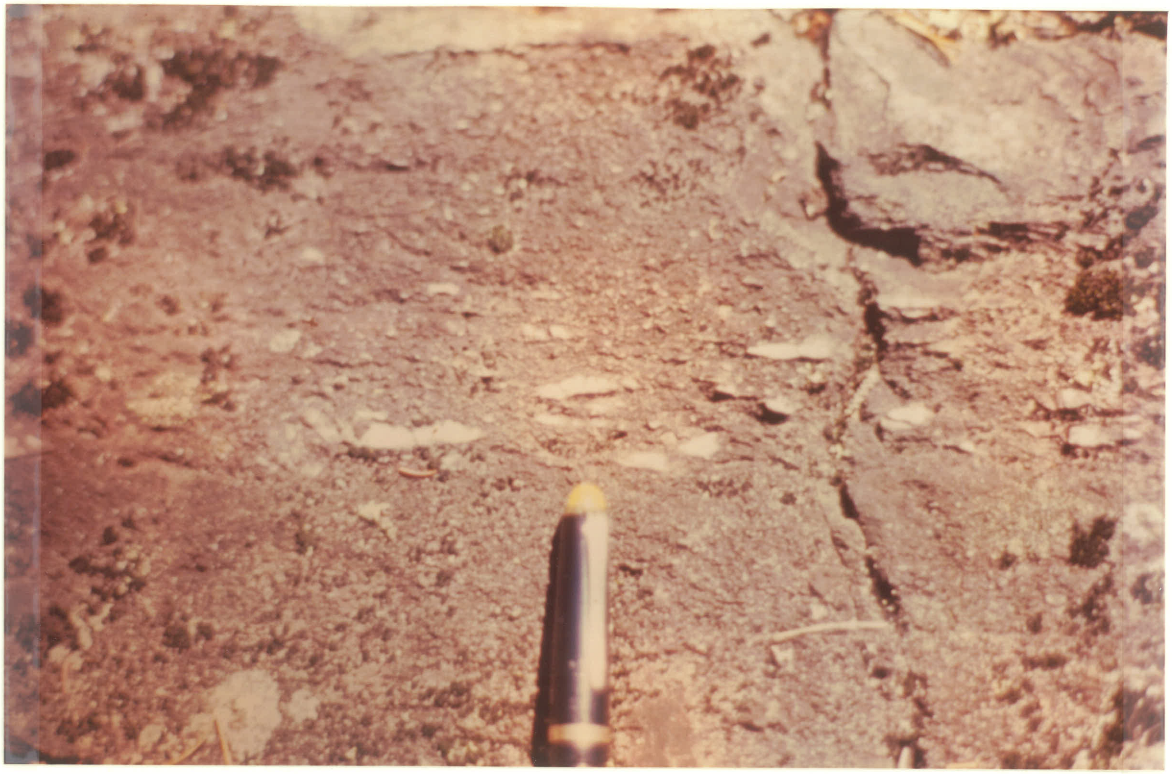


Figure 34: Felsic volcanic granules and pebbles at the base of Type 3 pebbly sandstone bed at locality 49. Top of pen is a bedding plane. Pen is 6 cm long and points to stratigraphic tops.

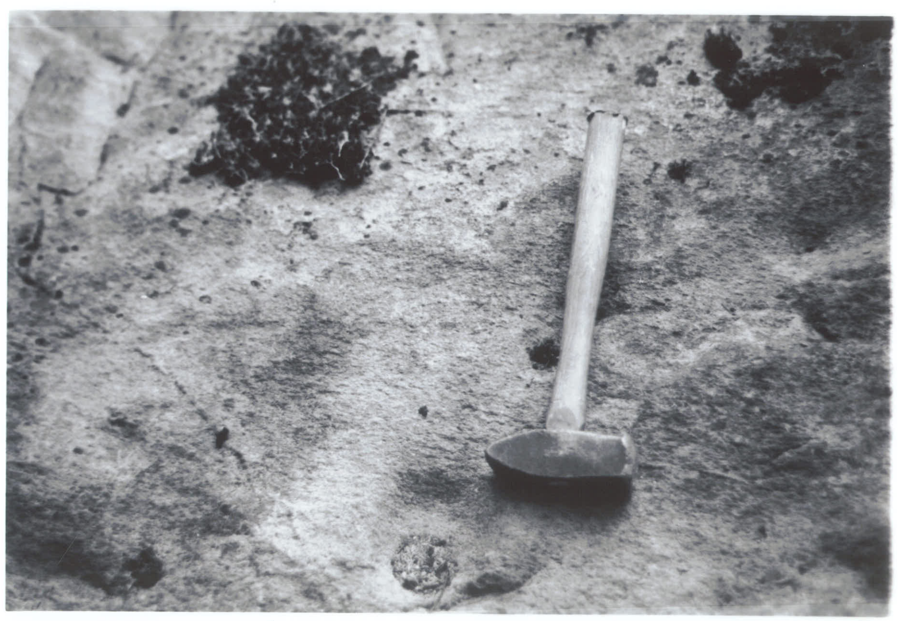


Figure 35: Massive thickly bedded sandstone at locality 20. Hammer handle is 30 cm long and points to stratigraphic tops.

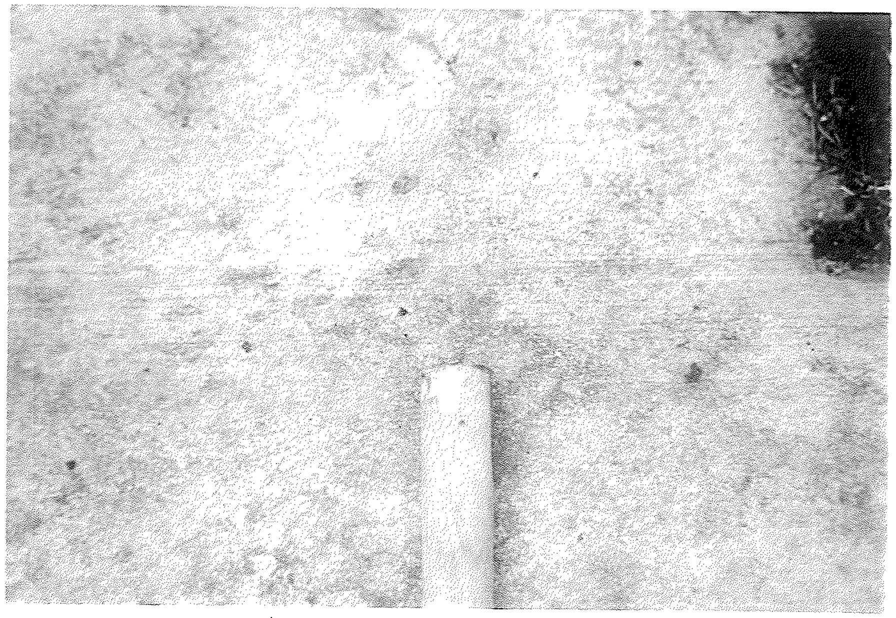
from coarse to fine sand, although locally, grading in this interval is absent. This bedding type forms 5 percent of the member but is mainly in the lower two thirds of the member.

4) Massive sandstone beds that lack grading and range in thickness from 10 cm to 2 m and average 50 cm (Figure 35). Bedding is indistinct and is defined by shaly laminae less than 1 mm thick. These beds are found mainly in the lower two thirds of the member and form 15 percent of the member.

5) Massive sandstone beds that are similar to type 4 beds, except for the presence of laminations and grading in the upper 10 percent of the bed (Figure 36), are found mainly in the lower two thirds of the member. They form 4 percent of the member and range in thickness from 40 cm to 3 m and average 1 m. Sedimentary structures such as shallow scouring and soft sediment deformation are well defined.

6) Beds that can be described using the Bouma (1962) model for turbidite deposition form 20 percent of the member and are found mainly in the upper part. Only Bouma A & AB sequences were observed; Bouma C, D and E intervals are apparently absent. Beds in the A interval are continuously graded from very coarse to fine sand, range in thickness from 2-60 cm, and average 20 cm. Locally, the A interval comprises a succession of graded beds that both thin, and become finer-grained upwards. Such successions have an average thickness of 40 cm (Figure 37). Bouma B intervals range from 1-10 cm thick and average 7 cm; they comprise laminated very fine sand to fine sand and silt.

a)



b)

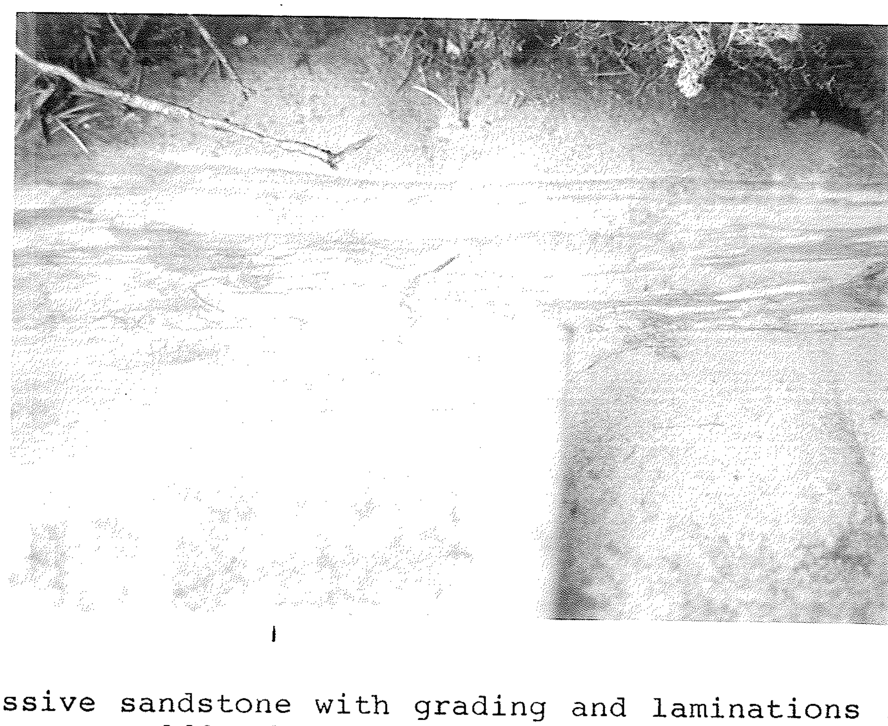


Figure 36: Massive sandstone with grading and laminations in the upper 10% of the bed at locality 120. Photo a) shows shallow scouring by the overlying sandstone. Photo b) shows soft sediment deformation. Hammer handle is 3 cm wide and points to stratigraphic tops.

Figure 37: Series of graded beds that thin and become finer upwards. Photo from locality 124. Hammer handle is 3 cm wide and points to the stratigraphic tops.

Figure 38: Interbedded felsic tuffs (white), shale (dark grey) with massive sandstone (light grey) at locality 112. Hammer handle is 24 cm long and points to stratigraphic tops.

7) Interbedded silty shale and tuff in beds 5 cm to 50 cm thick form sequences that range in thickness from 20 cm to 4 m and average 1 m. These beds are found mainly in the upper third of the member and form 6% (Figure 38).

8) Thinly laminated siltstone and very fine sandstsone that form sequences 10 to 60 cm thick and have an average thickness of 40 cm are found mainly in the upper third of the member and form 6% (Figure 39).

In general, there appears to be a systematic fining upwards sequence in the member with relatively coarse, thick bedded sandstones of types 3 to 5 mostly in the lower two thirds of the member and the relatively finer-grained and thinner bedded sandstones of types 6 to 8 mostly in the upper third of the member. In addition, the conglomerate of bedding types 1 and 2 are found only at the east end of the member and could imply a lateral fining of the member from east to west.

The most important characteristic of the bedding is the presence of grading. Graded bedding is recognized in fluvial environments, lacustrine environments (below storm wave base), and in submarine fans (Reineck and Singh, 1975). Graded bedding in fluvial environments is unusual and is restricted to areas of relatively quiet water (Reineck and Singh, 1975). In lacustrine environments graded beds are found in the delta front area of prograding deltas, but the graded beds lack laminations and other structures at the top of the bed and form only a small percentage of the total sediment (Reineck and Singh, 1975). Submarine fan deposits

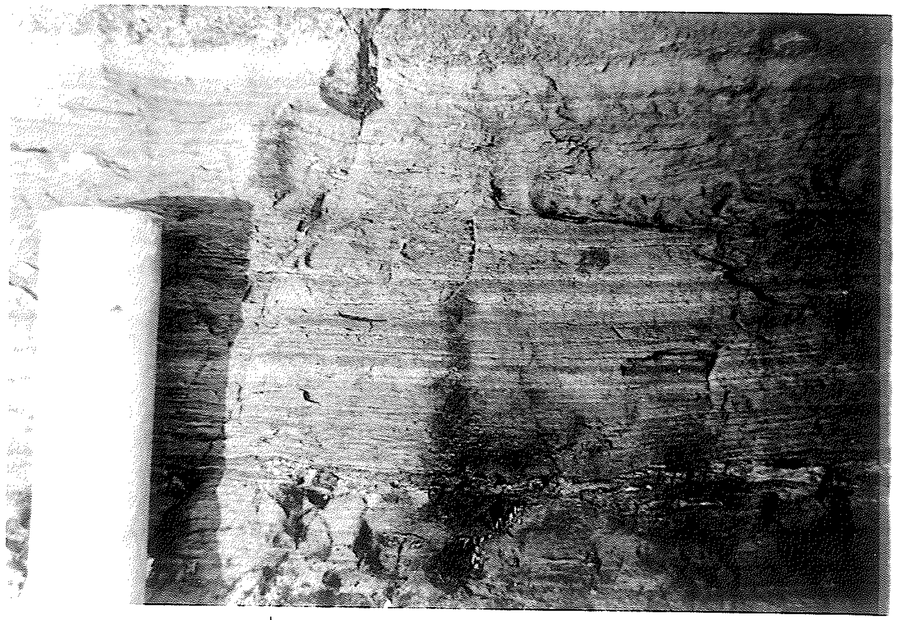


Figure 39: Thinnly to thickly laminated very fine sandstone and siltstone from locality 124. Hammer handle is 3 cm wide and points to stratigraphic tops.

are characterized by graded bedding and are formed by deposition from sediment-laden turbidity currents. To be preserved in the geologic record, trubidites must be deposited below storm-wave base and away from the influence of currents (Walker and Mutti, 1973).

The common occurrence of graded bedding in the sandstones and conglomerates, and the recognition of Bouma sequences in the Sandstone Member support turbidity currents as the main mechanism of sediment deposition. Such currents flow by gravity down a slope to a basin plain where a submarine fan is developed (Walker and Mutti, 1973). The morphology of an idealized slope-fan-basin floor system is shown in Figure 40. The fan is zoned and the zoning is characterized by various facies associations of bedding types reflecting changes in current flow velocity and confinement.

Bedding Types Compared to Submarine Fan Facies

The eight bedding types recognized in the Sandstone Member correspond to Facies A, B, C and G as defined by Walker and Mutti (1973) and related to submarine fan formation and morphology by Walker and Mutti (1973) and Walker (1978b) (Table 8).

These facies are as follows:

1) Facies A

This facies consists of thick beds, ranging in thickness from 1 to 10 m, of coarse-grained, pebbly

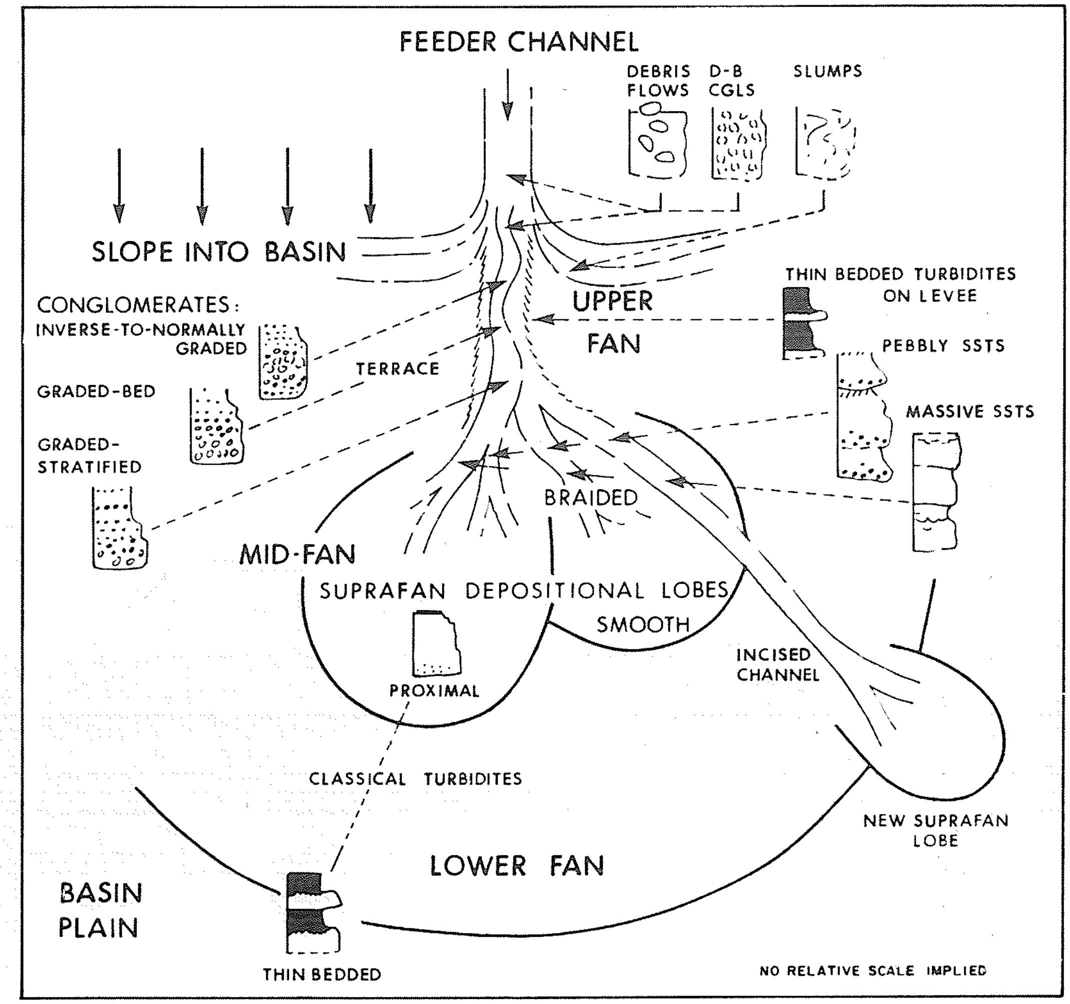


Figure 40: Model of submarine fan deposition, relating facies, fan morphology, and depositional environment (Walker, 1978).

TABLE 8 Comparison of bedding types in Sandstone Member with the turbidite facies classification proposed by Walker and Mutti (1973)

THIS STUDY	WALKER AND MUTTI (1973)		
Bedding types	Facies classification	Name	Mode of deposition
1	A1	disorganized conglomerate	debris flow
2	A2	organized conglomerate	turbulent, coarse sediment-laden flow
3 (in part)	A3	disorganized pebbly sandstone	poorly defined transport mechanism intermediate between slumps and turbidity currents
3 (in part)	A4	organized pebbly sandstone	
4 and 5	B2	massive sandstone	fluidized sediment or grain flow
6	C	classical turbidites	turbidity currents
7 and 8	G	interturbidite deposits	pelagic and hemipelagic deposition

sandstone and conglomerate. For purposes of description this facies can be divided into four subfacies.

A1 Disorganized Conglomerates are dominantly pebbly, cobble and boulder deposits that normally have a sandy matrix. Beds tend to be very irregular and lack internal stratification, graded bedding, preferred clast elongation and imbrication. Disorganized conglomerates are found in the main feeder channel to the submarine fan and the more proximal portion of the upper fan (Figure 40). This subfacies is similar to bedding type 1 in the Sandstone Member of Formation K.

A2 Organized Conglomerates are those conglomerates which have distinct sedimentary structures and/or fabrics such as graded bedding and crude internal stratification. There is an apparent lateral gradational sequence from disorganized conglomerates (A1) proximally to organized conglomerates more distally on the fan (Walker, 1978b). The organized conglomerates grade laterally from inverse to normally graded conglomerates proximally to normally graded conglomerates and graded stratified conglomerates more distally (Walker, 1978b). Organized conglomerates are found in the distal portion of the upper fan (Figure 40) but can extend to the braided channel portion of the mid-fan (Walker and Mutti, 1973). This subfacies is similar to type 2 normally graded conglomerates in the Sandstone Member.

A3 Disorganized Pebbly Sandstones are thick, irregularly bedded sandstones ranging in thickness from 50 cm to 10 m. These sandstones contain granules and pebbles irregularly distributed throughout the bed. Graded bedding is rarely developed. This subfacies is found in the proximal braided channel portion of the mid-fan and the distal portion of the upper fan (Walker and Mutti, 1973, Figure 40). The subfacies is similar to part of bedding type 3 of the Sandstone Member.

A4 Organized Pebbly Sandstones are characterized by graded bedding in beds 20 cm to 2 m thick. Internally, the graded beds may be stratified with the layering being shown by small changes in grain size in adjacent layers. Pebbles are distributed throughout the lower part of the bed. This subfacies is found in the proximal braided channel portion of the mid-fan and is locally developed in the depositional lobe portion of the distal mid-fan (Walker and Mutti, 1973; Walker, 1978b; Figure 40). Bedding type 3 of the Sandstone Member, in which pebbles are concentrated at the base of the bed and a crude stratification defined by grading occurs in the upper 10 percent of the bed, is similar in part to this subfacies.

2) Facies B

This facies consists of thick, lenticular, massive beds of medium-fine to coarse sandstones and has been divided into two subfacies.

B1 Massive Sandstones with "Dish" Structures consists of massive sandstones from 50 cm to 2 m thick with a pattern of faint dark lines that are arc-shaped and concave upwards and are termed "dish" structures. This subfacies is found in the distal portion of the braided channel part of the mid-fan (Walker and Mutti, 1973; Walker, 1978b, Figure 40). "Dish" structures were not found in the Sandstone Member.

B2 Massive Sandstone Without "Dish" Structures includes massive sandstones similar to subfacies B1 but lacking "dish" structures and ranging in thickness from a few tens of centimeters to 2 m. Beds are poorly defined and amalgamated with scouring at the base common. This subfacies is found in the distal portion of the braided channel part of the mid-fan (Walker and Mutti, 1973; Walker, 1978b; Figure 40). This subfacies is similar to bedding types 4 and 5 of the Sandstone Member.

3) Facies C

This facies contains classical turbidites which can be described by the Bouma sequence and in particular those turbidites which begin with Bouma's division A. These beds would be termed "classical" proximal turbidites by Walker (1967) and are sharply defined and flat-based. The sandstones range from 10 cm to 1 m in thickness. This facies is found in the depositional lobe portion of the mid-fan (Walker and Mutti, 1973, Walker 1978b; Figure 40). This facies is similar to bedding type 6 in the Sandstone Member.

4) Facies D

This Facies also contains classical turbidites which can be described using the Bouma sequence but in contrast to Facies C, the A division, and in many places the B division are missing. This facies is characterized by base cut-out sequences of the types BCDE, BDE or CDE. This facies is found in the distal portion of the depositional lobe part of the mid-fan and is the dominant facies type in the outer fan (Walker and Mutti, 1973; Walker 1978b; Figure 40). This facies was not found in the Sandstone Member.

5) Facies E

This facies is similar to Facies D but has 1) higher sand/shale ratios; 2) thinner, more irregular beds and 3) more discontinuous beds. This facies is interpreted to be related to overbank deposition along more or less confined channels (Walker and Mutti, 1973). This facies is found as levee deposits in the upper fan (Walker and Mutti, 1973; Figure 40). This facies was not found in the Sandstone Member.

6) Facies F

Facies F contains all beds that have undergone downslope mass movement after deposition and is characterized by chaotic bedding and ruptured and folded bedding. This facies is found in the feeder channel onto the fan and the proximal portion of the upper fan, and occurs as slump deposits and debris flows (Walker and Mutti, 1973; Figure 40). This facies was not found in the Sandstone Member.

7) Facies G

This facies consists of pelagic and hemipelagic, in part silty, shales and marls, with either indistinct and poorly developed laminations, or distinct, even parallel bedding. This facies is found 1) in the upper part of the feeder channel onto the fan, 2) between channels in the upper fan, 3) between depositional lobes of the mid-fan that have been temporarily removed from active turbidite deposition and 4) outer fan deposits interbedded with Facies D (Walker and Mutti, 1973; Figure 40). This facies is similar to bedding types 7 and 8 in the Sandstone Member.

Relation of Facies to Submarine Fan Morphology

As pointed out by Walker and Mutti (1973) and Walker (1978b), Facies A through G do not occur randomly in the stratigraphic record. Some facies are spatially related to form facies associations which correspond to specific depositional environments on a submarine fan. Figure 40 shows the relationship of fan morphology and depositional facies. The following facies associations have been described by Walker and Mutti (1973) and Walker (1978b).

1. Feeder Channel Facies Association

Morphologically, this association included deposits of the slope into the basin and the deposits of major channels or canyons incised into the slope (Figure 40). The submarine channels and canyons may be plugged by either coarse materials (slumps, debris flows, conglomerates) or by very fine material (clays, mudstones). The upper part of the slope is characterized by facies G (pelagic and hemipelagic muds), whereas the lower slope commonly contains channels filled by the various Facies A lithologies (pebbly sandstones and conglomerates). The instability of the slope is reflected by the common occurrence of slumped or chaotic beds of Facies F. In a prograding fan, this facies association may show a vertical facies sequence of thinning and fining-upward beds (Walker and Mutti, 1973).

2. Upper Inner Fan Facies Association

The upper fan is characterized by a single channel that may be aggrading, with levees, or entrenched with erosive walls (Figure 40). The facies association of the channel deposits includes the various lithologies of Facies A, with B2 and perhaps B1, together with levee deposits of Facies E. The entire channelized complex is enclosed by muds of Facies G. In a prograding submarine fan a vertical facies sequence of thinning and fining-upwards beds is proposed for this facies association (Walker and Mutti, 1973).

3. Middle Fan Channeled Association

This facies association is found in the proximal portion of the mid-fan (Figure 40) and is characterized by abundant braided channels. The facies in this association are mainly coarse to braided channels (Facies C, with some A and B), and finer in the interchannel areas (Facies D and E). In a prograding fan (Walker and Mutti, 1973) deposits of channels in this association can be recognized by a thinning and fining-upwards sequence of beds.

4. Middle Fan Depositional Lobe Association

This facies association is found distally in the sparsely channeled distal portion of the mid-fan (Figure 40).

The dominant facies present are D and C, with possible development of Facies B2 and A4. Channeling is not important and individual beds tend to be more continuous laterally. In a prograding fan this association would be characterized by a thickening and coarsening-upward sequence of beds (Walker and Mutti, 1973).

5. Outer Lower Fan Association

The lower fan is the portion of the fan transitional from the convex upward middle fan to the flat basin floor (Figure 40). The lower fan is not channeled and receives the deposits of thin, broad flows. The dominant facies is D in the active portion of the lower fan and Facies G in the inactive portion. In a prograding fan the facies association would be characterized by a thickening upwards vertical sequence of beds (Walker and Mutti, 1973).

6. Basin Plain Association

Deposits of the flat basin floor (Figure 40) are typified by slow hemipelagic deposition of Facies G interrupted periodically by tubidity currents of Facies D. No facies sequence have been proposed for this association.

Facies Associations of Bedding Types

Of the relevent facies and subfacies defined by Walker and Mutti (1973) only Facies A1, A2, A3, A4, B2, C and G were recognized in the Sandstone Member (Table 8). The seven facies and subfacies occur throughout the member but their distribution is not random. Accordingly four distinct facies associations can be defined (Figure 2), each of which is characterized by one or two of Walker and Mutti's facies and subfacies (Table 9).

Association 1 (Figure 41) This is the dominant association in the member. Facies B and C are interbedded and together comprise 90 percent of the beds and 85 percent of the total thickness (Table 9). The interbedding of proximal turbidites of Facies C with channel-fill deposits of Facies B represent a middle fan channeled association as defined by Walker and Mutti (1973). The coarser channel-fill deposits of Facies A which are a relatively minor component of the association are consistent with this interpretation. The finer deposits of Facies G may represent periodic abandonment of channels and filling by pelagic and hemipelagic units.

Association 2 (Figure 42) This association forms the upper part of the member and is dominated by Facies C which forms 70% of the total thickness and 75% of the beds (Table 9). The interbedding of even, horizontal beds of Facies C with Facies A and B, which together occupy only 15% of the association, is consistent with the depositional lobe part of the mid-fan (Walker and Mutti, 1973). Facies G is also present in small amounts and represents periodic abandonment of channels and of depositional lobes on the fan.

Association 3 (Figure 43) This association forms local lenses characterized by channel deposits of Facies B with moderate proportions of both Facies C and G (Table 9).

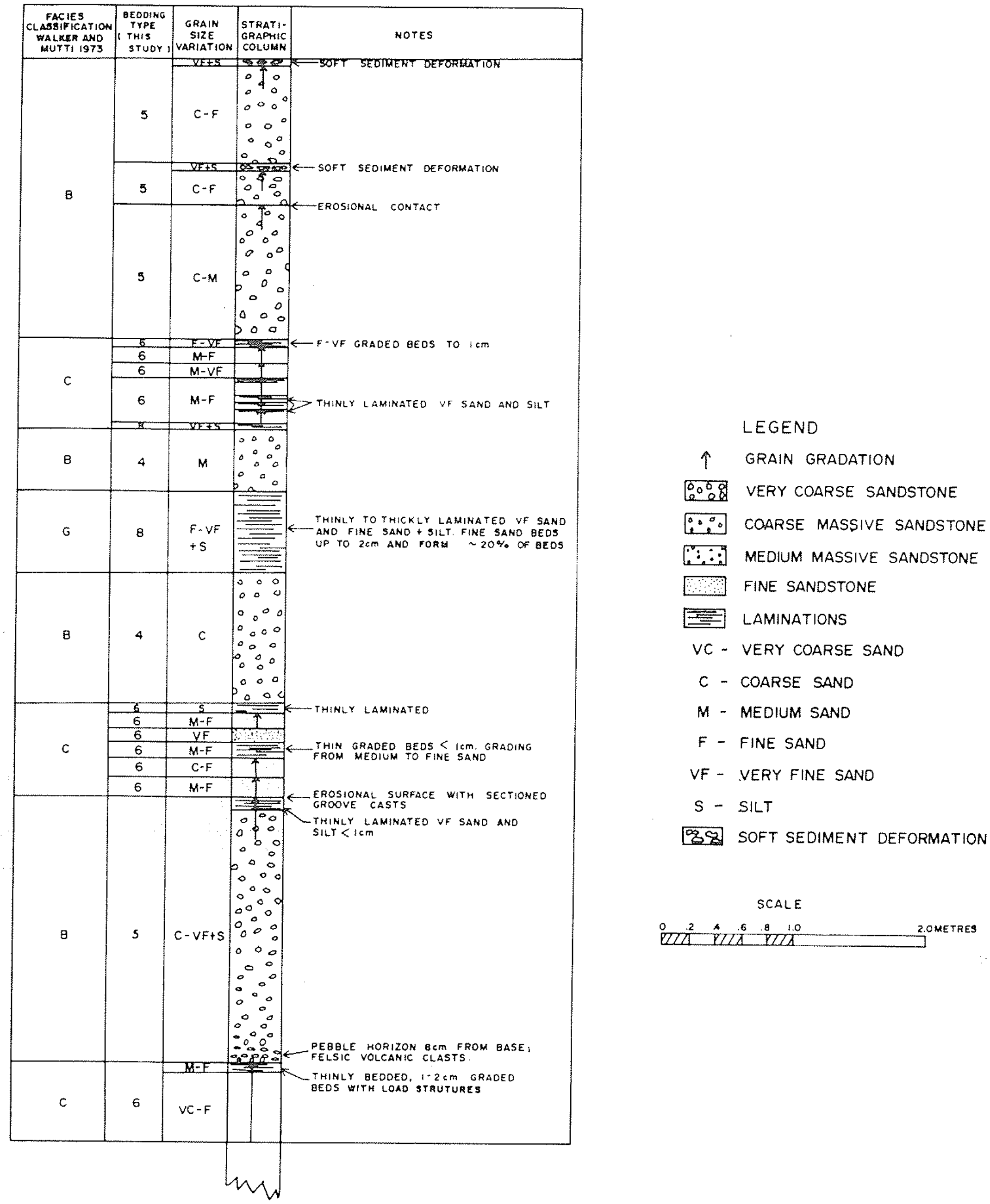


Figure 41: Association 1 Facies Association from Locality 120 in the Sandstone Member.

TABLE 9 Facies associations in Sandstone Member. The groups were defined spatially on Figure 2 by concentrations of a bedding type or an association of types in both the measured stratigraphic sections and other outcrops.

A) The proportions of beds were calculated from the stratigraphic sections within each group

Facies association	Turbidite Fan interpretation	Proportion of beds (Table 8) in stratigraphic Section 1,2,3	4,5	6	7,8
Association 1	channel deposits of middle fan	5	30	75	5
Association 2	depositional lobes on middle fan	5	10	75	10
Association 3	intermittent channel on middle fan depositional lobe	8	64	13	15
Association 4	channel deposits of upper fan	50	22	25	3
	Facies Classification (Walker and Mutti, 1973)	Facies A	Facies B	Facies C	Facies G

B) The percent thickness of beds was calculated from the stratigraphic sections within each group

Percent thickness of bedding types (Table 8) in stratigraphic Sections 1,2,3	4,5	6	7,8
3	60	25	12
5	10	70	15
20	50	10	20
55	20	15	10
Facies A	Facies B	Facies C	Facies G

Facies classification (Walker and Mutti, 1973)

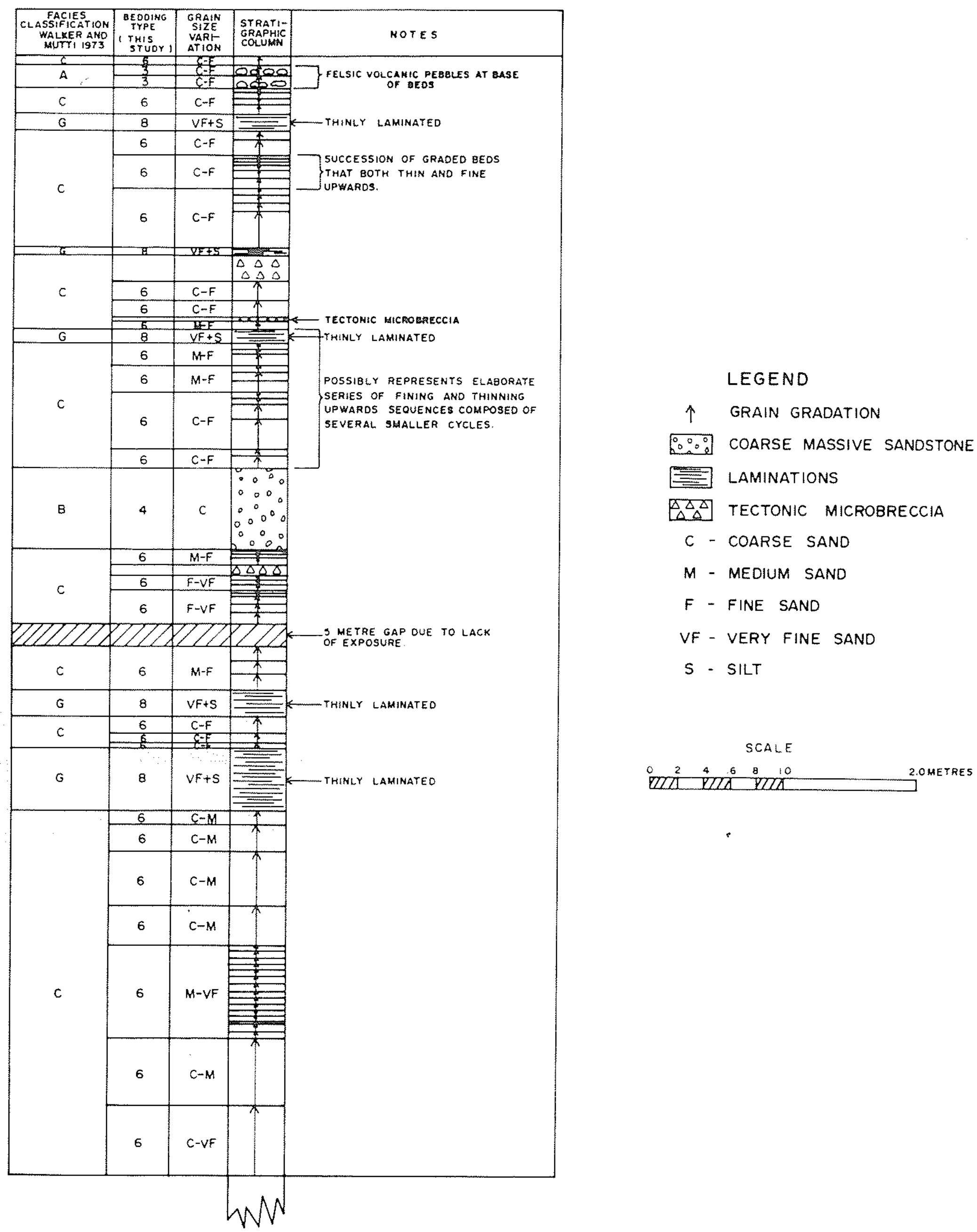
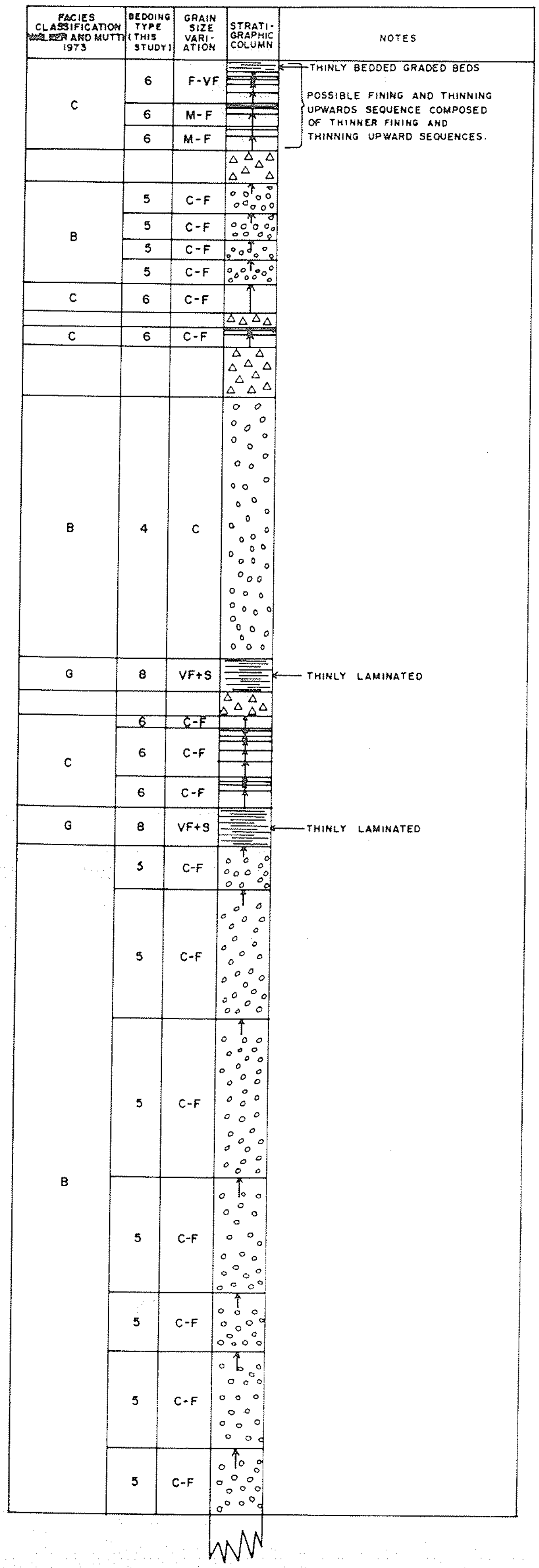


Figure 42: Association 2 Facies Association from Locality 96 in the Sandstone Member.



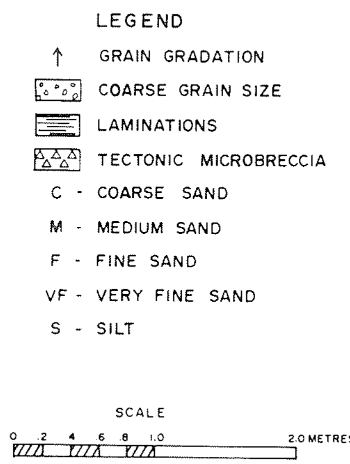


Figure 43: Association 3 Facies Association from Locality 112 in the Sandstone Member.

Facies C forms 10 percent of the association and 13 percent of the beds present whereas Facies G forms 20 percent of the association and 15 percent of the beds. This association contains a higher proportion of Facies G than the other facies associations, and this suggests longer and more frequent abandonment allowing deposition of shale and minor tuff beds. The distribution and thickness of Facies G units in the section suggests more frequent abandonment as the most likely reason for the higher proportion of Facies G in this association. Although Facies A forms 20% of the total thickness it represents only 8% of the beds present. This may indicate thicker than average Facies A beds or thinner than average Facies B beds in the association. Comparison of bed thicknesses of Facies B in this association with those in other associations suggests that the lower proportion of Facies A beds represent thicker than average beds.

Association 3 does not fit any of the facies associations defined by Walker and Mutti (1973). Walker (1978b), however, indicated that local incised channels could develop in the mid-fan area from larger or coarser than average turbidity currents. These channels, which would result in deposition of Facies B sandstone distally and pebbly sandstones of Facies A proximally, fed more distal depositional lobes in the outer fan area. The lenticular nature of this Association 3 and the high proportion of Facies B suggests that this association could represent incised channels in the mid-fan area of a submarine fan.

Facies A would represent larger than average flows in the channel and classical turbidites of Facies C could represent a break in sedimentation within the channel and resumption of deposition of the mid-fan deposition lobe. Facies G deposition would also represent a break in sedimentation and deposition of pelagic and hemipelagic sediments. The incised channels were eventually covered by reactivation and deposition of the mid-fan in this area.

Association 4 (Figure 44) This association is restricted to the east end of the member and is characterized by a high proportion of Facies A which forms 55 percent of the association and 50 percent of the beds (Table 9). Facies B and C form 35 percent of the association and 47 percent of the beds, but Facies G is relatively minor, forming 10 percent of the association and only 3 percent of the beds. This association compares with the upper fan association of Walker and Mutti (1973). Facies C could represent deposition in the channels from a waning current and Facies G could represent deposition in the channels of pelagic and hemipelagic sediment following periodic channel abandonment.

Depositional Environment

The Sandstone Member is a vertical section through a turbidite fan. The distribution of the facies associations, and the environments of deposition they represent, is not random but defines the development, with time, of a turbidite

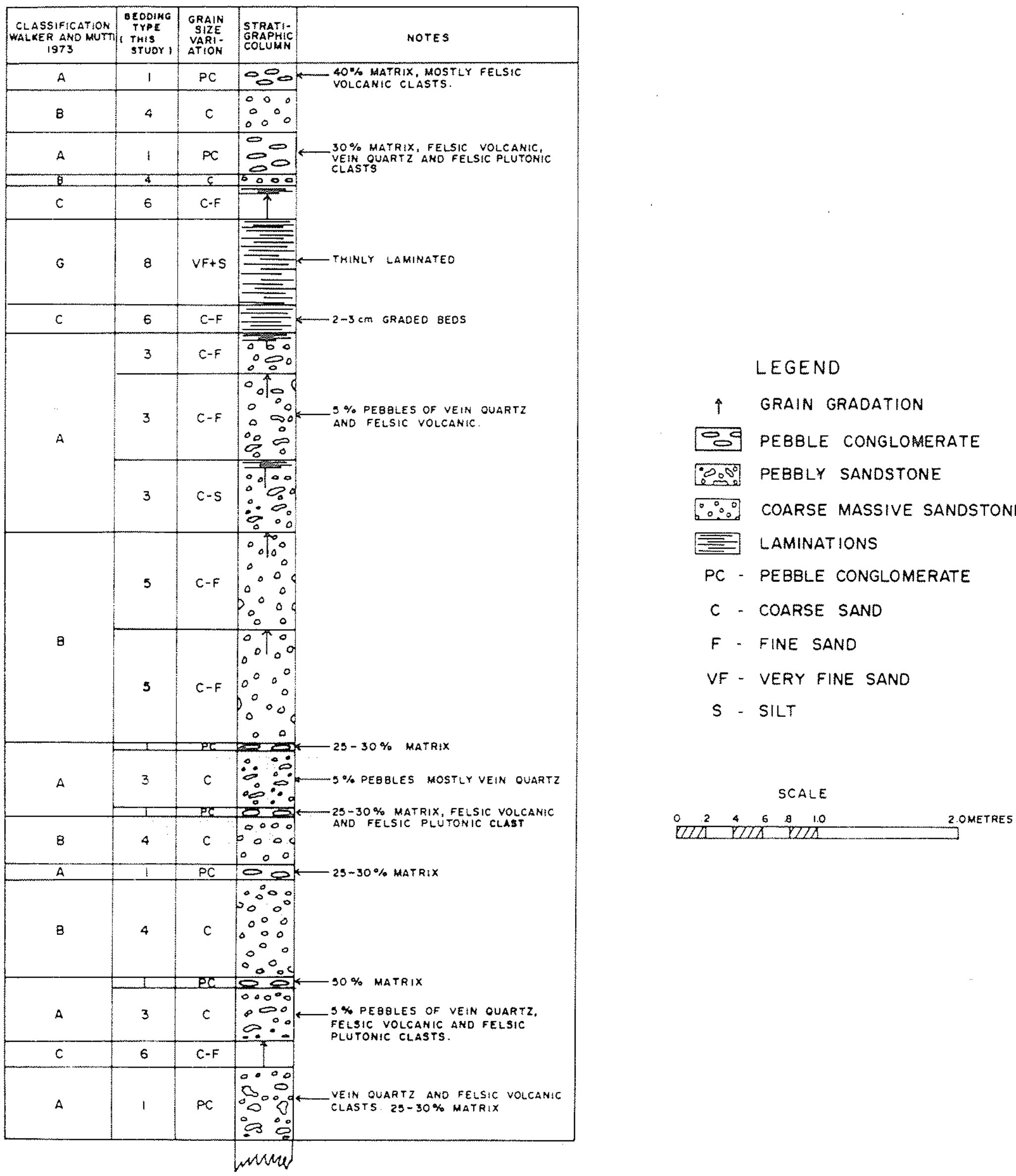


Figure 44: Association 4 Facies Association from Locality 63 in Sandstone Member

fan that was initially prograding but was retrograding in its later stages.

A turbidite fan can be either prograding or retrograding depending of the relative rates of sedimentation into the basin and basin subsidence. In a prograding fan the rate of sedimentation is faster than the rate of basin subsidence. A vertical section through such a fan would show an upward transition from lower fan through middle to upper fan deposits. In a retrograding fan the rate of basin subsidence is faster than the rate of sedimentation into the basin. A vertical section through a retrograding fan would show an upward transition from the upper fan through the middle fan to lower fan deposits.

In the Sandstone Member the lower 300 to 500 m is poorly exposed, except at locality 66-67, west of the northeast-trending fault. Where the lower part is exposed, channeled middle fan deposits of Association 1 are in close proximity (within 200 m) of the underlying conglomerates of the Conglomerate Member and basalts of Formation J with no apparent upper fan deposits of Association 4. The prograding or retrograding nature of the fan in the lower part is impossible to determine due to the lack of exposure. At the top of the lower section at locality 67 quartz greywacke is overlain by shale. This could represent a local break in sedimentary supply to the basin during which mechanical and chemical weathering of the sediment may have resulted in the upgrading of the sediment, with respect to sand-size quartz, prior to deposition. The shale would represent a period of relative quiescence in the basin with deposition of pelagic and hemipelagic mud. In the well exposed upper two thirds of the member there is an upward transition from more proximal channeled middle fan deposits of Association 1 to more distal depositional lobes of the middle fan (Association 2) which are locally channeled by Association 3. This distribution of facies is consistent with that of a retrograding fan.

At the east end of the member a wedge-shaped unit of the upper fan channeled association (Association 4) is bounded to the east by the northeast-trending fault. This upper fan association is overlain and underlain by middle fan channeled deposits of Association 1. This stratigraphic relationship may represent the initial development of a prograding fan which was succeeded upward by a retrograding fan; the relative apex of the fan would be to the east. The transition between a prograding and a retrograding fan at this locality would be about two thirds up the sequence in the middle fan channeled association.

Although there is very little offset of formation boundaries along the northeast-trending fault there is an apparent break in stratigraphy in the Sandstone Member across the fault. East of the fault there is an upward transition from middle fan channeled deposits of Association 1 to upper fan channeled deposits of Association 4 representing a prograding fan. The eastward wedging out of Association 1 and the apparent dominance of Association 4 further east indicates that the relative apex of the fan is to the east.

Predominantly vertical motion, relative to the present erosional surface, along the fault could have placed different portions of a submarine fan in apparent formational stratigraphic continuity. Vertical movement does not appear to have been excessive, because stratigraphically similar sediments are traceable across the fault at the top of the member. lateral grain-size variations in the Sandstone Member are not apparent except for the presence of conglomerate at the east end of the member only.

In summary, the Sandstone Member represents a subaqueous turbidite fan with its relative apex to the east. The distribution of facies associations indicates a prograding fan in the middle of the member grading upwards to a retrograding fan at the top of the member. There is an apparent break in sedimentation towards the base of the member at locality 66-67 with an intervening period of quiescence marked by the deposition of quartz greywacke and shale. Assuming the basin was continuously subsiding this would indicate a faster rate of deposition in the middle of the member, than at the top of the member.

Chemistry

Although sandstones of the Sandstone Member generally have chemically anomalously high SiO_2 and sand-size quartz contents there is a wide range in compositions. Chemically (Table 7) SiO_2 contents range from 63 to 84 percent and averages 74 percent whereas modally (Table 6) the sand-size quartz content ranges from 29 to 64 percent and averages 40 percent. This compositional variance shows up both between individual beds at the same locality, as shown by samples at locality 67 (Table 6 and 7) and within individual beds, as shown by samples from the same bed at locality 120 (Table 6 and 7). Three separate sandstone bed samples at locality 67 have modal sand-size quartz contents that range from 43 to 64 percent and SiO_2 contents that range from 73 to 84 percent. At locality 120 three samples taken from the base, middle and top of a graded bed, 0.7 m thick, have modal sand-size quartz contents that range from 36 to 51 percent and chemically have SiO_2 contents that range from 70 to 78 percent. At this locality there is an upward increase in both sand-size quartz and SiO_2 contents with the highest sand-size quartz and SiO_2 contents being in the fine-grained upper portion of the graded bed. This implies that detrital quartz grains in the source area were dominantly fine sand.

Sandstones of the Conglomerate Member differ chemically from those of the Sandstone Member (Table 10) in lower contents of SiO_2, Na_2O and K_2O but higher contents of FeO, Fe_2O_3, MgO and CaO. Modally these chemical differences are reflected by higher contents of biotite and sand-size quartz and plagioclase in sandstones of the

TABLE 10: Chemical Compositions of Formation K Sandstones Compared to other Sandstones

OXIDES	A	B	C	D
SiO_2	73.96	61.50	83.90	69.83
TiO_2	0.28	0.35	0.30	0.54
Al_2O_3	11.15	11.23	8.10	14.20
FeO	2.55	6.63	3.00	3.99
Fe_2O_3	0.93	1.50		0.44
MnO	0.08	0.26	0.10	
MgO	2.91	5.65	1.30	2.41
CaO	1.67	7.33	1.80	1.81
Na_2O	3.17	2.01	0.50	2.80
K_2O	1.77	1.06	0.90	1.70
H_2O	1.07	1.32		1.69
P_2O_5	0.06	0.07		0.11
CO_2	0.28	0.08		0.10
TOTAL	99.92	99.29	99.9	99.69

A Feldspathic greywacke from the Sandstone Member of Formation K (mean of 21 samples)

B Lithic greywacke from the Conglomerate Member of Formation K (mean of 3 partly altered samples)

C Archean quartz-rich greywacke, North Spirit Lake, northwestern Ontario (mean of samples 1 and 2, Table III Donaldson and Jackson, 1965)

D Archean metagreywacke, Gamitagama Lake greenstone belt, Lake Superior Park, Ontario (mean of samples 2, 7 and 8, Table 7, Ayres, ms).

Sandstone Member, and the high hornblende and diopside contents of the sandstone of the Conglomerate Member. Quartz-rich sandstones in the North Spirit Lake area (Donaldson and Jackson, 1965) described as being derived from a mixed granitoid-sedimentary source terrain, differ from those of the Sandstone Member by having higher SiO_2 contents and lower Al_2O_3, total Fe, MgO, Na_2O and K_2O contents (Table 10).

The lower SiO_2 content and higher K_2O and Al_2O_3 contents of Formation K Sandstone Member sandstones is reflected modally by lower sand-size quartz and higher sand-size plagioclase contents relative to the North Spirit Lake sandstones (Table 11).

More typical greenstone-belt sandstones have lower quartz contents. This is shown by comparison with sandstones from the Gamitagama Lake area of northern Ontario (Ayres, manuscript) which are described as being derived from a predominantly felsic volcanic source terrain. Gamitagama Lake sandstones differ from those of the Sandstone Member by having lower SiO_2, MgO and Na_2O and higher Al_2O_3, CaO, and total Fe (Table 10). The higher SiO_2 content of the Sandstone Member is reflected by its markedly higher sand-size quartz contents (Table 11). The higher Al_2O_3, CaO and Fe and lower Na_2O contents of the Gamitagama Lake sandstones is reflected by their higher content of matrix and more calcic plagioclase.

TABLE 11 Modal Analyses of Formation K Compared to Other Sandstones

Component	A	B	C	D
Sand-size Quartz	40.1	35.4	54.3	19.1
Sand-Size Plagioclase	13.5	12.6	.86	17.2
Sand-Size Potassium Feldspar	trace	2.7		trace
Matrix	12.2		44.85	37.7
Rock Fragments	4.7	7.9		2.3
Biotite	12.5	6.5		15.0
Hornblende	trace	24.3		
Diopside		5.4		
Chlorite	trace			
Sphene	trace	.6		4.6
Fe-Ti Oxides	trace	.4		1.13
Apatite	trace			trace
Zircon	trace			trace
Carbonate	trace			
Epidote	trace			
Muscovite	trace			

A Feldspathic greywacke from the Sandstone Member of Formation K (mean of 19 samples).

B Lithic greywacke from the Conglomerate Member of Formation K. (mean of 3 partly altered samples).

C Quartz-rich greywacke, North Spirit Lake, northwestern Ontario (mean of samples 1 and 2, Table II, Donaldson and Jackson, 1965).

D Mean of Archean greywacke samples 2, 7, and 8, Table 3 from Ayres (ms).

Provenance

If the Sandstone Member is a turbidite fan with its relative apex to the east the provenance should also be to the east. Clasts in the conglomerate at the east end of the member are, in order of importance, intermediate volcanic, felsic volcanic, felsic plutonic, vein quartz and felsic subvolcanic. This represents a mixed felsic-intermediate volcanic terrain with some subvolcanic and deeper seated plutons. This requires erosion of older volcanoes, not just transport of unconsolidated volcanic products that are continually being replenished. Intermediate volcanic clasts are subrounded whereas the other clasts are rounded, and this suggests a relatively more proximal source for the intermediate volcanic clasts and a more distal source for the felsic plutonic, vein quartz and felsic subvolcanic clasts.

A variety of source terrains have been postulated for Archean sedimentary sequences. The source of the high contents of quartz sand in Archean greywackes and arenites in the North Spirit Lake area has been ascribed by Donaldson and Jackson (1965) to a combined granitoid and sedimentary source area. This was corroborated by the discovery of orthoquartzite pebbles in the conglomerates (Donaldson and Ojakangas, 1977). Walker and Pettijohn (1971) and Pettijohn (1972) concluded that a sialic plutonic source was necessary for pebbly arenites near Sioux Lookout, Ontario. Some Archean greywackes of other volcanic-sedimentary sequences of the shield have had volcanogenic sources (Ayres, 1969; Ojakangas, 1972 a, b) or mixed granitoid-volcanic sources (Henderson 1972). In the volcanogenic Knife Lake Group of Minnesota Ojakanagas (1972 a, b) showed that the source of minor felsic plutonic detritus was a coeval pluton rather than a cratonic source.

Ayres (manuscript) suggested that erosion of ash flow tuffs produced in Plinian eruptions of silicic rhyodacite and rhyolite composition could explain the moderate quartz sand enrichment in greywackes of the Gamitagama Lake area, Ontario. A plutonic-metamorphic cratonic provenance was a subsidiary source.

In the Sandstone Member of Formation K, clasts found in the conglomerate and sandstones indicate that the following possible source rocks must be considered:

a) Intermediate volcanoes

b) Felsic subvolcanic plutons

c) Felsic plutonic

d) Quartz veins

e) Felsic volcanoes

f) Older sedimentary rocks

Intermediate volcanic clasts are abundant in the conglomerates at the east end of the member but are a relatively unimportant component of the pebbly sandstones. The clasts are fine-grained and aphyric and thus intermediate volcanoes could not have supplied the sand-size quartz grains.

Felsic subvolcanic clasts are medium-grained and contain up to 5 percent, 0.5-4 mm quartz phenocrysts. Erosion of subvolcanic plutons could produce sand-size quartz grains.

Felsic plutonic clasts are porphyritic with up to 25 percent, 2-5 mm quartz pheoncrysts. A crustal remnant of a similar composition has been described northeast of Formation K (Hillary and Ayres, 1980) and could be a source for these clasts. Intense mechanical and chemical weathering of these rocks which are about 200 Ma older than the sandstone (Corfu et al, 1981) could produce sand-size quartz and must be considered as a possible source.

Quartz veins could provide sand-size quartz to the sediments under conditions of prolonged transport and mechanical weathering but are not likely to be a major source because of low volumes in most source terrains.

Felsic volcanic clasts in the Sandstone Member are fine-grained and aphyric. Because of this, felsic volcanoes of comparable composition are not considered to be a suitable source of sand-size quartz.

Older sedimentary rocks that have been eroded and subjected to abrasion during prolonged transport could supply a large abundance of sand-size quartz to the sediments. A pre-existing sedimentary terrain is supported by the discovery of a possible orthoquartzite pebble at locality 127, and by a 200 Ma age hiatus between the deposition of the Sandstone Member and the underlying volcanic rocks (Corfu et al, 1981).

Based on the clast lithologies found in the Sandstone Member, the high sand-size quartz component of the sandstones could be derived from a terrain of felsic plutons and/or felsic subvolcanic plutons with quartz veins, combined with a pre-existing sedimentary terrain containing possible orthoquartzites. When the clast lithologies in the Conglomerate Member are considered, however, the relative importance of a terrain composed largely of felsic plutons and felsic subvolcanic plutons with quartz veins in the provenance of the Sandstone Member is decreased. Well rounded felsic plutonic, felsic subvolcanic and vein quartz clasts are found throughout the Conglomerate Member and form a larger proportion of the clast population than in the Sandstone Member. However, the interbedded sandstones in the Conglomerate Member are not unusually enriched in sand-size quartz.

What must be considered in the provenance of sand-size quartz in the Sandstone Member is the relative importance of felsic volcanic clasts in the member and the interbedded felsic tuffs. Felsic volcanic clasts form 20 percent of the conglomerates and are equal in importance to intermediate volcanic clasts. In addition, felsic volcanic clasts form 70 percent of the pebbles in the sandstone and over 80 percent of sand-size lithic fragments. This shows the relative importance of felsic volcanic rocks in the source terrain compared to other rock types. In addition, 40 percent of the sand-size quartz grains are monocrystalline with some still retaining evidence of magmatic corrosion in the form of embayments and hence could be volcanic quartz. Thus, although the felsic clasts lack quartz phenocrysts, a felsic volcanic source must be reconsidered.

A plinean eruption of felsic composition in the source terrain could supply large volumes of tuffaceous material. Quartz crystals could be readily transported and concentrated from such unconsolidated tuffaceous deposits. Pumice and volcanic glass constituents of the tuff are readily eroded and the volcanic glass portions altered to clay. The clay would be deposited in the deeper portions of the basin as mud or in the matrix of the sandstone. The plagioclase, potassium feldspar and quartz crystals released from the pumice as well as in the tuff would be abraded and in the case of the feldspars, altered during transport. This would also be the case if the sediment was deposited in a beach environment prior to redeposition as a turbidite fan. The feldspar content of the tuff is more susceptible to erosion and alteration than the quartz crystals and would be preferentially removed over the quartz crystals. Phenocryst-poor felsic volcanic clasts and sand-size lithic fragments could have been derived from pre-existing felsic volcanic sequences or from phenocryst-poor felsic flows related to the plinean eruption. If the quartz-poor interbedded tuffs in the Sandstone Member are related to the plinean eruption they could be derived from a secondary vent source of different composition located at some distance from the plinean eruption.

Although a plinian eruption in the source terrain is a possible source of the sand-size quartz in the Sandstone Member, erosion of a pre-existing felsic volcanic sequence is also possible. If the interbedded quartz-poor tuffs in the member are related to a plinian eruption in the source terrain as air-fall tuffs, then an unusual amount of compositional sorting of the sediment during transport would be required over a relatively short period of time. The erosion of a pre-existing quartz-rich felsic tuff and subsequent upgrading during transport of the sand-size quartz content of the sediment could supply large volumes of quartz. A process of this nature would require a more extended period of time than that available during deposition with coincident volcanism. A 200 Ma hiatus is indicated prior to the deposition of the Sandstone Member (Corfu et al, 1981) and would be sufficient to upgrade the sand-size quartz content of the sediment. Aphyric felsic volcanic clasts and lithic fragments in the Sandstone Member could be derived from the erosion of phenocryst-poor flows in the pre-existing felsic volcanic sequence.

Although erosion of tuffs related to a plinian eruption in the source terrain or erosion of pre-existing felsic volcanic sequence could supply large volumes of quartz, the latter is preferred. Erosion of a pre-existing felsic volcanic sequence is a more adequate source of the phenocryst-poor felsic volcanic fragments in the member than erosion of phenocryst-poor flows related to a crystal-rich plinian eruption. Also felsic volcanism unrelated to quartz-rich plinian volcanism is considered a more likely source for the interbedded quartz-poor tuffs in the member. Erosion of a pre-existing felsic volcanic sequence and the time required to upgrade the sediment in sand-size quartz is supported by the 200 Ma hiatus prior to the deposition of the Sandstone Member.

In summary, detritus for the Sandstone Member was derived from a source terrain containing felsic volcanoes, and subvolcanic plutons and an older felsic plutonic terrain with quartz veins distally and intermediate volcanoes more proximally. The high sand-size quartz content of the sandstones was derived mainly from the weathering of felsic tuffs from a pre-existing felsic volcanic sequence with some of the quartz derived by the weathering of felsic plutons, felsic subvolcanic plutons and quartz veins. The relative importance of a pre-existing sedimentary terrain possibly containing orthoquartzite is unknown but could have been significant.

DEPOSITIONAL HISTORY OF FORMATION K AND ITS RELATIONSHIP TO VOLCANISM

As it is presently exposed, Formation K represents a two-dimensional vertical section through a relatively small intervolcanic depositional basin about 10 km long with a sedimentary thickness of about 2 km. The basin was periodically exposed and submerged possibly due mostly to isostatic loading of the volcano and partly due to tectonic uplift or uplift produced by magma emplacement. The detritus infilling the basin was derived from the relative west and east in the Conglomerate Member and relative east in the Sandstone Member. The extent of uplift and subsidence is unknown but subsidence below storm wave base is required for the deposition and preservation of the Sandstone Member. Storm wave base varies according to the size of the body of water and can be more than 200 m in the open ocean (Reineck and Singh, 1975). This would imply at least 2.2 km of subsidence. The depositional history of Formation K can be considered in four stages (Figures 45, 46, 47, 48).

Stage 1: The Setting Prior to Deposition of the Conglomerate Member

The unit underlying the Conglomerate Member is a sequence of subaqueous, pillowed, mafic flows that were probably part of a shield volcano (Ayres, 1977). In the study area Formation K wedges out to the east but the Sandstone Member does continue to the west and may wedge out to the west as well. With the sediment being derived from the relative west and east in the Conglomerate Member the original depositional basin may have been a topographic depression formed by the merging of the flanks of several mafic shield volcanoes (Figure 45).

Stage 2: Intermediate Volcanism and Deposition of the Conglomerate Member

A period of uplift must have occurred prior to deposition of the Conglomerate Member as a subaerial alluvial fan (Figure 46). This uplift may have been related, in part, to intermediate volcanism in the provenance area which followed the shield-producing mafic volcanism or alternatively it may be related to a hiatus with uplift related to the emplacement of early plutons. The intermediate volcanic event is supported by the high proportion of intermediate volcanic clasts and the small proportion of mafic volcanic clasts in the conglomerate.

The alluvial fan was deposited as, at least, two coalescing fans with their relative apices to the west and east. In the west the source terrain was largely felsic plutons, and subvolcanic plutons with quartz veins distally and intermediate volcanoes more proximally. In the east the source terrain was felsic volcanic units and subvolcanic plutons, iron formation and chert distally and intermediate and mafic volcanic rocks more proximally.

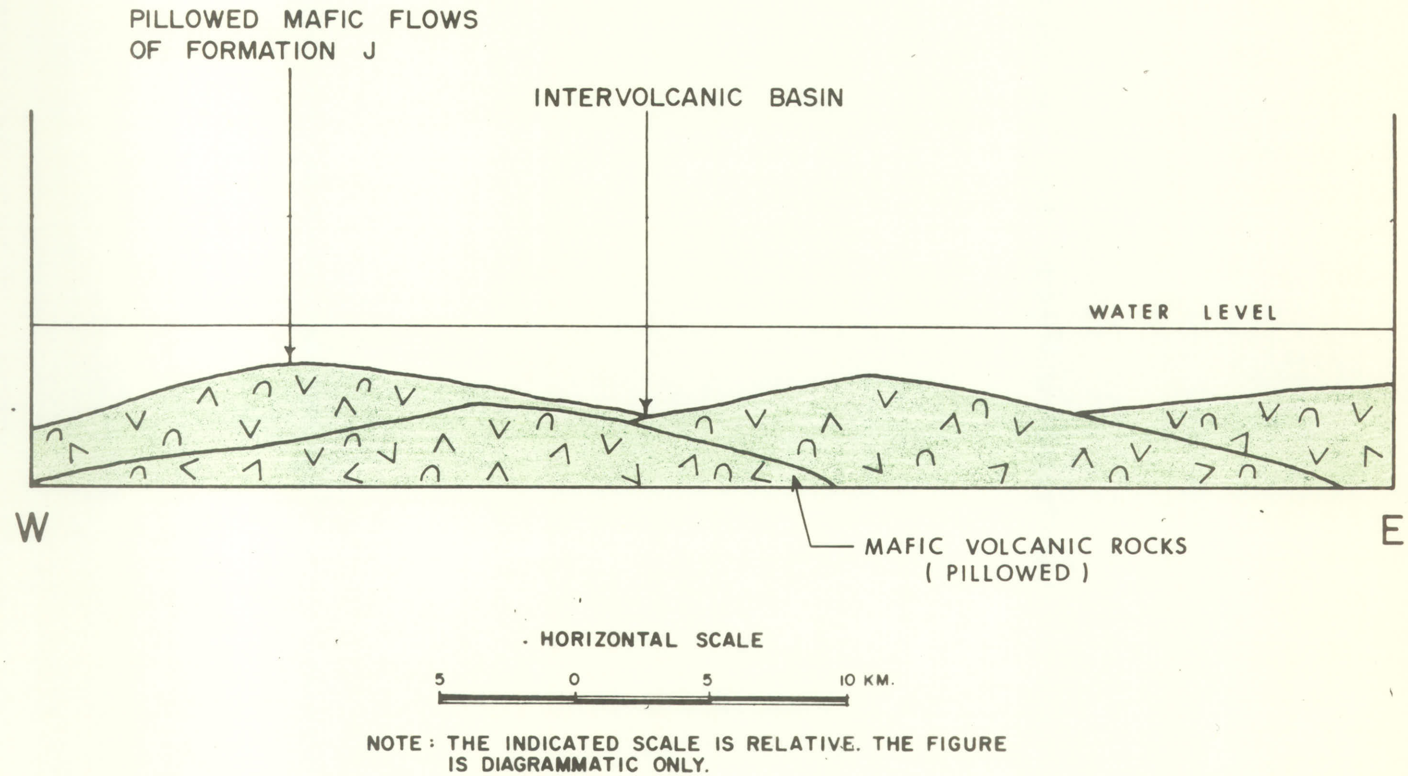


Figure 45: Stage 1: The setting prior to deposition of Formation K. The merging flanks of subaqueous shield volcanoes could provide a topographicl basin for the deposition of the Conglomerate Member.

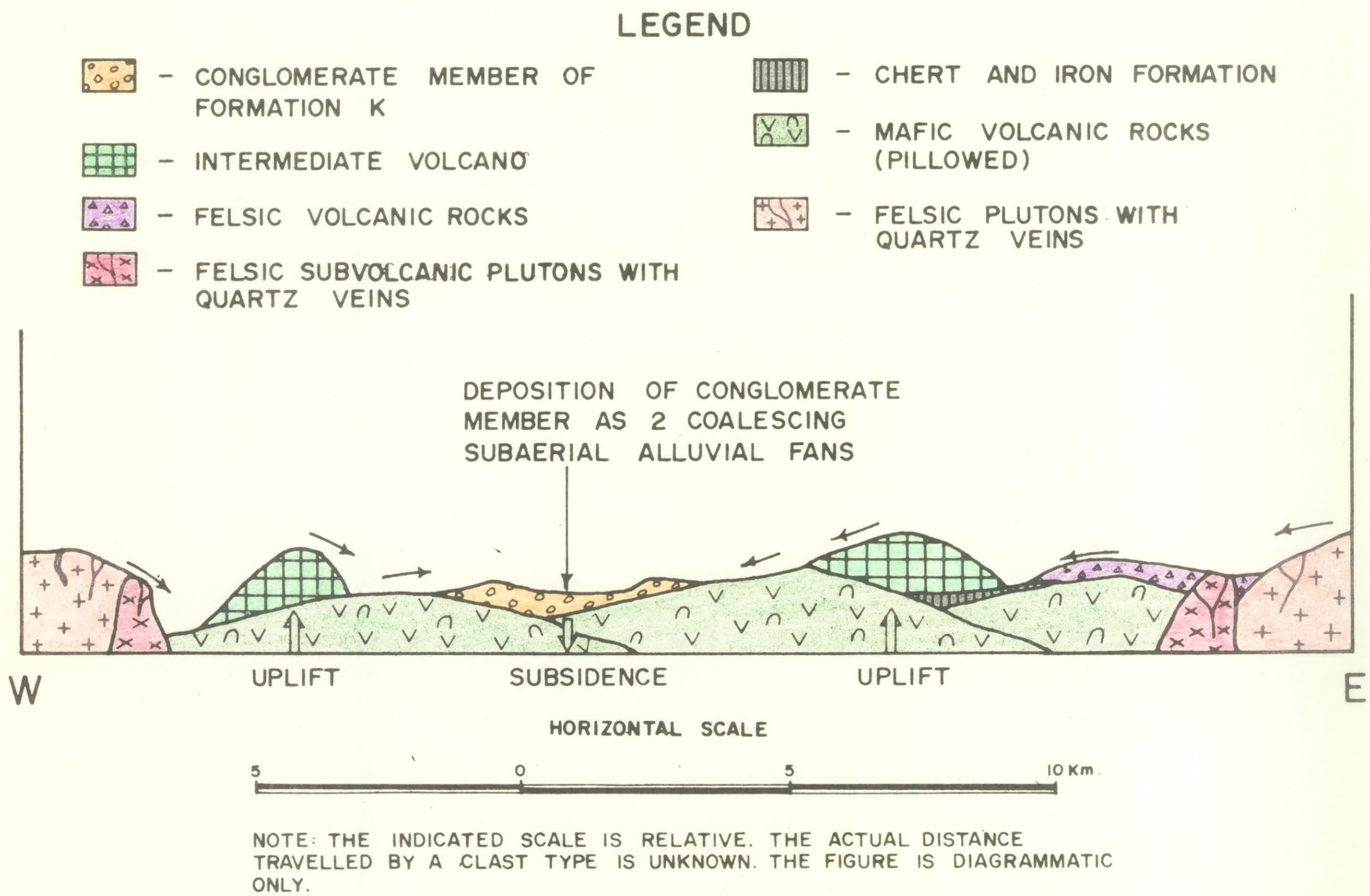


Figure 46: Stage 2: Intermediate volcanism and deposition of the Conglomerate Member

Stage 3: Subsidence and Deposition of the Sandstone Member

Subsidence of the volcano resulted in the sinking of the alluvial fan below sea level. Evidence for this is the subsequent subaqueous deposition of the overlying Sandstone Member (Figure 47).

The subaqueous submarine fan had its relative apex to the east. The relative rate of sedimentation was initially faster than the rate of subsidence producing a progradational fan. In the upper part of the fan the relative rate of sedimentation was slower than the rate of subsidence and the fan became retrogradational. The apparent retrograde nature of the upper fan could also represent ceasation of subsidence in the basin prior to a period of uplift.

Detritus for the Sandstone Member was derived from a source terrain containing felsic volcanoes and subvolcanic plutons and an older felsic plutonic terrain with quartz veins distally and intermediate volcanoes more proximally. The high sand-size quartz content of the sandstones was derived mainly from the weathering of felsic tuffs from a pre-existing felsic volcanic sequence with some of the quartz derived by the weathering of felsic plutons, felsic subvolcanic plutons and quartz veins. The discovery of a possible orthoquartzite pebble suggests that an unknown proportion of sand-size quartz could have been derived from a pre-existing sedimentary source terrain.

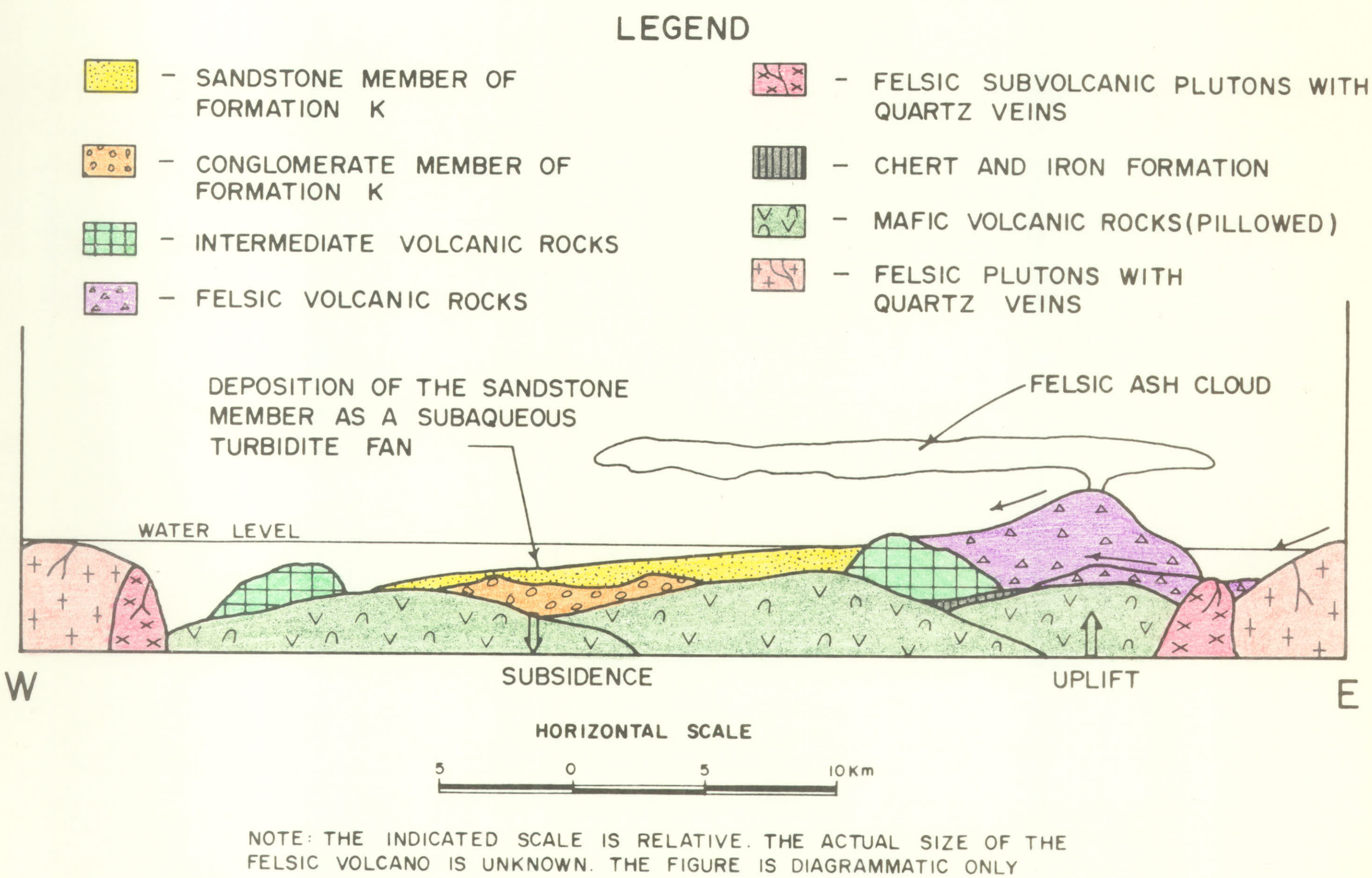


Figure 47: Stage 3: Continued subsidence and deposition of the Sandstone Member. Felsic volcanism was concomitant with deposition of the Sandstone Member.

Stage 4: Period of Uplift and Eruption of Mafic Volcanic Flows

If the mafic flows of Formation M south of the bedding plane thrust fault represent the next cycle of volcanism, then there must have been renewed uplift prior to their eruption. These flows are described by Ayres (1977) as possibly subaerial (Figure 48). The mafic sills in the Sandstone Member could be related to this period of mafic volcanism.

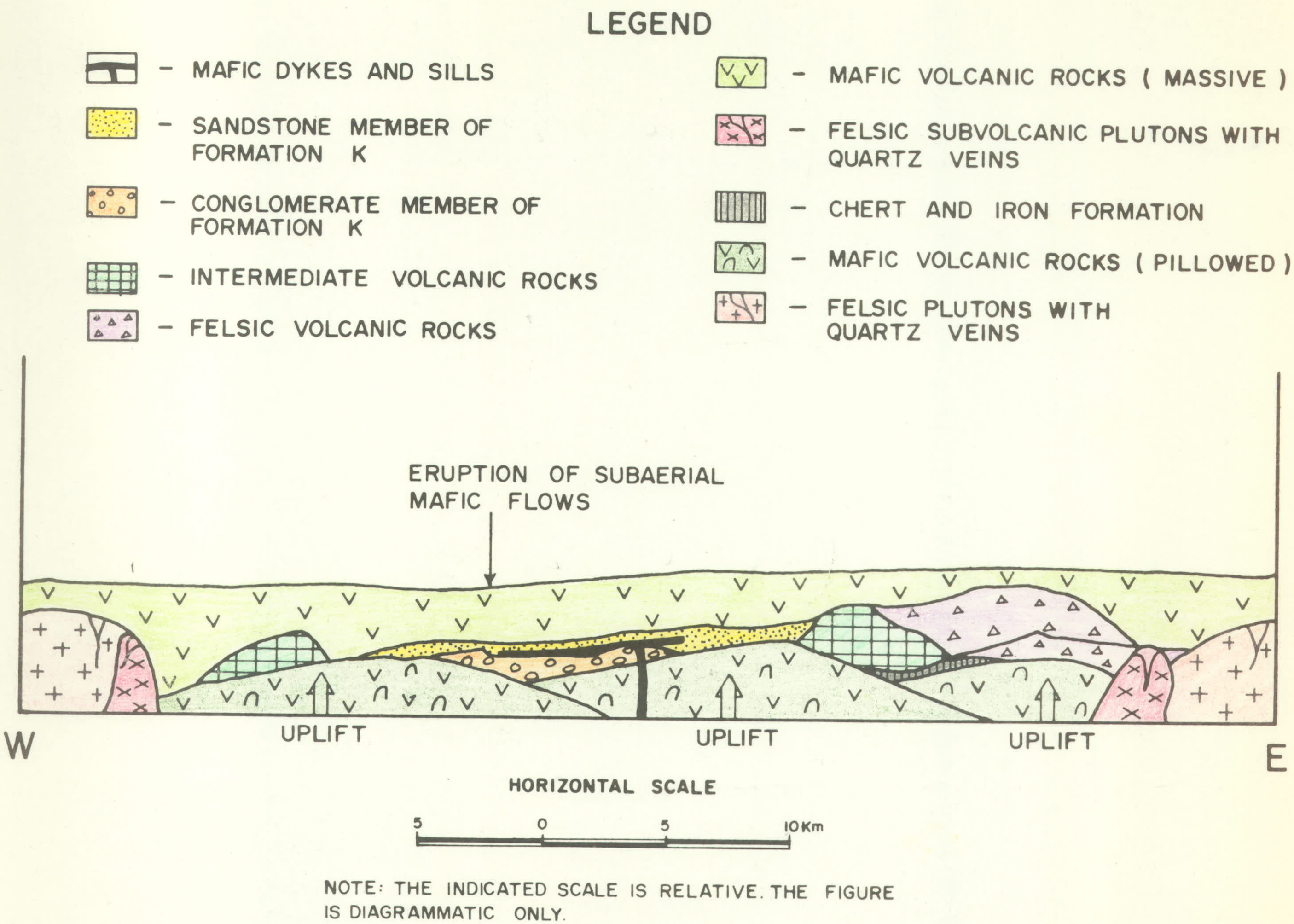


Figure 48: Stage 4: Period of uplift and eruption of mafic volcanic flows

REGIONAL SIGNIFICANCE OF FORMATION K

Semi-quantitative sedimentology applied to Formation K has documented volcanism in the provenance area that is not presently found in the Favourable Lake metavolcanic-metasedimentary belt. Intermediate volcanic clasts in the Conglomerate Member are interpreted as being derived from a relative westerly source although there are no intermediate volcanic rocks exposed west of Formation K. Concomitant felsic volcanism documented in the Sandstone Member may be related to Cycle 3 volcanism that is not exposed in the present section through the belt.

Formation K stratigraphy has documented two periods of uplift with an intervening period of subsidence of possibly 2.2 km over a stratigraphic thickness of only 2 km and is a record of the relative instability of the area during deposition.

Although the stratigraphy documents the relative instability of the area during deposition of Formation K, the possible discovery of an orthoquartzite pebble in the Sandstone Member suggests an area of relative tectonic stability in the provenance area. The proximity of a basement enclave 3 km north of the formation further supports an area of potential tectonic stability where texturally and compositionally mature sediments could have developed.

The similarity between Formation K and the sedimentary rocks in the North Spirit Lake area described by Donaldson and Jackson (1965) is notable and may reflect a similar history. If the orthoquartzite pebbles found in the North Spirit Lake area represent a depositional regime similar to that represented by the pebble found in Formation K then the area of tectonic stability may be more extensive than previously considered. The area of tectonic stability may have been an original Archean sialic crust of regional proportions represented today by crustal enclaves such as that described by Hillary and Ayres (1980).

CONCLUSIONS

Formation K in the Favourable Lake metavolcanic-metasedimentary belt, represents deposition as a basal subaerial alluvial fan succeeded by a submarine turbidite fan. The alluvial fan was deposited, not as a single fan, but at least two coalescing alluvial fans with sediment derived from the relative west and east of the member. The upper submarine fan was deposited as a single fan with sediment derived from the relative east.

The sandstones in the Conglomerte Member (alluvial fan) are lithic greywacke and not unusually enriched in sand-size quartz whereas the feldspathic greywackes in the Sandstone Member (submarine fan) are enriched in sand-size quartz. Derivation from a granitoid terrain, represented by felsic plutonic clasts, is not an adequate source for the sand-size quartz because clasts of this type are found in both members and are more important in the Conglomerate Member. The increase in sand-size quartz is related to an increase in importance of felsic volcanic clasts in the Sandstone Member. The enrichment of sand-size quartz in the Sandstone Member is the result of weathering and transportation of felsic tuff from a pre-existing felsic volcanic sequence. In addition to this source, an unknown quantity of sand-size quartz could have been derived from a pre-existing sedimentary source terrain. Evidence for this is the discovery of a possible orthoquartzite pebble in the Sandstone Member. Some of the quartz could have been derived from the weathering of felsic plutonic and subvolcanic rocks with quartz veins.

Formation K is a sedimentary record of concomitant felsic volcanism, in the Sandstone Member, that is presently not exposed in the Favourable Lake belt and thus is an integral part of the volcanic record. In addition, Formation K documents the possible existence of a pre-existing orthoquartzite sedimentary terrain possibly related to a relatively stable cratonic terrain represented today by crustal enclaves such as that exposed 3 km north of Formation K. Sedimentary basins, such as Formation K, are important sources of information that should be considered in the formulation of volcano-tectonic models in the Archean.

REFERENCES

Ayres, L.D. 1969. Early Precambrian metasandstone from Lake Superior Park, Ontario, and its implications for the origin of the Superior Province. Geological Society of America, Abstracts with Programs for 1969, pt. 7, p. 5.

__________ 1972. Guide to granitic rock nomenclature used in reports of the Ontario Division of Mines: Ontario Div. of Mines, MP52, 14 p.

__________ 1974. Geology of the Trout Lake Area, District of Kenora (Patricia Portion): Ontario Div. of Mines, Geological Report 113, 199 p.

__________ 1977. Importance of stratigraphy in Early Precambrian volcanic terrains: cyclic volcanism at Setting Net Lake, northwestern Ontario. In: Volcanic Regimes in Canada. W.R.A. Baragar, L.C. Coleman, and J. Ade-Hall (eds.). Geological Association of Canada, Special Paper 16, p. 248 - 264.

__________ Ms. Bimodal volcanism in Archean greenstone belts, as exemplified by sedimentologic data, Lake Superior Park, Ontario. Submitted to Canadian Journal of Earth Sciences.

Ayres, L.D., Raudsepp, M., Averill, S.A., and Edwards, G. 1973. Favourable Lake-Berens Lake; Ontario Div. Mines Geol. Compilation Series, Map 2262. Scale 1 inch to 4 miles.

Bouma, A.H. 1962. Sedimentology of some flysch deposits. Amsterdam: Elsevier. 168 p.

Bouttcher, S.M.A., Edhorn, A.S., and Moorhouse, W.W. 1966. Archean conglomerates and lithic sandstones of Lake Timiskaming, Ontario. Proceedings, Geological Association of Canada, 17, pp. 21-42.

Bull, W.B. 1972. Recognition of alluvial fan deposits in the stratigraphic record. In: Recognition of ancient sedimentary environments. J.K. Rigby and W.K. Hamblin (eds.). Society of Economic Paleontologists and Mineralogists, Special Publication 16, pp. 63-83.

Corfu, F., Nunes, P.D., Krogh, T.E., and Ayres, L.D. 1981. Comparative Evolution of a plutonic and polycylic volcanic terrain near Favourable Lake, Ontario as inferred from Zircon U-Pb ages. GAC-MAC Joint Annual Meeting, Calgary, Alberta, V6, p. A-11.

Donaldson, J.A., and Jackson, G.D. 1965. Archean sedimentary rocks of North Spirit Lake area, northwestern Ontario. Canadian Journal of Earth Sciences, 2, pp. 622-647.

Donaldson, J.A., and Ojakangas, R.W. 1977. Orthoquartzite pebbles in Archean conglomerate, North Spirit Lake, northwestern Ontario. Canadian Journal of Earth Sciences, 14, pp. 1980-1990.

Dott, R.H. Jr. 1964. Wacke, greywacke and matrix - what approach to immature sandstone classifications? Journal of Sedimentary Petrology, 34, pp. 625 - 632.

Glikson, A.Y. 1978. On the basement of Canadian greenstone belts. Geoscience Canada, Volume 5, Number 1, pp 3-15.

Goodwin, A.M., and Ridler, R.H. 1970. The Abitibi orogenic belt. In: Symposium on Basins and Geosynclines of the Canadian Shield, ed. A.J. Baer, Geological Survey of Canada, Paper 70-40, pp 1-30.

Goodwin, A.M. and Shlanka, R. 1967. Archean volcano-tectonic basins: form and pattern. Canadian Journal of Earth Sciences, 4, pp. 777-795.

Henderson, J.B. 1972. Sedimentology of Archean turbidites at Yellowknife, Northwest Territories. Canadian Journal of Earth Sciences, 9, pp. 882-902.

Hillary, E.M., and Ayres, L.D. 1980. Trondjhemite basement enclave near the Archean Favourable Lake volcanic complex, northwestern Ontario, Canada. Canadian Journal of Earth Sciences, 17, pp 652-667.

Ingram, R.L. 1954. Terminology for the thickness of stratification and parting units in sedimentary rocks. Geological Society of America Bulletin, 65, pp. 937-938.

Lane, E.W. 1947. Report of the subcommittee on sediment terminology. Trans. Amer. Geophys. Union, V. 28, pp 936-938.

McGowen, J.H., and Groat, C.G. 1971. Van Horn sandstone, west Texas: an alluvial fan model for mineral exploration. The University of Texas at Austin, Bureau of Economic Geology. Report of Investigations No. 72, 57 p.

Nunes, P.D., and Wood, J. 1979. A 300 m.y. hiatus in the stratigraphy of the North Spirit Lake greenstone belt, northwestern Ontario. GAC Annual Meeting, Quebec, 1979, Programs with Abstracts, 4: 70 p.

Ojakangas, R.W. 1972 a. Archean volcanogenic greywackes of the Vermilion District, northeastern Minnesota. Geological Society of America Bulletin, 83, pp. 429-442.

__________ 1972 b. Greywackes and related rocks of the Knife Lake Group and the Lake Vermilion Formation, Vermilion District. In: Geology of Minnesota: a centennial volume (P.K. Sims and G.B. Morey, Eds.). Minnesota Geological Survey, pp. 82-90.

Pettijohn, F.J. 1954. Classification of sandstones, Journal of Geology, V. 62, pp. 360-365.

__________ 1975. Sedimentary Rocks, third edition, Harper and Row, New York, 628 p.

Pettijohn, F.J., Potter, P.E., and Siever, R. 1972. Sand and Sandstones: New York, Springer, 618 p.

Reineck, H.E., and Singh, I.B. 1975. Depositional Sedimentary Environments, Springer-Verlag, New York, 439 pp.

Turner, C.C., and Walker, R.C. 1973. Sedimentology, stratigraphy, and crustal evolution of the Archean greenstone belt near Sioux Lookout, Ontario. Canadian Journal of Earth Sciences, 10, pp. 817-845.

Walker, R.G., 1978 a. A critical appraisal of Archean basin-craton complexes. Canadian Journal of Earth Sciences, 15, pp. 1213-1218.

____________ 1978 b. Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. American Association of Petroleum Geologists, V. 62, No. 6, p. 932.966.

Walker, R.G., and Pettijohn, F.J. 1971. Archean sedimentation: analysis of the Minitaki basin, northwestern Ontario, Canada. Geological Society of America Bulletin, 82, pp. 2099-2130.

Walker, R.G., and Mutti, E., 1973. Turbidite facies and facies associations, In: G.V. Middleton, and A.H. Bouma, eds., Turbidites and deep water sedimentation: SEPM Pacific Sec. Short Course, Anaheim, California, pp. 119-157.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments, Journal of Geology, V. 30, pp. 377-392.