GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES, OTTAWA

BULLETIN 246

SEDIMENTOLOGY OF THE ARCHEAN YELLOWKNIFE SUPERGROUP AT YELLOWKNIFE, DISTRICT OF MACKENZIE

John B. Henderson

1975

SEDIMENTOLOGY OF THE ARCHEAN YELLOWKNIFE SUPERGROUP AT YELLOWKNIFE, DISTRICT OF MACKENZIE

Critical reader

F.H.A. Campbell

Technical editor

R.G. Blackadar

Énergie, Mines et
Ressources Canada

Energy, Mines and
Resources Canada

GEOLOGICAL SURVEY
BULLETIN 246

SEDIMENTOLOGY OF THE ARCHEAN YELLOWKNIFE SUPERGROUP AT YELLOWKNIFE, DISTRICT OF MACKENZIE

John B. Henderson

Available by mail from *Information Canada*, Ottawa, K1A 0S9

from the Geological Survey of Canada
601 Booth St., Ottawa, K1A 0E8

and

Information Canada bookshops in

HALIFAX — 1683 Barrington Street
MONTREAL — 640 St. Catherine Street W.
OTTAWA — 171 Slater Street
TORONTO — 221 Yonge Street
WINNIPEG — 393 Portage Avenue
VANCOUVER — 800 Granville Street

or through your bookseller

A deposit copy of this publication is also available
for reference in public libraries across Canada

Price - Canada: $5.00
Other Countries: $6.00

Catalogue No. M42-246

Price subject to change without notice

Information Canada
Ottawa
1975

PREFACE

The area around Yellowknife Bay contains some of the best preserved and best exposed examples of Archean supracrustal rocks known anywhere in the Slave Province of the Canadian Shield. The region also is one of the largest gold producing areas in Canada and the ore deposits are localized in complex shear zone systems in mafic volcanic rocks of the Yellowknife Supergroup.

Like the Superior Structural Province, the Slave Province is a part of the Canadian Shield that has not been subjected to any major tectonic event since the close of Archean time. The rocks of the Yellowknife Supergroup are mainly thick sequences of dominantly mafic volcanics and immature greywackes and mudstones. They are highly deformed and most have been metamorphosed to the cordierite-amphibolite facies.

In this report the author presents the results of a detailed study of the sedimentary units of the Yellowknife Supergroup designed to provide a paleoenvironmental interpretation of the area, an understanding of the mode of deposition, an insight as to the nature of the crust at that time in the earth's history and an understanding of the relationships between the sediments and the associated volcanic rocks. Two units, the Jackson Lake and Burwash Formations, which represent contrasting sedimentary environments, are described in detail and the data presented are used to reconstruct the geological history of the region. Although the area described is but a small part of the Slave Province, the postulated sequence of events may be applicable to other basins in the province.

A major role of the Geological Survey is to provide a comprehensive inventory and understanding of the geological framework of the nation's territory and thereby enable estimates to be made of the potential abundance and probable distribution of the mineral and fuel resources available to Canada. This thorough account of the geological history of an interesting part of the Canadian Shield will be of use and interest not only to those interested in the more theoretical aspects of Precambrian geology but also to those directly concerned with economic development.

D.J. McLaren,
Director,
Geological Survey of Canada.

Ottawa, January 23, 1974

CONTENTS

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

Tables

Tables (cont'd.)

Illustrations

SEDIMENTOLOGY OF THE ARCHEAN YELLOWKNIFE SUPERGROUP AT YELLOWKNIFE, DISTRICT OF MACKENZIE

ABSTRACT

At Yellowknife the Jackson Lake and Burwash Formations of the Yellowknife Supergroup represent contrasting sedimentary environments at the margin of an Archean basin in the Slave Structural Province.

The Jackson Lake Formation, exposed on the west side of Yellowknife Bay, consists of a local discontinuous basal conglomerate derived largely from the thick mafic volcanic sequence that it unconformably overlies. The remainder of the formation consists of approximately 1,000 feet (300 metres) of crossbedded felsic volcanic lithic wackes with minor thin beds or lenses of conglomerate also largely of silicic volcanic derivation. The formation is a terrestrial braided river deposit that is considered to be the basin margin equivalent of the Burwash Formation that occupies the main part of the basin.

The Burwash Formation, exposed on the east side of Yellowknife Bay, consists of approximately 15,000 feet (4,500 metres) of interbedded greywackes and mudstones and shows many of the features characteristic of turbidites. Analysis of the sedimentary structures indicate that the turbidites were derived from the west, possibly from an area occupied by an extensive granitic terrain, and accumulated in depositional fan valleys on a submarine fan complex near the margin of a large sedimentary basin. The high percentage of dominantly felsic volcanic rock fragments, together with abundant quartz and feldspar, and minor but ubiquitous granitic rock fragments in the greywackes, indicates a mixed silicic volcanic and granitic provenance. The modal and chemical composition, and volumetric abundance of these sediments indicates an extensive sialic crust prior to the accumulation of the Yellowknife Supergroup at Yellowknife.

RESUME

A Yellowknife, les formations de Jackson Lake et de Burwash constituent des milieux sédimentaires contrastants à la bordure d'un bassin archéen situé dans la province structurale de l'Esclave.

La formation de Jackson Lake, exposée sur le côté ouest de la baie Yellowknife, est constituée par un conglomérat de base discontinu et local qui provient en grande partie de la séquence volcanique ferromagnétique sur laquelle il repose en discordance. Le reste de la formation se compose d'environ 1 000 pieds (300 mètres) de wackes lithiques volcaniques silico-feldspathiques à stratification croisée ainsi que de petits lits minces ou lentilles de conglomérat en grande partie de provenance silico-volcanique. La formation consiste en un dépôt terrestre de rivière anastomosée que l'on considère comme l'équivalent de la bordure du bassin dont la formation de Burwash occupe la majeure partie.

La formation de Burwash, exposée sur le côté est de la baie Yellowknife, se compose d'environ 15 000 pieds (4 500 mètres) de grauwackes et de pélites interstratifiés et présente de nombreuses caractéristiques propres aux turbidites. Une analyse des structures sédimentaires révèle que les turbidites proviennent de l'ouest, possiblement d'une région occupée par un vaste terrain granitique, et qu'elles se sont accumulées en dépôts dans des vallées en forme d'éventail faisant partie d'un ensemble de cônes sous-marins situés à proximité de la bordure d'un vaste terrain sédimentaire. Le pourcentage élevé de fragments de roches volcaniques à dominante silico-feldspathique, associé à l'abondance du quartz et du feldspath ainsi qu'à la présence de fragments de roches granitiques que l'on retrouve partout dans les grauwackes mais en petite quantité, indique une provenance à la fois silico-volcanique et granitique. La composition modale et chimique ainsi que l'abondance volumétrique de ces sédiments révèlent qu'il y avait une croûte sialique de grandes dimensions avant que ne se produise l'accumulation du super-groupe de Yellowknife à Yellowknife.

CHAPTER I

INTRODUCTION

The city of Yellowknife is situated on the western margin of a major Archean basin in the southern part of the Slave Structural Province. The area about Yellowknife Bay on the north shore of Great Slave Lake contains some of the best-preserved and exposed examples of Archean supracrustal rocks known anywhere in the Slave Province. The area is easily accessible, as the best exposures are all within a few miles of the city of Yellowknife. This ease of access and high quality of preservation and exposure make the Yellowknife area an ideal locality for the study of these ancient rocks.

Yellowknife is the site of one of the largest gold producing areas in Canada which, until 1967 when Yellowknife became the capital city of the Northwest Territories, was the main reason for its existence. Since 1938, when the Con-Rycon mine came into production, over 80% of the gold production in the Northwest Territories has been from this area, mainly from the Con-Rycon and Giant Yellowknife mines. The ore deposits are localized in complex shear zone systems in the mafic volcanic sequence of the Archean Yellowknife Supergroup. Several smaller mines, none of which remain in operation, were developed on quartz vein systems in the sediments of the Yellowknife Supergroup. Some of the rare element pegmatites in the region have been mined for short periods for columbite-tantalite and lithium minerals.

The first geological survey of the area was made by R. Bell (1900) who visited Great Slave Lake to investigate reports of lead and gold prospects in the area. He noted the similarity of the rocks at Yellowknife to the Precambrian in Ontario. Camsell and Malcolm (1919) made a tentative correlation of these rocks with the Keewatin and "Huronian" (Timiskaming) of Ontario but with some reservations. J.M. Bell (1929) in discussing the rocks at Yellowknife, first referred to the Early Precambrian as the Yellowknife series and correlated it with the Tazin series in the Lake Athabasca area. Stockwell (1932) included the Yellowknife rocks in his informal Point Lake-Wilson Island group which included the Archean supracrustal rocks between Great Slave Province. J.F. Henderson (1938) renamed the sedimentary and volcanic rocks of the Beaulieu River area, immediately to the east of Yellowknife, the Yellowknife Group, thus establishing the group name. The Yellowknife Group was later raised to Supergroup status (J.B. Henderson, 1970). The immediate area around Yellowknife was mapped at 1 inch = 1 mile scale by Jolliffe (1942, 1946). Detailed maps of the basic volcanic sequence at Yellowknife have been published by Henderson and Brown (1952, 1966). Boyle (1961) has described the geology, geochemistry, and origin of the gold deposits at Yellowknife. In addition, studies on the geochronology of the area (Green and Baadsgaard, 1971) and pegmatites of the region (Kretz, 1968) have been conducted.

This study is particularly concerned with the sedimentary formations of the Yellowknife Supergroup at Yellowknife and had the following objectives:

1. to provide a paleoenvironmental interpretation of the area during Archean time;
2. to understand the mode of deposition of the sediments;
3. to gain some insite as to the nature of the crust at this time through an analysis of the provenance of the sediments;
4. to understand their relationships to the associated volcanics;
5. to provide criteria for future regional studies of the Yellowknife Supergroup in the Slave Structural Province.

ACKNOWLEDGMENTS

The advice and interest of Prof. F.J. Pettijohn of the Johns Hopkins University where this study was done is greatly appreciated. The author was ably assisted in the field by Mr. Heinz Ambach and Mr. Melvin Lomenda. Dr. R.G. Walker of McMaster University kindly provided computer programs for the analysis of sedimentary structure data. Dr. P.F. Hoffman initially proposed the study.

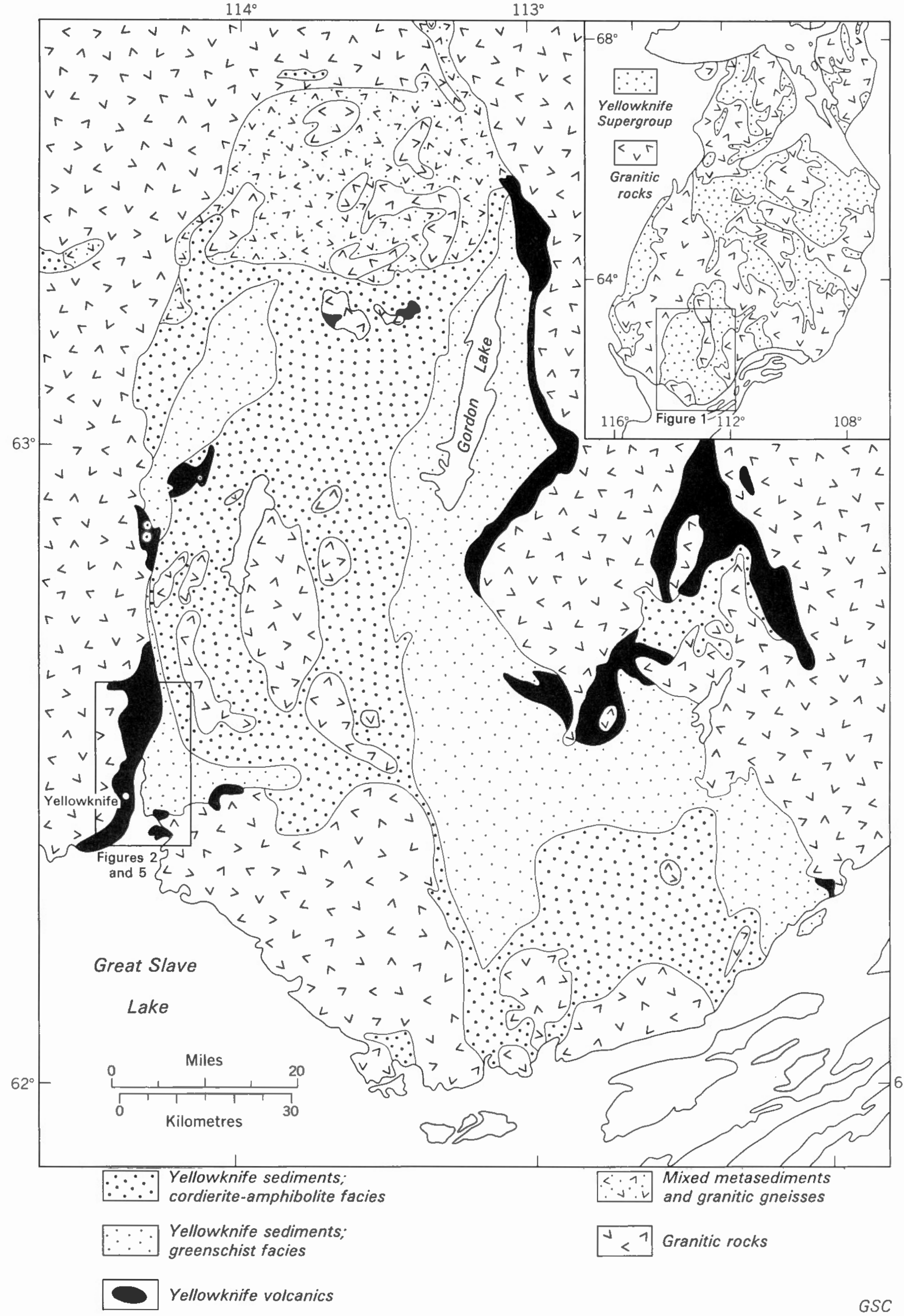


Figure 1. Archean basin containing Yellowknife supracrustal rocks in the southern part of the Slave Structural Province. The area of interest is located at Yellowknife on the southwest margin of the basin. The inset is a generalized map of the Slave Structural Province.

CHAPTER 2

GENERAL GEOLOGY

REGIONAL GEOLOGY

The area of interest at Yellowknife occurs in the southern part of the Slave Structural Province (Fig. 1, insert). This province together with the very much larger Superior Structural Province, are regions of the Canadian Shield that have not been subjected to any major tectonic event since the end of the Archean. With the exception of the cover sediments of Aphebian age at the margins of the province the supracrustal rocks are all of Archean age and members of the Yellowknife Supergroup (McGlynn and Henderson, 1970, 1972). As in most Archean terrains the supracrustal rocks consist mainly of thick sequences of dominantly mafic volcanics and immature greywackes and mudstones. Sediments reflecting deposition under stable platform conditions have not been recognized. Over half the Slave Province is underlain by Yellowknife sedimentary and volcanic rocks or their metamorphic and granitized equivalents. Of these over 80 per cent are of sedimentary origin which contrasts strongly with most areas of the Superior Province and most other Archean terrains of the world where mafic volcanic rocks predominate.

Throughout the province the supracrustal rocks are highly deformed; the volcanics typically form steeply dipping monoclinal successions while the less competent sediments occur in complex isoclinally folded sequences. For the most part the supracrustal rocks have been metamorphosed to the cordierite-amphibolite facies of the Abukuma lower pressure facies series. In a few locations, however, the sediments and volcanics have been metamorphosed only to the greenschist facies, one such example being at Yellowknife.

The best preserved and exposed area of Yellowknife sedimentary and volcanic rocks occurs in the southern part of the province east of Yellowknife (Fig. 1). Here a segment of a north-south trending Archean basin is preserved. On its east and west margins it is bordered in part by a thick sequence of predominantly mafic volcanics. The main part of the basin is filled with the typical interbedded greywacke mudstone sediments of the Yellowknife Supergroup. A central ridge of cordierite-amphibolite facies metamorphism is penetrated by granitic intrusions while to the east and west between the thermal ridge and the margin of the basin the sediments have undergone only greenschist grade metamorphism. To the north the basin becomes unrecognizable in an area of extensive high grade metamorphism, granitic intrusion and migmatization. The whole basin is contained in a "sea" of granitic rocks which bear intrusive relationships to it, although it has been suggested (Baragar, 1966; Davidson, 1972) that at least part of the granitic body bordering the northeast part of the basin may be older than the supracrustal rocks.

GEOLOGY OF THE YELLOWKNIFE BAY AREA

The Yellowknife Bay area (Fig. 2) provides a good example of the geology of the region and of the province as a whole, due largely to the relatively low grade of metamorphism and the high quality of the exposures.

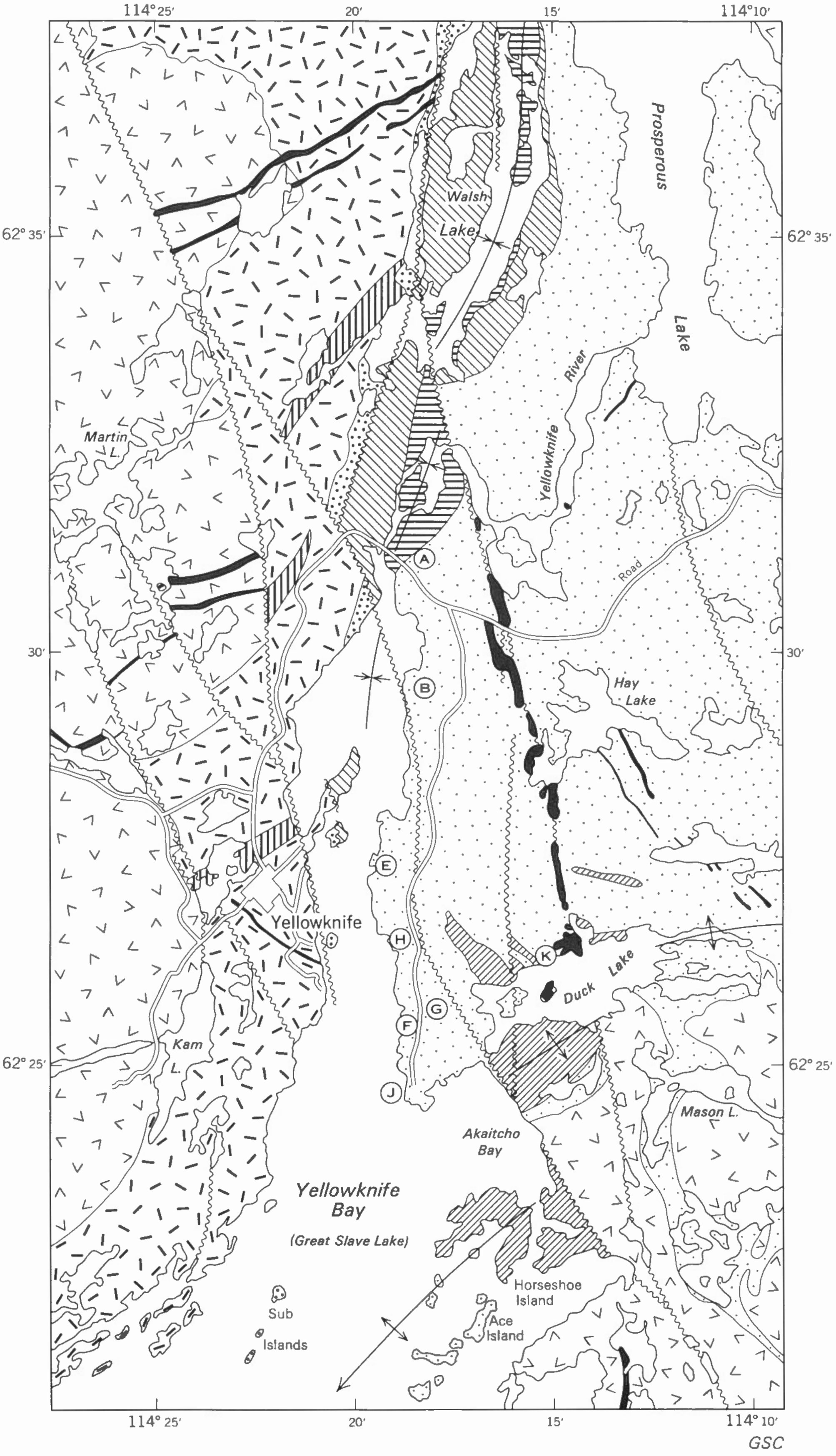
Supracrustal Rocks

At Yellowknife the Yellowknife Supergroup has been subdivided into six formations in two groups, the Beaulieu Group and the Duncan Lake Group (*see* Table 1). The Beaulieu Group consists of two formations: the Kam mafic volcanics - the main volcanic sequence in the area west of Yellowknife Bay, and the Duck intermediate volcanics east of the bay. A third formation, the felsic volcanic Banting Formation has not been assigned to a group. The three sedimentary formations of the Duncan Lake Group include the sedimentologically similar Burwash and Walsh Formations composed of greywacke and mudstone, and the Jackson Lake conglomerate and lithic sandstone.

Kam Formation

The Kam Formation consists predominantly of basaltic lava flows in which the thickness of the maximum single continuous section is 22,000 feet (6,700 m). Almost 40,000 feet (12,000 m) of volcanics can be measured at Yellowknife if correlations along strike are made across fault blocks. It seems unlikely, however, that the maximum thickness of the sequence at any single location was much in excess of 22,000 feet (6,700 m). The greater aggregate thickness probably reflects the shift of the locus of extrusion along strike resulting in an en echelon growth of the volcanic sequence analogous to the progradation of a series of crossbeds. The volcanic sequence has been mapped and studied in detail by Boyle (1961), Baragar (1966) and Henderson and Brown (1966) the following account is abstracted from their work.

In the volcanic pile massive and pillowed flows occur in about equal abundance. The individual flows vary in thickness from only a few feet (1 m) to as much as 500 feet (150 m) and are of equally variable lateral extent. Flow contacts are often difficult to distinguish unless clearly marked by flow top breccia or tuffaceous material. In general, individual flows are either pillowed or massive; only rarely are individual flows


114°25′
20′
15′
114°10′
62°35′
62°35′
30′
30′
62°25′
62°25′
Prosperous Lake
Walsh Lake
Yellowknife River
Road
Martin L.
A
B
Hay Lake
E
Yellowknife
H
K
Duck Lake
G
F
Kam L.
J
Mason L.
Akaitcho Bay
Yellowknife Bay
(Great Slave Lake)
Horseshoe Island
Ace Island
Sub Islands
114°25′
20′
15′
114°10′

GSC

made up of both a pillowed and a massive part. Pillows in the pillowed flows vary in size from only a few inches (10 cm) to in excess of 5 feet (1.25 m) with the average diameter between 1 and 2 feet (Fig. 3). There is a gradation from closely packed pillowed flows with little or no debris between the individual pillows through to what is termed a pillow breccia in which generally smaller, more irregularly shaped pillows occur unsupported in an abundant matrix of hyaloclastic debris.

The massive flows tend to be slightly coarser grained than the pillowed flows and are distinguishable from the compositionally identical sills in the sequence only by the presence of amygdules, ropy flow tops or other structures characteristic of extrusive flows.

In addition to the normal rather similar pillowed and massive mafic flows there are eight groups of variolitic flows that are useful marker horizons in the volcanic pile. The variolitic flows are almost always pillowed and contain lighter coloured variolites 5 to 10 mm in diameter, some of which still retain their radial structure.

In the central part of the pile just north of Yellowknife is a distinctive light weathering, 1,200 foot thick (400 m) dacitic unit referred to as the Brock or Townsite flows. These flows are typically porphyritic with phenocrysts of quartz and feldspar. The more felsic units are commonly coarsely fragmental, and are characterized by discontinuous layers of breccia and agglomerate. Pillows occur in some of the more basic flows.

Thin, continuous, tuffaceous units, as well as agglomerate and volcanic breccia, occur throughout but are particularly thick and abundant towards the top of the formation. Some tuffs contain a high proportion of sulphur and carbon which Boyle (1961) suggests may have been concentrated by biogenic processes.

The flows are extensively intruded by dykes, sills and irregularly shaped bodies with similar composition to the flows. There is no direct evidence which indicates that the dykes are feeders to the flows, although it is believed that the basic intrusions and flows are closely related in origin and time of intrusion. The irregularly shaped intrusions are interesting for there

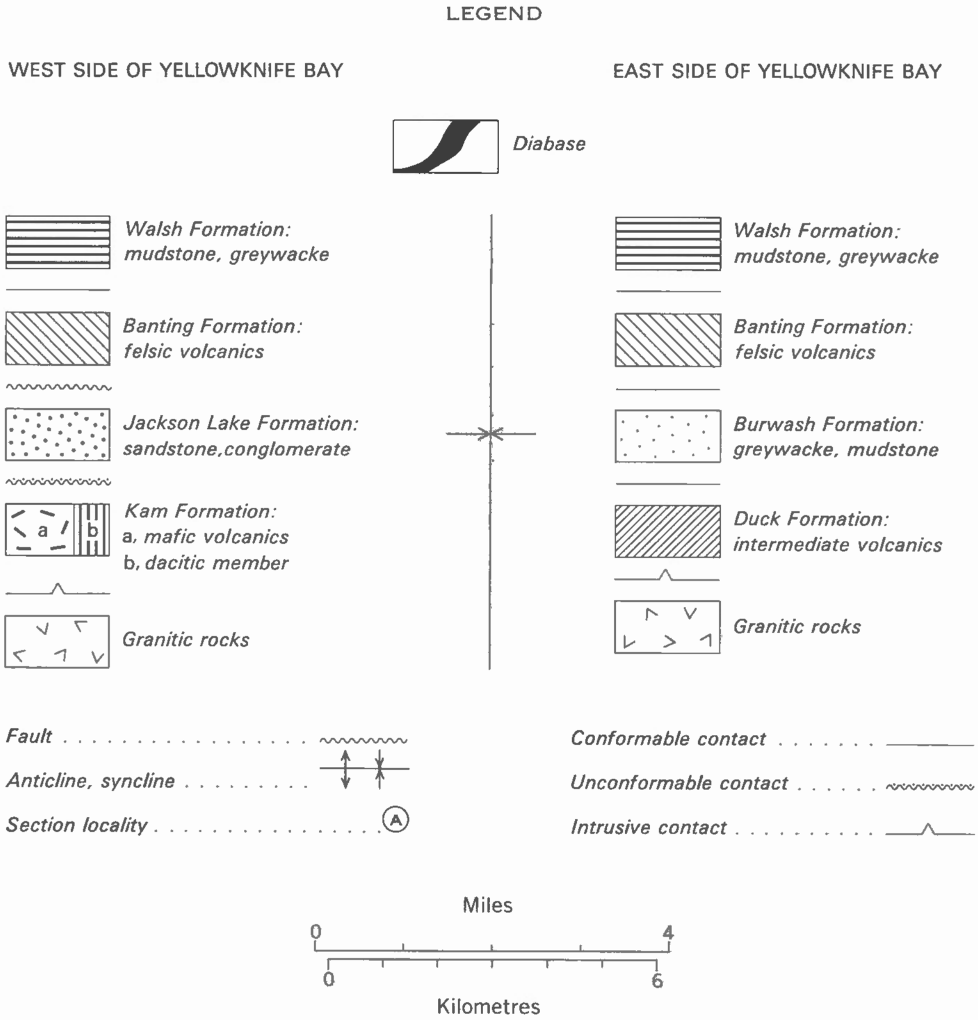


Figure 2. General geology of the Yellowknife Bay-Prosperous Lake area. Section localities referred to in the text are noted.

TABLE 1

Table of Formations

		WEST SIDE OF YELLOWKNIFE BAY			EAST SIDE OF YELLOWKNIFE BAY		
ERA	SUPERGROUP	GROUP	FORMATION	LITHOLOGY	LITHOLOGY	FORMATION	GROUP
Cenozoic				glacial deposits	glacial deposits		
Profound Unconformity							
Proterozoic				diabase gabbro	diabase gabbro		
Intrusive Contact							
Archean				Western granodiorite Quartz-feldspar porphyry Gabbro diorite	Prosperous Lake granite Southeastern granodiorite Quartz-feldspar porphyry Gabbro diorite		
	Intrusive Contact						
	Yellowknife	Duncan Lake	Jackson Lake	Volcanic lithic sandstone conglomerate	Slate with interbedded siltstone and greywacke	Walsh	Duncan Lake
			Unconformity		Felsic volcanics, agglomerate and tuff	Banting	
				Diorite gabbro			
			Intrusive Contact		Greywacke with thin slate interbeds	Burwash	
		Beaulieu	Kam	Pillowed and massive basalt, andesite and dacite flows	Intermediate volcanics	Duck	Beaulieu

commonly is no evidence that the intrusive body has disturbed the host flows. In places inclusions in the intrusive body retain their original orientation relative to the adjoining flows.

Detailed chemical studies on the Kam Formation indicate mixed tholeiitic and calc-alkaline trends. Baragar (1966) has interpreted this as indicating the Kam volcanics were derived from a tholeiitic magma on which calc-alkaline characteristics were imposed by sialic wall-rock contamination.

Jackson Lake Formation

The Jackson Lake Formation lies unconformably with a small angular discordance above the volcanic Kam Formation. It consists of a basal conglomerate of mainly local mafic volcanic derivation that is overlain by a several hundred foot sequence of crossbedded silicic volcanic sandstones with local thin conglomeratic horizons. The upper part of the formation is always in fault contact with the predominantly silicic volcanic Banting Formation to the east. The formation can be traced from the lakes north of Yellowknife Bay along the west side of the Bay through to the Sub Islands at the mouth of the Bay. This formation will be discussed in detail in a later section.

Duck Formation

In the southeastern part of Yellowknife Bay the Duck Formation of volcanic flows of intermediate to mafic composition is exposed in the core of a northeast-trending anticline north of the southeastern granodiorite (Fig. 2). These flows are well exposed at Duck Lake and on Horseshoe Island in Yellowknife Bay. The total thickness of this unit is unknown as only the upper portion appears in the core of the anticline. The flows are light greyish green, of intermediate composition and are commonly pillowed. Pillows are smaller than those in the Kam Formation and appear to have more

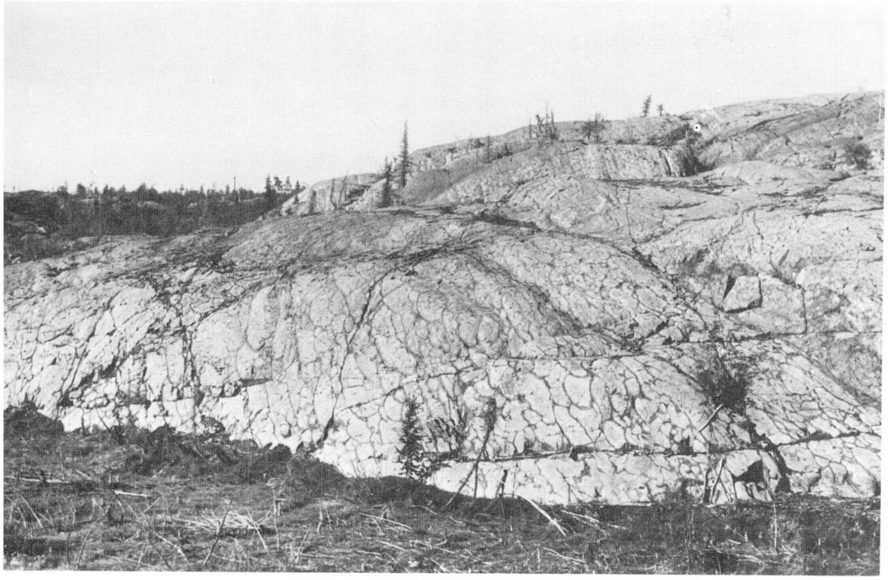
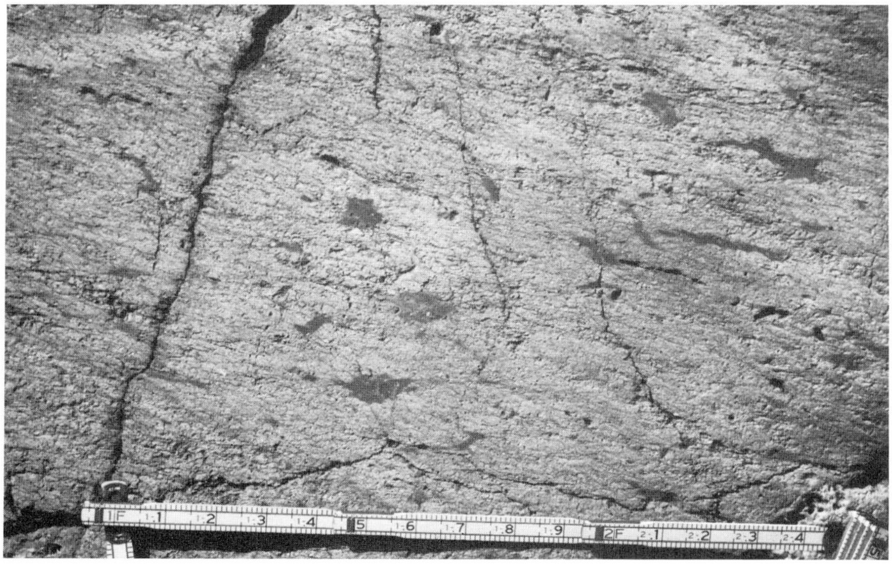


Figure 3.

Pillowed volcanics of the Kam Formation. Top of sequence is towards the left.

Figure 4.

Banting Formation felsic volcanics. A massive welded tuff with dark fiamme possibly representing flattened pumice fragments.



associated hyaloclastic debris. They are commonly vesicular with abundant quartz-filled amygdules. The contact with the overlying Burwash Formation appears to be conformable although it is commonly obscured by shearing. The Duck Formation may be an eastern lateral equivalent of the Kam Formation.

Burwash Formation

The Burwash Formation is well exposed between Walsh Lake and Akaitcho Bay, although its equivalents are found as far east as the East Arm of Great Slave Lake, a distance of 70 miles (110 km) and as far north as Fishing Lake and Gordon Lake, 50 miles (80 km) and 70 miles (110 km) respectively (Figs. 1, 2).

The Burwash Formation is about 15,000 feet (4,500 m) thick and consists of interbedded greywackes and mudstones that exhibit features characteristic of turbidites. It is conformable with the underlying Duck volcanics and thin volcanic flows and tuffaceous layers occur in the formation well above the first occurrence of the typical greywacke mudstone turbidites. The upper part of the formation grades into the Walsh Formation turbidites, although in most places in the Yellowknife area they are separated by the felsic volcanic Banting Formation.

The Burwash Formation, in area the most important formation in the region, will be discussed in detail in a later section.

Banting Formation

The Banting Formation is volcanic in origin but is highly variable in composition. It consists of porphyritic dacite flows, felsic agglomerate, pillowed andesite and crystal tuff (Fig. 4). Weathered surfaces of the volcanic rocks, especially the felsic varieties, are a light grey to pinkish grey. In the northern exposures, shearing and deformed clasts in the agglomerate impart a streaked appearance to the rock. Euhedral plagioclase crystals are abundant in many of the flows, and commonly occur in the matrix of the agglomerates. Quartz occurs in some of the more felsic units and is also present in the matrix of the agglomerates. The strata are best preserved on the west limb of the syncline through Walsh Lake; on the east limb they are more metamorphosed and commonly sheared, particularly near the contacts with the sediments. Near the top of the formation, west of the Yellowknife River, is a 200 foot (60 m) thick conglomerate comprised mainly of rounded cobbles of volcanogenic sandstone, similar to the Jackson Lake Sandstone, and cobbles of shale, siltstone and felsic volcanics. This unit is conformable with the over- and underlying volcanic agglomerates and tuffs.

The formation has a maximum thickness of about 4,000 feet (1,200 m) on the western limb but thins towards the southeast to about 2,500 feet (750 m). The base of the formation is in fault contact with the Jackson Lake and Kam Formations to the west. On the eastern limb shearing obscures the contact with the underlying Burwash Formation and locally the overlying Walsh Formation, but the three appear to be conformable. The Banting does not appear on the southeastern limb of the fold, west of the Hay-Duck fault suggesting that it may not have been laterally persistent. To the north extensive faulting and shearing make it difficult to estimate thickness but it appears much thinner.

Walsh Formation

This formation is composed of turbidites but differs from the Burwash in that it contains much more mudstone. The greywacke and siltstone portions of the beds are generally much thinner and finer grained.

The formation is much more highly deformed due to incompetence caused by its predominantly argillaceous nature and proximity to the axis of the syncline. The resultant structural complexity makes it impossible to estimate the thickness of this formation. There is no evidence of any overlying formation. Along the east and west shores of the lake the Walsh strata conformably overlie the volcanic Banting rocks locally with a gradational contact indicated by the interbedding of tuffs with the normal greywackes, siltstones and mudstones. Unfortunately, the contact between the Walsh Formation and the Burwash Formation is poorly exposed where the Banting is missing. The interpretation favoured here is that the Walsh and Burwash Formations have a gradational contact in these areas.

Granitic Rocks

Three major units of granitic rocks display intrusive relationships to the Yellowknife Supergroup in the Yellowknife area (Fig. 1).

North and west of Yellowknife, outside and to the west of the basin, the granitic rock is a massive to locally weakly foliated, grey to pinkish grey, equigranular, biotite to biotite-hornblende granodiorite. It is generally homogeneous in the southern part except for minor irregular dykes of pegmatite and aplitic granite. To the north, the granodiorite to quartz diorite is intruded by large, massive, coarse-grained, commonly porphyritic, more felsic plutons about which the granodiorite is distinctly gneissic. Several of these plutons have caused the cusp-like shape of the western margin of the bordering volcanics.

The large granitic body with the basin southwest of Yellowknife is a generally uniform white to pink massive granodiorite. It contains extensive zones of metasedimentary (locally metavolcanic) inclusions which serve to outline distinct plutonic lobes within this large granitic complex. Where well preserved, the inclusions are similar to the Burwash Formation turbidites into which the complex was intruded.

To the north of this complex is a series of plutons that occur along the central zone of a regional thermal ridge in the west-central part of the basin. The plutons consist of massive biotite-muscovite granites with abundant crosscutting pegmatites, locally with complex mineralogy, that extend into the adjacent sediments.

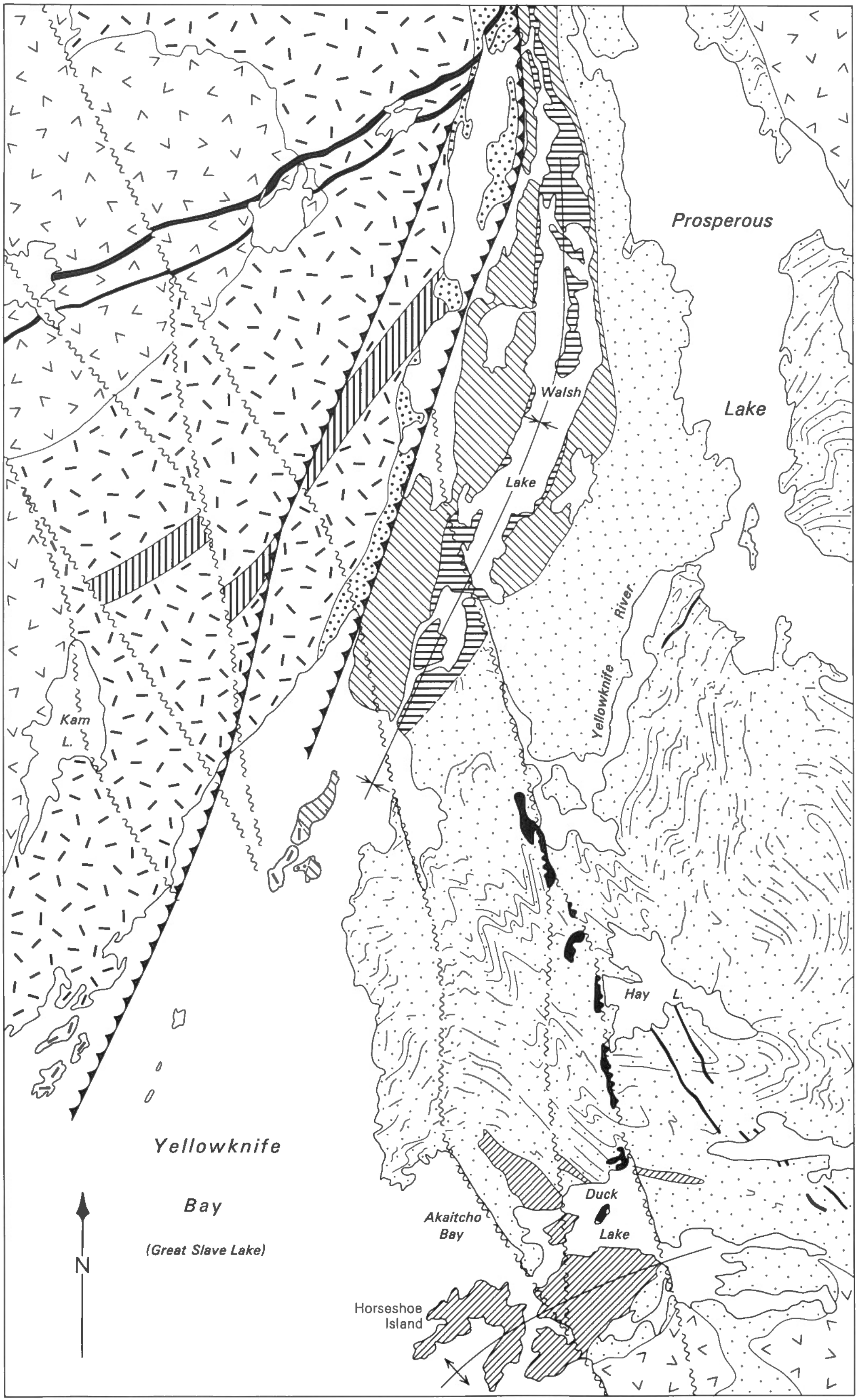
Structure

A northerly trending, isoclinal, upright to slightly overturned syncline which extends through Yellowknife Bay and the lakes to the north is the dominant structural element in the area (Fig. 5). The Kam volcanics and Jackson Lake conglomerate and lithic sandstone are found on the west limb while the Duck intermediate volcanics and Burwash greywacke-mudstones are found only on the east limb. The Banting felsic volcanics and Walsh sediments occur on both limbs north of Yellowknife Bay. At the base of the section on the east limb, the Duck Formation outcrops in the core of a shallowly plunging anticline whose axis parallels the contact with the granitic body to the southeast.

The steeply dipping to overturned beds of the Burwash Formation on the east limb have been refolded into a series of steeply plunging to overturned cross-folds. These second-order folds are related to the intrusion of a large granitic pluton to the northeast of Yellowknife Bay. The more competent volcanic formations are not refolded. The Kam Formation however contains extensive shear zones believed related to early faulting (Campbell, 1947; Henderson and Brown, 1966). These shear zones contain the important gold deposits at Yellowknife.

The last important tectonic event was the development of a series of left lateral, steep to vertical, predominantly strike slip, post-Archean faults. The west Bay Fault which parallels the west side of Yellowknife Bay and then cuts across the Kam volcanics and the granitic rocks to the west is a well known example. The displacement on this fault at Yellowknife has been calculated as 16,140 feet (4,930 m) horizontally and 1,570 feet (480 m) vertically (Campbell, 1948).

The stratigraphic relationships between some member formations of the Yellowknife Supergroup at Yellowknife are not clear due to structural complexity and coverage of critical areas by the waters of Yellowknife Bay. On the west limb the Jackson Lake conglomerates and lithic sandstones rest with angular unconformity on the Kam volcanics. On the east limb, the Duck, Burwash, Banting and Walsh Formations are in conformable contact. The Banting and Walsh Formations occur on both east and west limbs but on the west limb a fault occurs between the Banting volcanics and the underlying Jackson Lake. The main stratigraphic problem is the relationship between the formations in the lower part of the section on both limbs. It has been suggested (Henderson, 1970) that the Duck Formation may be basinward lateral extension and equivalent of part of the Kam Formation. The Jackson Lake conglomerate and lithic sandstone may represent the shallow-water basin margin equivalent of the Burwash Formation with which it has certain lithologic affinities. The hiatus implied by the angular unconformity between the Jackson Lake and the Kam Formations is not regarded as major but rather as an indication of instability in the region during deposition of the Yellowknife Supergroup.


Prosperous
Lake
Walsh
Lake
Yellowknife River
Kam L.
Hay L.
Duck Lake
Akaitcho Bay
Horseshoe Island
Yellowknife Bay
(Great Slave Lake)
N

GSC

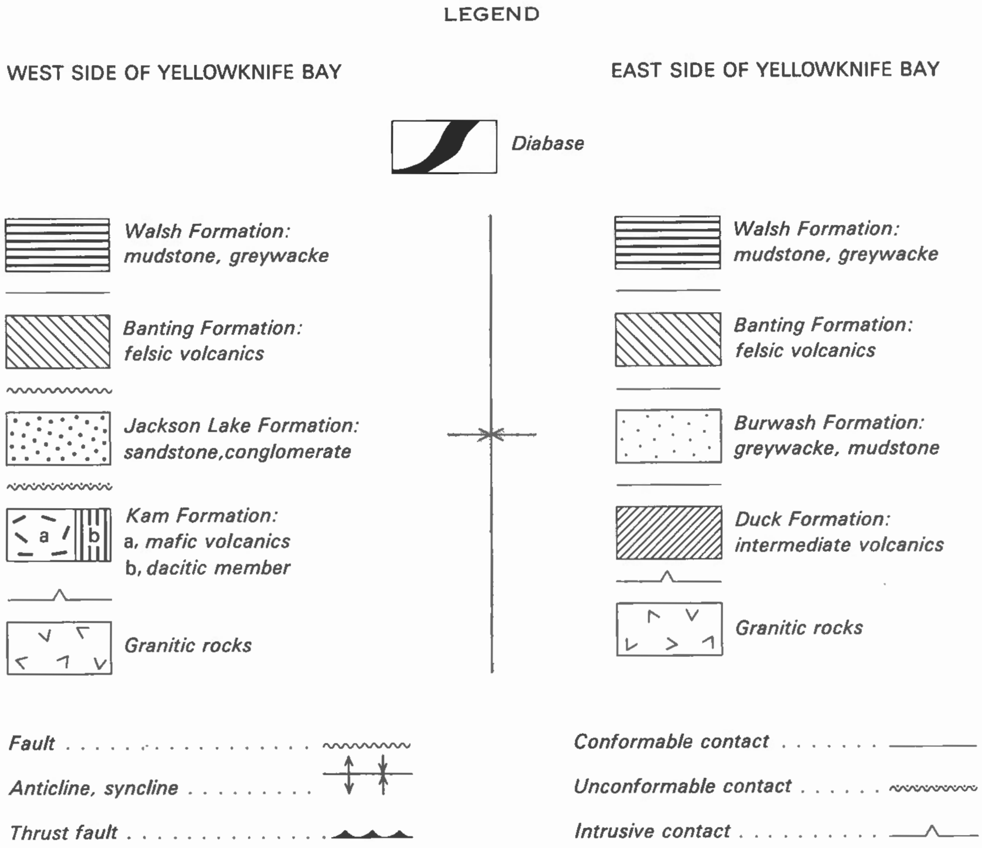


Figure 5. Structural Geology of the Yellowknife Bay region. The effect of the post-Archean dominantly strike slip faults (location indicated by broken lines) has been removed. Various topographic features such as lakes, rivers and the shoreline of Yellowknife Bay are distorted (compare with Fig. 2). Since only the major faults were considered some offsets still remain such as the offset of the felsic unit in the Kam volcanics which is due to many small-scale unmapped dislocations in the large triangular-shaped block. The northerly-trending, isoclinal, upright to slightly overturned syncline is the dominant structural element in the area. A subsidiary anticline parallels the margin of the granitic body at the southeast corner of the map. The dominantly northwest-facing Burwash Formation has been intricately cross-folded due to granitic intrusion to the northeast of the map area. Shear zones in the volcanics are very complex and may represent early thrust faulting.

CHAPTER 3

THE BURWASH FORMATION

TURBIDITE FACIES

The various formations of the Yellowknife Supergroup are unusually well exposed in the immediate Yellowknife area with abundant large, clean, relatively lichen-free exposures (Fig. 6). The near vertical bedding and minimal effects of postglacial weathering and erosion has resulted in smooth, typically flat exposures of sections in the Burwash Formation in which the internal sedimentary structures are particularly well displayed. Bedding plane exposures are rare.

Almost all the characteristic sedimentary features ascribed to turbidite deposition (Kuenen, 1964) are present in the Burwash Formation.

Graded bedding, probably the most frequently observed characteristic, is abundant (Fig. 7). The graded nature of the beds is commonly preserved even in the more metamorphosed terrains where, even though not apparent due to the growth of metamorphic minerals, the original textural variation can be detected by noting the change in pitch when a knife or similar pointed object is scraped across the bed. This grain gradation in the sediments, together with pillow-top determinations in volcanic sections has aided greatly in the deciphering of the complex structure of many Archean areas.

The often quoted Bouma (1962) sequence of sedimentary structures present in an ideal turbidite can be observed in whole or part in the Burwash greywackes (Fig. 8). As with turbidites of other areas and ages the complete sequence is the exception rather than the rule. The order within the cycle, almost always maintained, is (A) a graded lower division followed by (B) a parallel-laminated division above which is (C) a current-ripple laminated division. A second or upper division of parallel lamination (D) is next followed by (E) the uppermost pelitic division.

The base of each individual bed is invariably sharp but is not necessarily straight or even. There may or may not be sharp contacts between the other various parts of the bed. The thickness of the turbidite beds varies from less than half an inch (1 cm) to more than 20 feet (6 m), although in many of the thicker sands there is evidence of combination or amalgamation of two or more separate turbidite units.

The individual beds, on an outcrop scale, are laterally continuous. The exposures at Yellowknife are not well suited for studying variation of the beds along strike, as the formation is cut by a series of north to north-northwesterly trending faults. Pinch-outs of beds are rarely observed although in places a pair of greywackes can be traced laterally into a single amalgamated bed. Even the thinnest beds can be traced across large outcrops (up to several hundred feet (100 m)). In one case where detailed parallel sections were measured at a spacing of approximately 300 feet (100 m) less than 10% of the beds in each section of 175 beds were not correlative. The missing beds in most cases were thin-bedded fine-grained types eroded in one section prior to the deposition of the overlying bed. A few were the thick-bedded coarser-grained variety; these typically are amalgamations of two similar beds,

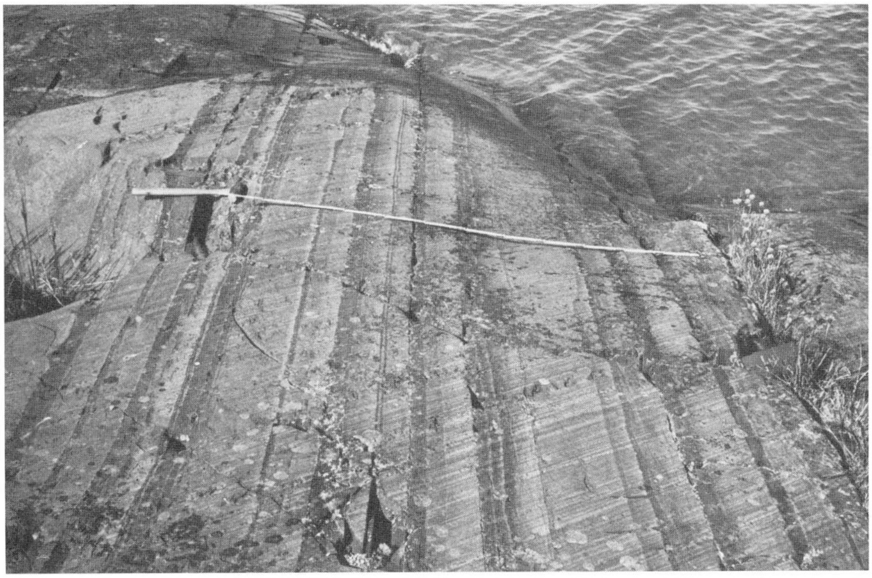


Figure 6.

Shoreline outcrop of vertically-dipping greywacke-mudstone turbidites of the Burwash Formation. The lighter coloured layers are greywacke while the more argillaceous beds are darker in colour. Note the variation in bedding thickness. The striations at a high angle to bedding are a result of Pleistocene glaciation.

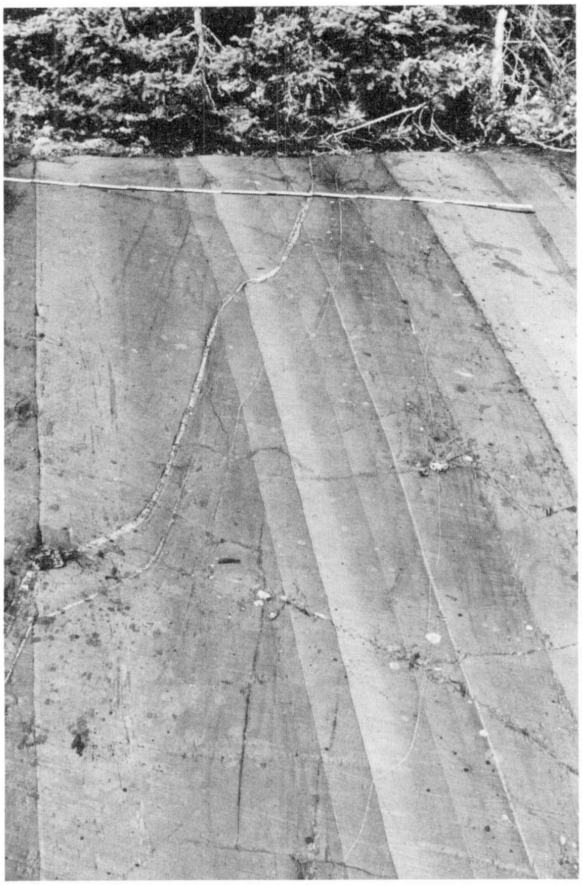


Figure 7. Series of graded beds in the Burwash Formation. The degree of grading is reflected in the change of colour from the lighter greywackes to the darker, more argillaceous siltstone and mudstone and by the refraction of the quartz filled cleavage fractures as they pass through the series of graded beds.

recognized as such in one section but missed in the corresponding section. In a few cases however, there appears to have been extensive local erosion with subsequent deposition only in the erosional depressions until a relatively flat topography was re-established. Many correlative beds in the two sections differ considerably in the development of the various divisions of the Bouma sequence. Some divisions are present in the bed in one section but missing in the other or commonly differ in thickness if present in both.

Paleocurrent directions indicated by current ripples with very few exceptions show a strong constancy of direction both in a single outcrop and throughout the whole section. (*See* later section.)

Turbidites are generally interpreted as a deep water product although great depth is not a requisite for turbidite deposition. Deep water deposition in many younger formations is indicated by deep water fauna in the pelagic layers. This of course cannot be used as a criteria in sediments of this age. One can only say that there is no evidence of shallow water sedimentation or associated shallow water sediments in this greywacke-mudstone sequence.

Figure 8. Relatively rare example of a turbidite containing all five divisions of the Bouma sequence (Fig. 14). In most beds one or more divisions of the sequence are missing.

As has been frequently stated, none of these characteristics by themselves are diagnostic of turbidite deposition but when taken together provide few alternatives.

Part of a representative sequence of Burwash turbidites can be seen in Figure 9.

NON-TURBIDITE FACIES

Non-turbidite zones occur in a few places in the formation. These are rare and consist of units ranging from 10 to 80 feet (3 to 25 m) in thickness. They are dominantly mudstone with silty laminations. The laminations differ from normal turbidites in that the silty bases are not sharp but gradational with the mudstone. The laminations, although sometimes rippled, are not particularly continuous and commonly exhibit a flaser form. They may be caused by reworking of previously deposited material by normal bottom currents during an extended period of quiescence.

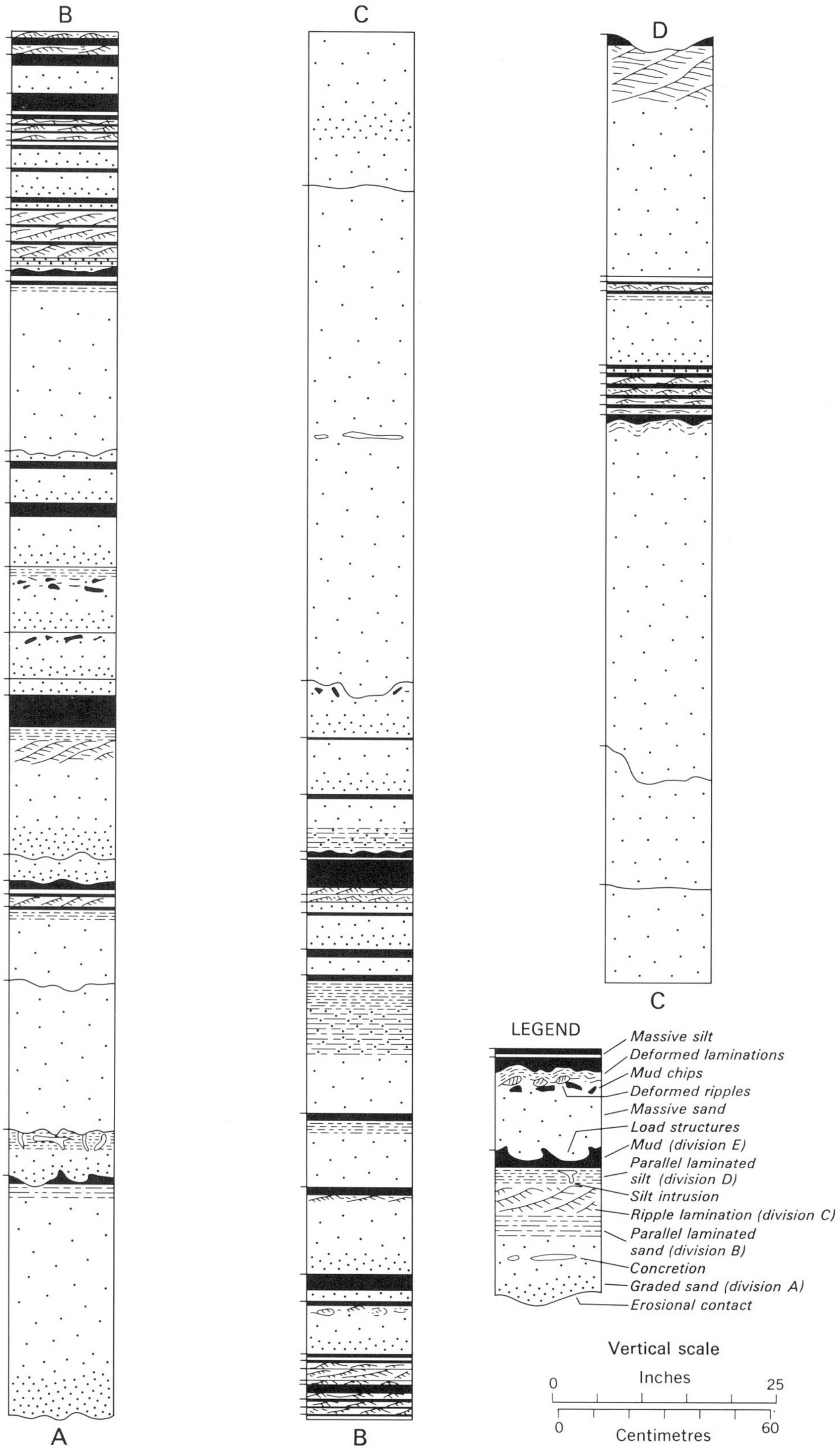


Figure 9. A representative section of the Burwash Formation turbidites consisting of 65 beds from section J.

Figure 10.

Felsic tuff clasts in the Burwash turbidites. Large rip-up clasts of interbedded bright yellow, thin-bedded well-graded felsic tuffs and black mudstone are found throughout the Burwash Formation. Their presence is indicative of continued felsic volcanism during accumulation of the Burwash Formation.

Two types of thin tuffaceous beds are also associated with the normal turbidites, particularly in the lower part of the section. First are the thin continuous tuffaceous beds interbedded with the greywackes. They are generally light yellow to greenish and are more affected by low-grade metamorphism; many are completely recrystallized. These tuff beds rarely show any internal structure other than weak grading. They are typically three to four inches (7 to 10 cm) thick -- in a few cases tens of feet (6 m) in thickness. They occur almost exclusively in the Duck Lake area, in the lowermost part of the formation close to the volcanic Duck Formation.

The second type of tuffaceous rock occurs only as large blocks in the turbidite beds (Fig. 10) and never in place in the immediate Yellowknife area. The blocks are angular, large, up to several feet (1 m) in length, and commonly occur in groups. These tuffaceous blocks are quite spectacular as they weather a bright yellow in contrast to the dull greenish-grey greywacke in which they are contained. Individual beds within the blocks are parallel-sided and commonly exhibit perfect grading from medium to coarse sand-sized material to mudstone in less than an inch. The mudstone between tuff layers is an intense black colour. The major constituent recognized in thin section is euhedral, usually highly altered, feldspar. These blocks occur throughout the formation and do not appear restricted to a particular stratigraphic level. Similar yellow tuff beds occur in place in the Burwash Formation in the central part of the basin east of Yellowknife. They consist of five or six inch beds in a normal succession of Burwash turbidites. The blocks seen at Yellowknife are evidently redeposited ripped up rafts of similar tuffaceous deposits.

Although these tuffaceous units make up an extremely small percentage of the formation they indicate that volcanic activity was present during the deposition of the Burwash.

PRIMARY INTERNAL STRUCTURES

The bedded nature of the Burwash Formation is one of its most striking features. It is best shown by the strong colour contrast between the lower and upper parts of the beds with the lower coarser, lighter grey-weathering greywackes in contrast to the overlying black mudstones. Bedding is commonly apparent from the air and the gross bedding variations are clearly visible on airphotographs.

The beds vary greatly in thickness from a maximum of about 28 feet (8. 5 m) to thin laminations less than one quarter of an inch (. 5 cm) (Figs. 11, 12). The deviation of bedding thickness from the average of about 7 inches (18 cm) is log-normally distributed as in the case with most sedimentary sequences (Pettijohn, 1957a). Mo Most of the extremely thick sands are the result of amalgamation of two or more units. Amalgamation is indicated by an abrupt increase in grain size in the central part of a bed, an irregular scour within the sand bed (Fig. 13), or as a layer of scattered angular mudstone chips. In many cases, however, there is no evidence of amalgamation until the unit is traced and found to divide into two independent sand layers separated by mudstone. One spectacular case of amalgamation was noted where six beds, each about one foot (30 cm) thick with thin mudstone upper parts abruptly disappeared into a single thick, homogeneous sand body with a few randomly scattered mudstone chips throughout the unit indicating the original multiple nature of the thick bed. Amalgamated units are thought to form in one of two ways. Most common is extensive erosion of the underlying unit prior to the deposition of the second sand (Wood and Smith, 1958). This erosion is usually indicated by a sharp reversal in grain size in the normal graded sand, or by an obvious scour surface commonly marked by slightly darker material. A second method of amalgamation is complete

Figure 11.

Very thick-bedded turbidite with concretions. Thick bedded units such as this are commonly composite in nature with the contact between the separate turbidites often indistinct if there is little contrast in grain size or composition of the sands. The indistinct lighter coloured layer in the upper central part of the unit is a zone of carbonate metaconcretions. The bed is about 7 feet (2.1 metres) thick.

mixing of two or more beds due to movement of water during compaction destroying the shale division between them. The only evidence of the originally continuous mudstone layers is a few scattered chips.

The proportion of sand to mud in graded couplets in the Burwash is variable, but generally sand greatly exceeds the argillaceous material, although the reverse is true in the very thin units. There does not appear to be any correlation between the thickness of the sandy and argillaceous parts of the beds (Fig. 31). This would support the pelagic origin of the mudstone independent of the turbidity current although possible erosion prior to the deposition of the succeeding bed no doubt would have some influence on the mudstone thickness.

Evidence of intraformational erosion is abundant. Many beds show scouring in the case of amalgamated units (Fig. 13). The normally flat basal contact in many places is irregular because of these scours. In some cases the scours have been exaggerated by later loading. As mentioned previously, several beds locally have been completely eroded by subsequent strong currents.

The Bouma cycle or sequence of sedimentary structures so commonly observed in turbidite successions (Bouma, 1962) is commonly seen in whole or in part at Yellowknife. This ideal sequence can be seen in Figures 8 and 14. The sequence indicates the change in flow conditions under which the sediments were deposited (Walker, 1965, 1967). In the Burwash turbidites all five divisions of the cycle are present although in any individual bed the sequence is rarely complete. The frequency of occurrence of the cycle and parts of the cycle are summarized for a typical section of the Burwash Formation in Table 2.

Basal Contact

The basal contact of any given bed is almost invariably sharp but varies from perfectly flat to highly irregular. Basal irregularities occur under all types and thicknesses of beds and on many scales. They

Figure 12.

Very thin-bedded turbidites. These units consist of light coloured very fine sand and silt that are commonly laminated or ripple laminated overlain by darker silty mudstone to black mudstone.

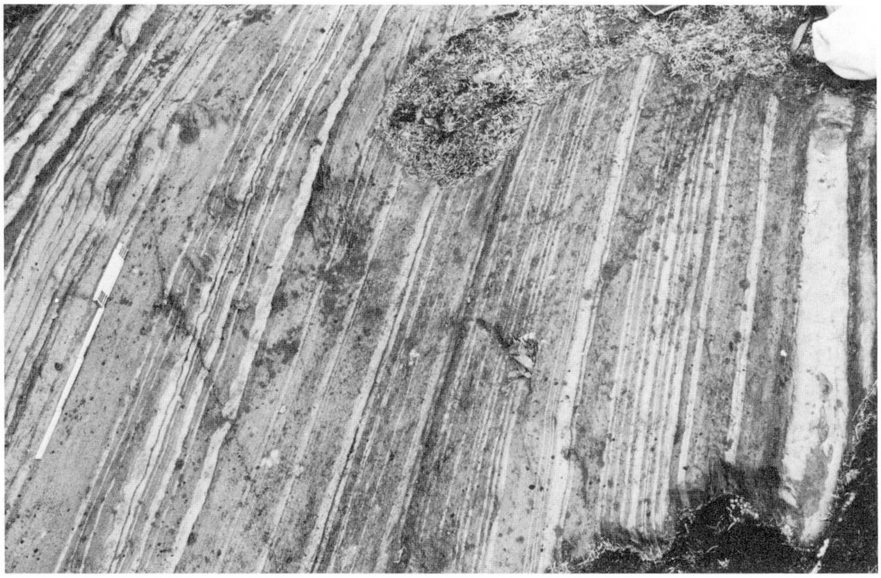


Table 2

Sedimentary Structure Statistics for a Representative Section of Burwash Formation Turbidites

Section J (Fig. 2) - 614 beds

Occurrence and Thickness of Particular Division (in cm)

	No. of Beds	Per cent	Average Thickness	Total Thickness
DIVISION A	247	40.2	27.2	6716.0
DIVISION B	80	13.0	15.0	1198.5
DIVISION C	335	54.6	4.2	1403.9
DIVISION (A→E), D*	114	18.6	1.8	206.3
TURBIDITE (TOTAL)	614		15.5	9524.7
INTERTURBIDITE	561	91.4	3.0	1704.7
D DIV.**	90	14.7	3.4	304.8
E DIV.	525	85.5	2.7	1399.9

*when not preceded by other divisions
**when preceded by other divisions

Occurrence and Thickness of Sequences of Divisions (in cm)

A	SEQUENCES	141	23.0	25.8	3639.0
ABC	SEQUENCES	21	3.4	53.0	1112.5
AB	SEQUENCES	11	1.8	74.3	816.9
A C	SEQUENCES	74	12.1	29.3	2165.9
B	SEQUENCES	13	2.1	24.2	315.2
BC	SEQUENCES	35	5.7	19.3	675.7
C	SEQUENCES	205	33.4	2.9	593.1
(A→E), D	SEQUENCES	114	18.6	1.8	206.3

PER CENT BEDS BEGINNING DIV. A	40.2	PER CENT BEDS BEGINNING DIV. C	33.4
PER CENT BEDS BEGINNING DIV. B	7.8	PER CENT BEDS BEGINNING DIV. (A→E), D	18.6

Occurrence of Structures within Divisions

		No. of Beds	Per cent of Section	Per cent of Division
DIVISION A	GRADING	191	31.1	77.3
	SHARP TOPS	148	24.1	59.9
DIVISION B	GRADING	38	6.2	47.5
DIVISION C	SIMPLE RIPPLES	167	27.2	49.9
	CLIMBING RIPPLES	144	23.5	43.0
	CONVOLUTE RIPPLES	22	3.6	6.6
DIVISION (A→E), D	MASSIVE	73	11.9	37.1
	GRADED	18	2.9	9.1
	LAMINATED	106	17.3	53.8
AMALGAMATION	DIVISION A	37	6.0	15.0
	DIVISION B	6	1.0	7.5
	DIVISION C	6	1.0	1.8
	TOTAL	49	8.0	

are generally primary and are a result of scouring and erosion by the turbidity current prior to deposition of the overlying sediment (Fig. 15). The scours are normally filled with material notably coarser than that immediately overlying the inter-scour areas. In some scours a tangentially cross-laminated fill suggests that the local flow regime was momentarily lower than that under which the overlying graded sands were deposited. In places these scours are steep-sided channels several feet (1 m) across that cut well down into the underlying strata, in some cases through several beds.

Graded Division (A)

The basal graded division of the Bouma sequence is among the most common of the divisions present (Table 2). It varies from those which are completely homogeneous and massive with no suggestion of grading whatsoever to others which are evenly graded from base to top. In some, particularly the thicker beds, the grading is not obvious unless the grain size at the top and base are directly compared. Many are graded only in the lower few inches (8 cm) whereas others are essentially massive, except for an abrupt gradation at

Figure 13.

Amalgamated turbidites. Many of the thicker greywacke units consist of two or more amalgamated turbidites, in which the upper, finer-grained more argillaceous parts of the sequence has been eroded. In this case the deposits of four turbidity current events can be seen. The arrows indicate the bases of individual turbidity current deposits. Note the extensive scouring along two of the eroded contacts. Prominent striae are glacial in origin. Scale in tenths of feet.

the top of the division. The graded nature of the greywackes is normally on too large a scale to be detected in a single thin section. Grain size gradation is accomplished by the gradual depletion of the coarser material towards the top. Reverse grading is extremely rare in these beds. When present it occurs at the base of the bed and invariably reverts to the normal fining-upward gradation within a few inches.

A two-part subdivision of division A occurs in a few cases. The lower subdivision consists typically of medium-grained normally graded greywacke. After a sharp straight contact it is followed by a more massive, finer-grained, more argillaceous greywacke. The topmost part of the upper subdivision commonly has abundant mudstone chips together with diffuse dewatering structures (discussed later). There is little evidence of current activity as the B and C divisions of the normal turbidite are missing. The top of the unit is capped by silty D laminations and the normal pelitic division. The two part nature of the division may be a result of local ponding of the turbidity current in a depression on the depositional surface, the lower part representing deposition from the moving current while the upper part is a result of deposition from the locally ponded water-sediment mass.

Division of Parallel Lamination (B)

The lower parallel laminated division of the Bouma sequence is the most poorly represented part of the cycle (Table 2). Most laminations are straight to slightly wavy and tend to be diffuse rather than sharply defined. In thin section they consist of alternations of coarser and finer grains, with the finer-grained zones appearing darker due to a higher content of chlorite. The laminated division varies from medium sand to silt and can be graded. If only the laminated division is present and the sediment is very fine grained, it is often difficult to determine to which of the two laminated divisions it belongs. In places the B division merges laterally into the rippled division and then returns to the parallel laminated form, suggesting fluctuations in the flow conditions of the depositing current. The poor representation of this division may be in part due to poor exposure on the normal weathered surface, particularly where there is little compositional variation between laminae. In some cases the laminated nature of an apparently massive bed containing scattered carbonate concretions is revealed only by the differential weathering of the concretions. The absence of this division may be related to the flow conditions under which it forms. Walker (1965) has speculated that it may be possible to pass through to a lower flow regime bed form without the formation of the parallel laminated division with the right combination of decreasing current velocity and grain size.

The Rippled Division (C)

The ripple-laminated division can either arise imperceptably from the underlying divisions (Fig. 17) or starts very abruptly with fine scours. In many cases it consists of a single set of ripples at the top of the A or B division but in others it consists of spectacular trains of climbing ripples traceable through a two or three foot (0. 6 or 0. 9 m) interval. The angle of climb of the ripple train remains constant or increases in the higher part of the division except at the very top of the division where the angle of climb flattens as the ripples fade out (Fig. 17). This is to be expected in turbidites as it is a reflection of the decreasing flow regime under which deposition took place.

The external ripple form may be all that is visible as there is insufficient contrast in grain size and composition to bring out the internal structure. When the internal laminations can be seen, several ripple types are present. These vary from completely preserved climbing laminations (Type B of Jopling and Walker,

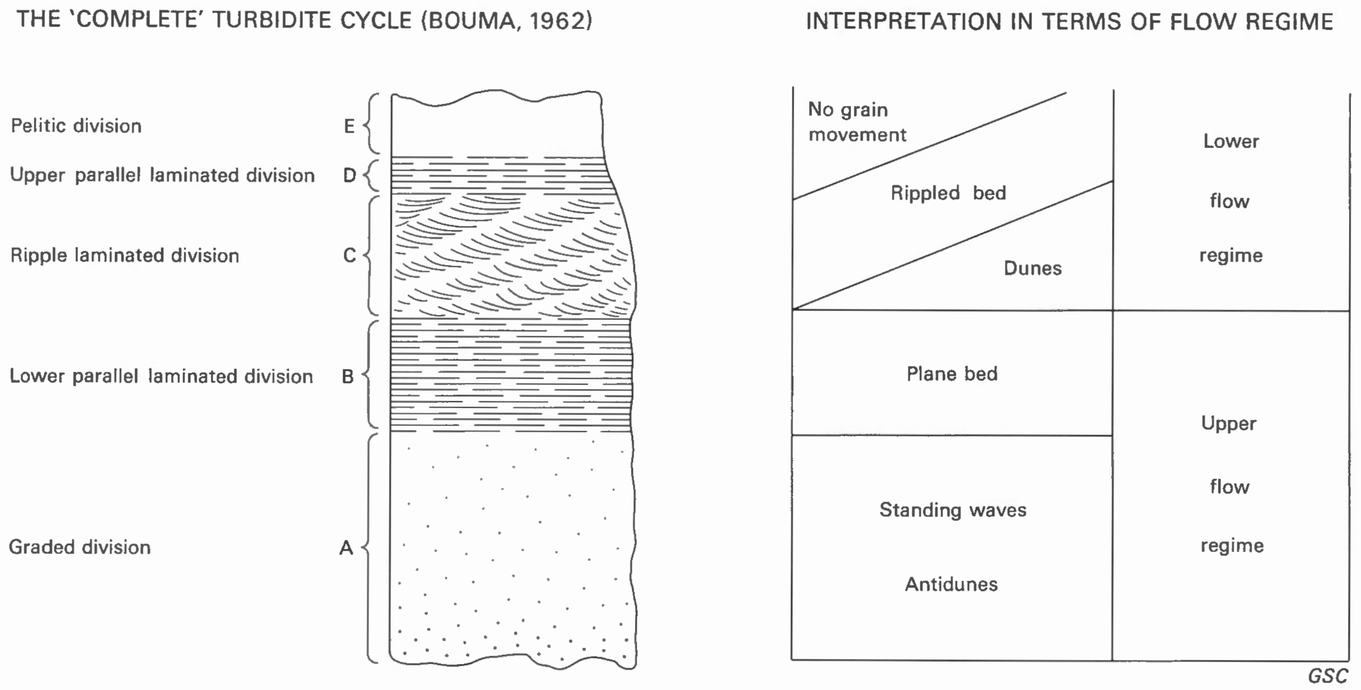
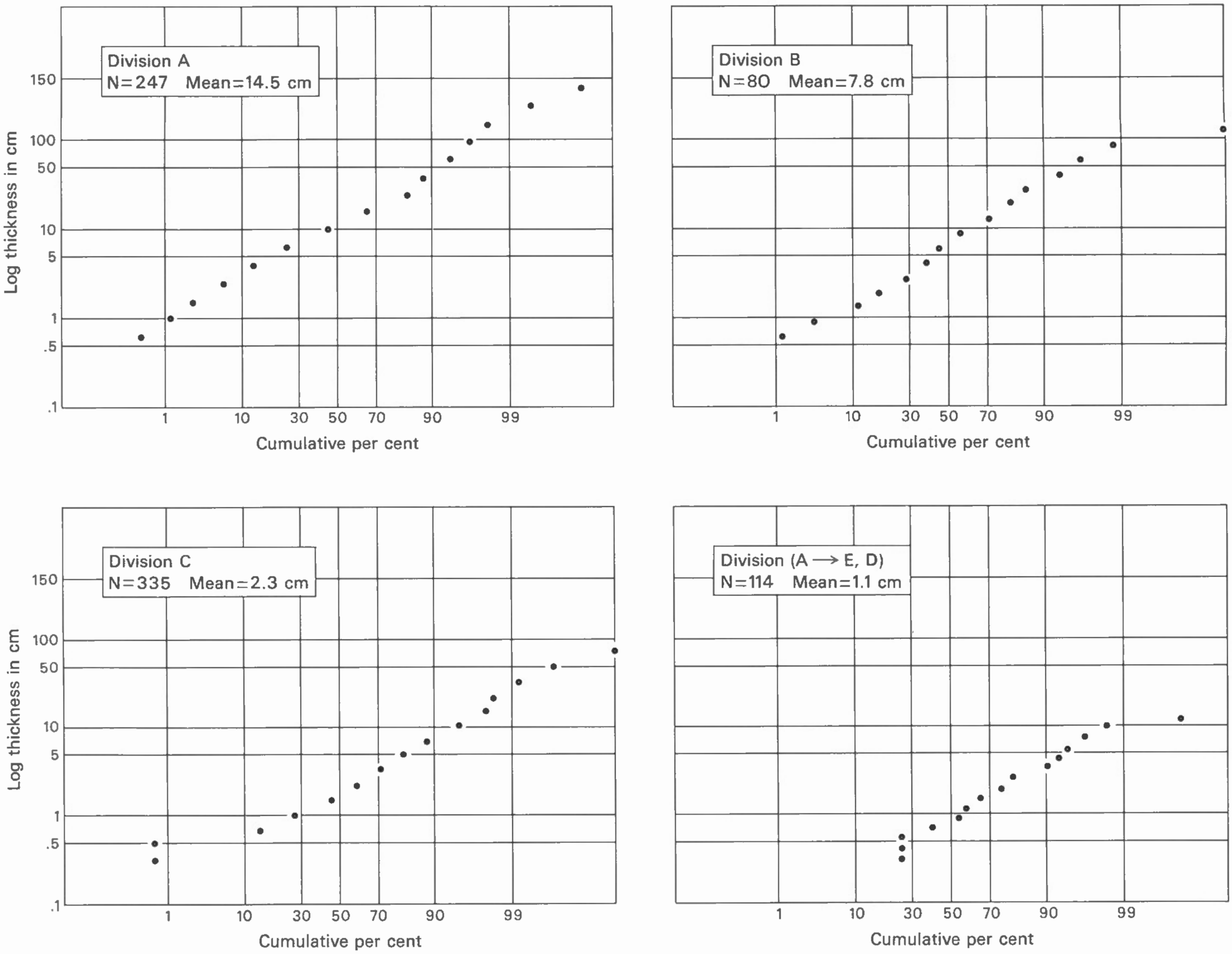


Figure 14. The Bouma sequence of sedimentary structures and their interpretation in terms of flow regime (after Walker, 1967). The vertical sequence of sedimentary structures reflects a waning flow regime with the basal part of the bed deposited under higher flow conditions than those under which the upper part of the bed formed. This is the ideal or complete sequence. In most cases one or more divisions of the sequence are missing.



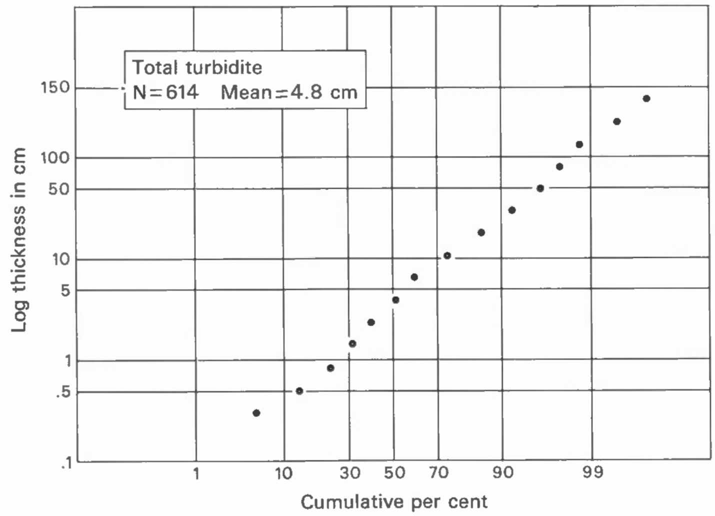


Figure 15.

Logarithmic probability plots of turbidite division thickness, Section J. Burwash Formation. Bedding and individual division thickness of the turbidites approximate a log normal distribution.

Figure 16.

Erosional scours at the base of a turbidite unit. Note the eroded wave-like form of the scours in the underlying mudstone. The scours are filled with coarser-grained, tangentially crossbedded sand with the cross-laminations approximately parallel to the more prominent glacial striae.

1968) (Fig. 18), to a series of foresets where the stoss side of the ripple was an area of nondeposition or erosion (Type A, Jopling and Walker, 1968), to irregular ripples where the tendency to form ripple sets was very short lived. In most cases there is a vertical gradation in grain size through the ripple-laminated division ranging, from a medium to fine sand at the base of the ripple train up to an argillaceous silt at the top. The sediment is commonly differentiated across the ripple with the coarser material concentrated on the crest or upper part of the stoss side and the finer material segregated in the trough. In such cases all that may be seen are diffuse zones of silt alternating with more argillaceous zones at a low angle to bedding (Fig. 19). Only on close examination can individual ripple laminations be traced across the zones. In thick units where the ripple laminations are not apparent, this segregation may produce a false or pseudo-crossbedding which, if interpreted as crossbedding, gives a reverse current sense from that indicated by the ripples.

In a few cases there is a repetition of the ripple division within the bed. In one example a vague ripple form grades up into a parallel lamination which is then overlain by a second rippled zone. As mentioned previously, in some cases it is possible to trace a rippled division laterally into parallel-laminated material and back again into the rippled form. In such cases, the flow parameters do not change in a regular manner but waiver back and forth between upper and lower flow regime. The good correlation between the thickness of the bed and the thickness of the ripple-laminated division would suggest that the rippled division is a result of deposition from the initial turbidity current rather than later reworking of the sediment by independent bottom currents.

Upper Parallel-Laminated Division (D)

The upper division of parallel lamination is commonly gradational from the underlying C division. The

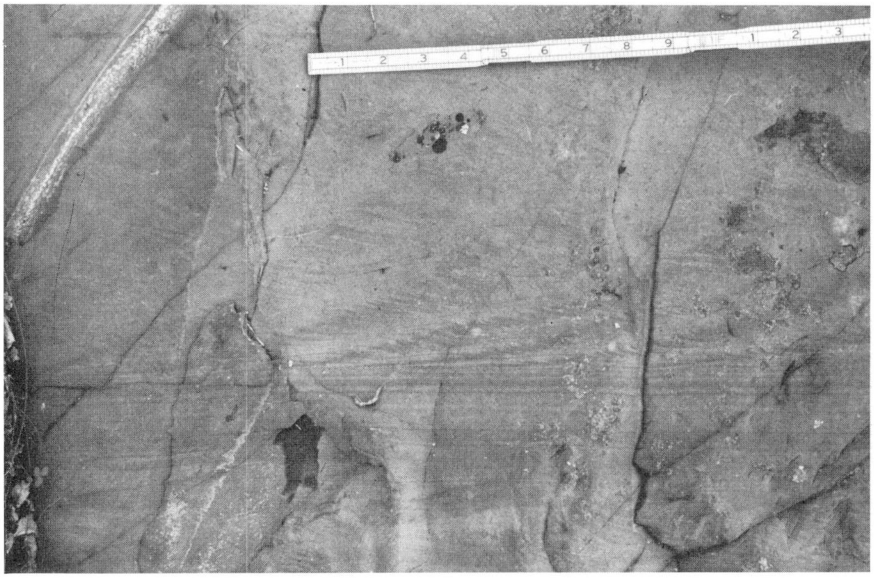


Figure 17.

Transition from parallel-laminated division (B) to ripple-laminated division (C). Note the increasing angle of climb of the ripple foresets, reflecting the decreasing flow regime and accompanying increased rate of sediment deposition.

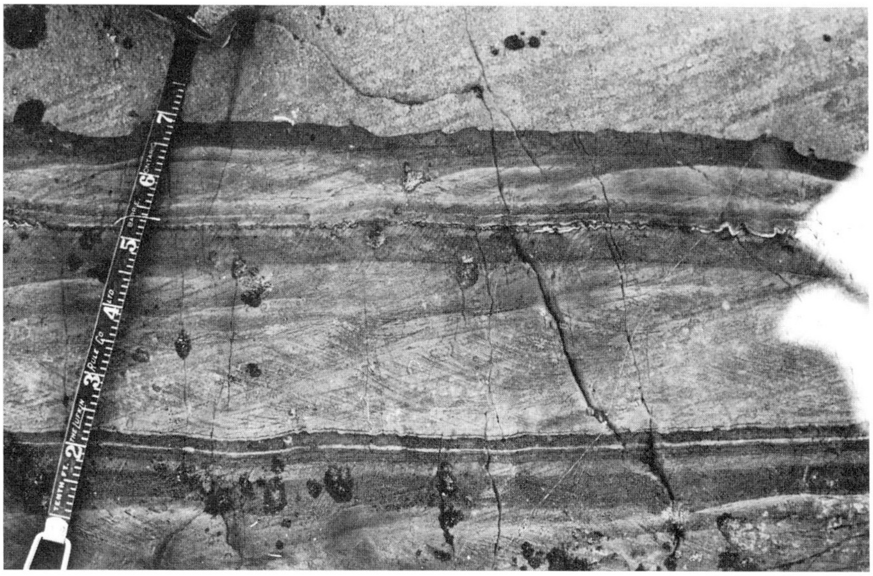


Figure 18.

Two turbidites that start with the rippled division (C) of the Bouma sequence and show the characteristic sequence of climbing ripple foresets. Grain size in this division is typically less than fine sand and is commonly graded.

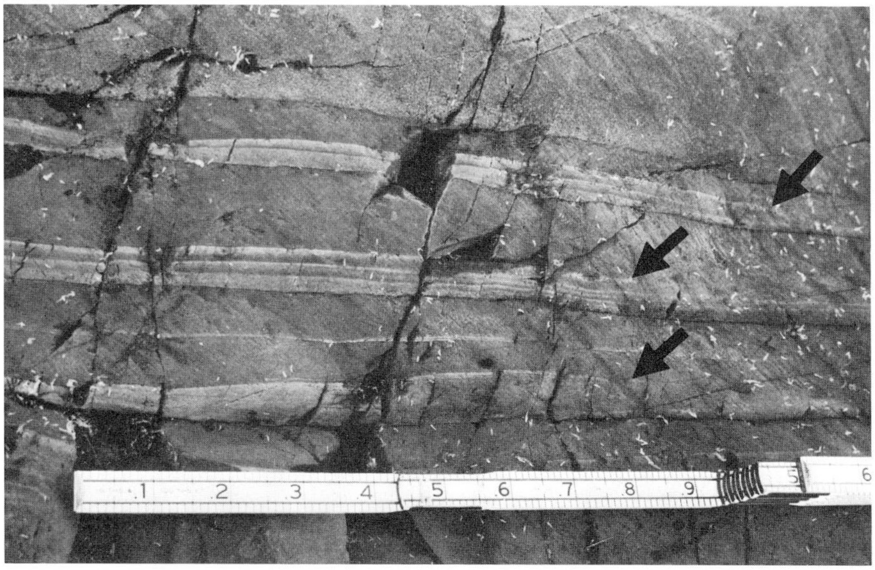


Figure 19.

Very low-angle climbing ripple trains. Three thin turbidites beginning with the rippled division (C) underlie a much thicker, coarser-grained, graded turbidite beginning with division A. The ripple turbidites consist of zones of light coloured silt separated by darker more argillaceous siltstone and mudstone oriented at a very low angle to bedding. Each band is a climbing ripple set in which individual ripple cross-laminations are not visible. The banding is caused by the differentiation of grain size across the ripple form with coarser silt at the crest and the finer more argillaceous material in the trough between. The low angle is in part due to the section being oblique to the current direction.

D division is generally undulatory as it passes over the ripple crests but becomes flatter higher in the division (Fig. 20). Although the laminations are commonly undulatory they can be distinguished from the upper ripple laminations of C by their consistent thickness, compared to the laterally variable thickness characteristic of ripple laminations. The laminae are composed of very fine-grained silt to argillaceous silt and are generally gradational into the overlying pelitic division. The nonlaminated graded argillaceous silts that can also occur in this position in the sequence are considered to be equivalent of this division. It seems unlikely that the sediment of this division was deposited under the direct influence of the turbidity current itself, but is more likely a result of the deposition of suspended material left after the passage of the current.

Closely related to this division are the (A→E) units of Walker (1967). These are thin fine-grained sands or silts that grade evenly up into the pelitic division showing neither parallel nor cross-lamination. These (A→E) units are interpreted as a special case of the more common DE unit in which the laminations did not develop. These characteristics, together with their association with beds starting with divisions C and D, indicate deposition under low flow regime conditions.

Pelitic Division (E)

The uppermost pelitic division is gradational from the upper parallel-laminated interval and differs from it by the absence of the more silty laminations. It is generally massive, although in some cases there is a faint gradation in colour suggesting decreasing content of silt. In very few cases there is an abrupt break near the top of the interval where the normally very dark-brown, grey-weathering, often silty mudstone gives

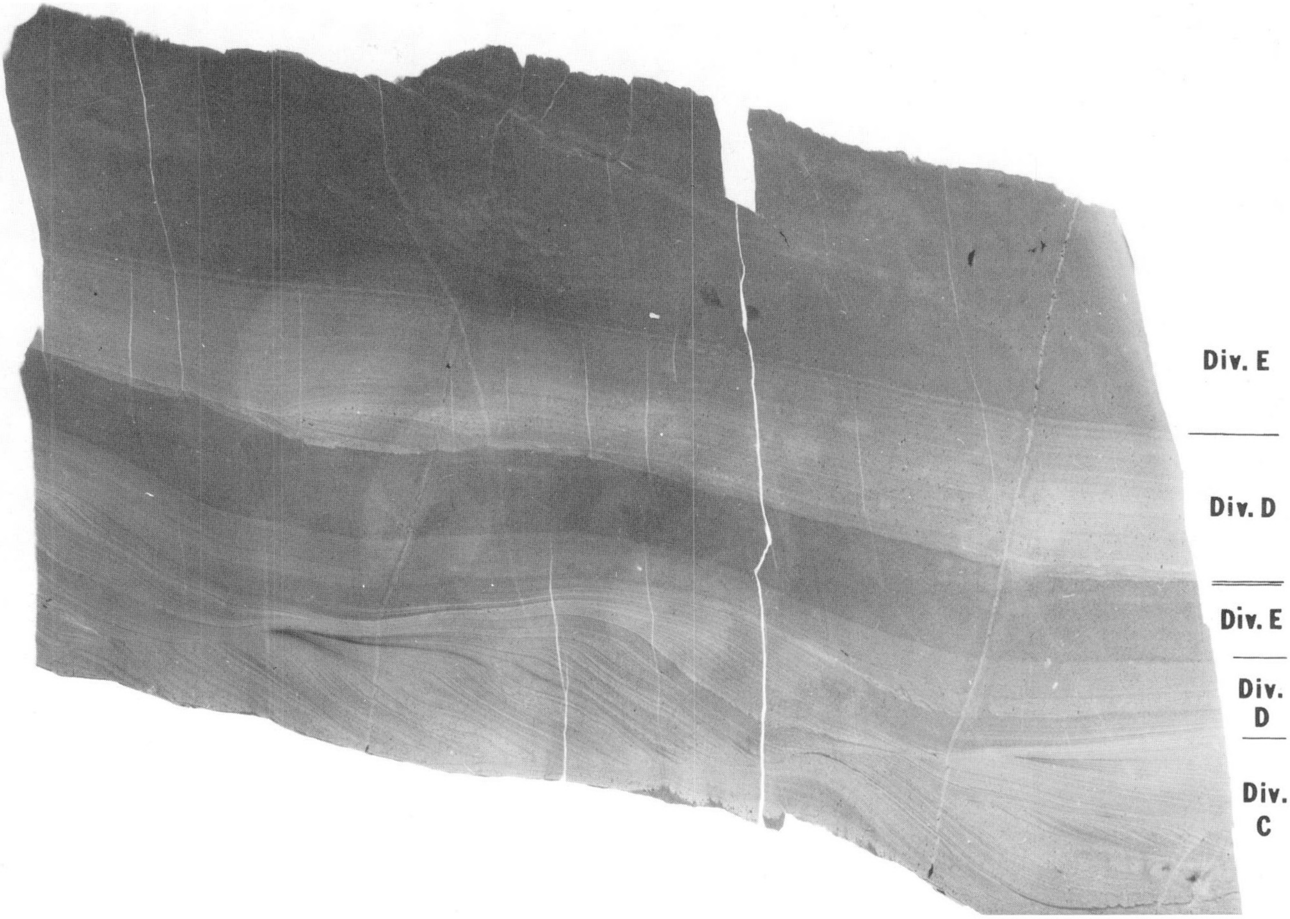


Figure 20. Transition from the rippled division (C) to the upper parallel-laminated division (D). X-radiograph in which the lighter tone is silt and darker tone mud. The specimen is 6 inches (15 cm) across.

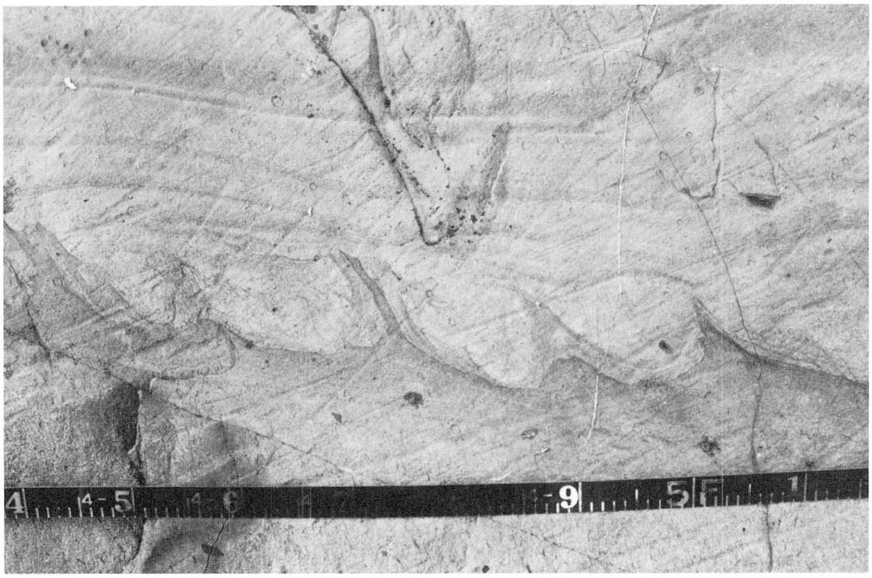


Figure 21.

Load and flame structures. The sand lobes which were originally sand filled scours have sunk downwards while the underlying mud has been intruded upward between the descending lobes of sand. Note the lack of effect on the overlying laminated sands. Scale in tenths of feet.

way to jet black mudstone. This black mudstone may be a true pelagic deposit whereas the browner siltier mudstone represents the deposition of the last of the material brought in by the waning current.

DEFORMATION STRUCTURES

In addition to the primary structures discussed above there are a great number of post-depositional nontectonic structures in the Burwash Formation that involve destruction or alteration of the primary features of the beds.

Load Structures

Among the most abundant of the deformation structures are load structures at the contact between sand and mud at the base of the turbidite. There is a complete gradation from normal undeformed basal scours to highly deformed load structures and completely disrupted bedding. Bedding-plane surfaces are rare so that almost all observations of these structures are in cross-section. Load structures are due to differential loading that resulted in the sinking of the basal sand of a bed into the underlying mud and the concomitant injection of mud into the overlying sand between the sinking sand lobes to form flame structures (Fig. 21). Differential loading is believed to be due either to the concentration of sand in scours or other depressions, by the vertical piling up of sediments as in ripples, or by the formation of an undulatory surface and liquefaction of the sediment by the passage of earthquake waves (Dzulynski and Walton, 1965). The few exposed bedding planes show features similar to sole marks of current or soft-sediment deformational origin (Fig. 22). Because these structures are invariably oriented parallel to the fold axes they are thought to be sole marks formed by either current activity, or soft-sediment deformation, or a combination of both, but have been reoriented parallel to the fold axes during subsequent tectonic deformation.

Load Balls

If loading is extreme, the sand or silt protuberances may become completely detached from the overlying bed and form load balls or pseudonodules (Dzulynski and Walton, 1965). These may be massive or laminated depending on the original nature of the bed. In the case of thin ripple-laminated siltstones often all that remains of a once continuous bed is a series of these laminated load balls near the top of the underlying unit. Commonly, the generation of these structures can be traced from a completely undeformed bed through the development of load structures to the complete break-up of the bed and then back again to the normal undeformed unit over the space of a few tens of feet (10 m). In one exceptional case, the detached load balls sank completely through the underlying mud and argillaceous sand before piling up above a cleaner coarser massive sand near the base of the underlying unit (Fig. 23). In most cases these load balls are composed of silt to very fine sand-sized material. In one case, however, slightly elongate to equidimensional blocks of massive medium sand up to six inches (15 cm) occur at the top of one unit, presumably derived from the lithologically similar overlying sand.

Convolute Bedding

Convolute bedding, a common feature in most turbidite sections, is rare in the Burwash Formation. Only one or two examples with the usual sharp-crested anticlines and the broad open synclines were seen (Fig. 24). An oversteepening to generally irregular deformation of ripple foresets is more common. In some cases, the lower part of the ripple-laminated

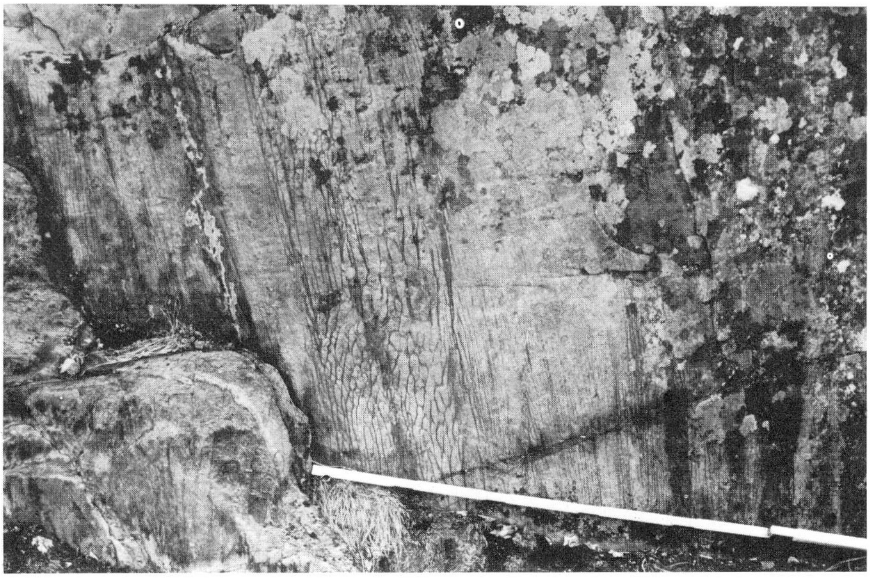


Figure 22.

Sole marks on base of greywacke bed. Exposures of basal sole marks are relatively rare in the Burwash Formation as bedding planes are rarely exposed. The structures are commonly tectonically reoriented parallel to local fold axes.

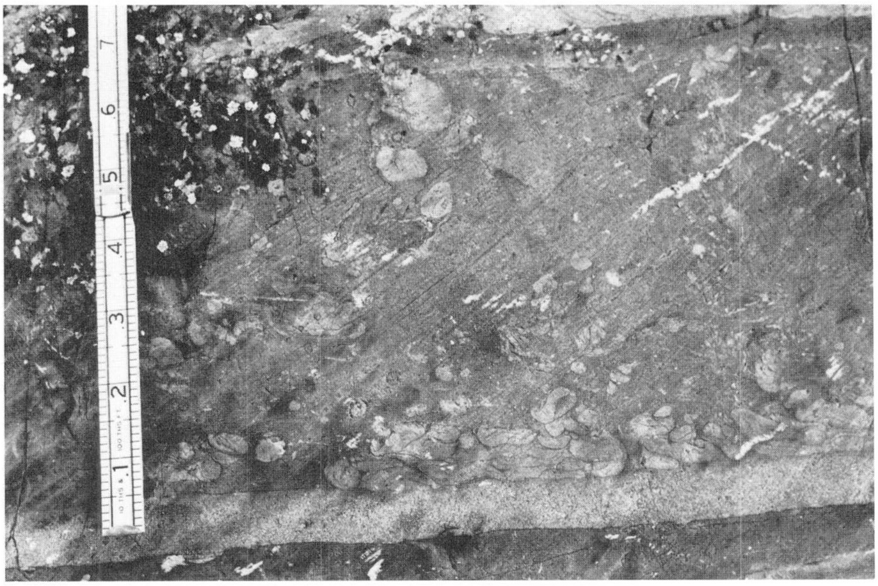


Figure 23.

Detached load structures. These detached load structures, originally formed from a now destroyed rippled silt bed near the top of the photograph, have completely sunk through the underlying more argillaceous fine grained sand and have accumulated near the top of a coarser-grained less argillaceous sand. When the bed is traced laterally these load balls can be seen in all stages of development from the undisturbed rippled silt to what is seen here. The striae at high angle to bedding are of glacial origin.

Figure 24.

Convolute bedding in Burwash turbidite. Despite the extreme soft-sediment deformation of the main part of the bed, the overlying silty laminations and rippled division of the next bed are not disturbed.

division is strongly distorted while the upper part is essentially undisturbed indicating syn-depositional deformation.

Dewatering Structures

In some beds a structure interpreted as due to dewatering is present. These structures commonly occur at the top of very argillaceous sands -- at the relatively sharp contact between the sand and mud. The unit consists of a basal, massive, relatively clean sand followed sharply by an equally massive, somewhat finer-grained, much more argillaceous sand. These structures are commonly associated with mudstone chips at the top of such units (Fig. 25). This structure varies from turnip to carrot-shaped in cross-section having a sharp conical top that gently projects above the surrounding sand. The sides of the structure are much more diffuse and taper down to an equally diffuse point. The structure is approximately half an inch (1. 3 cm) wide and about an inch (2. 5 cm) long although the size is quite variable. They weather much lighter than the surrounding sand. Thin sections show that both the host and the structure are texturally wackes but the latter is almost free of chlorite whereas the surrounding sand contains an abnormally high amount. They are believed to be due to the expulsion of water from the saturated sands, that which locally flushes out some of the argillaceous material and results in the formation of the sand blisters at the top of the unit below the more impervious mudstone.

Intrusions

Although sedimentary intrusions are by no means common, one or two examples can usually be seen in

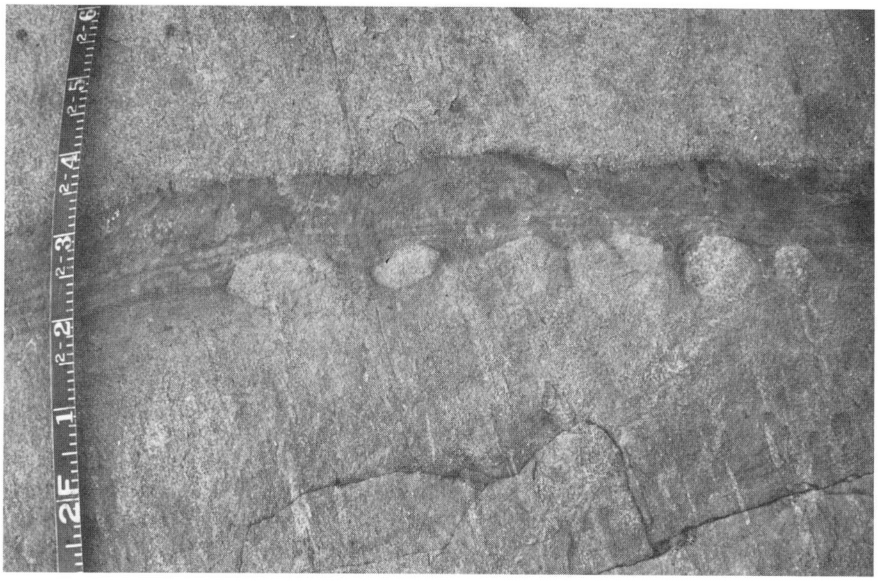


Figure 25.

Dewatering structure at the top of a massive greywacke unit. This structure forms as a domal blister at the interface between the greywacke and the overlying silts and muds as a result of the expulsion of water from the saturated greywacke.

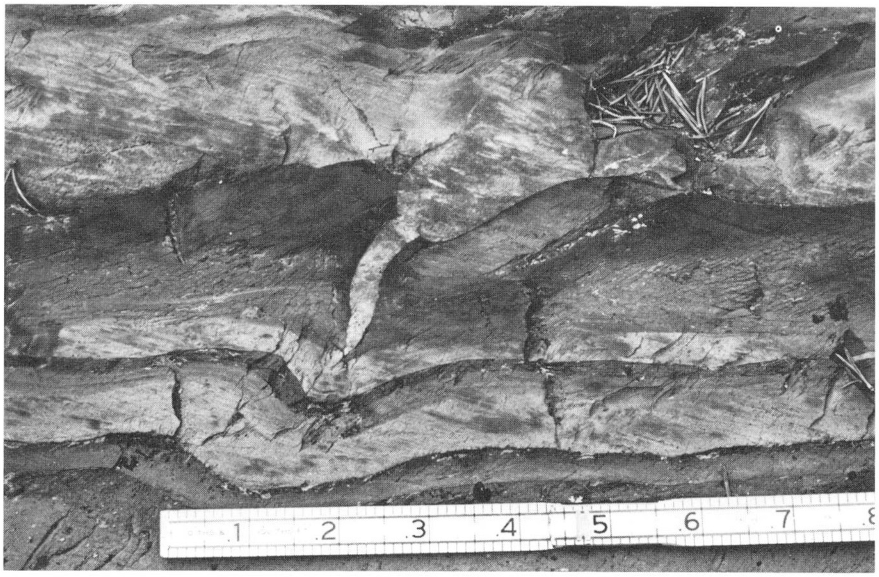


Figure 26.

Intrusion of fine sandstone dyke into the underlying mudstone. Compaction of the sediment has resulted in the fracturing of the more mobile sand from the load structure at the base of the overlying sand.

most sections of the turbidites. They include: thin dyke-like structures of sand which pass through one or more beds up or down into the sand of an adjacent unit (Fig. 26); sills to lensoid bodies of sand of varied thickness in the silty or shaly parts of some units; and funnel-shaped structures (in section) that expand upward and also commonly extend through several beds. The intruded material is almost always structureless sand, except for included shale chips in some of the larger intrusions, particularly the funnel-shaped type. In many cases the source of the sand is not apparent as the exposed part of the intrusion does not always project from a potential source of sand. These structures are a result of compaction and resultant expulsion of excess water contained in the sediment.

OTHER STRUCTURES

Intraformational Conglomerate

Intraformational conglomerates composed of dark-coloured, massive to laminated argillaceous siltstone and mudstone fragments and chips are a common feature of these beds. The mudstone clasts are angular to well rounded, equidimensional to elongate in the larger clasts and vary in size from small chips to elongate blocks or rafts several feet (1 m) in length (Fig. 27). They occur anywhere in the bed and in all concentrations but typically are found in small groups in the upper part of the massive sand division of the bed. The clasts are local in origin, largely ripped-up previously

Figure 27.

Angular mud chips in an otherwise massive structureless greywacke. It seems unlikely that mud chips as angular as this could have been transported any distance without some abraision of the sharp projections. This breccia is more likely the result of intrusion and brecciation in place of an originally much larger raft of mudstone.

Figure 28.

Mudstone layer distorted by the loading of overlying laminated sand and the accompanying intrusion of irregular fine grained dykes and sills. If this soft sediment deformation had continued the result would have been the obliteration of the mudstone layer leaving only angular chips and fragments of mudstone (*see* Fig. 27).

deposited mudstones. The extreme angularity of many clasts may be due to post-depositional compaction of the soft fragments, as the delicate projections on many clasts could not otherwise have been preserved during transport. Some of the angular clasts are formed by massive irregular intrusion of sand (Fig. 28) into a more competent mudstone resulting in the amalgamation of two individual turbidites with the total disruption in place of the thin argillaceous divisions.

A second type of intraformational breccia, found locally throughout the section, consists of large scattered blocks of thin-bedded tuff. These are very angular and vary in size from several inches to several feet (8 cm - 3 m) in length. They consist of several beds of perfectly graded, bright yellow-weathering tuff that consists of primarily medium sand-sized euhedral feldspar grading to jet black shale. This tuff is believed to be intraformational but was only seen as blocks in the greywackes -- never as continuous beds (Fig. 10). In the main part of the Archean basin east of Yellowknife similar tuffaceous zones consisting of five or six beds occur interstratified with the normal turbidites.

Concretions

Metacarbonate concretions are a common feature of many of the thicker greywacke beds. Similar concretions have been reported from many Archean and younger turbidites (Eskola, 1932; Pettijohn, 1940). Typically they occur in the central part of thick, massive greywacke beds as scattered nodules to continuous layers less than three or four inches (9 cm) thick. The scattered concretions are always at the same level in the unit and if traced laterally commonly join into a continuous layer. The concretions weather lighter

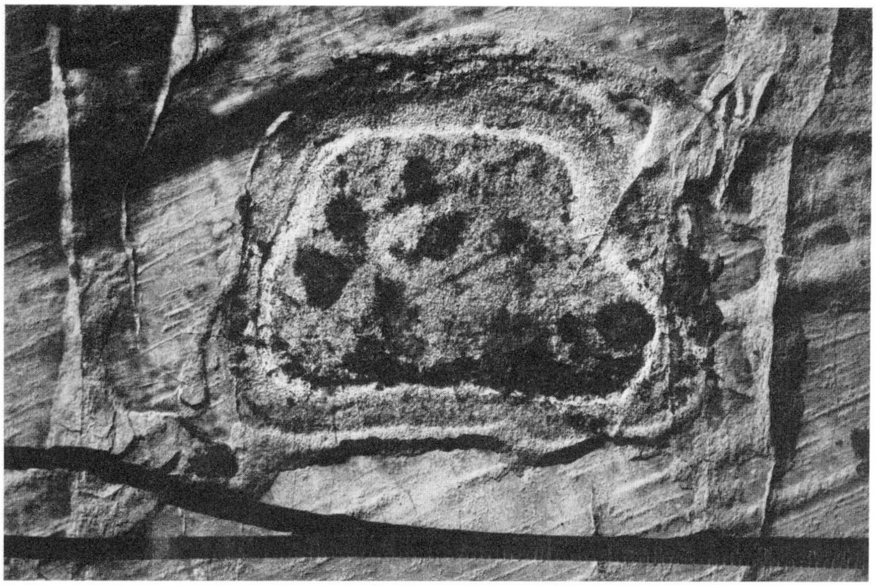


Figure 29.

Zoned meta-concretion in massive greywacke. Due to metamorphosed to a calc-silicate mineral assemblage. In addition to individual structures such as this, the meta-concretions commonly occur as a series of elongate bodies at the same level in the greywacke bed.

than the normal greywacke and commonly show differential weathering. Any internal structures in the greywacke are accentuated in the weathered concretion. Greenschist-grade regional metamorphism has resulted in the reaction of the original carbonate with the silicate phase in the sediment to produce a calc-silicate mineral assemblage within the metaconcretion. The concretions commonly display concentric zones (Fig. 29) due to the varied concentrations of calcic plagioclase and fibrous feathery green amphiboles.

GREYWACKE PETROGRAPHY

Despite low-grade regional metamorphism and altered mineralogy the rocks are referred to by their sedimentary names. Thus greywacke and mudstone will be used instead of the more accurate meta-greywacke and slate.

The Burwash Formation consists of interbedded greywacke and mudstone units with greywacke greatly predominating in most places. On the weathered surface the rock is generally light grey to light brownish grey, exceptionally almost black to dark greenish grey. The weathered colour is a function of composition and a crude estimate of the relative proportions of the constituents can be made. The light-coloured to light greenish grey greywackes tend to be high in silicic volcanic rock fragments while the more quartzose varieties weather a darker grey. Commonly there is an abrupt change in the colour of a bed suggesting that the upper part of the greywacke is significantly different in composition than the lower part. The greywackes display the magnificently exposed sedimentary structures which have been discussed previously.

In hand specimen the greywackes are very uniform, invariably dark grey on the fresh surface with a lighter weathered rind about one-eighth inch (3 mm) thick. They are massive, extremely tough and break with a conchoidal fracture. On fresh surfaces, the quartz is broken across the grains and occurs as black glassy fragments against the dark-grey background. The sedimentary structures which are so well exposed on the weathered surface are not visible on fresh surfaces. There is little shearing in the massive sands but the mudstones are commonly highly cleaved particularly where thin. Although the area is metamorphosed to the greenschist facies, the metamorphic effects are megascopically almost negligible, although in places small metacrysts of biotite appear as small knots in the mudstone and as small brownish pits on the weathered surface of the greywacke.

The Burwash Formation greywackes are typically homogeneous, massive, and composed of a framework of angular quartz, rock fragments of mainly volcanic origin, and feldspar in an abundant matrix of chlorite, muscovite and fine-grained quartzo-feldspathic material. The maximum grain size is medium to coarse sand with a complete gradation down to matrix-sized material. They are good examples of greywackes by any definition (Fig. 30).

On the weathered surface individual quartz and feldspar grains are apparent. The surface, although flat and smooth due to glacial polish, has weathered enough to accentuate these grains due to breakdown of the softer and weaker matrix. The relatively easily-weathered rock fragments in the sandstone are not normally visible on the weathered surface.

The grain size of the greywacke is, on the whole, less than medium to coarse sand. Maximum grain size is of the order of 0. 7 mm to 1. 5 mm with the typical framework grains between 0. 3 mm and 0. 7 mm. There is a complete gradation of size from the maximum observed down to matrix (<. 02 mm). On the whole quartz tends to be the coarsest material although in a few cases there are some large volcanic rock fragments. Coarser material, where present, occurs as scour-fill deposits at the base of some of the beds. Pebble or cobble-sized material was noted at only two places. One, at the top of the formation, consists of a three-foot (1 m) gravel bed that grades upward to medium

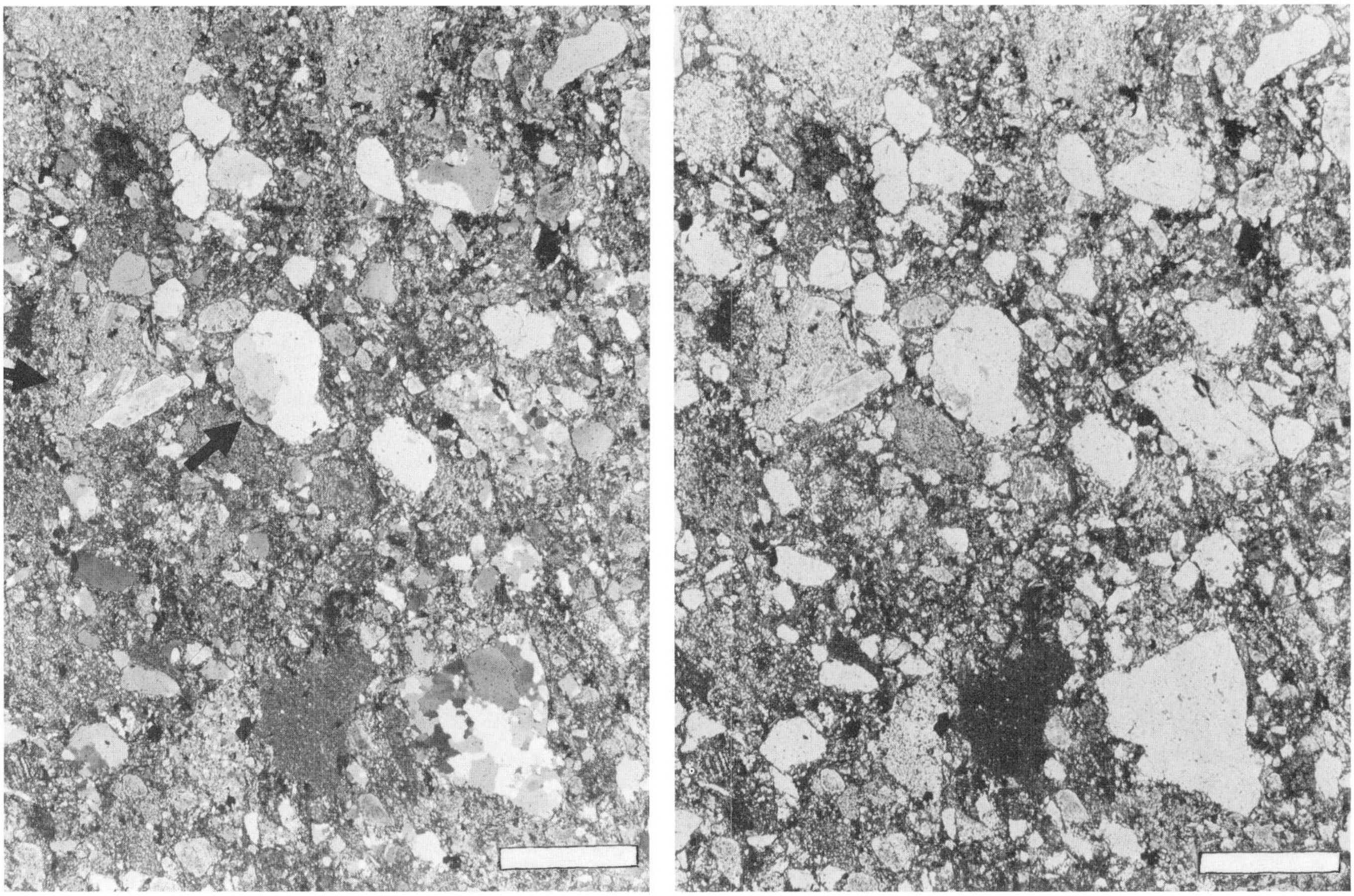


Figure 30. Photomicrographs of coarse-grained Burwash Formation greywacke showing typical greywacke texture. Left and right photographs are under polarized and plane light respectively. Rock fragments of predominantly silicic-volcanic origin are abundant. They commonly have a diffuse contact with the matrix. In particular note the felsic volcanic fragment containing feldspar phenocrysts in the upper left quadrant and the feldspar grains immediately to the right. The large, fine-grained, dark clast in the lower central part of the photographs is mudstone of probable intraformational origin. Length of bar is 1 mm.

sand-sized material. The coarsest detritus (5 mm) occurs as single and composite grains of rounded quartz and silicic volcanic rock fragments. The following two or three beds are also atypically coarse with a maximum grain size of coarse sand. The second case occurs in the central part of the formation (in section G, Fig. 2) where, in the upper part of a two-foot (60 cm) graded bed, well-rounded granitoid pebbles with a maximum size of 3 inches (7 cm) are disseminated in the upper part of the unit at intervals of one foot (30 cm) or less.

The grains are angular. Many quartz grains display serrated grain outlines due to the metamorphic development of chlorite. A few quartz grains have euhedral to subhedral outlines but for the most part are broken fragments. The feldspar grains are also poorly rounded, occurring mainly as cleavage fragments or as euhedral to subhedral crystals. The rock fragments, however, exhibit a complete gradation from clearly identifiable, sharply-defined, angular clasts through to very diffuse grains that merge with the matrix.

The degree of packing is dependent on the interpretation of the origin of the matrix. The rock now is poorly packed because virtually none of the coarser grains are in contact with each other. They are almost invariably enveloped by a chlorite-muscovite matrix. If, however, the fines are due to the post-depositional breakdown of some of the coarser material (Cummings, 1962) then indeed the original sediment as deposited might have been much closer packed than it would now appear. However the matrix developed, it reduces the present porosity of the rock to nil.

Most of the "framework" grains show little or no orientation. Any orientation that is present tends to be parallel or at a low angle to bedding and is thought to be tectonic in origin. This precludes the use of grain orientation studies for paleocurrent determinations.

The greywackes are mineralogically, chemically and texturally immature. This is shown by the abundance of chemically and mechanically unstable rock fragments and feldspar and the relatively low ratio of alumina to soda (*see* Chemical Analyses Table 4) which is an index of chemical immaturity (Pettijohn, 1957). Textural immaturity is indicated by the angular nature of the coarser fraction and perhaps the abundance of fine-grained matrix. Again care has to be taken in the interpretation of the origin of the matrix. If, as suggested by Cummings (1962), greywacke matrix is derived from the post-depositional mechanical and chemical breakdown of unstable grains it really cannot be used as an indicator of textural maturity. If, on the other hand, it is diagenetically produced, it is further evidence of mineralogical immaturity of the original sediment.

Modal analyses of representative samples of the Burwash greywacke are presented in Table 3. The samples are taken from various points in the formation and represent a vertical section through it (Fig. 2). Modal analyses of greywackes present some difficulties in that the results tend to be rather subjective due to the difficulty of objectively differentiating between matrix and some of the framework components, particularly rock fragments. It has been shown that a given operator is quite consistent but analyses by different operators are not usefully comparable (Welsh, 1967). The analyses in Table 3 were all done by the same operator and thus can be used for comparative purposes. Comparison with analyses of other greywackes probably would not be very useful.

Quartz

Quartz, with a few exceptions, is the most abundant framework constituent, making up between 19% and 30% (average 25%) of the sandstones. The quartz grains are classified as one of three types: 1) single grains, 2) polycrystalline with less than six crystals, 3) polycrystalline with greater than six crystals. Blatt (1967) has suggested that the degree of polycrystallinity may reflect the past history of the grain. Polycrystalline grains with greater than six crystals are more likely to have been derived from a metamorphic source than a plutonic source. From Table 3 it is apparent that monocrystalline quartz grains are by far the most abundant, making up between half and three quarters of the total quartz. Polycrystalline quartz with less than six crystals is commonly less than one third the total amount while highly polycrystalline grains make up less than one tenth of the total.

The single crystals are anhedral for the most part but rare euhedral crystals, some with embayments, are present. The polycrystalline aggregates are tightly interlocked and vary from equant equigranular mosaics to ragged aggregates with a bimodal size distribution and a distinct preferred orientation of the long axes of the grains. Almost all the grains exhibit undulatory extinction. No secondary overgrowths on the quartz grains were seen. Many of the grains have dusty trains or bands of fine inclusions. The development of chlorite and muscovite in the matrix at the expense of the quartz commonly has resulted in very irregular to serrate margins on the quartz grains.

The low proportion of probable metamorphic quartz (polycrystalline grains with greater than six crystals and exhibiting a bimodal distribution of crystal size within the grain) suggests that a metamorphic terrain was not important in the provenance of these sediments. On the other hand, the abundance of single quartz crystals and the occasional embayed euhedral grain suggests an igneous, in part volcanic, component in the source area. Most grains, however, are of indeterminate provenance.

Rock Fragments

The rock fragment component is of great interest because it provides the best information as to the nature of the source of the detritus in the greywackes.

In the Burwash greywackes rock fragments make up between 14% and 30% (average 22%) (Table 3) of the sediment although the distinction between rock fragments and matrix is somewhat subjective. Rock fragments have been classified into different types and the proportions of each (expressed as a percentage of the total amount of rock fragments in the sample) are listed for a representative suite of samples from the Burwash Formation (Table 3).

Volcanic rock fragments are by far the most abundant and of these the most important are the more silicic varieties. These silicic volcanic rock fragments are colourless to light brown in plane light and are made up of a tightly interlocking mosaic of low birefringent material with sweeping to irregular extinction pattern. Tiny grains of pale-green chlorite are scattered throughout this mosaic. In some cases a phenocryst of quartz or feldspar is found in the grain but this is not common. The "cleaner" varieties bear a strong resemblance to recrystallized chert with which they might be easily confused. There is a complete gradation from silicic to more mafic volcanics which are characterized by an abundance of chlorite, darker colour, and thin plagioclase laths. The grain boundaries vary from sharp and distinct to almost continuous with the matrix. An objective criteria to separate rock fragments from matrix is difficult to establish.

Sedimentary rock fragments are the next most abundant variety. Mudstone clasts are distinguished by their dark colour, abundant muscovite and generally flattened or squeezed appearance. They commonly have a well-developed foliation due to this compression. Mudstone fragments grade into siltstone with decreasing amounts of silt-sized quartz grains. In some cases the grains in these clasts are coarse enough for them to be classified as fine sandstones. The sedimentary clasts are interpreted as dominantly intraformational due to their similarity to the mudstone within the sequence.

Plutonic rock fragments, although making up less than 10% of the rock fragment component, are present in all the samples. They are tightly interlocked aggregates of quartz, plagioclase and in some cases chlorite, and exhibit typical granitic texture. Usually the grain is composed of only two or three crystals. The chlorite may represent altered primary biotite. These rock

Table 3

Modal Analyses of Burwash Formation Greywackes

	J.348	G.2	F.122	H.38	E.149	E-1.66	B.96	75b	L.2
Total Quartz	21.8	19.0	30.5	18.8	26.1	23.8	29.9	28.3	26.2
Monocrystalline	67.0	63.7	58.7	49.5	64.0	76.5	65.5	85.2	37.0
Polycrystalline <6 crystals	28.4	28.9	34.4	35.6	28.7	17.6	29.1	12.7	47.7
Polycrystalline >6 crystals	4.6	7.4	6.9	14.9	7.3	5.9	5.4	2.1	15.3
Rock Fragments	23.2	29.9	14.5	21.7	20.8	24.8	15.8	24.0	20.5
Silicic Volcanic	19.8	63.4	29.2	34.2	49.5	46.8	12.5	57.2	9.1
Intermediate Volcanic	3.6	15.8	12.5	19.8	19.6	0.0	22.5	8.1	2.0
Mafic Volcanic	12.6	0.7	0.0	6.3	1.9	12.9	1.2	4.7	2.0
Siltstone	6.3	8.3	22.3	18.9	.9	6.5	16.3	8.1	63.7
Mudstone	20.7	4.8	13.9	10.8	3.7	5.7	7.5	14.5	15.2
Plutonic	5.4	6.2	9.7	0.9	8.4	3.2	8.7	4.0	8.1
Unidentified	40.5	0.7	12.5	9.0	15.9	24.9	31.2	3.2	0.0
Feldspar (Plagioclase)	12.6	11.3	18.7	19.1	14.4	7.0	11.5	7.1	11.3
Heavy Minerals	2.9	1.0	2.1	1.4	1.3	1.0	1.2	1.0	.6
Total Matrix	39.0	37.8	33.5	38.0	31.7	39.8	39.1	32.5	41.3
Chlorite-muscovite	75.6	42.9	80.9	89.7	24.9	72.9	89.5	85.2	61.5
Quartz-feldspar	24.4	57.1	19.1	10.3	75.1	27.1	10.5	14.8	38.5
Carbonate	.6	-	.5	1.0	-	-	-	7.1	-
Coarse Chlorite-muscovite	-	1.0	.1	-	0.8	3.6	2.6	-	-
Metamorphic Biotite		-	-		5.0		-	-	-
	100.1	100.0	99.9	100.0	100.1	100.0	100.1	100.0	99.9

Modal Analysis expressed as a percentage of 500 counts per section. Component breakdown expressed as a percentage of proportion of that component in modal analysis.

fragments indicate that a plutonic source may have been present in the region. Much of the quartz and feldspar in the greywacke may also have been derived from such a source.

Some rock fragments are very difficult to classify. There seems to be a complete gradation from polycrystalline quartz through to the fine mosaic of the devitrified silicic volcanic fragments. A miscellaneous category was set up for those fragments which did not seem to fit either of the above but are composed dominantly of quartz and chlorite. Their origin is not understood, but they may represent a more recrystallized form of the silicic volcanics.

The character of the majority of the lithic fragments is a further indication that the source area of the Burwash greywackes was a combination of volcanic (mainly felsic) and granitic rocks.

Feldspar

Of the three major framework components in the greywackes, feldspar, though always present, is the least abundant. It forms between 7% and 19% of the sandstone (average 13%). The feldspar is always plagioclase. Not one grain of detrital orthoclase or microcline was seen in any of the thin sections examined, all of which were stained using the standard HF etch and sodium cobaltinitrate stain.

On the whole, the plagioclase is finer grained than the quartz in the same sample. It occurs in two varieties, namely a relatively fine-grained, plagioclase with well-developed albite twinning and as an untwinned plagioclase that shows a greater degree of alteration than the twinned variety in the same section. In both varieties the alteration is insufficient to obscure the optical properties of the grain. Although a few cases of zoned plagioclase were seen, by far the most showed uniform extinction. The composition of the plagioclase is albitic.

The two types of plagioclase suggest two different sources. The significance of twinning or the lack of it is not clear. Commonly plagioclase that is a product of low-grade metamorphic plagioclase is untwinned. The higher degree of alteration of the untwinned plagioclase may suggest that it was originally more calcic and has been albitized. Such a grain might be derived from a source of more intermediate composition. The more common twinned plagioclase is similar to the "plutonic" rock fragments.

The deficiency of potassic feldspar in the greywackes requires an explanation. Rocks that could be expected to provide quantities of quartz and plagioclase such as granites, adamellites and granodiorites, usually have at least some potassium feldspar. On the other hand, Bass (1961) in his study of conglomerates of similar age in Ontario, suggests that deep-seated potassic granites may not have been exposed during the Archean to contribute cobbles to the conglomerates or, in this case, potassium feldspar to the greywackes. Glikson (1971) on the basis of experimental work by Green and Ringwood (1968) suggests that sodic granites would form the earliest granitic crust. An alternative suggestion is that potassic feldspar was present originally but has since decomposed due to diagenesis or low-grade metamorphism. Hemley (1959) in an experimental study showed that the breakdown of K-spar to mica and silica is a function of the K+/H+ activity ratio and the temperature -- with higher water content and low temperature favouring the breakdown of the K-feldspar. If so, any relict grain would now be composed of muscovite and quartz and might be lost in the matrix. Middleton (1972) has suggested that the deficiency of potash feldspar in the Cambrian Charny Formation near Quebec City is due to the alteration of the original K-feldspar to albite by the action of sodium-rich pore waters. Gluskoter (1964) suggests that the K-feldspar deficiency in the Franciscan in greywacke of California is due to its secondary breakdown.

Minor Framework Components

In addition to quartz, rock fragments, and feldspar, a few minor primary detrital constituents are also present. These include heavy minerals such as epidote, altered pyroxenes, detrital biotite and muscovite, apatite and zircon. Metamorphic biotite is also present locally depending largely on compositional restraints. In addition most sections contain ragged aggregates of secondary pyrite, some of which show euhedral outlines. Secondary calcite is also present in irregular patchy grains. Some sections show coarse aggregates of chlorite. These may be altered detrital biotite flakes. These minor constituents rarely make up more than 3% of the rock.

Matrix

The matrix of the greywackes is more abundant than any one of the framework components, making up between 30% and 40% (average 37%) of the whole rock. As has been previously noted the estimation of matrix versus framework is subjective, as in some cases there is a complete gradation between distinct rock fragments and matrix.

Two types of matrix are recognized. The first is a dense, very fine-grained tightly meshed intergrowth of chlorite, muscovite, and fine quartzo-feldspathic particles that envelope the framework elements. The coarser quartz grains display an intergrowth of matrix with the grain margins. This feature gives the greywacke its characteristic toughness. The maximum grain size of the matrix is arbitrarily defined as 0.02 mm as there is a continuous size gradation across this artificial boundary. The second type of matrix is very fine-grained quartzo-feldspathic material with minor amounts of chlorite and bears a distinct resemblance to the previously described silicic volcanic rock fragments. As the chlorite-muscovite matrix, this material completely envelopes the larger detrital grains preventing contact between them. Again there is a complete gradation from a diffuse matrix to clearly bounded rock fragments. In addition the two matrix types are gradational into one another.

The origin of the matrix in greywackes has been a subject of controversy; the essential problem is whether or not the matrix is primary or secondary. In the Burwash greywackes a strong case can be made for the diagenetic origin of the matrix, as suggested by Cummings (1962) who proposed that the matrix of greywackes is largely due to the mechanical and chemical post-depositional breakdown of mineralogically unstable grains. The abundant chemically and mechanically unstable sedimentary and volcanic fragments in the Burwash greywacke provide such a source for the matrix. In most thin sections a gradation can be seen from sharply bounded rock fragments through indistinct grains to the matrix itself. The chlorite-muscovite type matrix is formed by breakdown of sedimentary rock fragments while the fine-grained quartzo-feldspathic material is formed from the breakdown of the silicic volcanic rock fragments. Thus in the modal analyses of the greywackes (Table 3) the proportions of volcanic and sedimentary rock fragments should be considered as minimum estimate because much of the present matrix has been derived by the alteration of original rock fragments.

Mudstone

The greywacke beds grade up into, or at least are separated by, relatively thin mudstones. Petrographically the mudstones show the greatest effect of low-grade metamorphism in that the original detrital minerals have been completely recrystallized to chlorite, biotite, muscovite, quartz and feldspar, and the primary texture of the sediment has been lost.

MAJOR ELEMENT GEOCHEMISTRY

From petrographic studies it is evident that the Burwash sediments are very immature. Chemical analyses of this material, then, should give a close indication of the composition of the source terrain thereby providing evidence of the nature of the crust prior to, or at least during, the deposition of the Yellowknife Supergroup.

Three samples of greywacke and three of mudstone were analyzed with the results presented in Table 4. Each analysis is a composite in that the sample analyzed was composed of 50 chips of greywacke from the base of the bed, or mudstone from the top taken from different beds at the indicated section. In each case the local section was sampled over a stratigraphic thickness of about 100 feet (30 m). The locations and relative positions within the formation can be seen in Figure 2 where the east shore of Yellowknife Bay represents a section through the formation.

The Burwash Formation sediments qualify as greywacke chemically as well as petrographically. In comparison to the average sandstone (Pettijohn, 1963) the

Table 4

Chemical Analyses of Burwash Formation Greywackes and Mudstones

	1	2	3	4	5	6
SiO_2	66.97	64.88	66.37	50.57	54.12	54.45
Al_2O_3	15.10	15.90	14.73	22.43	19.66	19.60
Fe_2O_3	0.72	0.67	0.71	1.19	1.26	1.29
FeO	4.52	4.88	4.17	6.98	7.32	7.01
MgO	2.79	2.82	2.57	4.86	4.83	4.69
CaO	1.33	1.83	1.95	1.21	1.37	1.14
Na_2O	3.01	3.34	2.99	2.03	2.15	2.38
K_2O	2.04	1.79	1.89	4.14	3.20	3.20
H_2O^+	2.32	2.51	2.61	4.58	4.79	4.45
H_2O^-	0.08	0.05	0.11	0.14	0.09	0.10
CO_2	0.08	0.16	0.90	0.08	0.08	0.14
TiO_2	0.62	0.70	0.60	1.01	0.91	0.87
P_2O_5	0.11	0.13	0.11	0.17	0.15	0.16
MnO	0.05	0.06	0.07	0.08	0.08	0.10
Total	99.74	99.72	99.78	99.47	100.01	99.58

Analyst - L. Seymour, Geological Survey of Canada.

1. Section E. Greywacke
2. Section G. Greywacke
3. Section J. Greywacke
4. Section E. Mudstone
5. Section G. Mudstone
6. Section J. Mudstone

SiO_2 content is relatively low while the Al_2O_3, MgO, FeO and Fe_2O_3 content is relatively high. The high ratios of FeO/Fe_2O_3 and Na_2O/K_2O are particularly characteristic of greywackes. For the corresponding mudstones the relatively higher proportion of chlorite and muscovite over quartz and feldspar is shown by the even lower SiO_2 content the higher proportion of alumina, total iron and magnesium and the reversed ratio of Na_2O/K_2O over that seen in the greywackes. The chemical immaturity of the sediments is reflected by the low Al_2O_3/Na_2O ratios ($\sim$5) as compared to that of the average sandstone ($\sim$10).

There is no significant variation among the samples analyzed, although one of the mudstones is slightly less siliceous and richer in alumina than the others. In comparison with an average of 20 Archean greywackes (Table 5) the Burwash is less calcic and when compared to Pettijohn's (1957) average greywackes of all ages is slightly more aluminous, enriched in magnesium and reduced in calcium. The Burwash mudstones have slightly less silica and calcium and more aluminum and magnesium than an average of 20 Archean slates (Table 5). When compared to an average Phanerozoic slate the Burwash mudstones are deficient in silica and contain more aluminum iron and magnesium.

The high ferrous to ferric iron ratio of greywackes in general has been suggested as evidence for deposition under reducing conditions but may be more a function of metamorphism (Pettijohn, 1963). Taken as a group, Archean greywackes (the Burwash greywackes in particular) have an even higher ferrous to ferric iron ratio (Table 5). However, since the majority of Archean greywackes tend to be more metamorphosed than younger Precambrian and Phanerozoic examples, this ratio is not considered a reliable environmental indicator. The high Na_2O/K_2O ratio for greywackes has been explained by Pettijohn (1963) as related to the high albite content of the feldspars in the sediment. In the Burwash greywackes the albitic composition of the feldspar would support this suggestion. In addition, a matrix derived from the breakdown of rock fragments - in this case largely intermediate and silicic volcanic rock fragments - would also have a high Na_2O/K_2O ratio. On the other hand a matrix of primary detrital origin composed of predominantly fine argillaceous material, would tend to have a lower Na_2O/K_2O ratio more comparable to that of the mudstones and hence would tend to reduce the average Na_2O/K_2O ratio of the greywacke.

PROVENANCE OF THE BURWASH FORMATION

The chemical resemblance of greywacke and granodiorite has frequently been noted (Pettijohn, 1957; Condie, 1967) and the Burwash greywackes are no exception. In Table 5 their composition is compared with the average chemical analyses of 137 granodiorites (Nockolds, 1954). Silica and alumina are essentially the same while the greywackes are richer in iron and magnesium and depleted in sodium, potassium and calcium. It cannot be assumed that because of the

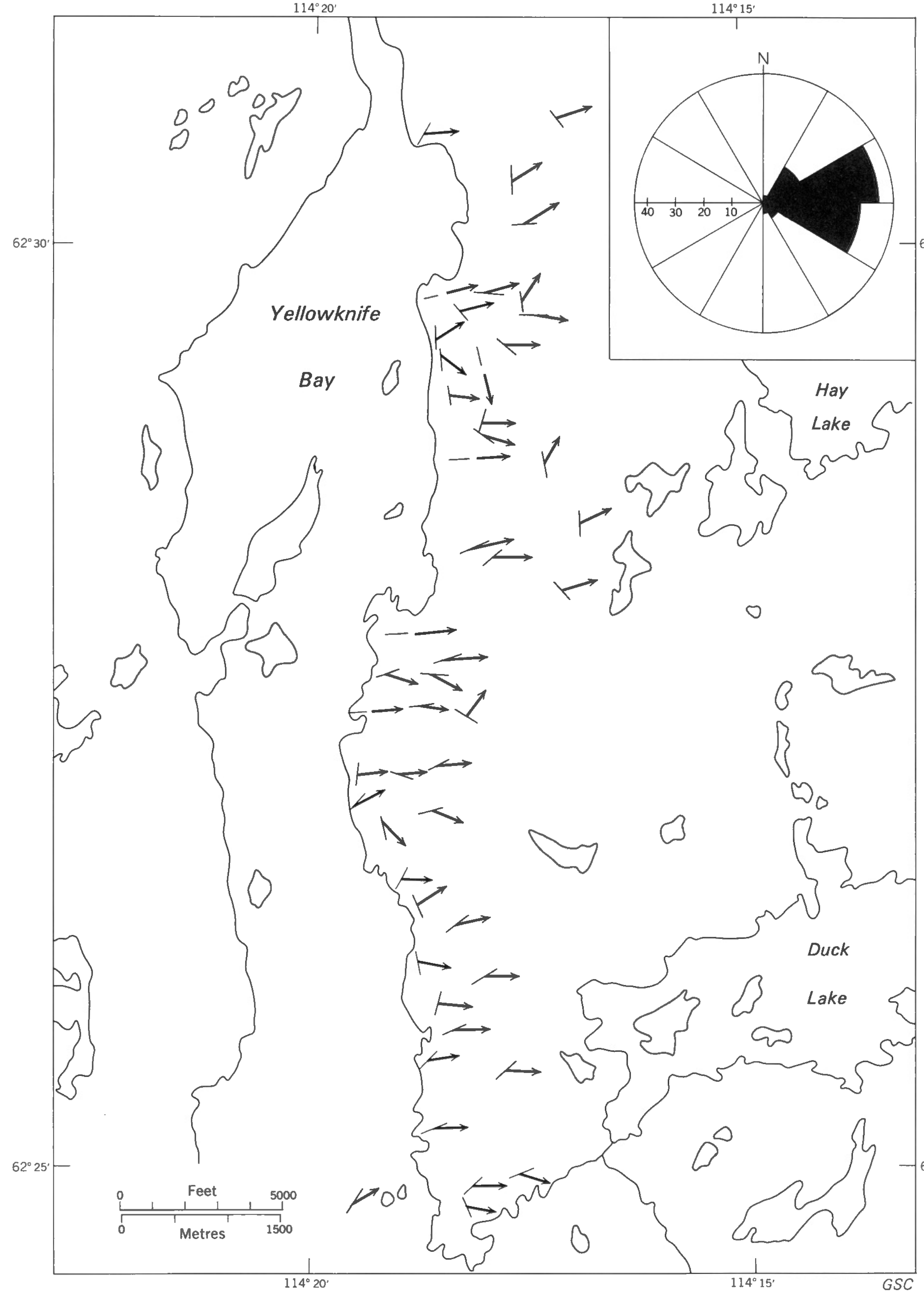

114° 20′
114° 15′
N
40
30
20
10
62° 30′
62° 30′
Yellowknife
Bay
Hay
Lake
Duck
Lake
62° 25′
62° 25′
0
Feet
5000
0
Metres
1500
114° 20′
114° 15′
GSC

Table 5

Averages of Greywacke and Mudstone Chemical Analyses

	1	2	3	4	5	6	7	8	9*
SiO	66.07	63.66	66.75	53.47	57.80	60.64	77.6	65.2	66.88
Al_2O_3	15.24	14.85	13.54	20.56	18.37	17.32	7.1	15.8	15.66
Fe_2O_3	0.70	1.01	1.60	1.25	1.67	2.25	1.7	1.2	1.33
FeO	4.52	4.67	3.54	7.10	6.21	3.66	1.5	3.4	2.59
MgO	2.73	2.99	2.15	4.79	3.93	2.60	1.2	2.2	1.57
CaO	1.70	2.63	2.54	1.24	1.89	1.54	3.1	3.3	3.56
Na_2O	3.10	3.14	2.93	2.19	2.19	1.19	1.2	3.7	3.84
K_2O	1.91	2.30	1.99	3.51	3.26	3.69	1.3	3.23	3.07
H_2O^+	2.48	2.17	2.42	4.61	3.11	3.51	1.7	.8	0.65
H_2O^-	0.08		0.55	0.11		0.62	0.4		-
CO_2	0.38	1.49	1.24	0.10	0.17	1.47	2.5	.20	-
TiO_2	0.64	0.57	0.63	0.93	0.70	0.73	0.4	.57	0.57
P_2O_5	0.12	0.14	0.16	0.16	0.19	-	0.1	.17	0.21
MnO	0.06	0.11	0.12	0.09	0.09	-	0.1	.08	0.07
Other	-	0.26	0.48	-	0.39	0.38	.1	.11	
Total	99.73	99.99	100.61	100.11	99.99	99.60	100.0	100.0	100.0

1. Average of 3 Burwash Formation greywackes (Table 2).
2. Average of 20 Archean greywackes (including #1). Henderson (1970b).
3. Average of 61 greywackes of all ages. Pettijohn (1957).
4. Average of 3 Burwash Formation mudstones (Table 2).
5. Average of 20 Archean slates (including #4). Henderson (1970b).
6. Average of 36 Phanerozoic slates. Eckel (1904) (in Nanz, 1953).
7. Average sandstone (Pettijohn, 1963).
8. Average composition of Canadian Shield. Eade and Fahrig (1971).

9*. Average granodiorite. Nockolds (1954).

similarity in chemical composition the greywackes were derived strictly from a granodiorite source; in fact the textural characteristics of the greywackes make this most unlikely. What is important however, is that the average chemical composition of the source area resembles that of a typical granodiorite -- in other words, that a sialic source was available to provide detritus.

Petrographically, it is evident that the Burwash greywackes were derived from a mixed source involving both granitic and volcanic rocks. The abundance of intermediate to silicic volcanic rock fragments in the greywackes suggests that this was an important component. The relatively high proportion of iron and magnesium may result from the contribution of mafic volcanics as well. The few granitoid rock fragments indicate that a granitic source made some contribution, and the volume of quartz and feldspar of unestablished source in the greywackes suggests the contribution could be quite substantial.

While the area of study at Yellowknife Bay is relatively small, the Burwash Formation as a whole is extensive. It is the major unit of the basin east of Yellowknife (Fig. 1), occupying an area of approximately 3,000 square miles (8,000 square km) (Henderson *et al.*, 1972). Thus the sialic source terrain indicated from the study at Yellowknife is not just a local feature but perhaps an indication of the nature of the Archean crust in the Slave Province at that time.

Figure 31 (opposite)

Paleocurrent directions in the Burwash Formation along the east side of Yellowknife Bay. Each arrow at a location at which measurements were made indicates the average rotated current direction. The finer line at each location represents the bedding strike at that location. The inset is a composite of the mean paleocurrent direction at each station. It is evident that the sediments were derived from the west approximately perpendicular to the present margin of the basin.

There is a marked similarity between the composition of the greywackes and the estimated composition of the Canadian Shield (Eade and Fahrig, 1971) (Table 5). The silica and alumina content are similar but that iron and magnesium are greater in the greywackes while the calcium, sodium and potassium contents are less. It seems probable that the crust on which the sediments of Yellowknife were deposited or at least derived from, was chemically not unlike the estimated average present composition of the Shield of today.

PALEOCURRENTS

Archean sediments on the whole do not lend themselves particularly well to paleocurrent studies, due to structural and metamorphic complexities. The Burwash Formation turbidites at Yellowknife are no exception as they occur on the vertical to overturned east limb of the major syncline in the area which, in addition, has been cross-folded into a series of steeply plunging to overturned second-order folds. It has been shown (Ramsay, 1961) that large errors in paleocurrent directions that increase exponentially with degree of deformation will occur unless the folded strata are properly returned to the horizontal. Thus, all directional data collected on the Burwash sediments had to be rotated twice stereographically; first to remove the effect of the steeply dipping limbs of the major fold which is assumed to have a negligible or minor plunge, and secondly to remove the effect of the second-order cross folds. In addition to structural problems, low-grade metamorphism has welded the mudstones to the bases of the overlying beds with the result that bedding plane surfaces are rarely exposed. This prevents the use of basal sole marks as a directional element. In the few instances where bedding plane surfaces are exposed it is apparent that the sole marks have been reoriented parallel to the axes of the cross folds.

In the Burwash Formation the ripple foresets in the ripple-laminated (C) division of the Bouma cycle were used as paleocurrent indicators. Being more in the central part of the turbidite they are not as subject to shearing as structures at the base or top of the bed as most movement took place in the relatively thin less competent pelitic divisions of the beds. But there is some uncertainty as to the utility of ripples as reliable indicators of the directions of sediment transport. The main objection to their use is the possibility that the ripple trends may be significantly divergent from basal sole mark trends. The ripple cross-lamination is formed relatively late in the depositional event when conceivably the current may have been spreading laterally, with respect to the direction indicated by the basal sole marks formed presumably during the passage of the head of the current. It was felt however, that the ripple data would give at least the correct quadrant for sediment transport direction which is really all that can be expected considering the assumptions made in returning the strata to the horizontal.

Paleocurrent data were collected at 49 stations through the Burwash Formation along the east side of Yellowknife Bay, with an average of 15 measurements of ripple foresets at each station. In Figure 31 the positions of the stations are plotted showing average rotated current direction, present bedding strike and the composite current rose for the formation. Evidently the turbidites were "poured in" from what is now the western margin of the basin and not transported parallel to the present north-south long axis of the basin. As the current direction is approximately normal to the present basin margin, this may indicate that this margin is close to the original Archean margin, the Burwash Formation at Yellowknife representing a section relatively high on the basin margin slope before regional basin topography farther away from the margin diverted the currents.

BURWASH FORMATION GROWTH PATTERN

The Burwash Formation at the margin of the basin at Yellowknife consists of approximately 15,000 feet (∿4,500 m) of turbidites. It is interesting to speculate on the manner in which this considerable thickness of turbidites accumulated. To this end an analysis was made of the sedimentary structures in the turbidites following the method of Walker (1967).

An index based on the internal sedimentary structures in a sequence of turbidites has been developed that estimates the "proximality" of the sequence relative to the point where the current first started depositing (Walker, 1967). This index is based on the proportion of beds in a given group of turbidites that start with division A, division B or division C of the Bouma sequence.

The ABC index is a number between 0 and 100. A low ABC index value for a group of turbidites at a given point indicates a high proportion of the beds began deposition from low regime currents, whereas a high value indicates most beds began deposition from high regime currents. It was assumed by Walker (1967) that in a system with only one source, high regime currents were proximal and lower regimes indicated more distal areas. In general beds starting with division A, were deposited in a higher flow regime closer to their initial source than beds starting with division C indicating much lower flow-regime deposition (Fig. 14).

The ABC index is calculated by the relationship: ABC index = A - $(A \rightarrow E)$ + $\frac{1}{2}$B where A and B are the percentages of beds in the group of turbidites starting with divisions A and B. $(A \rightarrow E)$ is the percentage of beds in that group that are thin, fine grained with no internal current structures and grade smoothly up into mudstone. Although similar to division A in that they are graded and contain no other internal structures, they are thought to represent deposition from the almost stagnant current. They are commonly associated with beds beginning with the upper divisions (C, D) of the sequence. Thus for the purposes of the index they should be grouped with beds beginning with divisions C and D and not with those beginning with division A.

The proximality index is determined for "homogeneous" groups of similar turbidites within a section. In order to define these groups objectively the ABC

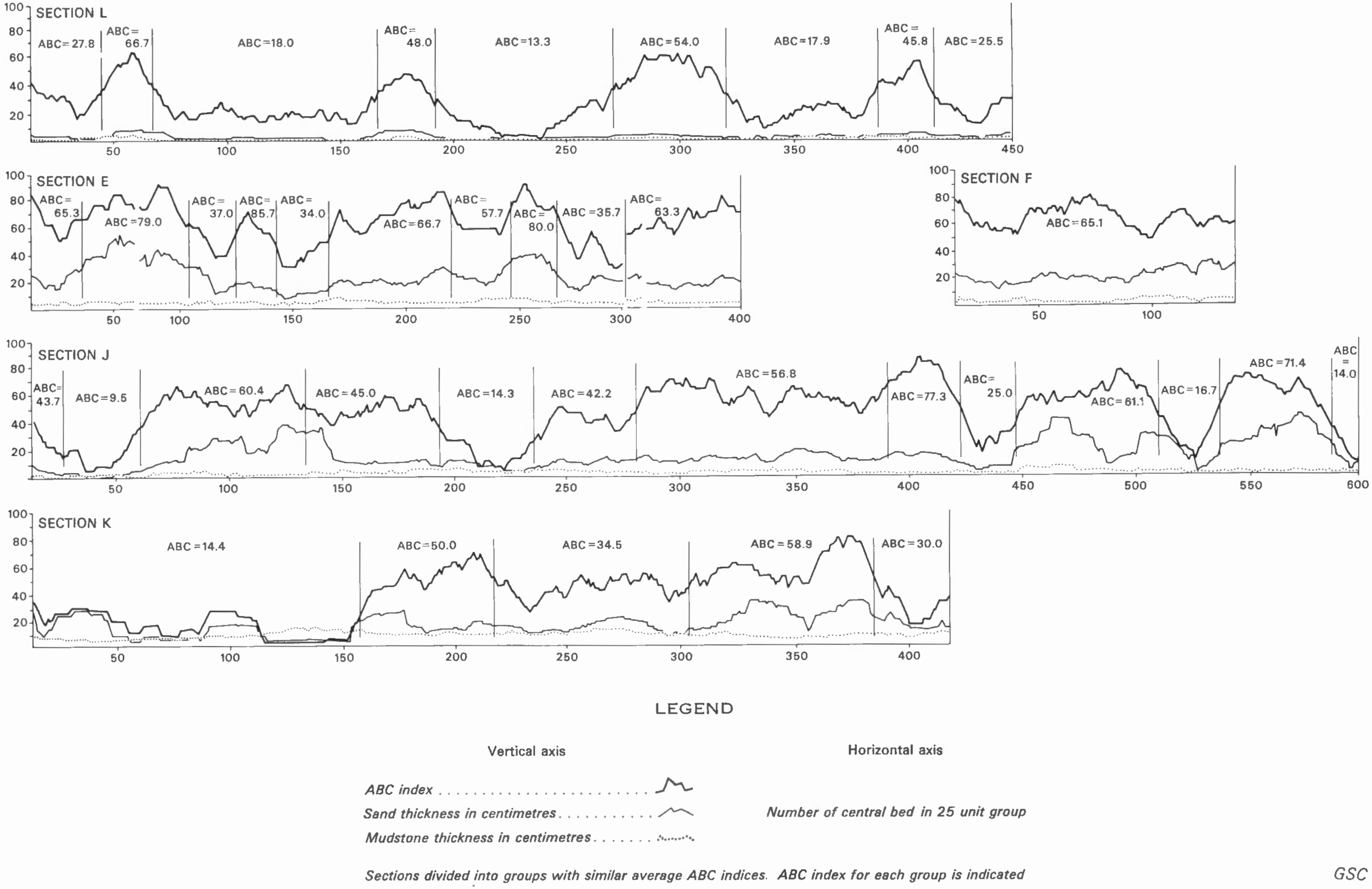


Figure 32. Twenty-five unit moving average plots of the ABC index and thicknesses of sand and mud for five sections in the Burwash Formation. Location of sections is indicated in Figure 2. Sequences of turbidites with a generally higher proportion of "proximal" characteristics are reflected by higher ABC index values. The fluctuation of the index is particularly evident in Section L and Section J.

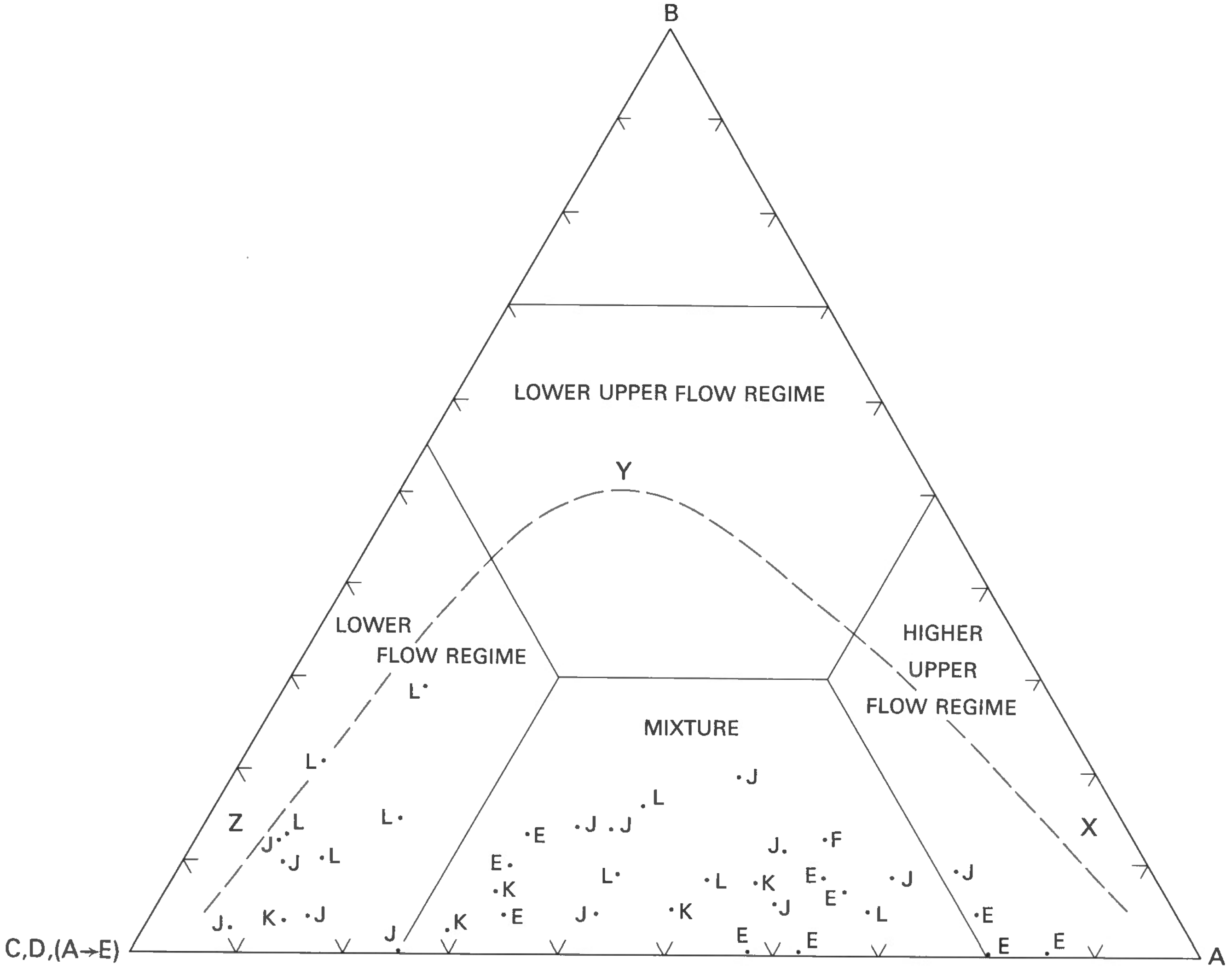
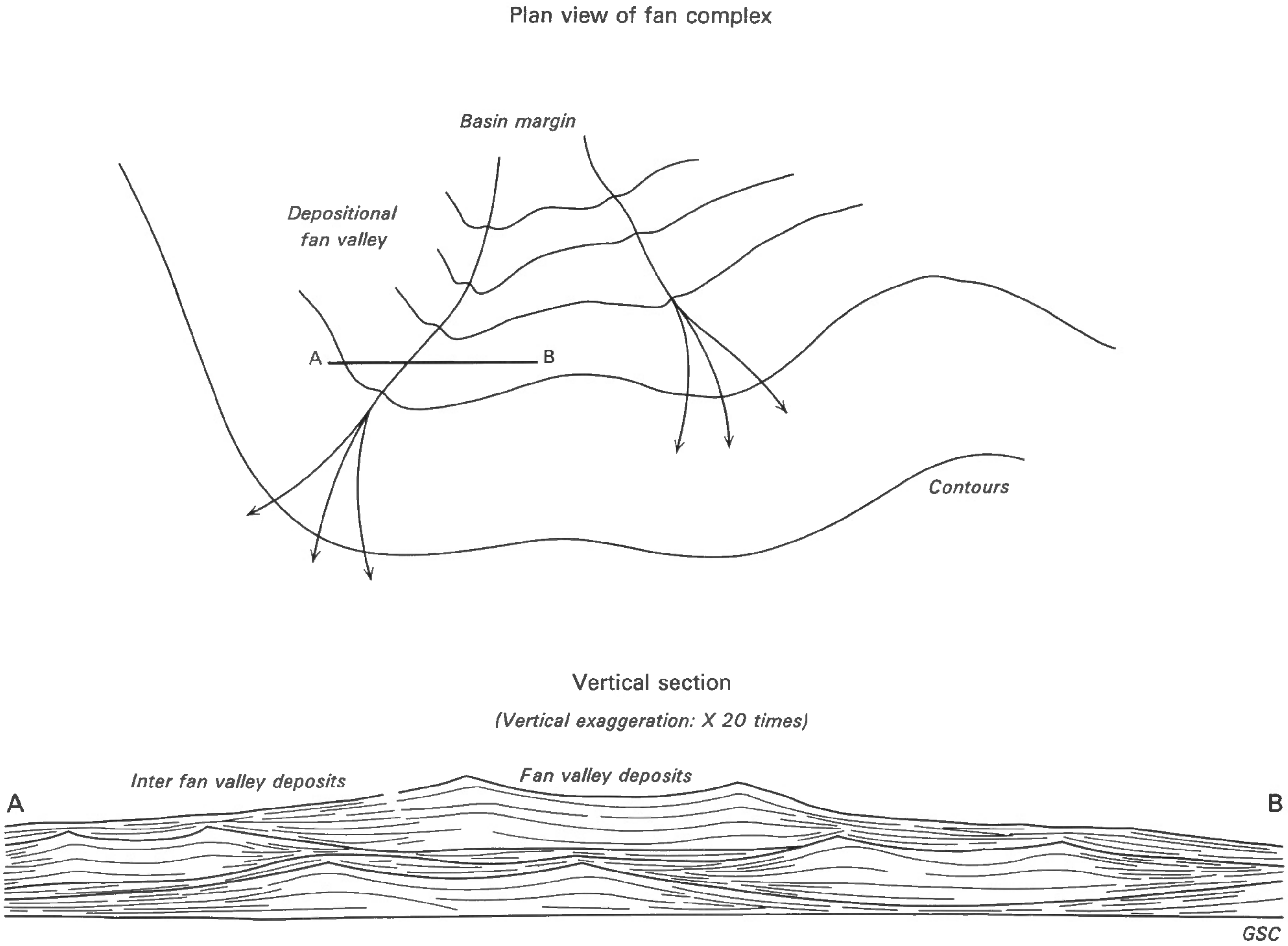


Figure 33. Ternary plot of the number of beds starting with division A versus those starting with divisions B versus those beginning with divisions C and D and (A→E) type beds for the groups of turbidites defined in the various sections plotted in Figure 31. The line XYZ is a hypothetical line along which homogeneous groups of turbidites deposited under decreasing flow regime conditions would be expected to occur.

index was calculated as a 25 unit moving average for a whole section. ABC index values were plotted on a scale of 100 versus the number of the central bed in each 25 unit group. The result is a fluctuating curve as in Figure 32. Homogeneous groups of similar character are defined by significant changes in the ABC index curve. ABC indices of these newly defined groups are then recalculated for the section.

In this study ABC index determinations were made on five sections in the Yellowknife Bay area -- sections K, J, F, E, and L in order of increasing stratigraphic height (Fig. 2). Figure 32 shows the moving average of the ABC index for the various sections and moving averages for the thickness of total sand and mud. The most notable feature of the plots is the variation in ABC index in each section. In none of the sections is it particularly constant and in some there appears to be a regular alternation between high and low ABC index value. This is particularly evident in sections J and L and to a lesser extent in K and E.

Interpretation of the index presents problems because the index is only a function of the flow regimes under which the member beds were deposited. It does not reflect the size of the depositing current or the absolute distance it has travelled from its source. Thus, several large currents originating from a great distance could deposit a group of beds at a given point with an index similar to that deposited by a series of small locally derived currents. Thus the ABC index pattern is open to interpretation and perhaps should not be considered purely a function of proximality. This difficulty in interpretation has been pointed out by Haner (1971) concerning turbidites on the Quaternary Redondo submarine fan.


Plan view of fan complex

Vertical section

(Vertical exaggeration: X 20 times)

Figure 34. Diagramatic sketch at Burwash Formation turbidites deposited on a complex of submarine fans on which the main part of the turbidity current was restricted to depositional fan valleys resulting in thicker, coarser-grained deposits in that area while the upper part of the turbidity current containing dispersed, fine-grained material extended beyond the confines of the valleys to form thin, fine-grained beds analogous to overbank deposits on the inter-valley part of the fan.

The data from the Burwash turbidites may be interpreted as the interaction of two sources, one proximal and the other distal. The more or less regular alternation of the ABC index through the various sections suggests that the contribution from any one source was periodic. On closer examination it can be seen that there was more or less constant deposition of "distal" beds with the more "proximal" beds periodically superimposed on this background. This is apparent in Figure 33 which is a ternary plot of the proportion number of beds starting with division A, division B, and divisions C and D and (A→E) type beds, for the homogeneous groups of turbidites defined in the various sections plotted in Figure 32. The line XYZ is a hypothetical line on which homogeneous groups of turbidites deposited under decreasing flow regime conditions (and perhaps representing decreasing proximality) would be expected to fall. It is apparent that the groups of Burwash turbidites show no tendency to follow this trend line but fall mainly in the "mixture" field. Thus some groups consist of dominantly "proximal" turbidites (4 groups) or "distal" turbidites (11 groups) or mixtures of these two extremes (23 groups).

An alternative explanation of the apparent mixture of proximal-type and distal-type turbidites in the Burwash section utilizes a single source and, like Haner (1971), questions the validity of the terms proximal and distal as applied to particular types of turbidites. It is suggested that the sediments were introduced into the basin from submarine canyons onto a large complex of submarine fans that extend out into the basin. The turbidity flows would be restricted mainly to depositional valleys (as opposed to erosional valleys) on the fans rather than occurring as massive sheet flows that covered a large part of the fan during passage of the turbidity current. This mechanism has been suggested by Hamilton (1967) for deposits in the

Gulf of Alaska and by Normark (1970) for the development of the San Lucas deep sea fan. The upper parts of the turbidity current, containing highly dispersed fine-grained material, may have extended well above and beyond the limits of the depositional valley. The resulting deposit from any major current would consist of relatively coarser-grained, thicker, "proximal" beds, restricted mainly to the fan valley, and an associated thinner, finer-grained "distal" bed deposited on the fan. These distal deposits can be considered to be analogous to overbank deposits in a fluvial environment. Local small slumps and slides might initiate small turbidity currents that would result in thin fine-grained, distal-type deposits within the fan valley. Overbank material from active valleys may extend into a currently inactive adjacent depositional valley. Both mechanisms would result in the intermixing of "distal" and "proximal" type deposits in the valleys while only "distal" deposits would accumulate on the fan between the valleys. Eventually the depositional valley becomes unstable and the locus of deposition shifts to another lower part of the fan. The final product is a sequence of mixed proximal-type and distal-type depositional valley deposits and distal-type open fan deposits -- a sequence similar to that seen in sections of the Burwash Formation (Fig. 34).

CHAPTER 4

THE JACKSON LAKE FORMATION

The Jackson Lake Formation lies unconformably above the predominantly mafic volcanic Kam Formation and consists of a locally developed basal conglomerate of mainly volcanic derivation overlain by felsic volcanic lithic sands. It is restricted to the western margin of the basin east of Yellowknife where it can be traced over a distance of 23 miles (37 km) (Fig. 2). The formation varies in thickness depending on the topography on the erosional surface in the Kam Formation, but is approximately 1,000 feet (300 m). The top of the formation is not exposed and, where not covered by Yellowknife Bay is faulted against the dominantly silicic volcanic Banting Formation. At one locality the highest part of the formation preserved is a thick, but highly deformed unit of mudstone that is different from anything seen elsewhere in the formation. This may be all that is preserved of an overlying formation and may suggest that only a minor amount of the Jackson Lake Formation is missing with faulting taking place close to the formational boundary.

CONGLOMERATES

Where present, the basal conglomerate fills depressions on the erosion surface above the Kam Formation. Although commonly rather shallow, the depressions reach a depth of some 700 feet (200 m) in places as between Jackson and Walsh Lakes, 8 miles (13 km), north of Yellowknife. They are invariably filled with large angular blocks of mafic volcanics. Examples can be seen at the previously mentioned south end of Jackson Lake, at Walsh Lake and also on Yellowknife Bay at the southernmost exposure of the formation in the northern part of the Bay.

Other major conglomerates outcrop on the west side of Jolliffe Island and on the three Sub Islands at the southernmost extremity of the Bay. The precise stratigraphic position of these conglomerates is not known as they are exposed on islands. They differ from the basal conglomerate in that the proportion of locally derived mafic volcanic clasts is greatly reduced suggesting that the conglomerates may be some distance above the unconformity. Exceptionally, as on the

Table 6

Pebble counts and Modal Analyses, Jackson Lake Formation

Pebble type	Giant conglomerate			Jolliffe Is. conglomerate			Sub Island conglomerate		
	1	2	3	1	2	3	1	2	3
Granitic	2.0	1.8	1.2	7.1	11.4	11.9	0	0	0
Altered Granitic	3.5	6.1	2.4	0	0	0	15.8	22.3	13.2
Mafic Volcanic	42.9	76.1	76.3	0	0	0	2.2	3.1	2.6
Inter. Volcanic	8.0	14.1	17.1	.4	.6	.5	17.8	25.2	26.8
Silicic Volcanic	1.5	2.3	3.0	0	0	0	13.2	18.7	20.5
Altered Volcanic	0	0	0	0	0	0	1.6	2.2	3.7
c. Sandstone	0	0	0	2.2	3.5	3.6	0	0	0
m. Sandstone	0	0	0	23.1	37.2	33.7	17.0	24.0	27.4
f. Sandstone	0	0	0	17.9	28.8	29.5	3.0	4.2	5.3
Siltstone	0	0	0	8.9	14.3	16.6	0	0	0
Shale	0	0	0	.6	1.0	1.5	0	0	0
Chert	0	0	0	0	0	0	0	0	0
Quartz	0	0	0	1.0	1.6	1.5	.2	.3	.5
Miscellaneous	0	0	0	1.0	1.6	1.3	0	0	0
Matrix	43.5	-	-	37.8	-	-	29.2	-	-
#Pts./#Pebbles	515	-	169	507	-	193	500	-	190

1. Modal Analysis
2. Modal Analysis excluding Matrix
3. Pebble Count

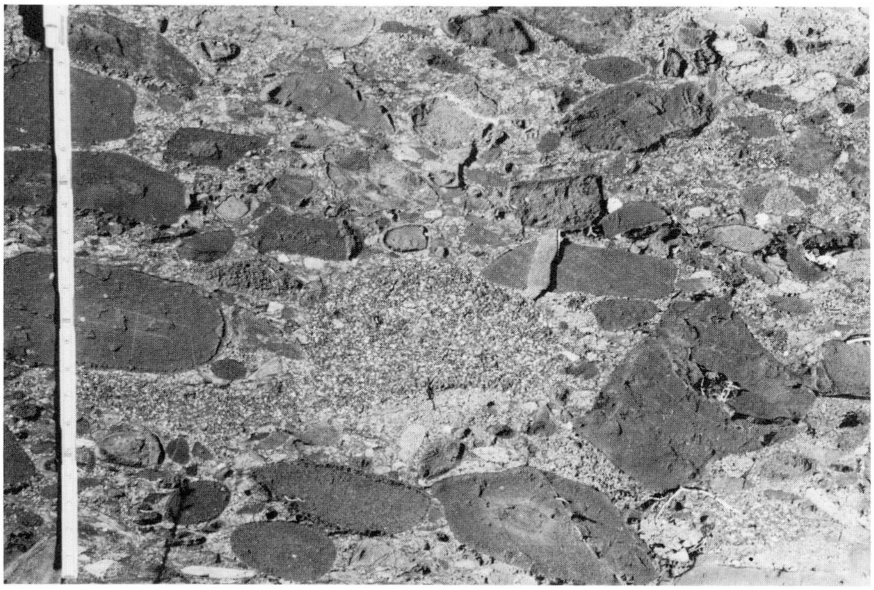


Figure 35.

Jackson Lake Basal Conglomerate. Angular basal conglomerate composed mainly of mafic volcanic clasts derived from the underlying Kam Formation. Note the reaction rim about many of the volcanic clasts that may be a result of Archean weathering. The diffuse boulder in the central part of the photo is a highly altered granitic cobble.

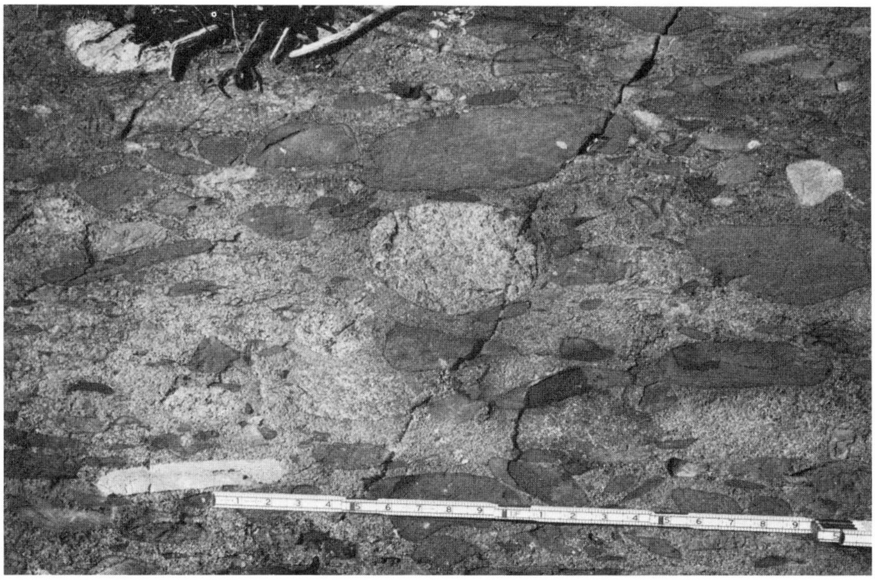


Figure 36.

Jackson Lake Basal Conglomerate. Mafic volcanic clasts predominate although a few lighter-coloured, more felsic, varieties are present as well. The large well-rounded boulder in the central part is granitic. The abundant matrix is composed mainly of quartz and both felsic and mafic volcanic rock fragments.

southernmost of the Sub Islands, the conglomerate is composed almost completely of greenstone cobbles with minor granitic clasts. The relationship of these exposures to the rest of the formation and the underlying Kam Formation is complicated by the large fault systems in the Bay between the mainland and the islands.

Megascopic modal analyses were made of the conglomerates on the Sub Islands and Jolliffe Island, and on the basal conglomerate on the Giant Yellowknife Gold Mines Ltd. property on Yellowknife Bay (the Giant conglomerate). In order to have volumetric estimate of each pebble lithology present, a pebble count of the various lithologies was also made but it differs from the usual type in that all the pebbles within the area of the analysis were not considered - only those involved in the point count. The results of these analyses can be seen in Table 6.

The Giant conglomerate (Table 6) is typical of the basal conglomerate except that it has a higher proportion of granitic cobbles than do most of the basal conglomerates. Most conglomerates to the north have few or no granitic boulders. Dark green mafic volcanic clasts are by far the most abundant lithology. These tend to be poorly rounded to subangular, usually somewhat elongate, and average about 6 inches (15 cm). They commonly have a thin, darker-coloured rind that is interpreted as a post-depositional low-grade metamorphic product although it may be due to pre-depositional weathering (Fig. 35). In addition to the greenstone blocks there are also lesser amounts of granitic plutonics, altered granitic rocks, intermediate and felsic volcanics, vein-quartz cobbles and chert clasts. In contrast to the greenstone cobbles, the pink granitic cobbles are well rounded, and in many cases

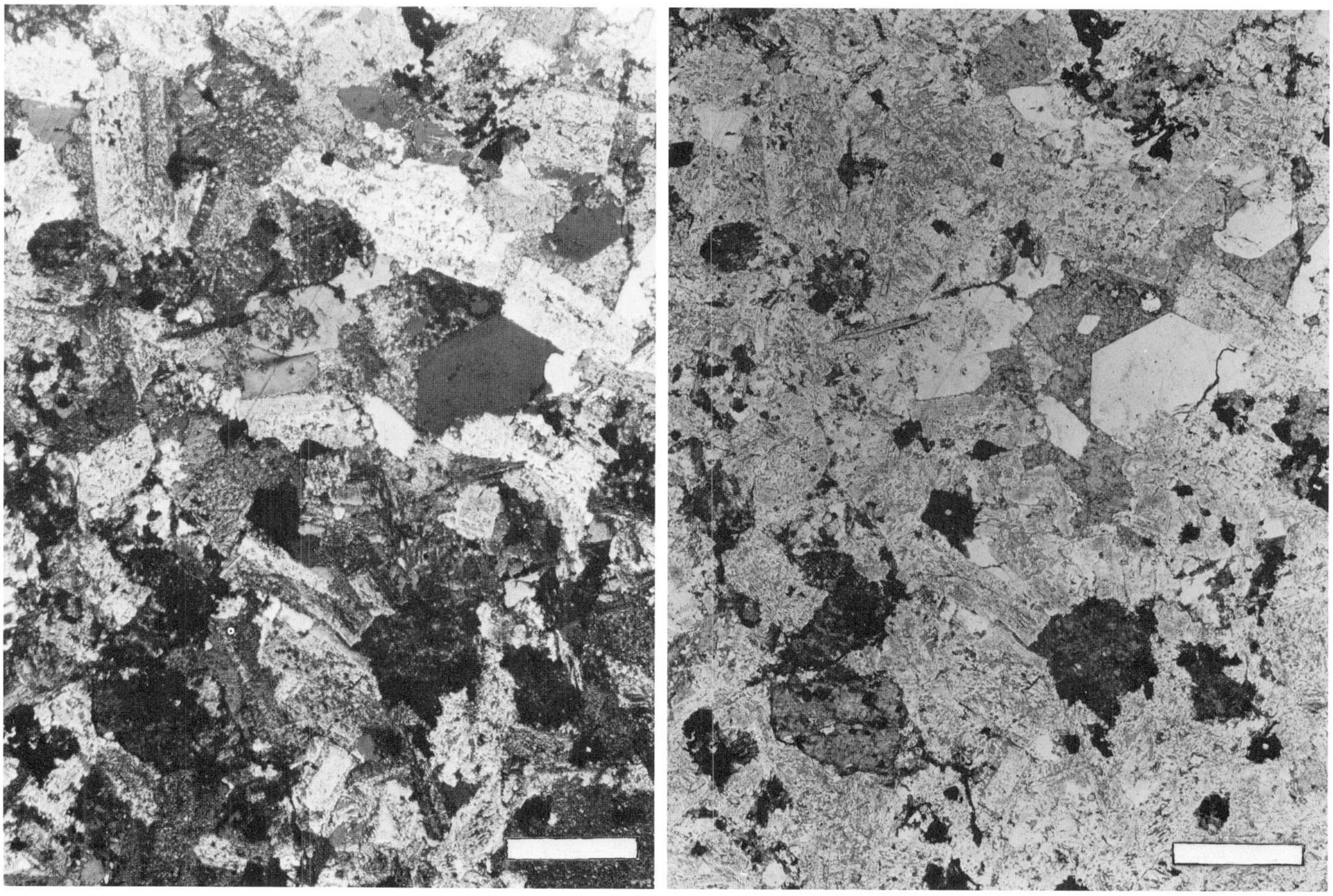


Figure 37. Photomicrograph of epizonal granitic cobble in Jackson Lake basal conglomerate. The rock consists of euhedral plagioclase quartz, myrmekite and chlorite. Note the perfectly-terminated quartz crystal projecting into a carbonate-filled miarolitic cavity.

are the coarsest material in the conglomerate (Fig. 36). The altered granitic boulders are also quite large and contain a high proportion (up to 40 per cent) of coarse quartz, the only primary mineral that is preserved. The matrix of the conglomerate consists of (in order of decreasing abundance), coarse quartz, silicic volcanic rock fragments, and feldspar. Locally the matrix is so abundant that the cobbles are rarely in contact with one another (Fig. 35). There is a crude compositional grading of the pebbles; the granite is somewhat more abundant in the lower part of the sequence. In some of the other conglomerates this grading is much more apparent; the more silicic volcanic clasts are more abundant towards the top. In places, current-laminated volcanic sands occur in small discontinuous lenses in the conglomerates.

The basal conglomerate occurs in other erosional depressions on the Kam Formation to the north. The conglomerates are locally variable but in general the coarsest most angular material (clasts up to several feet in size) is found at the base and is similar in composition to the underlying volcanics. For example, felsic volcanic clasts in the basal conglomerate are abundant only in the thick deposit west of the south end of Jackson Lake where a major dacitic unit in the Kam Formation is truncated by the unconformity. Towards the top of this deposit the clasts tend to be smaller and felsic volcanic material if present is more abundant. In general the conglomerates are sharply gradational with the overlying sandstones; there being an abrupt increase in the proportion of sand beds to conglomerate.

The conglomerate on Jolliffe Island contrasts in many respects with the basal conglomerates. It consists of a sequence of graded conglomerate layers alternating with massive sands. Higher in the section the conglomerate layers are thinner and the cobbles smaller. Within a given conglomeratic bed the cobbles themselves are graded; in one case, a 15-foot conglomerate bed passes upward from granitic cobbles with a maximum diameter of one and one half feet (50 cm) to ragged shale clasts generally less than one inch (2.5 cm) in length at the top. As can be seen in Table 6 the most abundant cobbles are well-rounded medium to fine-grained volcanic lithic arenites with the volcanic cobble complement almost nil. Rounded granitic cobbles are much more numerous in this conglomerate than in

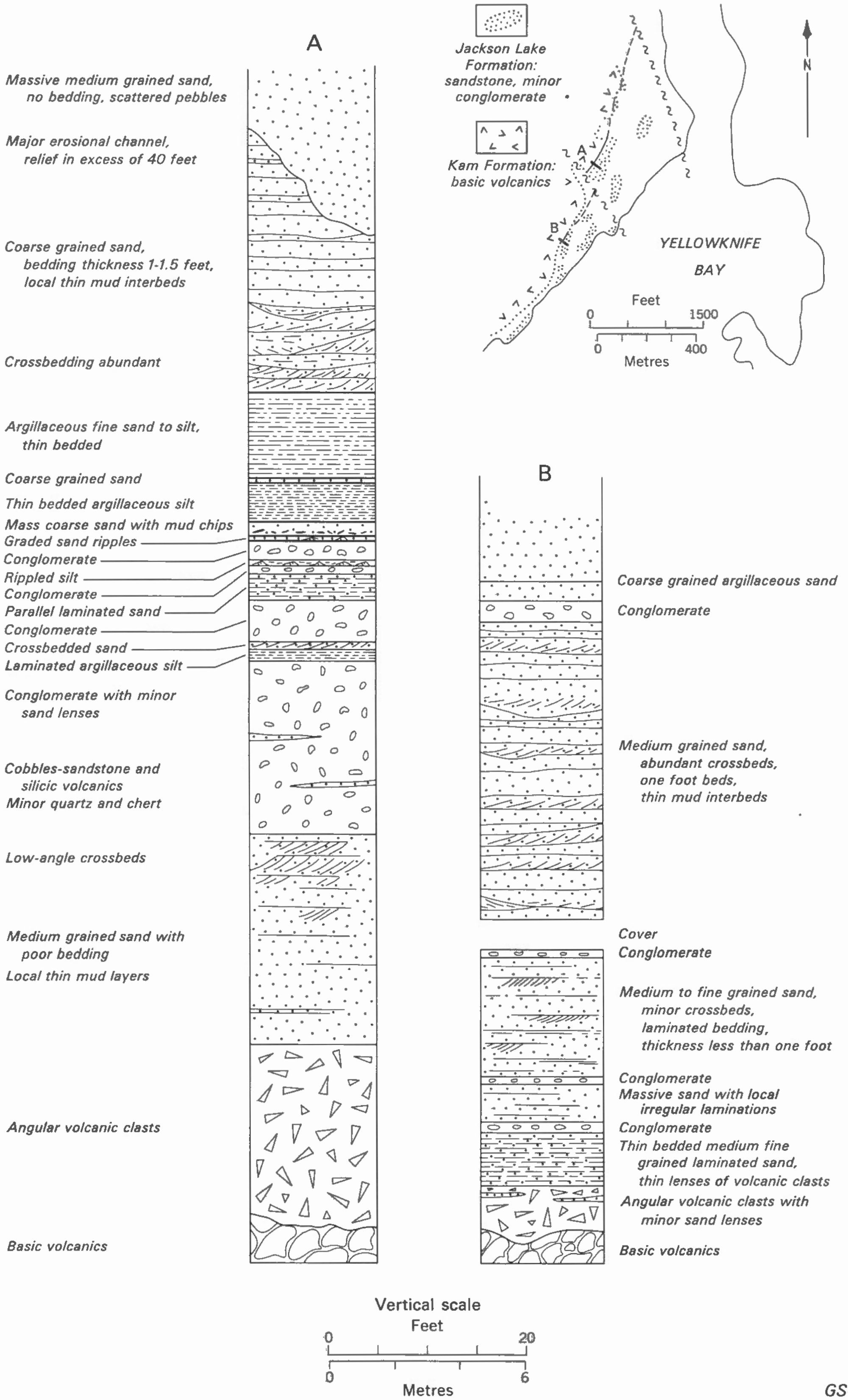


Figure 38. Two sections of the lower part of the Jackson Lake Formation laterally separated by approximately 1750 feet (530 metres). Despite the relative proximity of the two sections, little in the way of lithologic correlation can be made between the various members of the two sections.

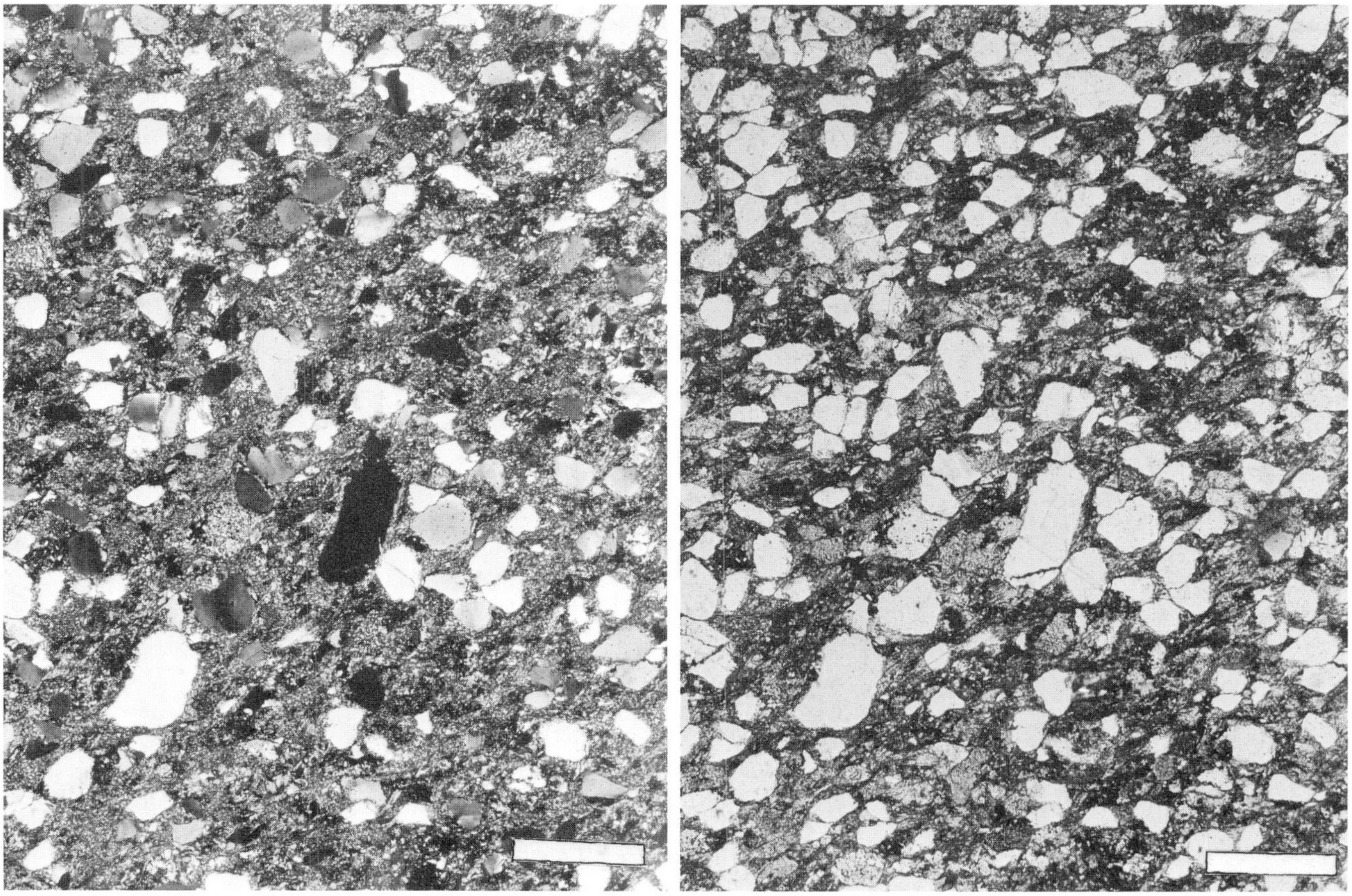


Figure 39. Photomicrograph of Jackson Lake lithic wacke. The sandstone is composed of angular monocrystalline quartz and silicic volcanic rock fragments that are here somewhat altered and diffusely bounded. Plagioclase feldspar is typically a very minor component. Note the large grain of myrmekite.

the "Giant conglomerate". Minor quantities of vein quartz pebbles, chert and silicic volcanics are also present.

One of the thickest conglomerates occurs on the northernmost of the Sub Islands. While its total thickness is not known, it cannot be less than 300 feet (100 m). It is intermediate in character between the "Giant conglomerate" and that of Jolliffe Island in that both volcanic and lithic sandstone cobbles are common (Table 6). Very few fresh granitic cobbles were observed on the northern islands and only minor pink granitoid clasts are present on the southernmost island. Highly altered granitic cobbles, however, are abundant. The conglomerate is massive except for local discontinuous beds of crossbedded lithic sandstone. The cobbles are well rounded in contrast to the basal conglomerates to the north. The conglomerate is divided by a thick unit of crossbedded lithic sandstone with local pebbly horizons identical to the sandstones that normally make up the upper part of the formation.

The third type of conglomerate occurs as elongate lensoid bands in the bedded sandstones higher in the formation. These conglomeratic beds are rarely more than five feet (1.5 m) and commonly usually only six inches to one foot (15 to 30 cm) thick. However there are a few beds up to 60 feet (18 m) thick. The cobbles in these conglomerates are less than three inches (7 cm). in diameter, are usually very well rounded and have a wide range of composition. Megascopically the most common pebble looks like a very impure sandstone but in thin section it consists of closely packed aggregates of quartz (with extremely abundant dusty inclusions that give the quartz a brownish colour) and scattered grains of relatively clear quartz. In addition, pebbles of white quartz porphyry, silicic volcanics, vein quartz and chert are common. Mafic volcanic clasts are rarely, if ever, present.

The granitic cobbles that are a minor but ubiquitous component of the conglomerates are of interest as they indicate the existence of a granitic source terrain during the deposition of at least part of the Yellowknife Supergroup at Yellowknife. The most abundant is a trondhjemite with an average of about 55% plagioclase, 35% quartz and 10% mafics. The mafics consist of biotite and/or amphibole but in most cases have been altered to chlorite. The plagioclase is also altered by low-grade metamorphism and typically occurs as subhedral to euhedral laths. Closely related to this type is a finer-grained trondhjemite in which the coarser plagioclase occurs as more elongate euhedral laths with interstitial finer-grained feldspar, myrmekite and quartz. In both, potassium feldspar is rare to absent. Miarolitic cavities are present in one cobble examined (Fig. 37) which together with the other textural features of the rock suggest shallow emplacement of the parent granitic body.

VOLCANIC LITHIC WACKES

The main part of the formation consists of a thick sequence of well-bedded heterogeneous volcanic lithic wackes. Interspersed with the sands are the previously described, thin, lensoid conglomerates that are most common in the lower part of the section (Fig. 38). The sands range from massive beds two or more feet (60 cm) in thickness and of uniform grain size, to beds less than one inch (2.5 cm) thick with highly variable grain size. Many of the sandy beds are separated by thin shale layers. Many exhibit trough crossbedding and a few are graded. The sandstones, lighter in colour than the greywackes, vary from light greyish-green through to a pale-brownish colour on the weathered surface; on fresh surfaces they are grey to greenish grey.

Megascopically, on the weathered surface, quartz grains are readily apparent in a 'matrix' of what appears to be altered feldspar but is actually silicic volcanic rock fragments. Individual rock fragments are not apparent in this 'matrix', as they merge with the true matrix of the rock. In thin section the volcanic provenance of these rocks is much more apparent, as the rock consists of silicic volcanic rock fragments and quartz in a matrix of more finely comminuted rock fragments, chlorite and muscovite.

On the whole, these sandstones are homogeneous in thin section (Fig. 39). Many have been sheared so that the rock fragments are unidentifiable and no primary grading or lamination is visible. The original fabric of the sediment typically has been obscured by post-depositional breakdown of the rock fragments. For the same reason, the present porosity is negligible although the original depositional porosity of the sediment presumably could have been substantial. Although the sand fraction of individual beds is better sorted than in the greywackes of the Burwash Formation, the grain size within the formation as a whole is much more variable, ranging from pebbly beds to silts. Rock fragments tend to be slightly larger than the quartz grains although there are numerous exceptions to this.

Compositionally, as indicated by the abundance of unstable rock fragments, the Jackson Lake sandstones are very immature. The degree of textural maturity of the original sediment is less clear because much of the abundant matrix may be in part the product of post-depositional diagenesis and tectonic deformation.

Quartz

Quartz is the second most abundant "framework" element after the rock fragments, making up on the average between 20 and 30 per cent of the rock (Table 7). The three classes of quartz described in the Burwash greywackes also occur in these sands; the single quartz grains are by far the most abundant. Polycrystalline types are present, but not common, and include those with a bi-modal mosaic of component quartz crystals suggestive of a metamorphic origin (Blatt, 1967).

Table 7

Modal Analyses of Jackson Lake Formation Lithic Wackes

	197-68	7B-68	9a-68	13-18-68	Sub 5-67	6-67
Total Quartz	14.0	21.0	31.4	20.0	23.7	32.8
Monocrystalline	9.4	16.6	24.0	15.2	20.4	22.0
Polycrystalline (<6 crystals)	4.2	2.8	5.4	2.8	1.6	7.6
Polycrystalline (>6 crystals)	.4	1.6	2.0	2.0	1.6	3.2
Silicic Volcanic Rock Fragments	30.8	28.0	30.0	*	28.4	22.8
Other Rock Fragments	0.0	0.0	0.0	0.0	6.8	0.0
Feldspar	15.0	0.2	3.5	0.0	2.0	0.0
Heavy Minerals	1.8	.4	0	0.0	1.6	0.0
Matrix	37.6	33.4	31.2	57.5*	32.0	39.0
Chlorite	0.0	1.8	0.0	0.0	0.0	0.8
Chloritoid	0.0	15.0	0.0	20.5	5.6	4.6
Muscovite	0.0	0.0	0.0	2.0	0.0	0.0
Calcite			4.1			
Quartz/Rock Fragments + Matrix	.13	.34	.51	.35	.39	.64

Modal Analysis expressed as a percentage of 500 counts per/section. *Due to deformation of sample rock fragments counted with matrix.

The grains are typically poorly rounded. As in the greywacke the irregular serrate appearance of some of the grain margins suggests a reaction with the matrix. Many, however, have sharp, smooth, gently curved contacts, typical of the conchoidal fracture of freshly broken quartz. A few show a distinctive hexagonal outline which, together with embayments typical of partially resorbed quartz phenocrysts suggest derivation, at least in part, from a volcanic source. Secondary quartz overgrowths occur on some grains. The original outlines of the grain are marked by a pale brown line and are similar to the sharp clean margins of grains without overgrowths. This clearly indicates the original angular nature of the grains. The contact between the matrix and the overgrowth is diffuse. The overgrowth is not of uniform thickness and generally seen only at one corner or along one side of the grain. This overgrowth is post-depositional in origin and is not interpreted as an indication of second-cycle quartz. As in the greywacke, almost every quartz grain shows undulose extinction - a further reflection of tectonic deformation.

Rock Fragments

The rock fragments are predominantly felsic volcanics. The generally well-rounded, more or less elongate, grains have a clear outline, although in some cases there is complete gradation into the homogeneous matrix. The detrital nature of the clast is sometimes more clearly seen in plane light, where compositional and textural variation among the clasts is more apparent. The fragments consist of equant areas of very low birefringence that in a few cases have a bluish tinge. The individual fields in the mosaic have a sweeping extinction that has the effect of changing the shape of the field as the stage is rotated. Adjacent fragments show slight differences in colour, internal grain size and the development of rare feldspar crystallites which reflect small compositional variation among the clasts. Relict flow banding was observed in one fragment. In rare cases quartz and plagioclase phenocrysts were noted. The felsic volcanic rock fragments are essentially similar to those in the greywackes. Granite rock fragments are locally present but are extremely rare. One grain of myrmekite was seen. In a few places sedimentary mudstone clasts are present that are interpreted as interformational.

Feldspar

Feldspar is generally a minor component making up only a few per cent; in only a few beds it is a major component of this sandstone (Table 7). In this respect the sandstone contrasts strongly with the Burwash greywackes which typically contain over 10% plagioclase. As in Burwash greywackes the feldspar is always plagioclase and is present as angular clasts that have undergone minimal alteration; it also occurs in very minor amounts as small phenocrysts in the felsic volcanic rock fragments. The relatively fresh unaltered nature of the feldspar suggests that its scarcity is primary and not due to post-depositional diagenetic breakdown.

Matrix

The matrix of the Jackson Lake sands forms between 30 and 40% of the sediment. As in the Burwash greywackes it is derived largely from the post-depositional breakdown of the volcanic framework clasts. Commonly, a complete gradation can be seen from discrete, sharply-bounded rock fragments through rather diffuse grains, to an unbounded fine mosaic of low birefringent quartzo-feldspathic material that is the major matrix component. As the major component of the sediment is silicic volcanic rock fragments that may have been largely glass at the time of deposition, the post-depositional mechanical and chemical breakdown of such clasts would be expected accompanying the devitrification of the glass. A primary origin of the matrix seems unlikely as the sediment was deposited under rigorous alluvial conditions (*see* later section) - an environment more likely to produce a clean, well-sorted deposit with minimal fine-grained matrix material.

Metamorphic minerals, of which the most important is chloritoid, make up between 5 and 20% of the rock. Chloritoid occurs as scattered single crystals but where more abundant or concentrated, is present as radiating masses within the matrix and gives the rock its pale greenish colour. Fairly coarse-grained chlorite and fine-grained muscovite also occur in small amounts as secondary minerals. Alteration is more extensive in the southern part of the area and the matrix of many of the rocks is carbonatized. These sandstones resemble the Burwash greywackes in that they are composed primarily of quartz and lithic rock fragments and have a matrix that exceeds 15% by volume of the rock. They do, however, differ, in that on the whole the framework is much better sorted and is deficient in feldspar. Also the matrix is composed of disintegrated silicic volcanic rock fragments with minor amounts of sericite and chlorite as compared with the mixture of quartz, feldspar, chlorite and sericite that makes up the matrix of the Burwash greywackes.

PROVENANCE OF THE JACKSON LAKE FORMATION

The petrographic evidence leaves little doubt that the source of the Jackson Lake Formation was mainly volcanic terrain. Other sources contributed little.

The locally derived basal conglomerate with large angular to subrounded clasts of greenstone occupies depressions in the erosional surface on the Kam Formation. The source of these greenstone blocks is obviously the immediately underlying, predominantly mafic volcanic, Kam Formation. The basal conglomerate locally contains large well-rounded granitic boulders. The paucity and high degree of rounding of these suggests a source somewhat removed, although not necessarily a great distance from, the area of deposition. Plutonic granitic rocks clearly were exposed in the region.

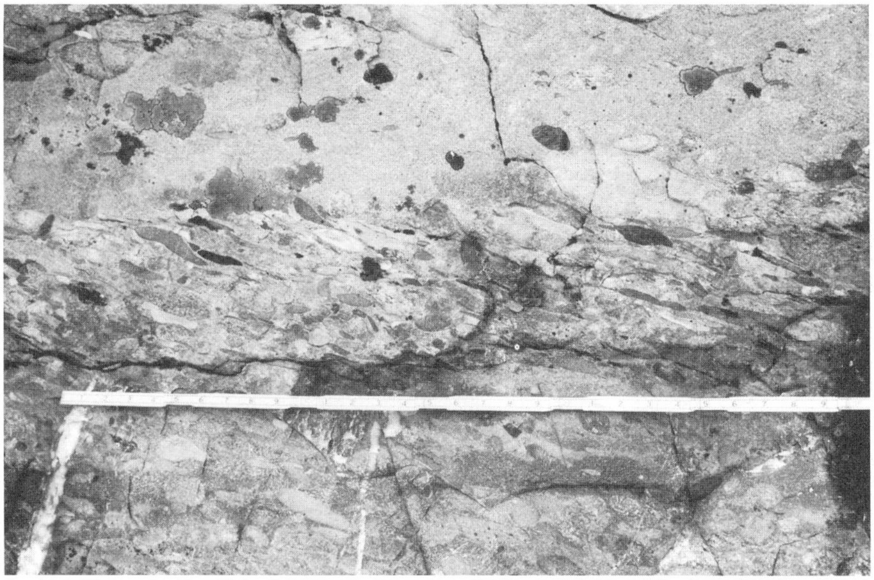


Figure 40.

Thin conglomerate in Jackson Lake Formation. The clasts in the thin discontinuous conglomeratic beds in the upper part of the formation are dominantly of silicic volcanic composition. The apparent imbrication in this case is tectonic.

The abundant silicic rock fragments in the sands and the large number of cobbles of silicic volcanics in the thin lensoid beds of conglomerate in the sandstone indicates that the main part of the formation, consisting dominantly of lithic wackes, was derived from silicic volcanic terrain. The nature of some of the quartz in the sands also indicates a volcanic provenance.

There is on the whole a distinct petrographic similarity between the sandstones of the Jackson Lake and Burwash Formations, particularly in the character of the rock fragments. This indicates that they may have shared, at least in part, a common provenance which was dominated by silicic volcanic material.

SEDIMENTARY STRUCTURES OF THE JACKSON LAKE FORMATION

The Jackson Lake Formation, consisting of basal conglomerate and overlying lithic wackes, differs markedly from the Burwash Formation in that the abundant crossbedding, extensive scouring and channelling, and presence of numerous pebble horizons contrast strongly with the regular, laterally persistent turbidites of the Burwash. The basal conglomerates (*see* previous section) are characterized by local provenance and lenses of current-laminated sands within them. The overlying sandstones are well bedded and of variable grain size and internal structure.

Bedding

The basal, locally derived conglomerate that occurs in depressions on the erosional surface of the Kam Formation is for the most part structureless (Figs. 34, 35), although in a few places thin discontinuous beds of current laminated sandstone are present. Sands of the transition zone into the overlying sandstone are generally thinly bedded and more argillaceous; on the whole the beds show a greater variability in thickness and grain size than higher in the formation. Thin elongate lenses of pebbly conglomerate are abundant in the lower part of the formation and decrease in number upward (Fig. 40). In the upper part of the formation the sandstone beds are in general more homogeneous, massive, and more thickly bedded.

The sandstones display many types of bedding. Most typical are the massive sand units ranging from six inches to ten feet (15 cm to 3 m) with an average thickness of about one foot (30 cm). These thick beds are commonly separated by thin layers of argillaceous siltstone or mudstone (Figs. 41 and 42). The sand beds are commonly parallel-sided but in places are lenticular and pinch and swell due to scouring and channelling. In some cases the scours and channels are lined with thin mudstone layers deposited before the succeeding sand (Fig. 42). Elsewhere the mudstone is eroded resulting in local minor mud-chip conglomerates. Large-scale channels are also present with relief in excess of 40 feet (12 m) in one case. Thinner bedded units are also present with bedding only inches in thickness. These tend to be more variable, in general with a greater range in bed thickness and grain size. Thin mud laminae are also commonly associated with these thinly bedded sands, and soft sediment deformation is also more abundant. Locally, thin members (six inches to one foot) of very thin-bedded silt and mud occur in the formation. In general beds of a given type tend to occur in groups. Discontinuous conglomeratic horizons are present throughout the section but are more abundant in the lower part of the formation (Fig. 40). These have a maximum thickness up to 60 feet (18 m), but more typically are on the scale of one to two feet (.5 m).

Internal Structures

The most common structure in the beds of the Jackson Lake Formation is a parallel lamination characterized by abrupt variation of grain size within the laminations. It is commonly accentuated by shearing

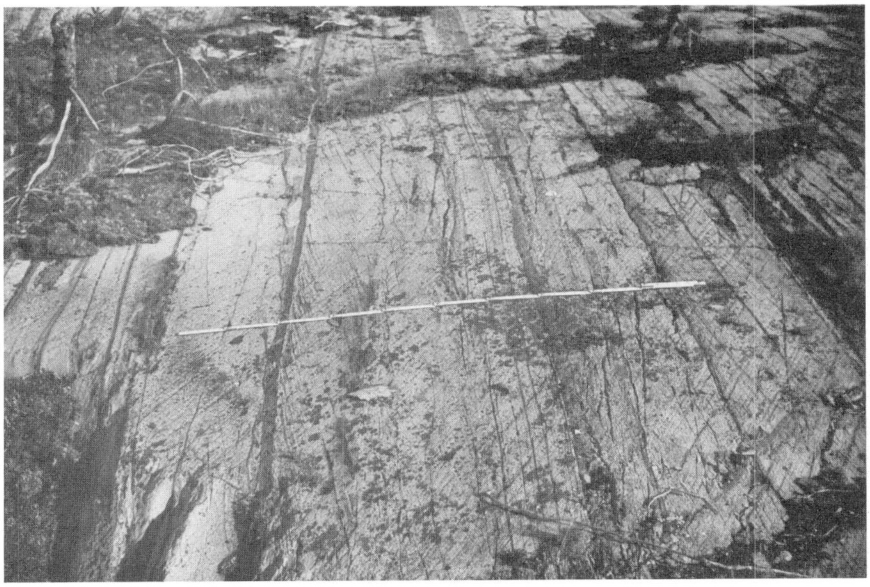


Figure 41.

Jackson Lake Lithic Sandstone. The parallel-sided sandstones have well-developed crossbeddings particularly in the lower part of the beds. The general current direction is away from the viewer. Continuous, in this case relatively thick, dark mudstone interbeds are prominent. The straie at high angle to bedding are glacial in origin.

Figure 42. Jackson Lake lithic sandstone. Typical exposure of Jackson Lake sandstone showing irregular scoured bedding planes, parallel and cross lamination and occurrence of darker discontinuous mudstone interbeds that in many cases define the bedding surfaces.

parallel to bedding. The abundance of these laminations indicates deposition under relatively high-flow regime conditions.

Medium-scale crossbedding (∿6 in., ∿15 cm) is also abundant. In many of the thicker sands the crossbedding is concentrated at the base of the beds whereas the upper part is massive (Fig. 41). The crossbedding is mainly of the festoon type but some is planar-tabular. All are typically of low inclination, a further indication of deposition from high velocity currents. However this may be due at least in part to tectonic deformation. At any one locality the crossbeds indicate a dominantly unidirectional current sense. Ripples are relatively rare and are present only in some of the thin lensoid silts.

Grading is also rare. Most thicker beds are fairly homogeneous or, if laminated, have an alternating grain size. On the other hand, some of the thinner beds associated with siltstones and shales show spectacular grading - in some cases, from gravel to silt (Fig. 43). The typical sand, however, is homogeneous and in sharp contact with the overlying mud.

Scattered pebbles occur within many of the massive sand beds either singly or in scattered open-packed groups. The pebbles are similar to those in the associated thin conglomerate in that they are well rounded, one to two inch (∿4 cm), dominantly silicic volcanic composition.

Soft sediment deformation structures are not common in this formation, but where present are usually in the thinner bedded units. They include fine load structures and rare small sandstone dykes. Concretionary structures are also present in some sands. They are typically brown-weathering poorly defined features commonly associated with crossbedding sets. Differential weathering of the concretions accentuates the cross-lamination.

Tectonic breccias are present locally (Fig. 44); an example occurs in the formation west of the northern part of Yellowknife Bay, and is associated with highly sheared sediments. It may be related to shear zone systems similar to the shear zones found in the underlying mafic volcanics.

PALEOCURRENTS OF THE JACKSON LAKE FORMATION

The Jackson Lake Formation represents a very different environment of deposition from the Burwash Formation, the main sedimentary unit in the region. Paleocurrent data were collected to further document these differences and further clarify the environment of deposition.

Paleocurrent data were collected at 15 stations - six north of the Akaitcho fault south of Jackson Lake, six south of the fault and three on the Sub Islands in the southern part of the Bay (Fig. 45). An average of twenty-one readings were taken at each station. All readings were taken on medium-sized festoon-type crossbeds. As the bedding is invariably steeply dipping, the flat outcrop exposures provided a good cross-sectional view. Fractures, joints or weathered concretions provided the third dimension for finding the true attitude of the crossbedding lamination.

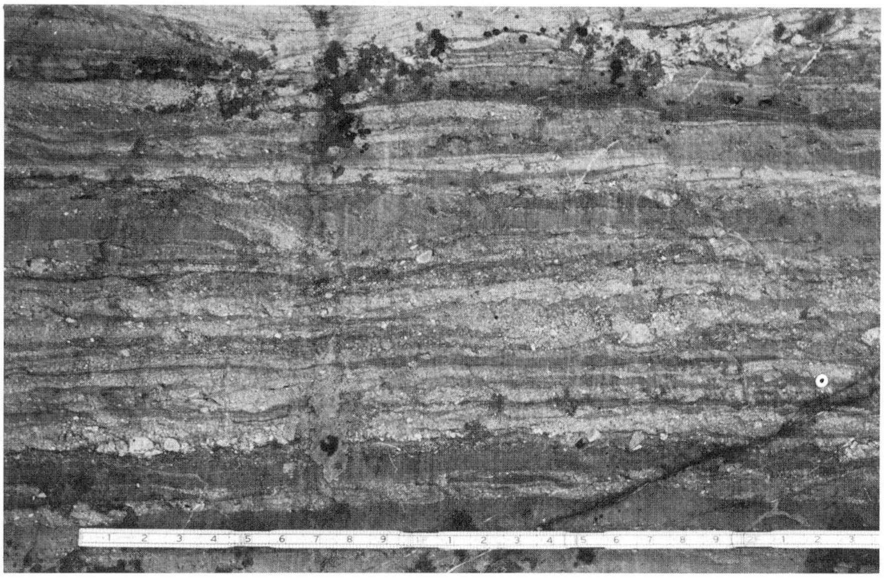


Figure 43.

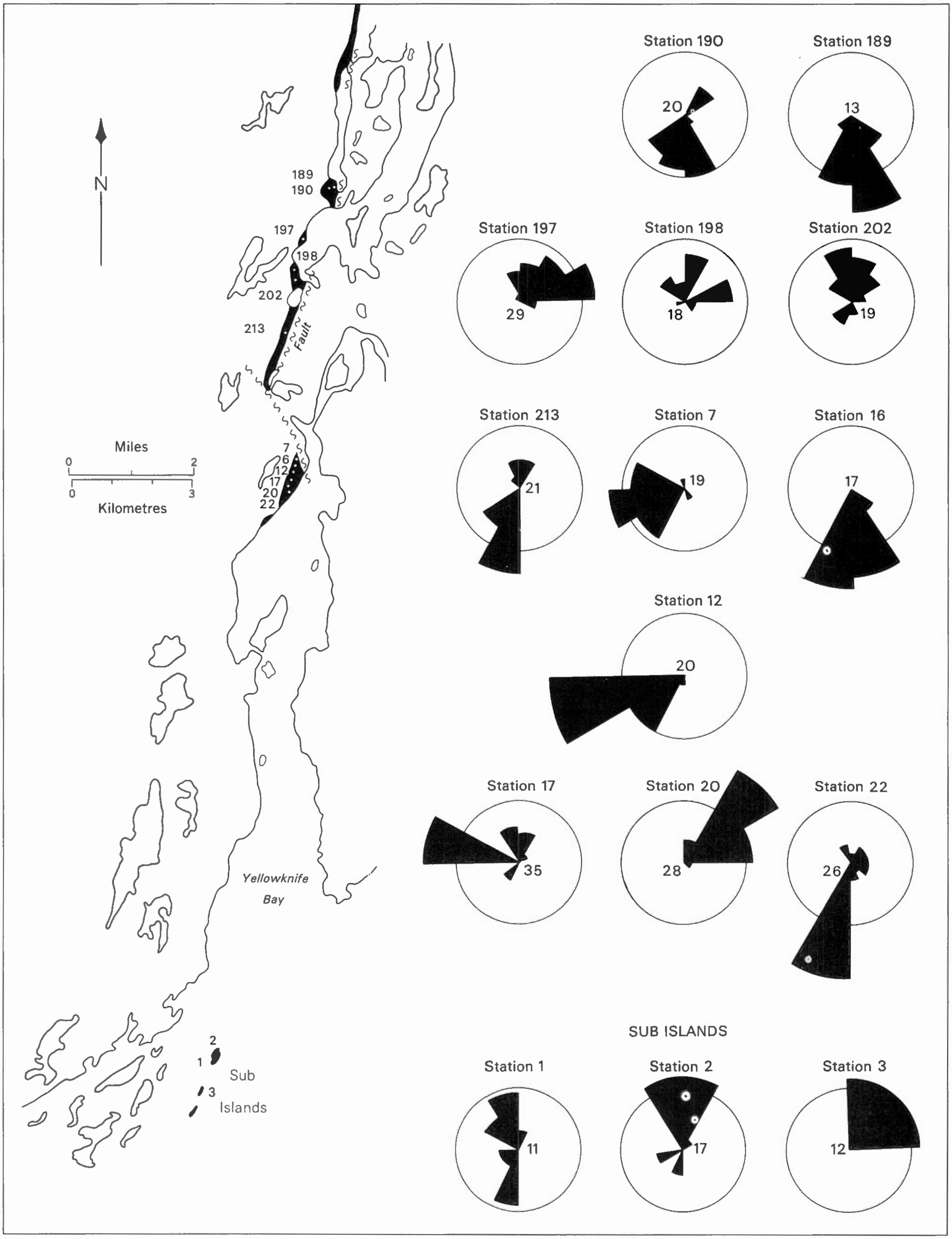
Jackson Lake poorly sorted sands and gravels. Note the relatively thin beds and wide range of grain size in these sediments. Crossbedded scour fills are abundant.

Figure 44.

Jackson Lake tectonic breccia. Tectonic breccias composed of angular blocks of the Jackson Lake sandstones are believed related to the fault that marks the upper contact of the formation; it may be related to the extensive shear zones in the underlying mafic volcanic sequence.

Figure 45 (opposite)

Paleocurrents in the Jackson Lake Formation. Paleocurrent data for 15 sites were taken from medium scale cross beds in the lithic sands. The number beside each current rose represents the number of measurements made at each station. The class interval is 30 degrees and a 30% reference circle is drawn for each station. With a few exceptions the directions at each station are unimodal but are non consistent along the formations exposure, in general alternating between a northerly and southerly sense of transport.



N
189
190
197
198
202
213
Fault
Miles
0
2
0
3
Kilometres
7
6
12
17
20
22
Yellowknife
Bay
2
1
3
Sub
Islands
Station 190
20
Station 189
13
Station 197
29
Station 198
18
Station 202
19
Station 213
21
Station 7
19
Station 16
17
Station 12
20
Station 17
35
Station 20
28
Station 22
26
SUB ISLANDS
Station 1
11
Station 2
17
Station 3
12

GSC

In the Jackson Lake sandstones the structure is less complex than the Burwash greywackes because the formation is located on the un-refolded west limb of the major syncline. The only structural restoration required was rotation of the crossbedding readings about a horizontal axis parallel to the strike of the beds to return the bedding planes to the horizontal. Because the plunge of the major syncline is interpreted as small, its effect was considered negligible. Shearing parallel to bedding may have affected the crossbedding attitudes to some unknown degree.

The data for each station are shown in Figure 45 as rose diagrams of the restored current directions. It should be noted that with a few exceptions the results are strongly unimodal. This unimodal direction varies somewhat from station to station although stations close to each other exhibit similar directions. Figure 46 is a composite rose diagram of measurements taken at all 15 stations.

Most stations show either a north to northeast or a south to southeast sense of transport; there is very little mixing of these two dominant directions. The current sense also tends to alternate along the outcrop belt of the formation. For the most northerly pair of stations the current sense is from the north, while for the next group of stations about a mile to the south the current sense is reversed, with movement from the south (Fig. 45). This alternation is repeated along the entire exposure. This almost complete repeated current reversal requires explanation as does the fact that the mean of all the current directions is oriented approximately parallel to tectonic strike.

The data may reflect a sampling bias. Crossbeds which are not oriented in a favourable orientation to be viewed in a horizontal section might be overlooked (Pettijohn, 1957b). This bias is most probable in the case of tabular crossbedding where a section parallel to the strike of the crossbed would display only parallel laminations and so would not be recognized as crossbedding. In the Yellowknife area, however, the crossbedding is mainly of the trough or festoon type, so that no matter how the crossbedding surface is cut the components of both sides of the trough should be present. The resulting paleocurrent rose diagram would have the shape of a drooping "bow tie" with the true down current direction bisecting the smaller angle between the two maxima. This is not the pattern in this case.

Shearing may also have an effect on the orientation of crossbedding planes. As the unit is sheared, the crossbedding plane will migrate into or away from the plane of shearing depending on the original orientation of the plane of crossbedding relative to the sense of shearing. The laminations that are steepened tend to become thicker while those that are flattened tend to be obliterated. The sense of shearing is assumed to be constant along the outcrop belt for the Jackson Lake Formation. The movement is mainly vertical. This does not satisfactorily explain the apparent alternation of current directions along the outcrop belt, although it appears to be a possible mechanism by which the current sense tends to be rotated into the plane of shearing.

It is concluded then that while the shearing of the formation has had some effect on the orientation of the directional data the general current sense is reasonably correct to the degree that it indicates the correct quadrant. That is to say current directions varied in direction from either a northerly direction or southerly direction along the outcrop belt of the formation.

ENVIRONMENT OF DEPOSITION

The Jackson Lake Formation in spite of certain lithological affinities, provides a strong contrast to the Burwash Formation as far as environment of deposition is concerned. The Burwash Formation, volumetrically the most abundant unit in the region, is a product of deep water deposition. The Jackson Lake, on the other hand, was deposited in a shallow water, probably terrestrial, environment.

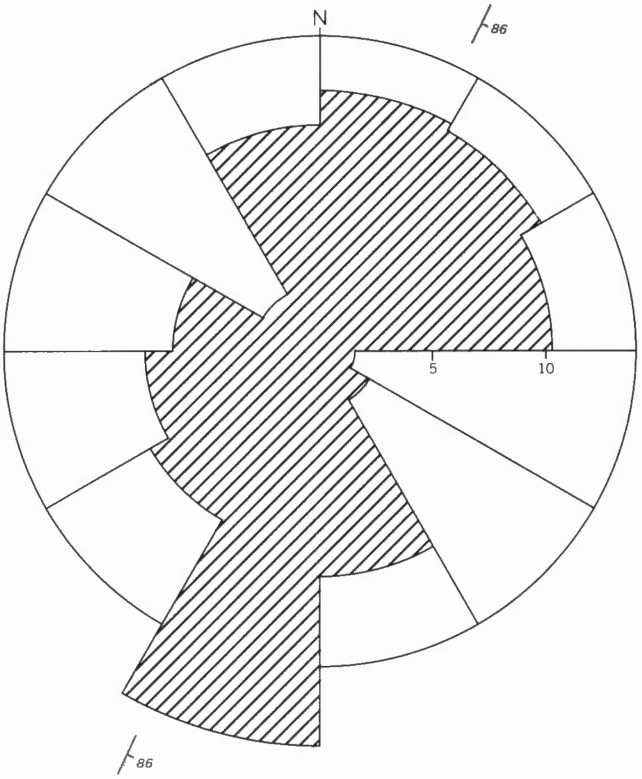
The formation was depositioned unconformably on the mafic volcanic Kam Formation. Depressions or valleys in the unconformity surface are up to 700 feet (200 m) deep and 1,200 feet (370 m) wide. In most cases however the relief is much less with a much smaller depth to width ratio.

As the subaqueously extruded volcanic pile was tilted and raised above "sea" level, the higher parts of the volcanic pile were eroded and deposited as angular clasts in the adjacent lower areas, thus filling irregularities on the volcanic surface. The local, discontinuous beds and lenses of current-laminated sandstone within the basal conglomerate suggest aqueous transport of at least some of the material and that erosional depressions on the unconformity surface may have been the locus of streams and small rivers. Thus, the conglomerates are more than mere talus deposits. The upper part of the formation, consisting mainly of sandstone and minor relatively thin lenses of conglomerate, were deposited on a relatively even surface of conglomerate or Kam volcanics.

That the sediments were deposited by strong currents is indicated by scours and channels, abundant parallel lamination in the sands, low-angle crossbedding and the coarse grain size of some of the beds. Scattered lensoid gravel beds in the sandstones are interpreted as lag deposits transported by periodic high velocity currents. On the other hand, there are many thin interbeds of silt and mud that could only be deposited in relatively quiet water. Thus there would appear to have been violent influxes of sediment followed by relatively quiet periods during which the mud and silt could settle out and form the silt and mud interbeds.

Turbidites are deposited under such a regime but turbidites are not noted for the abundance of medium-scale crossbedding that is so characteristic of most of the Jackson Lake Formation.

A shallow water "marine" environment seems unlikely as it would be difficult to account for the thin muddy interbeds that are so common among the thicker parallel-laminated to cross-laminated sands. Such a combination would require an extreme fluctuation in current regimes that would be difficult to achieve in a shallow marine environment where currents on the



Average bedding attitude 26°/86°E GSC

Figure 46. Composite paleocurrent rose diagram for Jackson Lake Formation. Diagram is based on 305 measurements taken at 15 stations.

whole tend to be semi-permanent and governed by wind and general circulation patterns. Sediments deposited under tidal influence have yet to be identified in the Archean but the apparently mono-directional paleocurrents at individual stations may indicate that the sands were not influenced by tidal currents.

The sands are very restricted suggesting that, like the underlying conglomerate, the source was local. Because the sands are composed almost entirely of quartz and silicic volcanic rock fragments a local acidic volcanic terrain might be considered as the source. Because the small amount of silicic volcanics in the presently exposed underlying Kam Formation is too small to supply the large volume of sand in the Jackson Lake Formation, and because there is no Kam-derived mafic material in the sands, one must conclude that a large dominantly silicic, volcanic terrain was present in the nearby region to supply the detritus found in the sediments.

The restricted composition and compositional immaturity of the sands suggest the sands were deposited close to their source, perhaps on an alluvial fan complex developed adjacent to a high rapidly eroding dominantly silicic, volcanic terrain. Alluvial fan deposits are characterized by both fluviatile and mudflow deposition which produce a chaotic deposit reflecting highly varied modes of deposition. In the Jackson Lake sandstones there is little evidence of mudflow deposition, the sediments being generally well sorted, parallel-laminated to crossbedded sands with thin argillaceous to silty interbeds and local elongate lenses of well packed conglomerate. There is little doubt that the Jackson Lake sands were deposited in a shallow water environment - one that was most likely terrestrial in locale.

The Jackson Lake sands seem best interpreted as a fluvial deposit on the lower part of an alluvial fan or alluvial plain. There is no evidence of the typical fining upward sequence characteristic of point bar deposits of meandering rivers. The sands of this formation, on the whole, represent a braided river environment with the depositional locus shifting randomly over the alluvial plain resulting in no regular cyclical deposition of sediments.

In general current-direction indicators in braided river complexes parallel the trend of the river (Rust, 1972). However, in the Jackson Lake Formation current indicators tend to be opposed at 180° at the various measurement localities along the outcrop belt, although at any one locality the directions are generally unimodal. This might be caused by a rather narrow alluvial plain in close proximity to an open coast. If a barrier was present along the coastline, the river flowing across the alluvial fans would be deflected parallel to the coast until a point was reached where the barrier was breached. With time the barrier would be breached at other localities and the movement of material inside the barrier reversed. Thus current directions at any point in the formation would depend on their location relative to the breach in the barrier at the time of deposition.

It has been suggested (Schumm, 1968) that before the appearance of significant terrestrial plant life most streams and rivers were braided river type, with wide braided streams occupying the entire floor of alluvial valleys. Material would be immediately transported down onto the alluvial plain during successive flash floods as soon as it was eroded. Without stabilizing vegetation, meander belts would not form and with each flood the abundant sediment would be moved through a succession of braided river channels. A modern analogue can be seen in arid or semi-arid areas where plant life is greatly restricted.

The sands of the Jackson Lake Formation were deposited in periodic pulses representing floods in the source areas and were deposited under high flow-regime conditions, as indicated by the sedimentary structures and relatively coarse grain size. The thin conglomerate lenses represent lag deposits that formed bars in the river channels. After a flood, a period of quiescence followed during which the fines settled out, producing the fine silts and muds at the tops of the sands. In recent braided stream analogues this clay layer is commonly not preserved as it dries and breaks up into mud chips which either blow away with the wind or are swept away with the succeeding flood. There are abundant examples of these mud layers in the Jackson Lake Formation, and little evidence of subaerial desiccation; this may indicate an extremely humid atmosphere during its deposition.

CHAPTER 5

DISCUSSION

INTRAFORMATIONAL RELATIONSHIPS

Throughout the Slave Province it has generally been assumed that the volcanic units of the Yellowknife Supergroup are in general older than the sedimentary units, although exceptions do occur. Ross and McGlynn (1965) for example, report that in the Mesa Lake area on the western margin of the Slave Province sedimentary units occur both above and below a major volcanic unit. However, the greywacke-mudstone units in general conformably overlie the volcanic units. This is the situation near Gordon Lake, 50 miles northeast of Yellowknife where one can walk up-section across a conformable and in some places gradational, contact from volcanic flows and tuffs to the greywacke-mudstones of the Burwash Formation. The situation at Yellowknife is anomalous in that there is an unconformity between the major basic volcanic unit and the overlying sediments, and the sedimentary formation above the volcanics, the Jackson Lake Formation, does not consist of the typical turbidite that is the characteristic Yellowknife Supergroup sedimentary facies.

A map of the Yellowknife "basin" (Fig. 1) shows that the volcanics are exposed only along the margins of the basin; in fact only along the east and west sides of the basin. They are always in contact with granodioritic batholiths on one side and on the other with Yellowknife sedimentary formations. They appear in part to mantle the batholiths. The southeastern granodiorite batholith forms part of the southern boundary of the basin. Along most of this contact with the Yellowknife Supergroup there are no volcanics except for the relatively minor Duck Lake Formation at the northwest. In the central part of the basin there are essentially no volcanics, except for the minor flows east and west of Gordon Lake enclosed completely within the Burwash Formation. These minor flows are for the most part less than a few hundred feet (100 m) in thickness and thus are not comparable with the major volcanic piles along the margins of the basin.

The regional gravity map of the region (Hornal and Boyd, 1972) shows the thick sequence at Yellowknife has a distinct positive Bouguer anomaly as does, to a lesser extent, the much thinner basic sequence on the east side of the basin. On the whole, the central part of the basin has a similar gravitational expression as the surrounding granitic terrain. Thus it would seem that the volcanics are restricted to the margins of the basin, and there is little evidence that the sediments are underlain by a significant thickness of mafic volcanics.

What then is the relationship of the sedimentary formations to the mafic volcanic Kam Formation in the Yellowknife area? There are two possibilities. First, the main sedimentary formation (Burwash) may be time-equivalent to the Kam Formation; deposited in the central part of the basin while the volcanics were being extruded on the margin. Second, the sediments may be younger than the volcanics and deposited after or during the late stages of the development of the volcanic belt. Unfortunately the two major formations are always in fault contact, so it is difficult to prove either possibility unequivocally. Elsewhere in the basin, however, there is a single sharp contact between sediments and volcanics. That is, there is no interlayering of volcanics and the greywacke-mudstone turbidites that should occur if they accumulated together over a long period of time. The second possibility is thus considered the most likely.

In the Yellowknife area the Duck Formation which conformably underlies the Burwash (*see* Fig. 2) may be an eastern lateral equivalent of the upper part of the main volcanic sequence. Several thin volcanic units and many tuffaceous beds are associated with the Burwash turbidites in this area, indicating basic volcanism was still active during the early sedimentation of the Burwash Formation. Within the basin but higher in the section, there is no evidence of active basic volcanism taking place although the presence of blocks of thin felsic tuff within some turbidite beds indicates volcanism was still active elsewhere. The high proportion of intermediate to felsic, rather than basic, volcanic rock fragments within the Burwash greywackes indicated that although the provenance of the sediment was volcanic the mafic Kam Formation was not a major contributor.

Previous workers have not agreed on the relationship of the Jackson Lake Formation to the other formations of the Yellowknife Supergroup. Although the formation rests with angular unconformity on the Kam mafic volcanics its relations to the other formations cannot be observed directly. The formation occurs only on the west limb of the major northerly trending syncline and its upper contact with the overlying Banting volcanics is faulted. Jolliffe (1942) who first mapped the area concluded that the Jackson Formation formed the basal part of his division B (Jackson Lake, Banting and Walsh Formations).

Henderson and Brown (1952, 1966) suggested that the formation might be significantly younger, possibly

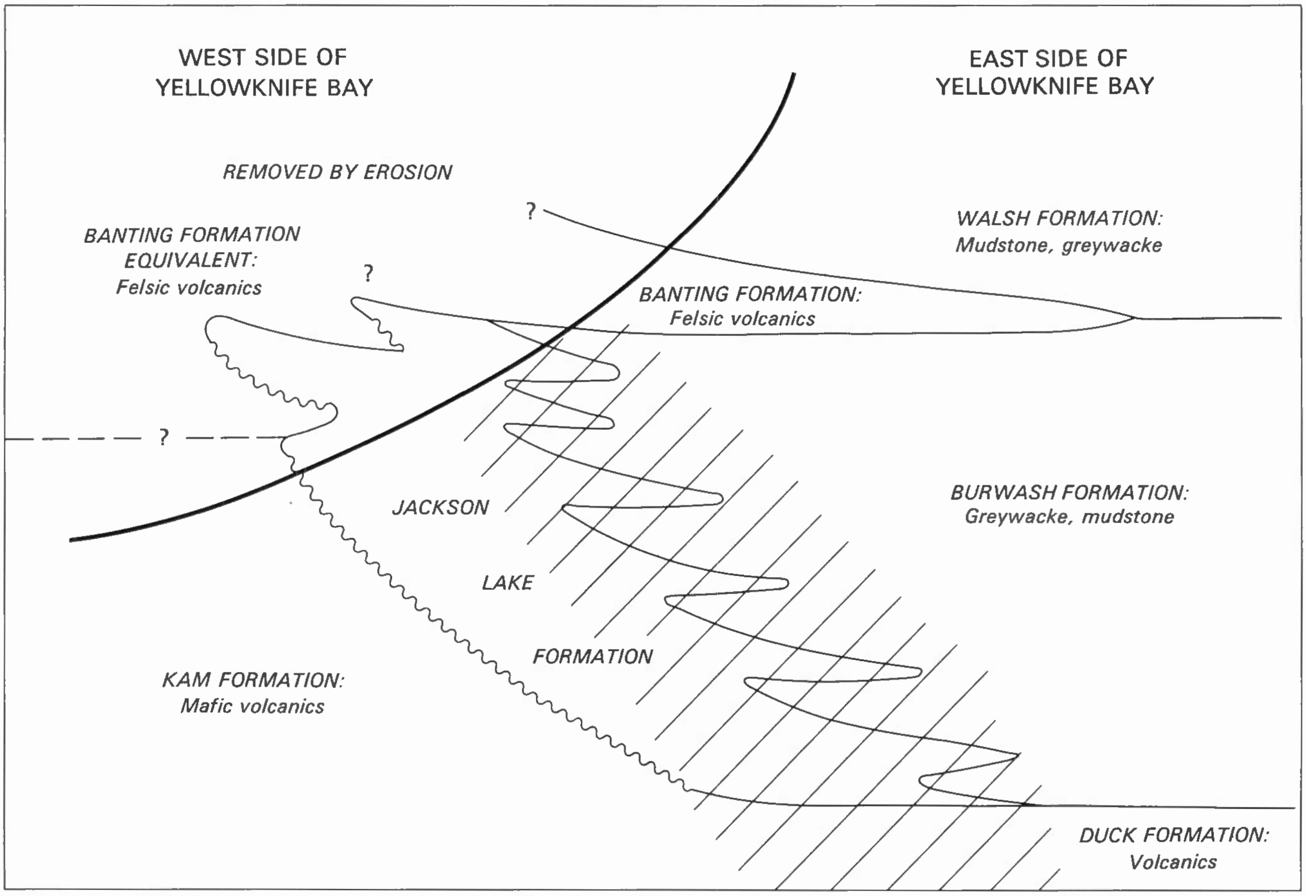


Figure 47. Suggested stratigraphic cross-section of the formations of the Yellowknife Supergroup at Yellowknife. The heavy line indicates the approximate present level of erosion. The cross hatched area represents the area now covered by Yellowknife Bay or missing due to faulting. On the east side of the bay the volcanic Duck Formation, a possible eastward lateral extension of the Kam Formation, is conformably overlain by the Burwash greywacke-mudstone turbidites. The felsic volcanic Banting Formation lies conformably between the turbidites of the Burwash and Walsh Formations. On the west side of the bay the Jackson Lake conglomerates and volcanic lithic sandstones unconformably overlie the mafic volcanics. The Jackson Lake Formation, derived largely from a silicic volcanic source represents the shallow-water equivalent of the deeper-water turbidites of the Burwash and Walsh Formation.

post-Yellowknife, in age. This was based on the contrast in the lithological and sedimentological characteristics of the formation which reflect its terrestrial shallow-water deposition in contrast to the more typical turbidites so characteristic of Archean sediments in the region. As further evidence they noted that the basic intrusions in the Kam, Banting and Walsh Formations do not occur in the Jackson Lake Formation indicating that the Jackson Lake may have been deposited after the intrusion of the basic rocks. They also indicate that the sediments of their division B of the Yellowknife "Group" are in conformable contact with the Kam volcanics along the northwest shore of Yellowknife Bay. They cite the tectonic difficulties of having two sedimentary units of the same age with such contrasting structural relations with a common basement. However this writer feels that their division B in this particular area is part of the Jackson Lake Formation and that a disconformable to angular unconformable relationship exists between it and the underlying Kam Formation.

Green and Baadsgaard (1971) and Folinsbee *et al.* (1968) suggest that the Jackson Lake was derived at least in part from the erosion of the large granitic complex southeast of Yellowknife that was intruded, in their opinion prior to the deposition of at least part of the Yellowknife turbidites.

The Jackson Lake Formation consists of a dominantly locally derived (Kam Formation) basal conglomerate overlain by extensively crossbedded sands with minor thin conglomerate horizons that were deposited in a braided river environment on an alluvial plain. The sands were derived from a restricted source that was silicic volcanic in character. The formation is restricted to a narrow outcrop belt unconformably on the mafic volcanic Kam Formation. The Burwash Formation on the other hand represents the main fill of the basin east of Yellowknife and was deposited as turbidites in presumably deep water on a complex of submarine fans. Paleocurrent information indicates the Burwash turbidites were derived from a source that lay to the west. From the modal composition of these sediments it is apparent that they were derived from a dominantly felsic volcanic source with a significant granitic input as well. It seems likely the Jackson Lake braided river deposits are the terrestrial basin margin equivalent of the Burwash Formation turbidites.

The Banting Formation, composed of intermediate to silicic volcanic flows, tuffs and agglomerates, conformably overlies the Burwash Formation. Its relationship to the mafic Kam volcanics on the west side of the Bay is not exposed. Baragar (1966) has suggested that the Banting Formation is a cap of predominantly silicic volcanics above the Kam that presumably represents an explosive period of silicic volcanism that extended away from the main volcanic pile into the basin where the Burwash turbidites were accumulating. However a normal contact between the Kam and Banting Formations has not been preserved. The Banting Formation does not represent the start of silicic volcanism in the area because approximately 15,000 feet (5,000 m) of Burwash greywackes and mudstones, composed largely of silicic volcanic rock fragments, underlie the Banting.

The Walsh Formation, conformably overlies the Banting volcanics, and is, like the Burwash, another turbidite formation, it represents the continuation of normal basinal sedimentation that was interrupted locally by the Banting volcanics (Fig. 47).

NATURE OF ARCHEAN CRUST

There can be little doubt that sialic crust existed in the Slave Province during deposition of the Yellowknife supracrustal rocks. It would be impossible to derive sediments with as high a quartz content as the Burwash Formation from a strictly mafic volcanic or simatic crustal source (Donaldson and Jackson, 1965). At least half the Slave Province is overlain by Yellowknife supracrustal rocks or their metamorphosed equivalents and the great majority are of sedimentary origin with an average "granodiorite" chemical composition. Thus the sialic source must have been extensive. Many recent studies of Archean sediments in other parts of the Shield have resulted in similar conclusions regarding the felsic composition of source areas, although the nature of the felsic sources vary considerably. In the North Spirit Lake area of Ontario, Donaldson and Jackson (1965) concluded that the rather quartz-rich sediments were derived largely from a granitic and/or metasedimentary terrain with only a local volcanic contribution. Walker and Pettijohn (1971) suggested that the sediments at Minnitaki Lake southeast of Sioux Lookout, Ontario were derived from a granitic terrain with some contribution from a local identifiable quartz porphyry body. Roussell (1965) found pre-volcanic basement granodiorite at Cross Lake, Manitoba. Ojakangas (1972) found that the sediments of the Vermillion District, northeastern Minnesota were derived largely from volcanics of felsic to intermediate composition with a minor contribution from an identified granitic area. In the Lake Superior Park area the Archean sediments have a rhyodacitic provenance (Ayres, 1969) and the parent volcanics are believed to have been derived by anatexis of an existing sialic crust.

In the Slave Province and the Yellowknife area in particular, the proportion of sediments to volcanics is very large so that the potential volume of sialic detritus that might be expected from the felsic portions of the volcanic sequences is minimal. It is certainly insufficient to supply the volume of sialic detritus that makes up the Burwash Formation.

It appears likely then that an extensive positive terrain of sialic composition existed prior to deposition of the Yellowknife supracrustal rocks. The modal composition of the sediments at Yellowknife indicates that this sialic terrain probably included both epizonal plutonics, as in the Jackson Lake basal conglomerate and the Burwash greywackes and volcanic material, and as represented in the sands of both the Burwash and Jackson Lake Formations. This sialic terrain must have existed as a highland west of Yellowknife. The erosion of the sialic highland could provide sufficient detritus that would ultimately be deposited in the adjacent basin to the east to form the Jackson Lake and Burwash Formations. A model that would satisfy the requirements of such a terrain could be similar to that proposed by Hamilton and Myers (1967) for the large batholiths in the western United States. There granitic batholiths were intruded as relatively shallow bodies capped by their own extrusive equivalents. The present day granitic terrain west of Yellowknife may have been a region of such granitic activity resulting in the formation of a highland dominated by felsic volcanics which when eroded would include areas of exposed epizonal granitic rocks as well.

SUMMARY

A sialic crust was established in the Slave Province prior to the accumulation of the Yellowknife volcanics and sediments although the nature and form of this crust is not clear. Extensive granodioritic batholiths that occur between the areas underlain by Archean supercrustal rocks may be related to pre-Yellowknife crust, and possibly represent positive areas or areas of greater thickness, with the Yellowknife basins formed on thinner downwarped parts of the same sialic crust (McGlynn and Henderson, 1970).

In the Yellowknife area the Kam volcanics were extruded, possibly as a result of deep fracturing, at the margin between the relatively thin crust underlying the basins and the thicker positive sialic crustal element to the west. This may have been related to tectonic events associated with inferred felsic magmatic activity west of the basin. Large volumes of pillowed and massive mafic volcanic flows were extruded marginal to the basin ultimately forming a linear chain of volcanic islands bordering the basin. Differential subsidence, in part associated with the buildup of the volcanic pile, resulted in minor tilting of the pile as shown by the angular discordance between the Kam and overlying Jackson Lake Formation. Concomitant with basic volcanic activity at the basin margin, shallow sialic batholiths were emplaced to the west, with extensive felsic volcanism as a surface manifestation of this activity. Possibly the felsic volcanic Banting Formation may be representative of this event at the margin of the basin.

The basin to the east began to fill with dominantly silicic volcanic debris accompanying the erosion of the rising highlands. With the continued dissection of the batholithic complex, higher level granitic intrusions were exposed and granitic detritus also began to be contributed to the growing volume of sediment being delivered to the east. Alluvial fans of predominantly volcanic debris formed adjacent to the rising highlands. Silicic volcanism continued with this material being eroded and carried easterly toward the basin by periodic floods. Alluvial plains formed consisting of complexes of braided river deposits. These fans eventually overwhelmed the marginal basic volcanics and are preserved as the Jackson Lake Formation.

The detritus that ultimately formed the Burwash Formation in the basin east of Yellowknife was emplaced by turbidity currents. The turbidity currents flowed out into the basin across a complex of large subaqueous fans on which the main part of the turbidity currents were restricted to depositional valleys on the fans. This resulted in relatively thick-bedded deposits with "proximal" characteristics within the valleys and thin-bedded fine-grained "distal" deposits analogous to overbank on the inter-valley areas. Thin, fine-grained turbidite deposits initiated from local slumps within the fan valleys and possibly overbank deposits from adjacent active valleys accumulated as well in the valleys resulting in mixed "proximal" and "distal" deposits in the depositional valleys and distal deposits alone in the inter-valley areas. Approximately 15,000 feet (5,000 m) of such deposits accumulated in the basin east of Yellowknife.

Volcanic activity continued during sedimentation providing abundant seismic shocks to initiate the turbidity currents. Throughout the sedimentary section the presence of tuffaceous beds and exotic blocks of tuffaceous sediment is further evidence of this continued volcanic activity. One such sequence of explosive volcanic activity may account for the origin of the sialic volcanic Banting Formation some distance west of the margin of the basin. Normal sedimentation resumed after this volcanic event with the deposition of the Walsh turbidites which mark the end of the record of preserved Archean stratified rocks in the Yellowknife area.

Although the area under investigation represents but a small part of the Slave Province, this mode for the origin and deposition of the sediments at Yellowknife may be applicable to other parts of the Archean basin east of Yellowknife and other basins in the province.

REFERENCES

Ayres, L.D.
1969: Early Precambrian metasandstone from Lake Superior Park, Ontario, and implications for the origin of the Superior Province (abs.); Geol. Soc. Amer. Abstracts with programs for 1969, pt. 7, p. 5.

Bagnold, R.A.
1954: Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear; Proc. Roy. Soc. London (Ser. A), v. 225, p. 49-63.

Baragar, W.R.A.
1966: Geochemistry of the Yellowknife volcanic rocks; Can. J. Earth Sci., v. 3, p. 9-30.

Bass, M.N.
1961: Regional tectonics of part of the southern Canadian Shield; J. Geol., v. 69, p. 668-702.

Bell, J.M.
1929: Great Slave Lake; Proc. Trans. Roy. Soc. Can., 3rd Series, v. 23, p. 5-38.

Bell, R.
1900: Mackenzie District; Geol. Surv. Can. Ann. Rept., v. XII, p. 103a-110a.

Blatt, Harvey
1967: Original characteristics of clastic quartz grains; J. Sed. Pet., v. 37, p. 401-424.

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

Boyle, R.W.
1961: The geology, geochemistry and origin of the gold deposits of the Yellowknife District; Geol. Surv. Can., Mem. 310.

Campbell, N.
1947: Regional structural features of the Yellowknife area; Economic Geology, v. 42, p. 687-698.

Camsell, Chas., and Malcolm, Wyatt
1919: The Mackenzie River Basin; Geol. Surv. Can., Mem. 108, p. 59.

Condie, K.C.
1967: Geochemistry of early Precambrian greywackes from Wyoming; Geochim. Cosmochim. Acta., v. 31, p. 2135-2149.

Cummins, W.A.
1962: The greywacke problem. Liverpool Manchester; Geol. J., v. 3, pt. 1, p. 51-72.

Donaldson, J.A., and Jackson, G.D.
1965: Archean sedimentary rocks of North Spirit Lake area, northwestern Ontario; Can. J. Earth Sci., v. 2, p. 622-647.

Davidson, A.
1972: Granite studies in the Slave Province (Parts of 85I); *in* Report of Activities, Part A; Geol. Surv. Can., Paper 72-1, pt. A, p. 109-115.

Dzulynski, S., and Walton, E.K.
1965: Sedimentary features of flysch and greywackes; Developments in Sedimentology 7; Elsevier, Amsterdam.

Eade, K.E., and Fahrig, W.F.
1971: Geochemical evolutionary trends of Continental Plates - a preliminary study of the Canadian Shield; Geol. Surv. Can., Bull. 179.

Eskola, Pentti
1932: Conditions during the earliest geological times as indicated by the Archean rocks; Annales Acad. Scient. Fenn., Series A, v. 36, no. 4.

Folinsbee, R.E., Baadsgaard, H., Cumming, G.L., and Green, D.C.
1968: A very ancient island arc; Amer. Geophys. Un., no. 12, p. 441-448.

Glikson, A.Y.
1971: Primative Archean element distribution patterns: chemical evidence and geotectonic significance; Earth Planet. Sci. Lett. 12, p. 309-320.

Gluskoter, H.J.
1964: Orthoclase distribution and authigenesis in the Franciscan Formation of a portion of western Marin County, California; J. Sediment. Petrology, v. 34, p. 335-343.

Green, D.C., and Baadsgaard, H.
1971: Temporal evolution and petrogenesis of an Archean crustal segment at Yellowknife, N.W.T., Canada; J. Petrol., v. 12, p. 177-217.

Green, D.H., and Ringwood, A.E.
1968: Genesis of the calc-alkaline igneous rock suite; Contr. Mineralogy and Petrology, v. 18, p. 105-162.

Hamilton, E.L.
1967: Marine geology of Abyssal Plains in the Gulf of Alaska; J. Geophys. Res., v. 72, p. 4189-4213.

Hamilton, W., and Myers, W.B.
1967: The nature of batholiths; U.S. Geol. Surv., Prof. Paper 554-c.

Haner, B.E.
1971: Morphology and sediments of Redondo Submarine Fan, southern California; Bull. Geol. Soc. Amer., v. 82, p. 2413-2432.

Hemley, Julian J.
1959: Some mineralogical equilibria in the system K_2O-Al_2O_3-SiO_2-H_2O; Am. J. Sci., v. 257, p. 241-270.

Henderson, J.B.
1970a: Stratigraphy of the Archean Yellowknife Supergroup, Yellowknife Bay — Prosperous Lake, Area, District of Mackenzie; Geol. Surv. Can., Paper 70-26.

1970b: Petrology and origin of the sediments of the Yellowknife Supergroup (Archean), Yellowknife, District of Mackenzie; Ph.D. Thesis, 262 p., The Johns Hopkins University, Baltimore, Md. U.S.A.

Henderson, J.B., Cecile, M.P., and Kamineni, D.C.
1972: Yellowknife and Hearne Lake map-areas, District of Mackenzie with emphasis on the Yellowknife Supergroup (Archean) *in* Report of Activities, Part A; Geol. Surv. Can., Paper 72-1A, p. 117-119.

Henderson, J.F.
1938: Beaulieu River area, Northwest Territories; Geol. Surv. Can., Paper 38-1.

Henderson, J.F., and Brown, I.C.
1952: The Yellowknife greenstone belt, Northwest Territories; Geol. Surv. Can., Paper 52-28.

1966: Geology and structure of the Yellowknife greenstone belt, District of Mackenzie; Geol. Surv. Can., Bull. 141.

Hornal, R.W., and Boyd, J.B.
1972: Gravity measurements in the Slave and Bear Structural Provinces, Northwest Territories; Gravity Map Series, Earth Physics Branch, Nos. 89-95.

Jolliffe, A.W.
1942: Yellowknife Bay, District of Mackenzie, Northwest Territories; Geol. Surv. Can., Map 709A.

Jopling, A.V., and Walker, R.G.
1968: Morphology and origin of ripple-drift cross lamination with examples from the Pleistocene of Massachusetts; J. Sediment Petrology, v. 38, p. 137-147.

Kretz, R.
1968: Study of pegmatite bodies and enclosing rocks, Yellowknife-Beaulieu region, District of Mackenzie; Geol. Surv. Can., Bull. 159.

Kuenen, Ph.H.
1964: Deep-sea sands and ancient turbidites, *in* Bouma, A.H., and Brouwer, A., ed., Turbidites; Elsevier, Amsterdam, p. 3-33.

McGlynn, J.C., and Henderson, J.B.
1970: Archean volcanism and sedimentation in the Slave Structural Province; *in* Symposium on basins and geosynclines of the Canadian Shield; A.J. Baer, ed. Geol. Surv. Can., Paper 70-40.

Middleton, G.V.
1972: Albite of secondary origin in Charny Sandstones, Quebec; J. Sed. Petrol., v. 42, p. 341-349.

Nanz, R.H., Jr.
1953: Chemical composition of Precambrian slates with notes on the geochemical evolution of lutites; J. Geol., v. 61, p. 51-64.

Nockolds, S.R.
1954: Average chemical compositions of some igneous rocks; Bull. Geol. Soc. Amer., v. 65, p. 1007-1032.

Normark, W.R.
1970: Growth patterns of deep sea fans; Bull. Amer. Ass. Petrol. Geol., v. 54, p. 2170-2195.

Ojakangas, R.W.
1972: Archean volcanogenic greywackes of the Vermillion district, northeastern Minnesota; Bull. Geol. Soc. Amer., v. 85, p. 429-442.

Pettijohn, F.J.
1940: Archean metaconcretions of Thunder Lake, Ontario; Bull. Geol. Soc. Amer., v. 51, p. 1841-1850.

1957a: Sedimentary Rocks; Harper and Bros., New York, 718 p.

1957b: Paleocurrents of Lake Superior Precambrian Quartzites; Bull. Geol. Soc. Amer., v. 68, p. 469-4680.

Pettijohn, F.J. (cont'd.)
1963: Chemical composition of sandstones exclusive of carbonates and volcanic sands; U.S. Geol. Surv., Prof. Paper 440-S.

Ramsay, J.G.
1961: The effects of folding upon the orientation of sedimentary structures; J. Geol., v. 69, p. 84-100.

Roussell, D.H.
1965: Geology of the Cross Lake area, Man.; Mines Branch Publ. 62-4.

Rust, B.R.
1972: Structure and process in a braided river; Sedimentology, v. 18, p. 221-245.

Schumm, S.A.
1968: Speculations concerning paleohydrologic controls of Terrestrial Sedimentation; Bull. Geol. Soc. Amer., v. 79, p. 1573-1588.

Stockwell, C.H.
1933: Great Slave Lake - Coppermine River area, Northwest Territories; Geol. Surv. Can., Summ. Rept. 1932, pt. C, p. 37-63.

Walker, R.G.
1965: The origin and significance of the internal sedimentary structures of turbidites; Proc. Yorkshire Geol. Soc., v. 35, p. 1-32.

1967: Turbidite sedimentary structures and their relationship to proximal and distal depositional environments; J. Sediment. Petrology, v. 37, p. 25-43.

Walker, R.G., and Pettijohn, F.J.
1971: Archean sedimentation: Analysis of the Minnitaki Basin, northwestern Ontario, Canada; Geol. Soc. Amer. Bull., v. 82, p. 2099-2130.

Welsh, W.
1967: The value of point-count modal analysis of greywackes; Scott. J. Geol., v. 3, pt. 2, p. 318-328.

Wood, A., and Smith, A.J.
1958: The sedimentation and sedimentary history of the Aberystwyth Grits (Upper Llandoverian); Quart. J. Geol. Soc. London, v. 114, p. 163-195.

Index