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**PETROGRAPHY OF KUGMALLIT SEQUENCE SANDSTONES,  
BEAUFORT-MACKENZIE BASIN**

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## CONTENTS

### VOLUME 1 OF 3

1	ABSTRACT
3	ACKNOWLEDGEMENTS
5	INTRODUCTION
5	STRATIGRAPHY
7	METHODOLOGY
7	CORE DESCRIPTIONS
7	THIN SECTION PREPARATION
11	Staining of Epoxy
12	Staining of Feldspar and Carbonates
12	OPTICAL MICROSCOPY
13	X-RAY DIFFRACTION ANALYSIS
13	SCANNING ELECTRON MICROSCOPY
13	ELECTRON MICROPROBE ANALYSIS
14	OTHER METHODS
14	TERMINOLOGY
15	DETRITAL COMPONENTS OF KUGMALLIT SEQUENCE SANDSTONES
15	MONOCRYSTALLINE QUARTZ GRAINS (23-49%)
15	POLYCRYSTALLINE QUARTZ GRAINS (1-18%)
15	CLEAR CHERT CLASTS (8-39%)
16	BLACK CHERT CLASTS (2-15%)
16	ALKALI FELDSPAR GRAINS (1-12%)
16	PLAGIOCLASE GRAINS (0-1%)
17	PHYLLOID CLASTS (4-28%)
18	VOLCANIC ROCK FRAGMENTS (0-2%)
19	CHLORITE (0-4%) AND MICA FLAKES (1-18%)
20	SILTSTONE (0-3%)
20	COAL GRAINS, FLAKES AND FILMS (0-8%)
20	UNIDENTIFIED DETRITAL GRAINS (0-22%)
21	OTHER DETRITAL GRAINS (0-5%)
22	DISCUSSION OF DETRITAL COMPOSITION
25	DIAGENESIS
25	INTRODUCTION
26	INDURATION
28	AUTHIGENIC QUARTZ (0-5%)
30	CARBONATE CEMENTATION, REPLACEMENT AND DISSOLUTION
36	AUTHIGENIC CLAYS
36	Kaolinite
38	Montmorillonite
38	Illite
38	Chlorite
40	PYRITE
42	POROSITY AND PERMEABILITY DIAGENESIS
46	CONCLUSIONS
49	RECOMMENDATIONS
52	REFERENCES
54	ILLUSTRATIONS
54	FIGURES
54	1. Boreholes from which Kugmallit Sequence conventional core samples were analysed.

FIGURES (CONTINUED)

- 55 2. Classification of Kugmallit Sequence sandstones according to Folk (1980).  
56 3. Percentage of detrital components versus increasing median grain size.  
57 4. Relation between modal grain size and sorting. Permeability zones were established on the basis of 41 selected measurements.

TABLES

- 58 1. Conventional drill core intervals in the Kugmallit Sequence. Available A, B and C unit subdivisions of the Kugmallit Sequence are after Morrell and Schmidt (1988).

60

PLATES

- 61-68 1-8. Thin section photomicrographs.  
69-82 9-22. Scanning electron photomicrographs.

VOLUME 2 OF 3

- 83-412 APPENDICES: Core and sample descriptions/analyses arranged alphabetically by well name.

VOLUME 3 OF 3

- PHOTOGRAPHS: Core photographs with identified sampling sites (108 black and white photographs and 112 colour slides).

The plates and appendices are not included in the open file report but can be viewed at the Geological Survey of Canada library, Institute of Sedimentary and Petroleum Geology, 3303 - 33rd St NW, Calgary, Alberta.

## ABSTRACT

The late Paleogene Kugmallit Sequence has been penetrated in 70 boreholes in the Beaufort-Mackenzie Delta area comprising a cumulative 84 kilometres of drilled clastic sediments/rocks. Conventional drill core (0.7 km total) was obtained from 27 of these wells. Detailed petrographic analyses were carried out for 100 samples of conventional drill core from 17 of these wells. The sandstones are variably indurated litharenites with detrital compositions similar to the underlying Reindeer and Moose Channel sandstones. Volcanic rock fragments, however, are significantly less common. Grain size is the first order control on detrital composition with higher chert content in the coarser sandstones. Paleoenvironment is the second order control. Sandstones deposited in a high energy environment and low rate of deposition have a higher quartzose content and are better sorted than those with a similar median grain size that were deposited in a low energy environment with a high rate of deposition. Over half of the sandstones contain glauconite pellets suggesting a predominantly shallow marine paleoenvironment.

The diagenetic history is complex. Quartz overgrowths are accompanied by planar and sutured pressure solution contacts in the deeper moderate-to-well sorted sandstones. This does not apply to the poor-to-very poorly sorted sandstones where quartz overgrowths are insignificant, irrespective of burial depth. Cementation, replacement and dissolution of shallow mesogenetic carbonate was responsible for the formation of secondary porosity, which accounts for at least half of the present

porosity. The carbonate compositions are highly variable within and between samples, a fact that must be reconciled in hydrodynamic/hydrogeochemical models of the Beaufort-Mackenzie basin. Authigenic clay minerals include kaolinite, montmorillonite, illite and chlorite. Framboidal pyrite lines pores of secondary origin. Controls on porosity and permeability diagenesis include median grain size and sorting, ductile (pseudomatrix) component abundance, overburden pressure, abundance, locality and morphology of authigenic minerals and finally, the distribution and amount of primary and secondary porosity.

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## INTRODUCTION

The Kugmallit Sequence, an important oil- and gas-bearing clastic unit of Late Paleogene age occurs in the subsurface of the Mackenzie Delta-Beaufort Sea area of Arctic Canada (Fig. 1). The main objective was to develop a better understanding of sandstone petrology, especially as regards relations between detrital composition, grain size distribution, lithofacies, depth, diagenesis and other factors. Some of these relations also define reservoir characteristics and may be useful in the future exploration and recovery of hydrocarbons. Other accounts bearing on sandstone petrology of the Kugmallit Sequence include Bushell (1980) and Schmidt (1987).

A cumulative 84 km of the Kugmallit Sequence has been drilled in 70 boreholes in the Beaufort-Mackenzie Basin. Only 0.70 km or about 0.8% of this comprises conventional drill core obtained from 27 wells. The present study is limited to 100 samples of conventional drill core obtained from 17 of these (Table 1). Most of the sample localities are identified in the core photographs (volume 3).

## STRATIGRAPHY

The Kopanoar Sequence as defined by Dietrich *et al.* (1985) is now included as a subsequence of the Kugmallit Sequence (Dixon and Dietrich, 1988), a change which effects the following boreholes where the Kopanoar Sequence was originally identified; Aiverk 2-I-45, Alerk P-23, Inkaluk B-35, Koakoak O-22, Kopanoar 2-I-44 and M-13, Nerlerk J-66 and M-98, Orvilruk O-03 and Uviluk P-66. Consequently, conventional drill cores from the Kopanoar 2-



I-44 and Nerlerk J-67 wells, which were previously assigned to the Kopanaoar Sequence at the time of sampling were excluded in this study. The sequence boundaries were determined by J. Dixon and were obtained from the ISPG Beaufort/Mackenzie Computer Well Data Base. Subdivision of the Kugmallit Sequence into several subsequences has been achieved by Morrell and Schmidt (1988). In addition, a comprehensive account of the Kugmallit Sequence in the Nipterk area, with the exception of diagenesis is contained in James and Baxter (1988).

## METHODOLOGY

### CORE DESCRIPTIONS

Cores were described for the following boreholes where company core descriptions were too abbreviated (descriptions in volume 2); Aiverk 2-I-45, Amauligak I-65, Koakoak O-22, Mallik L-38, Taglu H-54, Taglu West P-03, Tarsiut P-45 and Unark L-24.

### THIN SECTION PREPARATION

The samples were fashioned into rectangular slabs about 1 cm thick. Residual water was removed by heating in a vacuum oven. Crude oil was removed by immersion in a 5% methyl hydrate/95% naptha gas mixture by volume at room temperature. The solvent was replaced at least five times over a 2 week period after which the samples were removed from the solvent and left to dry in air for 2-3 days. Any residual solvent was removed by gentle heating over a hot plate. A low-viscosity (60 centipoises) thermally-curing epoxy (Spurr Resin) was chosen as the impregnating medium and was prepared in a fume hood using rubber gloves as follows (components in proportions by weight according to Polysciences Data Sheet 127, 1973).

1. Flexibilizer: Diglycidyl ether of polypropyleneglycol (DER 736: 12 units).
2. Cycloaliphatic diepoxide: Vinylcyclohexene dioxide (VCD: 20 units).
3. Hardener: Nonenyl succinic anhydride (NSA: 52 units).
4. Cure accelerator: Dimethylaminoethanol (DMAE: 0.4 units).
5. Blue dye: Oil Blue N, C.I. 61555: 1 unit.

These components are manufactured by Polysciences, Inc.,

Warrington, PA. 18976-2590. Components 1 to 4 are distributed in Canada by J.B. Em Services Inc., P.O. Box 693, Pointe Claire-Dorval, Quebec, H9R 4S8. Item 5 is distributed by Analychem Corp. Ltd., 7321 Victoria Park Ave., Unit 16, Markham, Ont. L3R 2Z8.

All of the samples were vacuum and pressure impregnated. Cure accelerator was not added because early curing was undesirable. After evacuating the samples, pressure was increased in increments of about 4000 kilopascals per day (to a maximum of 26,000 kilopascals). A slow pressure increase was chosen because sample permeability for samples with a high percentage of ductile components decreases dramatically with increasing overburden pressure. Curing was accomplished by heating in an oven at 60 degrees C for 2 weeks. Higher temperatures are not recommended because the dye added to the epoxy may fade and turn pink. In spite of these attempts, some of the low-permeability samples were only impregnated to a depth of 1 mm or less. Only one thin section could be prepared from such a small quantity of impregnated material. Re-impregnation was required to obtain suitable material for a second thin section. This was accomplished by placing the samples in a mixture of about 60% epoxy and 40% anhydrous acetone for several days in a desiccator. They were then removed and air dried for 2 days. Any remaining acetone was evaporated by gentle heating over a hot plate. Although the manufacturers caution that the epoxy may not cure if it absorbs water, the 2 days in contact with air did not noticeably effect curing. It is probably critical, however, that the acetone be anhydrous.

Two polished thin sections were prepared from the material.

The glass microscope slides were machined to a uniform thickness of 1.200 mm by lapping. They were held to a lapping jig mechanically by means of a 30 degree bevel on each of the long sides of the slides. A circulating slurry system comprising 400 grit (25 micrometre-sized) silicon carbide particles was used with a cast iron plate and a conditioning ring. The impregnated sample stubs were ground flat on one side by hand using a slurry comprising 3 micrometre-sized aluminium oxide particles on a glass plate. The use of abrasives larger than 5 micrometres on a glass plate is to be avoided because of gouging of ductile grains and fracturing of brittle grains (especially along the edges). In addition, the percussive nature of loose abrasive grains may loosen the contact between grains and epoxy. A viscous formulation of cyanoacrylate (e.g. Superglue) was used to mount the samples to the glass slides. Heavy and immediate pressure results in glue thickness of less than 5 micrometres. The sample stubs were cut off with a thin continuous rim diamond saw blade (220 grit) leaving a 250 micrometre thick slice of the sample on the glass slide. An eight inch Disco Hi-Tec America Inc. segmented diamond wheel (DISCO Technical Bulletin T-B-043, May/87) with round edges and approximately 20/30 micrometre-sized diamond particles (order no. RS-01-2-20/30-NM-C) was adapted for use on a Felker Model 80BQ precision cut-off machine. The samples were routinely thinned from 250 to 50-70 micrometres with only one pass of the wheel, a procedure requiring about 5 minutes per thin section. The ideal machine would be a surface grinder, such as a miniature version of the series Disco Rotary Surface Grinder

Series 650 model DFG-83H/6, equipped with three vertical spindles. The thin sections would pass under three diamond cup wheels the last of which would contain 5-10 micrometre-sized diamonds. For silicon wafers, the maximum surface roughness obtained is only 0.2 to 0.5 micrometres. This particular surface grinder, which is capable of producing about 80 six inch diameter silicon wafers per hour is heavy (3,850 kilograms) and extremely expensive. A miniature version of the machine but incorporating the same features would be well adapted for the making of petrographic thin sections.

The slides were then lapped by hand to a thickness of about 35 micrometres, using a slurry of 3 micrometre-sized aluminum oxide particles in water. An unfortunate consequence of this step is that the extremities of brittle quartzose grains are fractured and removed, resulting in a 3 micrometre wide/deep groove along grain margins. While this may not at first seem important, clays coating the grains are obscured and for silt-sized material, the groove may be a significant fraction of the grain diameter which later causes errors in grain size analysis. Polishing was accomplished using 1 micrometre followed by 0.3 micrometre sized particles of aluminum oxide in water on a glass plate. Heavy thumb pressure on the central part of the thin section combined with a twisting action was required to polish the center as well as the extremities of the thin sections. The glass plate was first conditioned using slurries of 3 followed by 1 micrometre-sized aluminum oxide particles. Polishing with diamond impregnated cloth is not recommended because excessive relief is formed between hard and soft grains. Experience with grooved soft

metal laps charged with diamonds resulted in scratching of the sample, undoubtedly because relatively large grains plucked from the sample were embedded in the lap.

### **Staining of Epoxy**

The recognition of small pores, especially intragranular pores is difficult by ordinary petrographic methods. A method of staining the surface of the epoxy with a fluorescent dye was developed by Ruzyla and Jezek (1987) and was adapted for use with Spurr Resin. The method involves heating the thin section to no more than 60 degree C followed by immersion in fluorescent green dye (PS Hi Brite Lime Green Concentrate). The stain will not take if the epoxy overheated during curing, which is indicated by fading and discolouration of the oil blue dye added to the epoxy from blue to pink. The method also has a number of limitations. It overestimates porosity in siltstones because it stains the epoxy surrounding plucked grains. Further, it commonly soaks into the thin section at the grain-epoxy contacts. It also requires a microscope equipped with a UV source and special exciter and barrier filters. In spite of these problems, it does reveal details of pore geometry in some samples (plate 2b, 4a,b). The ideal thin section would be one in which a thin but highly reflective coating such as aluminum was somehow selectively coated to the surface of the epoxy. Ordinary vertical incident illumination would then show up pore space as a highly reflecting metallic film. However, such a method has yet to be developed. Alternatively, the pore spaces could perhaps be lined by

electroplating if the surface of the grains could be made conductive. This method would be most useful for ultra thin sections (5-10 micrometres) of very fine grained sandstones and mudstones. The difficulty lies in finding a soluble material that upon evaporating would bond to the surface of the grains, be conductive, and also form a bond with the electroplated metal.

### **Staining of Feldspar and Carbonates**

It was originally planned to stain one of the thin sections for alkali feldspar and carbonates. The hydrofluoric acid etch, however damages the polish and it was found that alkali feldspar could be more easily identified by cleavage and alteration. Feldspar staining was therefore omitted. Carbonate staining was modified from Dickson (1965; 1966). The acid pre-etch was omitted to prevent dissolution of carbonate cement in the small pores; consequently, only the alizarin red S solution was used. The second thin section was polished but left unstained to permit analyses with the electron microprobe. Each thin section was analysed qualitatively and 30 were analysed quantitatively (volume 2). The details of the method used for modal and grain size analysis are discussed in detail in Nentwich (1980).

### **OPTICAL MICROSCOPY**

Optical microscopy was carried out with binocular and petrographic microscopes using both incident and transmitted light. A very useful technique for estimating porosity and sorting involved examining artificial sample fracture surfaces with the petrographic microscope in incident light with medium

power (10-20X) high numerical aperture objectives. Although the depth of field and working distance is limited, a 3 dimensional view can be obtained by focusing up and down on the sample. The different colours of detrital components allow easy distinction of particles compared to monochrome images of the scanning electron microscope (compare, for example plate 1a,b and 9a as well as plate 1c,d and 9b). Vertical incident illumination was also useful for thin section grain size analysis (compare plate 6c, d).

#### **X-RAY DIFFRACTION ANALYSIS**

Ten x-ray diffraction analyses, mainly of the matrix of the poorly sorted sandstones were undertaken. The samples were disaggregated in water and the fine matrix material skimmed onto a glass slide. After drying the analyses were run (volume 2).

#### **SCANNING ELECTRON MICROSCOPY**

Scanning electron photomicrographs were taken of 31 of the 100 samples (plates 9-22). A few semi-quantitative energy dispersive x-ray analyses were also obtained for the ISS2061-N15, NIPL19-20 and TAGG33-12 samples (volume 2).

#### **ELECTRON MICROPROBE ANALYSIS**

A large number of chemical analyses of carbonates (64) and silicates (53) were carried out on 12 unstained thin sections with the electron microprobe. Total weight percent counts do not add up to 100 because the method does not detect the presence of



elements lighter than sodium and there may be small quantities of elements other than those analysed. A special case of this is intragranular porosity filled with epoxy. Epoxy is composed of the undetectable light elements carbon, oxygen, hydrogen and nitrogen which lowers the total weight percent counts. Finally, the top of the thin section should be flat and polished for good results. The volume of material analysed with the electron microprobe is about 10 micrometres in diameter and 3 micrometres deep, which although very small, may include a number of different particles in the phylloid and volcanic rock fragments (see plates 9-22).

#### OTHER METHODS

It was originally planned to investigate fluid inclusions in the carbonate cement in an attempt to determine depth of formation but no fluid inclusions were found. It was also planned to undertake a few carbon/oxygen isotope analyses but the carbonate cement contains too much iron to permit reliable isotopic methods with established methods. The cement also contains excess calcium which may be either in the dolomite structure or may represent calcified dolomite developed on the surface of intragranular micropores.

#### TERMINOLOGY

The terminology used is after Folk (1980) except that his verbal sorting scale was applied to Inman's sorting coefficient. In addition, the clay/silt transition is considered here to be at 4 micrometres.

## DETRITAL COMPONENTS OF KUGMALLIT SEQUENCE SANDSTONES

The detrital composition of the Kugmallit sandstones is related to source terrain and depositional environment. It contributes to petrophysical properties and has an important bearing on diagenesis. The following summarises the main detrital sandstone components as determined from polished thin sections.

### MONOCRYSTALLINE QUARTZ GRAINS (23-49%)

Monocrystalline quartz grains are among the easiest components to identify in thin section. They are most common in samples with a median grain size ranging from 70-220 micrometres and are less abundant for samples with a larger median grain size, probably because less monocrystalline quartz is available in the larger grain sizes (Fig. 3).

### POLYCRYSTALLINE QUARTZ GRAINS (1-18%)

Polycrystalline quartz is clear composite quartz in which the average crystal size is larger than 20 micrometres. It is slightly more common in sandstones with a median grain size larger than about 150 micrometres and appears to be anomalously abundant in some of the Issungnak and Amauligak samples.

### CLEAR CHERT CLASTS (8-39%)

Clear chert is inclusion free clear composite quartz with an average crystal size less than 20 micrometres. It is more abundant in sandstones with a larger median grain size (Fig. 3).

#### BLACK CHERT CLASTS (2-15%)

Black chert is semi-opaque composite quartz with an average crystal size less than 20 micrometres. It is not squeezed between other grains, polishes easily and has a reflectivity in vertical incident light similar to quartz. Chemically, black chert with these properties contains more than 90% silicon dioxide. There is more black chert in sandstones with a median grain size larger than about 260 micrometres (Fig. 3).

#### ALKALI FELDSPAR GRAINS (1-12%)

Alkali feldspar, recognized by cleavage, shows no change in abundance in the very fine to medium grained sandstones. It is apparently much more stable than plagioclase. Interestingly, an electron microprobe analysis of a polysynthetically twinned feldspar superficially resembling plagioclase in sample UNAL24A-N2 had a chemical composition similar to orthoclase or microcline (volume 2). If this phenomenon is common, then plagioclase may be significantly overestimated. Alkali feldspar is also common in the mud-sized matrix as shown by a prominent albite peak at 3.1858 in about 8 of the 10 x-ray diffraction analyses.

#### PLAGIOCLASE GRAINS (0-1%)

Plagioclase shows no change in abundance with grain size. An electron microprobe analysis carried out on a plagioclase grain in sample AME009-11 showed anomalously high silicon and abnormally low aluminum, sodium and/or calcium values. Apparently, leaching accompanied silicification but it is not clear whether this

alteration was pre- or post-depositional.

#### PHYLLOID CLASTS (4-28%)

This term was coined to include ductile low-reflectivity semi-opaque argillaceous grains including mudstone, shale and finely crystalline chloritic metamorphic rock fragments. Although the variation with grain size is erratic (Fig. 3), phylloid clasts decrease in abundance for sandstones with a median grain size larger than about 230 micrometres. Some altered volcanic rock fragments which never had a feldspar lath texture are undoubtedly included in this category. A comparative electron microprobe study of some phylloid clasts and variously altered volcanic rock fragments containing feldspar laths was carried out in an attempt to discriminate between the two. Phylloid clasts (some of which may be volcanic fragments lacking a feldspar lath texture) were analysed in samples AME009-11 (analyses RF10.1, 10.2, RF2B.1, .2), UNAL24A-N2 (analysis RF3A.1), sample UNAL24A-N9 (analyses and RF2C.1, 2, 3, RF3B.1, 2) and possibly UNAL24A-N5 (analysis 4B.1). Altered volcanic rock fragments which have been depleted in magnesium, iron, sodium, potassium, calcium and/or have been sericitized or silicified are difficult to distinguish from phylloid clasts. More analyses of phylloid (or altered phylloid clasts) would be required to statistically determine with a large number of analyses the proportion which represents unrecognised altered volcanic rock fragments. Where present, high values for phosphorous (probably in apatite) and titanium are more indicative of a volcanic origin.

### VOLCANIC ROCK FRAGMENTS (0-2%)

This category includes variously altered rock fragments with feldspar lath texture, irrespective of whether the laths have been replaced or dissolved. There appears to be no relation between median grain size of the sandstone and abundance (Fig. 3). An electron microprobe study was undertaken in an attempt to chemically characterize the known volcanic rock fragments and thereby determine the proportion of variously altered volcanic rock fragments which have been included in the phylloid category. The matrix of about 15 known volcanic rock fragments (with feldspar-lath texture preserved) was analysed by means of an electron microprobe.

The known volcanic rock fragments (with preserved feldspar lath texture) have a variable composition, reflecting different states of alteration. Sericitization is reflected by high potassium and aluminum values (sample AME009-11/4378.77 m, analysis RF11.1). Replacement by dolomite is indicated by high calcium and magnesium values (and lower total oxide weight percent counts). High intragranular porosity is reflected by anomalously low total counts and high silica content is indicative of silicification. Alteration to clay minerals has also been documented (Schmidt, 1987). Comparisons with average chemical compositions of common igneous rocks (in Hyndman, 1972) provides some indication of the degree of alteration. It is assumed in the following that the volcanic rock fragments do not have a peridotite or nepheline syenite composition.

An unaltered igneous rock should have a total oxide weight

percent count close to 100% because less than 1% undetectable elements (mainly hydrogen and oxygen) are present and intragranular porosity is negligible. However, the volcanic rock fragments in the Beaufort-Mackenzie Basin with the highest total counts are not the least altered of the volcanic rock fragments. Rather, the high totals are a result of silicification, which probably occurred in the source terrain. Sample UNAL24A-N2/2955.80 m (analysis RF1B.1, 2), for example, contains 80 to 90% silica. Compared to the common igneous rock types, the known but altered volcanic rock fragments have anomalously low magnesium (10 of 16 analyses), iron (10 of 15), sodium (10 of 15), potassium (4 of 15), calcium (5 of 15), and phosphorous (4 of 15). High phosphorous values are generally accompanied by high calcium values, suggesting the presence of apatite. Except for silicification, which undoubtedly occurred in the source terrain, and minor sericitization with a net increase of potassium and aluminum, most of the important ions have been leached from the volcanic rock fragments. The question of where these ions have gone, and whether they have contributed to local carbonate or clay cementation remains unanswered.

The known volcanic rock fragments (with preserved feldspar lath texture) have a variable composition, mainly reflecting different states of alteration.

#### **CHLORITE (8-4%) AND MICA FLAKES (1-18%)**

Detrital chlorite, as relatively large flakes, decreases in abundance slightly in sandstones with a median grain size larger than about 140 micrometres (Fig. 3). Authigenic chlorite occurs

mainly as partly altered muscovite flakes and mud-sized material of unknown origin (x-ray diffraction peaks at 7.0774 and 13.8840). Of 10 x-ray diffraction analyses, the first and second chlorite peaks were significant in the following (analyses in volume 2): AIV2I45-N1, ALEP23-N2, ISS2061-N7, KAD007-6 AND NIPL19-6. How much of this mud-sized chlorite is detrital and how much is replacing illite (by analogy with chlorite replacing muscovite flakes on a larger scale) is difficult to assess.

Mica is present almost exclusively as flakes of muscovite/illite. Its X-ray diffraction peak at 9.9822 is significant in 9 of the 10 x-ray diffraction analyses (AIV2I45-N1, ALEP23-N2, ALEP23-7, ISS2061-N7, KAD007-6 AND 23, NIPL19-6(?), TAGG33-12, AND TARP45-N1).

#### **SILTSTONE (0-3%)**

Grains were classified as siltstone if they consisted predominantly of silt rather than clay-sized material.

#### **COAL GRAINS, FLAKES AND FILMS (0-8%)**

Coal occurs as discrete particles or thin films and is most common in the very fine sandstones (with a median grain size of less than 90 micrometres). It does not exceed 2% in the coarser grained sandstones (Fig. 3).

#### **UNIDENTIFIED DETRITAL GRAINS (0-22%)**

Unidentified grains are most common in the siltstones where a combination of small particle size, overlapping grains and

moderate quality thin sections combined to make identifications impossible. For sandstones with a median grain size larger than 90 micrometres, however, unidentified material comprises less than 6% of detrital grains.

#### **OTHER DETRITAL GRAINS (0-5%)**

This category includes grains which were identified but did not fit in any of the other categories. Chemical analyses of heavy minerals with the electron microprobe suggest the presence of tourmaline, chromite, zircon, rutile and siderite.

Unaltered glauconite pellets (plate 7A) occur in 40% of the samples in trace amounts and never exceed 1%. Questionable identifications of altered glauconite pellets comprise a further 20% of the samples. The larger proportion of samples containing glauconite or altered glauconite pellets is not surprising, given that most of the samples were obtained from shallow marine deposits (Morrell and Schmidt, 1988). Detailed environmental interpretation of the Nipterk conventional drill cores has been undertaken (James and Baxter, 1988). It is noteworthy that unaltered glauconite pellets identified in the present study occur in material considered by James and Baxter (1988) as offshore prodelta and delta front. Further, no glauconite pellets were identified in their outer stream mouth bar or fluvial channel deposits.



## DISCUSSION OF DETRITAL COMPOSITION

The Kugmallit Sequence sandstones are litharenites compositionally similar to the those of the underlying Reindeer Sequence (Fig. 2). Easily identifiable volcanic rock fragments with feldspar laths, however, are much less common, a difference also noted by Schmidt (1987). Volcanic rock fragments in sandstones of the underlying Reindeer Sequence are most common in the medium grained sandstones where they comprise up to 12.7% of the detrital components (Nentwich and Yole, 1982). Volcanic rock fragments are also common in the Moose Channel Sequence sandstones underlying the Reindeer Sequence. The basal sandstone member of the Moose Channel Formation southwest of the delta contains 7% volcanic rock fragments (on average) and one medium grained sandstone contained 29% (Young, 1975). Similar results were obtained by Holmes and Oliver (1973). Since the volume of volcanic rock fragments varies with the median grain size of the sandstone, comparison of similarly sized sandstones between the three sequences is required to determine whether differences are significant. When only fine grained sandstones are considered, it is clear that volcanic rock fragments are much less common in the Kugmallit Sequence than in either of the Reindeer or Moose Channel sequences (see below).

UNIT	MEAN %	STANDARD DEVIATION	NO. OF ANALYSES
Kugmallit	0.5	0.5	14
Reindeer	4.2	3.0	21
Moose Channel	4.6	3.9	9

This change in composition may be related to a change from a relatively volcanic-rich source terrain in the southwest to a volcanic-poor source terrain to the south (Holmes and Oliver, 1973; Young, 1975).

The present study reveals that the Kugmallit Sequence sandstones display the same compositional variation with median grain size as those of the Reindeer Sequence. These include decreasing proportions of the following with increasing median grain size; monocrystalline quartz grains, phylloid clasts, mica flakes and coal clasts. Conversely, competent grains comprising polycrystalline quartz as well as clear and black chert are more common in samples with a larger median grain size. Other detrital components, including alkali feldspar, plagioclase, volcanic rock fragments, chlorite flakes, siltstone and other grain types show no overall variation in abundance for samples of differing median grain sizes. Within the overall trends there are, however, significant small-order variations. Samples from the two Tarsiut boreholes contain more phylloid clasts and fewer quartz and chert clasts than samples from other wells with similar median grain size. The lower permeabilities observed at Tarsiut may be related to poor sorting and high ductile grain content. The opposite is true for the Issungnak and Amauligak samples which contain more

( quartz and chert grains and fewer phylloid clasts. They are also better sorted than other Kugmallit sandstones with a similar median grain size.

## DIAGENESIS

### INTRODUCTION

Diagenesis includes all physical and chemical changes since deposition of the Kugmallit Sequence about 40 to 25 million years ago. Diagenesis was undoubtedly affected by a major lowering of sea-level from about 170 m above present sea level to about 200 m below present sea level in the Late Oligocene about 30 million years ago (Harland *et al.*, 1982). This eustatic sea level change, as well as changes of lesser magnitude must have had pronounced effects by returning sediments from the mesogenetic to the eogenetic realm for a period of several million years. It should be kept in mind that the diagenetic history is a sequence of events in which some authigenic minerals have grown, have been dissolved or corroded, and perhaps later been regrown. The difficulty lies in reconstructing the diagenetic sequence of events. For ephemeral minerals only obscure textural relations may remain, if any. In spite of the overwhelming number of variables, the diagenetic history can be approximately reconstructed from a large number of individual observations. Sandstone diagenesis is discussed from the point of view of induration, diagenetic minerals and those textures which are important to determine a diagenetic sequence in the context of factors such as detrital composition, median grain size, sorting, lithofacies, depth of burial and position in the basin. There is a common misconception that diagenesis has not been important in poorly or very poorly consolidated sandstones. This could not be further from the truth because the same processes responsible for

producing secondary porosity were also the ones which decreased induration.

#### INDURATION

The induration of dry samples was assessed as follows:

INDURATION	PERCENT
very poor	22
poor	36
moderate	27
good	8
excellent	7

The induration of water wet rather than dry samples is more significant, both from a geological and from an engineering point of view. Small chips broken from the samples were immersed in water. Of these, 72% were either very poor to poorly indurated or disaggregated by themselves in a few minutes. Only 28% were of moderate to excellent induration and did not disaggregate. It may be argued that only the samples that did not disaggregate in water should be classified as rocks. At the depths from which these samples were obtained, however, confining pressures are such that even unconsolidated sediments at surface conditions are rock-like. On this basis, the samples are classified herein as rocks.

These simple observations on induration are particularly relevant for examiners of drill cuttings. If the Kugmallit drill core samples are representative of the Kugmallit Sequence as a

whole, then at least 70% of the drill cuttings are likely to be disaggregated and represented as individual grains. Unless drill cuttings have a moderate to excellent degree of induration, ordinarily as a result of quartz or carbonate cementation, they are unlikely to remain intact in a water saturated state passing over the shaker screen at the drill site. There is also the problem of properly separating these from disaggregated mudstone, drilling mud and caved material. In spite of these problems, integration of information from drill cuttings, wireline logs, seismic data and conventional drill core is essential for developing a comprehensive understanding of all aspects of the diagenesis of the Beaufort-Mackenzie basin.

#### AUTHIGENIC QUARTZ (0-5%)

Authigenic quartz occurs as overgrowths on grains of quartz and to a lesser extent polycrystalline quartz and chert (e.g. plate 2C, 10b,c, 11a,d). Although it is generally present in 1% or less by volume there are a few examples where it is more common. In those 6 samples where quartz overgrowths comprise 2-3%, the degree of pressure solution is high (high planar and concavo-convex sutured contacts between quartzose grains). In addition, they are moderately sorted sandstones at present burial depths in excess of 2700 m. Only 2 samples have 5% quartz overgrowths, and these are moderately sorted sandstones characterized by concavo-convex sutured contacts between quartz grains and a present burial depth in excess of 3500 m. Poorly sorted sandstones buried to similar depths do not contain more than 1% quartz overgrowths. Sandstones without quartz overgrowths (17%) are mainly poorly or very poorly sorted.

To summarise, Kugmallit sandstones are likely to contain 2-3% quartz cement if they are moderately to well sorted and buried to more than 2700 m. They are likely to contain 4-5% quartz cement if they are buried to depths of more than 3500 m. Quartz overgrowths may not be developed at all if the sandstones are very poor to poorly sorted, probably because the overburden pressure is borne by a much larger number of particles. This is a good example where a depositively inherited property (sorting) has an important effect on diagenesis. One may hypothesise that pressure solution and quartz overgrowth formation are part of a single process. Pressure solution may be enhanced in well sorted

sandstones where the overburden pressure is supported only by the point contacts between competent grains. In very poor or poorly sorted sandstones, pressure solution is probably less important because matrix material helps support the framework grains. Other variables such as carbonate cementation/replacement and dissolution complicate these relations. In many of the sandstones quartz overgrowths line pores of secondary origin and it is probable that some quartz cement was removed during the formation of secondary porosity.



### CARBONATE CEMENTATION, REPLACEMENT AND DISSOLUTION

The present distribution of authigenic dolomite in the 100 samples is as follows; 41% contain no authigenic dolomite, 45% contain 5% authigenic dolomite and 7% contain more than 5% authigenic dolomite. Samples in which porosity has been almost obliterated by carbonate cement are common in the southernmost wells (Mallik L-38, Taglu H-54, and the Unark L-24 and L-24A boreholes). The core samples by themselves are probably not, however representative of the Kugmallit Sequence. A more in-depth study would require a complete study of drill cuttings and well logs. Calcite, another authigenic carbonate mineral, is present in only 7% of the samples.

Authigenic carbonate occurs in sandstones irrespective of median grain size or sorting, which suggests that permeability variations of up to 5 orders of magnitude (Fig. 4) have little or no bearing on the amount or type of authigenic carbonate. Apparently, enough fluid can pass through the sandstones that such permeability variations are not significant given the time available. Carbonate cementation differs markedly from quartz cementation, because sorting does not seem to be a control.

Replacement by carbonate was an extremely important diagenetic process. Where carbonate has not been dissolved there are excellent examples of carbonate replacing the extremities of grains (plate 7c,d, 8a,d). Muscovite flakes are also commonly replaced by carbonate, especially where they are compactionally deformed (plate 8b).

Dissolution of carbonate cement, and more importantly, carbonate-replaced material was largely responsible for the

production of secondary porosity mainly as oversized and elongate intergranular pores. The dissolution of carbonate-replaced grains also contributed grain moldic porosity (plate 2d, 5a, 6a). Further, carbonate-replaced grain extremities upon dissolution contributed corroded grains, commonly with partial rhombic dissolution molds (compare the outline of grain margins in plate 2d, 3a,d, 7b,c,d and 8a,b,c,d). Grains partially replaced by carbonate upon dissolution contributed a significant amount of secondary porosity (compare plate 2b, 4c, 5c, 8c and 14b). Although the intragranular porosity sometimes comprises relatively large pores (many of which are rhombic), most of the intragranular porosity is underestimated or is invisible using ordinary optical petrographic methods (compare plates 4a, b). Of all these types of secondary porosity, enhanced intergranular porosity is volumetrically the most significant. The evidence for secondary porosity provided by rhombic indentations should be used with caution because they may be inherited from a previous cycle of deposition, cementation, dissolution and erosion. An indeterminate amount of recycled material from the Reindeer and older sequences where this carbonate replacement/dissolution process was also operative is undoubtedly also present in the Kugmallit Sequence. The inferred presence of former carbonate cement should be based on the presence of elongate and oversized pores in addition to the occurrence of rhombic indentations. The elongate pores in many cases actually terminate in a rhombic shape. It is noteworthy that all of the sandstones have abundant secondary porosity and textural evidence points to the presence

of a former replacive carbonate cement even though 41% of the samples now contain no carbonate cement at all. The cement was in all cases introduced after burial to several hundred metres, judging by the proportion and degree of squeezed ductile grains. In addition, samples from the shallowest cores (1300-1500 m) show evidence of extensive secondary porosity. These constraints suggest that most of the secondary porosity was probably formed mesogenetically in the depth range of perhaps 500-1200 m. Of course there are exceptions (plate 2c). A comprehensive explanation of the behaviour of authigenic carbonate requires a better understanding of the present distribution of calcite and dolomite. It is assumed that calcite was the mineral originally precipitated and that dolomitization occurred later. It is not clear, however, why some calcite remains. Perhaps all the calcite is calcified dolomite. Another problem concerns the large volume of carbonate necessary in the generation of secondary porosity. Sediments currently buried to the depth range 500-1200 m in the Beaufort Sea are unconsolidated. It may be that carbonate was never much more abundant than at present, but that it was constantly being dissolved and reprecipitated and forming secondary porosity in the process. Changes in temperature and to a lesser extent pressure, fluid composition, fluid flow and their relation to carbonate solubility over large time spans are poorly known, though some strides have been made in understanding some of these factors in the Beaufort-Mackenzie Basin (Sauveplane and Mortensen, 1986). Two approaches may be used to refine our understanding. One is to compare the diagenesis of units younger and older than the Kugmallit. The other is to characterize the

carbonates chemically and relate these data spatially on a small scale (core to edge chemical changes) and on a large scale (depth and position in the basin). Chemical analyses of carbonate cement by electron microprobe were undertaken for samples AMAI65-N6 (3567.5 m), AME009-11 (4378.8 m), KIGA43-N2 (2114.0 m), KOA022-N4 (3493.3 m), MALL38-N1 (920.8 m), TAGH54-N1 (1104.6 ), UNAL24A-N2 (2955.8 m) UNAL24A-N5 (2966.4 m), UNAL24A-N6 (2967.3 m), and UNAL24A-N9 (2976.31 m) (see volume 2 for raw data). Classification is best carried out by converting the atomic proportions of calcium, magnesium and iron to atomic percentages. The analyses show diverse carbonate compositions. Two generations of ferroan/calcian dolomites were determined in AMAI65-N6/3567.50 m (plate 10a,b,c). The iron content of the more ferroan dolomite varies from 12.8 to 14.6 mole percent and manganese (at one atomic percent) is relatively common. The composition of the calcian/ferroan dolomite in the AME009-11/4378.77 m sample is remarkably uniform, whether between grains, near the edge of grains, in grain fractures or replacing the matrix of volcanic rock fragments (plate 11c,d). It contains up to 58.5 atomic percent calcium and up to 7.1 atomic percent iron. The analyses of the authigenic ferroan low-magnesian calcite in the KIGA43-N2/2113.96 m sample are relatively homogeneous with a magnesium content of 2.1 to 4.3 atomic percent and iron varying from 2.9 to 3.3 atomic percent (plate 4a,b, 15c). The KOA022-N4/3493.3 m sample contains a ferroan dolomite with iron varying from 0.3 to 2.4 atomic percent (plate 15d, 16a). In the MALL38-N1/920.8 m sample there is an unusual concentrically-laminated internally

radiating dolomite cement (plate 4d, 16c,d, 17a,b). Fifteen analyses of the laminae reveal a significant variation from the inner (pore-lining) to the outer (pore-filling) laminae. The inner lamina in 2 different parts of the thin section (analyses 1D.1, 1D.2, 2A.1, 2A.2) were compositionally uniform calcian dolomite with calcium varying from 58.9 to 60.2 atomic percent and manganese at about 1 atomic percent. Three out of four analyses of the outer lamina (analyses 1B.1, 2E.1, 2E.2) suggest by contrast a relatively pure dolomite. Laminae between the inner and outer laminae are calcian dolomites that are compositionally similar to the innermost lamina. The manganese content of one of these (analysis 1C.2), however, is relatively high (2 atomic percent). The calcian dolomite cement in TagH54-N1/1104.6 m is uniform with calcium content varying from 57.2 to 60.4 atomic percent. Iron and manganese occur at less than 0.2 atomic percent and calcium varies from 57.2 to 60.4 atomic percent. Iron and manganese occur at less than 0.2 atomic percent. The carbonate in UNAL24A-N2 (2955.80 m) is calcian ferroan dolomite of relatively uniform composition with iron ranging from 12.9 to 15.4 atomic percent.

A number of analyses of calcite were also carried out. The texturally complex carbonate of sample UnaL24A-N5/2966.36 m (plate 20c,d) is a ferroan low-magnesian calcite with about 4 atomic percent iron and 3.3-5.7 atomic percent magnesium. The cement in the nearby sample UnaL24A-N6/2967.26 m (plate 7, 8, 21a,b) has a similar composition. With the exception of 3.0 atomic percent iron in calcite which has replaced a feldspar lath in a volcanic rock fragment, the iron content (1.9-2.4 atomic

percent) and the magnesium content (0.9-1.9 atomic percent) is significantly less than the UNAL24A-N5 sample only 90 cm higher in the core. In UNAL24A-N9 (2976.31 m), the carbonate cement is a low magnesian ferroan calcite with a uniform composition of 4.5 to 4.9 atomic percent iron.

To summarise, highly variable chemical compositions occur within but more importantly between samples. The fluids from which these carbonates were precipitated were probably also of highly variable composition and perhaps mainly of local derivation. This initial study shows that more chemical analyses would be of great benefit in reconstructing the history of fluid flow in the basin and thereby determine to what extent the system was open.

Carbonate cement is slightly more common in the underlying Reindeer Sequence sandstones and partly explains their better induration. If carbonate cement is locally derived, as is suggested from the highly variable chemical compositions, then overall differences in the amount of carbonate cement may be related to differences in detrital composition. The only significant difference in detrital composition between the Reindeer and Kugmallit sandstones is the volcanic content. Alternatively, the carbonate was derived from the siderite-rich mudstones of the delta-plain deposits of the Reindeer Sequence. There are many other possibilities, some of which might be assessed by trace element or isotopic analyses. An approach similar to that employed by Van Elsberg (1978) might prove useful.

## AUTHIGENIC CLAY MINERALS

### Kaolinite (0-10%)

Authigenic kaolinite typically comprises white curved vermicular booklets made up of a series of stacked hexagonal platelets (plate 12b). Although scanning electron photomicrographs reveal that they are commonly corroded (plate 11a,b, 13c, 14d(?) and 18a), they are easily identified by the vermicular growth habit and white colour in artificial sample fracture surfaces. Individual booklets are most commonly 10-15 micrometres wide though they are up to 30 micrometres wide in the NIPL19-20, 25, NIPL19A-3 and TARN44A-N1 samples. The largest (80 micrometres wide) were contained in the TARN44A-N3 sample. Energy dispersive X-ray analysis combined with scanning electron microscopy is very useful in helping to identify kaolinite, especially where it has been extensively corroded. A semi-quantitative analysis of a kaolinite booklet viewed in an artificial sample fracture surface of sample NIPL19-20 revealed the presence of aluminum and silicon with minor potassium and iron impurities (volume 2).

The amount of authigenic kaolinite varies widely and sporadically in the 0-5% range. It seems, however to be more abundant in sandstones deeper than 2000 m. Estimates of 5% were commonly made in the Amauligak well from 3561.8-3567.5 m, from the Tarsiut N44A well (2249.3-2257.8 m) and the Unark wells (2731.9-2976.3 m).

With the exception of the Unark samples in which the kaolinite (or dolomite pseudomorphs of kaolinite) occur in calcite cement, authigenic kaolinite mainly lines secondary

intergranular pores. Less commonly it occurs in compactionally-formed grain fractures (samples AMAI65-N2,N4,N5, ISS2061-N3, NIPL19-25, NIPL19A-3) and rarely lines or fills moldic pores (plate 6a). Kaolinite booklets in rare instances also fill intragranular carbonate dissolution molds (samples AMAI65-N2,N4 AND N5). Where these rhomb-shaped molds were inherited rather than formed in situ, the kaolinite formed after dissolution of the authigenic carbonate (decarbonatization). Other evidence includes kaolinitic masses which line or fill grain molds (samples AME009-5, 11, TARN44A-N1, UNAL24A-N8). It should be cautioned, however, that kaolinitic masses more commonly than not represent extensively altered grains rather than pore-filling kaolinite. Kaolinite as a pore-lining rather than pore-filling of grain molds is much better evidence of a relatively late diagenetic origin. Further textural evidence is provided by the AME009-5/3860.17 m sample in which kaolinite lines pores but not quartz overgrowths, suggesting kaolinite cementation prior to quartz cementation.

To summarize, it appears that kaolinite cementation occurred mainly after the decarbonatization event at depths less than about a kilometre but sufficient for compactionally-related grain fracturing to occur. Some of the extensively corroded kaolinite booklets probably formed prior to carbonate cementation.



### Montmorillonite

Montmorillonite (0.2-2.0 micrometre-sized fraction) in sandstones of the Taglu wells was converted to interstratified clays from 2825.8-3219.9 m in the Reindeer Formation (Foscolos and Powell, 1980). No systematic investigation using x-ray diffraction was undertaken in the present study of the Kugmallit Sequence. The large scale effects of expanding clays were noted, however, for a sample obtained from the Taglu G-33 well at a depth of 1353.9 m (see also plate 18b,c). Montmorillonite was tentatively identified on the basis of fused crystals (plate 19d) in sample TARP45-N1/2474.9 m.

### Illite

The characteristic wispy morphology of authigenic illite was not observed with the scanning electron microscope. Most of the illite in the matrix of the sandstones determined by x-ray diffraction is undoubtedly of detrital origin.

### Chlorite (0-5%)

Chlorite commonly replaced muscovite flakes and to a lesser extent muscovite in quartz-muscovite schist. This was observed in samples at all depths suggesting that most of the chlorite replacement probably occurred before burial to depths exceeding a kilometre. It seems probable by analogy that illite as discrete particles and in phylloid clasts would similarly be partly or perhaps even completely replaced by chlorite. Only one sample (ALEP23-N8) contained appreciable (5%) chlorite cement. This anomalous sample is of interest because it occurs only 1.7 m

( below an extensively pyrite-cemented zone. Chlorite also occurs as a partial or complete alteration of glauconite pellets (electron microprobe analysis 2A.1 for sample UNAL24A-N5).

### PYRITE (0-30%)

Traces of pyrite were found in 52% of the samples while 1 to 3% pyrite was observed in 16% of the samples. Only 2% of the samples contained more than 3% pyrite. The pyrite most commonly occurs as framboids (plate 22A) and less commonly as nodules and pore-filling cement. It occurs at all depths lining pores of secondary origin. It has also been observed in the cracks of compactionally-fractured grains (samples NIPL19-2, NIPL19-25), in intragranular pores (samples ALEP23-N7, AMAI65-N4, AME009-1, ISS2061-N2, KAD007-1,6, TARN44A-N5 AND UNAL24A-N1), along bedding plane partings and subvertical fractures in mudstone (sample ALEP23-8). There seems to be a slight tendency, in addition, for concentration of pyrite framboids in and near coaly laminae (samples ALEP23-8, AME009-1 and 5). Pyrite framboids occur on quartz overgrowths (sample UNAL24A/2955.8 m, UNAL24A-N7/2968.84 m and UNAL24A-N8/2969.61 m) and are surrounded by carbonate cement (AME009-11/4378.77 m, UNAL24-N2/2731.92 m, UNAL24A-N2/2955.8 m, UNAL24A-N3/2958.18 m, UNAL24A-N6/2967.26 m, UNAL24A-N7/2968.84 m, and UNAL24A-N9/2976.31 m). These data suggest that pyrite was formed after compaction and after decarbonatization. Exceptions or complications are rare. In the UNAL24A-N6/2967.26 m sample which contains both calcite (dedolomite?) and dolomite, pyrite occurs as framboids in authigenic calcite but also as a pore-filling in and between individual carbonate rhombs, suggesting pyrite cementation before and after carbonate cementation. This unusually late generation of pyrite may be related to dedolomitization which releases the iron in dolomite. Another exception is revealed in Ame009-1/1312.0 m, in which cellular

coaly structures containing pyrite have been compacted less than those containing no pyrite. Clearly, the pyrite grew before compaction of the cellular structure. In ALEP23-N7/2029.80 m, the abundant (15%) pyrite, which is pore-lining and to some extent pore-filling occurs in intragranular pores of phylloid and chert clasts and also defines moldic and partial moldic porosity. These textures point to two episodes of ongoing secondary porosity formation before and after pyrite cementation.

## POROSITY AND PERMEABILITY DIAGENESIS

The extent to which porosity and permeability are lowered is related in a general way to the original volume of ductile grains. Ductile grains include phylloid clasts, altered volcanic rock fragments, chlorite/mica flakes, siltstone clasts and coal grains. During burial these are squeezed between the more competent quartzose grains. Permeability is especially affected because the squeezed grains are forced into the pore throats of the competent framework grains. Obviously, the higher the percentage of ductile grains, the more important these effects become. Consider the endmember scenario where competent grains float without touching in pseudomatrix. In such a sample the permeability would be lower than that of the pseudomatrix itself. It is also noteworthy that ductile grains in samples from the shallowest cores have been extensively squeezed between competent grains. The limiting factor effecting the decrease in porosity and permeability in the Kugmallit samples seems to be related to the proportion of ductile grains originally present. Mechanical compaction is more apparent in the finer grained samples which contain a higher proportion of these ductile grains. It is especially striking in those sandstone samples with anomalously high ductile grain proportions such as at Tarsiut (Fig. 3). In sample TARN44A-N3/2254.15 m, for example, ductile grains comprise about 35% of the detrital components. Even though the sample has a median grain size of 151 micrometres and is moderately sorted with a porosity of 21.5%, the permeability is only 2.79 millidarcies. The Tarsiut permeability values are in fact so low that they were excluded from the data base used to construct the

permeability boundaries of Fig. 4.

Mechanical compaction is expressed to a much lesser extent by fractured competent grains. Grains are considered to be compactionally fractured if a large proportion of them propagate from the contact points between grains. Compactionally fractured grains were observed in 15 samples ranging in depth from 920.8 m (a conglomerate) to 3563.6 m where they occur in conglomerates and the coarser better sorted sandstones. The evidence suggests that at least some of the fracturing occurred at relatively shallow depths. In samples MALL38-N1/920.80 m, TAGH54-N1/1104.6 m, UNAL24A-N2/2955.80 m and UNAL24A-N9/2976.31 m the compactionally-formed grain fractures are filled with carbonate cement. Grain fracturing probably occurred at relatively shallow depths less than a kilometre after which the fractures were filled with carbonate cement. To summarize, the initial volume of ductile grains governs to a considerable extent the decrease in porosity and permeability during burial and compaction. This reduction may be so pronounced in samples with a high proportion of phylloid clasts that later secondary porosity formation by carbonate dissolution may be negligible. The reduction in porosity and permeability after secondary porosity formation was with few exceptions minor, as evidenced by uncommon phylloid clasts squeezed into the elongate/oversized pores and corrosion molds of adjacent competent grains. Significant compaction after secondary porosity development is limited to present depths in excess of 3000 m and to samples with an anomalously high phylloid clast content. While the proportion of ductile grains is

important in reducing permeability, the most important controls on permeability are sorting and to a lesser extent grain size. Grain size and sorting were plotted on 2 cycle log-log paper in order to obtain a good spread of the data (Fig. 4). Permeability to air values were measured by Core Laboratories-Canada Ltd. from core plugs taken near the samples. The permeabilities of the core plugs and of the samples taken for the present study are assumed to be the same. The permeabilities (to air without overburden pressure) range over at least five orders of magnitude (Fig. 4) and were obtained from samples with little or no carbonate cement. Permeabilities measured under overburden pressures ranging to 57,000 kilopascals showed highly variable decreases in both porosity and permeability, undoubtedly related to the proportion of ductile grains present. The permeability of sample 9 (2377.2 m) in the Issungnak well was reduced from 21,520 millidarcies (no overburden pressure) to 1250 millidarcies under an overburden pressure of 29,500 kilopascals and 243 millidarcies under an overburden pressure of 57,000 kilopascals. This represents an 88 fold reduction in permeability. The porosity of sample 9 was reduced from 33.1% (no overburden pressure) to 21.4% (57,000 kilopascals overburden pressure). In other cases the porosity/permeability reductions are much less dramatic. For example, sample 196 (3199.13 m), a very fine to fine-grained sandstone in the Issungnak 2-0-61 well had a permeability (no overburden pressure) of 378 millidarcies. The permeability of the same sample under an overburden pressure of 57,000 kilopascals was reduced to only 180 millidarcies. The corresponding porosity reduction was also minor (24.9 to 23.2%). The large differences

between the two samples is probably dependent on differences in the ductile (and apparently to some extent elastic) component percentages. It seems quite likely that a change of only 20% in the ductile component percentage could explain these very large porosity/permeability variations. It is also interesting that the grain density for the two samples is identical (2640 Kilograms/cubic metre).



## CONCLUSIONS

A shallow marine interpretation for many of the sandstones is supported by the presence of glauconite pellets, which occur in over half of the samples. Sandstones of the Kugmallit Sequence are variably indurated litharenites which are compositionally similar to those of the underlying Reindeer Sequence. Volcanic rock fragments, however, are significantly less common than in either of the underlying Reindeer or Moose Channel sequences. The difference is probably related to a change in flow direction of the Mackenzie River system or its precursor from a southwestern volcanic-rich terrain to a southern volcanic-poor terrain.

The first order constraint on detrital sandstone composition in the Kugmallit Sequence is grain size, with competent chert grain proportions increasing with median grain size. Local environmental conditions may cause second order variations. The Tarsiut sandstones, for example, have anomalously high ductile component proportions compared to other sandstones with a similar grain size elsewhere. The opposite is true for the Amauligak and Issungnak samples. These differences are accompanied by differences in sorting.

Diagenesis was very significant in the Kugmallit Sequence and involved a large number of minerals. Authigenic quartz generally occurs in amounts less than 1% as overgrowths on quartzose grains. It is more common (2-3%) in moderate to well sorted sandstones at depths greater than 2700 metres where it is accompanied by pressure solution. Only 2 samples contained more than 5% quartz overgrowths, and these were moderately sorted

sandstones from depths in excess of 3500 m. Quartz overgrowths line secondary pores in many of the sandstones, suggesting a second generation of quartz cementation after decarbonatization. The first generation of quartz overgrowths which formed at shallow depths prior to carbonate cementation was probably insignificant volumetrically. Most of the overgrowths were undoubtedly replaced by carbonate and subsequently dissolved. The process of cementation, replacement and dissolution of carbonate was responsible for the formation of secondary porosity, which is generally estimated as comprising at least half of the present porosity. About half of the samples contain carbonate, most of which is dolomite. Carbonate, which is most abundant in samples from the southernmost wells, was probably introduced in the depth range from 500 to 1200 m, judging by the proportion and extent of deformation of squeezed ductile grains, combined with the textural evidence of secondary porosity. The chemical composition of the carbonate is highly variable, both between and to a lesser extent within samples. Concepts involving large-scale movement of fluids in the basin must reconcile this highly variable carbonate chemistry.

Authigenic clays include kaolinite, montmorillonite, illite and chlorite. The kaolinite occurs as variously corroded vermicular booklets which most commonly line secondary intergranular pores and less commonly line the widened fractures of compactionally fractured grains. With the exception of extensively corroded booklets, kaolinite cementation mainly occurred after decarbonatization at depths less than about a

kilometre but sufficient for compaction and grain fracturing. Authigenic montmorillonite and illite appear to be of minor volumetric importance, though reactions within phylloid clasts could not be assessed using the petrographic methods employed in this study. Authigenic chlorite partly replaced muscovite (and undoubtedly illite on a smaller scale) as well as glauconite pellets. Pyrite generally occurs in trace quantities as framboids lining pores of secondary origin. These include the cracks of compactionally-fractured grains, intragranular pores and the hackly partings and bedding planes of mudstones. Most of it was probably formed after compaction and decarbonatization. Given the complexity of detrital and diagenetic processes, it is little wonder that porosity and permeability values vary widely. The most important controls are median grain size, sorting, the proportion of ductile grains as well as the quantity and textural relations of authigenic components. The initial volume of ductile grains determines to a large extent the porosity and permeability decrease with increasing overburden pressure. Mechanical compaction after secondary porosity development was generally of minor importance.

### RECOMMENDATIONS

The experience gained in experiments with pressure impregnation and to a lesser extent with impregnation using acetone-epoxy mixtures suggests that the vapour exchange method may be easier and perhaps even better than the vacuum/pressure method. It is undesirable, for example to subject the samples to confining pressures greater than those acting at the depths from which the samples were obtained. The following sample preparation procedure is contemplated for future evaluation. For simplicity of handling, the samples could be wrapped individually in perforated polyethylene (to permit separation after curing) and aluminum foil (to permit identification and to support poorly consolidated samples).

The vapour exchange method depends on the diffusion of epoxy molecules from a higher to a lower concentration in a fluid medium. It is therefore critical that all the pore space (including intragranular porosity) be filled. This can easily be accomplished by evacuating the samples, then adding acetone to cover them and finally letting air back into the vessel. Caution is required with acetone-air mixtures because they are potentially explosive. If the acetone is separated (using a stopcock) from the system this problem is avoided. A vacuum is drawn first, the pump is shut down and acetone is added to cover the samples. An aspirator instead of a vacuum pump is an easy and safe method of obtaining the necessary vacuum. According to polysciences data sheet no. 127 (Nov./1973), Spurr Resin is also compatible with tert-butyl alcohol, dioxane, hexylene glycol, isopropyl alcohol and propylene oxide. However, anhydrous acetone

is one of the better solvents because it has a very low viscosity (0.316 centipoise at 25 degrees C) and a low boiling point (56 degrees C). After soaking in acetone, the samples are immersed in a solution comprising 25% epoxy and 75% acetone by volume and kept in a separate sealed container such as a desiccator. After a few days the acetone should have diffused out of the sample and been replaced with the dilute epoxy-acetone mixture. The samples are then transferred to another container containing 50% epoxy and 50% acetone. The procedure is repeated for 75% epoxy/25% acetone and finally 100% epoxy mixtures. The method is explained in detail by Jim (1985) though undiluted epoxy was found to penetrate his unconsolidated clay samples. Initial experiments showed that vacuum impregnation with undiluted epoxy did not penetrate the compacted subsurface Mackenzie Delta-Beaufort Sea samples.

The cured Spurr Resin is unusual because it is soluble in acetone. This property could be used to advantage for poorly consolidated rocks because an impregnated sample could be cut and polished, the epoxy dissolved and the sample examined with an electron microscope. This cross-sectional view would permit differentiation of pore-lining clays and pseudomatrix formed by squeezed ductile grains.

The production of thin sections is extremely time consuming by traditional methods. A multiple spindle surface grinder equipped with diamond cup wheels of successively finer sized diamonds would greatly speed up the process and cause less damage than lapping methods using loose abrasives. Final polishing could

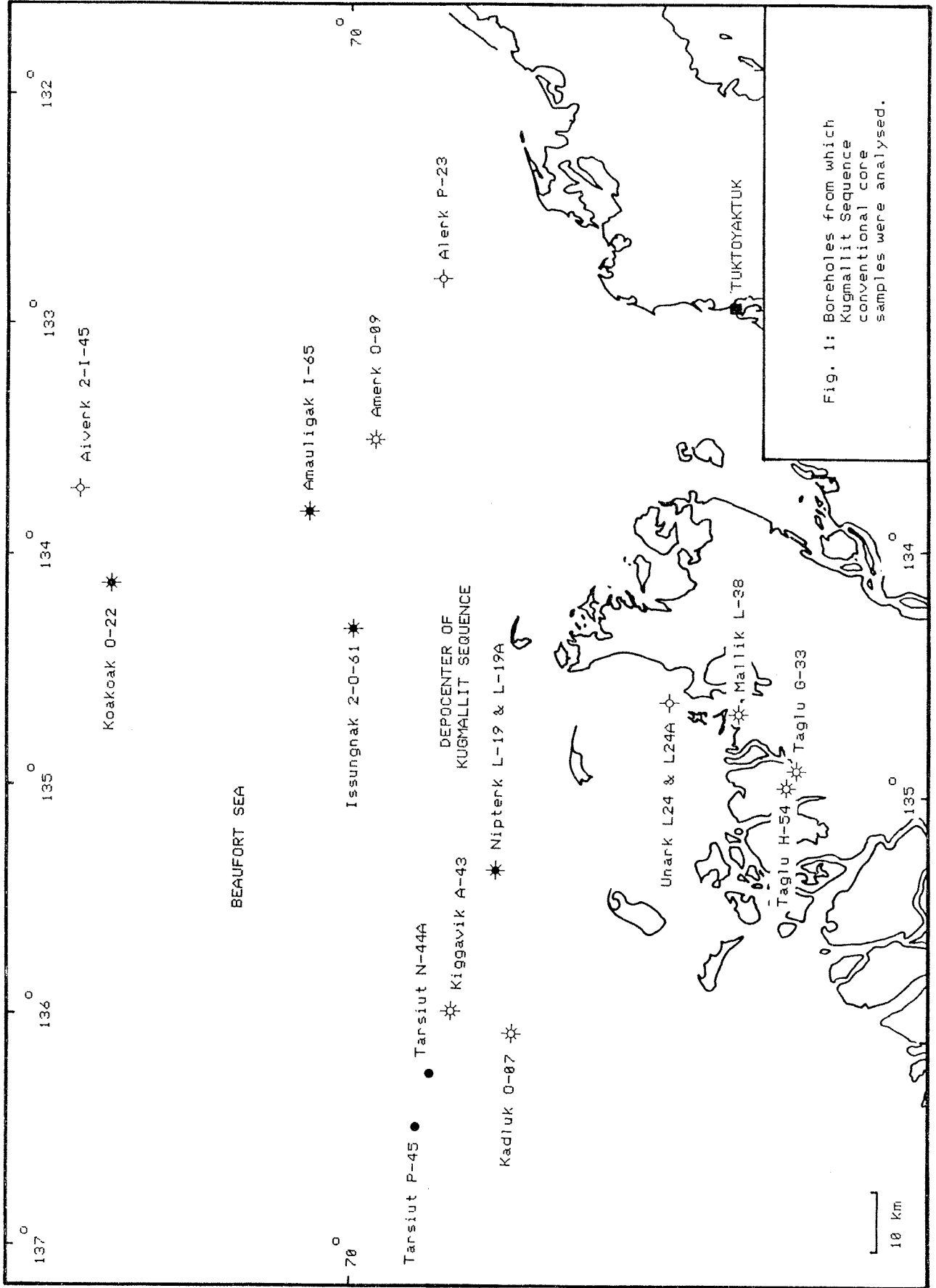
be accomplished using metal bonded diamond laps rather than loose abrasive particles. Such laps, with 6, 3 and 1 micrometres-sized diamonds could be used in lieu of loose abrasives which have a tendency in thin sections to create a groove just inside the grain/epoxy contact. Metal-bonded diamond laps are available from the suppliers of Jewellery makers. By eliminating the percussive action of loose abrasive particles, it should be possible to manufacture good quality ultrathin (5-10 micrometre) sections which would shed more light on the very fine grained sandstones and mudstones. Further research could include a study of thin sections of sidewall cores and drill cuttings. Detection and explanation of carbonate-cemented zones by analysis of drill cuttings and wireline logs are of particular interest.

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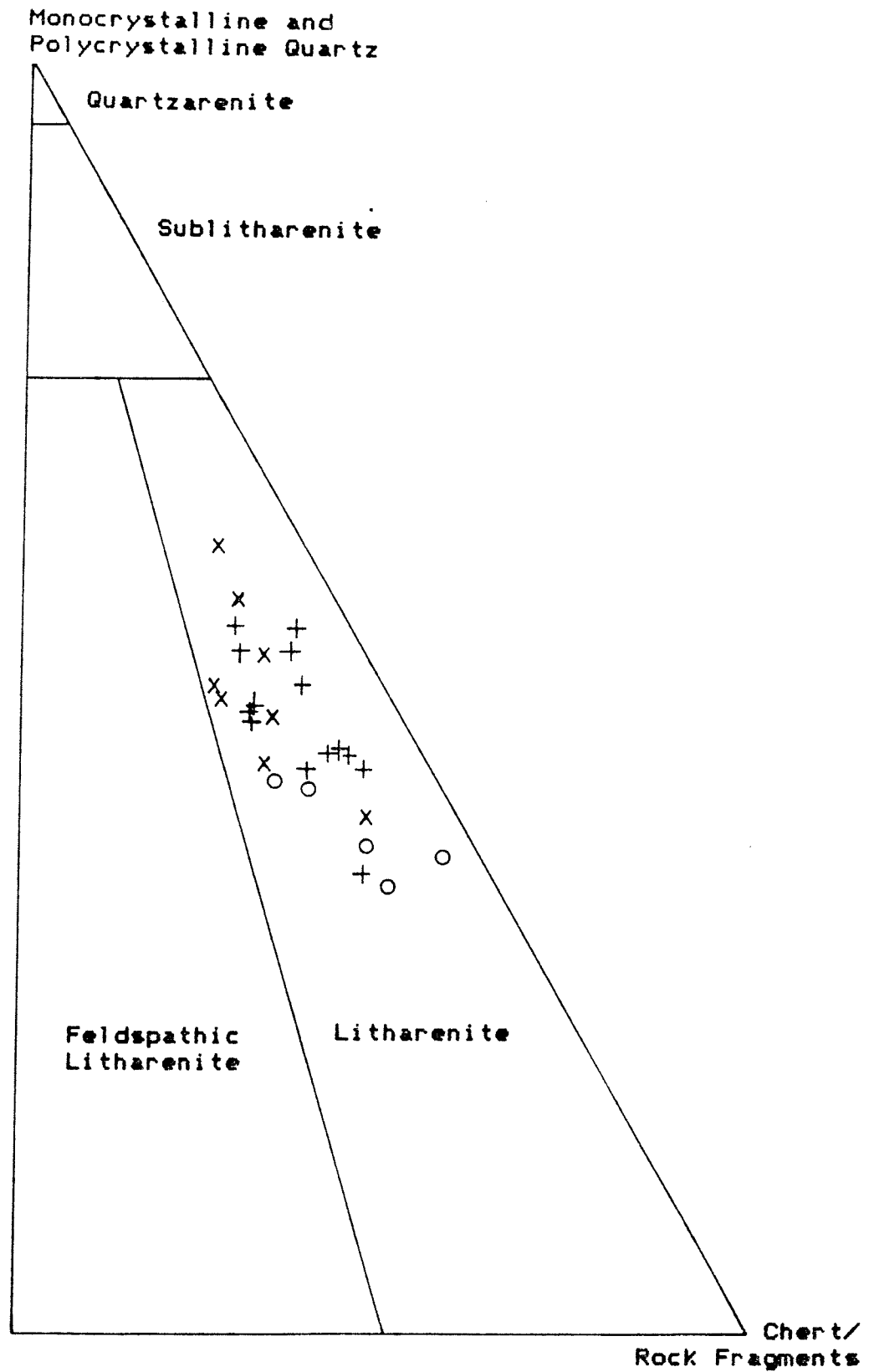


Fig. 2 : Classification of Kugmallit Sequence sandstones according to Folk (1980). The symbols represent very fine (X), fine (+), and medium (o) sandstones. Half of the triangle with the pole for feldspar, granite and gneiss fragments is omitted.

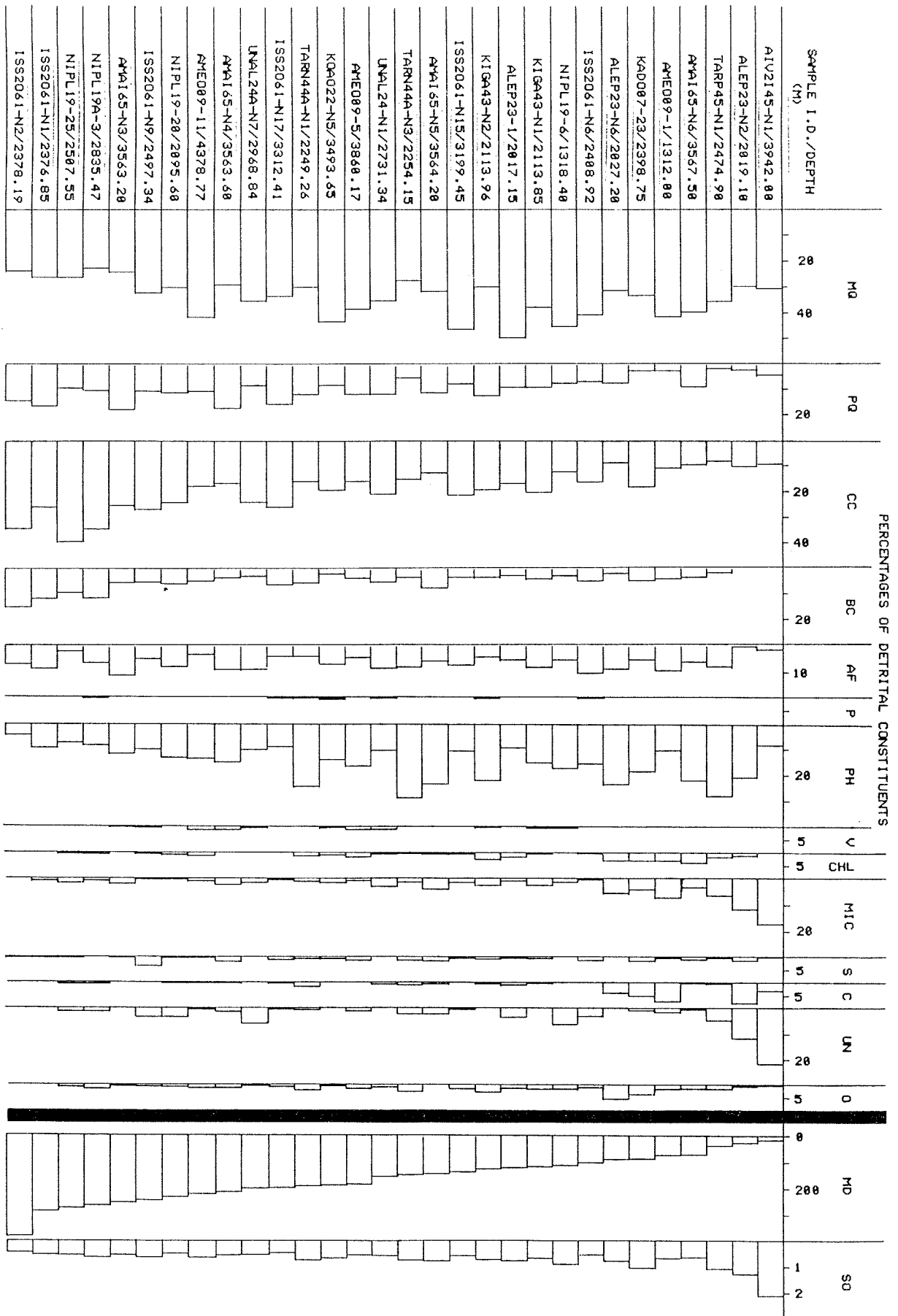


Fig. 3: Percentage of detrital components versus increasing median grain size based on modal and grain size analyses of thin sections. Symbols for columns are as follows: MQ (monocrystalline quartz), PQ (polycrystalline quartz), CC (clear chert), BC (black chert), AF (alkali feldspar), P (plagioclase), PH (phyllonoid clasts), V (volcanic rock fragments), CHL (chlorite flakes), MIC (mica flakes), S (siltstone), C (coal), UN (unidentified), O (others), MD (median grain size in micrometres), SO (sorting).

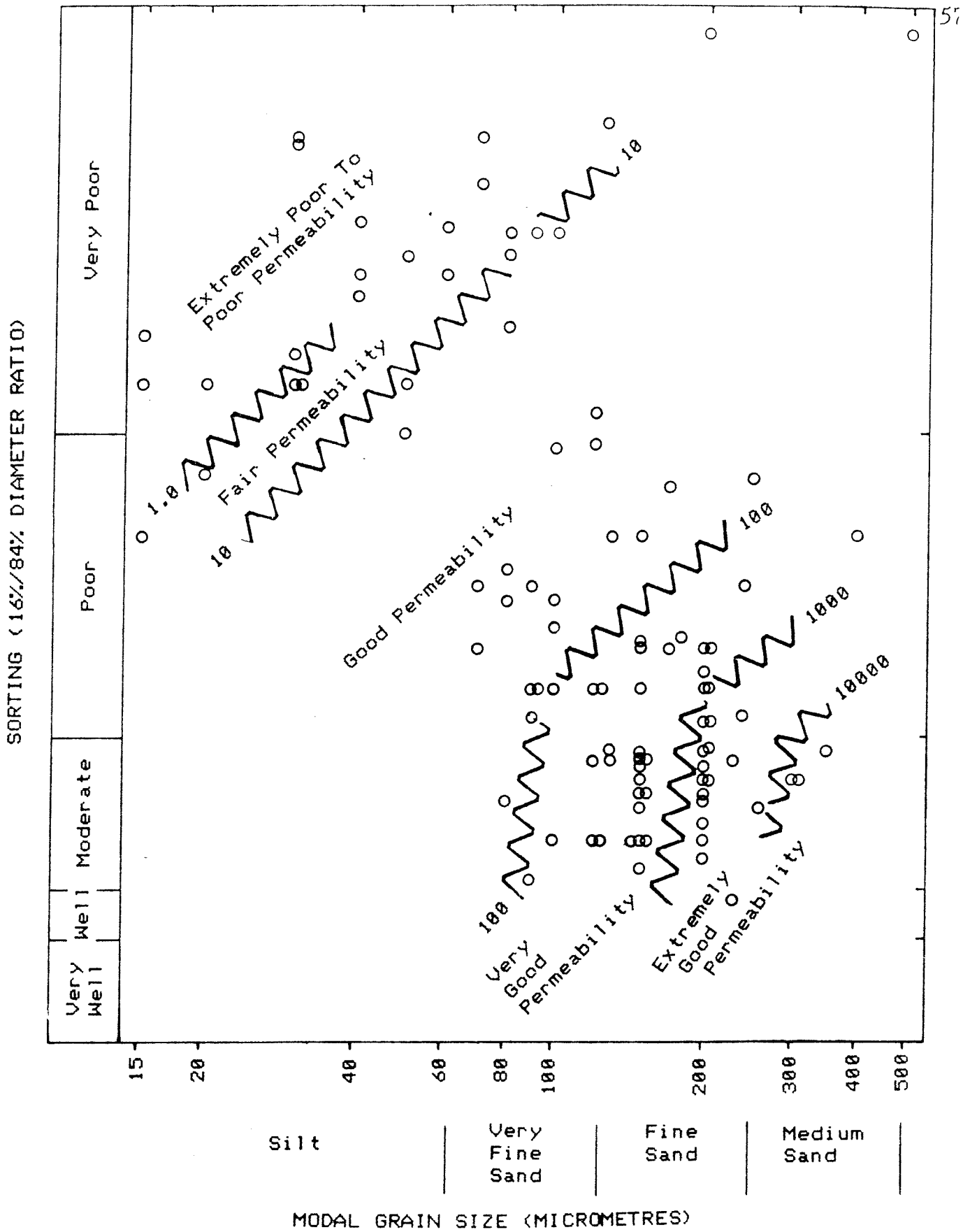


Fig. 4 : Relation between modal grain size and sorting. Permeability zones were established on the basis of 41 selected measurements. The boundary values are in millidarcies.

Nipterk L-19	1306	In Unit A 1306.1-1323.8 1405.8-1425.6	3450?
		In Unit B 1649.6-1652.3 1921.4-1933.4	
		In Unit C 2094.4-2102.6 2303.4-2311.8 2505.0-2512.0	
Nipterk L-19A	1347?	In Unit C 2336.8-2355.1 2807.0-2817.0 2825.6-2844.0	3490?
Taglu G-33	199	950.9-957.1 1379.2-1385.3	1593
Taglu H-54	335	1104.3-1105.2	1560.6
E. Tarsiut N44A	1985.0 (1700 T.V.D)	In Unit C 2245.1-2274.4	2928+ (2352 T.V.D.)
W. Tarsiut P-45	1805	In Unit C 2473.0-2482.0	2911
Unark L-24	652	2731.0-2743.8	2748
Unark L-24A	652	2218.6-2219.2 2955.3-2963.3 2963.9-2982.2	2980.3