A SUBSURFACE STUDY OF THE MIDDLE-LOWER SILURIAN THOROLD SANDSTONE FROM CONSUMERS' GAS SILVER CREEK 004 GRIMSBY POOL; NORTH-CENTRAL LAKE ERIE

By

MARTIN DOUGLAS HEWITT

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AUTHOR: Martin Douglas Hewitt

SUPERVISOR: Dr. G.V. Middleton

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ABSTRACT

Examination of subsurface cores of the Middle-Lower Silurian Thorold Sandstone from Consumers' Gas Silver Creek 004 Grimsby Pool indicate the presence of a single laminated sandstone facies deposited in a lower shoreface environment. Subsurface thin sections show greater development of quartz cement in the form of quartz overgrowths when compared to thin sections from surface outcrop leading to a porosity decrease of 20%. Petrographic and cathodoluminescence studies reveal that concavo-convex and sutured grain contacts, responsible for 80% of the grain contacts within the Thorold Sandstone, are generally between authigenic overgrowths and not detrital grains indicating that pressure solution is not the major source of silica within the Thorold Sandstone. Studies of detrital and authigenic clays utilizing a combination of thin section, scanning electron microscope and X-ray diffraction techniques show that illite (both detrital and authigenic) is the dominant clay mineral within the Thorold Sandstone in the 004 Pool, followed by approximately one half as much detrital kaolinite and minor authigenic chlorite. Shallow maximum depth of burial (786 to 1160m) and low diagenetic temperatures (30°C) suggest that clay minerals are unlikely to have undergone extensive diagenetic transformation. Consequently,

detrital minerals represent the clay minerals present at the time of deposition while authigenic clays form by direct precipitation from pore fluids. During eodiagenesis mechanical compaction has reduced sandstone porosity from 40% to 28 to 29% while during mesodiagenesis the progressive paragenetic assemblage of authigenic quartz overgrowths, authigenic chlorite and authigenic illite have reduced porosity to its present value of 4 to 10%.

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To

My Mother and Father

for their encouragement,

understanding, and love.

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CHAPTER 1

INTRODUCTION AND PURPOSE OF STUDY

Consumers' Gas Silver Creek 004 Grimsby Pool was discovered October 10, 1967. The Pool is located in north-central Lake Erie approximately 16 km southwest of Port Burwell, Ontario (Figures 1-1, 1-2). Production is from the Middle-Lower Silurian Thorold Sandstone and the Lower Silurian Grimsby Sandstone. The Thorold Sandstone has a subsurface depth range from 1514 to 1605 feet (461.4 to 489.2 m) in the study area. The average thickness of the producing interval within the Thorold Sandstone is 4.6 feet (1.4 m). Both gas and oil have been discovered in the majority of wells in the study area, however, government regulations stipulate that only gas can be produced from wells drilled in Lake Erie.

The Thorold Sandstone, although studied in detail from surface sections has not been examined thoroughly in the subsurface. Cores from seven wells in the 004 Pool were analyzed and sampled by the present author for the purpose of:

i) comparison with surface studies;

ii) determination of factors contributing to porosity reduction;

FIGURE 1-1 Location of 004 Pool with respect to the Great Lakes region of Canada and United States.

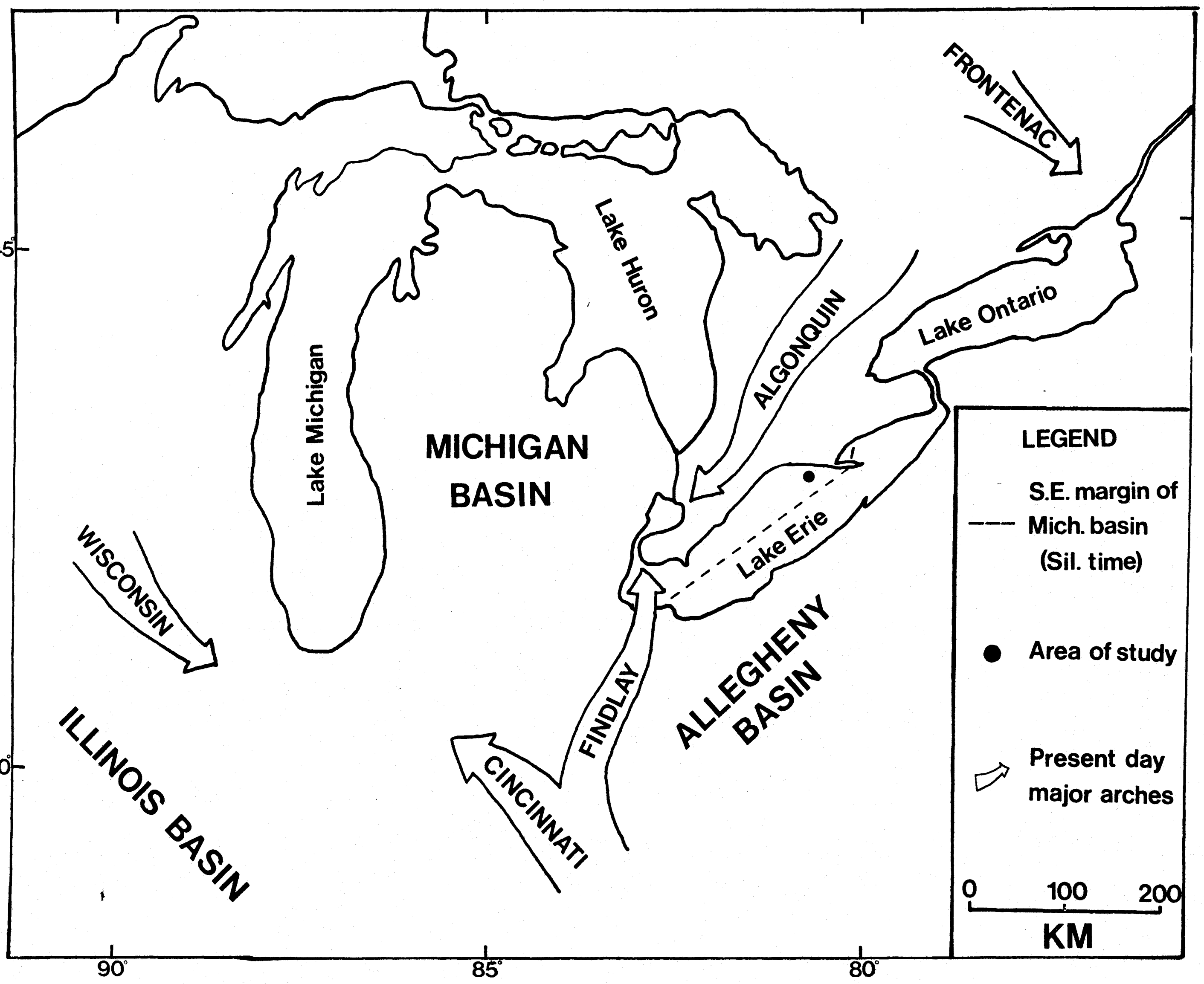
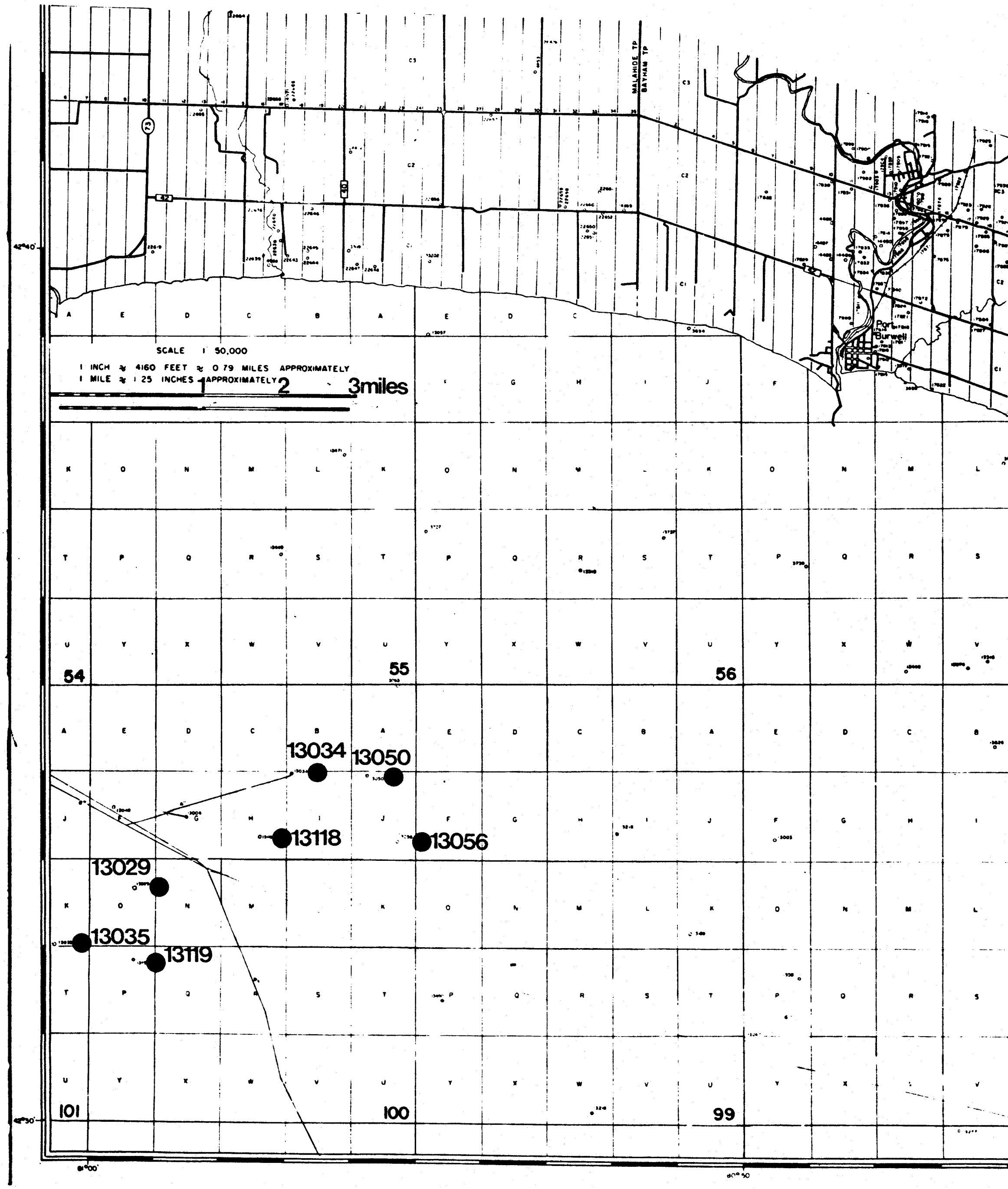

FRONTENAC
Lake Huron
Lake Michigan
Lake Ontario
ALGONQUIN
MICHIGAN
BASIN
Lake Erie
WISCONSIN
ALLEGHENY
BASIN
FINDLAY
CINCINNATI
ILLINOIS BASIN
45°
40°
90°
85°
80°
LEGEND
S.E. margin of
Mich. basin
(Sil. time)
Area of study
Present day
major arches
0
100
200
KM

FIGURE 1-2 Consumers' Gas Silver Creek 004 Grimsby Pool. Well locations are denoted by shaded circles. Refer to Figure 1-1 for exact location of study area. (Courtesy of Consumers' Gas)


MALAHIDE TP
BAYHAM TP
Port Burwell
SCALE 1:50,000
1 INCH ≈ 4160 FEET ≈ 0.79 MILES APPROXIMATELY
1 MILE ≈ 1.25 INCHES APPROXIMATELY
1
2
3miles
54
55
56
101
100
99
13034
13050
13118
13056
13029
13035
13119

iii) determination of the diagenetic history of the Thorold Sandstone.

GENERAL STRATIGRAPHY AND EXPOSURE

The marine orthoquartzite Thorold Sandstone differs considerably from the redbed deltaic deposits upon which it rests and is considered a basal transgression facies of the Reynales-Fossil Hill sequence (Sanford, 1969). Fisher (1954) felt that the Thorold was an eastward, transgressive unit, crossing time lines and becoming progressively younger towards the east. The Thorold is exposed along the base of the Niagara Escarpment between the Niagara River and Hamilton and gradually gives way to silty and shaly dolomites to the north to form the lower beds of the Reynales. Distribution is sporadic in the subsurface but it underlies most of southwestern Ontario and from eastern Elgin county, the depositional edge extends southward beneath central Lake Erie and into eastern Ohio. The Thorold is absent in a large area beneath eastern Lake Erie and New York State where equivalent rocks are presumably represented by Reynales dolomite (Sanford, 1969). The Thorold ranges in thickness from 1.8 m to 4.1 m in surface sections while subsurface sections in this study ranged from 0.6 m to 3.4 m.

The Thorold is composed of light grey, white to greenish grey, fine grained orthoquartzitic sandstone and siltstone in the eastern Niagara Peninsula. As the pinch-out edge of the Thorold is approached, the Sandstone contains numerous siltstone and grey shale interbeds. The irregular distribution, thickness and highly variable textures of the Thorold suggest that the formation may have been scoured in part from the subjacent Grimsby Sandstone as the Niagaran sea initially transgressed into the Ontario Peninsula (Sanford, 1969).

REGIONAL SEDIMENTOLOGY

The Middle-Lower Silurian Medina Formation is unconformably underlain by the Ordovician Queenston red shale. The origin of the red colour of the Queenston is controversial but Grabau (1913) believes that it was probably deposited on the top-set and fore-set beds of a large delta, namely the "Queenston delta". The delta was built out westwards from a land mass in the present position of the Appalachian Mountains. The region which is now Ontario rose out of the sea at the close of the Ordovician and there was little folding and faulting of sediments before deposition of the Silurian due to subsidence. The area of eastern New York State was severely folded, faulted and metamorphosed by the Taconic orogeny at the end of the Ordovician.

The first deposits of the Silurian belong to the upper part of the Lower Silurian. The stratigraphic units cropping out along the Niagara Escarpment can be seen in Figure 1-3.

Throughout Silurian time, southwestern Ontario formed a hingeline and marginal area to two major sedimentary basins; i) the elongated Allegheny Basin on the south, extending into the Niagara Peninsula and eastern Lake Erie, and ii) the Michigan Basin forming on the west, its eastern rim passing through western and central Lake Erie, then north along the axis of the Algonquin Arch (Sanford, 1969) (Figure 1-1). Sediments deposited in the Allegheny Basin were clastics thickening towards a source of terrigenous sediment to the southeast whereas the Michigan Basin was largely a carbonate and evaporite basin during Silurian time.

Silurian history can be summarized as follows:

a) General advance of an early Silurian sea over a fairly smooth Late Ordovician terrain with the majority of detrital materials (i.e. clastics or broken fragments of pre-existing rocks transported from their place of origin), being derived by erosion from the southeast (Middleton, 1971).

b) In the Early Silurian the Medina unit was formed from sediments provided by the reworking of sedimentary rocks of the Or-

FIGURE 1-3 Stratigraphic units cropping out along the Niagara Escarpment (Modified from Martini, 1971).

SYSTEM	SERIES	FORMATION	MEMBER
SILURIAN	MIDDLE	CLINTON	IRONDEQUOIT
			REYNALES
			NEAHGA and MAPLEWOOD
	MIDDLE-LOWER	MEDINA	THOROLD
	LOWER		GRIMSBY
			CABOT HEAD
			MANITOULIN
			WHIRLPOOL
~~ Unconformity ~~~			
ORDOVICIAN		QUEENSTON	

dovician Bald Eagle and Juniata Formations. In the eastern Great Lakes area, littoral sands (Whirlpool), deltaic and littoral to sublittoral sands and muds (Grimsby and Thorold) were deposited in northwestern New York and in the Niagara Peninsula. Farther from the Appalachian clastic sources (Niagara-Manitoulin Island area) open marine muds and carbonates were deposited in sublittoral environments (Martini, 1966).

c) During the Middle Silurian, little clastic material was supplied to the Great Lakes by the low-lying Taconic Hills. After the sandy deposition of the Thorold, the carbonate, minor evaporites and minor amounts of the Clinton were deposited (Bolton, 1957).

d) Normal marine conditions persisted, with occasional episodes of rapid subsidence (base of Neahga shale) followed by slow filling and shallowing of the sea. Shallow seas flooded at least half of the present North America at this time.

e) At the end of the Upper Mid-Silurian (Lockport) subsidence ceased and, with a slow rise in the overall continental surface the seas began to withdraw. In the Guelph, reefs served as barriers to free circulation but for the majority of Late Silurian time normal sea water was continuously flowing into the Michigan Basin and evaporating under a very warm arid climate.

f) The period closed with no major upheavals, even in the Appalachians. The emergent continent at that time must have been a vast desert (Middleton, 1971).

MARTINI'S DEPOSITIONAL MODEL

Martini (1966, 1971) constructed an interesting depositional model for the Medina Formation.

Generally, the vertical and lateral variations of faunal structures, fabrics, sedimentary structures and textures displayed in the Medina are consistent with a deltaic to shallow marine origin. The Thorold Sandstone is the result of the destructive phase of the Medina delta complex in Ontario which involved the reworking and distribution of sediments in uniform thickness over an area of at least 255 kilometres. The formation of the Thorold was perhaps the result of the slow subsidence of the Medina basin, a change in the power of sediment reworking for a fairly long period of time, and a reduced input of clastics into the exposed portion of the Medina basin.

Martini's model indicates that there are three possible sources for the sediments which form the Thorold:

i) The Niagara-DeCew Falls region, since eastward and westward from this area is a definite increase in the shaly content of the Thorold.

ii) The Oneida Conglomerate which is laterally transitional to the Thorold in the Clyde quadrangle (Gillette, 1947).

iii) Reworking of the upper beds of the Grimsby (as signified by the channelized contact between the Grimsby and the Thorold at a number of outcrops).

Martini interpreted the easternmost sections studied in New York State as being deposited in a tidal flat or interdistributory environment.

The uppermost expression of the destructive phase of the Medina delta complex was noted at Niagara and DeCew Falls. The Thorold was interpreted as being a derivative of the reworking of deltaic sediments in a sublittoral environment. The Thorold has been interpreted to represent a long-shore bar deposited under high wave conditions at the Niagara Glenn section. The Thorold displays definite marine characteristics westward from Niagara as the shale content increases indicating a greater distance from the clastic input area along with the weakening of long-shore currents. Sublittoral environments along with periodic littoral conditions prevail in this area. Towards Hamilton, the Thorold represents the spreading out of the Medina delta. High siltstone and shale content would indicate a greater distance from the source of sediments.

PEMBERTON'S STUDIES IN LOWER PALEOZOIC ICHNOLOGY

Pemberton's study (1979) involved the identification and significance of 27 different ichnogenera from the Thorold Sandstone of southeastern Ontario and New York. These ichnofossils were placed into four characteristic assemblages and were indicative of the shallow water, nearshore *Skolithos* and *Cruziana* ichnofacies. Lateral changes in the observed trace fossil assemblages provided valuable information on the interpretation of paleoenvironments and the delineation of ancient storm deposits (Chapter 2).

CHAPTER 2

FACIES ANALYSIS

INTRODUCTION

The Thorold Sandstone was logged and sampled from the core of 7 wells in the Consumers' Gas Silver Creek 004 Grimsby Pool in an attempt to determine the Thorold's environment of deposition. Parameters studied while logging the core included grain size, contacts, gross lithology, primary structures and fossils, constituents and accessories, roundness, induration, cement type, and colour (Appendix I).

The seven wells studied were:

13035 101-K, a suspended gas well
13119 100-P, a suspended gas well, now abandoned
13029 100-O, a producing gas well, now abandoned
13118 100-H, a suspended gas well, now abandoned
13034 100-I, a producing gas well, on pipeline
13050 100-J, a suspended gas well, now abandoned
13056 100-J, a suspended gas well, now abandoned
(Figure 1-2)

Figure 2-1 is a fence diagram correlating the wells of the 004 Pool while Figure 2-2 shows a typical gamma ray log response of the Thorold and associated Formations.

Porosities and permeabilities range from 5 to 20.4%

FIGURE 2-1 Fence diagram correlating the wells in the Silver Creek 004 Grimsby Pool. Shaded circles denote the wells studied. (Courtesy of Consumers' Gas)

SILVER CREEK 004 GRIMSBY POOL

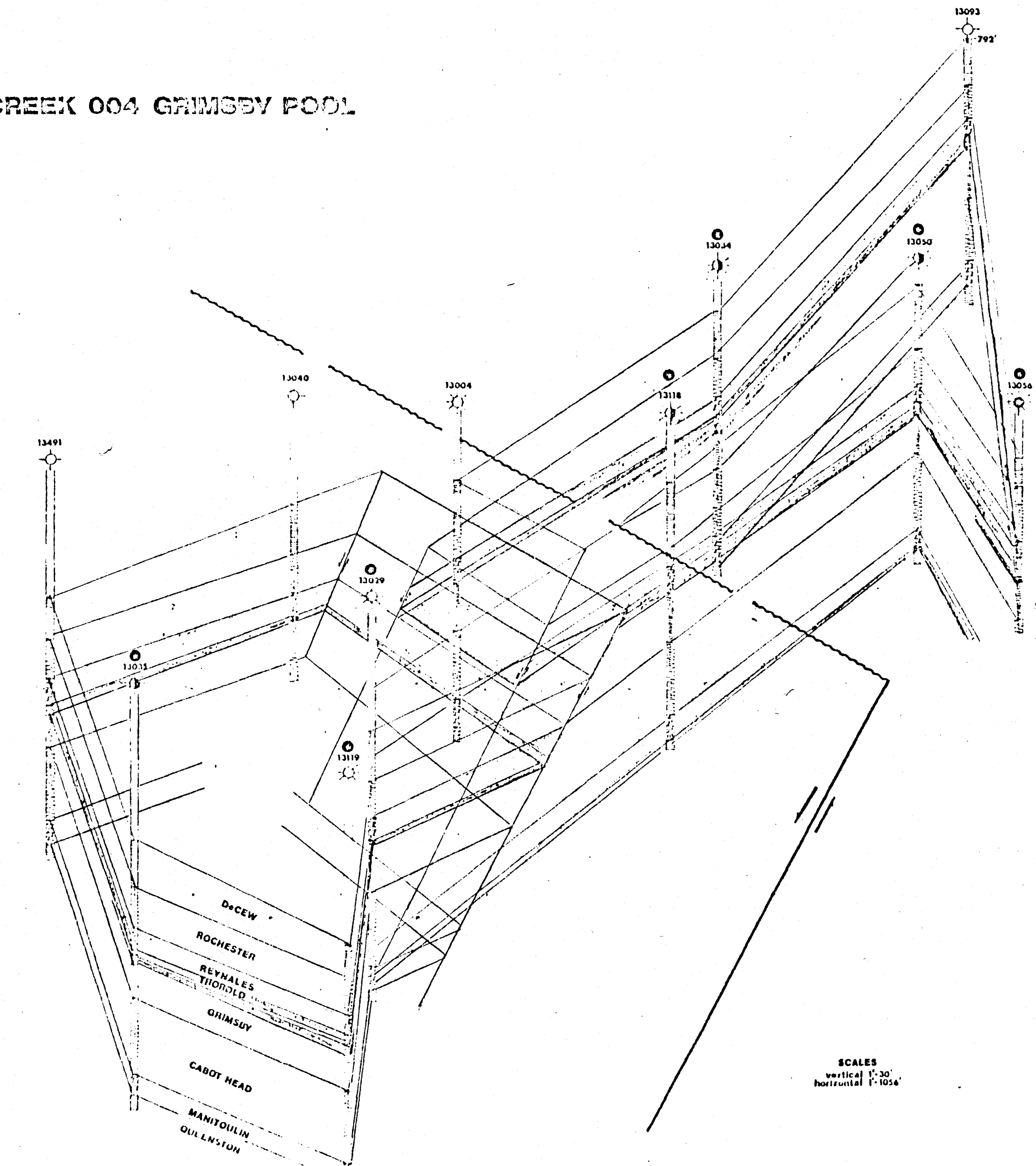
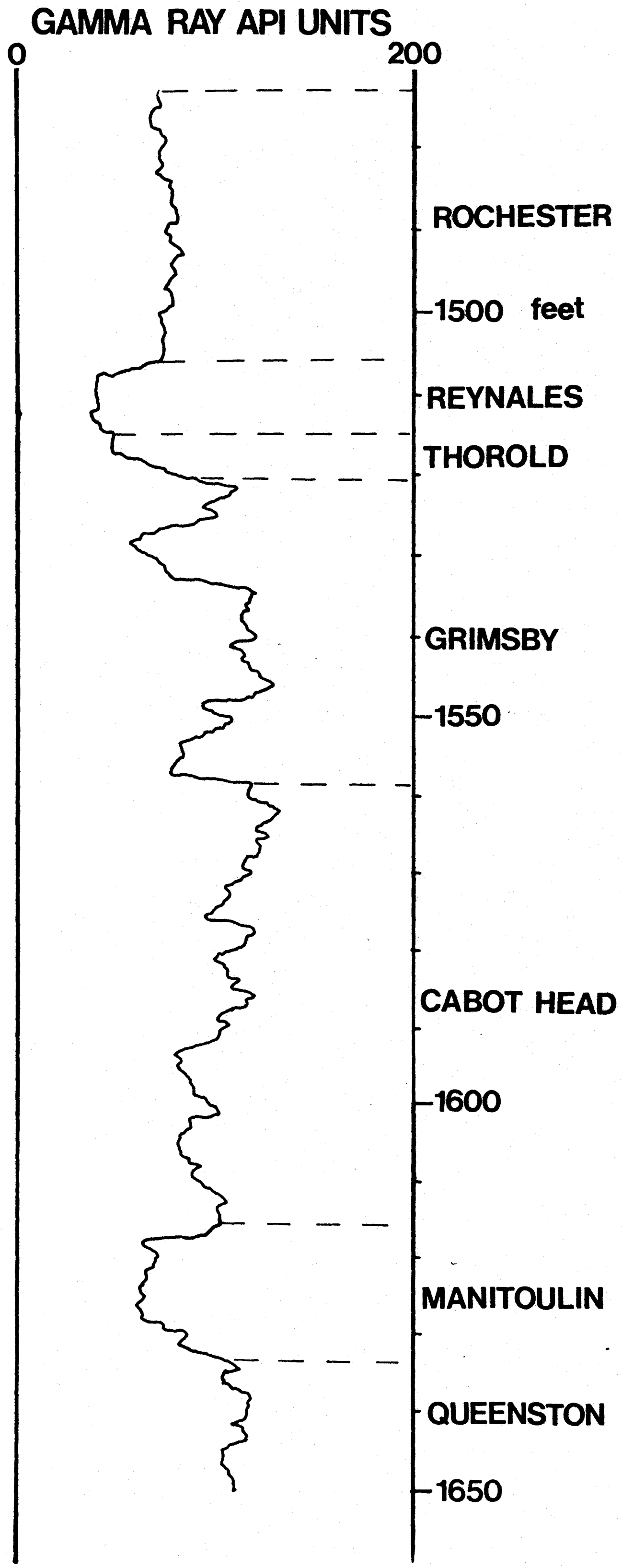


FIGURE 2-2 Typical gamma ray log response of the Thorold Sandstone and associated Formations.


GAMMA RAY API UNITS
0
200
ROCHESTER
1500 feet
REYNALES
THOROLD
GRIMSBY
1550
CABOT HEAD
1600
MANITOULIN
QUEENSTON
1650

and less than 0.01 to 126.0 millidarcys respectively with mean values of 15.03% and 37.8 millidarcys (Appendix I).

Table 2-1 summarizes productivity of the Consumers' Gas Silver Creek 004 Grimsby Pool to date.

TABLE 2-1

PRODUCTIVITY OF CONSUMERS' GAS SILVER CREEK 004 GRIMSBY POOL

October-September	Total Mcf	Total Mcf to Date
1969/70	154,738	293,171
1970/71	123,660	416,831
1971/72	35,795	452,626
1972/73	50,468	503,094
1973/74	44,306	547,400
1974/75	6,579	553,979
1975/76	23,625	577,604
1976/77	Shut-in	577,604
1977/78	151,196	728,800
1978/79	116,388	845,188
1979/80	48,656	893,844
1980/81	17,235	911,079

FACIES DESCRIPTION

One distinct facies was recognized during subsurface core analysis of the Thorold Sandstone from wells drilled in the 004 Pool. Characteristics used in the definition of this facies are on the logged sections (Appendix I).

Laminated Sandstone Facies

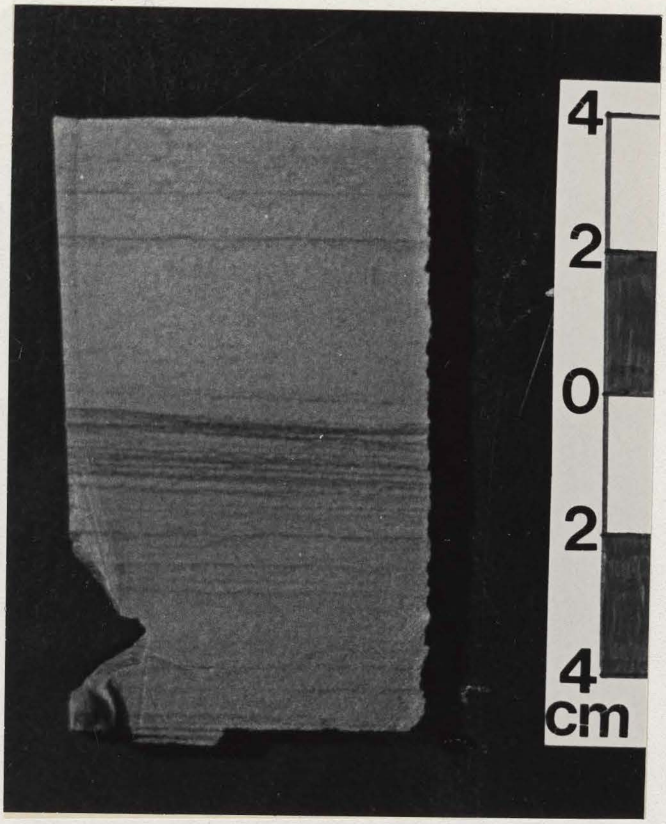
This facies is characterized by a fine-grained, well-sorted, well-rounded grey sandstone with horizontal, even parallel to slightly wavy parallel paper thin silt laminae (Plate 2-1). Rip up clasts of Grimsby (?) shale are commonly found throughout the facies (Plate 2-2). Small scale cross laminations were infrequently observed. Bioturbation was moderate to strong in the facies with unidentified trace fossils observed in a number of wells (Plate 2-3). Fossil fragments were abundant with Lingula comprising the greater part of the fossil fragment population, usually as lag deposits at the base of 2 or 3 cm thick fining upward sequences (Plate 2-4). Grains of pyrite and muscovite were observed without the aid of a hand lens in some wells. Basal contacts with the Grimsby Sandstone (when visible) are indicative of scouring. Generally, this facies tends to thicken towards the east of the 004 Pool.

INTERPRETATION

Examination of the Thorold Sandstone in the 004 Pool by the present author indicates that the Thorold was deposited in a barrier beach facies, lower shoreface deposit. For a discussion of barrier beach and related

PLATE 2-1 Horizontal, even parallel paper thin silt laminae within the Thorold Sandstone.

PLATE 2-2 Rip up clasts of Grimsby (?) shale within the Thorold Sandstone.


4
2
0
2
4
cm

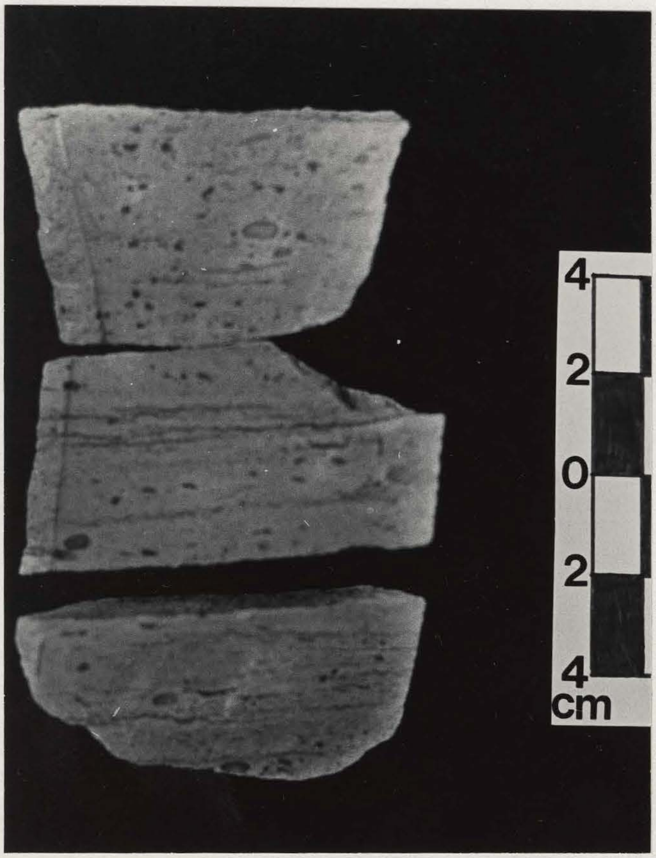
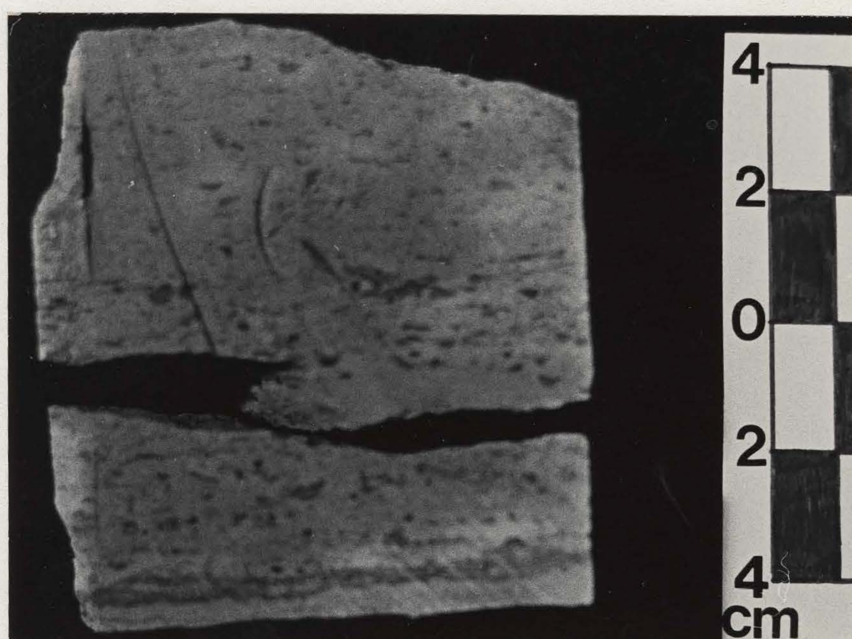

4
2
0
2
4
cm

PLATE 2-3 Burrows made by unidentified organisms within the Thorold Sandstone.

PLATE 2-4 Fossil fragments of *Lingula* present as a lag deposit at the base of a fining upward sequence.


4
2
0
2
4
cm


4
2
0
2
4
cm

facies see Reinson (in Walker, 1979).

Lower shoreface deposits generally consist of very fine to fine-grained wave agitated sands with interlayers of silt and sandy mud. Physical sedimentary structures include mainly planar laminated beds with abundant bioturbation and trace-fossil assemblages (Reinson, in Walker, 1979). All of these characteristics are consistent with observations made by the present author from Thorold Sandstone core. The presence of rip up clasts of Grimsby (?) shale would indicate an environment in which depositional processes were governed by wave energy.

Martini (1966, 1971) has interpreted the Thorold as being deposited in a range of environmental conditions from a tidal flat or interdistributory setting in easternmost sections to sublittoral with periodic littoral environments in the west.

Pemberton (1982) suggests that the trace fossil assemblage found in the main body of the Thorold is characteristic of the Cruziana ichnofacies indicating a generally mobile, deposit-feeding population reflecting low water energies, fine grain sizes, high detritus contents, and stable bottom conditions.

Recently, there has been a renascence in the interpretation of environments of deposition of the Thorold Sandstone (Dr. G.V. Middleton, Dr. M.J. Risk, personal communication). A deeper water model has been suggested for the Formation. Pemberton (1982) has noted the presence of a suite of filter-feeding organisms which inhabit vertical dwelling burrows, suggestive of the Skolithos ichnofacies. There appears to be a split in the nature and distribution of the ichnofossil suite (Cruziana vs. Skolithos). This dichotomy, coupled with the observation of hummocky cross-stratification in surface outcrop would suggest that the thick sandstone units which contain representatives of the Skolithos ichnofacies can be interpreted as being the result of periodic storm events (Pemberton, 1982). It has been concluded that burrows observed within the Thorold Sandstone from wells in the 004 Pool are not escape burrows which are commonly noted in storm deposits (M.J. Risk, personal communication). The suggestion of storm deposits is certainly viable in that the shoreface environment is subjected to excessive modification by storm processes since effective wave base can be lowered substantially by larger than normal, storm-generated waves (Reinson, in Walker, 1979).

CHAPTER 3

PETROGRAPHY

INTRODUCTION

A total of 9 samples were collected from the seven wells studied with 19 thin sections prepared. A sample from each well was impregnated with stained epoxy before the thin section was cut and polished in order to differentiate true secondary porosity from holes produced by grain removal during thin section preparation. In addition, 4 thin sections were specially polished to be observed with cathodoluminescence.

Petrographic compositions were determined by the microscopic examination of 300 points on each thin section using a mechanical stage point counter.

ANALYSIS

The mineral types observed and their abundances are recorded in Table 3-1. Minerals identified in the Thorold Sandstone include quartz, quartz cement (authigenic overgrowths), rock fragments, feldspar, detrital and authigenic clays, pyrite, chert, calcite, mica (muscovite), heavy minerals (zircon), and siderite. The majority of the porosity in the samples appeared to be primary inter-

TABLE 3-1 POINT COUNT DATA

SAMPLE NUMBER	DEPTH (feet)	QUARTZ	QUARTZ OVERGROWTHS	ROCK FRAGMENTS	FELDSPAR	POROSITY
13035 101-K "A"	1606	59.0	24.0	6.7	-	5.7
13119 100-P	1589	55.0	22.7	9.0	-	6.0
13029 100-O	1589	51.0	21.7	9.3	-	8.0
13118 100-H	1537	50.7	18.0	4.3	-	9.0
13034 100-I	1518	53.3	15.7	8.3	-	7.0
13050 100-J "A"	1517	27.0	15.0	4.0	-	10.0
13050 100-J "B"	1519	47.7	17.7	12.0	-	4.0
13056 100-J	1526	50.0	17.0	8.0	-	8.7

TABLE 3-1 POINT COUNT DATA
(continued)

SAMPLE NUMBER	CLAYS	OPAQUES	CHERT	CALCIUM CARBONATE	MICA	HEAVY MINERALS	TOTAL
13035 101-K "A"	5.0	-	-	-	-	-	100.4
13119 100-P	5.0	1.0	1.3	-	-	-	100.0
13029 100-O	4.0	2.0	1.0	-	2.0	1.0	100.0
13118 100-H	7.0	2.0	2.0	1.0	6.0	-	100.0
13034 100-I	5.0	1.3	1.7	1.0	7.0	-	100.3
13050 100-J "A"	5.0	2.0	4.0	-	32.0	1.0	100.0
13050 100-J "B"	4.0	2.7	3.3	-	8.7	-	100.1
13056 100-J	10.0	1.0	4.3	-	1.0	-	100.0

particle porosity with some secondary porosity produced by the dissolution of feldspar and calcite grains (Plate 3-1).

Quartz, in the form of detrital grains and authigenic overgrowths was the dominant mineral present in the samples. Rock fragments (including chert) were second in abundance to quartz. Detrital feldspars were rare to absent in the Thorold Sandstone. All of the samples plot as sublitharenites after the classification scheme of Folk (1968) (Figure 3-1).

Quartz Grains

The quartz grains within the Thorold Sandstone were monocrystalline with the majority of grains displaying strained extinction. The grains were subangular to subrounded with an average grain size of approximately 0.11 mm (3.25 ϕ) which remained relatively constant in all of the wells. Most grains possessed authigenic quartz overgrowths which were in crystallographic and optical continuity with the detrital grains. The overgrowths could be easily recognized in most cases due to the presence of a thin layer of clay and iron oxides which separated the detrital grain from the overgrowth (Plates 3-2, 3-3). The detrital grains were fairly well rounded while the authigenic overgrowths exhibited euhedral crystal shape where fully developed. Second generation overgrowths were often observed on the rims of primary overgrowths.

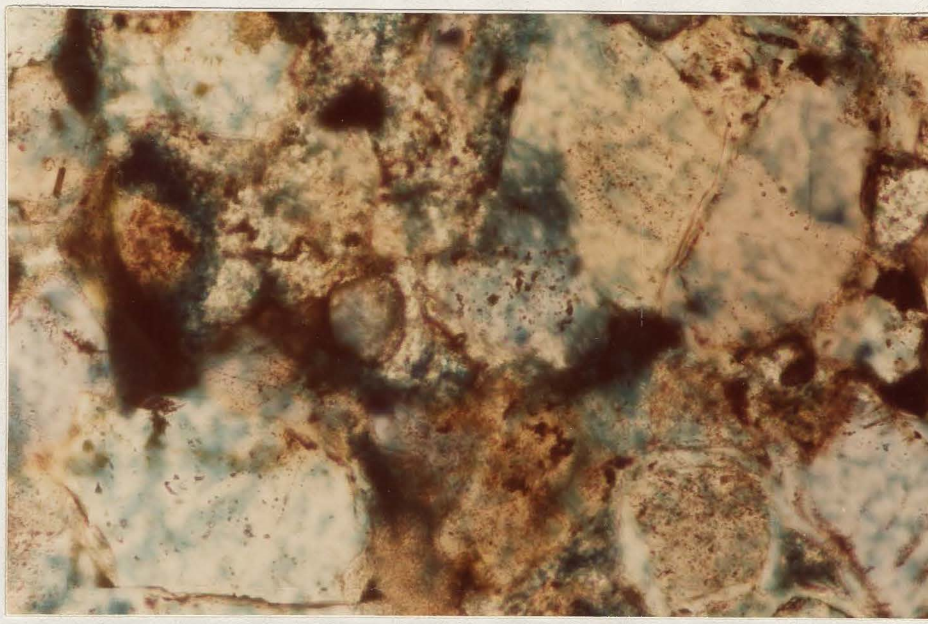
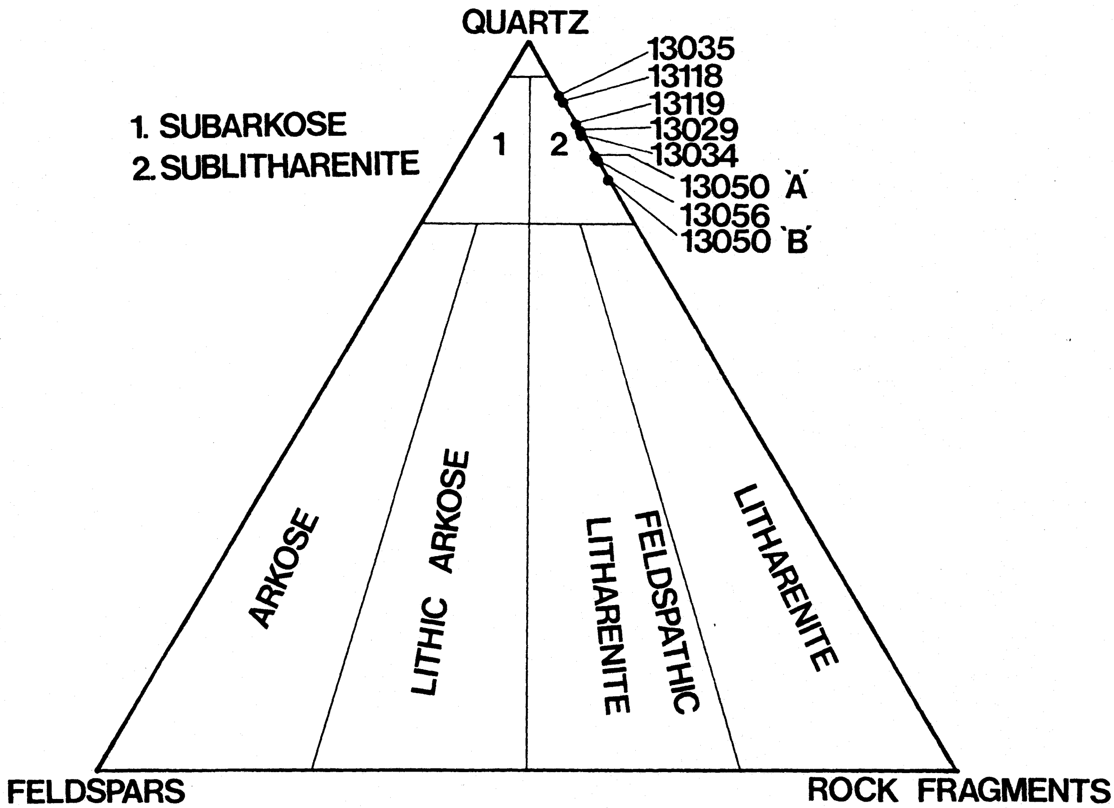


PLATE 3-1 Primary interparticle porosity (dark blue epoxy-filled seams between grains) with some secondary porosity (dark blue patches) due to the dissolution of feldspar and calcite grains. Blue epoxy on grain surfaces does not represent porosity. Sample 13035 101-K "A", 160X magnification. Plane polarized light.

FIGURE 3-1 Sandstone classification diagram (After Folk, 1968).


QUARTZ
1. SUBARKOSE
2. SUBLITHARENITE
1
2
13035
13118
13119
13029
13034
13050 'A'
13056
13050 'B'
ARKOSE
LITHIC ARKOSE
LITHARENITE
FELDSPATHIC
LITHARENITE
LITHARENITE
FELDSPARS
ROCK FRAGMENTS

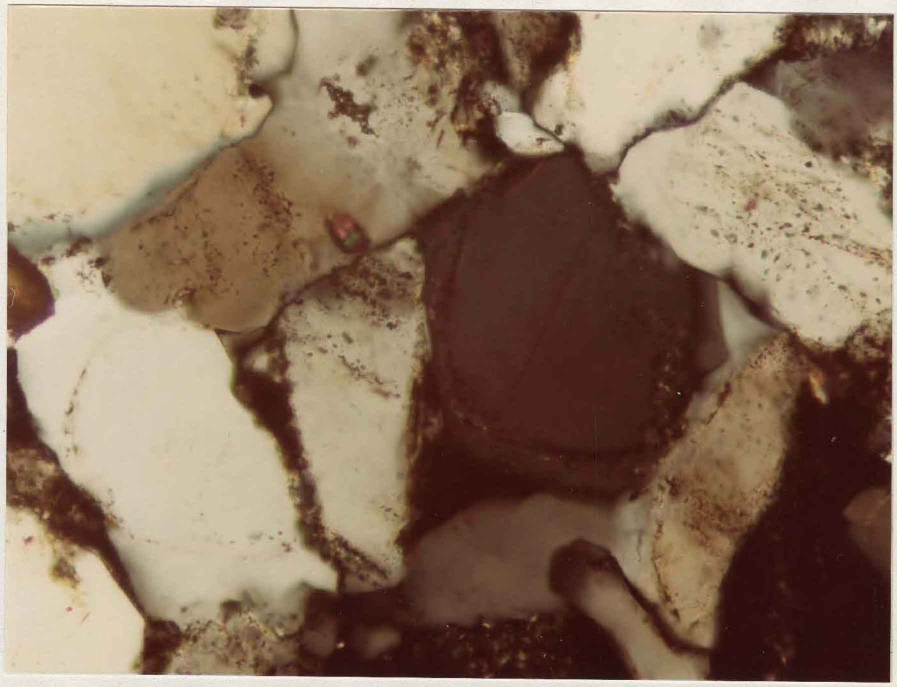


PLATE 3-2 Authigenic quartz overgrowths separated from rounded detrital quartz grains by a clay and iron oxide "dust rim". Note zircon grain near centre of photo. Sample 13035 101-K "A", 250X magnification.

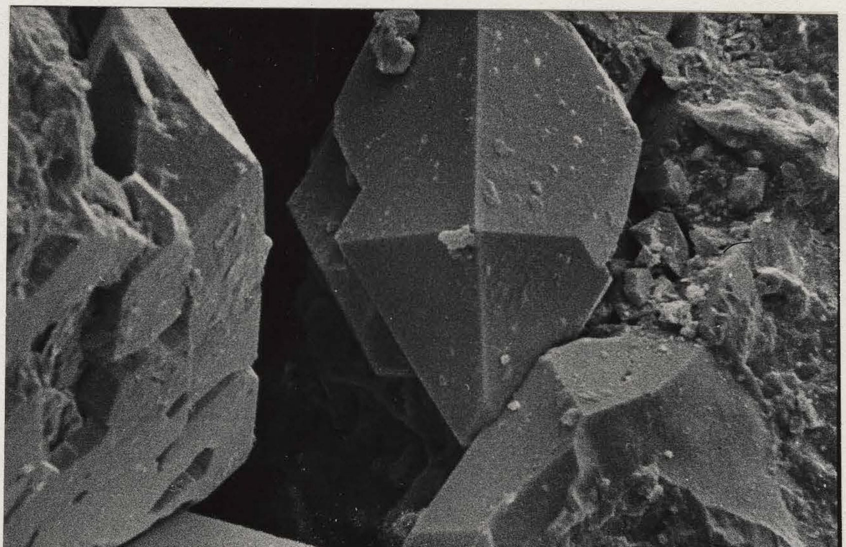


PLATE 3-3 Well crystallized authigenic quartz overgrowths which have grown into pore space from the surface of a detrital quartz grain. Scale bar equals 10 microns.

Rock Fragments

Detrital rock fragments were silty to micaceous to phyllitic in nature with angular clasts of quartz, feldspar, zircon, and pyrite (Plate 3-4). The fragments ranged up to 1.5 mm (-0.6 ϕ) in grain size. These rock fragments are a good indicator of a low grade metamorphic source due to their relative abundance of mica and the fact that they have not undergone extensive break down indicates a source area which is relatively close.

Detrital chert in the Thorold Sandstone is included as a rock fragment in this study. The subrounded grains were comprised of microquartz and megaquartz.

Feldspar

Feldspars were very uncommon in the Thorold Sandstone. The feldspar that is present, however, appears to be microcline with most grains displaying dissolution features leading to the development of secondary porosity (Plate 3-5).

Mica (Muscovite)

Detrital flakes of mica (muscovite) were commonly found in the interparticle space between quartz grains. The flakes were easily deformed around the quartz grains as the sediment became compacted during diagenesis (Plates 3-6, 3-7).

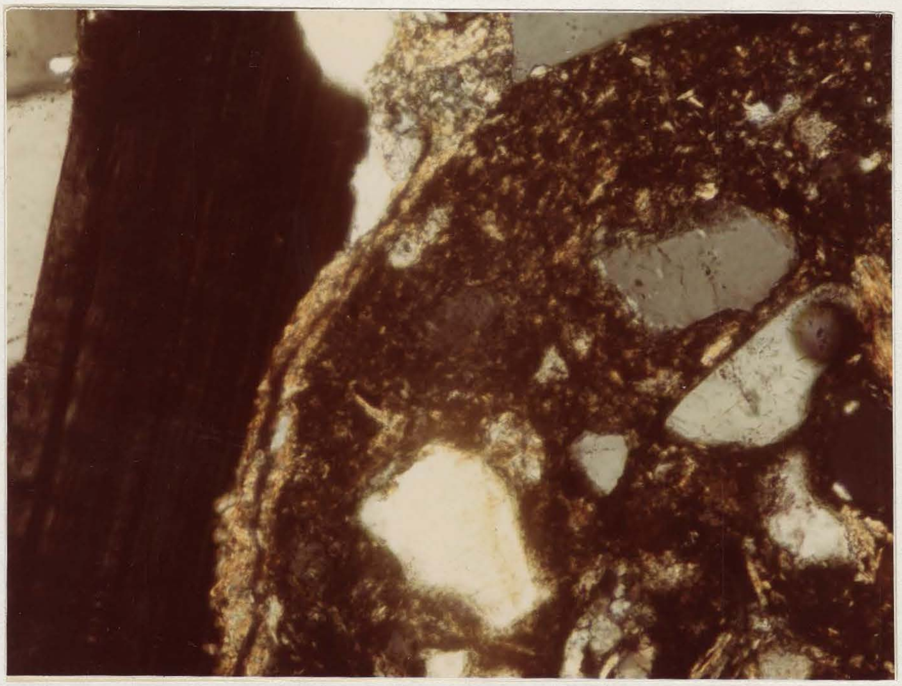


PLATE 3-4 Detrital rock fragment and collophane fragment. Note the micaceous to phyllitic nature of the rock fragment along with angular to subangular quartz grains. Sample 13029 100-0, 160X magnification.

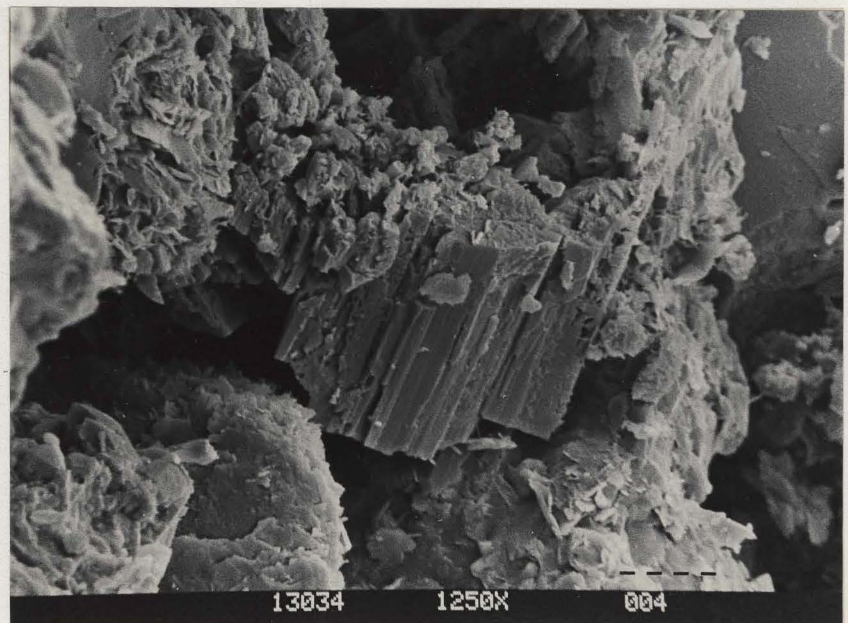


PLATE 3-5 Dissolution of feldspar grain leading to the development of secondary porosity. Dashed line equals 10 microns.

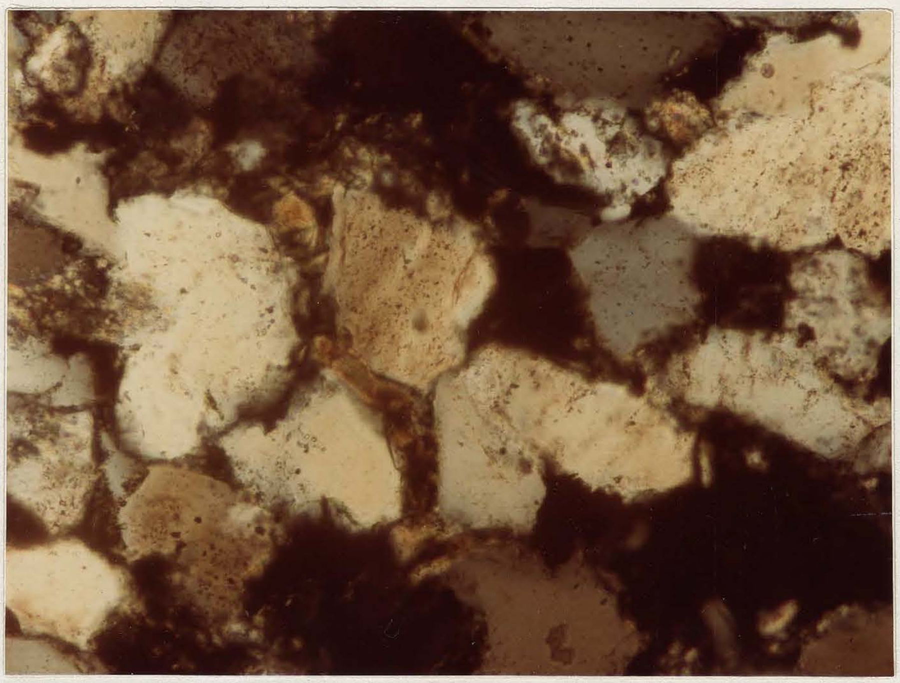


PLATE 3-6 Detrital muscovite flakes bent around quartz grains. Sample 13050 100-J "A", 160X magnification.

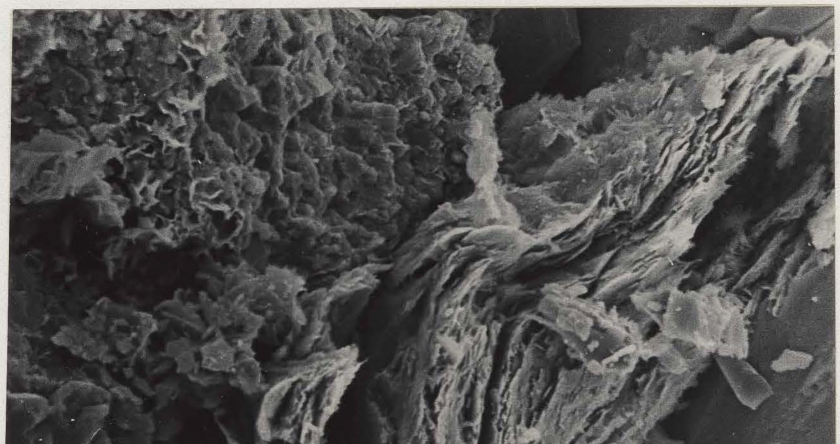


PLATE 3-7 Deformed detrital muscovite flake in pore space. Dashed line equals 10 microns.

Minor Constituents

The heavy mineral zircon was observed as a rounded detrital grain averaging 0.05 mm in grain size. It was observed in all samples as is expected in sedimentary rocks due to its great chemical and physical stability (Plate 3-2).

Calcite occurs as an authigenic cement between quartz grains in patches up to 0.25 mm. The cement, however, was rarely found throughout the Thorold Sandstone. Dissolution of calcite resulted in the production of secondary porosity in a few cases (Plate 3-8).

Collophane is present as elongate fragments up to 2 mm in length. Collophane is a massive cryptocrystalline variety of apatite that constitutes the bulk of phosphate rock and fossil bone. In this case it has been formed by phosphatic enrichment from the phosphatic-shelled inarticulate brachiopod Lingula (Plate 3-4).

Pyrite is present within the Thorold Sandstone as subhedral to anhedral grains and in rock fragments. The average grain size is 0.075 mm.

There is very little to no fine grained matrix present in the samples observed. When matrix is noted, however, siderite appears to be the major constituent. When coupled with the presence of pyrite, all of the iron in the Thorold occurs in the ferrous or reduced state suggesting

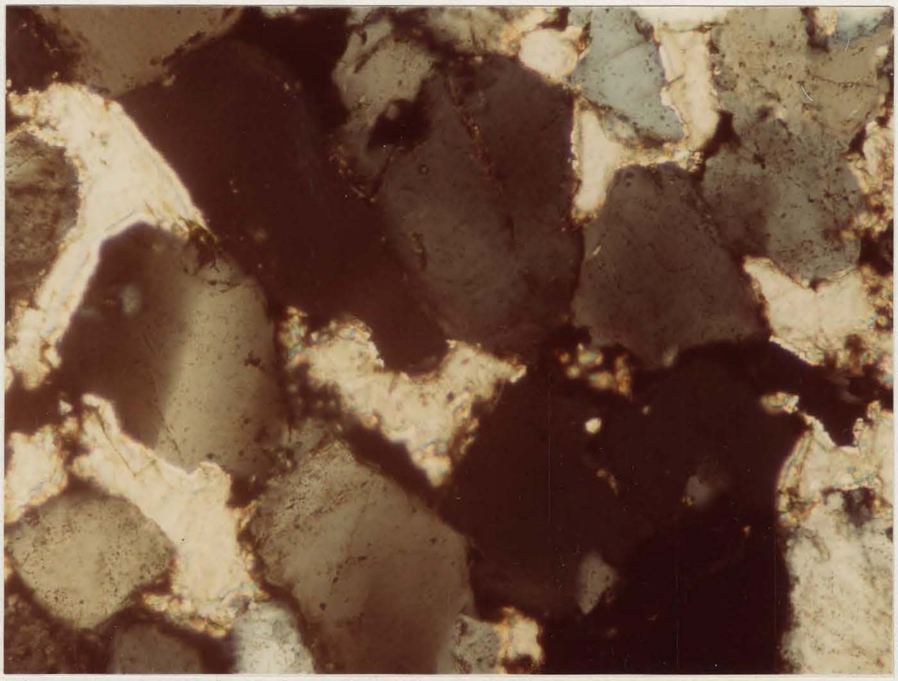


PLATE 3-8 Dissolution of calcite patches resulting in the formation of secondary porosity. Sample 13034 100-I, 160X magnification.

a reducing environment. These observations are in agreement with those of Martini (1966).

A number of samples were observed to have pore filling and pore lining hydrocarbon. It was very difficult to distinguish this residue from the clay mineral illite so sample 13034 100-I was soaked in an organic solvent, xylene, for 72 hours and it was found to dissolve the majority of this brown isotropic residue away (Plates 3-9, 3-10). It can therefore be concluded that the majority of the residue was hydrocarbon.

MINERALOGIC MATURITY

The Thorold Sandstone can be considered as mineralogically mature due to its monocrystalline quartz-rich nature (Table 3-1), the relative absence of unstable detrital grains such as micas and rock fragments, and the fact that zircon is frequently observed (Blatt et al., 1980).

TEXTURAL MATURITY

Following the textural maturity flow chart of Pettijohn (1972), detrital clays within the Thorold Sandstone account for less than 5% of the total mineral abundance. Quartz grains which are subangular to subrounded, (~ 3.00 ϕ) in nature are well sorted on average. Therefore, the Thorold Sandstone is texturally mature.

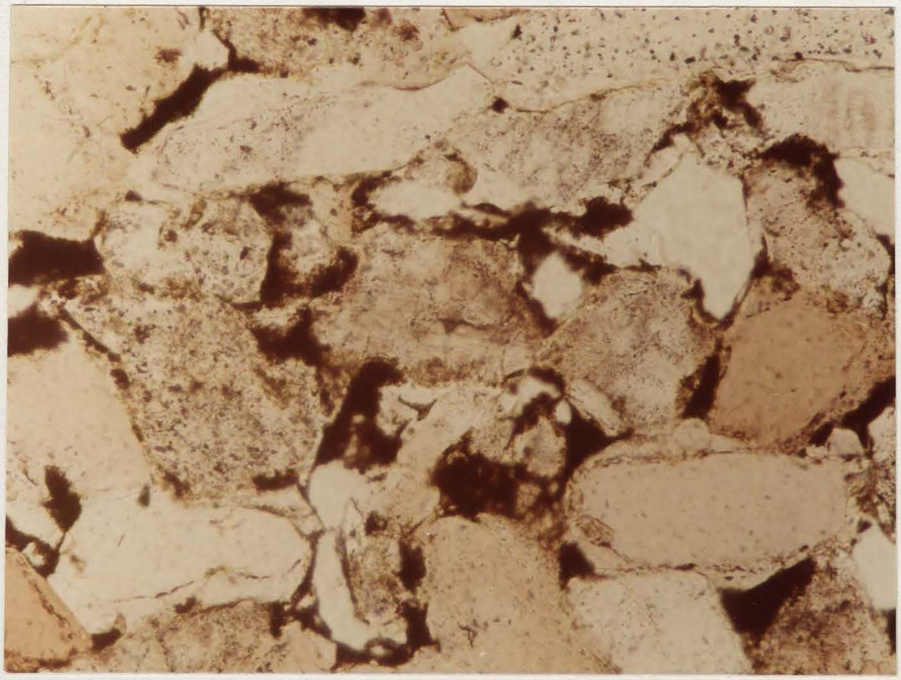


PLATE 3-9 Mixture of pore lining and pore filling illite and hydrocarbon residue. Sample 13034 100-I, 160X magnification. Plane polarized light.

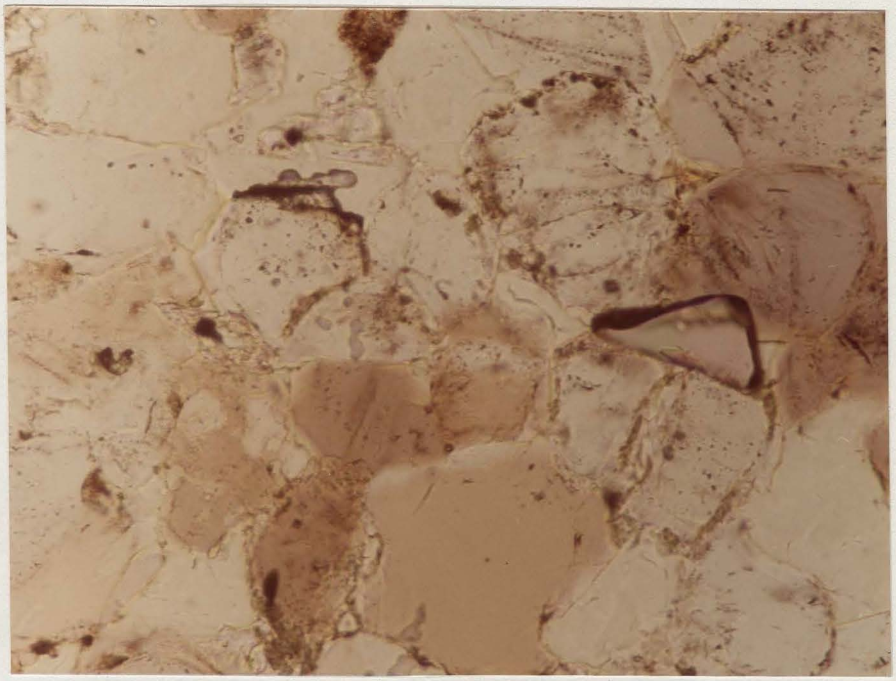


PLATE 3-10 Same area of sample 13034 100-I after sample was soaked in xylene for 72 hours. Note that the hydrocarbon residue has been dissolved away leaving minor illite between grains. Sample 13034 100-I, 160X magnification. Plane polarized light.

COMPARISON WITH MARTINI'S SURFACE THIN SECTIONS

Martini (1966) recognized three main lithologies in the Thorold from microscopic examination of thin sections from surface outcrop:

i) Orthoquartzite

ii) Calcareous Orthoquartzite

iii) Quartzose Dolomite

After examination of a selection of Martini's thin sections from each of the lithologies it appears that samples examined from the subsurface in the present study most closely resemble the "Orthoquartzitic lithology."

Modal analysis is very similar with quartzitic texture, grain size, sorting, grain sphericity and overall textural maturity displaying little variation between the surface and subsurface sections.

However, the subsurface thin sections of the present study show greater development of quartz cement in the form of authigenic quartz overgrowths which result in a substantial decrease in porosity.

The "Calcareous Orthoquartzite" and "Quartzose Dolomite" lithologies described by Martini were not observed in the Thorold sections in this study.

PORE SPACE REDUCTION

Grain Contact Study

The packing and type of contact between grains strongly affects both porosity and permeability. The four types of grain contacts, as they appear in the plane of a random thin section are classified as tangential, long, concavo-convex, and sutured (Taylor, 1950). These contacts have repeatedly been used (with the exception of tangential) as criteria of pressure solution throughout the literature (Sippel, 1968).

Grains were studied in a method after Füchtbauer (1974). One hundred grains were counted from the thin sections of four wells using a mechanical stage. All of the contacts per grain in a given field of view were recorded until one hundred grains had been counted. The formula,

$$\frac{1a + 2b + 3c + 4d}{a + b + c + d}$$

then renders a measure of contact strength where a = tangential, b = long, c = concavo-convex and d= sutured grain contacts.

From the study of contacts in samples from wells 13029 100-O, 13035 101-K, 13118 100-H and 13034 100-I the mean contact strength was 3.45 and the mean number of contacts per grain was 4.68. The latter figure represents a value much larger than would be expected from normal packing alone (Gaither, 1953). Taylor (1950) suggests that tangential contacts are the result of original packing, long contacts are the result of original packing, pressure, or precipitated cement, and concavo-convex and sutured contacts are generally the result of pressure.

Only contacts between detrital grains were attempted to be recorded in this study. Sutured and concavo-convex contacts accounted for approximately 80% of all grain contacts. However, although these contacts give every appearance of interpenetration and pressure solution, detrital grains are not involved in the majority of contacts, rather, authigenic overgrowths have grown together in concavo-convex and sutured patterns (Plate 3-11). This observation was confirmed by a cathodoluminescence study. Therefore, pressure solution is not the major source of silica cement in the Thorold Sandstone so it stands to reason that there must be alternate sources. Füchtbauer (1978) suggests two other possible sources, i) diffusion of silica from the surrounding shales or ii) to a lower degree from dissolution of quartz on stylolites within sandstones.

Diagenetic conversion of smectite or interlayered smectite-illite to pure illite resulting in a major source of silica (Towe, 1962) is certainly not applicable within the Thorold Sandstone due to low diagenetic temperatures and

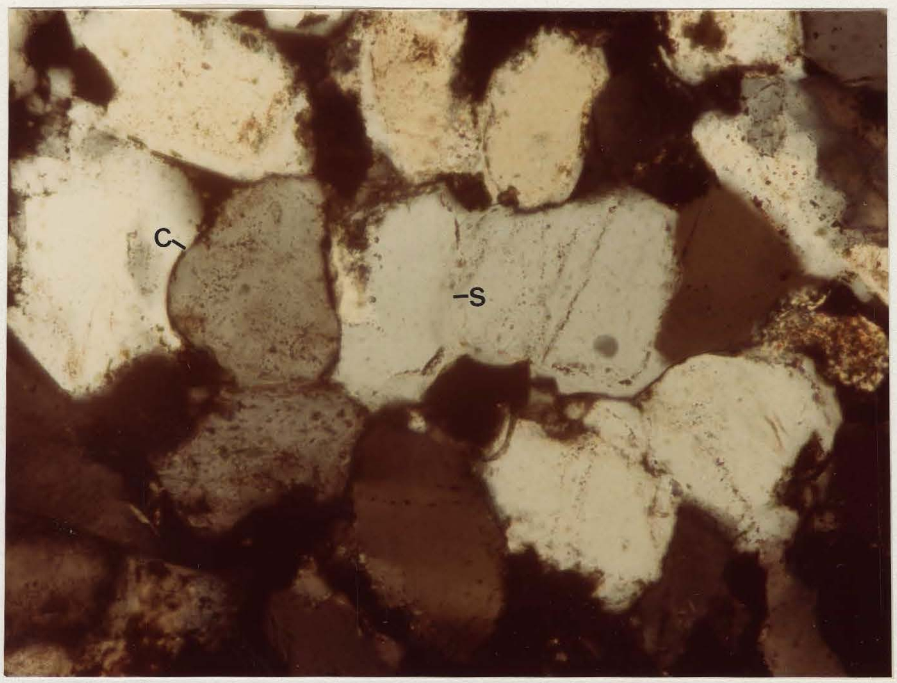


PLATE 3-11 Sutured (s) and concavo-convex (c) contacts between quartz overgrowths. Sample 13034 100-I, 160X magnification.

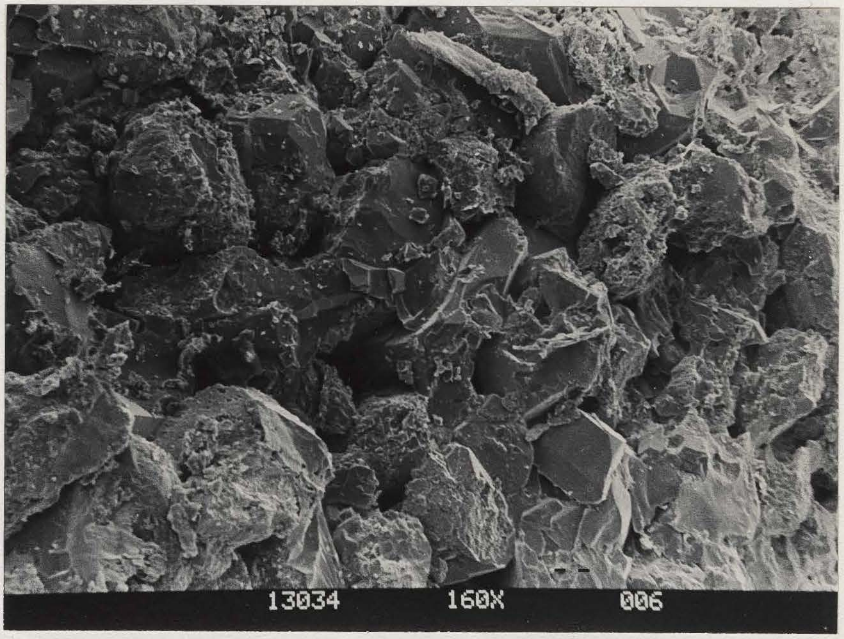


PLATE 3-12 Authigenic quartz overgrowths reducing porosity. Dashed line equals 10 microns.

shallow depth of burial.

Minus Cement Porosity

Minus cement porosity is the porosity that would occur if the cements were dissolved, thus indicating the porosity of the sand prior to cementation (Rosenfeld in Füchtbauer, 1974). Four samples (13035 101-K "A", 13029 100-O, 13034 100-I, and 13118 100-H) were studied for minus cement porosity by the microscopic examination of 270 points on each thin section. Criteria examined included "grains", "porosity","cement", and "matrix". Minus cement porosity values from the samples ranged from 23.67 Vol-% to 37.34 Vol-% with a mean value of 28.84 Vol-% (Plate 3-12).

LUMINESCENCE PETROGRAPHY

A substance that is bombarded by electrons can emit energy in a variety of forms including charged particles and radiation. The emitted energy in the form of visible radiation is considered in the process called cathodoluminescence (Mariano et al., 1975). The emission from individual minerals can be readily observed and related to the texture and chemical composition (Smith et al., 1965).

The luminescence study strengthened the conclusion that the majority of contacts within the Thorold Sandstone resulted from authigenic quartz contacts rather than detrital grain contacts. The true roundness of the detrital quartz grains was also observed in the luminescence study. The detrital cores, which originally came from an igneous or metamorphic rock that formed at elevated temperatures displayed a dull blue luminescence while the authigenic overgrowths, which formed at much lower temperatures and also had different trace element compositions did not luminesce and therefore contrasted sharply with the detrital grains. A number of quartz grains displayed a bright blue luminescence which could be due to the fact that they were from a different, higher temperature source, or, perhaps had a different trace element compostion (Dr. G.V. Middleton, personal communication).

CHAPTER 4

CLAY MINERALOGY

INTRODUCTION

Although the major reduction of porosity and permeability within the Thorold Sandstone is due to silica cementation, clay minerals also play a major role in porosity reduction. The study of clay mineralogy is also critical in determining a paragenetic sequence within the Thorold. X-ray diffraction techniques were employed to identify clay minerals and determine their compositions while observations concerning clay morphology and textures were best made through the use of a scanning electron microscope.

SCANNING ELECTRON MICROSCOPE

The identification and differentiation of clay minerals solely by the use of the petrographic microscope was extremely difficult and inaccurate. The scanning electron microscope, however, provides an excellent method of determining clay minerals and distinguishing between those which are allogenic and authigenic in nature.

Sample Preparation

Six Thorold sandstone samples were studied with the scanning electron microscope. The samples were attached to aluminum stubs with silver conducting paint and then sputter coated with a 240 angstrom thick layer of gold using a Polaron E 5100 sputter coater. Fresh fractured surfaces of the sample were examined with a Philips 501B scanning electron microscope.

DETRITAL CLAY MINERALS

Allogenic clays usually originate as terrigenous material such as dispersed matrix, sand sized floccules, and sand to cobble-sized mud or shale clasts or are introduced following deposition as a result of bioturbation or infiltration (Wilson and Pittman, 1977).

Detrital Illite

Detrital illite was difficult to recognize in thin section due to its extremely fine grain size but it appears that this dark brown clay mineral was mixed with hydrocarbon residue in the pore space between detrital quartz grains (Plate 3-9) Wilson *et al*. (1977).

AUTHIGENIC CLAY MINERALS

Authigenic Illite

Authigenic illite was recognized in thin section as a pore lining material covering quartz overgrowths. The illite is highly birefringent and is easily recognized under crossed polarizers. Authigenic illite observed with the scanning electron microscope has long lath-like projections which extend from quartz overgrowths out into pore space. The delicate projections are often curled and range up to 10 microns in length (Plates 4-1, 4-2, 4-3, 4-4).

Wilson _et al_. (1977) have described the lath-like projections of illite as the most delicate growth habit of all the authigenic clay minerals. The presence of wispy illites in sandstone pores significantly increases microporosity and pore tortuosity and decreases the permeability. The illite laths are fragile and flexible and can be easily broken into fine laths causing a migration of fines problem with consequent blocking of the pore throats (Guven _et al_., 1980).

Authigenic Chlorite

Chlorite was not recognized in thin section due to its fine grain size, low relief, and low birefringence. The most common form of chlorite, plate structures, (Wilson _et al_., 1977) is the form recognized in the Thorold Sandstone when using the scanning electron microscope. The plates are individual idiomorphic crystals which attach on their edge to the surface of quartz overgrowths (Plates 4-5, 4-6, 4-7, 4-8). The crystals are generally arranged with a face-to-edge orientation (two-dimensional "cardhouse" arrangement of Wilson _et al_. (1977)). The

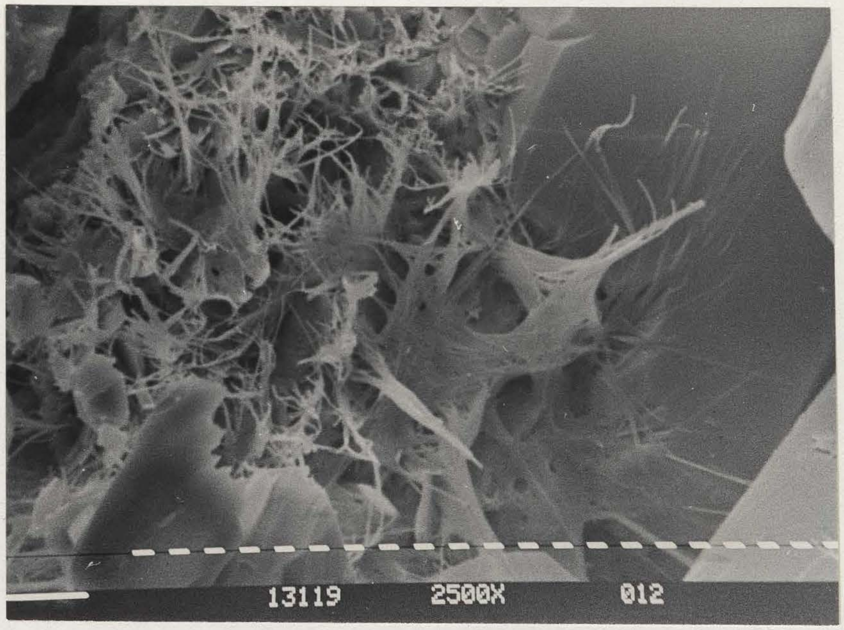


PLATE 4-1 Pore lining wispy authigenic illite laths growing from the surface of quartz overgrowths. Scale bar equals 1 micron

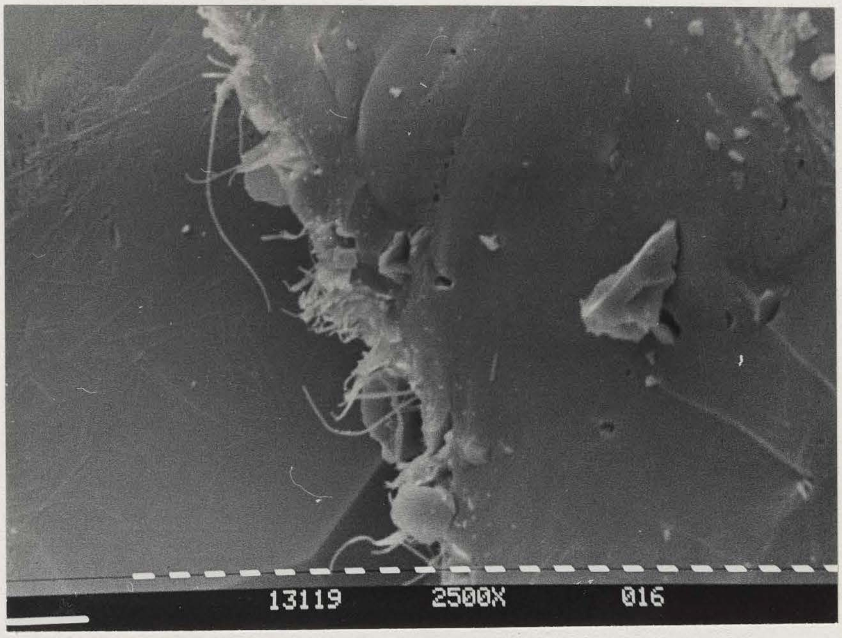


PLATE 4-2 Wispy authigenic illite extending into pore space from the edge of a quartz overgrowth. Scale bar equals 1 micron.

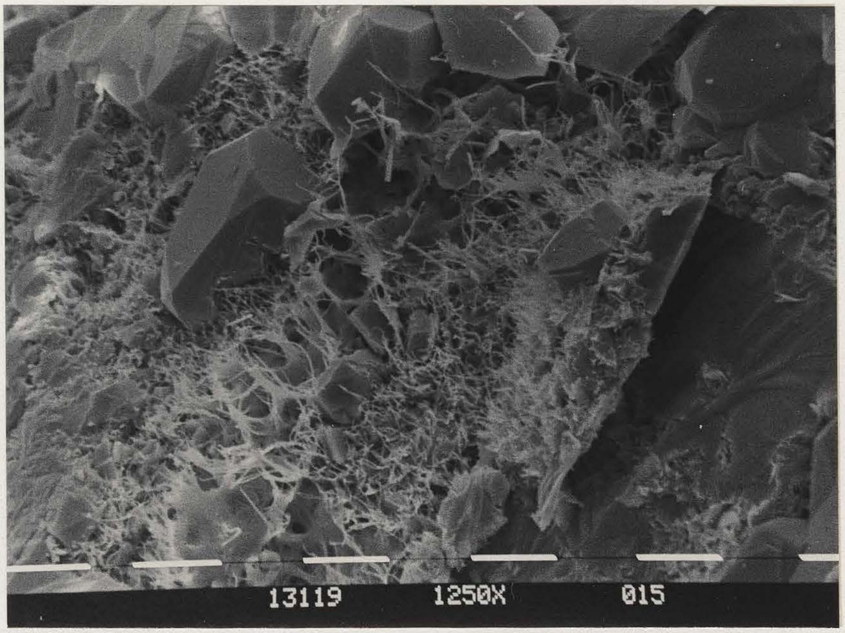


PLATE 4-3 Wisps of authigenic illite growing from the surface of quartz overgrowths. Scale bar equals 10 microns.

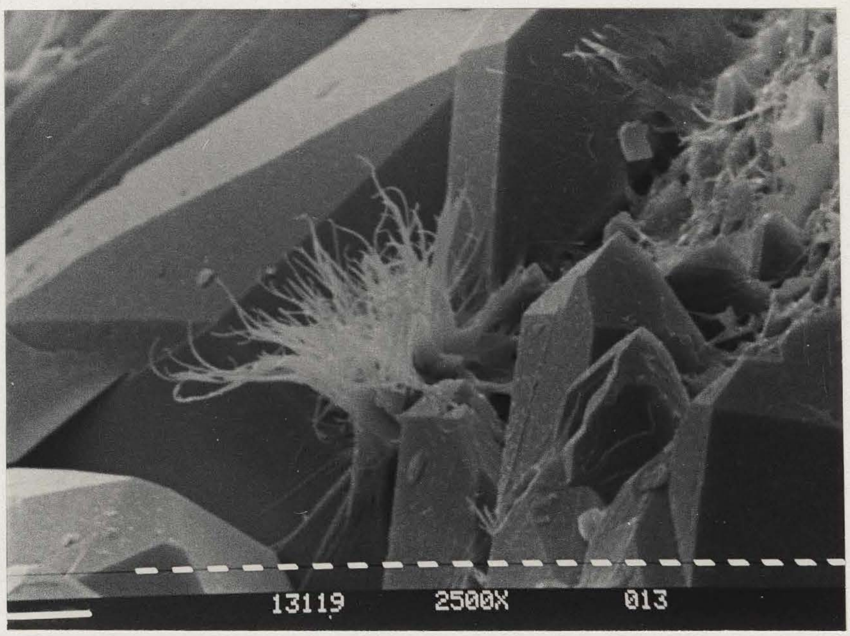


PLATE 4-4 Wispy authigenic illite laths growing from an illitic core on the surface of quartz overgrowths. Scale bar equals 1 micron.

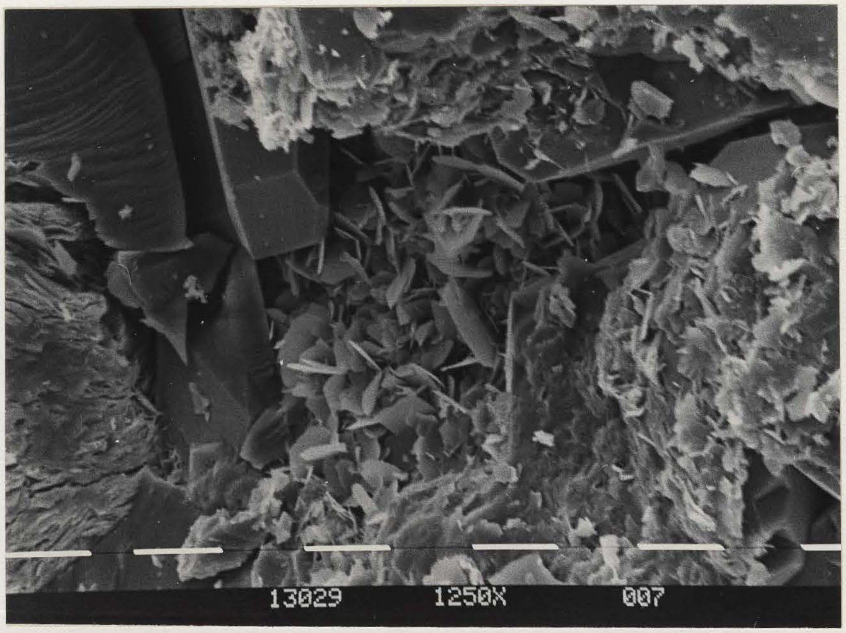


PLATE 4-5 Individual idiomorphic chlorite crystals attached on edge to the surface of quartz overgrowths. Scale bar equals 10 microns.

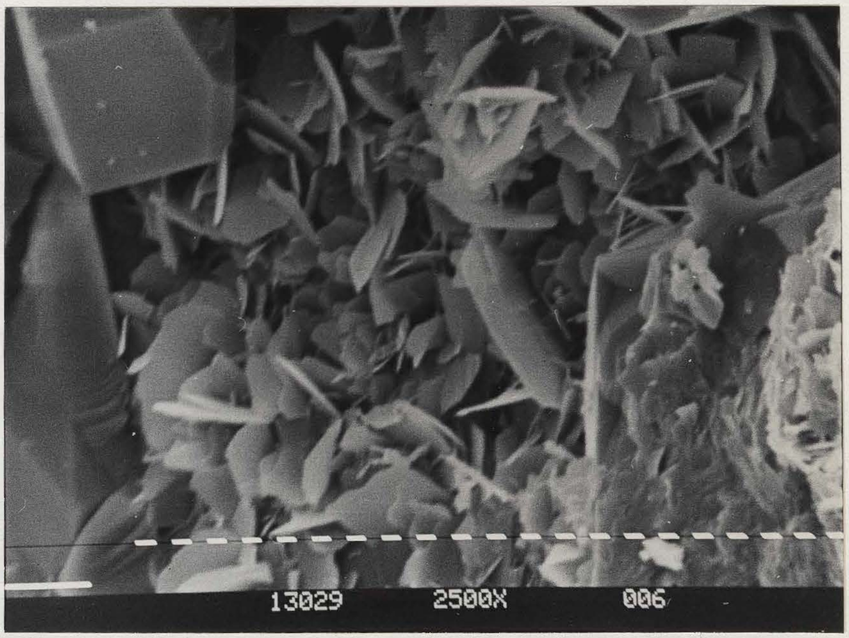


PLATE 4-6 Enlargement of Plate 4-5 showing the face-to-edge two dimensional "cardhouse" arrangement of chlorite plates. Scale bar equals 1 micron.

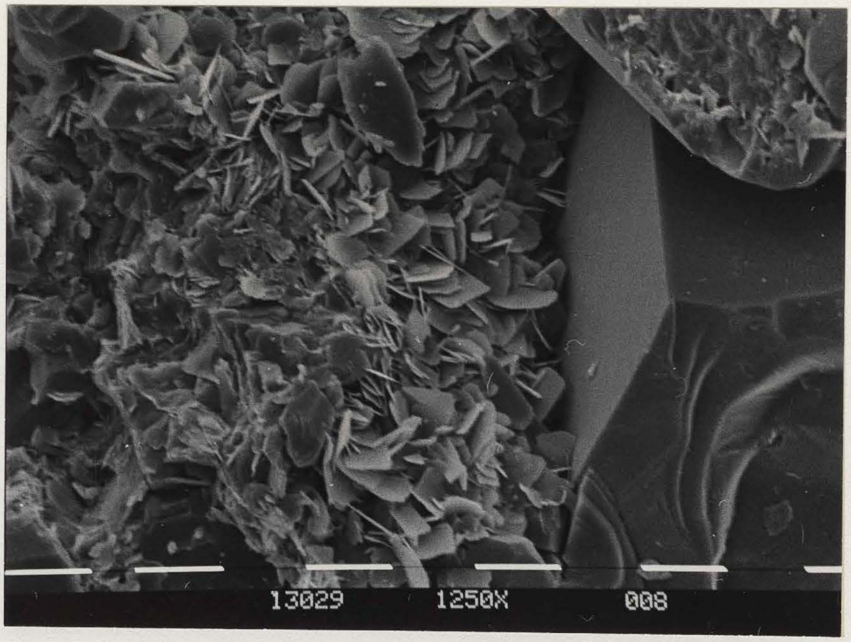


PLATE 4-7 Chlorite plates growing from the surface of quartz overgrowths. Scale bar equals 10 microns.

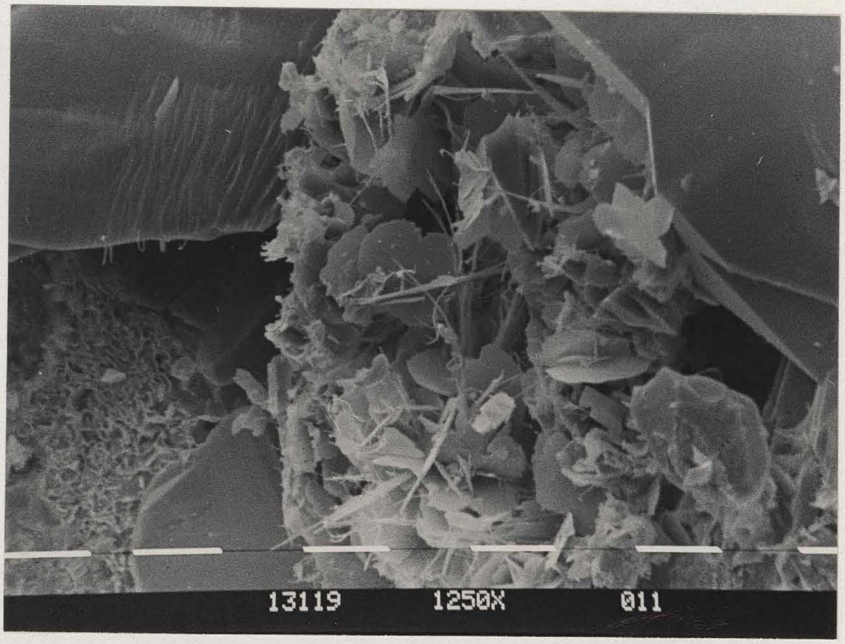


PLATE 4-8 Pore bridging chlorite plates growing from authigenic quartz overgrowths. Wispy authigenic illite laths appear to be growing from the surface of chlorite plates. Scale bar equals 10 microns.

chlorite is observed as both a pore lining and pore bridging material.

Chlorite is the most variable in form among the authigenic clays occuring as plates attached to detrital sand grains, rosettes, honeycombs, or cabbagehead-like growths (Wilson et al., 1977).

X-RAY DIFFRACTION

Sample Preparation

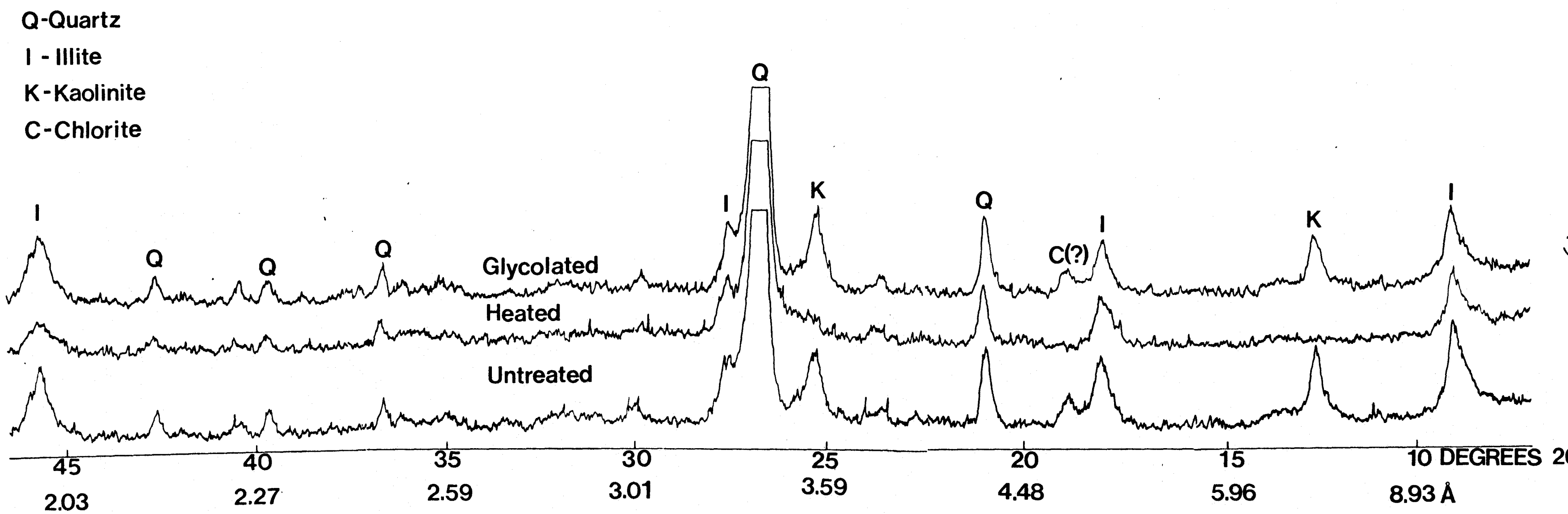
Clay mounts were prepared from core samples of 4 wells in the study area. Samples were treated in a manner described by Potocki (1981). Ultrasonification is a more effective method of segregating clays from clastic grains than blending but an ultrasonic probe was not available at the time the study was carried out. Authigenic and detrital clay minerals could not be separated on X-ray diffraction patterns since this technique could not avoid the mixing of the two clay types.

Illite

Illite is characterized by sharp diffraction peaks at approximately 9.9 Å (8.95° 2 θ), 4.98 Å (17.92° 2 θ), 3.24 Å (27.66° 2 θ) and 1.99 Å (45.72° 2 θ) (Figure 4-1). These peaks represent the 001, 002, 003, and 005 reflections of illite respectively. The sharp illite diffraction peaks would indicate the presence of

FIGURE 4-1 X-ray Diffraction Peaks.

Sample 13034 100-I.


Q-Quartz
I - Illite
K-Kaolinite
C-Chlorite
Q
I
K
Q
C(?)
I
K
I
I
Q
Q
Q
Glycolated
Heated
Untreated
45
40
35
30
25
20
15
10 DEGREES 2θ
2.03
2.27
2.59
3.01
3.59
4.48
5.96
8.93 Å

well crystallized illite (Plates 4-1, 4-2, 4-3, 4-4). The sharpness of the peaks and recognition of well crystallized illite using the scanning electron microscope would support the conclusion that the diffraction peaks are produced by illite rather than ground-up detrital mica.

There appeared to be a very slight shift in the 9.96 Å and 3.24 Å illite profiles upon glycol saturation which would suggest that illite/smectite mixed layering may be associated with illite in the Thorold Sandstone. The shift was extremely difficult to detect however. Slight decreases in peak intensity were noted after heating to 550°C. Brown (1961) states that the decrease in intensity may be due to a slight anhydrous modification of the illite structure.

Kaolinite

Kaolinite, which was not identified by either thin section or scanning electron microscope analysis was easily identified in X-ray diffraction patterns. Relatively sharp diffraction peaks were observed at 7.08 Å (12.61° 2θ) and 3.54 Å (25.32° 2θ)(Figure 4-1). The diffraction peaks, identified as the 001 and 002 reflections of kaolinite were observed to collapse to an amorphous meta-kaoline structure following heating for 3 hours at 550°C.

It was concluded that kaolinite was detrital in nature, mainly due to the fact that the characteristic "stacked booklet" morphology of authigenic kaolinite was not observed during thorough scanning electron microscope investigation.

Chlorite

Authigenic chlorite reflections were not observed from X-ray diffraction traces, however, its presence was definitely identified by the scanning electron microscope (Plates 4-5, 4-6, 4-7, 4-8).

It is possible that the 7.08 Å and 3.54 Å reflections of kaolinite mask the chlorite reflections at these d-spacings (002 and 004 orders) since even order chlorite reflections also disappear upon heating to 550°C.

A diffraction peak at 4.75 Å (18.81° 2θ) was tentatively identified as the 003 chlorite reflection. However, upon heating to 550°C for 3 hours, the peak disappeared which is not characteristic of this odd order chlorite reflection.

Unless chlorite is the dominant mineral in a clay suite, the diagnostic hol X-ray reflections may be masked by reflections from other minerals (Hayes, 1980). This certainly appears to be the case in the Thorold Sandstone where illite is the dominant clay mineral.

CLAY ABUNDANCE

Based on examination of clay mineralogy through the use of the petrographic microscope, the scanning electron microscope, and X-ray diffraction analysis along with Petro-Canada's computer integration program to calculate areas under X-ray diffraction peaks it appears that illite (detrital and authigenic) is the dominant clay mineral within the Thorold Sandstone in the 004 Pool followed by detrital kaolinite and minor authigenic chlorite. The approximate ratio of illite to kaolinite is 2 to 1.

ORIGIN OF DETRITAL CLAYS

The Thorold Sandstone is a product of the reworked clastic sediments of the Bald Eagle and Juniata Formations which were shed westward from the rising Taconic Mountains (Grabau, 1908). With a maximum depth of burial of approximately 1000 m (Chapter 5), a depth at which clay minerals are unlikely to be transformed a great deal, it is reasonable to assume that the detrital clay minerals within the Thorold Sandstone represent the clay minerals which were present at the time of deposition.

Detrital Illite

The relatively sharp and narrow illite peaks observed in X-ray diffraction analysis are indicative of well crystallized illites which have not been exposed to prolonged periods of surficial weathering (Potter *et al*., 1975). The fact that the illite has not been appreciably modified by weathering supports source rocks as the ultimate source for detrital illite in the Thorold Sandstone. Deformed laths of detrital muscovite have also been directly derived from the Taconic mountains source area. Illite is a general term for the clay mineral constituents of argillaceous sediments belonging to the mica group and their derivatives (Potter *et al*., 1975).

Detrital Kaolinite

Although kaolinite was solely recognized through X-ray diffraction analysis, it seems plausible that detrital kaolinite would be present in the Thorold Sandstone since it was deposited in nearshore conditions close to terrigenous sources. Kaolinite is generally confined to equatorial sediments and it may be considered the low latitude clay mineral (Griffin *et al*., 1968).

During Silurian times, the area of study was approximately 14° south of the equator which extended in what is now an east-west direction across Labrador, Quebec, Hudson Bay, and west across the prairies to the northwest corner of the United States. The widespread occurence of dolomite, limestone, coral reefs, evaporites, and red beds across the northern continents during the Silurian certainly indicates a very warm and rather arid climate (Habicht, 1979).

Kaolinite is not a primary rock forming mineral as mica and chlorite are, but rather, a secondary mineral resulting from soil-forming processes. The distribution and amounts of this mineral reflect the intensity of the soil-forming processes active in the source areas (Griffin *et al*., 1968).

CHAPTER 5

DIAGENESIS

INTRODUCTION

When considering the diagenetic history of a sandstone one must examine a number of important factors including:

i) diagenetic temperatures

ii) maximum depth of burial

iii) chemistry of circulating pore fluids

iv) source rocks

v) time

(Blatt *et al.*, 1980)

Choquette and Pray (1970) have classified these regimes of diagenesis, namely eodiagenesis, mesodiagenesis, and telodiagenesis. The eogenetic stage is the period between final deposition and burial of the newly deposited sediment below the depth of significant influence from surface processes while the mesogenetic stage is the time interval in which the sediments are buried at depth below the major influence of processes directly operating from or closely related to the surface. The telogenetic stage is the period in which long-buried carbonate rocks are influenced a great deal by processes associated with the formation of an unconformity. The stage does not really apply to the Thorold Sandstone within the study area and will not be considered further.

DIAGENETIC TEMPERATURES

To determine geothermal gradients for the upper portion of the earth's crust one must rely upon measurements made in boreholes drilled in search of petroleum and natural gas (Blatt *et al.*, 1980, p. 333). These temperature determinations are subject to large errors, however, depending upon surface temperatures and the time after cessation of drilling when the readings are taken.

The average bottom hole temperatures calculated from a number of wells immediately west of the 004 Pool was approximately 25.5°C (78°F) at an average depth of 630.77 m (2069 feet). However, temperatures taken immediately after cessation of drilling tend to be 10-20°C lower than those measured a significant time after active mud circulation has stopped since equilibration has not been reestablished by the formation pore waters (Blatt *et al.*, 1980, p. 333). Therefore, if a true bottom hole temperature of 35.5 to 45.5°C is considered with a surface temperature at 0 m of 7.5°C an average geothermal gradient of 4.4 to 6.0°C/100 m is obtained. A comprehensive series of measurements in several boreholes in southern Ontario was performed by Judge and Beck (1973) to investigate problematical areas in the measurement and interpretation of terrestrial heat flow.

A temperature gradient of 2.58°C/100m was calculated from a borehole in Elgin Co., just north of the 004 Pool, a gradient much less than that calculated by the present author from bottom hole temperatures in boreholes just west of the 004 Pool (Figure 5-1). Temperatures obtained from industrial logs are often in large error and the results of Judge and Beck (1973) are probably more reliable since their temperature measurements were accurate to 0.01°C or better.

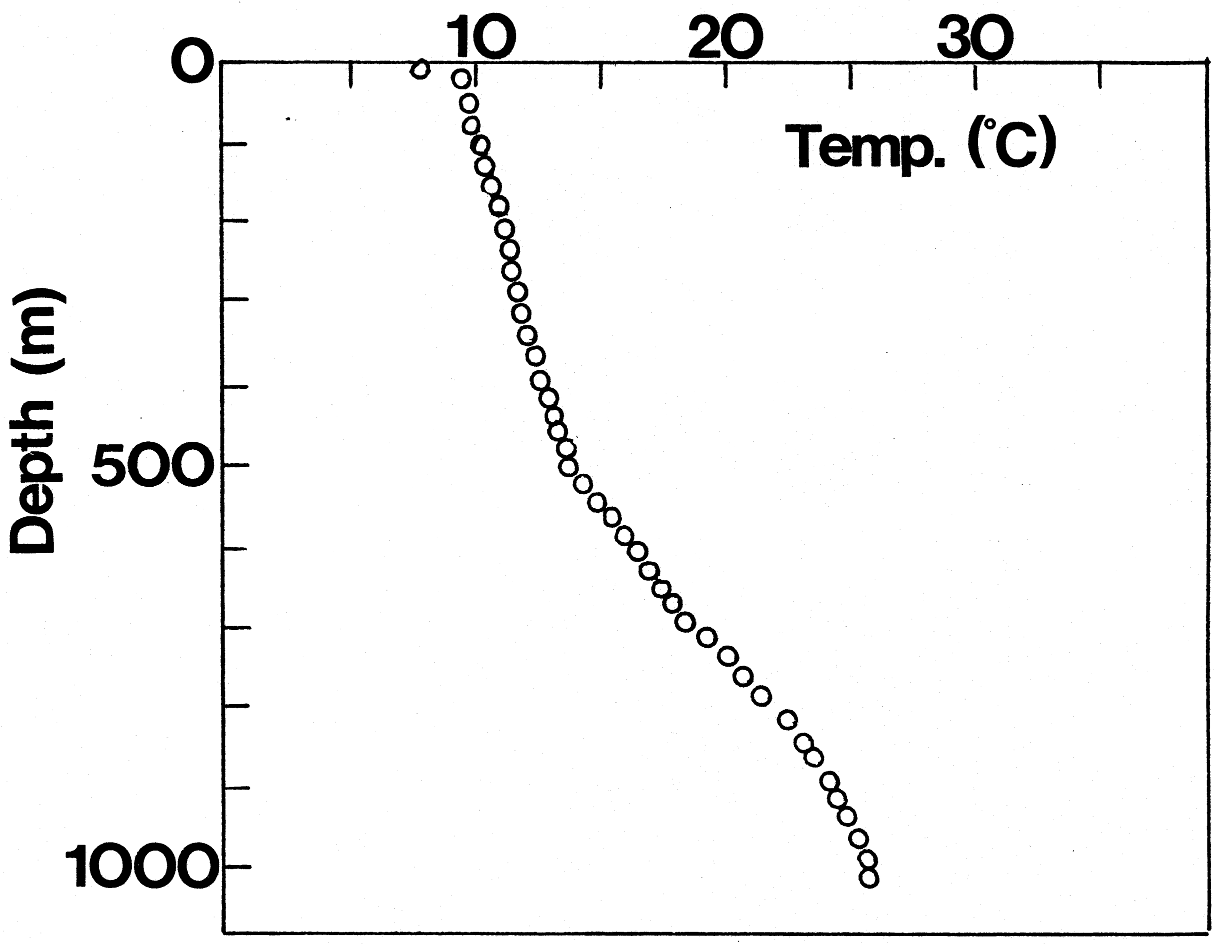
DETERMINATION OF MAXIMUM BURIAL DEPTH

The average depth of the Thorold Sandstone in the study area is approximately 473 m (1552 feet). This would be the maximum depth of burial for the Thorold assuming that there has been no erosion since its deposition. However, this is a poor assumption since there is evidence of at least Mississippian deposition in close proximity to the study area. There is certainly no evidence of any post-Permian deposition however.

Three different methods were used to estimate the maximum depth of burial:

(1) Isopach maps constructed by Colton (in Fisher *et al.*, 1970) give approximate thickness of sections from

FIGURE 5-1 Temperature-depth plot for Dunwich No. 7 well in Elgin County. (After Judge and Beck, 1973).



0
10
20
30
Temp. (°C)
Depth (m)
500
1000

the following periods within the area of study (Table 5-1):

Table 5-1 THICKNESS OF SECTIONS

	m	feet
Pennsylvanian	0	0
Mississippian	83.8	275
Devonian	457.2	1500
post-Thorold Silurian (from wells in 004 Pool)	245.6	806
Total	786.6	2581

(2.) A second method of determining the maximum depth of burial has been proposed by Magara (1978, Chap. 2) who has stated that the level of shale compaction is significantly controlled by depth of burial. One should readily notice shifts in shale compaction trends if there has been a great deal of erosion in the area. Values of increased shale compaction (decreased shale porosity) can be obtained by recording interval transit times from sonic logs. Interval transit times decrease with depth. Magara (1978, p. 20) has calculated a transit time of 200 microseconds per foot at 0m so if no erosion had taken place in the vicinity of the 004 Pool a plot of shale transit time versus depth would display a shale compaction trend which when extrapolated to the present surface would give a transit time of 200 microseconds per foot.

Figure 5-2 is a plot of shale transit time versus depth and indicates that approximately 1740 feet (530.3 m) of erosion has occured. Now, if it is assumed that the erosional surface is located at the present surface, the average maximum depth of burial of the Thorold Sandstone can be calculated by adding the present maximum depth of burial (473 m, 1552 feet) and the estimated erosion thickness producing an average maximum burial depth of 1003.3 m (3292 feet).

(3.) Maximum depth of burial can also be estimated from plots of porosity of sandstones versus maximum depth of burial (Füchtbauer, 1974, p. 132)(Figure 5-3). If one considers the composition of the Thorold Sandstone in the 004 Pool to be intermediate between the micaceous silty sandstones and quartz sandstones of Füchtbauer (1974, p. 132), a maximum depth of burial of approximately 1160 m (3806 feet) is estimated for the Thorold sands which have an average grain size of 0.11 mm and mean porosity of 15.03%.

In summary, the Thorold Sandstone in the 004 Pool has experienced a maximum burial depth of between 786 to 1160 m (2581-3806 feet). If one assumes that the geothermal gradient of 2.58°C/100 m (Judge and Beck, 1973) has remained fairly constant in the geologic past, the maximum temperature that the Thorold Sandstone has expe-

FIGURE 5-2 Plot of Shale Transit Time versus Depth of Burial.

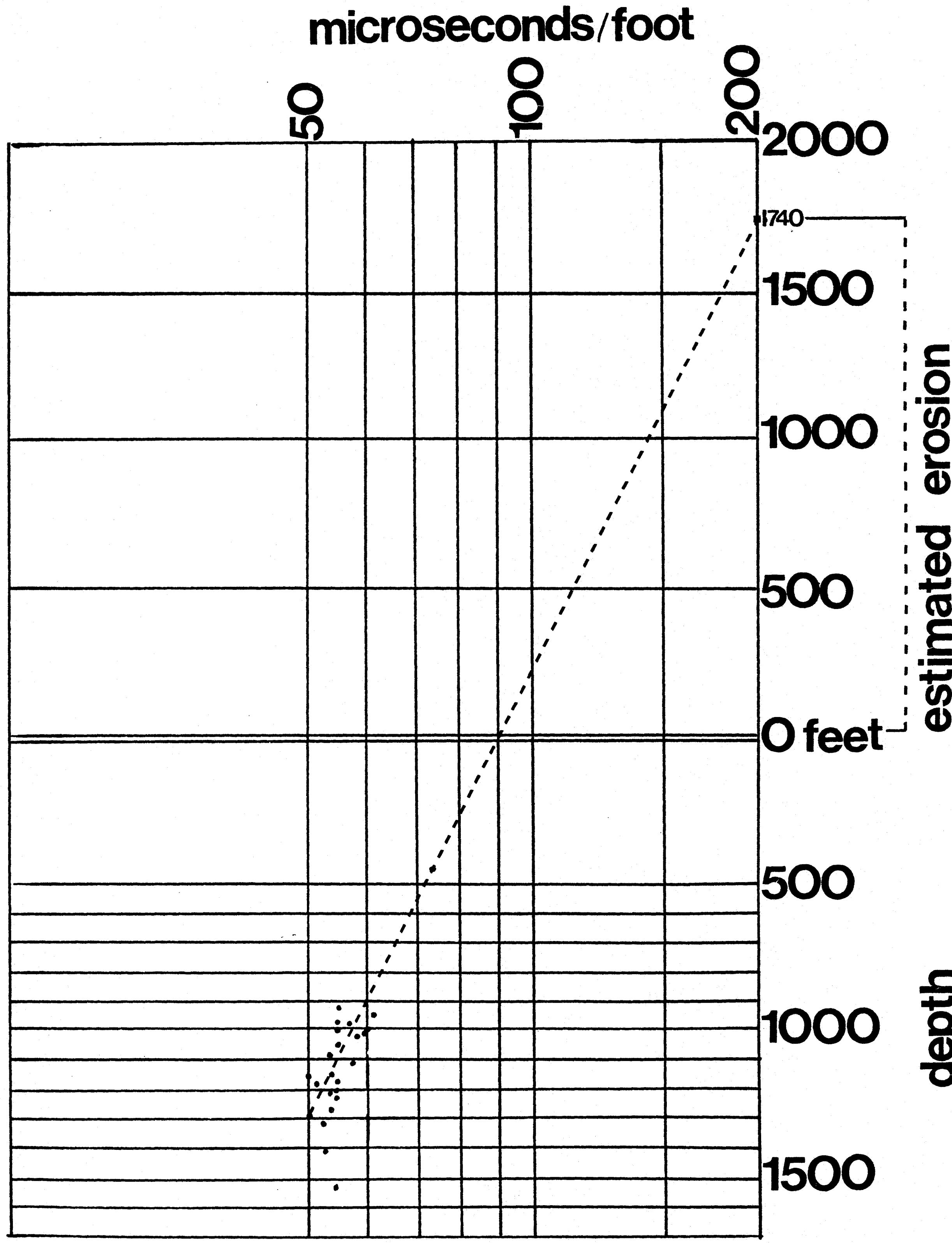
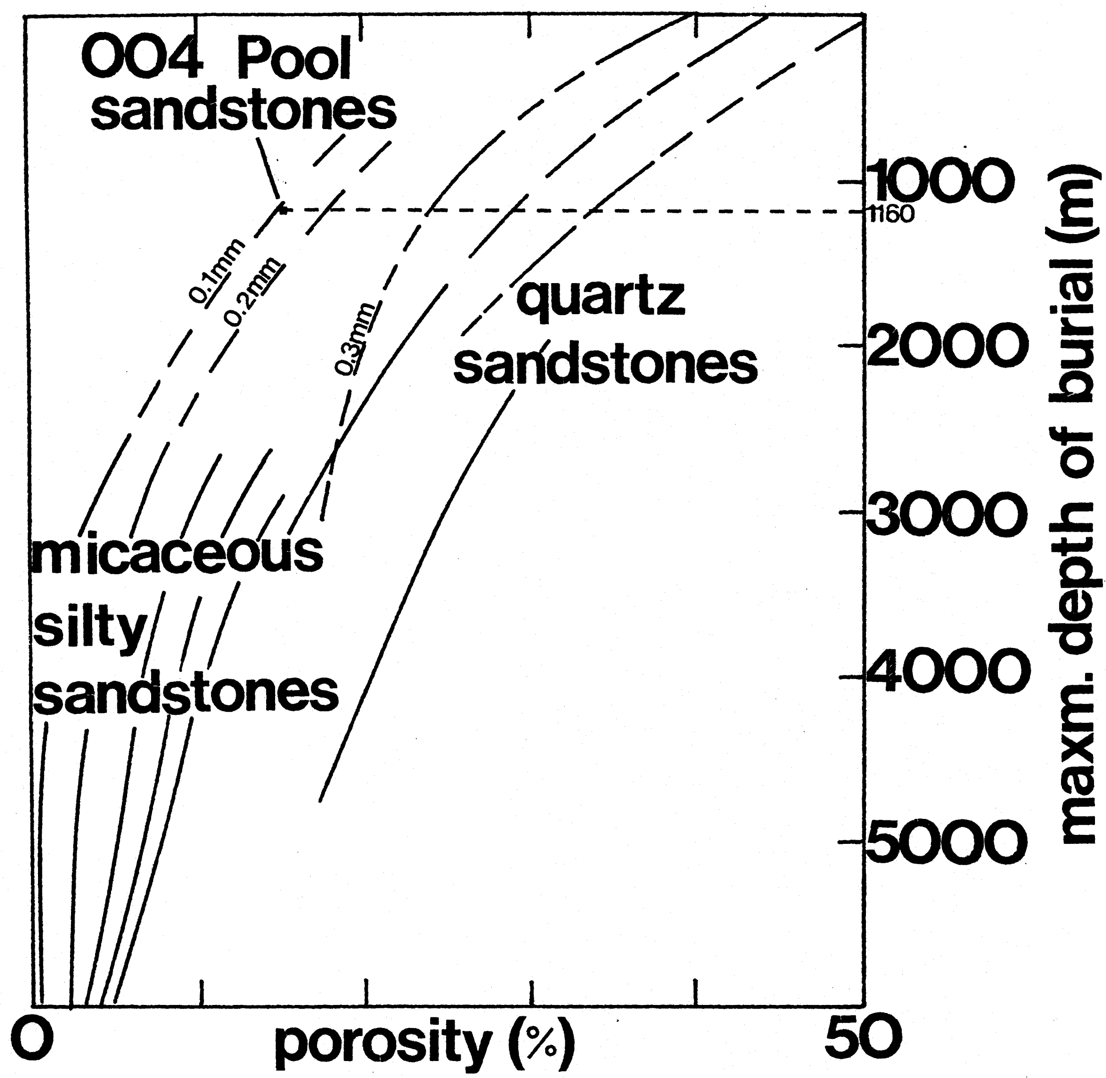

microseconds/foot
50
100
200
2000
1740
1500
1000
500
0 feet
estimated erosion
500
1000
1500
depth

FIGURE 5-3 Variation in porosity with maximum depth of burial (Modified from Füchtbauer, 1974, p. 132)



004 Pool
sandstones
0.1mm
0.2mm
0.3mm
quartz
sandstones
micaceous
silty
sandstones
1000
1160
2000
3000
4000
5000
maxm. depth of burial (m)
0
porosity (%)
50

rienced during diagenesis is approximately 30.0°C.

EOGENETIC STAGE

Mechanical Compaction

Although a minor portion of secondary porosity develops during eodiagenesis as a result of dissolution of sedimentary constituents, the major process which takes place during eodiagenesis is the mechanical reduction of porosity (Schmidt and McDonald, in Scholle and Schluger, 1979). Mechanical compaction has reduced initial porosity by 11-12% in the Thorold Sandstone if one assumes an initial sandstone porosity of 40% (Blatt et al., 1980, p. 417) and a calculated mean minus cement porosity of 28-29% (Chapter 3).

Formation of Pyrite and Siderite

Aerobic conditions are present in sediments up to only a few metres in depth with carbon dioxide being the major gas produced in this zone (Hunt, 1979, p. 152). Hydrogen ions are produced as P_{CO_2} increases thus lowering the pH in this zone. Consequently, any $CaCO_3$ in this zone will certainly be dissolved.

A reducing condition with available hydrogen is necessary before anaerobic reactions can be initiated. In marine sediments, sulfate-reducing bacteria are dominant at the top of the anaerobic zone until all available sulfate is reduced. The S^{2-} (as HS^-) combines with heavy metals such as iron to form pyrite, or in the absence of heavy metals it is released as H_2S (Hunt, 1979, p. 152). Zobell (in Hunt, 1979, p. 153) measured Eh values of -0.05 to -0.45 volt and pH of 5.5 to 9.8 in pore fluids from reducing environments. Siderite, like pyrite forms under low Eh conditions during the eogenetic stage (-0.30 to -0.40 volt) (Berner, 1971, p. 196). Siderite is found as a minor matrix constituent within the Thorold Sandstone.

MESOGENETIC STAGE

Authigenic Quartz Overgrowths

Authigenic quartz overgrowths result in the majority of porosity loss within the Thorold Sandstone. They form prior to all other major porosity reducing minerals in the Thorold. Quartz cementation was the dominant porosity reducing mechanism at the time the Thorold was at its maximum depth of burial (approximately 1000 m) while mechanical reduction took place at shallower depths.

Grain contacts between quartz grains give the appearance that pressure solution is the dominant mechanism for silicate cement formation within the Thorold Sandstone. However, the majority of contacts are between authigenic quartz overgrowths and not detrital grains thereby indicating that another major silica source is needed (Chapter 3).

Formation Waters

In sedimentary rocks, all of the pore spaces below the water table except those containing oil or gas are occupied by water. These pore waters or interstitial waters contain differing concentrations of ions in solution depending on their source and environment of diagenesis (Hunt, 1979, p. 190).

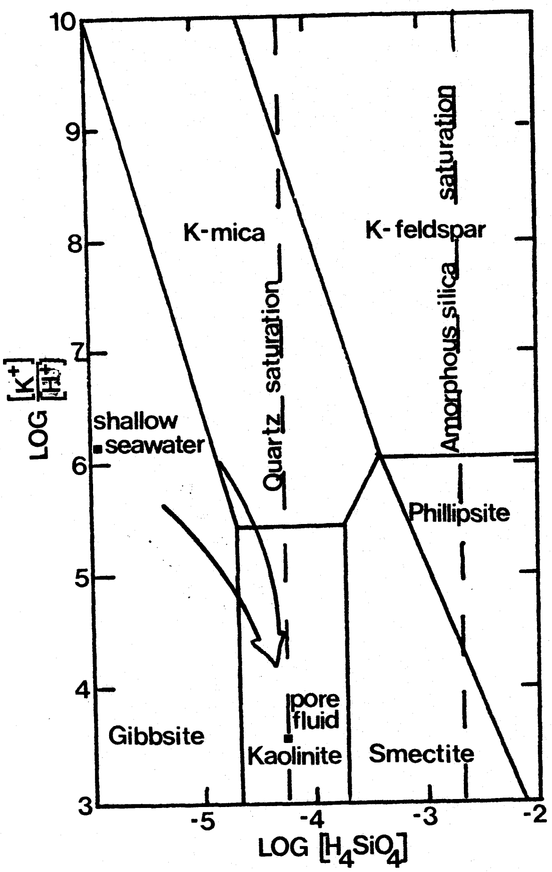
The initial pore fluids within the Thorold Sandstone which would have a shallow marine (lower shoreface) source would certainly be saline, closely approximating the composition of sea water. After deposition of the Thorold Sandstone, the Neahga Shale was deposited but is recognized in only the eastern Niagara Peninsula. One would then suspect a period of emergence which eroded the Neahga and resulted in a flushing of fresh waters through the pore spaces. Shallow marine conditions again prevailed with the deposition of the Reynales Formation. A corresponding increase in pore water salinity would certainly be expected. Following deposition of the Reynales sequence, the sea regresses from the Ontario peninsula and Michigan, initiating a period of intense erosion (Sanford, 1969). Consequently, pore waters would again experience a freshening trend. The Amabel sea then advanced into the Ontario area and marine conditions persisted to the end of the Silurian. Pore waters would again be saline in nature. At the close of the Silurian, southwestern Ontario was uplifted and subjected to intense erosion during an Early Devonian hiatus (Sanford, 1969). It is unlikely, however, that any fresh water would reach the pores of the now deeply buried Thorold Sandstone.

Figures 5-4 and 5-5 show stability relationships in the system K_2O-Na_2O-Al_2O_3-SiO_2-H_2O at 25°C. The arrows indicate the changing chemical composition of the pore fluids during mesodiagenesis. The chemical change would fluctuate in and out of the K-mica (illite) zone as pore fluid compositions were flushed with fresh water and subsequently became more saline in nature as marine conditions persisted. Fresh water is stable in the field of K-mica (illite)(Blatt et al., 1980, p. 262).

It is interesting that the pore fluid from well 13035 101-K plots in the stability field of kaolinite since authigenic kaolinite has not been recognized through petrographic and scanning electron microscope studies. Illite and chlorite are recognized as the stable authigenic clay minerals which would suggest a pore fluid composition somewhere close to the Mg-chlorite-illite field boundary (Figure 5-6).

It could very well be that the pore fluid analysis is not representative of the actual pore fluids since the sample was recovered from an open flow test after fracturing.

FIGURES 5-4, 5-5 Stability relationships in the system $K_2O-Na_2O-Al_2O_3-SiO_2-H_2O$ at 25°C. The arrows indicate the changing chemical compositions of the pore fluid during mesodiagenesis. (Modified from Drever, 1982, p. 102)


K-mica
K- feldspar
Quartz saturation
Amorphous silica saturation
shallow seawater
Phillipsite
pore fluid
Gibbsite
Kaolinite
Smectite
LOG [K+]/[H+]
LOG [H4SiO4]

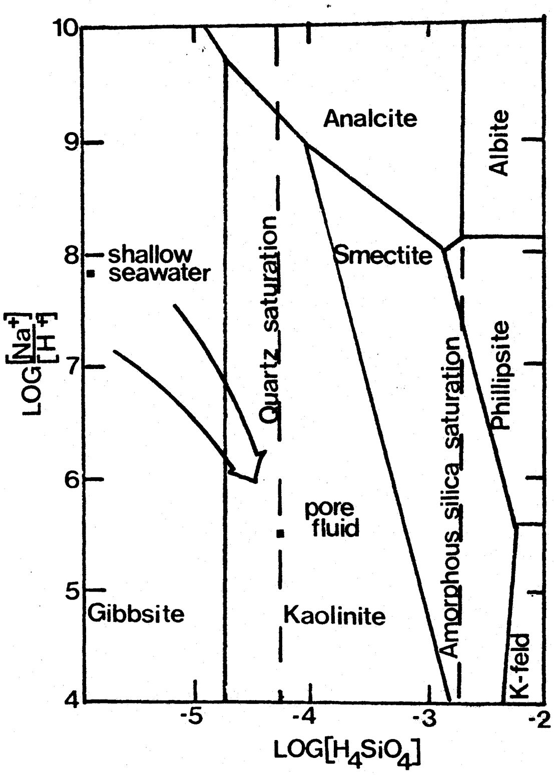
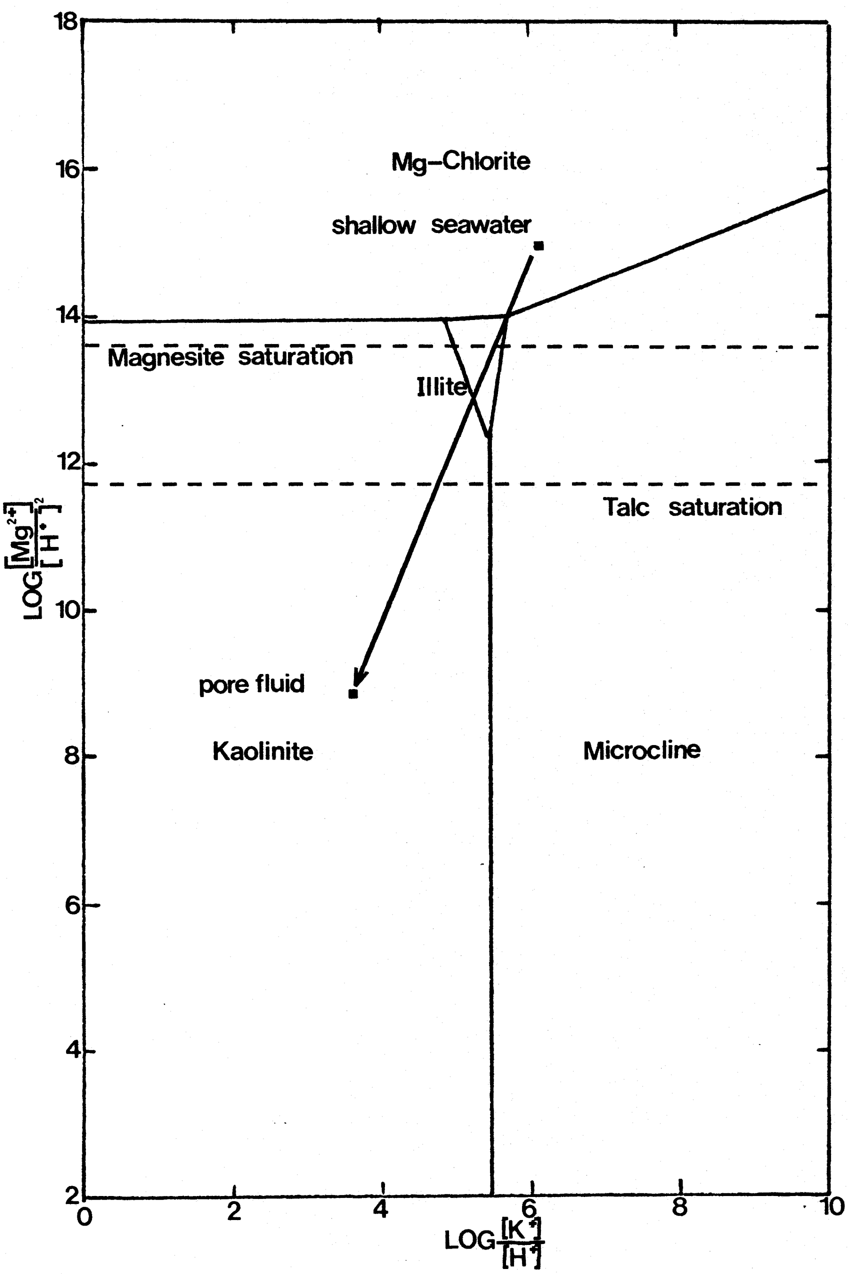

Analcite
Albite
Smectite
shallow seawater
Quartz saturation
Amorphous silica saturation
Phillipsite
pore fluid
Gibbsite
Kaolinite
K-feld
LOG[Na+]/[H+]
LOG[H4SiO4]

FIGURE 5-6 Stability relationships in the system $MgO-Al_2O_3-CO_2-K_2O-SiO_2-HCl-H_2O$ at 25°C. The arrow indicates the changing chemical composition of the pore fluids during mesodiagenesis. Log $[H_4SiO_4]$ = -4.00 = quartz saturation. (After Helgeson <u>et al</u>., 1969, p. 41).


Mg–Chlorite
shallow seawater
Magnesite saturation
Illite
Talc saturation
pore fluid
Kaolinite
Microcline
LOG [Mg2+]/[H+]2
LOG [K+]/[H+]
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10

The pH of the pore fluid (5.6) may, perhaps, be slightly low due to acid treatment in this well. A higher pH of approximately 7.0 would seem to be a more reasonable estimate for Thorold Sandstone pore fluids which would place the fluids within the illite (K-mica) stability fields in Figures 5-4 and 5-6.

Final pore fluid compositions in Figures 5-4, 5-5 and 5-6 were plotted using the following major ion analysis from a water sample taken from well 13035 101-K (Table 5-2).

Table 5-2 MAJOR ION ANALYSIS, 13035 101-K (1605-1610 feet)

	Major Ions (mg/l)
Sodium Na^{+}	19,277
Calcium Ca^{2+}	11,400
Magnesium Mg^{2+}	2,100
Potassium K^{+}	405
Chloride Cl^{-}	56,400
Bicarbonate HCO_3^{-}	43
Sulfate SO_4^{2-}	310
Carbonate CO_3^{2-}	0
Total	89,935

(Water samples from the Thorold Sandstone in other areas of Lake Erie generally are above 200,000 mg/l total dissolved solids compared to the 89,935 mg/l in the sample from 13035 101-K. Relative proportions of the major ions are similar to other samples throughout the Lake however).

Generally, dissolution of evaporites and membrane filtration of salts from the larger pore openings of shales during the early stages of compaction are responsible for the high salinities in formation waters (Drever, 1982).

AUTHIGENIC CLAY MINERALS

The Thorold Sandstone in the 004 Pool has never been buried to depths much greater than approximately 1000 m and has not been exposed to temperatures much greater than 30°C. Consequently, burial diagenesis reactions for the formation of authigenic clays are of little relevance.

Chlorite appears to be the first authigenic mineral to form after quartz overgrowths followed by the formation of authigenic illite. Plate 4-8 clearly shows lath-like projections of wispy illite extending into pore space from individual chlorite plates which are attached on edge to the surface of quartz overgrowths. However, examination of clays with the scanning electron microscope reveals that both authigenic chlorite and illite form on the surface of quartz overgrowths with the illite growth on chlorite plates observed in only one instance (Plates 4-2, 4-7).

Authigenic Chlorite

The authigenic pore lining chlorite observed in the Thorold Sandstone is the Ib ($\beta = 90^{\circ}$) polytype. There are three possible mechanisms for the formation of this chlorite polytype:

i) A type-I crystallization sequence through burial metamorphism from least to most stable Ib_d to Ib ($\beta = 97^{\circ}$) to Ib ($\beta = 90^{\circ}$).

ii) Formation from material which is being dispersed about the basin, while particles are suspended in water or being moved intermittently along the sediment-water interface, but prior to burial of particles. This process of mineral transformation or crystallization involving exchange between sedimentary particles and seawater is called halmyrolysis.

iii) Direct precipitation from pore fluids.

(Hayes, 1970)

The first mechanism would not be applicable to the Thorold Sandstone since temperatures and depth of burial are not large enough for this crystallization sequence to occur. The second mechanism can be eliminated as a possibility since this mineral transformation occurs prior to burial at the sediment-water interface. Recall that authigenic chlorite forms on authigenic quartz overgrowths which were formed at the maximum depth of burial. Consequently, the third mechanism appears to be the most viable alternative for the formation of authigenic chlorite. There would certainly be sufficient iron and magnesium within the pore fluids for chlorite to precipitate out of solution. Hayes (1970) states that in cases where authigenic chlorite lines pores, mobile ions or ionic complexes must have formed chlorite by precipitation from solution.

Authigenic Illite

Authigenic illite appears to have formed through a neoformation process since the observed morphologies are extremely delicate and fragile and the illite reflection peaks are generally narrow and sharp on X-ray diffraction traces indicating well developed crystallinity. The process involves direct precipitation from alkaline, cation-rich pore fluids resulting in the growth of the wispy laths from illitic cores and authigenic quartz overgrowths (Guven et al., 1980)(Plates 4-1, 4-2, 4-3, 4-4). There is no evidence of illite development from the breakdown of primary micas as burial diagenesis transformations are, again, not applicable to these shallow, low temperature conditions.

DIAGENETIC CLASSIFICATION

Schmidt and McDonald (in Scholle and Schluger, 1979) have proposed four textural stages of sandstone mesodiagenesis. In order of progressive burial they are:

i) immature stage

ii) semi-mature stage

iii) mature stage and,

iv) supermature stage

(Figure 5-7)

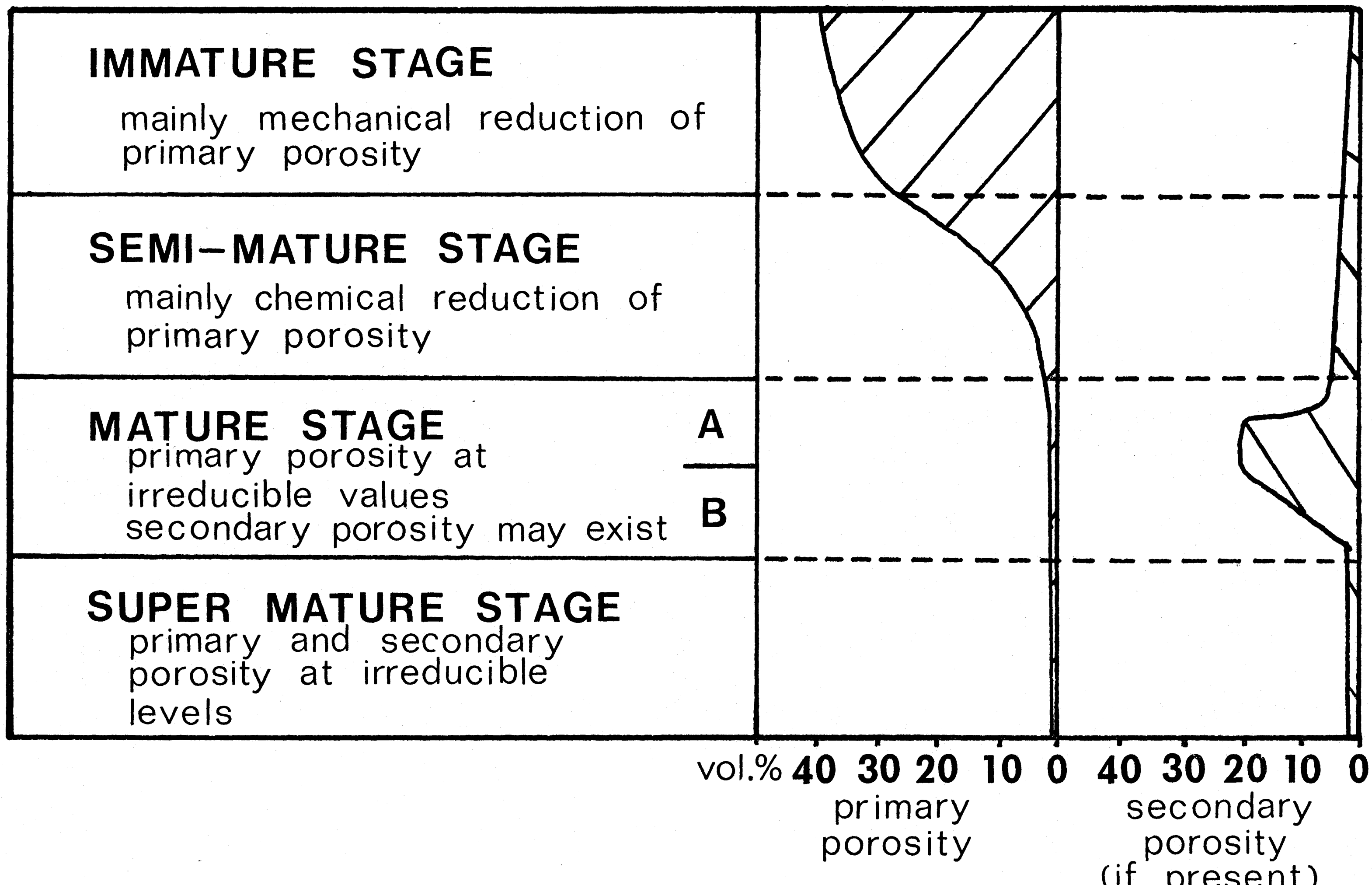
The Thorold Sandstone is in the semi-mature stage of meso-diagenesis.

The immature stage is characterized by mechanical compaction of clean, uncemented sands with primary intergranular porosity. Chemical compaction is absent or negligible (Schmidt and McDonald, in Scholle and Schluger, 1979). During the semi-mature stage mechanical compaction of primary porosity becomes insignificant while chemical compaction becomes dominant. Chemical compaction is accomplished through the dissolution of sand grains at points and interfaces of contact. The dissolved material reprecipitates through the sandstone as pore cement thereby reducing porosity. Secondary porosity originates in the semi-mature stage and by the time the semi-mature stage comes to an end, primary porosity has reached irreducible levels (Schmidt and McDonald, in Scholle and Schluger, 1979).

DIAGENETIC SUMMARY

During the eogenetic stage the minerals pyrite and siderite were formed. Mechanical compaction reduced the initial sandstone porosity from 40% to approximately 28 to 29%.

FIGURE 5-7 Textural stages of mesodiagenesis of sandstone porosity (After Schmidt and McDonald, in Scholle and Schluger, 1979).


IMMATURE STAGE
mainly mechanical reduction of primary porosity
SEMI-MATURE STAGE
mainly chemical reduction of primary porosity
MATURE STAGE
primary porosity at irreducible values
secondary porosity may exist
A
B
SUPER MATURE STAGE
primary and secondary porosity at irreducible levels
vol.%
40 30 20 10 0
primary porosity
40 30 20 10 0
secondary porosity (if present)

Authigenic quartz, in the form of overgrowths was the first authigenic mineral to form during the mesogenetic stage followed by the growth of authigenic chlorite. Illite was the next authigenic mineral to form and according to stability relationships in Figures 5-4, 5-5 and 5-6 the present pore fluids plot in the kaolinite stability field. However, authigenic kaolinite was not observed within the Thorold Sandstone from the 004 Pool. Chemical compaction has reduced porosity to 4 to 10% during mesodiagenesis. In addition secondary porosity originates during the mesogenetic stage.

CHAPTER 6

CONCLUSIONS

1. Examination of subsurface core of the Thorold Sandstone from wells in the 004 Pool indicates the presence of only a single laminated sandstone facies. The facies is characterized by a fine-grained, well-sorted, well-rounded grey sandstone with horizontal, even parallel to slightly wavy parallel paper thin silt laminae along with abundant rip up shale clasts and moderate to strong bioturbation. This facies is interpreted as being deposited in a lower shoreface environment.
2. A total of 9 samples were collected from the 7 wells studied in the 004 Pool. Petrographic examination indicates that all of the samples can be classified as sublitharenites which are texturally and mineralogically mature.
3. Samples examined from the subsurface in the present study closely resemble the "Orthoquartzitic lithology" described by Martini (1966) from microscopic examination of thin sections from surface outcrop samples of the Thorold Sandstone. However, subsurface thin sections show greater development of quartz cement in the form

of authigenic quartz overgrowths which lead to a 20% decrease in porosity.

4. Sutured and concavo-convex contacts accounted for 80% of all grain contacts within the Thorold Sandstone. Cathodoluminescence and detailed petrographic microscope examination revealed that the majority of contacts were between authigenic quartz overgrowths and not detrital grains. Therefore, pressure solution is not the major source of silica cement in the Thorold Sandstone. Diffusion of silica from surrounding shales is likely the major source.
5. Illite (both detrital and authigenic) is the dominant clay mineral within the Thorold Sandstone in the 004 Pool followed by detrital kaolinite and minor authigenic chlorite. The approximate ratio of illite to kaolinite is 2 to 1.
6. The Thorold Sandstone within the 004 Pool has experienced a maximum depth of burial between 786 to 1160 m (2581-3806 feet). Assuming the present geothermal gradient of 2.58°C/100m (Judge and Beck, 1973) has remained fairly constant in the geologic past, the maximum temperature that the Thorold Sandstone has experienced during diagenesis is 30°C. At this maximum depth of burial and temperature, clay minerals are unlikely to have undergone extensive diagenetic transformation. Therefore, the

observed detrital clay minerals represent the clay minerals which were present at the time of deposition. Authigenic chlorite and illite form by direct precipitation from magnesium/iron-rich and alkaline cation-rich pore fluids respectively, rather than by transformation of preexisting detrital clays.

7. Pyrite and siderite were formed during the eogenetic stage of diagenesis. During mesodiagenesis, authigenic quartz in the form of overgrowths was the first authigenic mineral to form followed sequentially by chlorite and illite. Present pore fluid compositions plot within the kaolinite stability field, but authigenic kaolinite was not observed.

8. Mechanical compaction has reduced sandstone porosity from 40% to 28 to 29% during the eogenetic stage while chemical compaction has reduced porosity to its present value of 4 to 10% during mesodiagenesis. The Thorold Sandstone is in the semi-mature stage of mesodiagenesis. Although this porosity reduction has certainly reduced the reservoir potential of the 004 Pool, gas is being produced economically from the Consumers' Gas Silver Creek 004 Grimsby Pool.

BIBLIOGRAPHY

Berner, R.A., 1971, Principles of Chemical Sedimentology. Toronto: McGraw-Hill Book Co., 240pp.

Blatt, H., Middleton, G.V., and Murray, R., 1980, Origin of Sedimentary Rocks. Englewood Cliffs, N.J.: Prentice-Hall Inc., 2nd ed., 782pp.

Bolton, T.E., 1957, "Silurian Stratigraphy and Paleontology of the Niagara Escarpment in Ontario," Geol. Surv. Can. Mem. 289, 145pp.

Brown, G., 1961, The X-ray Identification and Crystal Structures of Clay Minerals. London, Mineralogical Society, 2nd ed., 393-445.

Choquette, P.W., and Pray, L.C., 1970, "Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates," Amer. Assoc. Petroleum Geol. Bull., v.54, 207-250.

Drever, J.I., 1982, The Geochemistry of Natural Waters. Englewood Cliffs, N.J.: Prentice-Hall Inc., 388pp.

Fisher, D.W., 1954, "Stratigraphy of the Medinan Group, New York and Ontario," Amer. Assoc. Petroleum Geol. Bull., v.38, 1979-1996.

Fisher, G.W., Pettijohn, F.J., Reed, Jr.,J.C., and Weaver, K.N., (Eds.), 1970, Studies in Appalachian Geology: Central and Southern. Toronto: J.Wiley and Sons, 460pp.

Folk, R.L., 1968, Petroleum of Sedimentary Rocks. Austin, Texas: Hemphill's Book Store, 170pp.

Füchtbauer, H., 1967, "Influence of Different Types of Diagenesis on Sandstone Porosity," Reprint from the Proceedings of the Seventh World Petroleum Congress.

———, 1974, Sediments and Sedimentary Rocks 1. Toronto: Halsted Press, 464pp.

———, 1978, "Zur Herkunft des Quarzzements. Abschatzung der Quarzauflosung in Silt-und Sandsteinen," Geol.

Rundschau, v.67, #3, 991-1008.

Gillette, T., 1947, "The Clinton of Western and Central New York," New York State Mus. Bull., 341, 1-191.

Grabau, A.W., 1913, "Early Paleozoic Delta Deposits of North America," Geol. Soc. Amer. Bull., v.24, 399-528.

Griffin, J.J., Windom, H., and Goldberg, E.D., 1968, "The Distribution of Clay Minerals in the World Ocean," Deep-Sea Res., v.15, 433-459.

Guven, N., Hower, W.F., and Davies, D.K., 1980, "Nature of Authigenic Illite in Sandstone Reservoirs," Jour. Sed. Petrology, v.50, #3, 761-766.

Habicht, J.K.A., 1979, "Paleoclimate Paleomagnetism and Continental Drift," AAPG Studies in Geology, #9, 31pp.

Hayes, J.B., 1970, "Polytypism of Chlorite in Sedimentary Rocks," Clays and Clay Minerals, v.18, 285-306.

Helgeson, H.C., Brown, T.H., and Leeper, R.H., 1969, Handbook of Theoretical Activity Diagrams Depicting Chemical Equilibria in Geologic Systems Involving an Aqueous Phase at One Atm. and 0° to 300°C. San Francisco: Freeman, Cooper and Co., 253pp.

Hunt, J.M., 1979, Petroleum Geochemistry and Geology. San Francisco: W.H. Freeman and Co., 617pp.

Judge, A.S., and Beck, A.E., 1973, "Analysis of Heat-Flow Data - Several Boreholes in a Sedimentary Basin," Can. Jour. Earth Sci., v.10, #10, 1494-1507.

Magara, K., 1978, Compaction and Fluid Migration. Practical Petroleum Geology. New York: Elsevier Scientific Publishing Co., 319pp.

Mariano, A.N., and Ring, P.J., 1975, "Europium-Activated Cathodoluminescence in Minerals," Geochim. Cosmochim. Acta, v.39, 649-660.

Martini, I.P., 1966, "The Sedimentology of the Medina Formation Outcropping along the Niagara Escarpment. (Ontario and New York State)," Ph.D. Dissertation, McMaster University, 420pp.

————, 1971, "Regional Analysis of Sedimentology of the Medina Formation (Silurian), Ontario and New York," Amer. Assoc. Petroleum Geol. Bull., v.55, #8, 1249-1261.

Middleton, G.V., 1971, "Notes on the Geology of the Hamilton Area," Dept. of Geol., McMaster University, Unpubl. Tech. Memo 71-1.

Pemberton, S.G., 1979, "Selected Studies in Lower Paleozoic Ichnology," Ph.D. Dissertation, McMaster University, 516pp.

———, 1982, "Opportunistic Ichnofossils from the Silurian Thorold Sandstone of Southern Ontario," in press, IAS 1982, Abstracts.

Potocki, D.J., 1981, " A Study of the Lower Cretaceous, Niton Basal Quartz Sandstones of Western Alberta; with specific reference to Porosity and Permeability Modification," Unpubl. B.Sc. Thesis, McMaster University, 83pp.

Potter, P.E., Heling, D., Shimp, N.F., and Van Wie, W., 1975, "Clay Mineralogy of Modern Alluvial Muds of the Mississippi River Basin," Bull. Centres Recherches Pau - SNPA, v.9, 353-389.

Sanford, B.V., 1969, "Silurian of Southwestern Ontario," Technical Paper #5, Ont. Petroleum Institute, 8, Eighth Annual Conference.

Scholle, P.A., and Schluger, P.R., (Eds.), 1979, "Aspects of Diagenesis," Soc. Econ. Paleon. Mineralogists Spec. Pub., 26, 443pp.

Selley, R.C., 1978, "Concepts and Methods of Subsurface Facies Analysis," AAPG Continuing Education Course Note Series, #9, 82pp.

Sippel, R.F., 1968, "Sandstone Petrology, Evidence from Luminescence Petrography," Jour. Sed. Petrology, v.38, #2, 530-554.

Smith, J.V., and Stenstrom, R.C., 1965, "Electron Excited Luminescence as a Petrologic Tool," Jour. Geol., v.73, 627-635.

Taylor, J.M., 1950, "Pore-Space Reduction in Sandstone," Amer. Assoc. Petroleum Geol. Bull., v.34, 701-716.

Towe, K.M., 1962, "Clay Mineral Diagenesis as a Possible Source of Silica Cement in Sedimentary Rocks," Jour.

Sed. Petrology, v.78, 353-368.

Walker, R.G. (Ed.), 1979, "Facies Models," Geoscience Canada Reprint Series 1, Geol. Assoc. Canada, Kitchener, Ont.: Ainsworth Press Ltd., 211pp.

Wilson, M.D., and Pittman, E.D., 1977, "Authigenic Clays in Sandstones: Recognition and Influence on Reservoir Properties and Paleoenvironmental Analysis," Jour. Sed. Petrology, v.47, #1, 3-31.

APPENDIX I

LEGEND-CLASTIC LOGGING FORM
(Courtesy of Petro-Canada)

Number of each category (e.g. 2. PERMEABILITY) refers to numbers at the top of each logged section.

2. PERMEABILITY

a) plot actual values from service company report, or
b) identify estimated permeability using numerical scale.

1 — <0.01 md. (ineffective)
2 — 0.01 - 0.1 md. (doubtfully effective)
3 — 0.1 - 1.0 md. (poor)
4 — 1.0 - 10.0 md. (fair)
5 — 10.0 - 100.0 md. (good)
6 — 100.0 - 1000.0 md. (very good)
7 — >1000.0 md. (excellent)

Note: identify scale most practical for range of values.

3. POROSITY

a) plot actual values from service company reports, or
b) record estimated values.

Note: identify scale most practical for range of values.

4. SAMPLE

- note location of any samples taken.

5. STAINING

- estimate degree of hydrocarbon colouration using numerical scale.

0 — absent
1 — trace
2 — moderate (brown)
3 — heavy (black)

6. GRAIN SIZE

- estimate mean grain size (mm).

7. DEPTH INTERVAL

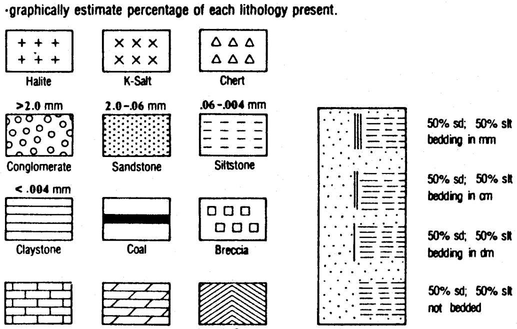
- use metric or imperial form as appropriate.

8. BEDDING CONTACTS

- Sharp, conformable
- Gradual transition (< 1 cm)
- Gradual & slow transition (hardly visible)
- NV Not visible
- Inclined
- Undulating
- Concave
- Convex
- Erosional

9. GROSS LITHOLOGY (AND BEDDING SCALE)

- graphically estimate percentage of each lithology present.

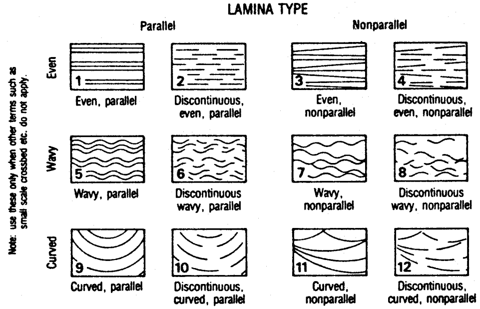


10. SEDIMENTARY STRUCTURES

(left to right in order of importance)

- H Homogeneous
- Current ripples
- Climbing ripples
- Wave ripples
- Planar cross-beds
- Trough cross-beds
- Horizontal, even parallel laminations
- Vague, horizontal, even parallel laminations
- Inclined, even parallel laminations
- Wavy parallel laminations
- Flaser
- Lense (lenticular)
- Wavy lenticular
- Wedge
- Scour and fill
- Normal, graded bedding
- Reverse, graded bedding
- Groove cast
- Flute cast
- Load cast
- Flame structure
- Sand dyke
- Stylolite
- Mud cracks
- Rip up clasts
- Imbricated clasts
- Armoured mud ball
- Convolute, laminae or bedding
- Slump structure (flowage)
- Microfault
- Fractures, vertical, inclined
- Carbonaceous debris (plant remains)
- Carbonaceous laminae
- Rootlet
- Burrow, vertical, horizontal
- Weakly bioturbated
- Moderately bioturbated
- Strongly bioturbated
- Trail
- General fossil
- Gastropod
- Pelecypod
- Fish remains
- Shells (Brachiopods . . . etc.)

LAMINA TYPE



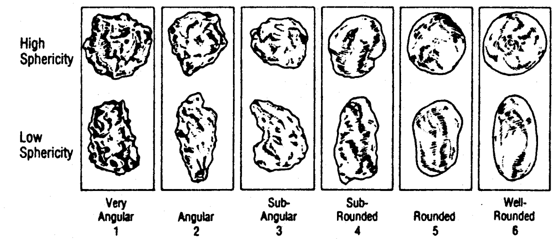
11. CONSTITUENTS AND ACCESSORIES

- ●● Phosphate
- G Glauconite
- P Pyrite
- Q Authigenic Quartz
- B Bentonite
- S Siderite
- Y Sulphur
- I Iron Oxide
- △▲ Chert light, dark
- M Micaceous
- K Kaolin
- Nodule
- Concretion
- Bitumen
- Bituminous laminae

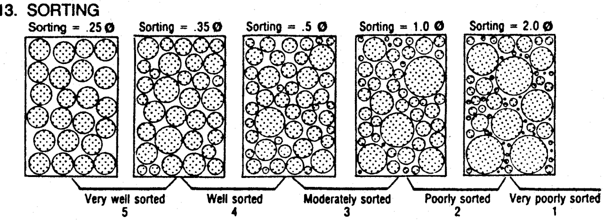
x = mineralogy

0 - 5% — one symbol
6 - 25% — two symbols
26 - 50% — three symbols
> 50% — four symbols

12. ROUNDNESS



13. SORTING



14. TERM

TERM	DEGREE OF INDURATION
1. Unconsolidated	Grains falling apart in dry conditions, loose
2. Friable	Grains can be detached using a fingernail
3. Moderately hard	Grains can be detached with a knife
4. Hard	Sample breaks around most grains
5. Very hard	Sample breaks across most grains

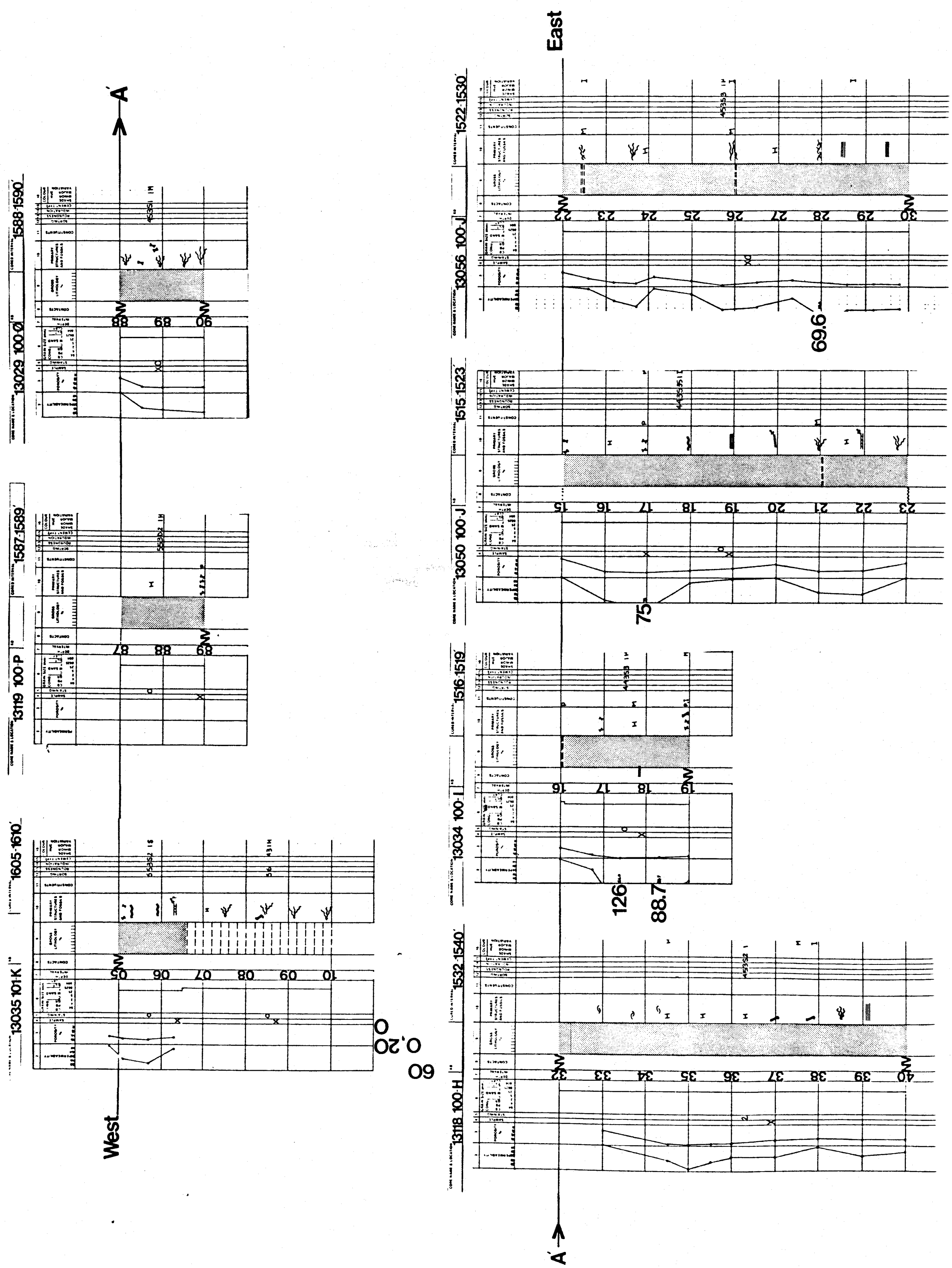
15. CEMENT TYPE

- A Anhydrite
- ✳ Bitumen
- C Calcite
- D Dolomite
- H Halite
- I Iron Oxide
- ¢ Iron Carbonate
- P Pyrite
- S Silica
- Y Sulphur

16. COLOUR

SHADE	HUE		VARIATION
1. Very Light	1. Grey		M Mottled light & dark
2. Light	2. Brown	6. Blue &/or Violet	S Speckled (salt & pepper)
3. Medium	3. Red	7. Cream	V Varicoloured
4. Dark	4. Orange &/or Yellow	8. White	I Interbedded light & dark
5. Very Dark	5. Green	9. Black	H Homogenous

FIGURE A-1 Stratigraphic sections of wells logged from Consumers' Gas Silver Creek 004 Grimsby Pool


West
East
A′
A′
13035 101-K
1605-1610′
13119 100-P
1587-1589′
13029 100-0
1588-1590′
13118 100-H
1532-1540′
13034 100-I
1516-1519′
13050 100-J
1515-1523′
13056 100-J
1522-1530′