1977

The depositional environments of the Grimsby Formation, in the subsurface of central Lake Erie, Ontario.

Robert Joseph. Writt

University of Windsor

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS REÇUE
THE DEPOSITIONAL ENVIRONMENTS
OF THE GRIMSBY FORMATION, IN THE
SUBSURFACE OF CENTRAL LAKE ERIE, ONTARIO

A Thesis
Submitted to the Faculty of Graduate Studies through the
Department of Geology
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science at the
University of Windsor

by

Robert Joseph Writt

Windsor, Ontario 1977
ABSTRACT

The Grimsby Formation, and the overlying Thorold sandstone, consist of quartzose sandstones with minor shales; these formations are part of the Lower Silurian Medina clastic succession, which developed in the northwestern portion of the Appalachian basin. The Medina sequence records the northwestward progradation of the Grimsby delta into a shallow epeiric sea. The Thorold sandstone represents the reworking of the topmost Grimsby sediments during subsequent marine transgression.

A wide variety of primary and biogenic sedimentary structures are found within the Thorold and Grimsby Formations. Many of these structures are described with explanations of processes responsible for their formation. Of fundamental importance is that suites of these structures may be related to certain depositional environments.

Five genetically significant lithofacies, based upon the gross lithology and the associated sedimentary structures, were established and are representative of the environments of deposition of the Grimsby and Thorold Formations and the subjacent argillaceous upper Cabot Head Formation. These lithofacies occur within a preferred stratigraphic order, in accordance to Walther's Law. In generalized sequence, from stratigraphically lowest to highest, the lithofacies are, (1) prodelta to marine shelf; (2) a beach face of a sand bar or barrier island; with (3) a landward associated tidal flat;
(4) a distributary complex which, for the most part, is laterally equivalent to and also overlies the tidal flat and associated beach deposits, but locally may directly overlie the prodelta to shelf deposits; and at the highest stratigraphic level, (5) a beach complex (representing deposition during Thorold marine transgression), with minor interstratifications of tidal flat to lagoon, tidal channel point bar, and fluvial channel fills.

The Grimsby deltaic sediments show much evidence of strong processes of reworking. Strong storm waves and tides eroded coastal sand deposits and redistributed the coarser material seaward, together with abundant shells, as sandstone and coquinooidal storm sheets in the prodelta and shelf muds. Strong flood-related fluvial currents may also be responsible for much reworking in the distributary complex.

The combined Grimsby and Thorold sandstones wedge out into the prodelta to marine shelf mudstone along the north-westward rim of the depositional basin; the sandstones 'thicken' towards the southeast within the Appalachian basin.
ACKNOWLEDGEMENTS

The author sincerely thanks Dr. Mary Davis for her guidance, discussion, and encouragement throughout the preparation of this thesis. Dr. Davis directed the study and made valuable suggestions towards the interpretation of the thesis material. Furthermore Dr. Davis unselfishly provided the core upon which the study is based.

Appreciation is also due to Dr. Frank Simpson who critically reviewed various drafts of the thesis and made recommendations in regard to the interpretation and the presentation of the thesis material. In addition Dr. Simpson kindly supplied the camera for the photography of the core specimens.
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INTRODUCTION

Location

The study area (Fig. 1) is located in the central Lake Erie region of southwestern Ontario. It is offshore Elgin County and forms a rectangle, 21 miles long in an east-west direction, by 18 miles wide in a north-south direction. The center of the rectangle is at 42°25'N and 80°45'W longitude. Consumers' Gas Company's Clear Creek gas field, producing from the Grimsby Formation, is located within the study area.

Previous Work

The Silurian strata of southwestern Ontario have been studied since the mid-1800's. A bibliography of the relevant publications, dated up to 1955, is given by Bolton (1957).

The Niagara escarpment, a prominent cuesta which crosses southwestern Ontario, gives excellent exposures of the Lower and Middle Silurian section over an outcrop distance of more than 200 miles. From these exposures, Fisher (1954) presents a stratigraphy of the Lower Silurian Medina sediments of the Niagara Peninsula and western New York. Bolton (1957), expanding on Fisher's earlier work, reports the stratigraphy of the entire outcrop section from the Niagara River to Tobermory, Ontario.
B.V. Sanford (1968, 1969) discusses the stratigraphy of the complete Silurian column of southwestern Ontario and presents paleogeographic maps of the various lithostratigraphic units. Recently Martini (1966, 1971, 1972, 1974a, and 1974b) studied the Lower Silurian Medina sediments of the Niagara Peninsula and adjacent New York. His work differs from the earlier stratigraphy efforts in that Martini approaches the stratigraphy from a sedimentological viewpoint. Martini, in effect, subdivides the larger stratigraphic units of Fisher and Bolton into smaller, genetically meaningful depositional units.

Beards (1973) comments upon the Lower Silurian clastics encountered in the subsurface of Norfolk County, Ontario. Kelly and McGlade (1968), Knight (1969), and Overby and Henniger (1971) give the results of subsurface studies in Pennsylvania and Ohio. Knight presents lithological correlations across northern Ohio based upon geophysical well logs.

Reservoir studies of the Grimsby sandstone from the present study area are documented by B. W. Shelton (1973) and Tovell (1976).

Studies of the petrology of the Grimsby Formation have been carried out by Martini (1966) and Lumsden and Pelletier (1969), and similar observations are also included in the works of Shelton and Tovell.

A deltaic depositional environment has been proposed for the Lower Silurian clastic sequence of southwestern Ontario, western New York, Ohio, and Pennsylvania (Fisher, 1954; Martini, 1966; Knight, 1969; and Overby and Henniger, 1971). A series of
shore-parallel sand bars is postulated by Beards (1973) for the sandstones of the Grimsby Formation, in Norfolk County, Ontario.

**Present Study**

The objective of this study is to determine the environment of deposition of the sandstones and shales encountered in drill core from the central Lake Erie region of Ontario. This study is not concerned with the large-scale, local stratigraphy or stratigraphic nomenclature of southwestern Ontario, but rather with the interpretation of depositional environments, suggested by the sedimentary units or facies within this complex sequence. **Subsurface study from drill core**

The study of drill core readily permits the determination of the vertical lithologic succession; whereas the width of a core disallows the direct determination of the lateral variation of a given bed or facies. However, Walther's Law of Succession of Facies (Blatt et al., 1972) states that facies sequences observed vertically are also found laterally. Furthermore, Visher (1965) demonstrates that the vertical profiles of Recent depositional environments may be used as reference frameworks for interpreting the sedimentary history of any stratigraphic section. Therefore, despite the difficulty of interpreting small-scale lateral variations from core, large-scale variations may be understood through application of basic stratigraphic principles.
Method of study

The present study is based entirely on subsurface data and involved the detailed examination of slabbed drill core. Lithologies and both primary and secondary sedimentary structures were logged at a scale of once inch to one foot for each of 27 cores, representing a total footage of approximately 1300 feet. Cores were generally 45 to 60 feet in length and consisted of the base of the Reynales Formation, the entire Thorold Formation, and the sandstones of the Grimsby Formation. All cores ended in the shales of the lower Grimsby or upper Cabot Head Formation.

The sample locations (Table 5; Figure 15) are exploration wells of the Consumers' Gas Company. The distance between any two sample locations was always in excess of a mile. The percentage of core recovery was not reported by the drillers; however, the recovery is considered to be good by the author.

Definitions

The following few miscellaneous definitions are given to help eliminate any possible confusion;

a) Thickness. Semiquantitative terms (Table 1) describing the thickness of stratification and bedding units are used in accordance with the terminology of Ingram (1954).

b) Colour. Descriptive rock-colour terms are those defined in the Geological Society of America Rock-Colour Chart (1975).
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<th>English</th>
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<td>0.0 - 0.3</td>
<td>0 - 1/10 in.</td>
<td>thinly laminated</td>
</tr>
<tr>
<td>0.3 - 1.0</td>
<td>1/10 - 2/5</td>
<td>thickly laminated</td>
</tr>
<tr>
<td>1 - 3</td>
<td>2/5 - 1</td>
<td>very thinly bedded</td>
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<td>3 - 10</td>
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<td>10 - 30</td>
<td>4 - 12</td>
<td>mediumly bedded</td>
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<tr>
<td>30 - 100</td>
<td>1 - 3 ft.</td>
<td>thickly bedded</td>
</tr>
<tr>
<td>100 -</td>
<td>3 -</td>
<td>very thickly bedded</td>
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Table 1.— Classification of the thickness of stratification of sedimentary rocks (from Ingram, 1954)
c) Measurement units. The English Standard System is used for the measurement of large distances and lengths since much of the data used was originally presented in this form. However, where convenient (especially in the description of small-scale sedimentary structures) the Metric System is used.

d) Grimsby sand body. This term is used for convenience by author to define the combined sandstone sequences of the Grimsby and Thorold Formations.
GEOLOGICAL SETTING

Age and Stratigraphic Terminology

The unmetamorphosed sedimentary Paleozoic rocks of southwestern Ontario consist of nearly flat lying (dipping less than 5 degrees south) carbonates, shales, and sandstones. The rocks range in age from Cambrian to Mississippian and have a maximum thickness of 5000 feet near Sarnia, Ontario.

The stratigraphic units encountered in the study are Alexandrian (Lower Silurian) in age; the lithologies and thicknesses of the formations and members are given in Figure 2. The Thorold Formation is often considered to be Niagaran (lower Middle Silurian) in age by some stratigraphers (Bolton, 1957; B. V. Sanford, 1969).

Several names have been suggested in the literature to designate the Lower Silurian sediments in the study area. The plethora of names is due to the fact that the study area is in a zone of interfingering between a marine carbonate-shale megafacies, developed in the Michigan basin, and a marine to continental sandstone megafacies of the Appalachian basin (J. T. Sanford, 1972).

The sandstone megafacies alone occurs in New York, Pennsylvania, and Ohio. In western New York, the terms "Medina" or "Albion" are preferred (Fisher, 1954). In northern Pennsylvania the name Medina is also used (Kelly and McGlade, 1968), whereas
<table>
<thead>
<tr>
<th>AGE and GROUP</th>
<th>FORMATION</th>
<th>THICKNESS in Feet</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Silurian</td>
<td>Irondequoit</td>
<td>3 - 10</td>
<td>Limestone, light-grey, crystalline, porous, reeal masses</td>
</tr>
<tr>
<td></td>
<td>Reynales</td>
<td>8 - 15</td>
<td>Limestone and dolomite, light grey, dense, massive, minor shale partings</td>
</tr>
<tr>
<td></td>
<td>Neahga</td>
<td>1 - 6</td>
<td>Shale, dark-grey, locally fossiliferous; minor limestone</td>
</tr>
<tr>
<td></td>
<td>Thorold</td>
<td>1 - 14</td>
<td>Sandstone, light-grey, fine-grained, quartzose; shale interlayers</td>
</tr>
<tr>
<td>Lower Silurian</td>
<td>Grimsby</td>
<td>5 - 74</td>
<td>Sandstone, red with grey mottling, fine- to medium-grained, quartzose; red-grey shale interlayers</td>
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<tr>
<td></td>
<td>Cabot Head</td>
<td>0 - 50</td>
<td>Shale, grey, fossiliferous; minor thin siltstone and silty limestone layers</td>
</tr>
<tr>
<td></td>
<td>Manitoulin</td>
<td>0 - 12</td>
<td>Dolomite to dolomitic limestone, medium grey, crystalline, bioclastic</td>
</tr>
<tr>
<td></td>
<td>Whirlpool</td>
<td>0 - 20</td>
<td>Sandstone, light-grey, fine- to medium-grained, quartzose</td>
</tr>
<tr>
<td>Ord. Richmond</td>
<td>Queenston</td>
<td>150 - 1,100</td>
<td>Shale, red, minor interlayers of grey-green shale, red silalton, and grey silty dolomite</td>
</tr>
</tbody>
</table>

Figure 2. -- Stratigraphic units cropping out along the lower part of the Niagara Escarpment from Hamilton to Fulton, New York. ( from Martini 1971; Bolton 1957 ).
in Ohio the name "Clinton" is loosely used to identify the Medina clastics (Overby and Henniger, 1971). The latter name should not be confused with the Middle Silurian Clinton Group of southwestern Ontario (Bolton, 1957).

In southwestern Ontario, the marine carbonate-shale megafacies is well developed. The term "Cataract" is generally used (Bolton, 1957; Sanford, 1969). However, Fisher (1954) and Martini (1966) favour the use of the term Medina for the sedimentological unit between the Queenston and the Reynales Formations in the Niagara Peninsula, where representatives of both the sandstone megafacies and the marine carbonate-shale megafacies intertongue.

Since this thesis is concerned only with sedimentology and depositional environments, and not with regional stratigraphy, the term Medina will be used, for convenience, to define the lithological sequence between the Queenston and Reynales Formations. Thus the term Medina refers to the sandstone megafacies of the Appalachian basin, which extends into the Niagara Peninsula and eastern and central Lake Erie. The stratigraphic units described by Bolton (1957), such as the Cabot Head, Grimsby, Neahga, Reynales, and Thorold are referred to as formations.

Regional Sedimentation

Regional clastic sedimentation of southwestern Ontario, during Alexandrian time, is discussed by Yeakel (1962) and Lumsden
Figure 3. — Regional geology of the Grimsby Formation
and Pelletier (1969). Alexandrian sedimentation represents the final phase of deltaic deposition which was initiated during the Upper Ordovician (Richmond). Outcrop and subsurface grain size trends and formational thickness trends of the Medina clastics (Fig. 3) indicate a southeastern provenance within central Pennsylvania, eastern West Virginia, and northern Maryland. Here, uplift associated with the Taconic orogeny resulted in the deposition of the Upper Ordovician Juniata and Bald Eagle conglomerates and the Lower Silurian Tuscarora quartzites, which formed broad alluvial plains. The Grimsby Formation is the fine-grained equivalent of the Tuscarora quartzites; thus the Grimsby "zero line" marks the northwestern feather-edge of the Tuscarora clastic wedge.

**Lower Silurian Stratigraphy of Southwestern Ontario**

The following summary of Lower Silurian stratigraphy in southwestern Ontario and adjacent areas is based upon the works of Fisher (1954), Bolton (1957), Martini (1966, 1971), B. V. Sanford (1969), and Kilgour (1972).

The Medina stratigraphy (Fig. 4) records the eastward transgression, and in turn, the westward regression of the Alexandrian Sea. This was ultimately followed by a period of renewed eastward transgression (by the Niagaraan Sea?). Medina sedimentation encompasses the simultaneous deposition of distinct contiguous lithostratigraphic units.
Stratigraphic units
1. Queenston shales
2. Whirlpool sandstone
3. Power Glen shale
4. Manitoulin dolomite
5. Cabot Head shale
6. Grimsby (marine), sandstone and shale
7. Grimsby (non-marine) sandstone
8. Thorold sandstone
9. Neahga shale
10. Reynales dolomite

Depositional environment
- tidal flats
- beach, aeolian
- open marine shales
- open marine carbonate
- delta outer fringe, prodelta, open marine shales
- beach, tidal flat, distributary complex, delta outer fringe?
- beach, fluvial channel
- lagoon - tidal flat
- marine carbonates

Figure 4. -- Restored stratigraphic cross-section of the Lower Silurian in southern Ontario and western New York (after Fisher, 1954); a comparison between the stratigraphic units of Fisher (1954) and depositional environment (primarily from Martini, 1974; also from Fisher, 1954; Bolton, 1957).
Transgression

At the beginning of the Silurian, eastward transgression spread the sands of the Whirlpool Formation upon the exposed Queenston shale (Richmond) tidal flats. Continued transgression resulted in an overlap of the Whirlpool sandstone by the Power Glen shale, and the carbonate facies equivalent, Manitoulin dolomite. In western New York, Queenston deposition was contemporaneous with the Whirlpool deposition in southwestern Ontario. In the western New York area, the Queenston shale is conformable with the overlying Grimsby sandstone and its lower Whirlpool equivalent.

Deltaic progradation

Withdrawal of the Alexandrian sea was accompanied by the northwestward buildout of the Grimsby delta. Martini (1966) subdivides the Medina stratigraphy into various depositional environments; a comparison between these depositional environments and the stratigraphic units of Fisher (1954) is given in Figure 3. The depositional environment approach is of significance since the redbed Grimsby Formation includes various coastal and deltaic topset environments. The lateral equivalent Cabot Head Formation represents prodelta and shelf deposition. A coarsening-upward vertical profile represents the progradational deltaic stratigraphy.

Niagara transgression

A second eastward transgression reworked the upper Grimsby sands and redeposited them as an inshore quartzitic facies known as the Thorold Formation. The Thorold Formation represents the
destructional phase of the Grimsby delta. The Thorold-Grimsby formation contact is a paraconformity.

The relationship among the Thorold sandstone, the Neahga shale, and the Reynales dolomite is unclear. B.V. Sanford (1969) believes they are, in part, all laterally equivalent. Kilgour (1972) theorizes a major unconformity divides the Reynales dolomite from the underlying Thorold sandstone and Neahga shale.

**Lower Silurian Tectonism.**

Silurian sedimentation of southwestern Ontario occurred within two large depocenters (Fig. 5); (1) the elongate Appalachian basin in the south, extending into the Niagara Peninsula and eastern Lake Erie, and (2) the Michigan basin in the west, with its eastern rim passing through western and central Lake Erie and northward along the axis of the Algonquin arch. Southwestern Ontario formed a hinge line and marginal area between these two basins, as they are separated by the Algonquin arch, a positive basement structural trend which plunges southeast in the Precambrian shield under the Ontario peninsula. Other basement structural features, such as the Findlay arch and Chatham sag, did not influence sedimentation until the Upper Silurian and Devonian (Brigham, 1971).

During the Lower Silurian, the cratonic Michigan basin was a center for carbonate formation while the Appalachian basin was an area of clastic input. Southwestern Ontario represents
Figure 5. -- Silurian depositional basins in southwestern Ontario and adjacent United States (from B.V. Sanford, 1969)
a critical area in Silurian stratigraphy for here the cratonic carbonate megafacies of the Michigan basin interfingers and pinches out within the geosynclinal detrital megafacies of the Appalachian basin (J. T. Sanford, 1972). The complex stratigraphy of interfingering and pinch outs of lithological units may have been controlled to a large degree by the Algonquin arch.

The influence the Algonquin arch had upon the distribution of the Medina clastics is unclear. Bolton (1957) views the Algonquin arch as a broad shallow water platform which hindered the distribution of clastic material from the Appalachian basin into the Michigan basin. B. V. Sanford (1969) suggests the Algonquin arch was a physical barrier which completely obstructed the eastern clastic sediment input to the Michigan basin. In contrast, Brigham (1971) and J. T. Sanford (1972) discount any physical barrier hypothesis; they postulate the clastic facies patterns occurring near the Algonquin arch simply reflect the distance of detrital grain transport from the source rock.

Despite the lack of understanding of the Algonquin arch, nevertheless, the Lower Silurian stratigraphy of southwestern Ontario does indicate that the tectonic movement within the study area was relatively minimal when compared to the tectonism of the areas of the rising Taconic Mountains or of the subsiding Michigan basin (J. T. Sanford, 1972). Furthermore, the stratigraphy also suggests a shallow Silurian sea (Bolton, 1957; Martini, 1971); the shore lines of this sea migrated long distances in response to the slight tectonic movements.
GENERALIZED DELTAIC FRAMEWORK

A progradational deltaic sequence has been proposed for much of the Lower Silurian clastic sequence of southwestern Ontario and western New York (Fisher, 1954; Martini, 1966). In order to gain a better understanding, in general, of the Medina sediments, and in particular, the Grimsby Formation, the broad properties of deltaic deposits are briefly reviewed in the following paragraphs.

**Vertical Profile**

Visher (1965) presents a basic vertical profile of progradational deltaic deposits. Such deposits exhibit a generalized coarsening-upward vertical profile as (1) the distal prodelta clays grade upward into (2) the prodelta silts and clays, which in turn grade upward into (3) the fine sands and minor clays of the delta fringe and delta topset deposits.

**Delta Types and Net Deltaic Sand Distribution**

Debouching sediment at the mouth of a river is influenced by waves, tides, and littoral and fluvial currents (Coleman and Wright, 1975). Studies of modern deltas reveal a spectrum of delta types ranging among wave-, tide-, and river-dominated end members, based upon the relative strength of the marine and
**Figure 6.** Net sand distribution models (from Coleman and Wright)
fluvial processes. Each end member is characterized by a distinctive vertical profile of depositional environments (Miall, 1976). Furthermore, the relative intensities of the marine and fluvial processes also determined the geometry of the deltaic deposits; hence, Coleman and Wright (1975), from the study of 34 modern deltas, present six net deltaic sand distribution models. Features of the sand distribution patterns and the corresponding sand body descriptions are given in Figure 6.

**Stratigraphy**

Traditional layer cake stratigraphy cannot be rigorously applied to deltaic sequences. This is because the stratigraphic framework commonly exhibits abrupt lateral and vertical variations in lithology with the lensing and erosional truncation of many bedding units. Such a stratigraphy is the result of (1) the simultaneous deposition of various deltaic facies within a restricted area, and (2) the overlapping and/or downcutting of deltaic topset environments (such as distributary channel, distributary mouth bar, and crevasse deposits) onto or into older prodelta, delta front, tidal flat, and interdistributary bay deposits.
GRIMSBY FORMATION

This chapter represents a compilation of information relevant to the present study found in the geological literature on the Grimsby Formation.

Stratigraphy

At a regional scale, Martini (1971) attributes the stratigraphy of the Grimsby Formation to shifting deltas and a reworking and redistribution of the delta-borne sediments by tides and strong longshore currents. The combination of a relatively low rate of clastic input, a shallow Silurian sea, and a very slow subsidence yielded a complicated interfingering of deltaic topset environments and of prodelta and/or interdeltaic environments.

At an outcrop scale, in the Niagara area, Martini (1971) demonstrates the Grimsby stratigraphy is the result of sandstones of distributary channel fills, which merge with, or cut into, deltaic fringe sandstones, tidal flats, and marine shales. The bedding commonly is lensitic. Consequently, abrupt lateral and vertical variations of the bedding units are frequently observed.

Petrology

The Grimsby Formation is comprised primarily of red sandstone.
<table>
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<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Clear Creek Field central L.Erie</td>
<td>Niagara escarpment</td>
<td>Niagara escarpment in the Niagara Peninsula</td>
<td></td>
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<tr>
<td>Formation</td>
<td>Grimsby</td>
<td>Thorold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain size in mm</td>
<td>0.063-0.13</td>
<td>0.10-0.16</td>
<td>0.036-0.11</td>
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</tr>
<tr>
<td>Composition (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>92</td>
<td>82</td>
<td>81-94</td>
<td>91-95</td>
</tr>
<tr>
<td>Feldspar</td>
<td>1</td>
<td>14</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Accessories</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- hematite</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- clay</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- rock fragments+chert</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- others</td>
<td>4</td>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Notes</td>
<td>Rounded to subrounded quartz grains with optically continuous quartz overgrowths. Microscopic hematite dust outlines primary grains. Cemented by silica and subordinate calcite.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 — Petrology of the Grimsby Formation.
with minor shale; the shale gains in importance in the lower portion of the formation and as the Grimsby "zero line" is approached. The Thorold Formation consists of grey sandstone with subordinate shale (Bolton, 1957).

The composition and grain size of the sandstones which make up the Grimsby and Thorold Formations is reported by Martini (1966) and Lumsden and Pelletier (1963) from outcrops along the Niagara escarpment; B. W. Shelton (1973) and Tovell (1976) give values from the Clear Creek gas field within central Lake Erie. The data is presented in Table 2. All analysis consistently yield a very fine-grained, highly quartzose sandstone.

**Paleontology**

The Grimsby Formation, on the basis of paleontology, may be divided into marine and continental components (Fig. 4); in western New York the Grimsby Formation is entirely continental; in the Niagara Peninsula the marine component appears, and progressively gains in importance until the sequence is entirely marine in the vicinity of Hamilton, Ontario.

The continental sequence contains only a trace fossil assemblage (discussed under sedimentary structures) plus *Lingula clintoni*. The marine strata contain an open-marine fauna (Brachiopoda and Pelecypoda dominate the assemblage) and trace fossils (Fisher, 1954; Bolton, 1957; Martini, 1966). According to Bolton (1957) the faunal content of the Grimsby strata is sparse. *Lingula clintoni* is interpreted as indicating brackish
water stress environments (Bolton, 1957; Martini, 1974).

Isopach Maps

Isopach maps of the Grimsby Formation are given by (1) Martini (1966, p. 330) for the Niagara Peninsula and western New York (Fig. 7), (2) B. V. Sanford (1969, p. 28) for the Niagara Peninsula and adjacent Lake Erie, and (3) Beards (1973, p. 20) for Norfolk County, Ontario, and offshore Lake Erie. A detailed comparison among the three maps is difficult because of the uncertain manner in which the gradational Grimsby-Cabot Head contact was derived from one map to the next. Nevertheless, some general patterns are observed:
a) the Grimsby Formation non-uniformly thickens to the southeast into the Appalachian basin,
b) on a regional scale, assuming a regular basin surface of deposition, Martini (1966) suggests the presence of three distributary complexes, two of which extend into southwestern Ontario (Fig. 7),
c) on a more detailed scale, Beards (1973) depicts in Norfolk County a series of northeastward trending, localized, small, pod-shaped sandstone thickenings, possibly representing sand bars.

Reservoir Geology

Mechanisms for the entrapment of hydrocarbons are stratigraphic in nature. The limits of a field are formed by the
Figure 7. — Isopach map of the Grimsby sandstone in the Niagara Peninsula and western New York. Solid lines show trends of three possible distributary channel complexes (from Martini, 1966). Contour interval is 10 feet.
lateral thinning, pinch out, and/or shale out of reservoir sandstones (Kelly and McGlade, 1968). The optimum area for hydrocarbon production occurs between continental and marine environments, where bodies of well sorted sandstone are sealed by surrounding shales (Martini, 1974a). Oil and gas fields of the Tuscarora clastic wedge (Fig. 3) occur where the sandstone-to-shale ratios are less than 2:1, with the greater number of fields occurring where the ratio is less than 1:1 (J. W. Shelton, 1973). Therefore, large areas of Medina production occur just east of the western limit of overall sandstone occurrence (Kelly and McGlade, 1968).

Economic accumulations of natural gas occur in the Grimsby Formation (Clear Creek Field) in central Lake Erie. However the actual gas flow within the Grimsby Formation is poorly understood, as even non-producing wells show a high porosity and good permeability; Tovell (1976) suggests that grain-size distribution and packing has a great influence on the flow properties through the sandstone. The situation is further complicated by variable silica cementation throughout the sandstone (B. W. Shelton, 1973).
The clastic succession of the upper Cabot Head, Grimsby, and Thorold Formations in this thesis is described in terms of five genetically meaningful lithofacies, each characterized by certain gross lithologies and associated sedimentary structures. The generalized descriptions of the lithofacies are given below (a more comprehensive description and explanation of the lithofacies is offered in subsequent chapters of the report); the generalized stratigraphic column of the Medina sequence represented by these lithofacies is given in Figure 8. From stratigraphically highest to lowest, the generalized lithofacies are:

**Facies A** - (1) a fine-grained, quartzose sandstone, exhibiting plane-lamination, dune-scale inclined lamination, large-scale low- and moderate-angle planar cross-stratification, small-scale trough and ripple-drift cross-stratification; and (2) minor interstratifications of thin to very thick mudstone beds. This lithofacies is comprised mainly of beach deposits with secondary channel fill and tidal flat to lagoon deposits.

**Facies B** - a complex fine-grained, quartzose sandstone succession with subordinate shale comprised of interstratifications of (1) sandstone beds exhibiting asymmetrical and trough ripple sets in both unidirectional and multidirectional oriented groups, micaceous plane-laminae, and intermittent very thin silty-shale partings, (2) sequences of medium- to thick-bedded plane- and dune-scale inclined laminated sandstone separated by numerous
erosional discordances and rare shale partings; the sandstones carry abundant floated shale and shell debris, and (3) thick successions of structureless sandstone. The above sandstones represent delta front (distributary channel to distributary mouth bar) depositional environments.

**Facies C** - (1) a fine-grained clean to dirty, quartzose sandstone characterized by plane-lamination, dune-scale inclined lamination, large-scale low-angle planar cross-stratification, and abundant shells and small shale clasts, with (2) subordinate interstratified thin to medium, shell and/or shale clast intraformational conglomerates. Facies C is interpreted as a storm-influenced beach deposit.

**Facies E** - very broadly, a fining-upward sequence passing vertically from clean quartzose sandstone to rhythmic alternations of shale and siltstone laminae, with interlayered argillaceous zones of intensive biogenic reworking. This lithofacies represents a tidal flat deposit.

**Facies D** - (1) a mudstone succession with varying amounts of interlayered siltstone and fine-grained sandstone as lenticular laminae to continuous, very thin beds; with interstratified (2) thin to thick sandstone beds; and (3) very thin to very thick coquroid sandstone beds. Facies D represents the muddy prodelta to open marine deposits with interlayered coarse storm layers.

The lithofacies described above are very similar to lithofacies from other shallow water epeiric sea deposits, such as those described by Potter and Glass (1958), Masters (1967),
Michaels and Dixon (1969), Wunderlich (1970), Harms et al. (1975) and Simpson (1975). With the exception of those deposits displaying unconformities or periods of non-deposition, these lithofacies reflect the orderly development of a succession of depositional environments which migrated through time, both laterally and vertically, in response to transgression and regression of the shoreline (Walther's Law; Blatt et al., 1972).
Figure 8 - Generalized stratigraphic section of the Grimsby sand body in the subsurface of central Lake Erie
SEDIMENTARY STRUCTURES

Various types of sedimentary structures are common in certain lithofacies of the present study. It is believed that their occurrence in the lithofacies reflects the conditions under which sedimentation took place. Furthermore, their presence and associated gross lithology may be related to certain types of depositional environments and subenvironments.

Many of the sedimentary structures encountered in the lithofacies of the Thorold and Grimsby Formations are presented in Table 3. Brief descriptions and the environmental significance of the various sedimentary structures are given in the following pages.

**Ripple Cross-stratification**

Ripple cross-stratifications are intrastratal sedimentary structures, whereas ripple marks are the surface forms. Ripples are produced on the surfaces of non-cohesive material, such as sand or silt, by currents or waves. In many ripple systems, the erosion of sand from the stoss side and its subsequent deposition on the lee side causes the ripple to migrate downstream (Pettijohn et al., 1973). Thus, sediment movement through ripple migration entails the bed load transport of sand; frequently ripple migration is accompanied by the deposition of sediment from suspension.
<table>
<thead>
<tr>
<th>Stratigraphic unit(s)</th>
<th>Thorold Formation; upper Grimsby Formation; Neahga shale (?)</th>
<th>Grimsby Format</th>
</tr>
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<td><strong>Facies</strong></td>
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<td>A</td>
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<td>Interpretation</td>
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<td>Lithology</td>
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<td>sandstone, mudstone, siltstone/shale interlaminations</td>
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<td>Sedimentary Structures</td>
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<td>Colour</td>
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<td>light grey (N7), dark grey (N3)</td>
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<td>Ripple cross-stratification</td>
<td>asymmetrical ripples</td>
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<tr>
<td></td>
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<td></td>
<td>ripple drift</td>
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<td></td>
<td>small-scale trough</td>
<td>X</td>
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<tr>
<td>Large-scale cross-stratification</td>
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<td>X</td>
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<td></td>
<td>moderate angle planar</td>
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<tr>
<td>Plane lamination</td>
<td>micaceous laminae</td>
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<td>heavy mineral laminae; colour banding</td>
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<tr>
<td>Dune-scale inclined lamination</td>
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<td>Biogenic structures</td>
<td>horizontal burrows</td>
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<td><em>Arthropodiform</em></td>
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<td>Irregular <em>Teichichnus</em></td>
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<td></td>
<td>vertical burrows</td>
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<tr>
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<td>zones of intensive biogenic reworking</td>
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<td>Other structures</td>
<td>scour-and-fill</td>
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* X = present, - = absent

Table 3.
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<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>tidal channel point bar</td>
<td>distributary complex; distributary mouth bars; distributary channel fills (?)</td>
<td>beach; sandbar to barrier island</td>
<td>prodelta to open marine shelf</td>
</tr>
<tr>
<td>tidal bedding</td>
<td>sandstone; subordinate mudstone</td>
<td>sandstone</td>
<td>mudstone</td>
</tr>
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<td>reworked sandstone</td>
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<td></td>
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<td>stratified component</td>
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<td>interlayered sandstone and coquina-oid sandstone storm layers in mudstone</td>
</tr>
<tr>
<td>greyish red (5R4/2), dark grey (N3)</td>
<td>pale red (5R6/2), greyish red (5R4/2); 10R4/2</td>
<td>greyish red (5R4/2), light grey (N7)</td>
<td>light grey (N7), greyish red (10R4/2)</td>
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Table 3. - Occurrence of sedimentary structures in lithofacies
The preservation in the sedimentary record of a ripple form, or of a substantial amount of sediment originally contained within the ripple form, indicates that the rate of aggradation is large compared with the rate of migration of the ripple form (McKee, 1965; Blatt et al., 1972). If net deposition is high, involving much fall out of sediment from suspension, the stoss side is protected from erosion, and the complete ripple form is preserved (McKee, 1965). With reduced deposition from suspension, the ripple stoss-side undergoes erosion and the degree of preservation is dependent upon the sediment supply (Allen, 1963). If net sediment deposition is low, and/or the rate of deposition is substantially smaller than the rate of ripple migration, the ripple has little chance of preservation (Blatt et al., 1972). Thus the form of ripple cross-stratification is related to a balance between the current or wave strength, rate of sediment supply, and the amount of deposition from suspension.

**Symmetry**

The meaning of ripple symmetry is unclear. Very broadly, ripples with symmetrical cross-sections are attributed to wave-generated oscillatory currents, whereas those with asymmetrical cross-sections are produced by unidirectional currents (Pettijohn, et al., 1973; Harms et al., 1975). However, some reports (McKee, 1965; Reineck and Singh, 1973) indicate that simple ripple geometry cannot unambiguously lead to a distinction between wave and unidirectional current formed ripples, since oscillation ripples are commonly asymmetrical. In addition, the issue is further complicated by combined-flow ripples, that is,
ripples produced by a combination of both oscillatory and uni-
directional currents (Blatt et. al., 1972; Harms et. al., 1975).
Similarly, the internal structure of ripples does not always
permit an easy distinction between wave and unidirectional current
ripples. Both asymmetrical wave ripples and current ripples are
commonly similar; each may show foreset laminae dipping in a
single direction (Reineck and Singh, 1973). Furthermore, combined-
flow ripples may exhibit an internal structure resembling that
of current ripples (Blatt et. al., 1972). However, in contrast,
the internal structure of symmetrical wave ripples are commonly
characteristic (Reineck and Singh, 1973; Harms et. al., 1975);
the distinguishing features are (1) bundle-wise arrangement of
foreset laminae, (2) foreset laminae with off-shoots, and (3)
the chevron-like arrangement of foreset laminae (see Fig. 9).

 Identification

The precise identification of rippled deposits in core is
commonly difficult. This is because: (1) ripple cross-stratifica-
tion depicted in literature stresses the configurations of
laminae in vertical sections cut normal or parallel to the
ripple crest. Vertical sections cut other than normal or
parallel to the ripple crests may yield unidentifiable configura-
tions of laminae; (2) a specific ripple type (lingoid, undulatory,
straight-crested, etc.) exhibits various configurations of
laminae in vertical sections cut normal or parallel to the
ripple crests (Fig. 8). However, the configuration of laminae
observed in a single vertical section does not always unequivo-
cally indicate the specific ripple variety which produced the
Various kinds of chevron structures developed in wave-generated ripple marks. The oppositely dipping laminae join in central trough zone, which may show variants: a-d chevron structure in ripple crests; e-f chevron structure in ripple troughs. (After Boersma, 1970)

**Figure 9. Ripple cross-stratification.**
1. Block diagrams showing cross-bedding produced by the migration of (A) straight-crested current ripples, and (B) lingoid current ripples, and (C) undulatory current ripples. 2. Wave-generated ripples, (D) chevron structures, and (E) internal structure of asymmetrical wave ripples and the resulting cross-bedding. Note irregular lower bounding surface, bundle-wise arrangement of foreset laminae with off-shoots. 3. Ripple-drift cross-stratification, (F) Kappa variety, and (G) Lambda variety. (A-E from Reineck and Singh, 1973; F and G from Allen, 1963).
ripped deposit; (c) some ripple varieties exhibit parallel-laminations in certain vertical cuts, thus masking the rippled nature of the sediment.

Therefore, vertical sections oriented both normal and parallel to the current or wave direction are desired for ripple cross-stratification identification. But within core, the slabbed faces are not apt to be cut normal and/or parallel to the ripple crest. Moreover, the size and shape of a slabbed core specimen essentially provides only a single vertical section of view.

Depositional environments

In almost any environment with non-cohesive sediment where current or wave ripple marks are formed, ripple bedding is produced. It is most abundantly developed in beach shoreface and upper foreshore, and intertidal sand flats (Komar, 1975); tidal channel and fluvial sediments - upper point bars and levees (Reineck and Singh, 1973); distributary mouth bars and distributary channels (Coleman and Gagliano, 1965); and sandy shelf where the current is available to produce ripples (Reineck and Singh, 1973).

Occurrence

A wide spectrum of ripple cross-stratification is found in the cores from the Medina clastics. Ripple cross-stratification is a common structure exhibited by thin to very thin beds and laminae of siltstone or fine-grained sandstone interlayered within sequences of mudstone. Such a structure records the migration of sand or silt across the mud bottom; frequently the cross-
stratified sediments grade into overlying mud, inferring deposition from a waning current.

Ripple cross-stratification occurs abundantly in the Grimsby sand body. The major emphasis of the following discussion is upon ripple cross-stratification varieties encountered in Facies A, Facies B, and Facies C sandstone and their geological significance.

**Symmetrical ripple cross-stratification**

Small-scale symmetrical ripple forms (pl. 1C) occur uncommonly within Facies B sandstone. The symmetrical geometry suggests that the ripple was wave generated. Ripple cross-stratifications in which the foreset laminae are arranged in a chevron-like fashion were also uncommonly observed in Facies B sandstone; these ripples are interpreted as being wave generated.

**Asymmetrical ripple cross-stratification**

In a single vertical section oriented parallel or near-parallel to the current direction ripple cross-stratification is commonly found to be composed of groupings of asymmetrical ripple sets. According to Allen (1963), in the production of this cross-stratification (excluding the ripple-drift variety) it is necessary for each asymmetrical ripple to receive from suspension a volume of sediment less than the volume of sediment less than the volume of the ripple body. Such cross-stratification may be be found in all sandstone lithofacies of the present study, but it is observed most commonly in the sandstones of Facies B.
A characteristic ripple cross-stratification of Facies B sandstone is illustrated in Plate 1A. The ripple form is strongly asymmetrical and occurs as solitary or grouped sets. The lower bounding surface is generally non-erosional and planar. The foreset laminae are defined by mica wisps and show tangential relationships with the lower bounding surface and ripple topsets. The foreset laminae commonly merge into silty-shale laminae. Frequently the upper surface of the ripple form may show slight erosion. This cross-stratification implies unidirectional flow conditions; the associated silty-shale laminae suggests fluctuations in current strength.

Small-scale trough cross-stratification

Slabbed core faces exhibiting small-scale trough cross-stratification may result from a vertical section cut through several ripple cross-stratification varieties (Fig. 8), including undulatory and lingoid current ripples and certain wave ripples. Also certain vertical cuts through ripple-drift cross-stratification exhibit laminae similar in structure to through cross-stratification. Therefore trough cross-stratification does not unequivocally indicate a specific ripple variety.

Small-scale trough cross-stratification is developed abundantly in Facies A and is a characteristic of this facies; it has a lesser occurrence in Facies B and Facies C. Small-scale trough cross-stratification occurs as grouped ripple sets (Pl. 3A, 3B, and 1B) in which an individual set never exceeds the width a core in length and is only one or two
centimeters thick. The lower bounding surface is erosional and trough-shaped.

Interstratifications of groupings of asymmetrical ripple sets and small-scale trough sets may be found in Facies B sandstone (Pl. 1B). This cross-stratification infers that the sediment was influenced by changes in flow orientation and possibly flow conditions. Changes of water depth and current orientation associated with tidal currents may be responsible for the formation of such a structure (Reineck and Singh). Coleman and Gagliano (1965) report multidirectional ripple cross-stratification in distributary mouth bars; they are the product of both wave and current processes.

**Ripple-drift cross-stratification**

Ripple-drift cross-stratification consists of grouped ripple sets which are small in scale and are divided at the base and top from each other by an imaginary planar surface. Individual foreset laminae are tangential at both the base and top with these surfaces and form sigmoidal-shaped curves. When clay is available a pseudobedded thin clay seam is formed by the progressive coalescing of foreset laminae across the width of a core.

Ripple-drift cross-stratification results from the migration
of trains of asymmetrical ripple structures, in which an individual ripple in advancing its own length, receives from suspension a volume of sediment greater than the volume of the ripple body (Allen, 1963). A low flow strength, along with an abundant, temporarily suspended sand supply, is implied (Harms et. al., 1975).

According to McKee (1965) the chief significance of ripple-drift cross-stratification in the geological record is that it is an indicator of environments involving large and rapid sand accumulation. Such depositional environments include river flood plains and point bars and deltaic subaqueous levee deposits. McKee (1965) further reports that despite abundantly developed ripple marks, beach and intertidal sand flat environments lack preserved ripple-drift cross-stratification because of low net sand deposition in these environments.

Ripple-drift cross-stratification occurs within Facies A sandstone (Pls. 1D and 2). A slight erosion of the ripple stoss side is commonly observed. The amount of shale between cosets varies from zero, through slight traces, through to continuous, thin, mudstone laminae. Therefore the ripple-drift cross-stratification may resemble either Type one or Type two ripple-drift cross-lamination varieties of Walker (1963). Accordingly, Type one infers net sand deposition from a steady current, and it is characteristic of fluviatile and shallow water environments. Type two indicates periodic changes in the competence of the current. The mudstone represents clay deposition from suspension. Type two suggests hydrodynamic conditions
intermediate between fluvial or shallow water traction currents and turbidity currents.

**Plane-lamination**

Plane lamination infers horizontal and near-horizontal bedding surfaces. Two distinct types of plane-lamination in sandstone are found:

a) The first type consists of alternating sandstone or siltstone laminae and extremely thin micaceous laminae. Such a structure suggests traction and suspension deposition within an environment where current velocity fluctuates (Sanders, 1965, p. 199). This variety of plane-lamination is commonly developed in Facies B sandstone where the micaceous laminae may coalesce vertically into a very thin silty-shale bed; the plane-lamination is commonly associated with zones of ripple cross-stratification.

b) A second variety of plane lamination suggests deposition of the upper flow regime. Plane-laminated sandstones of this nature are found in Facies A, Facies B, and Facies C. The plane lamination is defined by heavy mineral concentrations or by a faint colour banding. In Facies C the concentration of small flat shell fragments within the laminae results in a pronounced parting lineation (Pl. 3C). Plane-laminated sandstones may be formed in a river or tidal channel, or in the swash zone of a beach (Reineck and Singh, 1973). In a beach environment the plane-bed surfaces are related to the upper flow regime conditions produced by breaking waves.
Alternating Shale and Siltstone Laminae

This structure refers to alternating sets of horizontal to near-horizontal laminae of silt- and clay-sized material. The formation of such parallel-stratification is favourable in tidal flats and fluvial environments.

Tidal bedding

Tidal bedding consists of rhythmic alternations of siltstone and shale laminae. The laminae range from a millimeter to a centimeter in thickness. A sharp contact is found between the laminae; a distinct colour contrast is also observed. The rhythmic bedding is commonly gradational into thicker laminae and beds of sandstone or mudstone. Tidal bedding is a major component of Facies E (burrow facies). It is also developed within the shale interbeds of Facies A sandstone. The genesis of tidal bedding is attributed to changes in tidal current strength and direction. Sand is deposited during periods of current activity, both flood and ebb, while mud is deposited during the stand-still phase of high and low water (Reineck and Singh, 1973).

Fluvial bedding

In Facies A, the association of a unit comprised of alternating siltstone and shale laminae with an underlying ripple-drift cross-stratified sandstone unit suggests a fluvial depositional environment (McKee, 1965; Reineck and Singh, 1973). Parallel-stratified silt and mud is reported in the upper portions of channel point bar deposits. Deposition is from suspension within the shallow parts of a channel (low current velocities near river bank in upper part of point bar; Masters, 1967) and/or during slack water periods (Harms and Faehnstock, 1965).
Dune-scale Inclined Lamination

Inclined lamination refers to bedding in which the dip is a depositional characteristic. In core the presence of large-scale sedimentary structures is suggested by the recognition of dune-scale inclined lamination. Such lamination occurs in the sandstones of Facies A, Facies B, and Facies C. Possible sedimentary structures suggested by this lamination includes sand bars, subaqueous dunes, aeolian dunes, and giant ripples; these should be associated with sets of large-scale cross-stratification. Dune-scale inclined stratification also occurs in point bar deposits, which may exhibit longitudinal and large-scale cross-bedding (Reineck and Singh).

Swash Cross-stratification

Sets of low angle (less than 10°) cross-strata are associated with plane bedded sandstone, especially those with a well-developed parting lineation (Pl. 3C). The even low-angle truncation of an underlying plane-laminated sandstone by an erosional surface in which the lamination of the upper plane-laminated sandstone is parallel to the bevelled surface is analogous to swash cross-stratification (Harms et al., 1975). This cross-stratification is produced upon beach foreshores, longshore bars, the tops of distributary mouth bars, and other shoals where sand is subjected swash and backwash. The erosional surface is believed to be formed by periodic planation of the laminated sand during abnormal periods of high current activity, such as storms.

Swash cross-stratification is common in both Facies A and
Facies C sandstone. In Facies C, a lag deposit of small, angular shale clasts frequently rests upon the planar erosional surface.

**Moderate-angle Cross-stratification**

Both solitary and grouped sets of moderate-angle (10–30°) cross-stratification are commonly associated with plane- and dune-scale inclined-laminated sandstone. An individual set is generally less than half a foot in thickness. The lower bounding surface is erosional and may be planar or irregular. The sets are lithologically homogeneous; shale clasts and shell fragments may frequently be concentrated along the foresets.

Allen (1963) reports that cross-stratification of this general form may result from the migration of subaqueous dunes. Also, Allen reports that this variety of cross-stratification could be constructed in shallow water by the building of solitary banks in rivers or on beaches; longshore bars commonly display cross-stratification of similar angular relationships in their shoreward facing portions (Reineck and Singh, 1973). This structure occurs in Facies A, Facies B, and Facies C sandstone.

**Trough Cross-stratification/plane-lamination Cross-bedding**

An erosional contact between an underlying plane- or dune-scale inclined-laminated sandstone and an overlying small-scale trough cross-bedded sandstone (Pl.4A) is observed infrequently in Facies A sandstone. Since grain size is constant, this
feature infers the erosion of sand deposited under higher flow velocities by migrating ripples generated by lower flow velocities.

Such a situation may occur in a nearshore sandy environment where tidal fluctuation results in the intermittent emergence of large-scale structures such as dunes and sand bars. Wunderlich (1970, p. 112) illustrates the erosion of a dune by oscillation ripples at low tide.

Alternatively, such an erosional structure may reflect changing hydrodynamic conditions influencing the sediment in a river channel. Small-scale trough cross-beds typically overlie plane-stratification and large-scale cross-stratification in point bar sand sequences (Harms and Fahnstock, 1965; Reineck and Singh, 1973).

Scour-and-fill

Scour-and-fill structures are shallow depressions produced in loose, unconsolidated sediment in channel bottoms under certain current-velocity conditions and variations in turbulence (Reineck and Singh, 1973). Scour-and-fill structures occur infrequently in Facies B sandstone and Facies E tidal bedding. The infill generally consists of winnowed, slightly coarser sand than the substratum. However, rarely, a finer-grained infill (siltstone with foreset laminae) is observed in Facies B. Such a structure indicates a sudden loss of current power; such types of scour-and-fill structures are found in river environ-
ments (Reineck and Singh, 1973).

**Rip-up Shale Clasts**

Mud may erode by flaking into pebble-size mud flakes that are deposited downstream as intraformational conglomerates (Blatt et al., 1972). "Rip-up" shale clasts commonly are found within a plane- or dune-scale inclined-laminated sandstone unit. The clasts are angular, and are especially numerous when the sandstone directly overlies a scoured mudstone unit. Michaelis and Dixon (1969) indicate that the clasts occur only when the original clay sediment surface is compacted or desiccated, otherwise the eroded material is disaggregated and only a scoured surface is likely to record the erosional event.

Rip-up shale clasts (Pl. 4B) may be found in all lithofacies of this study.

**Scour Marks**

Very shallow depressions (scour marks) may be scoured in a soft mud bottom by currents (Blatt et al., 1972); decreased current velocity permits the infill of the scour marks by sand or silt. Scour marks are abundantly developed in Facies D mudstone. Sedimentary structures resulting from scour are described below:

a) Many lenticular laminae have resulted from a sparse infilling of a shallow scour mark by silt; the resultant structure is a
graded or ungraded siltstone lens enclosed in mudstone.

b) Scour marks are commonly preserved on the underside of sandstone beds as sole marks. Preservation is dependent upon the alternation of sand and clay. The cohesive clay retains the scour mark shape and a sand infill forms the mould. Flute moulds and groove moulds are found on the underside of many of the laminae and thin interbedded sandstone layers in Facies D mudstone. The flute moulds are small, several centimeters wide and a few millimeters in relief. The groove moulds are thin, several millimeters wide, and are over several centimeters in length. They occur rarely on a fluted surface. Flute moulds form by current scour, whereas groove moulds develop by the dragging of a tool, such as a shell, along the bottom by currents (Pettijohn et al., 1973).

**Load Structures**

Load structures are penecontemporaneous deformation structures (Blatt et al., 1972). They are commonly found on the soles of sandstone and siltstone laminae and very thin beds interlayered in Facies D mudstone. The load structures consist of small, less than a centimeter in width, bulbous protrusions on the sandstone sole. The protruding material represents sand that has sunk down into the underlying water-saturated mud. In Facies D mudstone, load structures commonly have modified the lower surface of scour marks. Pseudonodules, load structures which are detached from the overlying sandstone bed and are
completely enclosed in mudstone (Blatt et al., 1972) are infrequently observed. Reineck and Singh (1973) indicate that load structures are found in environments characterized by rapid mud deposition with intervals of rapid sand deposition.

Dish Structures

Dish structures are thin, subhorizontal, concave-upward, argillaceous laminations in fine-grained sandstone (Pl. 4C); they are found in the upper portions of some thick sandstone beds interlayered within Facies D mudstone. Lowe and LoPiccolo (1974) report that dish structures form during the dewatering and gradual compaction of rapidly deposited under-consolidated sand beds. Accordingly, dish structures form by the breaching of semi-permeable laminations (generally argillaceous) by upward moving pore water. This pore water was locally forced to flow horizontally beneath these layers, until an escape path (breach) was formed, permitting a continued upward migration. The formation of dish structures also entails the subsequent clay enrichment of semi-permeable laminations by clay and organic particles carried within the pore waters. Lowe and LoPiccolo (1974) report dish structures are associated with environments of general low sedimentation which are frequently interrupted by intervals of rapid sand deposition; they are reported in delta front, alluvial fan, and turbidite deposits.
Biogenic Structures

Biogenic structures are secondary sedimentary structures produced by the activity of an organism upon or within the particulate substrate (Frey, 1973). In an unconsolidated sediment organisms leave their record as burrows, trails, and fecal pellets. Also organic activity leaves a record of reworked sediment in which the primary stratification shows various degrees of disruption. The preservation of trace fossils indicates that the substrate was stabilized and not later reworked by waves or currents.

Trace fossils can furnish valuable information concerning (1) the general depositional process, (2) episodes of local deposition and erosion, and (3) characteristics of currents, substrate consistency, and in some cases causes of sediment sorting (Howard, 1975). A more comprehensive treatment of some aspects of the sedimentological significance of trace fossils is given in the detailed description of Facies D and Facies E.

Horizontal burrows occur in the argillaceous sections of the Medina clastic succession, but are most frequently observed in the uppermost stratigraphic sections (Facies A). The burrows are found (1) within very thin beds or laminae of sandstone enclosed in shale, and (2) at the contact between a thicker sandstone bed and an underlying shale bed; the organisms preferentially burrowed at a sand-clay interface. However, commonly, singular silt-filled burrows are found floated within a shale groundmass.
The horizontal burrows (Fig. 9) are similar in cross-section to the burrows depicted by Lessertisseur (1971, p. 51). In the Medina clastics, such burrows are Arthropycus alleghanensis and possibly Irregular Teichichnus (F. Simpson, personal communication). These burrows represent grazing patterns of an organism moving through the substrate at successive levels (Hantzscheh, 1975); retrusive spreiten patterns, indicating an upward displacement of the burrows, are observed most frequently.

In general, Crimes (1975) indicates that horizontal burrows are confined to specific environments (facies). Accordingly, horizontal burrows are found below daily wave base, in muddy sediments which typically contain sufficient organic material to allow sediment feeders to become established. The burrowers indicate depositional environments where desiccation or large and sudden fluctuations in temperature and salinity do not occur.

Arthropycus is restricted to the uppermost Grimsby and Thorold beds (Fisher, 1954; Martini, 1966). Arthropycus is found in Facies A of this report (Pl. 4D). It is considered to be a trace fossil that records marine or brackish water environments; moreover, it is not suggestive of open marine conditions (Martini, 1966, p. 314). Arthropycus is considered as a synonym for Phycodes (Hantzscheh, 1975). Small, horizontal burrows, possibly representing Irregular Teichichnus, have a sparse occurrence in the mudstone lithologies of Facies D.

Daedalus archimedes, a J-shaped burrow which takes on a spiral twist (Hantzscheh, 1975), showing both retrusive and protrusive spreiten patterns (Lessertisseur, 1971) is reported
Figure 10. — Biogenic structures. 1. — The horizontal burrows found within the Grimsby and Thorold Formations are similar in vertical section to the burrows depicted in (A), from Lessertisseur (1971, p. 51). 2. — (A) Phycodes (resembles Arthropycus); (B,C) Teichichmus; (D,E,F) Daedalus.
in the sandstones of the uppermost Grimsby and Thorold beds (Fisher, 1954; Martini, 1966). However, these burrows, as depicted in Fig. 9 and by Martini (1966, p. 315, pl. 4.58) were not observed in the present study.

Unidentified vertical burrows are abundant in lithologies consisting of rhythmic alternations of shale and siltstone laminae (tidal bedding) of Facies E (burrow facies). Also the vertical burrows are common within the thin to medium bedded fine-grained sandstone beds of the same facies. Very broadly, vertical burrows indicate harsh environments characterized by current and wave action, dessication, and rapid fluctuations in temperature and salinity (Crimes, 1975). The burrows serve a protective function for the burrowing organism. Also, in some cases, they may represent escape traces (Howard, 1975).
FACIES E - BURROW FACIES

Facies E, referred to as the "burrow facies", is not found in all core but when present it occurs within the mid-portions of the Grimsby sand body. A sharp scoured contact always exists between the overlying sandstones of Facies B and the underlying burrowed lithologies. A thin shale-pebble and brachiopod shell intraformational conglomerate is developed at this contact. The lower contact of Facies E is always gradational into the upper clean sandstones of Facies C.

Facies E ranges in thickness from 5 to 10 feet, and is characterized by a distinct primary stratification and zones of biogenic reworking. Biogenic structures are abundant in specific sections of the facies, and their formation is contemporaneous with the processes of sedimentation. The burrow facies is greyish red (10R 4/2) in color.

Lithology

The burrow facies is primarily composed of tidal bedding and intensively bioturbated beds (mottled beds) with minor, scattered, intercalations of sandstone. Generally, the burrow facies becomes progressively enriched in shale up the succession; no thick, dense mudstone units cap the sequence. The following lithologies characterize this facies.
Tidal bedding

This lithology consists of rhythmic alternations of horizontal to slightly wavy laminae of siltstone and shale (Pls. 5 A, B, C, and D). The laminae range from a millimeter up to a centimeter in thickness; a shale and siltstone couplet represents deposition from a single tidal cycle. In Facies E, units of tidal bedding range from beds relatively enriched in the gross amounts of interlayered shale, through to beds made up primarily of siltstone with delicate paper-thin shale laminae. The former resembles the tidal bedding of Wunderlich (1970, p. 106, Fig. 7), whereas the latter appears similar to a lithology, described by Reineck and Singh (1973), which resembles evenly laminated sand; accordingly this bedding develops in a tidal environment where little mud is available. Very broadly, the shale-rich tidal bedding is well developed in the upper half of a Facies E succession, with the silt-rich varieties generally characterizing the lower half.

Mottled beds

Simply, this lithology is the product of the intensive biogenic reworking of shale-rich tidal bedding; the primary stratification is nearly or completely destroyed. Intensively biogenic reworked beds typically cap a sequence of tidal bedding.

Sandstone beds

Very thin to medium beds of fine-grained sandstone are intermittently layered within sequences of tidal bedding. These beds may be massive, but for the most part they are ripple-
bedded. The lower contact is sharp.

**Biogenic Structures**

Biogenic reworked beds and unidentified vertical burrows (Pls. 6A, B, C, and D) are associated with the tidal lithologies. Very broadly, the intensity of biogenic reworking increases up the Facies E section; this corresponds to a general upward increase in the argillaceous content of the sequence.

Vertical burrows may be found at all stratigraphic levels within the Facies E sequence, but they are most numerous in the upper half of the section. An individual burrow is less than five millimeters in width; the length is speculative as a burrow weaves in or out of the planar viewing surface.

**Vertical burrows**

The widespread occurrence of vertical burrows within Facies E suggests that the depositional environment presented harsh ecological conditions for the fauna. The associated tidal lithologies support the interpretation, as tidal environments are characterized by daily fluctuations in salinity and temperature. Furthermore, such environments are subjected to strong sediment reworking and commonly rapid deposition from tidal currents (Reineck and Singh, 1973; Crimes, 1975).

**Rate of deposition**

In Facies E, the texture of the sediment and the intensity of biogenic reworking probably is related to the rate of deposition (Howard, 1975). Beds with an excellent preservation of...
primary stratification are typically silt- or sand-rich; only rare, long vertical burrows penetrate these sediments. In contrasts, beds displaying an intensive biogenic reworking generally have an enhanced argillaceous content, and are characterized by swarms of short vertical burrows, and infrequently, rare unidentified horizontal burrows. Therefore the balance between the gross amount of shale and siltstone or sandstone within a bed, together with the density and nature of the burrows, suggests that the intensively reworked beds represent, generally, reduced rates of deposition, whereas the silt- and sand-rich units represent increased rates of deposition. Accordingly, a reduced rate of deposition is related to lower energy conditions which permitted the accumulation of clay and gave the organism time to completely churn the sediment.

**Number of organisms**

Very broadly, Reineck and Singh (1973) indicate that the stronger the processes of sedimentation, the smaller the animal population. Following from the above discussion, it is conceivable that the intensively biogenic reworked shale-rich beds, which generally characterize the upper part of a Facies E sequence, may also be related to an increase, through time, of the number of organisms available to churn the sediment.

**Erosion**

Numerous erosional discordances are found in Facies E sequences. The truncation of vertical burrows or of a biogenic reworked bed is indicative of an erosional event. Such is observed (1) in tidal bedding, where an erosional discordance
commonly is only recognizable by such truncations, and (2) at the base of many interlayered sandstone beds in tidal bedding sequences.

**Escape structures**

Few, long vertical burrows commonly crosscut sandstone beds which truncate underlying tidal bedding sequences or bioturbated beds. These burrows probably represent escape structures as they are also found to crosscut erosional discordances and individual shale rip-up clasts (Pl. 6B). Moreover, they indicate the contemporaneous nature of the erosional events with the burrowing activity in Facies E.

**Discussion**

Facies E is interpreted as a tidal flat deposit. Reineck (1972) states that tidal flats develop within a marine shallow water environment, between high and low water lines. They are protected from strong marine processes by barrier islands or sand bars, or occur in sheltered bays. Facies E resembles, for the most part, a progradational tidal flat sequence described by Smith (1968), from the Lower Silurian of Pennsylvania. Two generalized Facies E profiles are given in Figures 11 and 12.

The relatively high argillaceous content and the high levels of biogenic reworking within the upper parts of the stratigraphic section suggests that Facies E may represent a progradational tidal flat deposit. The basic vertical framework of modern prograding tidal flats (Reineck, 1972) reflects the onshore movement
of comparatively finer-grained sediment resulting from the progressive shoreward decrease in the energy of tidal currents (Blatt et al., 1972). Hence mud-rich sediments (mud flats) are deposited near the high water line and consequently, are found at the top of a progradational sequence; the underlying sandier sediments reflect deposition from stronger tidal currents in areas away from the tidal flat shoreline. Very broadly, Facies E fits into such a framework, with the tidal deposits grading downward into a well-washed Facies C sandstone (sand bar deposit).

Tidal bedding and intensively biogenic reworked beds are the predominant lithologies of Facies E, with minor, very thin to medium sandstone beds layered intermittently within sequences of the above lithologies.

The biogenic reworked beds are attributed to low rates of deposition. In mud flats, the rate of deposition is relatively low; tidal currents are weak and little sand is transported (Blatt et al., 1972). Therefore organisms have sufficient time to intensively burrow the sediment. In the sandier, lower tidal flat environments, tidal currents are stronger and more sand is transported; thus organisms have less time to rework the sediment.

According to Reineck and Singh (1973), tidal bedding is indicative of deposition during calm weather, whereas the inter-stratified rippled sand beds within a tidal bedding sequence, represents deposition related to storm-generated waves. In addition, increased current velocities related to storms may account for many of the numerous small discordances within the
Facies E sequence.

The occurrence of a few small scour-and-fill structures in some Facies E sequences is suggestive of flowing water within a channel. Hence, it is possible that some portions of these Facies E sequences may represent point bar deposits of tidal channels. Point bar deposits are composed predominantly of tidal bedding with subordinate sandstone intercalations (Reineck and Singh, 1973).
sandstone

tidal bedding

tidal bedding with interlayered silty-shale laminae and rippled thin siltstone bed

mudstone

intensive biogenic reworking

vertical burrows

erosive surface

rip-up shale clasts

Explanation for Figures 11. and 12.
Figure 11: -- Vertical section through Facies E; Core 13082.
Figure 12. — Vertical section through Facies E; Core 13075.

Facies B sandstone

Facies C sandstone
FACIES D – PRODELTA TO SHELF MUDSTONES

Facies D represents the argillaceous sequence of the lower Grimsby Formation and the upper Cabot Head Formation; it is present throughout the entire study area. Coring terminated within the upper Cabot Head Formation, therefore the entire shale sequence between the Whirlpool and the Grimsby sandstones was not examined in this present study.

Lithology

The lithologies observed in Facies D are similar to the mudstone lithologies of other argillaceous sequences which also developed in close proximity to sand bodies in shallow epeiric seas (Michaelis and Dixon, 1969; Simpson, 1975, and others). Facies D is a mudstone succession with varying amounts of siltstone and sandstone interlayered within shale. The mudstones typically are dark grey (N3, N4) in colour, although commonly greyish red (10R 4/2) hues colour the mudstones directly below the sand body. Interbedded siltstone and sandstone layers are generally light grey (N7). The generalized lithologic components which comprise Facies D are;

a) a mudstone unit, with interlayered scarce lenses and rare continuous thin laminae of siltstone.

b) a mudstone unit, with lenses and continuous laminae of siltstone forming intermittent layers. Bioturbation is conspicuous
in some laminae.
c) a mudstone unit, with increased amounts of interbedded siltstone and fine-grained sandstone, as lenses and continuous laminae to very thin beds. Bioturbation is conspicuous in some layers.
d) thin to thick sandstone beds layered intermittently within the mudstone units described above; moreover, the sandstone beds are generally associated with the sandier mudstone units.
e) very thin to very thick coquinaid sandstone beds randomly interbedded within the mudstone units described above; frequently in scoured contact with the thin to very thick sandstone beds.

Lenticular Laminae to Very Thin Beds of Siltstone

Lenses, laminae, and very thin beds of siltstone and fine-grained sandstone form composite bedsets (Reineck and Singh, 1973, Fig. 137) with the shale groundmass (Pls. 7 A, B, and C). These coarse-grained layers commonly are normal graded into the overlying shale; the lower contact typically is erosional with current and load casts present on the sandstone soles. The siltstone and sandstone layers consist of (1) lenticular laminae, (2) continuous (across the width of a core) thin to thick laminae which are structureless or comprised of a simple ripple bedset with low angle foreset traces, and generally continuous thick laminae to very thin beds in which the layers are of uniform thickness or wedge-shaped. The layers are either structureless, horizontal-laminated, or are comprised of composite
and simple bedsets of ripple cross-stratification.

**Thin to Thick Siltstone and Sandstone Beds**

Thin to thick beds of siltstone and fine-grained sandstone are randomly interlayered within Facies D mudstone. The sandstone beds generally are less than a foot in thickness. The beds are consistently light grey (N7) in colour; no red sandstone beds (aside from coquinitoid sandstone beds) occur at this depth within the Medina sequence. In Facies D, no relationship between an individual bed thickness and depth below the Grimsby sand body is apparent.

**Structure**

The sandstones may be structureless, but for the most part, they are made up of plane and gently inclined laminae, with commonly associated low angle discordances. The lower contact is sharp; rip-up shale clasts and/or shell debris generally are incorporated within the basal parts of many of the sandstones. The upper contact is gradational into shale. The upper part of some sandstone beds are rippled; whereas some other beds may exhibit very thin micaceous plane laminae; rarely these laminae are deformed into dish structures. Many of the thicker sandstone beds are found to be comprised of several thin to medium sandstone units, each separated by erosional contacts (Pl. 8A).

**Biogenic reworking**

Biogenic reworking is rare within these beds, however a few
beds may show some reworking at the upper contact with the shale. Infrequently, a vertical burrow penetrates into the lower few centimeters of the sandstone bed (Pl. 8B), probably representing an escape attempt by an organism from the underlying bioturbated Facies D mudstone.

**Coquinoeid Sandstone Beds**

Very thin to very thick coquinoeid sandstone beds (Pl. 9A and B) are intermittently bedded within Facies D mudstone. The beds are made up of abundant shell debris with a matrix of fine-grained sand, silt, and clay. The shell material is aligned near-horizontal, possibly the result of sedimentation and compaction.

**Colour**

These coquinoeid beds are light grey (N7) to greyish red (10R 4/2) in colour. The red staining is secondary in nature. It may affect an entire bed or selective parts of a bed. Furthermore, any red colouration is confined only to the coquinoeid bed itself as the enclosing mudstone sequence is generally various shades of grey. The red staining is probably the result of a good original permeability for these beds, which permitted the flow of iron-rich solutions. Therefore, these coquinoeid beds must have acted as conduits within the impermeable shales. This raises the possibility that these beds were in hydraulic communication with the overlying red-stained Grimsby sandstone.
Grading

Textural grading is a common feature of the coquinoid sandstone beds. A coquinoidal bed may either consist of a single graded unit or be made up of several repeated graded units. A graded unit exhibits a scoured base followed by a normal or incomplete grading from shell debris with a sandstone matrix into siltstone, and frequently into a shale drape. Coquinoid sandstone beds over a foot in thickness are always comprised of several graded units. Close examination of an individual graded unit reveals that it is comprised of a gradation of many smaller subunits (each a few centimeters thick), each distinguished by subtle differences in colour, size of shell fragments, and the amount of matrix.

Biogenic Reworking of Laminae to Very Thin Beds of Siltstone

Distinct burrow forms are not widely found within the silt- and sand-rich Facies D mudstone units; most organic activity is recorded only as a reworking of the coarse-grained interlayers. Scarce horizontal burrows consist of small (less than one centimeter in width), silt-filled tubes (Irregular Teichichnus), whereas sparse vertical to subvertical burrows form tunnels which crosscut the siltstone and sandstone layers; these later burrows may represent escape traces, or perhaps, simply a vertical movement of an organism from one nutrient-rich argillaceous horizon to another.

Generally, within a vertical section of Facies D mudstone,
not all coarse-grained layers are reworked with equal intensity despite similar bedding styles and grain size. This is believed to be due to variable depositional rates (Howard, 1972, 1975; Rhoads, 1975). Simply, given sufficient time, an organism will burrow through a sand layer, and ultimately, will destroy much of the primary stratification. Thus, those layers showing a high degree of reworking suggest a reduced rate of sedimentation. Conversely, sand layers showing complete preservation of the primary stratification or a low degree of organic reworking suggest a subsequent rapid deposition of the overlying sand layers. An indication of the relative rates of deposition within a mudstone sequence is obtained by comparing the degree of biogenic reworking from one sand layer to the next.

Reservoir quality

The degree of biogenic reworking is an important factor in improving the overall reservoir quality of a sandstone in that burrowing organisms effectively destroy reservoir inhomogeneities (barriers to fluid flow), such as thin clay laminae and clay wisps of the foreset laminae of ripple cross-stratification (F. Simpson, pers. com.). This may be of importance in the argillaceous sections of the Grimsby sand body if the interstratified sand layers are laterally continuous, since they may act as conduits for fluid migration.

Discussion

The dominance of mudstone, the common interlayering of
siltstone and sandstone, and the stratigraphic position below the prograding Grimsby sand body indicates that Facies D represents a prodelta to marine shelf environment; such environments are found seaward of the delta front deposits. Coleman and Gagliano (1965) and Allen (1970), for the modern Mississippi and Niger deltas respectively, report thin layers of silt and fine sand interbedded in mud in the prodelta. These represent the thin continuations of the delta front sand deposits; the coarse layers diminish seaward as the prodelta grades into the muds of the open marine shelf.

In Facies D, marine clay sedimentation, under low energy conditions, was the dominant process. However the presence of coarse-grained interlayers within the mudstones suggests that higher-energy episodes periodically influenced the muddy environment. Such higher-energy events probably are storm induced; therefore it is believed that storms occurred as catastrophic events, spreading and rapidly depositing veneers of silt, fine-grained sand, and shells in the prodelta to shelf muddy environment.

Storm Layers

The internal organization of the coquinitid sandstone beds and of the siltstone laminae and lenses through to thick sandstone beds interlayered in Facies D mudstone suggests a storm-related origin for these beds. Storm layers are commonly reported in the geological literature; they are reported in
various proportions of clay, silt, fine-grained sand, rip-up shale clasts, and shell debris organized as lenticular laminae to thick sandstone beds and as coquinaic sandstone beds.

**Primary Structure**

1. Plane or gently inclined laminae and/or simple bedding (Reineck and Sint, 1971; Swift in Harms et al., 1975; and Simpson, 1975).

2. Normal grading from fine-grained sand or silt into suspension clay drape (Brenner and Davis, 1974; Simpson, 1975).

3. Erosional lower bounding surface, commonly with well-developed current-produced sole marks (Simpson, 1975).

4. Small rip-up shale clasts and/or shell debris within base of sand layer (Swift in Harms et al., 1975; Rhoads, 1975).

5. Dish structures — indicate rapid deposition

**Source of Material**

1. Erosion of coastal sand bodies, tidal flats, lagoons, etc., by strong storm waves and heavy tides; subsequent seaward transportation of eroded material into muddy shelf environment by turbulent water flows away from coast (Wunderlich, 1970; Reineck and Sint, 1971, 1973; Swift et al., 1971).

2. In situ grading by the reworking, winnowing, and concentration of relict sand and shell material in shelf mud by strong storm-generated currents (Swift et al., 1971; Brenner and Davis, 1974; Simpson, 1975).

**Evidence of Organic or Rapid Deposition**

1. Escape structures; a vertical burrow of an organism attempting to uncover itself after being buried by a rapidly deposited sand layer (Reineck and Sint, 1971; Howard, 1975).

2. The preservation of the primary stratification (i.e., little or no bioturbation) of a sand layer within a bioturbated sequence suggests a rapid deposition of that sand layer (Howard, 1975).

3. In a sequence exhibiting numerous storm layers, the overall relative rate of deposition is indicated by comparing the degree of biogenic reworking from one sand layer to the next. Sand layers showing a preserved primary stratification suggest a rapid deposition of the successive sand layers. Consequently, organisms had insufficient time to rework the sediment. In contrast, a series of intensively bioturbated sand layers indicated a reduced rate of deposition (Howard, 1972, 1975; Rhoads, 1975).

4. Medium to very thick, rapidly deposited sand beds always show an excellent preservation of the primary stratification. The great thickness of the bed prevents the organisms from intensively bioturbating the complete bed. Generally, only the topmost parts of the sand bed may show any organic reworking (Howard, 1972).

**Table 4.** — Storm Layers in Facies D (prodelta to shelf mudstones)
modern shelf areas (Swift et al., 1971; Reineck and Singh, 1973)
and in ancient equivalents (Masters, 1967; Brenner and Davis,
1974; Harms et al., 1975; Simpson, 1975). Table 4 summarizes
the properties of storm layers in the Medina clastics and gives
credit to the various authors who recognized similar characteris-
tics in the storm layers in the strata of their study.

Structure

Storm layers are comprised of various proportions of coarse-
grained silt, fine-grained sand, rip-up shale clasts, and shell
debris. An erosional lower bounding surface, commonly with
well developed sole marks, indicates deposition from a moving
suspension (Harms et al., 1975; Simpson, 1975). Furthermore,
deposition from a waning current is suggested by (1) plane- or
gently inclined-laminated and/or ripple-bedded sandstone normal
graded into mudstone, and (2), for coquinooidal sandstone beds,
a normal grading of shell debris and sand into mudstone.

Single and multiple events

The presence of storm layers interlayered within Facies D
mudstone indicates periodic short-term changes from low-to high-
energy conditions. Typically, the mudstone sequence exhibits
numerous individual siltstone or sandstone layers of various
thicknesses; each coarser-grained layer is enclosed in the shale
groundmass and is attributable to a single storm event which
raked the shelf and deltaic environments. However, many
storm layers in mudstone (especially the thicker sandstone
and coquinooidal sandstone beds) are found to be comprised of
several sandstone and/or coquinooidal units, each separated by
distinct erosional surfaces; this suggests that these multiple coarser-grained units are a product of several storm-induced high energy events. Such a structure may indicate (1) storms in rapid succession, and/or (2) a down-cutting into pre-existing storm layers by subsequently deposited storm sands (Brenner and Davis, 1974).

Storms as geological agents

Textural grading in a shelf or prodelta muddy environment points towards the existence of an agent or mechanism which (1) transported silt, fine-grained sand, and shells to a region of mud deposition, and (2) produced a suspension from which the textural segregation of sediment took place. As demonstrated below, intense storms which produce large storm waves and high water levels are appropriate agents.

Erosion and transportation

Storms are suitable mechanisms for triggering the wholesale transport of sand and shell debris, eroded from coastal source areas, to the muddy platform or prodelta. Reineck and Singh (1971) demonstrate the deposition of sand from suspension clouds in muddy shelf environments of the North Sea. Moreover they find that turbulent storm waters can keep much sand in suspension, and these turbulent waters, flowing away from a coast after a storm, can transport sand in large quantities to the open shelf. Furthermore, Wunderlich (1970) reports, in the North Sea, that tidal currents associated with storms can erode and transport seaward large amounts of sediment within one tide. Likewise, Swift et al. (1971), in the Middle Atlantic Bight, indicates
that coarse-grained sediment, released from the shoreface by
erosion, can be transported seaward under the impetus of storm
waves, and deposited as a sand sheet in the off-shore environ-
ment. Reineck and Singh (1971) find that storm layers become
thinner and finer-grained towards the open shelf; towards the
shoreline they become thick and grade into coastal sand deposits.

A deltaic environment is an area of high and rapid sediment
accumulation. Therefore it should provide an ample sediment
supply available for reworking and redistribution by strong
storm waves and tides. Hence, it is conceivable in the Grimsby
delta complex that large volumes of delta front and beach
sediment were moved seaward during storms and subsequently
redeposited as very thin to thick storm sheets within the
prodelta and shelf muddy environments.

**In situ grading**

Another mechanism for the genesis of storm layers is an
in situ process in which large storm-generated waves and heavy
storm tides agitate the shelf bottom and winnow, concentrate,
and rework relict sand and shell material into storm sand or
coquinooidal storm sheets (Swift *et al.*, 1971; Breiner and
Davis, 1974). The lighter sediment fraction is put into
temporary suspension, and it is subsequently deposited as a
drape over the reworked coarser material.

**Response of organisms**

Organisms show a definite response to the rapidly deposited
storm sand layers. Escape traces (Reineck and Singh, 1971;
Howard, 1975) develop when an organism is buried by a rapidly
deposited sand layer and attempts to uncover itself by burrowing upward through the sand. Howard (1972, 1975) and Rhoads (1975) discuss the intensity of burrowing in respect to the rate of sand deposition; this has been reviewed previously.
FACIES C - BEACH; SAND BAR TO BARRIER ISLAND

Facies C, a fine-grained, quartzose sandstone development of the lower Grimsby Formation, occurs in most core. It represents the lowest sandstone facies of the Grimsby sand body as it directly overlies the Facies D mudstone. Facies C is most easily recognized when it grades into the overlying tidal bedding of Facies E (burrow facies). However, when the burrow facies is not developed, Facies C passes imperceptibly into the overlying reworked or massive sandstones of Facies B.

Sandstone

The sandstone ranges from greyish red (5R 4/2) to light grey (N7) in colour. Plane lamination with associated low-angle planar cross-stratification (swash cross-stratification) is the predominant structure; minor intervals of dune-scale inclined-stratified and massive sandstone also occur. Small-scale ripple cross-stratified sandstone is generally subordinate, but in some core ripple-bedding is of local importance, especially where the sandstone grades into Facies E tidal bedding. Trace fossils are not found in Facies C.

Conglomeritic components

Small, flat, shell fragments and small rip-up shale clasts occur abundantly in some intervals of Facies C sandstone. This debris may constitute sporadic, thin, intraformational conglom-
erals, but moreover, the debris is found as concentrations along the primary stratification (Pl. 10A). Furthermore, the flat shells may impart a pronounced parting lineation to the plane-laminated sandstones (Pl. 3C).

In some core, a relatively major conglomeritic unit (Pl. 10B), several feet thick, is developed directly upon the Facies D mudstone. This unit is comprised of several, repeated, thin sandstone beds, separated by erosional surfaces. An individual bed is graded and is composed of various proportions of sand, shells, and rip-up shale clasts; rarely a very thin shale seam tops a graded sandstone bed.

In most core, Facies C represents a "cleaning-upward" sequence, as shells, rip-up shale clasts, and subordinate interstitial mica are relatively enhanced in the basal sandstones. A parallel-stratified sandstone variety, exhibiting thin micaceous laminae and small shale pebbles (Pl. 10C) is associated with thin, shale pebble conglomerates in the basal parts of some core. This sandstone resembles a lithology depicted by Wunderlich (1970, p. 117) on the borders (lower shoreface?) of modern sand bars.

Discussion

The conglomeritic developments and the described primary sedimentary structures suggest a depositional environment influenced by higher flow velocities; possibly, in part, the result of strong storm-generated waves working the sands within a foreshore
(to shoreface?) beach environment. Furthermore, in core where Facies E (burrow facies) is developed, the stratigraphic position of Facies C (above the Facies D prodelta or shelf mudstones, and below the Facies E tidal flats) suggests a sand bar or barrier island complex which protected the tidal flat environment from strong storm waves.

A gradational relationship from shoreface, through foreshore, to offshore, as described by Howard (1972) and Harms et al. (1975) cannot be demonstrated in Facies C, as this facies typically passes abruptly from sandstone into the underlying Facies D mudstone. This probably is a reflection of the intense storm activity which reworked these beach sands. The conglomeratic units, developed in the basal part of the sandstones in some core, are viewed as storm layers; the storm layers probably continue seaward, intermittently stratified within laterally equivalent Facies D mudstone.
FACIES B - DISTRIBUTARY COMPLEX

Facies B occurs in most core, and it typically represents the greater part of the Grimsby sandstone. The facies is composed of pale red (5R 6/2) to greyish red (5R 4/2; 10R 4/2), fine-grained, quartzose sandstone with sporadic, very thin shale partings, and in a few cores, infrequent interstratifications of thin to medium silty-shale beds. When developed, Facies B passes imperceptibly into the overlying sandstones of Facies A. Furthermore, it is in erosive contact with the underlying Facies E tidal lithologies. When Facies E is not present in a core, Facies B either grades downward into the beach-like sandstones of Facies C, or possibly, it rests directly upon the prodelta to shelf Facies D mudstones.

Lithology

Facies B is a complex sandstone succession which varies considerably in structure within a single core and/or among adjacent core. Three sandstone components are recognized and are considered to be representative of the dominant bedding varieties encountered within this facies. These sandstone components may be interstratified among each other in a single core, or alternatively, one specific component may largely comprise the complete Facies B succession.
Ripple cross-stratified sandstone component

This unit is composed predominantly of sandstone with, for the most part, very subordinate shale. Typically this sequence is made up of (1) structureless sandstone, (2) ripple cross-stratified sandstone, with (3) commonly associated plane-laminated sandstone (laminations are continuous mica wisps); furthermore these plane-laminae and ripple foreset laminae may coalesce into intermittent, very thin, silty-shale partings (Pl. 11A). The sandstones are free of shells, shale clasts, and trace fossils; erosional truncations are rare. The ripple cross-stratification consists primarily of groupings of asymmetrical sets, small-scale trough sets, and interstratifications of the above varieties (Pls. 1A, B, and C, 11B).

In a few core, shale is more prevalent, occurring as intermittent, thin to medium beds within the above sandstones. The shale beds consist of very thin inter laminations of siltstone and shale; the bedding is similar to lithologies illustrated by Potter and Glass (1958, p. 34) from the delta margins of the Texas gulf coast.

Reworked sandstone component

Sequences of reworked sandstone contain very subordinate amounts of shale. These sequences are comprised (1) largely of plane-laminated sandstone, (2) minor dune-scale inclined laminated sandstone, and (3) sparse ripple cross-stratified sandstone (typically associated with any sporadic silty-shale partings). The sandstones generally are the coarsest-grained of the entire Grimsby sand body; furthermore they appear to be
the most porous. The thick to medium bedded sandstones are cut by numerous erosional truncations, generally low angle planar discordances and, less frequently, small irregular scours, and by very thin, rare shale partings. Abundant small shale clasts (remains of eroded shale partings?) occur as lag deposits over the erosional surfaces (Pl. 11C, D), and as concentrations, together with shell fragments, along the primary stratification (Pl. 12A, B).

Structureless sandstone component

Clean, monotonous sandstone successions, with negligible shale and rare current-generated structures, comprise large footages within a few core; these structureless sandstones are found at similar stratigraphic levels as the other Facies B units within adjacent core.

Discussion

The primary sedimentary structures and associated lithologies, together with the overall stratigraphic position of Facies B within a deltaic complex suggests a delta front (distributary complex) depositional environment;

a) Facies B, in stratigraphic position, overlies (1) the Facies E tidal flats, (2) the sand bar or barrier island complex of Facies C, and (3) the marine to prodelta mudstones of Facies D. In generalized progradational deltaic models, distributary complexes overlie and are laterally equivalent to the above mentioned environments. Furthermore, Martini (1966, 1971)
reports distributary channel fills and sandstone layers, representing distributary sands which have been reworked and dispersed by marine agents, at a similar stratigraphic level in outcrops of the Medina sediments in the Niagara Peninsula.

b) The lithology and sedimentary structures of Facies B (Table 3) compare to many of the various compositional and structural features of the delta front deposits of the modern Mississippi delta — including bar finger sands (Fisk, 1961) and the distributary channel fills and distributary mouth bars (Coleman et al., 1964; Coleman and Gagliano, 1965, p. 147, Table 1); and also of the modern Niger delta distributary mouth bars (Allen, 1970).

The delta front is an area of exceptional rapid sediment deposition brought about by the decreasing carrying capacity of a river. This results from the flaring out and the shoaling of the distributary channel and a corresponding decrease in stream current velocity (Coleman et al., 1964). The delta front is an area where the sediment is constantly reworked by waves and tides generated in the open sea and fluvial currents. The relative strengths of the above processes not only determines the large-scale geometry of the sandy delta front deposits, but also are responsible for the compositional and sedimentary fabric of even the smallest of stratification units.

The sandstone components of Facies B indicates that varying intensities of wave and current activity influenced the sediment. The reworked, plane-laminated sandstone sequences infer high energy conditions of deposition. Very broadly, in
distributary complexes, such conditions may be related to (1) the breaking of waves upon sandy shoals (distributary mouth bars), especially strong storm-generated waves and associated tides, which, as seen in example from Facies C and Facies D, occurred periodically during Grimsby deposition, (2) stronger than normal river currents associated with seasonal and storm-related floods (Coleman et al., 1964), and (3) the existence of strong littoral drift and/or tidal currents; Martini (1971) suggests such a paleocurrent system in the Grimsby sandstone.

On the whole, it is difficult to demonstrate a clear-cut dominant process of deposition of the reworked Facies B sandstone sequences. Sequences exhibiting large-scale low-angle (swash cross-stratification ?) and moderate-angle planar cross-stratification with associated plane and dune-scale inclined lamination are suggestive of sand bar developments (distributary mouth bars). In such a case, the sandstones would likely be genetically related to the Facies C beach and sand bar deposits of many core.

Alternatively, the above described stratification may be related to strong tidal currents. According to Pettijohn et al., (1973) tidal currents may transport large quantities of sand in near shore environments, especially if wave action initially puts sand into suspension. Therefore it conceivable that under strong tidal currents, the transport and deposition of Facies B sand resulted in the formation of possibly subaqueous dunes, tidal sand banks, and plane beds. Such a tidal interpretation is
supported by abundant rip-up shale clasts and shells concentrated along the stratification and the association with interlaminated shale and siltstone (tidal bedding) of Facies E (Pettijohn et al., 1973, Table 11.4), and also the sedimentary structures which characterize the ripple cross-stratified component (discussed below). However, large-scale herringbone cross-stratification, indicative of tidal current reversals, was not recognized within the cores.

The occurrence of abundant rip-up shale clasts and infrequent shale partings within the reworked, plane-laminated sandstone sequences may also possibly be related to a fluvial depositional process described by Coleman and Gagliano (1965) within distributary channel fills of the modern Mississippi delta. Accordingly clayey layers of various thicknesses, interbedded with coarser material, are deposited during low river stages; these may be eroded during subsequent flood periods marked by increased current velocities. The upper contacts of the clayey layers (similar to many shale parting within Facies B) display scour features; angular clay inclusions found in the coarser material may be remnants of eroded clay layers.

The ripple cross-stratified sandstone component of Facies B implies lower energy conditions; the assemblage of primary sedimentary structures and the associated intermittent very thin silty-shale partings suggest deposition from currents which fluctuated in strength and frequently in orientation (i.e. multidirectional ripple cross-stratification). Such a situation
may be possible within areas of the distributary environment subjected to weak tidal or fluvial currents. Furthermore, in some core, the interstratification of thin to medium beds of interlaminated siltstone and shale suggests deposition in close proximity to a quiet water muddy environment.

Facies B sequences comprised of structureless clean sandstone are difficult to interpret, aside from a general sandy environment subjected to strong winnowing by waves and currents.
FACIES A - BEACH: TIDAL FLAT TO LAGOON: TIDAL CHANNEL
POINT BAR: CHANNEL FILL DEPOSITS

Facies A is composed predominantly of very clean, dense, fine-grained, quartzose sandstone with variable, but for the most part, minor amounts of interbedded mudstone. Facies A occurs in the upper portion of the Grimsby sand body in all core; therefore it includes the entire Thorold Formation and probably the topmost part of the Grimsby Formation.

Sandstone

The sandstones typically are light-grey (N7) in colour in the upper part of Facies A; with increasing depth they pass gradually into pale red (5R 6/2) hues. Very thin shale partings and shale flakes are bedded intermittently within the sandstones. Very thick sequences of Facies A sandstone may be massive, but moreover, the Facies A sandstones exhibit a wide variety of sedimentary structures, which are summarized in Table 3.

Mudstone

Thin to very thick mudstone beds are interlayered at various levels, but generally, within the upper part of many Facies A sequences. In some core, the mudstone is a major component, whereas in other core, Facies A is completely free from the shale
interbeds. The mudstone beds are generally less than a foot in thickness, but in a few core, sequences up to about ten feet thick are observed. These thicker mudstone successions (1) may divide Facies A sandstone from the overlying Reynales dolomite, or (2) are interstratified within the upper Facies A sandstones, with the mudstone occurring several feet below the Reynales base. In the former case, the mudstone succession holds a similar stratigraphic position to the Neahga shale in the Niagara Peninsula (Bolton, 1957). The mudstones are dark grey (N3) to dark greenish grey (5G 4/1) in colour, although greyish red (5R 4/2) hues may be found in the lower stratigraphic occurrences.

Lithologies

The mudstone sequences are typically composed of one or more of the following described lithologies. These lithologies are gradational into each other, and consist of:

a) rhythmic alternations of very thin laminae of siltstone and shale (resembles tidal bedding).

b) dense mudstone (Pl. 13A) with subordinate thick to paper-thin continuous and lenticular laminae of siltstone interlayered within the mudstone groundmass. Some laminae exhibit ripple foreset traces and/or a normal grading from siltstone into shale.

c) a sandstone-predominant lithology (Pl. 13B), composed of alternating continuous thin beds of fine-grained sandstone or siltstone, and continuous thin to very thin beds of dense mudstone, similar to b), described above. This lithology has a minor occurrence.
Biogenic structures

Biogenic structures are found in most (but not all) of the mudstone beds. Vertical burrows are rarely observed; however, the horizontal burrow *Arthrophycus* (Pl. 13A and B) has a common occurrence. *Arthrophycus* is found sparingly within the alternating siltstone and shale laminae lithology, but moreover, its greatest concentration is within the mudstone lithologies (b) and (c), described above.

**Facies A - Reynales Dolomite Contact**

The Facies A - Reynales dolomite contact typically is sharp, but a conformable or erosional nature of the contact is unclear. However, two variations of the contact are observed and are described below;

a) in some core, the contact is found to be erosional when the Reynales dolomite directly overlies Facies A mudstone; frequently rip-up shale clasts (identical in composition to the underlying mudstone) are incorporated within the base of the dolomite.

b) in a few core, the contact zone is intensively bioturbated (Pl. 13C and D); *Arthrophycus* may be found in the sandstones immediately below the Reynales dolomite. This possibly suggests (1) a very slow rate of dolomite deposition upon the exposed sandstone surface, giving the organisms time to churn the sediment, or (2) since bioturbation within Facies A sandstone is observed only when it is in direct contact with a mudstone sequence, this bioturbation possibly indicates that an overlying
mudstone succession was removed by erosion before the deposition of the dolomite.

**Discussion.**

The primary sedimentary structures and associated gross lithologies suggest that Facies A is composed of the deposits of several depositional environments or subenvironments. In general, the abundance of current-generated sedimentary structures, the near absence of biogenic structures, and the clean nature of the sandstone sequences infer that Facies A sands were well-washed and worked by waves and currents. Furthermore, the interstratified mudstone beds may reflect either suspension deposition from waning stream currents, or the existence of lower energy depositional environments laterally equivalent to the Facies A sandy environments.

**Beach foreshore to sand flat**

The association of the following sedimentary structures in sandstone suggests a beach foreshore to tidal sand flat depositional environment for the greater part of Facies A. In the following discussion, no preferred vertical order of appearance of these structures is implied.

Within sequences of Facies A sandstone, plane-lamination with associated low-angle discordances is analogous to swash cross-stratification which develops upon beach foreshores. Moderate-angle cross-stratification and dune-scale inclined-stratification compare with the internal structures of dunes
and the shoreward facing portions of off-shore and longshore bars. Small-scale trough cross-bedding, which occurs abundantly, represents the development of ripple marks. Ripple marks occur frequently in beach troughs which form parallel to the shoreline, between the shoreline and off-shore bars (Komar, 1976); moreover, ripple marks occur profusely in extensive sand flats that may develop between high- and low-tide levels (Reineck, 1972; Komar, 1976).

To summarize, ripple cross-stratification, large-scale dune cross-stratification, and plane-lamination are the consistent bedding types observed within beach foreshore and upper shoreface sands, as indicated by Reineck and Singh (1973) from several profiles of the coasts of the North Sea and Mediterranean Sea.

Tidal flat to lagoon

Both tidal flats and lagoons are parts of tidal sequences in sedimentary deposits. Tidal flats and adjacent lagoons develop in sheltered locations, behind sand bars or barrier islands, in coastal environments. Lagoons are defined as shallow-water bodies which are water-filled, even at low-tide (Reineck and Singh, 1973).

Many of the thick to very thick mudstone beds interlayered within Facies A sandstone are interpreted as tidal flat to lagoon deposits. This explanation is based upon (1) the lithological make up of the mudstones, (2) the primary and biogenic structures displayed within the mudstones, and (3) the association of these mudstone beds with sandstones possibly
representing beach or sand flat deposits.

In the mudstone sequences, the rhythmic alternation of shale and siltstone laminae is suggestive of tidal bedding, which infers tidal current activity. Furthermore, the commonly associated dense mudstone lithology indicates a transition into a quiet water environment, which was probably characterized by a general low sedimentation rate. The presence of Arthropycus within the dense mudstone appears to support this interpretation plus indicating a marine or brackish water environment. However, the intermittent occurrence of laminae to thin beds of siltstone to fine-grained sandstone within the mudstone suggests that slack-water conditions were sporadically interrupted by higher-energy periods, possibly storm-generated.

**Tidal channel point bar**

In a few core, very thick sequences (up to five feet thick) of unbioturbated tidal bedding is found interbedded in, and gradational with, Facies A sandstone. The tidal bedding (Pl. 5C) resembles the tidal lens bedding of Wunderlich (1970, p. 105, Fig. 5). In Facies A, this bedding is characterized by small, flat, rippled siltstone lenses incorporated within the alternating siltstone and shale laminae. The ripple foreset laminae dip primarily in one direction; however some reversals in direction are noted. In addition to tidal bedding, thin, ripple cross-stratified siltstone beds are intermittently layered within the tidal succession.

A tidal channel point bar is a likely interpretation because such modern sequences are composed of tidal bedding lithologies;
typically the rate of deposition and growth of the bar is rapid, so that bioturbation is rather low (Reineck and Singh, 1973).

**Channel fill**

A channel fill deposit is a possible interpretation in certain sections of Facies A of some core. Since many of the primary sedimentary structures of Facies A sandstone can be found in both beach and fluvial environments, their presence alone cannot unequivocally imply a channel fill deposit. But the association of these structures with ripple-drift cross-stratification within a simple fining-upward vertical profile suggests the possibility of such a deposit. The fining-upward profile consists of several feet of fine-grained sandstone grading upward into an overlying mudstone bed, displaying the previously described lithologies. Moreover, many of these sandstone sequences exhibit a vertical arrangement of sedimentary structures which record a waning stream power (dune-scale inclined lamination with associated moderate angle discordances overlain by small-scale cross-stratification).
VERTICAL SEQUENCE OF LITHOFACIES

Examination of core through the Grimsby sand body reveals that the lithofacies do not occur in a random manner. A definite sequential order of lithofacies exists (Fig. 8).

Sedimentation of the Medina clastics is related to the northwestern progradation of the red bed Grimsby deltaic sand body (Facies A, B, C, and E) over the underlying and lateral equivalent prodelta to marine shelf mudstones of Facies D. Strong marine processes - longshore currents and/or tidal currents (Martini, 1966), and periodic storm-generated waves and tides - were responsible for much reworking and dispersal of deltaic sediment during the constructional phase of the delta. In the final stages of Medina sedimentation, strong marine processes associated with marine transgression (destructional phase of the delta) completely reworked the topmost Grimsby beds and redeposited these sediments within the beach complex of Facies A (approximately equivalent to the Thorold Formation; Fisher, 1954).

Facies D mudstone, which underlies the Grimsby sand body throughout the entire study area, represents prodelta to marine shelf environments. In these environments low energy conditions generally prevailed accompanied by low rates of clay deposition. However, strong storms periodically swept the deltaic environment. Coastal sand deposits were eroded and the strong storm waves and tides transported seaward large quantities of sand, and also
shells, and subsequently spread and rapidly deposited this coarse material as veneers within the prodelta to marine shelf muds. Furthermore, these storm currents probably also reworked and concentrated relict coarse-grained deposits contained within the muds. These relict deposits may have been introduced into the muddy environment by earlier storm episodes. The above storm layers are viewed as thin seaward continuations of beach and delta front deposits of Facies C and Facies B, respectively.

Facies C sandstone generally lies abruptly upon the Facies D mudstone, although in a few core some interfingering, over several feet, between lithofacies occurs. Facies C is interpreted as a beach deposit; the basal sandstones are typically rich in small shale clasts and/or shell fragments, which occur as concentrations along the plane stratification or as thin intraformational conglomerates; this conglomeritic material most likely was swept upon the beach by breaking storm waves.

The tidal flats of Facies E (burrow facies) are not developed in all core, but when present they are transitional into the underlying Facies C sandstones. In this case, the association of Facies C beach deposits with the tidal flats is suggestive of a sand bar or barrier island complex, which served to protect the landward lateral equivalent tidal flats from reworking by strong marine processes.

Facies E is composed predominantly of tidal bedding and intensively biogenic reworked beds with subordinate intercalations of sandstone. Very broadly, the tidal flats are a fining-upward sequence. The argillaceous content of the tidal sediments
is relatively enhanced in the upper part of the section; this increase is generally paralleled by an upward increase in the intensity of biogenic reworking.

Delta front (distributary complex) deposits of Facies B make up the greater part of the Grimsby sandstone. Facies B is a very complex sandstone development; it may be composed of very thick intervals of highly reworked sandstone; very thick suites of rippled and plane micaceous laminated sandstone; and thick sequences of massive sandstone. Generally, shale is very subordinate within the sandstone succession; it occurs as intermittent very thin shale partings and rare thin to medium mudstone interbeds.

In stratigraphic position, Facies B overlies, and is in erosive contact with, the Facies E tidal flats; but in core where Facies E is not developed, Facies B sandstone is laterally equivalent to the tidal flats (of adjacent core), and passes imperceptibly into the underlying Facies C beach deposits. In a few core, plane-laminated sandstones (typically rich in floated shale clasts and shell fragments) developed directly upon Facies D mudstone suggest either a beach deposit of Facies C, or the erosion of the Facies B distributary complex into the Facies D prodelta to marine shelf mudstones. On the whole, Facies B is viewed as a distributary complex, which through time, spread over and eroded into the underlying tidal flat, beach, and possibly, prodelta to marine shelf deposits.

The topmost beds (mainly sandstones with, generally, subordinate shale) of the Grimsby sand body are of Facies A.
This facies occurs throughout the entire study area and is gradational into the underlying Facies B sandstone. Facies A sandstone and shale display a wide variety of sedimentary structures which suggests that the greater part of the Facies is a beach development. However, minor interstratifications of tidal flat to lagoon, tidal channel point bar, and fluvial channel fill deposits are also suggested. In a few cores, thick sequences of mudstone occur in the uppermost parts of Facies A; very broadly, these hold a similar stratigraphic level to the Neahga shales (lagoon deposits; Bolton, 1957) in the Niagara Peninsula.
SAND BODY GEOMETRY

The geometry of the Grimsby sand body within the study area is illustrated by the fence diagram of Figure 13 and by cross-section A-B of Figure 14. The fence diagram is a simplified view of the sand body showing the generalized sandstone distribution and thickness trends, whereas cross-section A-B is a detailed illustration of the sequence of lithofacies across several panels of the fence diagram.

The base of the Reynales dolomite was used as the datum line in the construction of both figures. This datum was chosen because (1) the Reynales dolomite occurs throughout the entire study area, and (2) the base of the Reynales is an easy pick in the logging of the core.

Fence Diagram (Figure 13)

The following points summarize the important features shown by the fence diagram:

a) the Reynales dolomite overlies the Medina clastics throughout the entire study area.

b) the Facies D prodelta to shelf mudstones occurs throughout the entire study area, and underlies the Grimsby sand body.

c) the Grimsby sand body is very thin or absent in the northwesternmost drill holes (13029, 13040, and 13050). The Reynales dolomite directly overlies the Facies D mudstone in drill hole
Figure 13. Fence diagram of the Grimsby sand body in the subsurface of central Lake Erie.
13040; thin developments of sandstone separate the Facies D mudstone from the overlying dolomite in drill holes 13029 and 13050.

d) the Grimsby sand body thickens to the south and southeast; this corresponds to the regional thickening of the Grimsby Formation into the Appalachian basin (Martini, 1966; see Fig. 7).

e) Facies E (burrow facies) is correlatable through most of the drill holes. Typically, Facies E is interstratified within the sandstones of the lower part of the Grimsby sand body. The burrow facies is not found in many of the more southerly drill holes; furthermore Facies E does not occur in the most easterly drill holes examined in this study (13043, 13046, 13097 and 13114; these core are not included in Fig. 13).

f) a prominent mudstone sequence is developed in the uppermost part of the Grimsby sand body in drill holes 13006, 13027, and 13126. Very broadly this argillaceous sequence holds a stratigraphic position similar to that of the Neahga shale (tidal flat or lagoon deposits) in the Niagara Escarpment (Bolton, 1957).

g) B. W. Shelton (1973) demonstrates that the Grimsby Formation and the Thorold Formation of the Clear Creek Field exhibit a localized, pod-shaped thickening pattern, elongated along a NE-SW axis. Such a sandstone thickness pattern, within the area represented by the fence-diagram, is not indicated; possibly the result of a lack of data points (drill holes).
Cross-section A-B (Fig. 14) is taken from panels of the fence diagram (Fig. 13) from drill hole 13075 through to drill hole 13010. This cross-section represents a more detailed presentation of the drill hole data; the sequence of lithofacies and the corresponding gross lithologies are given for each drill hole represented in the cross-section.

Some important features revealed by the cross-section are summarized in the following points:

a) within Facies D, several thick sandstone and coquinooid sandstone beds are correlatable through parts of the study area. The correlation is particularly convincing through drill holes 13055, 13106, 13080 and 13082. Since storm episodes are "instantaneous" catastrophic events, these storm sheets may represent time planes.

b) Facies C consistently overlies Facies D mudstone.

c) Facies B occurs in most cores. It is developed below Facies A, and generally represents the greater part of the Grimsby sandstone. Facies B exhibits variable amounts of interstratified shale.

d) a probable Facies B development occurs below Facies E (burrow facies) in core 13015.

e) in the basal parts of the Grimsby sandstone in some core (13027, 13069, and 13138) some uncertainty exists in the interpretation of the sandstones; they may represent either Facies C beach deposits or, alternatively, the Facies B distributary
complex downcutting into Facies D mudstone.
f) Many drill holes, 13010, 13027, 13069, 13109, and 13138
display thick sequences of massive sandstone. The thickest
sequences of massive sandstone are found in the most southerly
drill holes (13069 and 13010) where they hold a similar
stratigraphic level as the Facies B sandstone in adjacent core.
Massive clean sandstone is suggestive of an environment where
wave or current action winnows the clay textural fraction
from the sands.
g) Very thick sequences of beds composed of rhythmic alternations
of siltstone and shale laminae occur in the upper portions
of the sand body in core 13055, 13069, and 13010. These probably
represent tidal channel point bar deposits.
h) Sequences interpreted as fluvial channel fills occur in the
upper portions of core 13075, 13082, and 13055.
i) Facies A occurs in all core; it is developed directly below
the Reynales dolomite and overlies Facies B sandstone.
THE GRIMSBY SAND BODY — A WAVE-DOMINATED DELTA

This chapter compares the Grimsby sand body to deltaic complexes in which deposition is controlled by strong marine processes, resulting from the interaction of strong waves, tides, and longshore currents. The chapter is based upon (1) the theoretical deltaic models found in the works of Miall (1976) and Coleman and Wright (1975), and (2) on information pertinent to the Grimsby sand body as demonstrated in this report and in the geological literature.

Modern deltas subjected to powerful marine processes in general, and strong waves in particular, have a very pronounced marine character. In such a delta the presence of a strong longshore drift current results in the formation of characteristic coast parallel sand bodies which reflect the transport direction of the current. These sand bodies are organized as distributary mouth bars, off-shore bars, barrier islands, and shoreline beach complexes. Furthermore, the occurrence of associated strong tidal currents brings about the formation of tide-generated sand ridges, which also become oriented parallel to sub-parallel to the coastline.

Associated distributary channels, which trend sub-perpendicular to the shoreline, may cut the above sand bodies obliquely. A significant tidal range typically results in the sand infilling of, and the dispersal of clays from, these channels.

Wave-dominated deltas displaying coast parallel sand bodies
stand in strong contrast to river-dominated deltas, where the sand bodies trend nearly perpendicular to the basin margin. Present day examples of deltas influenced by intermediate to high marine energies includes the Niger (Allen, 1970), Rhone (Oomkens, 1970), and Sao Francisco and Senegal (Coleman and Wright, 1975).

**Vertical Section**

In vertical section, deltas subjected to strong marine processes show quite a distinctive internal geometry of deposits. Such deltas characteristically exhibit thick buildups of sand representing a vertical stacking of beach, reworked distributary mouth bars, and sand filled distributary channels. Noteworthy in such a sequence is the fact that clayey layers are very subordinate and generally are confined to any distributary channel fills and tidal flat or lagoon deposits; these latter deposits form on the landward side of sand bars or barrier islands which may develop downcurrent from river mouths.

The above sequence is in sharp contrast to a river-dominated delta, such as the Mississippi. Here, the vertical section typically is comprised of several coarsening-upward cycles of mud to sand, representing sand deposition by crevassing or overbank splays into laterally adjacent marsh, swamp, and interdistributary bay muddy environments. Therefore a river-dominated delta may display numerous thick muddy layers interstratified within the vertical profile.
Examination of the cross-section (Fig. 14) through the Grimsby deltaic complex shows that the sand body consists of thick sequences of sandstone representing beach (Facies C) and distributary complex (Facies B) developments. Mudstone is generally restricted to the tidal flats of Facies E and to sporadic very thin partings and thin to medium mudstone interbeds within Facies B sandstone. Hence, the Grimsby stratigraphic section compares favourably to the generalized profile of deltas subjected to strong marine processes.

**Composition**

Coleman and Wright (1975) demonstrate that a clean, well-sorted sandstone with a highly quartzose mineralogy characterizes the sands of a deltaic deposit subjected to strong marine processes, especially high persistent wave energies. They report that despite a possible high suspended clay and silt content carried by incoming rivers, the strong waves are effective in winnowing the fines from the coarser deposits, and in the washing of this fine material into adjacent lower energy environments. Furthermore, the continuous reworking of the sands may also affect the mineralogy, as feldspar, which also may be abundant in the riverborne sediments, is commonly found to be a minor constituent in the sands (especially beach deposits) contained with the deltaic complex. Coleman and Wright (1975) suggest that high inshore wave powers may result in a clean, highly quartzose, well-sorted, permeable sand, whereas
low energy deltas produce a poorly sorted sand with clay bound sand grains and a resultant low permeability.

Therefore, it appears that many of the textural properties of the Grimsby and Thorold sandstones (generally moderate to good sorting, the clean, well-washed nature) are due to the intensive reworking of the sands during deposition. However, it would be somewhat presumptuous to suggest that highly quartzose mineralogy of these formations is due to the strong marine processes alone, since the Grimsby and Thorold upstream equivalents, the Juniata and Bald Eagle conglomerates and Tuscarora sandstone, are highly quartzose themselves (Yeakel, 1962). Therefore the sediment available for deposition was greatly enhanced in its quartz content.

Net Sand Distribution Pattern

Isopach maps of the Grimsby and Thorold Formations presented by Beards (1973) appear to be consistent with the interpretation of a deltaic complex in which marine processes dominated. Beards illustrates a series of northeastward trending, small, pod-shaped, localized sandstone thickenings for the Grimsby Formation in the subsurface of Norfolk County; he suggests that this pattern outlines a series of shore parallel sand bars. Furthermore, Beards depicts a nearly similar possible sand bar trend for the Thorold Formation.

From the sand body geometry depicted in the fence diagram (Fig. 13) of this report, together with the isopach map of
Beards (1973), the Grimsby sand body, on a regional scale, resembles a thick sand sheet with a possible natural surface relief of both the Grimsby and Thorold Formations due to local sand bar developments. If this is the case, then parts of the Facies B distributary complex and Facies A beach deposits, established in this paper, should represent sand bar developments.

Very broadly, the sand body geometry, together with the lithofacies established in this report, suggests a net sand distribution model somewhat analogous to the Type IV, Type V, and Type VI models (see Fig. 6) of Coleman and Wright (1975); these three models portray a thick sheet-like sand body geometry and/or coast parallel sand bar developments. The Type VI model compares well to the Grimsby isopach map of Beards (1973), however the Type IV model seems to be a better fit to the lithofacies of this paper.
CONCLUSIONS:

a) The Grimsby sand body is composed of sandstones and minor shales of (1) the red bed Grimsby Formation, deposited during deltaic progradation, and (2) the Thorold Formation, which was formed by a reworking of the Grimsby material during marine transgression (destructional phase of the delta; Fisher, 1954; Martini, 1966). The source of the clastic material is assigned to the Taconic mountains which, throughout the Upper Ordovician and Lower Silurian, shed detritus to the west and northwest within the Appalachian basin. The Grimsby sandstone is the fine-grained equivalent of the Tuscarora quartzites (to the southeast of the study area), which together with the Bald Eagle and Juniata conglomerates, formed broad alluvial plains bordering the Taconic mountains (Yeakel, 1962).

b) The Grimsby sand body in the subsurface of central Lake Erie resembles a thick sand sheet which, in the northwestern part of the study area, pinches-out (Grimsby "zero line") into the lateral equivalent prodelta to marine shelf mudstones (Cabot Head Formation). To the east and to the south, the sand body thickens into the Appalachian basin.

c) The Grimsby and Thorold Formations display a wide variety of sedimentary structures which record (1) the primary processes of sediment erosion, transport, deposition, and deformation, and (2) commonly, the secondary reworking by burrowing organisms. Furthermore, of fundamental importance is the fact that suites
of these sedimentary structures may be associated with certain depositional environments.

d) In the subsurface of central Lake Erie, the Grimsby deltaic complex can be described in terms of five genetically meaningful lithofacies, based upon gross lithology and associated sedimentary structures. Very generally, from stratigraphically lowest to highest, the lithofacies are (1) prodelta to marine shelf, (2) beach or sand bar to barrier island, (3) tidal flat, (4) distributary complex, and (5) beach (representing destructive deltaic phase) with minor laterally equivalent tidal flats to lagoons, tidal channel point bar, and fluvial channel fill.

e) The vertical profile of the Grimsby deltaic complex reflects the basic vertical framework of a progradational deltaic deposit (Visher, 1965). Furthermore, deltaic progradation, and subsequent deltaic destruction during marine transgression, resulted in a lateral and vertical array of depositional environments in accordance to Walther’s Law.

f) Storms periodically swept the deltaic environment, resulting in the reworking and the erosion of coastal sand deposits; the transport of large quantities of sand, together with shells, seaward; and the subsequent deposition of this coarser material as storm layers within the prodelta to marine shelf muddy environments. Many thick sandstone and coquoinoid sandstone beds, of storm origin, are correlatable over several miles.

g) Longshore and/or tidal currents were responsible for much reworking and dispersal of deltaic silts and sands (Martini, 1971). Beach deposits, and in many core, sand bar to barrier
island deposits occur in the lower part of the Grimsby sand body, and are believed to be a reflection of the above currents. Furthermore, these deposits show evidence of heavy storm activity. The sand bar to barrier island deposits protected landward, lateral equivalent, tidal flat developments from the strong marine processes. The distributary complex, of the lower and middle parts of the Grimsby sand body, displays much evidence of sediment reworking, again, possibly due to strong marine processes.

h) On the whole, the Grimsby sand body is interpreted as a deltaic complex which was subjected to strong marine processes resulting from the interaction of strong waves, tides, and long-shore drift—during deposition. This interpretation is suggested by (1) the vertical sequence of lithofacies and the internal character of the lithofacies, (2) the predominance of the gross amounts of sandstone over shale within a vertical section of the sand body, (3) the texture and composition of the sandstones, that is, the generally clean, well-washed nature and the moderate to good sorting, and possibly, the high quartzose mineralogy, and (4) the suggestion by Beards (1973) of a series of shore parallel sand bars in the subsurface of Norfolk County.
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APPENDIX

location of core
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Table 5. -- Location of core.
Figure 15 -- Location map of cores examined in thesis
Figure 15 - Location map of cores examined in thesis
Figure 15 - Location map of cores examined in thesis (continued)
PLATES

1 - all plate approximately natural size

2 - all photos represent the complete width of the core (6 to 8 centimeters)

3 - location of core of illustrated specimens is given in Table 5
PLATE 1

A  Asymmetrical ripple cross-stratification. Facies B. Consumers' 13139, 1780 feet K.B.

B  Interstratification of asymmetrical ripple sets and small-scale trough sets. This structure may represent various vertical sections cut through a single ripple variety. Such an interstratification of ripples suggests the sediment was influenced by changes in flow orientation. Facies B. Consumers' 13139, 1779 feet K.B.

C  Symmetrical ripple form. Facies B. Consumers' 13126, 1796 feet K.B.

D  Ripple-drift cross-stratification. Facies A. Core unknown.
Ripple-drift cross-stratification overlying small-scale trough cross-stratification in sandstone. Foreset laminae are defined by differences in colouration (C) and by mica wisps (S). Note that the small-scale trough cross-stratification may also possibly represent a vertical section cut through the ripple-drift cross-stratification variety. Consumers 13082, 1664 to 1667 feet K.B.
A  Small-scale trough cross-stratification. Facies A. Consumers' 13006, 1667 feet K.B.

B  Small-scale trough cross-stratification. Facies A. Consumers' 13109, 1762 feet K.B.

C  Low-angle-planar (swash) cross-stratification (S). The concentration of small flat shell fragments within the plane lamination results in a pronounced parting lineation. Note the brachiopod shell conglomerate (C). Facies C. Consumers' 13010, 1906.5 feet K.B.
PLATE 4

A An erosional contact between a dune-scale inclined laminated sandstone and an overlying small-scale trough cross-stratified sandstone. Facies A. Consumers' 13063, 1631 feet K.B.

B Rip-up shale clasts. Facies C. Consumers' 13082, 1697 feet K.B.

C Small dish structures in thick sandstone bed (interlayered within Facies D mudstone). Consumers' 13114, 1705 feet K.B.

D Vertical section cut through Athrophyccus (A), within siltstone laminae and thin beds interlayered within dense mudstone. Consumers' 13010, 1874 feet K.B.
PLATE 5

A Tidal bedding consisting of alternating sets of thin siltstone laminae and paper-thin shale laminae. Note the vertical burrows cross-cutting the laminae. Also note the truncation of a group of vertical burrows (E) suggesting an erosional event. Consumers' 13082, 1687 feet K.B.

B Tidal bedding. Note the interlayered thin to thick shale laminae and the deformation (due to loading or organic activity?) of most of the siltstone and shale laminae. Facies E. Consumers' 13075, 1619 feet K.B.

C Tidal bedding. Alternating sets of very thin laminae of siltstone and shale with small flat siltstone lenses incorporated within the alternating laminae. This lithology resembles the tidal lens bedding of Wunderlich (1970). Facies A. Consumers' 13055, 1709 feet K.B.

D Tidal bedding consisting of a varve-like rhythmic alternation of siltstone and shale laminae. Note the bioturbation. Facies E. Consumers' 13106, 1741 K.B.
PLATE 6

A  Bioturbated tidal bedding, overlain by Facies B sandstone. Note the erosional contact (E) and the brachiopod shell conglomerate (C). Facies E. Consumers' 13082, 1683 feet K.B.

B  Shale pebble conglomerate developed in Facies E tidal flat sequence. Note the vertical burrows (B) cross-cutting the shale intraclasts. Consumers' 13063, 1652 feet K.B.

C  Intensively bioturbated tidal bedding. Note that the thick shale laminae are disturbed only by cross-cutting vertical burrows. Facies E. Consumers' 13055, 1717 feet K.B.

D  Intensively bioturbated lithology. Note vertical cut through horizontal (?) burrows (H). Facies E. Core unknown.
PLATE 7

A Lenses, laminae, and very thin beds of siltstone and fine-grained sandstone interbedded within a shale groundmass. Note: plane to gently inclined laminae within the coarse-grained layers (L); zones of intensive biogenic reworking (B); and shell debris concentrated within sandstone layer (D). Facies D. Consumers' 13055, 1732 feet K.B.

B Very thin sandstone bed and generally discontinuous siltstone laminae within shale groundmass. Note the ripple bedding (R). Facies D. Consumers' 13126, 1795 feet K.B.

C Very thin graded sandstone beds within shale groundmass. The sandstone beds are comprised of either simple or composite bedsets of ripple cross-stratification. Facies D. Core unknown.
PLATE 8

A Thick sandstone bed interlayered within Facies D mudstone composed of two storm layers separated by an erosional surface (C). Note the sharp basal contact of the sandstone bed with the Facies D mudstone. Also note the floated rip-up shale-clasts (F) and the thin siltstone laminae (storm layers) enclosed within the shale groundmass. Core unknown.

B Escape structure (E) in the base of a very thick sandstone storm layer. Facies D. Consumers' 13126, 1797 feet K.B.
PLATE 9

A Thick coquinoind sandstone bed (C) in sharp contact with overlying sandstone bed. Facies D. Consumers' 13174, 1705.5 feet K.B.

B Very thin storm layer within Facies D mudstone. Note the abundant fossil debris within the siltstone. Facies D. Consumers' 13126, 1787 feet K.B.
PLATE 10

A Shell debris and shale clasts concentrated within plane and gently inclined laminae within sandstone. Facies C. Core unknown.

B Several, repeated conglomeritic beds separated by erosional surfaces. An individual bed is graded and is composed of varying proportions of sand, shells, and shale flakes. Facies C. Consumers' 13055, 1727 to 1728 feet K.B.

Parallel-stratified sandstone variety which resembles a lithology depicted by Wunderlich (1970) on the borders of modern sand bars. Note the thin micaceous laminae with small shale flakes. Facies C. Consumers' 13114. 1696 feet K.B.
PLATE 11

A  Very thin micaceous laminae in sandstone coalesce into silty-shale parting. Facies B. Consumers' 13139, 1776 feet K.B.

B  Ripple cross-stratification. Facies B. Consumers' 13115, 1747 feet K.B.

C  Small shale flakes concentrated along the primary stratification. Facies B. Consumers' 13139, 1797 feet K.B.

D  Small shale flakes overlying erosional surface in Facies B sandstone. Consumers' 13082, 1670 feet K.B.
PLATE 12

A Small flat shale flakes within Facies B sandstone. Core unknown.

B Small shale flakes and shells concentrated along primary stratification. Facies B. Consumers' 13139, 1795 feet K.B.
PLATE 13

A Dense mudstone with interlayerd siltstone laminae. Note the erosional contact between the mudstone and the overlying Reynales dolomite (R); the mudstone clasts (S) incorporated within the base of the dolomite; and the vertical cut through Arthrophyclus (A). Facies A. Consumers' 13021, 1804 feet K.B.

B Alternating beds of sandstone and mudstone (with interlayered very thin laminae of siltstone). Note: vertical section through Arthrophyclus (A); and possible load-deformed small sand filled channel (P). Facies A. Consumers' 13126, 1753 feet K.B.

C Bioturbated Thorold (Facies A sandstone)-Reynales dolomite contact. Note: Facies A sandstone (Th); Reynales dolomite (R); vertical cut through Arthrophyclus (A); and pyrite nodule (P). Consumers' 13027, 1803 feet K.B.

D Bioturbation in Facies A (Thorold) sandstone immediately below overlying Reynales dolomite. Consumers' 13010, 1870.5 feet.
VITAE AUCTORIS

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