THE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF THE LOWER ORDOVICIAN BELL ISLAND AND WABANA GROUPS, CONCEPTION BAY, NEWFOUNDLAND

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by

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ABSTRACT

The stratigraphy of the Lower Ordovician Bell Island and Wabana Groups was studied in order to determine their depositional environments. A proposed depositional model was then used to study the environment of formation of the Wabana ironstones.

Accessible stratigraphic sections were measured in detail and the data compared to documented examples of modern and ancient environments of a generally similar nature.

On the basis of this study a modified geological subdivision is proposed. The division of the succession into two groups is retained and their subdivision into nine formations is suggested.

It appears that sedimentation in the Bell Island and Wabana Groups was controlled by tidal processes. Two major environments are represented in the strata: interbedded sandstones, siltstones and shales interpreted to be a tidal flat complex, and massive sandstones interpreted to be an offshore barrier or tidal bar. Three subenvironments of the tidal flat complex were recognized: the subtidal, intertidal and supratidal.

Coarsening- and shoaling-upwards sequences at two locations may be prograding delta cycles, suggesting that the over all environmental control may have been that of a high-destructive, tide-dominated delta system. Paleocurrent directions support these interpretations.

Provenance studies indicate that the source terrain was Precambrian volcanic, plutonic and probably sedimentary rocks that are exposed nearby on the Avalon Peninsula. Detrital garnet, muscovite and metamorphic rock fragments may have been derived from a presently unexposed crystalline basement.

The chamosite oolites apparently formed as primary precipitates in shallow lagoons and accumulated on tidal bars and tidal flats where they were oxidized, possibly to goethite, forming hematite on diagenesis. The periodic occurrence of ironstones in the strata may be the result of migrating delta distributaries.

A general correlation of the Wabana iron ores with similar Lower Ordovician deposits of Nova Scotia, North Africa and Europe is known. The sedimentology of the host rocks, where studied, appears to be strikingly similar to that of the Bell Island and Wabana Groups.

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CHAPTER 1

INTRODUCTION

A sequence of sedimentary rocks and iron ores of Lower Ordovician age are exposed on three islands in Conception Bay, southeast Newfoundland (Fig. 1). The lower part of this sequence, the Bell Island Group (Rose, 1952), crops out on Kellys Island, Little Bell Island and Bell Island; the upper part of the sequence crops out only on Bell Island. Bell Island is approximately 43 square kilometres in area and is the largest and only inhabited island of the three. Five ironstone beds are exposed on Bell Island and three have been economically exploited, supporting a mining industry for over 70 years. Operations ceased in 1966.

The stratigraphic sequence is well exposed along narrow gravel beaches at the base of high coastal cliffs. (Fig. 2). On Bell Island, the majority of these exposures are within reasonable walking distance from a road. Other isolated coves, as well as Kellys Island and Little Bell Island, are accessible only by boat. Apart from the coastal cliffs, surface outcrops are of limited extent and are not well exposed.

Purpose of Study

This study has a threefold objective: (a) because no formal subdivision of the entire Lower Ordovician stratigraphic section of Conception Bay exists, the first objective will be to describe and subdivide the stratigraphy in a manner that conforms to formal rules of stratigraphic

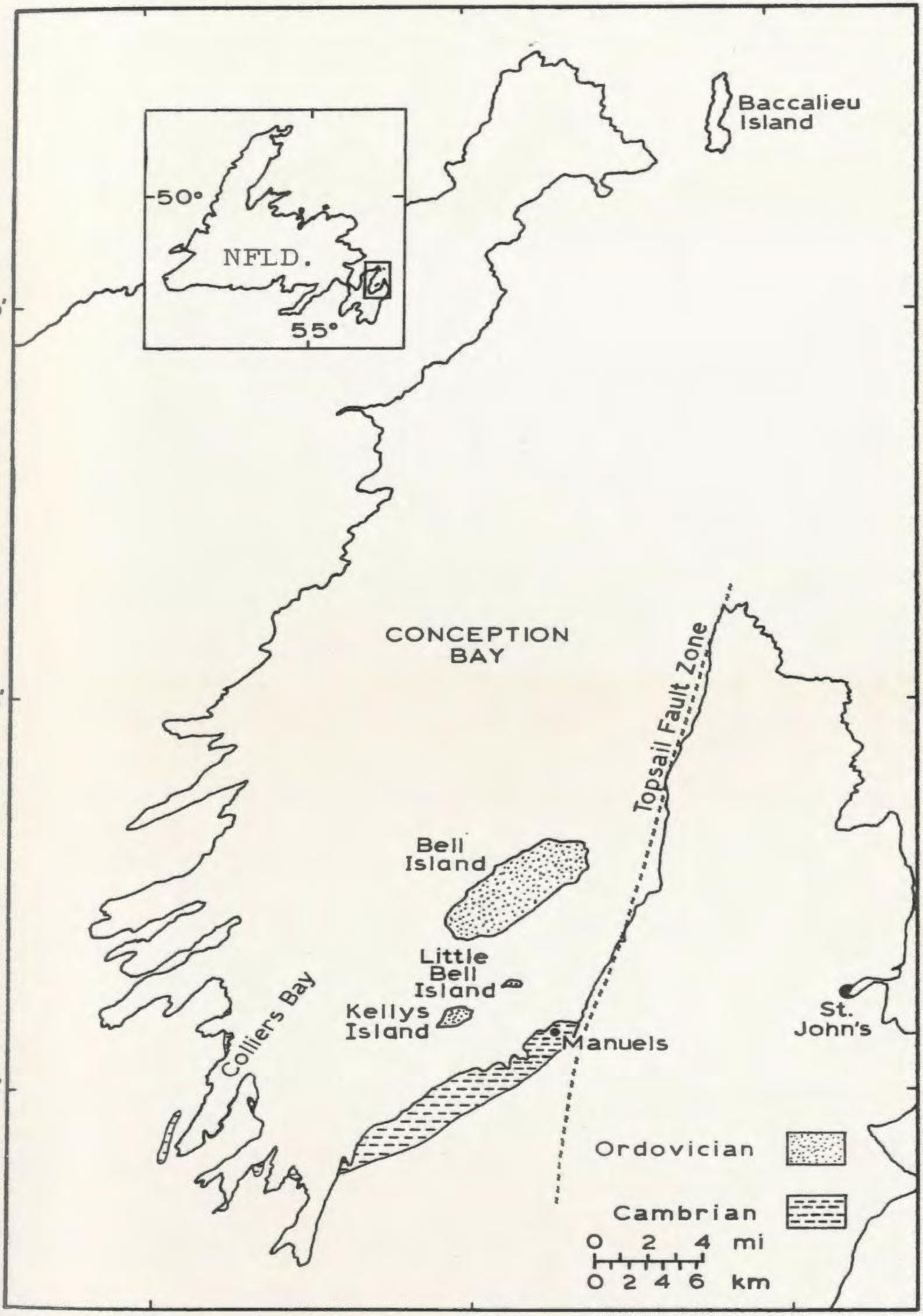


FIGURE 1

INDEX MAP

FIGURE 2. Typical coastal cliff exposure of the Bell Island and Wabana Groups at "The Bell", Bell Island. Note trees for scale; cliff is approximately 65 metres high.

nomenclature; (b) to expand the interpretation of the depositional environment of the Bell Island and Wabana Groups and attempt to relate this environment to regional geology; (c) to recognize which aspects of the depositional environment favoured the formation of the iron ore beds.

Regional Geology

The Island of Newfoundland constitutes the northeastern limit of the Appalachian Mountain System and, on a first order scale, has three principal stratigraphic-tectonic belts which trend in a northeasterly direction (Williams, 1964; Kay, 1967). The middle unit, the central mobile belt, comprises deformed Paleozoic geosynclinal sediments and volcanics. It is bounded on the northwest and southeast by Precambrian terrains that were gently subsiding stable elements during the Lower Paleozoic, upon which shelf deposits were accumulating (Williams, Kennedy and Neale, 1972).

The northwestern Precambrian belt consists of gneisses, schists and granites of the Long Range Mountains in western Newfoundland. The lithology and structure indicate that these rocks are Grenvillian inliers of the Canadian Shield (Clifford and Baird, 1962). The overlying shallow-water shelf sediments, dominantly carbonates of Cambrian to Lower Ordovician age, are typical of the lower Paleozoic continental margin whose development is recognized along the entire western margin of the Appalachians. The southeastern Precambrian belt or "Avalon Zone" (Williams, Kennedy and

Neale, 1972), on the other hand, consists of Precambrian rocks that are well exposed in Newfoundland, but poorly represented in the eastern part of the United States Appalachian system. The lithologies consist of little-deformed Late Precambrian sediments, volcanics and plutonic rocks.

On the Avalon Peninsula, the Precambrian rocks can be placed into three broad divisions. These are reviewed by McCartney (1967) and consist of (a) acid to mafic volcanics of the Harbour Main Group, (b) marine volcanic sediments and tuffs of the Conception Group and (c) marine and alluvial volcanic sediments of the Cabot and Hodgewater Groups. The geology has been interpreted by Hughes and Bruckner (1971) as the late Precambrian development of a volcanic island complex (Harbour Main and Conception Groups) and the post-volcanic phase of erosion and sedimentation (Cabot and Hodgewater Groups). The Holyrood Plutonic Series, consisting mainly of quartz monzonite and granite, intrudes the Harbour Main volcanics. It is considered by Hughes and Bruckner (1971) to be penecontemporaneous with the Harbour Main and Conception Groups.

Papezik (1972) has suggested that the geology could be interpreted instead as alkalic continental volcanism related to block faulting of a late Precambrian continental platform.

Overlying the Hodgewater Group either conformably or unconformably at a slight angle (McCartney, 1967) is from

6 to 150 metres of white unfossiliferous quartzite of the Random Formation, either latest Hadrynian or earliest Cambrian in age. McCartney (1967) considers the Random quartzite to be reworked continental sediments along the shoreline of an advancing Cambrian sea. The Random quartzite does not occur around Conception Bay and Cambrian beds here lie with angular unconformity directly upon the Harbour Main volcanics and the Holyrood Plutonic Series. At Manuels, near the Conception Bay coast just south of Bell Island (Fig. 1), the basal Cambrian is a conglomerate, six metres thick, consisting of coarse angular to subrounded clasts (Rose, 1952).

Paleozoic Rocks of the Avalon Zone

The Cambrian rocks of the Avalon Zone occur in widely scattered outcrops, but their lithological sequences are readily correlatable between outcrops (Hutchinson, 1962). Hutchinson (1962) estimated the maximum thickness of the Cambrian deposits to be up to 1300 metres. They consist mostly of shale with some shaly limestone and siltstone. There are a number of thin limestone beds near the base of the Lower Cambrian, and thin subeconomic manganiferous beds in the Middle Cambrian. The Upper Cambrian becomes gradually sandier towards the top (Hutchinson, 1962).

Three major periods of deposition during the Lower, Middle and Upper Cambrian Epochs are recognized and it is apparent from isopach maps that southeastern Newfoundland was a broad, intermittently subsiding basin whose axis trended just east of north during the Cambrian times, with probable shorelines to the east and west (Hutchinson, 1962).

Good fossil control is provided by trilobites which belong to the North Atlantic province (Walcott, 1888; Howell, 1925; Hutchinson, 1956; Fletcher, 1972).

The Lower Ordovician Bell Island and Wabana Groups consist of at least 1500 metres of interbedded micaceous sandstones, siltstones and shales. The Cambro-Ordovician contact probably occurs somewhere under the waters of Conception Bay between Kellys Island and the coast (Fig. 1). Both sequences dip gently 8 to 10° to the north-northwest suggesting a conformable contact (Rose, 1952). Thus, as Hutchinson (1962) points out, the depositional basin controlling sedimentation in earliest Cambrian times apparently persisted into the Lower Ordovician.

The only other Ordovician rocks of the Avalon Zone are exposed west of Trinity Bay, partly on Random Island (Christie, 1950). These sediments are mostly grey and black shales of the Clarenville Group believed to be of lowermost Ordovician (Jenness, 1963; Dean, 1970). They are possibly correlative with unexposed rocks below Conception Bay between Manuels and Kellys Island (McCartney, 1967).

History and Previous Work

The native people of Newfoundland, the Beothuck Indians, were traditionally known as the "Red Indians" due to the practice of staining themselves with red ochre. This was obtained from naturally occurring ferric hydroxide (Howley, 1915), for which the ironstones on Bell Island could have provided a ready source. There is no conclusive evidence of native visits to Bell Island, however Mr. Arthur Parsons of Parsonville, Bell Island, has shown the author a fragment of a ground, red slate spearhead which had been plowed up. This implement was subsequently shown to Dr. J. Tuck of the Anthropology Department, Memorial University, who maintains that it is of prehistoric origin, probably of a type used to hunt seals.

It appears that early white settlers knew of the ironstones probably as far back as the 18th century. Rev. L. A. Anspach, author of "A History of the Island of Newfoundland" (1819), cites:

> "... traditionary reports which are repeated with confidence by the oldest inhabitants (of Newfoundland)... that there is an iron mine at Back Cove, on the northern side of Bell Isle near Portugal Cove." (pp. 367-368).

These reports were either not generally known or were forgotten, because the commercial "discovery" of the deposits came only in the 1890's.

The first mention of the Bell Island strata in the geological literature was that of Jukes (1842), who made a general survey of Newfoundland geology as part of his "Excursions in and around Newfoundland during the Years 1839 and 1840". He refers to the "Belle Isle shale and gritstone" and gives a brief but accurate lithological description. Jukes did not recognize the ironstones, but he did note "a reddish stone" and "red marl" (p. 250) and, elsewhere in his report, the presence of a "bright red sandstone, 8 feet thick, in the upper beds of Belle Isle" (p. 276). Of what is now known to be a rich ichnofaunal assemblage, Jukes wrote:

> "On the firm pieces (of 'slate') occur singular markings in relief which sometimes assume the shape of leaves, branches or other organic bodies, but which are, I believe, entirely concretionary" (p. 250).

Alexander Murray (1881) published a stratigraphic cross-section through the Avalon Peninsula including a short lithological description of Kellys Island, Little Bell and Bell Island. The uppermost strata that he described were the white quartzites in the middle of the Bell Island sequence, thus missing the thick ironstone deposits in the upper beds.

The eventual discovery of the iron ores is recounted by Rev. Moses Harvey (1902):

> "A fisherman picked up what he supposed to be a heavy stone as ballast for his boat. Upon arrival in St. John's it was discovered by a mining prospector who investigated it and became satisfied of its value".

The rights to the property were acquired by the Nova Scotia Steel and Coal Co. in 1894 and quarrying began in 1895.

During 1912, 1913 and 1914 Van Ingen of Princeton University led field parties to examine the Cambro-Ordovician rocks of Conception and Trinity Bays, resulting in a series of contributions to the geology of Newfoundland by the Princeton University Department of Geology. Van Ingen (1914) produced a "table of geological formations of the Cambrian and Ordovician Systems about Conception and Trinity Bays" from his field work. He divided the Lower Ordovician of Conception Bay into the Bell Island Series and the Wabana Series, and named twelve formations based on paleontology and the appearance of the ore beds in the sequence. One of his students, A. O. Hayes, undertook a field study of the ore deposits during the summer of 1912, subsequently writing his doctoral thesis on the Wabana iron ores. The thesis was published as a memoir of the Geological Survey of Canada (Hayes, 1915).

Hayes concluded that the oolitic iron ores were of primary origin deposited under shallow water conditions and he discussed the chemistry of precipitation making the following points:

> -"penetration of the oolites by boring algae indicate the probable close association of algae with ore deposition.
>
> -"the alternating concentric layers of hematite and chamosite in the spherules suggest that most of the hematite was formed contemp-

oraneously with the chamosite. (p. 70).

-"it seems probable that the iron was derived by long continued weathering of earlier crystalline and sedimentary rocks, the solution of their iron content by mineral and vegetable acids and subsequent transportation of the iron salts into the sea. (p. 71).

-"Cayeux's theory... that an original limestone has been transformed into an oolitic iron ore is absolutely untenable for the Wabana ore." (p. 72).

In 1926, B. F. Howell summarized the Cambro-Ordovician stratigraphic column of southeastern Newfoundland, compiling much of his information from the Princeton expeditions.

Hayes (1929) published an article on "Further Studies of the origin of the Wabana Iron Ores of Newfoundland". His observations indicated that the Wabana iron ore, during the process of formation, was exposed to oxidizing conditions in a very shallow marine basin that was exposed to air over wide areas at low tide.

E. R. Rose (1952) produced a map and geological report of the Torbay map area, Newfoundland. Included in this report is the Lower Ordovician sequence of Conception Bay. In his report Rose changed Van Ingen's Bell Island Series and Wabana Series to group status, but otherwise the scope of Rose's work did not allow a more detailed description of the strata. His observations on the depositional environment were the following:

"Exclusive of the hematite beds, the rocks

> of the Bell Island Group are consolidated clastic, marine sediments, most of which seem to have been deposited in the shallow water of a tidal basin with its included and marginal deeps...
> "Thick zones of shales represent deposition in somewhat deeper water than that in which the sandstones accumulated and zones of interbedded shale and sandstone represent lateral gradational deposition to the more shallow water sandstones. The latter show ripple marks, cross-bedding, rain-drop impressions, worm burrows, and other evidences of shallow water deposition...
> "The fauna is further evidence of shallow water marine conditions of deposition, and indicates a Lower Ordovician age." (p. 34).

Rose (1952) accepted Hayes' (1915) conclusions for a primary precipitation of the ores.

The first study in any detail of the Cambro-Ordovician sequence in Conception Bay was undertaken by Nautiyal (1966). The emphasis of the study was on paleontology, and in particular, micropaleontology. A suite of microfossils including acritarchs and Chitinozoa was collected and described, and was referred to the Welsh-French province rather than to the interior North American-Northern Scotland province.

Nautiyal's (1966) study included a detailed geological map. The Bell Island Group of Rose and Van Ingen was retained (Van Ingen, 1914; Rose, 1952), but divided into three new formations. The Wabana Group was lowered to formational status and was divided into three members. This subdivision was not published and is therefore not formal.

The ore and host rocks were again considered to be "primary, shallow-water, possibly tidal marine sediments, ... with the ore owing its existence to both physical and chemical processes" -essentially in agreement with Hayes (1915, 1929).

Seilacher and Crimes (1969) recognized a close similarity in trace fossils and facies of the Upper Cambrian and Lower Ordovician in eastern Newfoundland, Wales and northern Spain, suggesting that these areas were originally in close proximity. Furthermore, they noted that the *Cruziana* species present in these areas are unknown in rocks of equivalent age and facies in mainland North America.

Bergstrom (1976) undertook a study of the prolific trace fossils from the Cambro-Ordovician sequence in Conception Bay. His published study included a short review of the local geology and an informal stratigraphic sub-division. The ichnofauna he catalogued was typical of an "Acado-Mediterranean Province" and the habitat was considered to be "very shallow, apparently partly intertidal."

Concerning the mine itself, many technical papers have been published over the more than seventy years of mining operations. Most have dealt with engineering aspects of the operation and cannot be considered as previous work in a geological sense. Only those of geological interest are reviewed.

In 1924, J. B. Gilliatt published a paper entitled

"Folding and Faulting of the Wabana Ore Deposits", which included a general summary of the geology of Bell Island. He observed that "deposition of the strata was accompanied by a gradual sinking of the basin of deposition, so that shallow water prevailed during deposition of many hundreds of feet of strata." Major persistent vertical cleavage directions were observed trending approximately north 63° east and north 35° west. The system of normal faults was related to compressional forces that produced the broad, shallow, synclinal structure of the Paleozoic rocks of Conception Bay.

The question of ore distribution prompted Hayes (1931) to review the structure of Conception Bay. The northwestern extent and termination of the Cambro-Ordovician succession (in particular as it affects the ore beds) was, and still is, unknown. Hayes (1931) postulated a major fault zone extending from Colliers Bay to a point east of Baccalieu Island (Fig. 1) as the possible terminating structure. McCartney (1954) did not believe there was sufficient evidence for the Colliers Bay Fault Zone. Whereas the Topsail Fault shows up as a linear anomaly on the aeromagnetic map accompanying McCartney's (1954) report, there is no similar feature trending along Hayes' (1931) postulated Colliers Bay Fault Zone. McCartney (1954) suggested that "west of Bell Island a north-plunging syncline or a structural basin may prove to be the dominant control of the ore horizons, with lesser complications introduced by faults".

Lyons (1957) presented an overview of the Wabana iron ore deposits, making reference to a delta pattern as a control of ore distribution and suggesting that the ore accumulated in a wide, shallow, tidal basin.

Still another overview of the Wabana operation was published by Southey (1969) three years after the closing of the Wabana mines. This was a comprehensive paper reviewing in retrospect the history and geology of the mines and the problems of ore benefication.

CHAPTER 2

METHODS

Field Methods

Stratigraphic sections were measured on two scales. Easily accessible exposures were measured in detail on the scale of 1 inch to 10 feet. (Sections are reproduced on a metric scale in this thesis.) This relatively large scale was found to be necessary in order to delineate individual units, which tend to be thin yet distinct from one another as to composition, degree of bioturbation and variety of sedimentary structures. Due to time restraints and because the cliffs were not always accessible, it was not possible to describe the entire stratigraphic column in such detail. However the entire column was measured as accurately as possible on a smaller scale and the general lithology was recorded.

Rock specimens, primarily sandstones, were collected from each exposure for later study.

Paleocurrent directions were measured wherever possible. Longitudinal current ripples were found to be best suited for this purpose. Most current ripples were only slightly asymetric, so that measurement of the foreset dip direction was required to determine the direction of flow. Suitable three dimensional exposures were not common. Corrections for regional dip of the rocks were not considered necessary when plotting the paleocurrent data. The dip varies between 8 and 10^{o} and would not significantly alter the paleocurrent vectors. Rose diagrams show the percentage of measurements in each modal class of 30^{o}.

Laboratory Methods

X-ray diffraction identification techniques were applied to a variety of green iron minerals in order to accurately describe the lithology. Both whole rock and the magnetic fraction of each specimen were pulverized and prepared as a smear mount. However, the two preparations showed little difference in the peak intensities of the iron minerals.

The x-ray technique was partly successful. Glauconite, septachlorite (chamosite), and 14Å chlorite were detected, but determination of the exact chlorite species would require chemical techniques.

Heavy mineral separations were carried out on several samples of silty sandstone and silty shale. This was accomplished by centrifuging the 3 to 4ø fraction of the crushed sample in tetrabromoethane for 20 minutes. After an acetone wash, the heavy minerals were placed in a beaker of dilute hydrochloric acid for ten minutes in order to remove any iron oxide staining. The grains were then rinsed, dried and mounted on slides using Canada balsam.

For the thin section petrography, a point count of two hundred grains was carried out on each sample. Some of the thin sections were stained with sodium cobaltinitrate in order to simplify the identification of orthoclase. Roundness was estimated using Powers' (1953) roundness scale and sorting was estimated by comparison to a set of standard deviation images prepared by Folk (1968). The sandstone classification of Folk (1968) was used in the petrographic descriptions.

Thin sections from the collection of Nautiyal (1966) were made available to the author. Several of the photomicrographs in the present study were taken using specimens from this collection in order to present the best example of a particular feature. In the photomicrographs, thin section specimens from Nautiyal's collection are prefixed with the letter "N" followed by the original reference number.

CHAPTER 3

STRATIGRAPHY

Introduction

Despite the economic importance and paleontological interest in the Lower Ordovician Bell Island and Wabana strata, a detailed stratigraphic section has never been published, although several small-scale and generalized descriptions are available (Van Ingen, 1914; Hayes, 1915; Rose, 1952; Nautiyal, 1966; Bergstrom, 1976). Most of these descriptions are based on informal geological divisions proposed principally to facilitate the study of some particular aspect of Bell Island geology.

The original detailed subdivision of eastern Newfoundland Lower Ordovician strata is that of Van Ingen, (1914) shown in Table 1. He recognized two major units, the Bell Island Series and the Wabana Series, separated by a disconformity and a thin pebble bed consisting of phosphatic shell fragments and shale clasts. Rose (1952) changed the status of the two units to the Bell Island Group and the Wabana Group, pointing out that the disconformity was a very minor one and that there is no evidence of any significant interval of nondeposition. Other workers (Nautiyal, 1966; Bergstrom, 1976) have pointed out that there is no real justification for dividing the sequence into two groups. Nautiyal (1966) proposed a new classification for the se-

TABLE 1. Table of Formations

AGE (Bergström 1976)		VAN INGEN 1914		NAUTIYAL 1966		THIS STUDY	
LOWER ORDOVICIAN	ARENIGIAN	Wabana Series (Wabana Group - Rose, 1952)	Gravel Head	Wabana Formation	Upper Member	Wabana Group	Gravel Head Formation (>14m)
LOWER ORDOVICIAN	ARENIGIAN	Wabana Series (Wabana Group - Rose, 1952)	Upper Ore Bed; unnamed; unnamed	Wabana Formation	Upper Member	Wabana Group	Grebes Nest Point Formation (18m)
LOWER ORDOVICIAN	ARENIGIAN	Wabana Series (Wabana Group - Rose, 1952)	Scotia Ore Bed	Wabana Formation	Middle Member	Wabana Group	Scotia Formation (4m)
LOWER ORDOVICIAN	ARENIGIAN	Wabana Series (Wabana Group - Rose, 1952)	Pyrite Bed	Wabana Formation	Middle Member; Lower Mbr.	Wabana Group	Powers Steps Formation (70m)
LOWER ORDOVICIAN	ARENIGIAN	Bell Island Series (Bell Island Group - Rose, 1952)	Dominion Ore Bed	Bell Island Group	Airfield Formation	Bell Island Group	Dominion Formation (4m)
LOWER ORDOVICIAN	ARENIGIAN	Bell Island Series (Bell Island Group - Rose, 1952)	unnamed	Bell Island Group	Townsquare Formation	Bell Island Group	Ochre Cove Formation (65m)
LOWER ORDOVICIAN	ARENIGIAN	Bell Island Series (Bell Island Group - Rose, 1952)	Redmond	Bell Island Group	Townsquare Formation	Bell Island Group	Redmond Formation (79m)
LOWER ORDOVICIAN	ARENIGIAN –?–?–? TREMADOCIAN	Bell Island Series (Bell Island Group - Rose, 1952)	unnamed; Eastern Head; Beach; McGraw Bed; Lance Cove	Bell Island Group	Townsquare Formation; Poll's Head Formation	Bell Island Group	Beach Formation (440m)
LOWER ORDOVICIAN	TREMADOCIAN	Bell Island Series (Bell Island Group - Rose, 1952)	not exposed	Bell Island Group	not exposed	Bell Island Group	not exposed (- 505m)
LOWER ORDOVICIAN	TREMADOCIAN	Bell Island Series (Bell Island Group - Rose, 1952)	Little Bell Island; Kellys Island	Bell Island Group		Bell Island Group	Kellys Island Formation (>298m)
LOWER ORDOVICIAN	TREMADOCIAN	not exposed (Clarenville Group?) (-420m)					
UPPER CAMBRIAN							

quence, lowering the Wabana Group to formation status and dividing it into three members (Table 1). The Bell Island Group was divided into three formations. The choice of some of the nomenclature was, however, inappropriate since in surface outcrop the Townsquare Formation does not include the local townsquare of Wabana and the Airfield Formation does not include the local airfield. This classification was never published and therefore not formally proposed.

While the author agrees that there is little justification for subdividing the Lower Ordovician into two groups, nevertheless since the classification has been well established for over 60 years and has been formally referred to in many publications, the nomenclature should be retained. Furthermore, although placing the entire Lower Ordovician sequence into a single group may appear a more natural classification today, there is certainly no advantage or usefulness to be gained. A revision can therefore not be adequately justified according to modern stratigraphic nomenclature rules (American Commission on Stratigraphic Nomenclature, 1970).

On the basis of the present study, the author feels that most of Van Ingen's original formational subdivisions (Van Ingen, 1914) are still acceptable. However, minor changes to some of the inappropriate formational names and outdated terminology have been made (Table 1) in keeping with formal nomenclature rules. The revised subdivision proposed here, along with the following description of formations, provides a necessary framework in which to discuss the sedimentology and depositional environment. Figure 3 is the stratigraphic section of the Bell Island and the Wabana Groups.

For easy reference, each locality that was measured in detail is identified by a reference letter. Within the text, these reference letters correspond to sections described in detail in the appendix and the localities are noted on the geological map by their reference letter.

Description of Formations

Kellys Island Formation

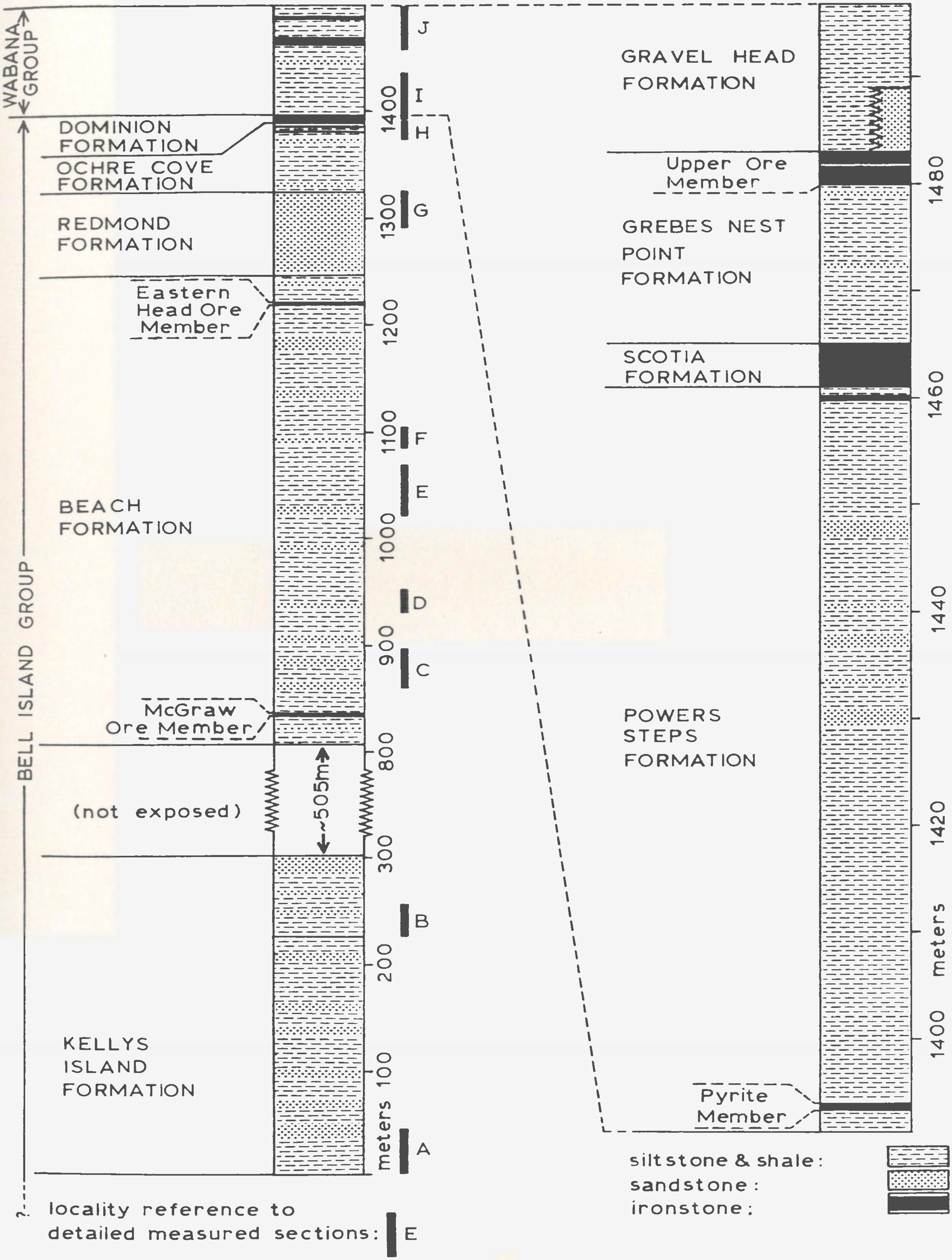
Name

Van Ingen (1914) included all of the rocks of Kellys Island in a single formation that he named after the island. He also considered the overlying strata, which crops out on Little Bell Island, to be a separate formation that was named the Little Bell Island Formation. However, the strata exposed on each of these two islands are not lithologically distinct from one another, and therefore the boundary between the two units is purely geographical. Thus, in keeping with the guidelines of stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1970) the Kellys Island Formation of Van Ingen (1914) should be expanded to include the overlying rocks of Little Bell Island.

Distribution and Thickness

This formation is exposed only on Kellys Island and

Figure 3. Stratigraphic section of the Bell Island Group and Wabana Group. (Detail of Wabana Group at right)



Little Bell Island, Conception Bay. Consequently these exposures constitute the type section. The entire exposed section is accessible by boat. The exposed thickness is approximately 298 metres, 224 metres on Kellys Island and 74 metres on Little Bell Island. The complete thickness is unknown, since the base as well as the top lie under the ocean.

It is questionable whether there is an unexposed section of the stratigraphic column between the rocks exposed on Kellys Island and those on Little Bell Island. The north-western shore of Kellys Island appears to lie approximately along strike from the southeastern shore of Little Bell Island and a continuous sequence may therefore be represented. A direct correlation could not be recognized, but this may be due to lateral variability in the strata or perhaps to faulting.

Lithology and Sedimentary Structures

The lithology consists of units of white, massive sandstone interbedded with fissile, dark, silty shale and intercalated, micaceous, sandy siltstone, silty shale and thin- to medium-bedded, rippled sandstone. The top of the exposed section is a massive, structureless, white sandstone unit at least 13 metres thick on Little Bell Island.

The massive sandstones are fine-grained quartz arenites and occasionally show traces of large-scale, parallel crossbedding with horizontal or shallow-dipping laminated bedding at the top. Some of these sandstone units on Kellys

Island are greenish, containing chamosite and chlorite.

Other sedimentary structures include wavy, flaser and lenticular bedding, runzel marks, mudcracks and scours, with current and interference ripples in the silty shale units.

Contact Relationships

The contact relationships of the Kellys Island Formation with underlying and overlying strata are unknown since both the base and the top lie under the waters of Conception Bay. It can be implied that neither the upper nor lower contact constitutes an angular unconformity, since the underlying Upper Cambrian beds at Manuels (Figure 1) and the overlying strata on Bell Island both have the same dip and strike as the strata of the Kellys Island Formation.

Beach Formation

Name

Van Ingen (1914) proposed the name "Beach Formation" for the approximately 70 metres of sediments exposed above The Beach, where the Bell Island ferry docks. Informal though it appears, The Beach is a legitimate geographic name on Bell Island. It is therefore retained here and expanded to include all the rocks of the middle part of the Bell Island Group from the base of Van Ingen's (1914) Lance Cove Formation up to, but not including, his Redmond Formation. It was found that these units are not lithologically distinct and are mappable only as a whole. The type section is at The Beach.

Distribution and Thickness

The formation is exposed along the entire southern, eastern and western shore of Bell Island from the Bell rock to Redmond's Head. The most easily accessible exposures are at Freshwater Cove (Parsonville), Lance Cove, the ore docks and The Beach. Exposed thickness is approximately 440 metres, but the total thickness is unknown, since the base of the formation is covered by the ocean.

Lithology and Sedimentary Structures

Lithology is characterized by lenticular-bedded units of white to dark grey sandstone, rarely more than one metre thick, interbedded with thick units of micaceous sandy siltstone, silty shale and dark shale. Sandstones are fine-to medium-grained orthoquartzites and are usually crossbedded and ripple marked. There are two thin, oolitic hematite beds less than 1 metre thick within the Beach Formation and these have been named the McGraw Ore Member and the Eastern Head Ore Member after Van Ingen (1914). Sedimentary structures include flaser, wavy and lenticular bedding, current and interference ripples, scour-and-fill, sand-filled channels, herringbone crossbedding, runzel marks, mudcracks, ball-and-pillow structures and load casts.

Contact Relations

The lower contact of the Beach Formation is inaccessible, lying under Conception Bay. The upper contact with the sandstones of the Redmond Formation is exposed between Eastern Head and Redmond's Head, but is not easily accessible. Generally, the shales and siltstones of the upper part of the Beach Formation become gradually sandier upward and the sandstone units become thicker, until the lithology has become virtually 100% sandstone. An arbitrary upper contact horizon with the Redmond Formation is defined as that point at which the proportion of sandstone exceeds the proportion of shale in the overall lithology.

Redmond Formation

Name

The name Redmond Formation was proposed by Van Ingen (1914) for the sequence of sandstones that form a resistant ridge striking along the length of the island and which are best exposed at Redmond's Head. Nautiyal (1966) included them in his Townsquare Formation. The type section is at Redmond's Head, Freshwater Cove.

Distribution and Thickness

The formation is exposed along the northern shore of Bell Island from Freshwater Cove (North) to the lighthouse, and along the northwestern shore at Bell Cove and Big Head. Thickness is approximately 79 metres.

Lithology and Sedimentary Structures

The Redmond Formation consists almost entirely of fine- to medium-grained, white, orthoquartzite sandstone with rare, very thin, silty partings. Almost all of the sandstones are crossbedded on a large or small scale and some display megaripple morphology. Bed thickness varies from 2 centimetres to more than 1 metre. Other sedimentary structures include trough crossbedding, herringbone cross-bedding, shallow-dipping planar beds, scour-and-fill, rill marks, swash marks and current crescents.

Contact Relations

The Redmond Formation overlies the Beach Formation conformably. The upper contact with the Ochre Cove Formation consists of a 15 metres thick sequence of massive sandstones interbedded with units consisting of siltstone, shale and thin sandstone lenses. The contact is gradual and conformable, but the base of this contact sequence is arbitrarily defined as the contact horizon.

Ochre Cove Formation

Name,

In Van Ingen's classification (1914), this formation remained unnamed. Nautiyal (1966) included it partly in his Townsquare Formation and partly in his Airfield Formation. It is named for the easily accessible type section at Ochre Cove.

Distribution and Thickness

The Ochre Cove Formation outcrops on the northwest shore of Bell Island between Gratton's Cove and Ochre Cove, and between Freshwater Cove and Gull Island South Head. Thickness is approximately 65 metres.

Lithology and Sedimentary Structures

The lower beds of the Ochre Cove Formation comprise a transition zone of close to 15 metres in which sandstone beds become thinner and the lithology changes upward into thick units of fine-grained, sandy siltstone and silty shales approximately 30 metres in total thickness. Glauconite is a significant component in some of these beds. Beds vary from less than 1 centimetre up to 12 centimetres thick. The upper 20 metres consist of alternating units of fine-grained sandstone, lenticular-bedded sandstone and siltstone, and silty shale, 20 to 60 centimetres thick. Oolitic hematite beds and lenses are common within the upper 20 metres of the formation. The sandstones and the oolitic hematite units are all crossbedded. Other sedimentary structures include herringbone crossbedding, current and interference ripples, lenticular, flaser and wavy bedding, ball-and-pillow structures, scour-and-fill, and runzel marks.

Contact Relations

The lower contact of the Ochre Cove Formation is gradual and conformable with the Redmond Formation. The upper contact with the Dominion Formation is sharp, but appears to be conformable. Minor scour surfaces are common along the contact as elsewhere in the formation, but these are presumably due to the shallow-water nature of the sedimentary environment and do not represent a major erosion surface or hiatus.

Dominion Formation

Name

The name "Dominion Bed" was applied to the lowermost workable iron ore bed when the mining rights to it were acquired by the Dominion Iron and Steel Co. in 1899 (Hayes, 1915). Van Ingen listed the name "Dominion Ore Bed" as a formational name in his classification of 1914. However, the terms 'bed' and 'formation' have distinct and different meanings in presently accepted stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1970). Since the Dominion and Scotia ore bodies are lithologically distinct units and have been mapped extensively above and below ground, they are here given formational status and Van Ingen's name, "Dominion Ore Bed" is revised to the

"Dominion Formation". Nautiyal (1966) included this unit as part of his Airfield Formation.

Distribution and Thickness

Much of the surface outcrop of the Dominion Formation has been strip-mined, including what may have been considered the type section. Remnants are found at Gull Island North Head and Youngsters Gulch immediately northeast of Ochre Cove. A complete section outcrops along the coast between Youngsters Gulch and Powers Steps, and is here designated as the type section. As the major ore horizon, this unit has been extensively delineated underground and is known to extend down-dip from the north shore of Bell Island for 5200 metres and laterally along strike for 6100 metres without termination (Southey, 1969). Thickness varies from 4 metres, common in the surface outcrops, to 13 metres in some of the underground workings (Southey, 1969).

Lithology and Sedimentary Structures

The lithology of the Dominion Formation is dominantly oolitic ironstone. Mineralogy of the oolites consists of hematite or concentric layers of chamosite and hematite. Interstices contain siderite, calcium phosphate as shell fragments and nodules, and small amounts of pyrite. Fine-grained, detrital sand makes up from 0 to 10% of the ironstone as oolitic nucleii or in interstices. Shale lenses, stringers and streaks are common throughout the formation and in places lowered the ore grade to the extent of making it uneconomic to mine (Lyons, 1957). Crossbedding is sometimes evident, but structures generally are obscured by intense surficial weathering.

Contact Relations

The lower contact of the Dominion Formation with the Ochre Cove Formation is sharp but apparently conformable. The upper contact with the Powers Steps Formation is a minor disconformity overlain in most places by 10 to 50 centimetres of phosphatic shell fragments and shale pebble conglomerate in a sandy matrix. This is also the contact between the Bell Island Group and the Wabana Group.

Powers Steps Formation

Name

Van Ingen (1914) referred to this as the "Pyrite Bed Formation". Since the terms 'bed' and 'formation' are conflicting terminology in modern nomenclature and since the name Pyrite Bed is non-geographical and describes only a few centimetres of a 70 metre thick sequence, the name proposed here is "Powers Steps Formation" after the location of the type section. The pyrite unit is given the status of member, and it was a major marker unit in the underground mining operation. In Nautiyal's classification (1966) the lower part of the Powers Steps Formation, including the Pyrite Member, was assigned to the Lower Member of his Wabana Formation and the upper part was included in the Middle Member.

Distribution and Thickness

The Powers Steps Formation outcrops along the northwest shore of Bell Island between Youngster's Gulch and Upper Grebes Nest Point, and between Gull Island North Head and the beach just east of Grebes Nest Point. Thickness is approximately 70 metres.

Lithology and Sedimentary Structures

Near the base of the Powers Steps Formation lies the sedimentary Pyrite Member, 20 to 40 centimetres thick. The pyrite occurs as oolites, spherules, pyritized graptolite fragments and pyrite-coated shale pebbles in a siliceous groundmass. The beds are graded or current ripple crossbedded. Several thinner, rippled pyrite beds, 1 to 5 centimetres thick, occur in shales within 3 metres above the Pyrite Member. Overlying this zone is approximately 30 metres of fissile, graptolitic, dark shale intercalated with occasional thin, rippled sandstone or siltstone lenses, 1 to 5 centimetres thick. Within the shales are several horizons along which limy septarian nodules, surrounded by cone-in-cone structures, are common (Fig. 4a, b). These are generally in the shape of a flattened spheroid, but occasionally irregular or dumbbell shaped. Fine-grained sandstone lenses and beds gradually become more common and thicker in the upper 40 metres of the formation and dark, fissile shale gives way to sandy siltstone and silty shale. Sedimentary structures in this upper 40 metres include flaser, wavy and lenticular

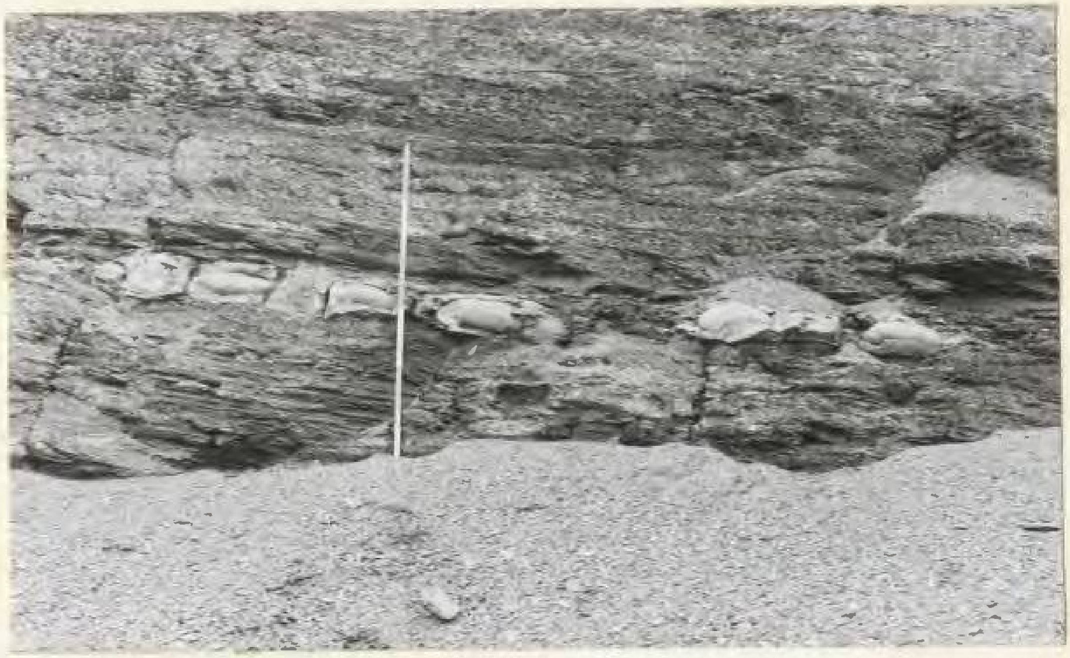


FIGURE 4a. Septarian nodule horizon in dark shales of the lower part of the Powers Steps Formation; just east of Youngsters Gulch, Bell Island. Rod is 6 feet long (1.8 m).

FIGURE 4b. Septarian nodules surrounded by cone-in-cone structure (arrows). Hammer is 28 cm long.

bedding, current, wave and interference ripple-marks, scour-and-fill, runzel marks, mudcracks and large ball-and-pillow structures.

Contact Relations

The lower contact of the Powers Steps Formation is apparently disconformable with the Dominion Formation. The upper contact with the Scotia Formation is lithologically sharp, but apparently conformable and is similar in appearance to the lower contact of the Dominion Formation as described above.

Scotia Formation

Name

The name "Scotia Bed", used for the middle of the three workable iron ore bodies, has been in common usage at least since the beginning of the 20th century (Hayes, 1915). It is named for the Nova Scotia Steel and Coal Co., which at that time owned the surface mining rights to this and the Upper Ore Bed. Van Ingen (1914) lists this unit as a formation with the name "Scotia Ore Bed". As discussed above in the description of the Dominion Formation, the term 'bed' used in the name of a formation is incompatible with modern stratigraphic nomenclature and the name is here revised to the "Scotia Formation". The type section is at Upper Grebes Nest Point. The Scotia Formation was included in the Middle Member of Nautiyal's (1966) Wabana Formation.

Distribution and Thickness

Due to extensive strip mining, little surface outcrop remains of the Scotia Formation. The only exposures remaining are in the sea cliffs between Upper Grebes Nest Point and Gravel Head, and at the beach and cliffs immediately east of Grebes Nest Point. It has been extensively delineated underground and has been mined offshore from Bell Island downdip for about 1370 metres and laterally along strike for roughly 2440 metres (Southey, 1969). Total extent may not be considerably more than this, since exploratory underground drilling indicates a definite narrowing trend in all directions and the ore body was considered to be nearing exhaustion (Southey, 1969). Maximum thickness is about 4 metres.

Lithology and Sedimentary Structures

The Scotia Formation consists dominantly of oolitic hematite, chamosite, or concentrically layered hematite and chamosite. A distinct band, several centimetres thick, of chamosite oolites occurs near the top. Accessory components are siderite and phosphatic shell fragments and nodules. Fine-grained detrital quartz sand occurs as rare oolitic nucleii or, more commonly, in the interstices. Evidence of large- and small-scale crossbedding is sometimes seen, but is generally obscured by intense weathering.

Contact Relations

The lower contact of the Scotia Formation with the underlying Powers Steps Formation is sharp, but appears to be conformable. The upper contact is marked by a thin (6 centimetres) but persistent pebble bed of phosphatic shell fragments and nodules, and shale chips. This may indicate a minor disconformity.

Grebes Nest Point Formation

Name

This name is proposed for the sequence of rocks overlying the Scotia Formation up to and including the upper ore beds. Van Ingen (1914) left this sequence unnamed except for the "Upper Ore Bed", which had formational status. This ore body is here relegated to the status of a member. It was not seen fit to consider the upper ore body as a separate formation, since strip mining has left little surface exposure except for sea cliffs and it is therefore not mappable. Furthermore, it was never exploited underground due to extremely irregular deposition (Southey, 1969) and as a consequence, is not extensively delineated. The name "Grebes Nest Point Formation" comes from the location of the type section. Nautiyal (1966) included this sequence in the Upper Member of his Wabana Formation.

Distribution and Thickness

The Grebes Nest Point Formation outcrops on the northwest shore of Bell Island between Upper Grebes Nest

Point and the beach cliffs immediately east of Grebes Nest Point. Thickness is approximately 18 metres.

Lithology and Sedimentary Structures

The lithology of the Grebes Nest Point Formation ranges from dark shales with sandy and silty lenses intercalated with phosphatic pebbly beds at the bottom, upwards into a series of interbedded and lenticular dark shales, sandy siltstones and fine-grained, rippled sandstones. Phosphatic pebbly beds are common throughout and oolitic hematite streaks become more frequent in massive dark shales towards the top. The top of the formation comprises several beds of oolitic hematite varying in thickness from 0.5 to 3 metres. Shaly lenses and partings are very common within much of the ore. Accessory minerals include oolitic chamosite, siderite, fine-grained detrital quartz sand, and phosphatic shell fragments and nodules. Bedding structures include flaser, wavy and lenticular bedding, longitudinal and interference ripples, and runzel marks.

Contact Relations

The lower contact of the Grebes Nest Point Formation appears to be a minor disconformity with the underlying Scotia Formation. The contact with the overlying Gravel Head Formation is a thin, discontinuous pebble bed consisting of phosphatic shell fragments and nodules, and shale chip conglomerate. This feature is similar to that observed to directly overlie both the Dominion Formation and the Scotia

Formation ore bodies and here again may be interpreted to be a minor disconformity.

Gravel Head Formation

Name

Van Ingen (1914) proposed this name for the sequence of shales overlying the Upper Ore Member and which forms the uppermost stratum exposed on Bell Island. It is named for the locality of the type section at Gravel Head. Nautiyal (1966) included this unit in the Upper Member of his Wabana Formation.

Distribution and Thickness

The Gravel Head Formation outcrops on the northwest shore of Bell Island between Gravel Head and Grebes Nest Point. This formation has been penetrated from below by exploratory drilling in underground offshore workings. The top of the formation is not exposed and was not reached during drilling. Exposed thickness is 14 metres and drilling has penetrated at least 165 metres (Lyons, 1957).

Lithology and Sedimentary Structures

In surface exposure the lithology consists entirely of dark, fissile shales, apparently non-fossiliferous. However, an exploratory drill hole described by Gilliatt (1924) penetrated a sandstone unit 6 metres thick underlying the dark shales and thus at the base of the Gravel Head Formation.

Contact Relations

The lower contact with the Grebes Nest Point Formation appears to be disconformable and the top is not exposed.

Age of the Strata

Evidence for the age of the Bell Island-Wabana sequence is thoroughly reviewed by Bergstrom (1976). A lower age limit is set by Olenid trilobites of late Cambrian age at Manuels. Psilocara (?) sp., a possible early Ordovician Olenid, was found by Bergstrom (1976) on Little Bell Island. The most reliable upper age limit is provided by graptolites of Didymograptus nitidus type found in the pyrite and the overlying shales of the Powers Steps Formation, indicating an early Arenigian age. There is no evidence that the overlying sediments are significantly younger (Bergstrom, 1976).

The occurrence of the trace fossils Cruziana semiplicata and C. furcifera overlaps in the lower Bell Island sequence. Since C. semiplicata is believed to range only into the Tremadocian (Crimes, 1970; Seilacher, 1970), its apparent disappearance in the Beach Formation above the base of the Eastern Head Ore Member led Bergstrom (1976) to suggest that the Tremadocian-Arenigian boundary lies approximately at that horizon (see Table of Formations, p. 20). (Note: Tremadocian is used here to refer to the Lower Ordovocian.)

CHAPTER 4

DEPOSITIONAL ENVIRONMENTS

Introduction

A number of readily apparent sedimentary structures suggest that almost the entire thickness of the Bell Island and Wabana strata was deposited in a shallow-water environment. Ripple-marks and small-scale crossbedding occur throughout the rocks and indications of periodic exposure such as mudcracks and rill marks are numerous. These structures, along with abundant brachiopods and marine trace fossils, indicated a shallow marine depositional environment to even the earliest workers however brief their study of the Bell Island rocks. Furthermore, a partly intertidal nature for the depositional environment has been suggested (Hayes, 1929; Rose, 1952; Lyons, 1957).

This chapter is an interpretation of the environments and subenvironments in which these sediments were deposited. It is based upon data recorded when measuring the sections described in the appendix and on a comparison with documented examples of both ancient and modern shallow-water environments. These postulated environments of deposition are then put in the broader context of a larger depositional system.

The evidence presented in this chapter indicates that the Bell Island and Wabana Groups represent an extensive

Lower Ordovician tidal flat complex with associated subtidal and offshore marine facies. Furthermore, there is evidence that the overall environmental control was that of a major delta system.

Two distinctive sedimentary styles dominate the geology of Bell Island: (1) thin- to medium-bedded, highly variable, lenticular sandstones, siltstones and shales, and (2) fine- to medium-grained, thick-bedded, white orthoquartzites which, due to differential weathering, form a resistant "backbone" striking across the length of the island. Both of these sedimentary styles exhibit characteristics of shallow-water deposition and in this study are interpreted respectively as a tidal flat complex and an offshore barrier or tidal bar complex.

Tidal Flat Complex

An idealized stratigraphic sequence for the tidal flat complex is illustrated in Fig. 5. Although the entire sequence is nowhere fully developed, almost all the exposed strata of the Beach Formation, the Ochre Cove Formation and the upper part of the Powers Steps Formation consists of a succession of units whose relationships and characteristics are reflected in this model. The model represents the sequence developed by a prograding tidal flat complex and as such, it is a regressive sequence. It consists of three facies representing closely related environments of deposition: the shallow subtidal, intertidal and supratidal.

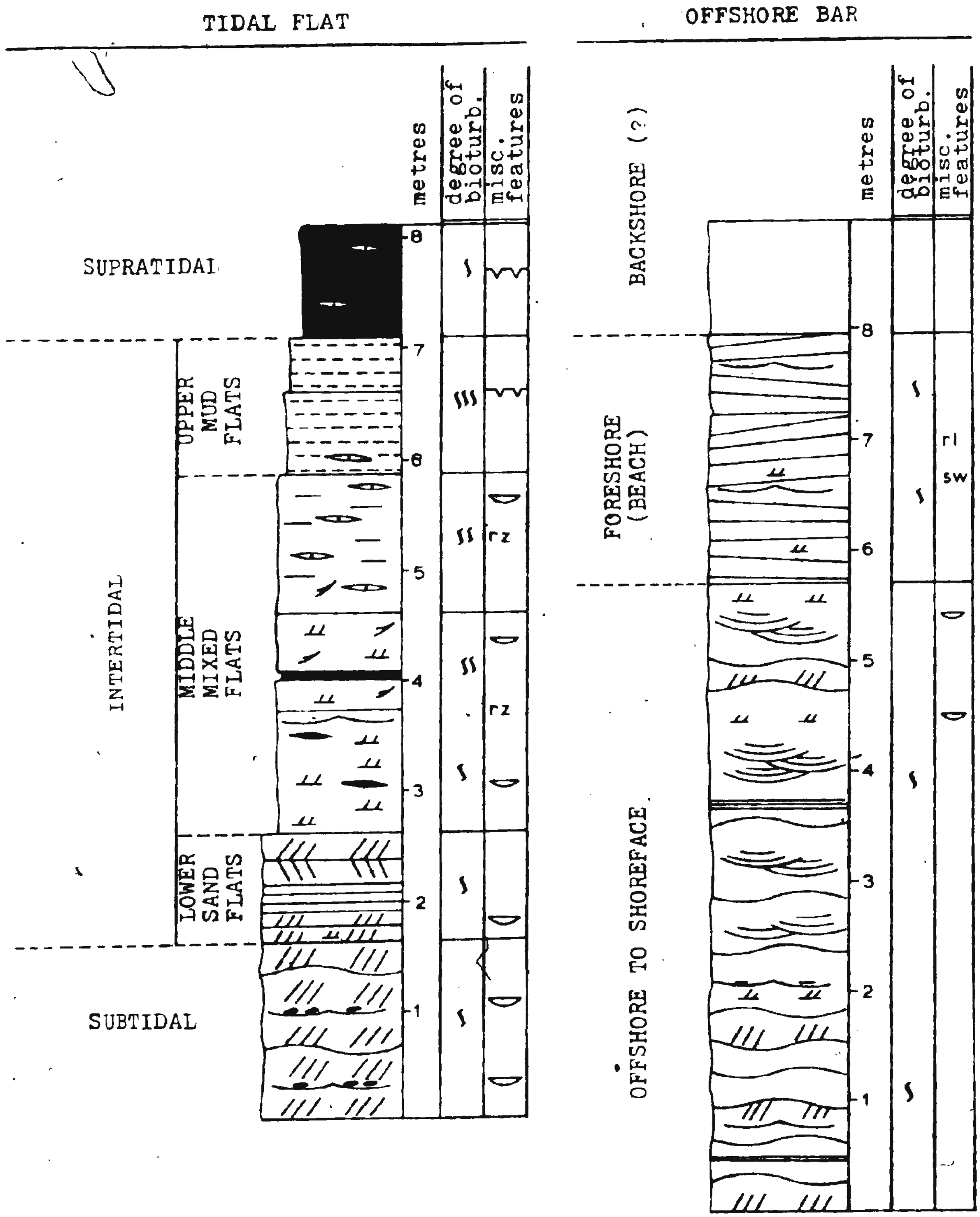


FIGURE 5

Depositional model and idealized stratigraphic sequence for the Bell Island and Wabana Groups. Legend: see p. 157.

Subtidal Facies

The subtidal facies (Fig. 6) consists of clean, white, current rippled or massive sandstones of medium to fine grain size. Large-scale parallel crossbedding is common and is characterized by many scour surfaces often with a shell fragment and shale chip lag deposit. Most of these sandstones are therefore interpreted as migrating channels of small size: no more than 2 to 3 metres in width and less than 1 metre in depth. Some of these may be fluvial in origin, but because of their relationship with other tidal facies and their position within the depositional model being developed here, most, if not all of these channel sandstones are probably tidal in origin.

Some of the massive sandstones appear to have a megaripple morphology and may represent low relief offshore or tidal flat bars, possibly partly exposed at low tides.

The sandstone weathers light yellowish to reddish brown. Carbonate and silica cements are both common. Bioturbation is rare, but Skolithos and Diplocraterian burrows do occur.

The subtidal-intertidal boundary is often well defined. It consists of a short transition zone in which beds become thinner, and drapes and partings become common, grading upwards into interbedded siltstones and shales. The lowest spring tides most likely exposed the upper subtidal zone on rare occasions.

The transition from the subtidal to intertidal environments also coincides with the first appearance in the sequence of a combination of structures indicative of late-stage emergent run-off prior to tidal flat exposure at low tide

(Klein, 1963, 1971). These features include small-scale current ripples superimposed on megaripple troughs (Fig. 7). The current direction is controlled by the strike of the trough, curving around slip faces and is indicative of nearly emergent conditions.

The subtidal facies is well exposed in the cliffs opposite the old Scotia pier at the southeastern end of the ore docks (locality D, unit 1) and attains a thickness there of 1 to 2 metres.

Intertidal Facies

The intertidal facies, if ideally developed, can be divided into three distinct subfacies representing the shoreward decline in energy and the associated changes in the sediment transport mode from traction to suspension (Klein, 1972). With respect to the Bell Island strata, these subfacies are here referred to as the lower sand flats, the upper mud flats and a thick transition zone, the middle mixed flats (Fig. 8).

Lower Sand Flats

The predominant sediment type in the lower sand flats is a light, fine- to medium-grained sandstone, occasionally interbedded with darker siltstone and shale. The average thickness of this subfacies is approximately 1 metre. Sandstone bedsets are parallel or current ripple crossbedded, or planar laminated. A distictive feature of this subfacies

FIGURE 6. Lenticular sandstones with scoured bases, resulting from migrating channels, probably tidal in origin; overlain by thin-bedded intertidal sandstone and siltstone; between the ore docks, Bell Island. Rod is 6 feet high.

FIGURE 7. Current ripples indicating water flow around the slip face of a megaripple (lower right): a late stage emergent run-off feature. Arrow indicates direction of flow; Freshwater Cove (north), Bell Island. Hammer is 28 cm. long.

FIGURE 8. A section through the intertidal facies showing the three subfacies, (a) the lower sand flats, (b) the middle mixed flats and (c) the upper mud flats; Freshwater Cove (Parsonville), Bell Island. Rod is 6 feet long (1.8 m).

is the development of herringbone crossbedding (Fig. 9), in which crossbedded units display foreset laminations dipping in opposite directions. Originally described by Reineck (1963), they are considered as a particularly good indicator of tidal influence on sedimentation processes (Klein, 1975a).

Interbedded siltstones and shales are wavy and thin bedded. Brachiopod shell fragments and shale chips sometimes occur as a lag deposit at the base of the sandstone beds. Bioturbation is rare in this subfacies.

As the lowest and most seaward subenvironment of the intertidal facies, the lower flat would have been exposed to high energies from waves and tidal currents throughout most of the tidal cycle and have been subaerially exposed for less time than any other part of the tidal flat complex. Some of these lower sand flat deposits may in fact be intertidal sand bars of low relief similar to those developed in the Minas Basin, Nova Scotia (Klein, 1970a) and separated from the tidal flat proper by a wide, shallow channel. Other bedsets which have a shell and shale chip lag deposit at their base and appear to have formed by lateral migration are interpreted to be small tidal channels.

This subfacies crops out at Freshwater Cove (Parsonville) (locality E, unit 3), at the Ore Docks (locality D, unit 2) and at Gull Island North Head (locality H, units 3, 10 and 13).

Middle Mixed Flats

This subfacies is highly variable in composition and structure, and makes up the bulk of the tidal flat sediments on Bell Island. It averages 3 to 4 metres thick and in general is a fining-upwards transition subfacies between relatively thinner lower sand flat and upper sand flat subfacies. The overall sedimentary style, not withstanding the dominant fining-upwards nature of the strata, is that of interbedded, silty sandstones and shales with rippled sandstone lenses from 1 to 20 centimetres thick and 20 centimetres to 2 metres in length (Fig. 10). The sandstones are fine grained, may be ripple crossbedded and often have an interference rippled surface.

Some of the commonest bedding features in the middle mixed flats are flaser, wavy and lenticular bedding (Fig. 11, 12) and numerous intermediate forms. These structures indicate rapid fluctuation in energy levels during the period of deposition and their abundant occurrence is evidence for a tidally influenced depositional environment (Reineck and Wunderlich, 1968). Flaser and related bedding are some of the most commonly documented sedimentary structures in both modern and ancient siliciclastic tidal flat environments (Ginsburg, 1975) and are also known in carbonate tidal flat environments.

A significant structure frequently observed in the middle mixed flat subfacies is the runzel or wrinkle mark

FIGURE 9. Herringbone crossbedding in the lower sand flat subfacies; Freshwater Cove (Parsonville) Bell Island. Hammer is 28 cm long.

FIGURE 10. Rippled sandstone lenses in siltstone of the middle mixed flat subfacies; Freshwater Cove (Parsonville) Bell Island. Hammer is 28 cm long.

FIGURE 11. Flaser, wavy and lenticular bedding; Lance Cove, Bell Island.

FIGURE 12. Mud-draped flaser-bedded sandstone overlain by starved ripples; The Beach, Bell Island. Bar represents 10 cm.

(Fig. 13). These interesting features are described by Reineck (1969) and he has reproduced them experimentally by simulating strong wind conditions over a partly cohesive sediment surface covered by a thin (1 centimetre or less) film of water. Similar structures are produced by wind driven foam on modern beaches (Allen, 1967). On Bell Island, these features are the commonest evidence for intermittent subaerial exposure and, supporting Reineck's (1969) experimental conclusion, they are developed only on muddy and silty fine-grained sandstones which originally would have been partly cohesive. Some of the runzel marks, however, display an imperfect honeycomb-like pattern, possibly due to runzel mark formation during a rain storm. All of these structures are regarded as direct evidence of subaerial exposure wherever observed.

The presence of fossil raindrop impressions has often been mentioned in previous studies of these rocks as a common indicator of subaerial exposure (Hayes, 1915; Nautiyal, 1966). This structure was found to be rare and was recognized at only one horizon: immediately below the Dominion Ore body (Fig. 14). Both Hayes (1915, plate XXVIII) and Nautiyal (1966, Fig. 72) show photographs of what is inferred to be raindrop impressions. It is obvious from these pictures that the structures are actually runzel marks, more like miniature ripples than circular or elliptical imprints.

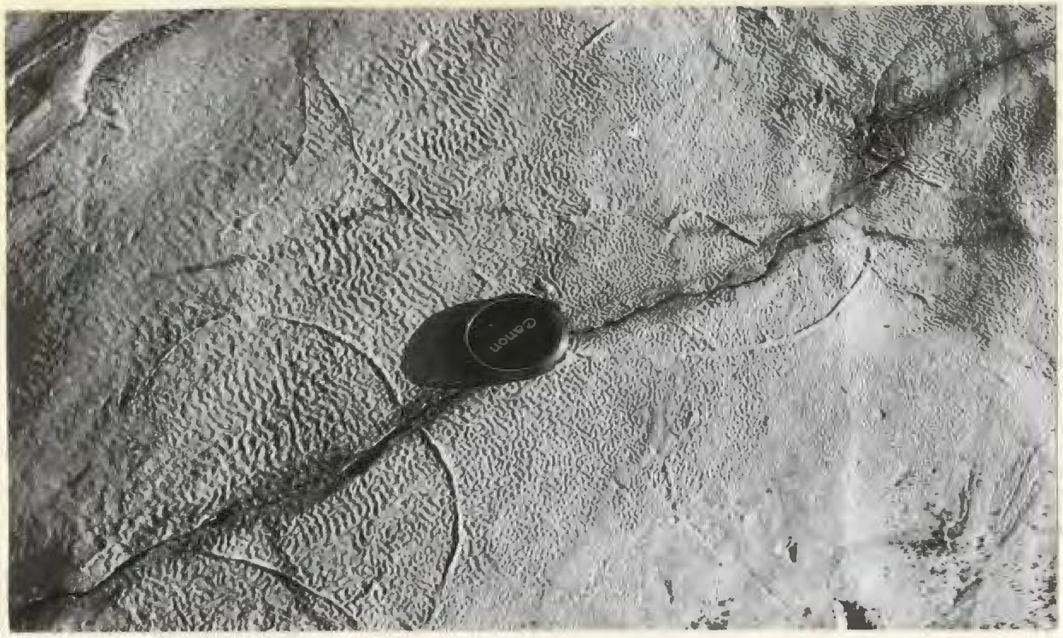


FIGURE 13. Runzel marks displaying wide variation in size. Note superimposed "scribbling" grazing traces; Ochre Cove, Bell Island.

FIGURE 14. Fossil raindrop impressions; on a bed surface in the basal part of the Dominion Formation, Bell Island. Hammer is 28 cm long.

Several features are indicative of rapid shallowing in the environment of deposition, so rapid in fact that shallow-water and subaerial features are superimposed on deeper water structures and subsequently preserved by rapid burial. These features are particularly good examples of late-stage emergent runoff structures. Figure 15 shows a flat sediment surface covered with runzel marks, but with a more or less regular pattern of oval depressions averaging 10 to 20 centimetres in length inside of which runzel marks have not formed. It seems evident that this is an interference rippled surface produced during deeper water high tide conditions and that subsequently the tops or nodes were planed off due to late-stage runoff conditions at low tide. Emergence is indicated by the superimposed runzel marks. Figure 16 is evidently an interference rippled surface on which late-stage runoff was only of sufficient energy, at least locally, to superimpose a pattern of rill marks and current lineations without destroying the ripple morphology. Rippled surfaces may also be truncated by scours (Fig. 17).

Double-crested ripples (Fig. 18), another indication of falling water level (Reineck, 1973), were recognized in this subfacies. They are rare, however, having been noted only at one outcrop.

Small sand-filled channels, averaging 30 to 50 centimetres in width, are a common feature in the middle mixed flat subfacies (Fig. 19), giving further support to the inter-

FIGURE 15. Runzel marks superimposed on a scoured interference-rippled surface; Ochre Cove, Bell Island.

FIGURE 16. Rill marks superimposed on an interference-rippled surface; Gull Island South Head.

FIGURE 17. Interference-rippled surface truncated by scour; Ochre Cove, Bell Island. Scour is approximately 1 metre in width.

FIGURE 18. Flattened, double-crested ripples; Gull Island South Head. Hammer is 28 cm long.

tidal nature of the depositional environment. Wide, shallow scours with parallel infill were frequently noted, but often tend to be camouflaged in the complexity of the bedding (Fig. 20). Many of the thicker sandstone lenses are probably the infilling of very shallow tidal channels which were abandoned shortly after they were established or after migrating only a few metres.

Bioturbation varies from weak to strong, generally increasing upwards. It also changes in nature with trilobite tracks and trails predominating at the bottom of the mixed flat, decreasing upwards, and with burrowing predominating towards the top. The tracks and trails include various species of Cruziana, Rusophycos, Isopodichnus and trilobite exite and telopodite scratches (Bergstrom, 1976). Burrowing is probably due to annelids, brachiopods and other unidentified animals.

The middle mixed flat subfacies makes up a large proportion of the sediments on Bell Island and can be observed at almost every exposure except within the offshore bar facies. There are excellent exposures at the Ore Docks (locality D, unit 13), The Beach (locality E, unit 13), Freshwater Cove (Parsonville) (locality E, units 4, 5) and Gull Island North Head (locality H, units 4, 11, 14).

Upper Mud Flats

The uppermost subfacies of the intertidal facies consists of light brown silty shales, weathering light yellowish brown. They are generally thin bedded, although bedding is usually destroyed by intense bioturbation,

FIGURE 19. Flat bottomed, sand-filled tidal channel; between the ore docks, Bell Island. Hammer is 28 cm long.

FIGURE 20. Scour-and-fill in the middle mixed flat subfacies. Arrows indicate scour surfaces; Freshwater Cove (Parsonville), Bell Island. Hammer is 28 cm long.

characteristically leaving very little structure (Fig. 21). This subfacies is referred to the upper tidal flat, which is flooded only periodically and where low energy conditions predominate due to the slack water period at high tide. Conditions are therefore such that clay and fine silt that are agitated into suspension by tidal currents and waves in the lower tidal flat are able to settle out in the upper tidal flat environment.

This subfacies averages 1 to 1.5 metres thick, usually with sharp upper and lower boundaries. Mudcracks are observed in places (Fig. 22), but are not common or are masked by bioturbation. Narrow (30 centimetres or less), sand-filled tidal channels are present but rare.

This upper mud flat subfacies is well developed at many localities. Its light colour and homogeneity produces much of the layering seen from a distance in the Bell Island cliffs. Outcrops are prominent and accessible at The Beach (locality E, unit 22), the Ore Docks (locality D, unit 5), Freshwater Cove (Parsonville) (locality F, unit 8) and Gull Island North Head (locality H, units 6, 12).

Supratidal Facies

A facies within the tidal flat complex, which is interpreted as supratidal, consists of dark shales, often interbedded with thin sandstones and graded siltstones

The typical development of this subfacies is inferred from the particularly good exposure at the northeast limit

FIGURE 21. Intense bioturbation in silty shales of the upper mud flat subfacies; Freshwater Cove (Parsonville), Bell Island.

FIGURE 22. Mudcracks; between the ore docks, Bell Island. Pen is 13 cm long.

of the Beach (Fig. 23). The outcrop consists of 1 to 2 metres of black shale interbedded with white rippled sandstones. Above the sandstones are, typically, several centimetres of light siltstone, grading upwards in texture and colour to dark grey shales (Fig. 24a, b). The tops of these shales display deep mudcracks, which have been filled with sand from the next cycle. Short, sand-filled burrows often extend down from the sandstone bed 1 or 2 centimetres into the underlying dark shale. A single cycle is typically from 4 to 12 centimetres thick with very sharp boundaries between the dark shale at the top of a cycle and the overlying sandstone forming the base of the next cycle.

These cycles suggest periodic flooding probably due to extreme spring tides or storm tides, which washed in undifferentiated sediments from sand to clay. The sands were deposited almost immediately from the traction load as evidenced by the ripples and small-scale crossbedding. Subsequently the silts and clays settled out from suspension, forming the graded bedding. The dark colour of the shales suggests a high organic content. Complete desiccation and the return to subaerial conditions produced the deep mudcracks on the new surface. It is apparent that some burrowing animals were washed in during the flooding and burrowed down through the newly deposited sands into the underlying surface. They probably would not survive long due to the development of euxinic or desiccated conditions and

FIGURE 23. Banded black shales of the supratidal facies, overlain by sandstone sheets and lenses of the intertidal facies; The Beach, Bell Island. Rod is 6 feet long.(1.8 m).

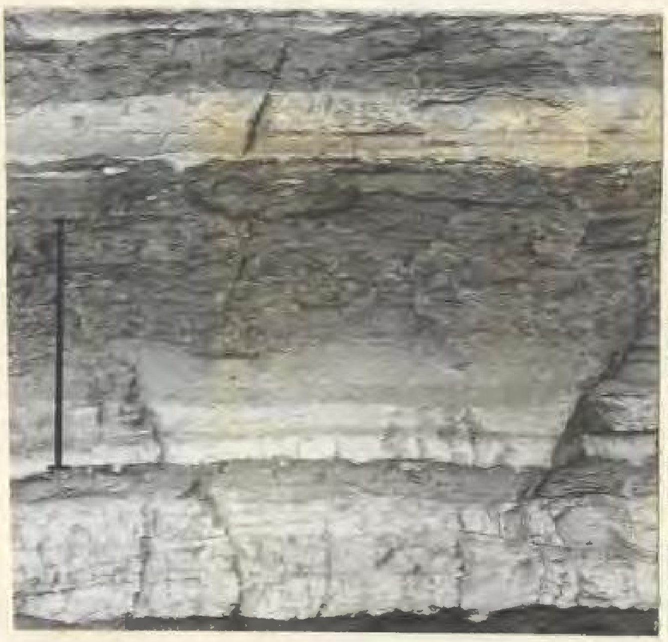


FIGURE 24a (left). Graded bedding, probably produced by storms or extreme high tides flooding the supratidal ponds; The Beach, Bell Island. Bar represents 10 cm.

FIGURE 24b (right). Mudcracks, in section (arrow), infilled with sand from an overlying cycle; The Beach, Bell Island. Bar represents 10 cm.

possibly high salinity.

The graded bedding suggests deposition from a quiet, standing body of water with no rapid runoff after flooding, as would normally be the case on an open tidal flat. This implies that this facies was a restricted environment, possibly a zone of supratidal ponds high up on the tidal flat complex. It would be the lower Ordovician equivalent to the salt marsh facies in the modern tidal flat environment. A second possibility is that this facies developed in a channelled belt as ponds or restricted lagoons dammed off by channel bank levees.

There is some field evidence to support this latter idea: at The Beach, these supratidal dark shales occur in an apparently intertidal facies in which sandstone sheets and small migrating channels, filled with sand, are uncommonly abundant (Fig. 23). In addition, a major sand-filled channel at least 4 metres deep and 7 metres wide is exposed approximately 100 metres laterally along the cliff to the southwest (Fig. 25). Although they cannot be correlated directly due to talus cover, their overall position in the stratigraphic column suggests close proximity in time and certainly in space. A major tidal channel periodically overflowing its banks is a logical proximal source for the uncommon abundance of sandstone sheets and lenses. The development of high levees may, on occasion, have dammed off the inter-channel areas allowing the development of ponds which were flooded only at extreme high tides.

The large sand-filled channel mentioned in the previous paragraph may be considered a minor subfacies of the tidal flat environment. This particular outcrop (Fig. 25) is the only one of its size so far observed in the sequence. Unfortunately, the complete cross-sectional morphology cannot be observed due to extensive talus cover on both sides and because the base is not exposed. The outcrop is at least 7 metres wide and 4 metres high and has channelled through sandy siltstones and silty shales of intertidal affinity, probably of the mixed flat zone. The sandstone making up the channel is coarse to medium grained with large-scale parallel crossbedding, often herringbone crossbedded (Fig. 26a). Shell fragments are a common constituent as are large, flat, shale chips, up to 15 centimetres in length, aligned along the bedding plane (Fig. 26b). Some of the chips are iron-rich, red-weathering shales. The channel may have been a minor fluvial distributary, but the presence of herringbone crossbedding implies a large tidal influence.

Offshore Tidal Bar Complex

The white quartzites of the Redmond Head sandstone represent a different sedimentary environment from the tidal flat complex. While both exhibit features characteristic of the littoral zone, the lack of shale and siltstone in the Redmond Head sandstone is a sharp contrast to the tidal flat

FIGURE 25. Sand-filled major tidal channel; The Beach, Bell Island. Scale is in feet.

FIGURE 26a (left). Herringbone crossbedding in sand-filled tidal channel; The Beach, Bell Island. Hammer is 28 cm long.

FIGURE 26b (right). Large shale chips forming lag deposits along bedding planes in sand-filled tidal channel; The Beach, Bell Island.

complex and suggests a shift to a higher energy system. It is here referred to as the offshore tidal bar complex.

This complex is approximately 79 metres thick and much of it is easily accessible at Freshwater Cove and at Redmond Head, especially at low tide. A proposed ideal stratigraphic sequence is shown in Fig. 5. It consists of two, and possibly three, units designated as: the offshore to shoreface facies and the foreshore-beach facies. A white structureless unit (locality G, unit 10) may be a supratidal backshore facies.

Offshore to Shoreface Facies

The lower part of this facies is dominated by fine- to medium-grained, megarippled sandstones (Fig. 27). Cross-sectional morphology is sometimes evident and the average ripple length is usually greater than 2 metres with a ripple height of 0.1 to 0.5 metres. Internal structures are not often observed because the homogeneity of the sand gives a massive appearance to the rocks. However large-scale parallel crossbedding and rare, small-scale ripple crossbedding are sometimes perceptible. Parallel laminated bedding is also evident in places, indicating a high energy regime. The megaripples may be tidal "sand waves" similar to those described by Off (1963).

Towards the top of this facies, massive, almost structureless, sandstone beds predominate in which cross-bedding and trough crossbedding are occasionally developed.

This represents a gradual change to shoreface environment, possibly partly intertidal. Herringbone and reactivation surfaces are occasionally observed. Both of these structures are indicative of a time-velocity assymetry of bedload transport due to tidal influences (Klein, 1970) and the trough crossbedding is probably due to the development of tidal channels within the shoreface (Fig. 28). Occasional rill marks and current lineations are probably late-stage runoff features. Planar laminated bedding and small-scale current and interference ripples are common.

Scours are frequently observed (Fig. 27), but there is no trace of associated coarse lag deposits of any kind. These scours or erosional surfaces are often draped with very thin greenish siltstones 0.5 to 1 centimetre thick. It is suggested that these scours represent the effects of storms, subsequent to which the silt drapes settled out of suspension from the turbid waters.

The offshore to shoreface facies is variable in thickness, but generally greater than 5 metres where exposed in outcrop. Bioturbation is rare to weak and consists exclusively of surface grazing trails (Fig. 29a, b).

Large stylolites are common throughout (Fig. 30) and the sandstones tend to part along these planes leaving a very rough surface.

FIGURE 27. Megarippled sandstones of the offshore to shoreface facies. Siltstones drape several scour surfaces. Scale is in feet; Freshwater Cove, Bell Island.

FIGURE 28. Trough crossbedding probably due to a tidal channel cutting through the shoreface sediments; Freshwater Cove, Bell Island. Scale is in feet.

FIGURE 29a. "Scribbling" grazing traces; Freshwater Cove, Bell Island. Hammer is 28 cm long.

FIGURE 29b. Ichnofossil of unknown affinity, possibly a grazing trace; top of bed at Freshwater cove, Bell Island.

FIGURE 30. Large stylolite surface forming a parting plane in massive sandstone; top of a bed at Freshwater Cove, Bell Island.

Foreshore-Beach Facies

The rocks of this facies consist of white to light yellow, fine- to medium-grained sandstone. Bedding is thin, 0.5 to 2 centimetres thick, planar laminated and horizontal or shallow-dipping. Many of the bedsets also display large-scale, broad, low-angle crossbedding. Scours are common, some filled with thin, silty laminae. These are probably either the effects of storms as described above in the subtidal megaripple zone, or, especially where there is no silty infilling, the scours may be fossil beach cusps.

Numerous beach related structures can be observed in this facies and are assigned to the effects of swash and backwash or emergent runoff. Possibly the structure most diagnostic of a beach environment, apart from bedding, is the presence of swash marks (Fig. 31a). Since the concave side of these swash marks is evidently the seaward direction, it is interesting to note that at least two seaward directions, opposed to each other at approximately 335° and 160°, are observed in this subfacies. Similarly, current crescents (Fig. 31b), which form by backwash or emergent runoff around an obstacle on the beach, also indicate a multi-directional seaward side. These observations lend substance to the idea that the Redmond Formation indeed represents an offshore barrier bar, as it is surrounded by

FIGURE 31a. Swash marks; wide spacing indicates a very gently sloping beach. Compass points to shoreward direction; the reservoir, Bell Island.

FIGURE 31b. Current crescent; current or backwash moving towards top of photo; Freshwater Cove, Bell Island.

beaches. Poorly preserved foam swash marks were observed at one locality and well developed rill marks (Fig. 32a, b) are common. The thickness of the foreshore-beach facies averages between 2 and 3 metres (locality G, units 8, 9).

Bioturbation varies from nil to moderate, with Skolithos burrows at some localities. It may be that the variation in bioturbation in this subfacies, and possibly also in the offshore to shoreface facies, is a function of which side of the offshore bar is represented at that particular outcrop. That is, the landward or lagoonal side of the bar is apt to be more bioturbated than the oceanward side, which is exposed to high wave energy. Lack of regional outcrop exposure unfortunately prevents the delineation of bar morphology.

Supratidal Facies

A definite supratidal or aeolian facies has not been recognized in this offshore bar environment, however a massive, almost structureless, fine-grained sandstone overlies a beach zone unit at Freshwater Cove (locality G, unit 10). Bedding is very obscure, but appears to be horizontal planar laminated or very low-angle, large-scale crossbedding. Lacking further evidence, this may be either the uppermost foreshore (beach bar) or backshore zone of a beach.

Bioturbation is non-existent in this unit.

FIGURE 32a. Meandering rill marks on a bedding surface in the Redmond Formation; Redmond Head, Bell Island. Hammer is 28 cm long.

FIGURE 32b. Conical rill marks superimposed on swash marks; the reservoir, Bell Island.

Regional Environment - Evidence for a Delta

Since almost all of the 1,500 metre thick Bell Island-Wabana sequence of sediments was deposited under shallow-water conditions, it follows that the rate of sediment supply equaled or exceeded the rate of shelf subsidence or sea level rise. The question then arises as to how such an enormous amount of sediment was supplied to the depositional basin - a question not previously considered. The author suggests that the Bell Island and Wabana Groups represent tidal flat and tidal sand bar subenvironments of a major tide-dominated, high-destructive delta system in the sense of Fisher _et al_. (1969). There is some good field evidence to support this proposal, however it has not been possible to demonstrate conclusively due to two factors: (a) total outcrop area of the Bell Island and Wabana Groups combined is less than 50 square kilometres, so that the lateral facies variations cannot be observed on a regional scale and (b) tide-dominated deltas may be difficult to recognize in ancient rocks and there are few published descriptions of such deposits (Miall, 1976). According to Miall:

> "None of the characteristics of tidal delta deposits are distinctly 'deltaic'. Tide-generated sand ridges and tidal flats are widespread at the present day in areas without significant fluvial sediment input. The _thickness of the deposit_, reflecting the nearby presence of a major river mouth, may be the only clue in the ancient record to the presence of a

tide-dominated delta." (p. 221).
(emphasis added).

Field Evidence

At Lance Cove (locality C) on the southeast shore of Bell Island, cliffs approximately 60 metres high expose part of the lower sequence of the Beach Formation. The stratigraphy in this section is distinctly different from elsewhere on the island in that it is made up of a number of coarsening-upward, apparently shoaling-upward, sequences (Fig. 33). The base consists of dark, highly weathered, sometimes silty shales varying in thickness from 1.5 to over 10 metres. These basal shales contain an occasional very fine-grained, rippled sandstone or siltstone bed 1 to 3 centimetres thick. Towards the top of the shale zone, thin, planar and lenticular sandstone and siltstone beds become more common in a thin transition zone 0.5 to 1 metre thick, followed by rippled sandstone beds up to 15 centimetres thick intercalated with wavy, lenticular and occasionally flaser-bedded sandy siltstones, silty shales and dark shales, often moderately bioturbated. Towards the top of the sequence, sandstone beds up to 40 centimetres thick predominate, either large-scale, parallel crossbedded or massive. Where the sequence appears to be well developed, the arenaceous part of the coarsening-upward sequences (i.e. excluding the basal dark shale) is of fairly uniform thickness, approximately 4 metres. Large, sand-filled channels, 1 to 2 metres wide and 50 to 80 centimetres deep, are common (Fig. 34) and display longitudinal crossbedding, apparently of point bar origin (c.f. Reineck, 1958), with shale pebble and shell fragment lag conglomerate at the base of the crossbed sets. Runzel marks are notably absent and mudcracks are rare, but occasionally observed on the underside of sandstone beds near the top of a coarsening-upward sequence.

This stratigraphic sequence therefore appears to be comparable to typical coarsening-upward sequences described as river- or wave-dominated prograding deltaic cycles (Fisher et al., 1969; Pettijohn, 1975; Miall, 1976). These generally consist of prodelta clays at the bottom, passing upwards into delta front silt and sand. It would seem that at this stage of deposition of the Bell Island Group the tidal range was not large, a factor probably controlled by basin morphology. Therefore, the deltaic sequence is more recognizable as such, being typical of the much-studied, river-dominated or "Mississippi type" delta. With subsequent establishment or re-establishment of a large tidal range, the delta became a high-destructive, tide-dominated type with few "typical" deltaic characteristics.

Further evidence for a deltaic environment is provided by a section at Powers Steps (locality I), which exposes approximately 44 metres of highly weathered, dark,

FIGURE 33. Shoaling-upwards deltaic sequence; Lance Cove, Bell Island. Bar is approximately 6 m.

FIGURE 34. Sand-filled channel, displaying longitudinal point bar crossbedding. Note scour surfaces (arrow); Lance Cove. Scale is in feet.

somewhat silty, graptolitic shale of the lower Powers Steps Formation. The oolitic pyrite beds lie at the base of the shale unit and at the top of the unit there is a coarsening, shoaling-upward zone, several metres thick. The shale contains occasional fine-grained rippled sandstone or siltstone beds 1 to 3 metres thick. If one stands at the top of the west side of the gully at Powers Steps, the entire 44 metres of the opposite cliff face can be seen in cross-section (Fig. 35). On close observation it can be seen that the bedding in the upper part of the shale unit dips several degrees steeper than the lower part, indicating a possible angular unconformity. No sharp unconformity or erosion surface can be observed however, and there appears to have been simply a gradual change in the angle of deposition. Furthermore, the younger beds dip more steeply than the older beds, an unusual situation for an angular unconformity, requiring a reversal in dip direction after deposition of the younger beds. Also, this shale unit lies between the two main ore formations, the Dominion and the Scotia. Both of these ore formations have been mined down-dip for over 1 kilometre and are known to be parallel (Southey, 1969). It would thus appear that all the beds are in their original angle of deposition in relation to one another. The possibility that this structure is a large infilled fluvial channel is also unlikely because, as mentioned above, no erosional base is seen and there is no hint of channel

FIGURE 35. Section at Powers Steps, Bell Island, with Dominion Formation at base overlain by a prograding deltaic cycle making up the lower Powers Steps Formation. Primary angle of repose of the prodelta foreset bed is approximately 8°. Height from base is approximately 44 m.

morphology. Furthermore, the presence of graptolites within the shale and orthocone cephalopods, trilobite fragments and brachiopod fragments towards the top of the unit indicates a marine or at least a brackish environment. The author suggests that the shale unit represents the effects of a sudden transgression with subsequent seaward progradation of a deltaic cycle. The lower part of the shale unit represents offshore shelf deposits of marine clay, followed by prodelta silty clay deposited at a primary angle of repose of about 8° from the horizontal during rapid progradation. Overlying this is the shoaling-upward sequence of delta front silt and sand. This being the case, the seaward direction of the lower Paleozoic shoreline lay in the dip direction of the prodelta deposits, that is towards approximately 320°.

The Gravel Head Formation, immediately overlying the upper ore beds, also comprises thick shales similar to those of the Powers Steps Formation and may also represent a major transgression. Very limited outcrop exposure prevents a better interpretation.

Depositional Environment of the Kellys Island Formation

The rocks of Little Bell Island and Kellys Island consist of sequences incorporating many of the major environments described above. An ideal sequence is described and interpreted as follows:

At the base of the sequence are dark fissile shale and silty shale, becoming sandier and siltier within 1 or 2 metres of the top of the unit. Total thickness can vary from 2 metres to 15 metres or more. Overlying this shale is massive, thick-bedded, orthoquartzite sandstone. This may display faint megaripple structure and may be gently dipping planar laminated towards the top of the beds. Sandstone beds lying immediately above the shale unit are prone to convolute bedding, ball-and-pillow and other slump structures. The sandstone units vary between 2 and 8 metres thick. Overlying the sandstone is the topmost unit of interbedded rippled sandstones, sandy siltstones, silty shales and black, fissile shales. Wavy, flaser and lenticular bedding are common. These sediments are thin bedded and weakly to moderately bioturbated. Runzel marks and mudcracks are common features.

The basal shales in the sequence are probably off-shore marine clays and are similar to shales higher up in the section in the lower part of the Beach Formation, which are interpreted as possible prodelta sediments. The over-lying massive sandstone probably represents a barrier bar, behind which the rippled and bioturbated sandstones, siltstones and shales have accumulated. This latter facies is similar in almost all respects to the tidal flat facies described previously, however no distinctly zoned subfacies were recognized.

The occurrence of the massive bar sandstones as a regular component in the Little Bell Island and Kellys Island sequences makes their stratigraphy distinct from that exposed on Bell Island. On Bell Island, the massive sandstones form a single, thick formation. A possible explanation for this is that high tidal ranges associated with wide tidal flats are represented on Bell Island. Resulting high current velocities dispersed much of the sand in the system into broad offshore bars. Therefore, two separate, areally expansive environments developed, encompassing a zone perhaps 5 to 10 kilometres or more in width. On Little Bell Island and Kellys Island, the tidal or barrier bars may have been preserved in almost every progradational sequence because the tidal range was not excessive, and wide tidal flats had not developed. The bar-tidal flat system prograded then, as a closely related unit, whereas the replacement of one major environment by another in the Bell Island sequences possibly reflects a progradation-transgression cycle on a higher order of magnitude.

Table 2 summarizes the postulated depositional environments for each formation in the Bell Island and Wabana Groups.

TABLE 2

Depositional Environments of the
Bell Island and Wabana Groups

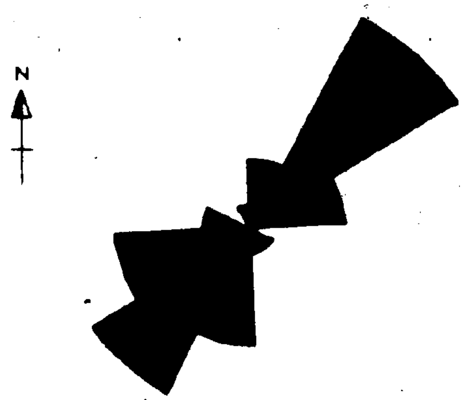
Formation	Interpreted Environment
Gravel Head Formation	Offshore shelf, possibly interdistributary bay or distal prodelta
upper ore beds	Tidal bar
Grebes Nest Point Formation	Shallow subtidal, probably lagoonal
Scotia Formation	Tidal bar
Powers Steps Formation	Shallow subtidal and intertidal flat
44m	Offshore shelf and prodelta, possibly interdistributary bay
Dominion Formation	Tidal bar
Ochre Cove Formation	Shallow subtidal and intertidal flat, high to moderate, tidal range
Redmond Formation	Tidal bar, probably high tidal range
Beach Formation	Shallow subtidal and intertidal flat, high tidal range
30m	Prodelta and delta front, little or no tidal range
Unexposed	
Kellys Island Formation	Tidal flat and tidal or barrier bar sequences, low tidal range, overlying marine shale

No scale implied.

Paleocurrent Analysis

Paleocurrent data is plotted in Fig. 36a and b. Current crossbedding measurements taken throughout the section apparently indicate two populations. Fig. 36a shows a well-distributed bimodal pattern for the lower part of the Beach Formation. The modal classes are 180° apart. This pattern is reported as typical of delta topset and higher tidal flat environments (Klein, 1967). Neither modal class dominates the other, so that the source direction probably lies either to the northeast or southwest, but cannot definitely be determined.

A composite of the current directions in the upper part of the Bell Island Group and the Wabana Group is plotted in Fig. 36b. The pattern is trimodal and is supposedly typical of tidal deposits. Tidal flat deposits generally show two modal classes 180° apart representing ebb and flow directions. A third and often fourth modal class may be developed perpendicular to the first pair and these represent long-shore tidal currents (Klein, 1970 1971). Once again, no modal class dominates and the source direction cannot be definitely determined. If the unpaired modal class (towards the north-northeast) represents long-shore currents, then the source lay either to the west-northwest or east-southeast. Shales in the Wabana Group that are interpreted as prodelta sediments have a primary angle of repose dipping towards the northwest



41 measurements

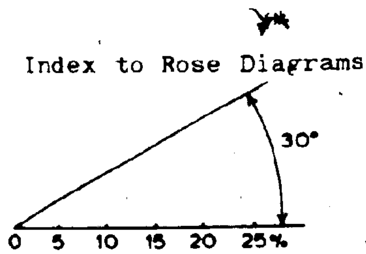
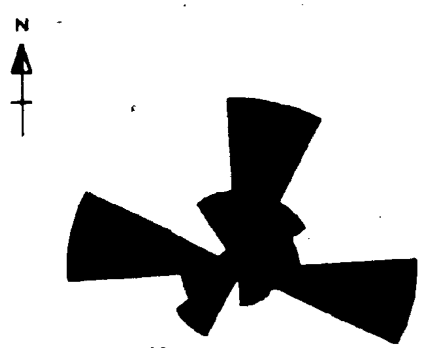


Figure 36A.

Paleocurrent cross-bedding directions in the lower part of the Beach Formation.



50 measurements

Figure 36B.

Paleocurrent cross-bedding directions in the Wabana Group and the upper part of the Bell Island Group.

(p. 81). This could indicate that the modal class oriented in the west-northwest direction represents the seaward direction and that the source was to the east-southeast.

The paleocurrent direction patterns support the hypothesis that the Bell Island and Wabana Groups represent a tidal flat and probably a deltaic environment. However, it is apparent that a detailed study backed by much more data is needed before a meaningful interpretation of the dispersal pattern can be made. Determining the dispersal pattern for each subfacies would probably produce the most significant data.

CHAPTER 5

PETROLOGY AND PROVENANCE

Sandstone Petrology

The basic petrology of the Bell Island-Wabana groups has been described by Nautiyal (1966). General descriptions of sandstone petrology for each subfacies of the depositional environment is documented here and is aimed towards an interpretation of provenance. Table 3 gives the mineral composition of 8 studied thin sections selected as typical of each facies,or considered to be important in the interpretation of provenance. Those in the latter category are coarse-grained sandstones, a size fraction which, although rare in the rocks of the Bell Island and Wabana Groups, was nevertheless found to be invaluable for source studies because of the rock fragments they contain.

Prodelta Silty Sandstone

These sandstones occur as thin, rippled beds within shales that probably represent a prodelta environment (p. 77) and which outcrop at Lance Cove, Kellys Island and Powers Steps. These rocks are light grey to white arenites (for example, specimen BI-76-14) and typically contain a variable but minor amount of volcanid rock fragments. Grain size varies from 0.25 to less than 0.05 mm, but averages approximately 0.1 mm making the sands fine to very fine grained and moderately sorted. Quartz is subangular and

TABLE 3

Sandstone Thin Section Petrology

% Composition

	BI-76-14	BI-76-27	BI-76-11	BI-64c	BI-65a	BI-56i	BI-76-101
quartz (undulose extinc.)	30	38	23	20	3	27	38
quartz (straight extinc.)	46	58	68	48	25	63	58
quartz (idiomorphic)	-	-	-	-	36	1	-
total quartz	76	96	91	68	64	91	96
orthoclase	1	3	TR	-	-	-	1
plagioclase	TR	TR	TR	TR	-	-	TR
microcline	TR	-	-	-	-	-	TR
muscovite	7	TR	1	1	2	-	-
altered grains	8	-	-	12	-	-	3
matrix	2	-	4	6	22	-	-
rock fragments	2	TR	3	-	TR	4	-
carbonate	-	TR	-	2	12	-	-
biotite	-	TR	TR	5	TR	1	-
bleached biotite	1	TR	1	-	TR	-	TR
phosphatic shell fragments	TR	TR	TR	TR	TR	2	-
zircon	TR	TR	TR	TR	-	-	TR
tourmaline	TR	-	TR	-	-	-	-
hematite	-	1	-	-	TR	1	-
magnetite	TR	-	-	-	-	-	-
glauconite	-	-	-	6	-	-	-
hornblende	TR	-	-	-	-	-	-
chlorite	3	-	-	-	-	-	-
chamosite	-	-	-	-	-	1	-

TR = trace amount

many grains have a low sphericity. Texture is immature to submature. The sands generally contain 75 to 85% quartz, some of which displays undulose extinction. Muscovite flakes up to 1 mm in length are invariably a significant component in proportions up to 5% of the rock. Bleached biotite and chlorite are always present in varying minor amounts. Unidentified altered grains probably include feldspars, fine-grained volcanic rock fragments and ferromagnesian minerals. Other minerals making up less than 1% of the rock include microcline, plagioclase (oligoclase), orthoclase, zircon, tourmaline, magnetite, phosphatic shell fragments and altered amphiboles. The cement is sericitic, making up from 2 to 5% of the rock, but quartz overgrowths are also very common. Bedding consists of the alignment of muscovite flakes and placered heavy minerals, typically chlorite and bleached biotite.

Subtidal-Lower Intertidal Sandstone

These sandstones are normally megarippled and thick bedded. They are white to light grey and classified as quartz arenites (for example, specimen BI-76-27). Grain size varies from 0.5 to 0.08 mm, but averages 0.2 mm giving a fine-grained, well-sorted sand. Quartz makes up 90% or more of the mineral components and is rounded to subrounded. Some of the quartz grains display a slightly undulose extinction. Grains with low sphericity are common. Texture is mature. Weathered acid volcanic rock fragments are easily recognized, but generally make up less than 1% of the rock. Up to 3% orthoclase may be present. In some of these sandstones the feldspars are replaced by carbonate. Other minerals making up less than 1% of the rock include green and brown biotite, zircon, phosphatic shell fragments and rare oligoclase. Large shell fragments and shale clasts are concentrated in scour lags. Muscovite is rare. Cement is generally overgrowths on quartz grains, but some beds are carbonate cemented with large calcite euhedra 2 mm or more in size, producing a crystal sandstone with 'lustre mottling' (Fig. 37). Rarely, a fringing radial crust of authigenic clay mineral (possibly kaolinite) is observed as a cement in thin section.

Intertidal Sandstone

Sandstones from this facies typically occur in rippled, thin- to medium-bedded lenses intercalated with silty shales. Associated sedimentary structures indicate intermittent subaerial exposure. These sandstones are highly variable in composition and texture (for example, specimen BI-76-11). Generally they are immature quartz arenites and some, with a significant fraction of volcanic rock fragments and volcanic quartz (Fig. 38), may be classified as volcanic arenites. In the middle part of the Ochre Cove Formation, glauconite is an important constituent (Fig. 47) and these sandstones can be classified as glauconitic arenites.

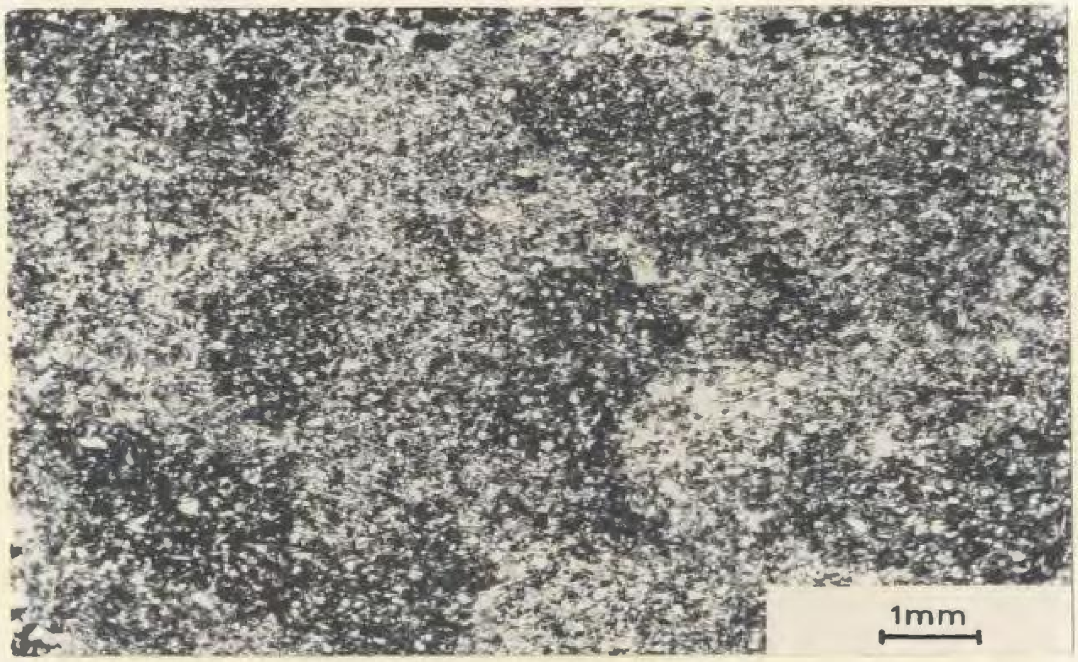


FIGURE 37. Fine-grained quartz arenite from the subtidal zone. Carbonate cement produces a lustre mottling. (X nicols) Sample BI-76-29; the Beach Formation.

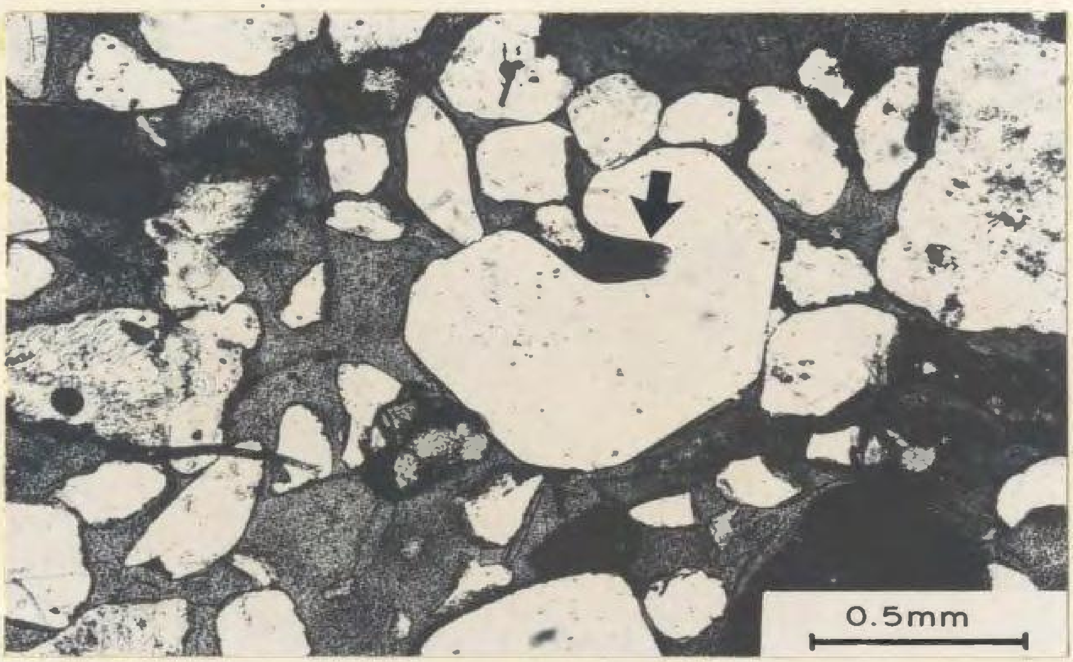


FIGURE 38. Detrital volcanic quartz fragment; bipyrimidal with embayment (arrow). Sample BI-65a; Ochre Cove Formation.

All quartz grains are subrounded to subangular. Grain size varies from coarse silt to medium sand and the sediment is moderately to poorly sorted. Clay content is generally greater than 5%. Quartz content varies from 60 to 70% and some grains display highly undulose extinction. Other major constituents may include green and brown biotite and bleached biotite, muscovite, phosphatic shell fragments, glauconite and chlorite. Orthoclase may make up 1 or 2% of the rock and is more or less sericitized. Feldspars are sometimes replaced by carbonate. Other minor components include oligoclase, zircon and tourmaline. Cement is clay-sericite, but quartz overgrowths are common. Bedding in thin section consists of alignment of micas and heavy mineral zoning.

Tidal Channel Sandstone

The sandstone described for this facies is a crossbedded tidal channel unit outcropping at The Beach in the Beach Formation. This sandstone is a quartz arenite (for example, BI-56i) containing 90 to 99% quartz grains, which range from angular to well-rounded. Sorting is poor and grain size ranges from 1.5 to 0.05 mm on average, a coarse to medium sand. Some of the quartz is partly idiomorphic with embayments and is obviously volcanic. A few rhyolite rock fragments are seen in thin section, as well as composite quartz grains, probably of granitic origin. Large shale pebbles up to 1 cm or more in length are common. These contain imbedded fine-grained quartz and occasionally chamosite pellets, some of which are oolitic. Orthoclase is generally less than 1% of the grains and is often almost wholly replaced by carbonate. Phosphate shell fragments are common, as is biotite and bleached biotite. Muscovite is rare. Glauconite is a minor component. Silty patches are probably animal burrows. Cement may be hematite or carbonate euhedra, forming a crystal sandstone. Chamosite is occasionally present as a cement. Bedding is obscure in thin section and is evidenced only by the alignment of shell fragments.

Offshore Tidal Bar Environment Sandstone

These sandstones comprise the white to light grey orthoquartzites of the Redmond Formation. They are classified as quartz arenites (for example, BI-76-101). Grain size varies from 0.25 to less than 0.05 mm, but averages 0.15 mm, a fine-grained, well sorted sand. Roundness is subangular to subrounded and the clay content is less than 1%, thus the texture is mature. The sands contain greater than 95% quartz grains, some of which display strongly undulose extinction. Some of these sandstones, particularly those from the 'swash' or 'beach' zone, contain up to 2% muscovite. Sericitized orthoclase makes up 1% or less of the rock, although many of the unidentified altered grains may be orthoclase. Microcline and oligoclase are also present in minor amounts. Other minerals present in quantities of less than 1% are altered biotite, zircon, clay minerals and rarely, phosphatic shell fragments. Fine-grained rhyolite fragments are rare. Cement consists of quartz overgrowths. However, pseudonodules within the Redmond Formation are cemented by large carbonate euhedra. Bedding is only evidenced by alignment of muscovite flakes if present in the rock.

Provenance

Quartz

Quartz grains generally are too fine grained to differentiate genetic types. Many quartz grains do show variable degrees of undulose extinction, however Blatt (1963) has concluded that there is no correlation between rock type and amount of strain in quartz. The occurrence of coarse, composite quartz grains is discussed under "Rock Fragments" below.

Volcanic quartz was identified as a major component in coarse-grained sandstones from several different horizons. In thin sections, these quartz crystals are idiomorphic with hexagonal-bipyrimidal shape. Embayments are common (Fig. 38). Crystals are water-clear with no inclusions and have straight extinction. Their association with porphyritic acid volcanic fragments leaves no doubt that they are derived from erosion of these volcanics. In fine-grained sandstones throughout the Bell Island-Wabana strata, much of the quartz with straight extinction and a lack of inclusions is therefore believed to be of volcanic origin.

Rock Fragments

The different rock fragments in several coarse-grained sandstones are tabulated in Table 4. Several different source lithologies are represented and are treated individually in the following descriptions.

Volcanic Fragments

Typically, these have a microcrystalline cherty appearance (Fig. 39) and consist almost exclusively of quartz with a rare, highly altered or carbonate-replaced patch. Phenocrysts of bipyrimidal quartz are sometimes enclosed in the fragment. At least one porphyritic grain displays a dusty outline, which may be a flow banding structure or perhaps the structure of a welded crystal tuff (Fig. 40). These rock fragments are similar in many respects to rhyolites of the Late Precambrian Harbour Main Group, which underlies and outcrops to the south and east of the Bell Island and Wabana Groups. Even the unusual spherulitic texture in some of the Harbour Main rhyolites has a similar detrital counterpart in the Bell Island-Wabana sandstones (Fig. 41).

Highly altered basic volcanic fragments were also identified, but these are rare and difficult to recognize.

Some of these volcanic rock fragments may be second

TABLE 4

Rock Fragments

% Composition

	BI-65a	BI-79b	BI-65e	BI-KB	BI-79a
acid volcanic	39	58	28	78	73
plutonic	32	11	18	4	20
recrystallized metamorphic	4	6	44	-	2
stretched metamorphic	22	25	9	18	5
basic volcanic	1	-	-	-	-
shale	2	-	1	-	-

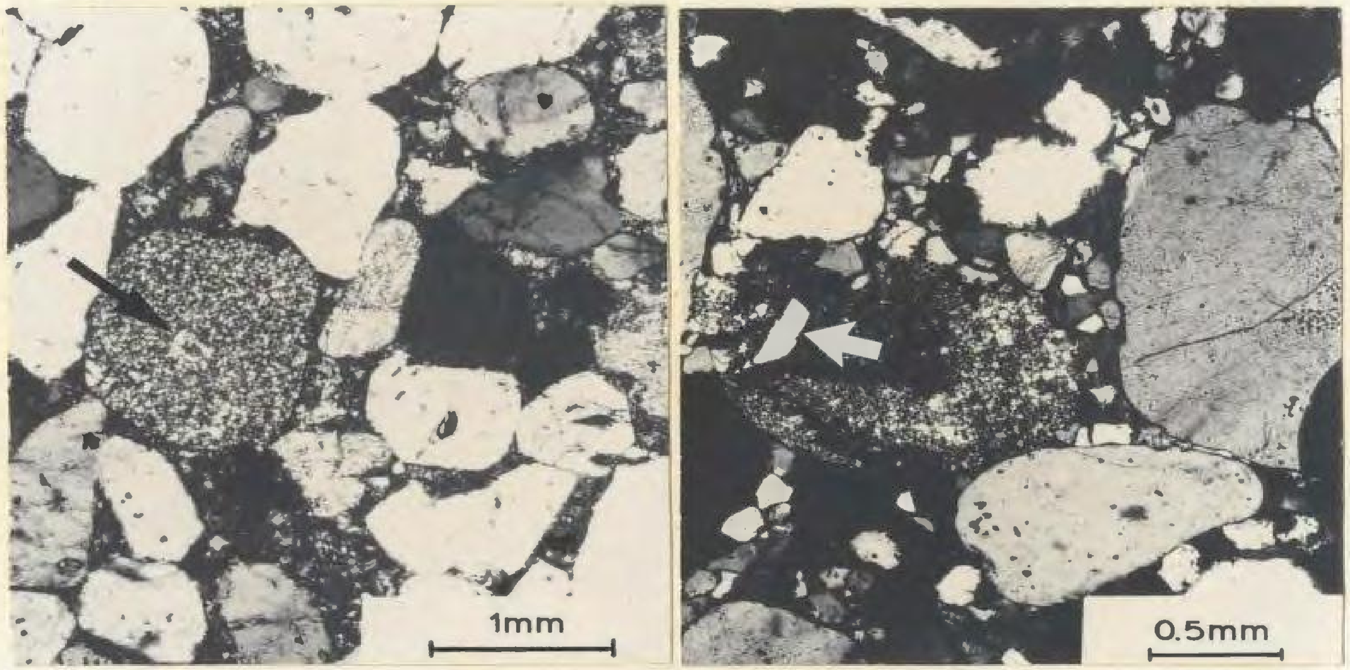


FIGURE 39a (left) and 39b (right).
Detrital acid volcanic fragments. Arrows indicate remnants of phenocrysts. (X nicols) Sample BI-65a, Ochre Cove Formation.

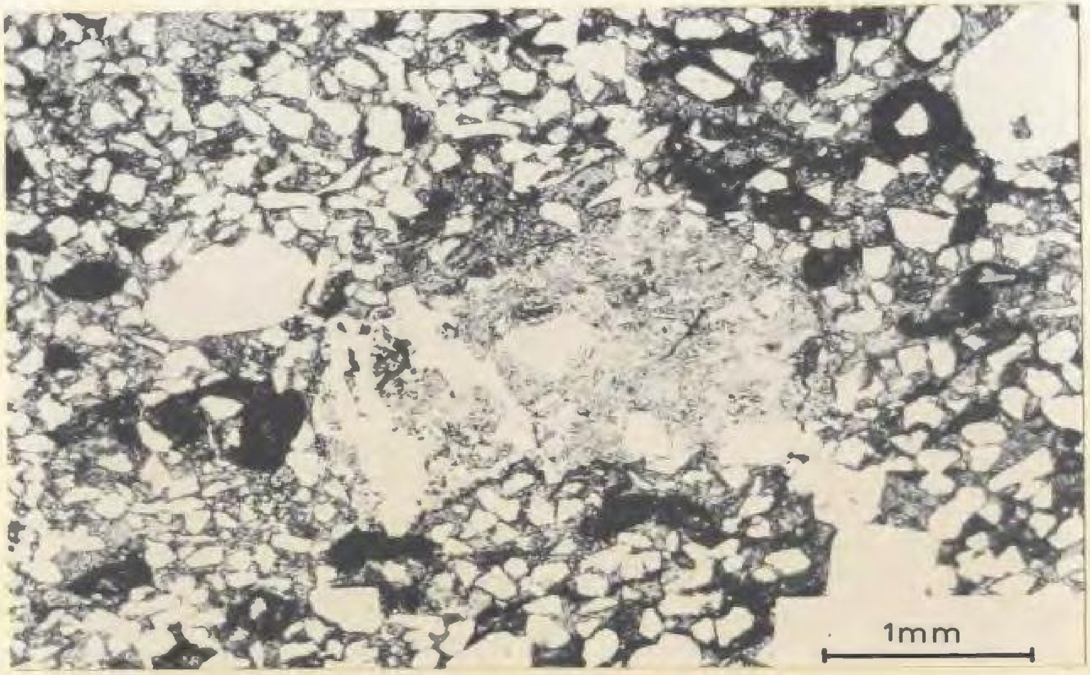


FIGURE 40. Detrital porphyritic volcanic fragment; possibly a welded crystal tuff (?). Sample BI-KB, the Beach Formation.

FIGURE 41. Spherulitic rhyolite fragment. Note radial structure (arrows). (X nicols) Sample N243h.

generation detrital grains. These could have been derived from volcanic sediments of the Conception Group, which may be partly contemporaneous with the Harbour Main Group (Hughes and Bruckner, 1971). It is not unreasonable to suggest that the sedimentary rocks of the Conception Group and also the Cabot Group were a considerable, if not a major, source of sediment.

Metamorphic Rock Fragments

Stretched metamorphic quartz (terminology after Folk, 1968) is a minor rock fragment component in some sandstones (Fig. 42). These polycrystalline grains meet all the criteria for gneissic quartz according to Blatt (1967): sand-sized grains are formed of more than five crystals with a bimodal size distribution; all crystals show undulatory extinction and have strongly sutured inter-crystalline boundaries; crystals are elongated with subparallel extinction. It is probable, therefore, that the source terrain encompassed in part a metamorphic, apparently gneissic, lithology.

Plutonic Rock Fragments

A second group of polycrystalline quartz rock fragments have the characteristics of plutonic quartz after the genetic classification of Folk (1968) and also that of Blatt (1967). The crystals are xenomorphic and subequant, sometimes with re-entrant angles. Undulatory extinction is

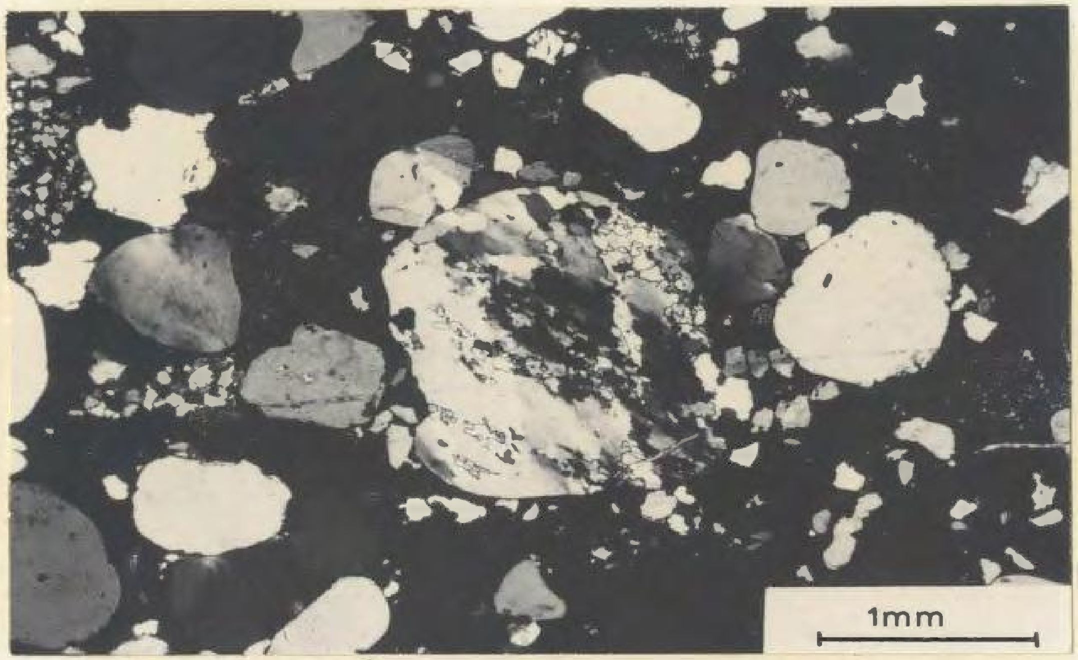


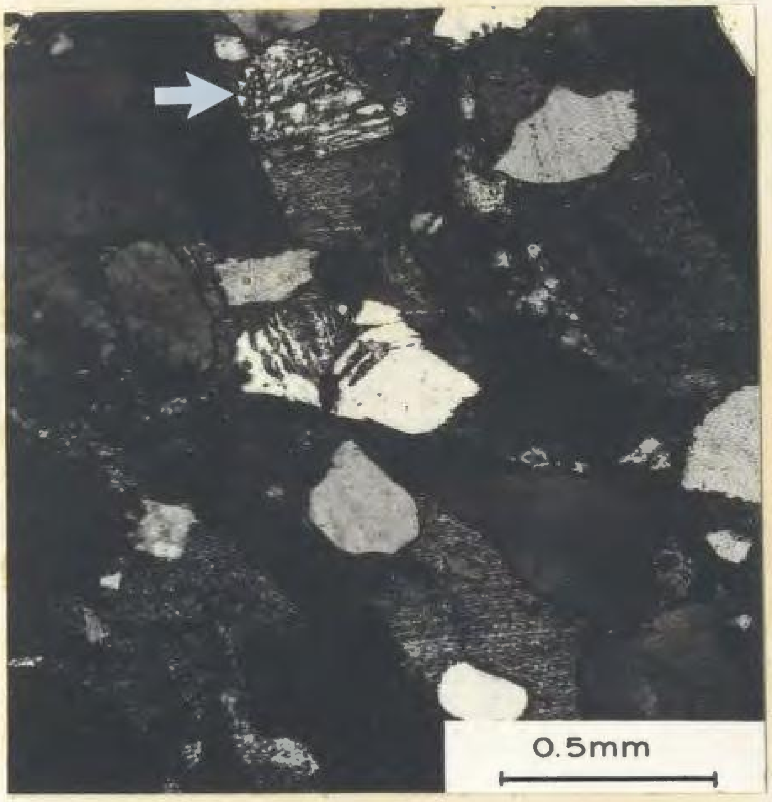
FIGURE 42. Stretched metamorphic (gneissic) rock fragment. Note subparallel extinction. (X nicols) Sample BI-65e, Ochre Cove Formation.

common, however there is no obvious crystallographic orientation of crystals within each grain. An obvious source for these grains is the Holyrood Plutonic Series. In several thin sections, grains of microcline-quartz intergrowths exhibit a micrographic texture (Fig. 43a). This texture has been described in pegmatites of the Holyrood Granite as "heiroglyphs" (Barning, 1965). Other clastic grains have intergrowths that are patchy or "wormy" (Fig. 43b), similar again to granophyres occurring in the Holyrood Granite (McCartney, 1967).

All other polycrystalline quartz grains, generally those which have straight or slightly undulose extinction and form a mosaic of equant, interlocking crystals with straight boundaries (Fig. 44), are classified as metaquartzite and are not further differentiated as to source. Folk (1968) refers to this type as recrystallized metamorphic quartz occurring in recrystallized metaquartzites and gneisses.

Sedimentary Rock Fragments

Shale pebbles and fragments are an extremely common component in many of the Bell Island-Wabana sandstones. However, the vast majority, if not all, are believed to be intrabasinal and probably of a very local source for the following reasons: (1) their relatively large size indicates a short transport distance, particularly considering (2) their abundance versus low potential for survival relative



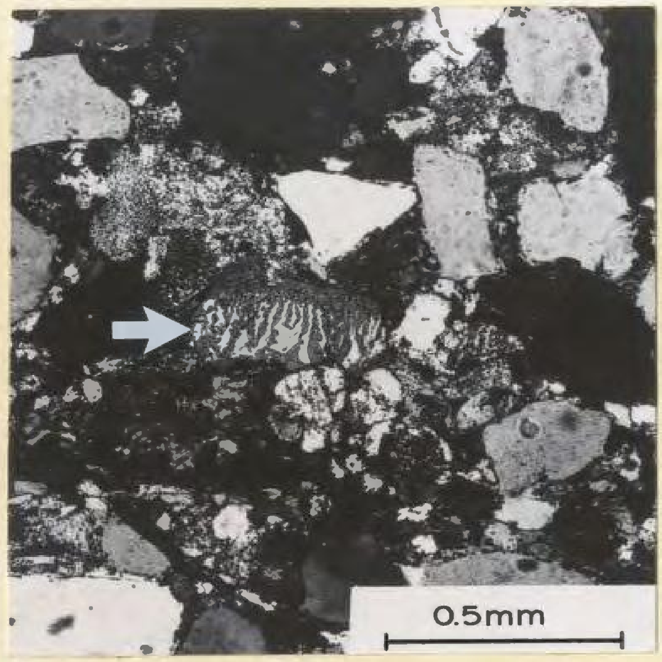


FIGURE 43a (left). Micrographic texture in plutonic rock fragment. Note "hieroglyphs" (arrow). (X nicols) Sample N402Q, Beach Formation.

FIGURE 43b (right). Granophyric texture in plutonic rock fragment. (X nicols) Sample N402T, Beach Formation.

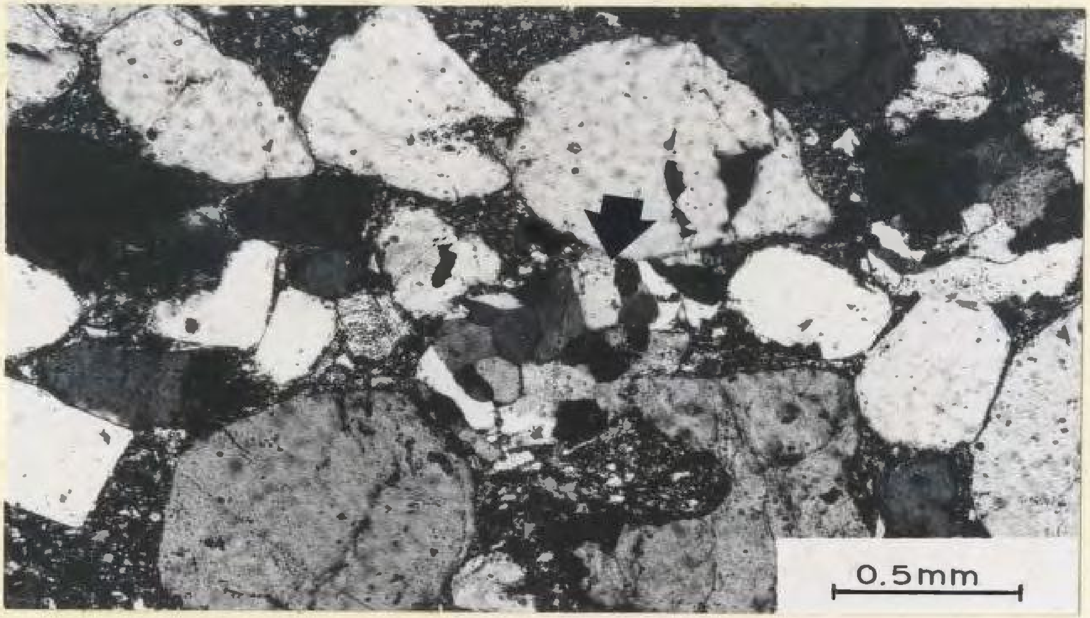


FIGURE 44. Detrital metaquartzite fragment. (X nicols) Sample BI-65a, Ochre Cove Formation.

to other harder rock fragments; (3) a tidal flat is a very favourable environment for the formation of shale chips due to subaerial exposure of mud flats; (4) shale fragments occasionally contain chamosite or hematite oolites, which are major allochems in the Bell Island-Wabana strata and therefore of intrabasinal origin.

Heavy Minerals

Heavy mineral separations were carried out on five samples as a possible aid in the interpretation of provenance. The results are shown in Table 5. Bleached biotite, opaques and zircon are the major components, all of which are ubiquitous. Zircon, sphene, apatite, magnetite and epidote are all known to occur in rocks of the Holyrood Plutonic Series (Barning, 1965; McCartney, 1967).

Of notable significance is the occurrence in all of the grain mounts of minor amounts of pinkish and colourless garnet, some of which is idiomorphic. Similar garnets also occur in sediments of the late Precambrian Cabot Group (Papezik, 1973).

Summary and Interpretation of Provenance

In light of the above analysis, it is evident that the source terrain of the Bell Island and Wabana Groups included several diverse lithologies, some of which outcrop in close proximity on the Avalon Peninsula. In summary these lithologies are: (1) acid volcanics, particulaly

TABLE 5

Heavy Mineral Grain Mounts

% Composition

	BI-55	BI-54a	BI-76-9	BI-76-14	BI-65a
biotite and bleached biotite	72	63	81	82	76
zircon	4	5	2	1	TR
opaques	7	20	9	7	14
altered grains	11	5	8	6	3
siderite	TR	1	-	-	TR
garnet	TR	TR	TR	TR	1
tourmaline	3	TR	TR	TR	TR
hornblende	TR	-	-	1	-
epidote	-	3	TR	-	3
sphene	TR	-	-	-	-
hematite	TR	TR	TR	TR	TR
clinopyroxene	2	3	-	-	TR
orthopyroxene	1	-	-	TR	3
chlorite	-	-	-	4	-
apatite	-	-	-	-	TR

TR = trace amount

porphyritic rhyolites and possibly welded crystal tuff, (2) basic volcanics, (3) granite and granophyre plutonic, (4) metamorphic, particularly gneissic and possibly meta-quartzite, (5) possibly a sedimentary lithology of volcanogenic origin (by inference only). All of these lithologies, except the metamorphic, occur on the Avalon Peninsula in the Harbour Main, Conception and Cabot Groups and the Holyrood Plutonic Series.

The gneissic rock fragments, as well ~~as~~ the presence of detrital garnet and the great abundance of muscovite flakes in the Bell Island-Wabana rocks, presents a major problem as to source. Gneissic rocks are unknown on the Avalon Peninsula and moreover, muscovite and garnet are not known to occur in the Harbour Main-Holyrood igneous complex (Papezik, 1973).

Poole (1972) suggested the existence of an area of late Precambrian or early Cambrian plutonic and metamorphic rocks underlying the Atlantic continental shelf or on opposite parts of Western Europe and Africa, that could have been the source of the detrital muscovite.

Small amounts of detrital muscovite, garnet and metamorphic rocks have been recognized in late Precambrian sediments of the Signal Hill Formation in the Cabot Group (Singh, 1969; Papezik, 1973). Reworking of these sediments could have been the source of the garnet and the metamorphic rock fragments that appear in the Bell Island-Wabana rocks. However, secondary reworking would probably have diminished the proportion of these components to very small amounts, whereas garnet was recognized in all the heavy mineral mounts and metamorphic rock fragments are common in all the coarse-grained sandstones. Furthermore, secondary reworking cannot explain the great abundance of muscovite in the Bell Island-Wabana rocks.

Papezik (1973) suggested that the Signal Hill Formation may be partly derived from a Precambrian basement with associated late Precambrian garnetiferous leucogranite intrusions, all lying to the east and northeast of the Avalon Peninsula and now covered by the ocean. This suggestion was prompted by the fact that such a terrain occurs along the western margin of the Avalon Zone and is considered by Kennedy and McGonigal (1972) to be "at least pre-Middle Ordovician in age and probably considerably older." Kennedy and McGonigal (1972) further suggest that the gneissic rocks may possibly underlie and form a sialic basement to the Avalon Platform.

Poole (1973) pointed out that the lithologic character of the Hadrynian and Paleozoic strata on the Avalon Peninsula, as well as the lack of severe deformation, metamorphism and extensive plutonism, favour the hypothesis that the Hadrynian and Paleozoic strata were laid down upon a continental crust. Geophysical studies also indicate that continental crust may underlie the continental shelf off southeast Newfoundland (Haworth and MacIntyre, 1975).

In this study, the appearance of detrital garnet and metamorphic rock fragments in the petrographic analyses contributes to the evidence that the sediments of the Bell Island and Wabana Groups may have been derived in part from a gneissic-leucogranite Precambrian basement. If so, then such a source probably accounted for a significant proportion of the sediment, considering the abundance of muscovite throughout the strata.

Although the paleocurrent data remains inconclusive, there is an indication that the source terrain of the Bell Island-Wabana sediments may have lain to the east-southeast, at least during the deposition of the lower part of the Wabana Group (p. 87). This would then support Papezik's (1973) suggestion that Precambrian basement may underlie the present continental shelf to the east of the Avalon Peninsula.

CHAPTER 6

DEPOSITIONAL ENVIRONMENT OF THE IRON ORES

Facies Relationships

Good coastal exposure of the major ironstone beds allows an interpretation of at least the vertical facies relationships of the ores.

Significantly, the occurrence of the ironstone beds is apparently related to certain facies of the tidal flat complex. Immediately below the ironstones of the Dominion orebody are several thinner, uneconomic ironstone beds interbedded with quartz sandstone, siltstone and shale. Where exposed at Gull Island North Head, these beds form a number of well-developed, fining-upwards sequences (Fig. 45). Each sequence consists of three subfacies referred to the lower sand flats, middle mixed flats and upper mud flats, corresponding closely to the tidal flat stratigraphic model illustrated in Fig. 5. However, where quartz sands usually appear in the lower sand flat subfacies, oolitic hematite ironstones appear instead. Sandstone beds and lenses in the overlying middle mixed flat facies are of two compositions. Oolitic ironstone appears in the lower half of the subfacies, but quartz sands make up the upper half, suggesting a hydraulic fractionation by density. Each fining upwards sequence is approximately 3 metres thick.

The oolitic hematite of the Dominion orebody overlies

FIGURE 45. Fining-upwards intertidal sequences immediately below the Dominion Ore Bed. (a) Lower sand flats consisting of oolitic hematite, (b) middle mixed flats, (c) upper mud flats. Note similar sequence immediately above. Sequences are approximately 3 metres thick. Compare this sequence to that in Fig. 8; Gull Island North Head, Bell Island.

these sequences and is also approximately 3 metres thick in outcrop. Little structure can be observed in the orebody except for faint evidence of large-scale crossbedding. This, together with its thickness and massive nature, suggests that within the tidal flat complex the Dominion orebody belongs to the offshore tidal or barrier bar facies.

Overlying the ore are black shales and black, silty shales, occasionally rippled, suggesting a lagoonal facies. Associated thin, discontinuous beds of dark siderite are found in this facies and contain chamosite oolites, which are almost completely replaced by siderite. Phosphatic shale pebble conglomerate beds overlie the black shale-siderite unit.

The Scotia orebody, approximately 70 metres above the Dominion orebody, shows similar facies relationships. Immediately below the main ironstone bed are several minor, uneconomic beds interbedded with shale, siltstone and sandstone. Rippled and wavy bedding, mudcracks and runzel marks indicate that this is an intertidal facies, although a tidal flat sequence has not been well-developed. The Scotia orebody is approximately 2½ metres thick at the type section at Upper Grebes Nest Point. The bed is generally massive, but may show faint large-scale parallel crossbedding (Fig. 46). With all these features, similar to those found in the Dominion orebody, it too is considered to be an offshore barrier or tidal bar facies. The composition of the Scotia

FIGURE 46. Large-scale, faint cross-bedding in the Scotia Ore Bed. Crossbedding defined by rock parting.

ore changes from oolitic hematite to concentrically layered oolitic chamosite and hematite within 10 centimetres of the top of the bed.

Overlying the Scotia Formation are dark shales and dark, silty shales of the Grebes Nest Point Formation. These are highly bioturbated in places and interbedded with fine-grained rippled sandstones. This is interpreted as a thick lagoonal facies. Thin beds or streaks of chamosite and hematite in a siderite cement are common in this facies, as are phosphatic shale pebble conglomerates.

The Upper Ore Member crops out near the top of the Grebes Nest Point Formation, but these beds are generally thin and streaked with sandstone and shale. Because of the presence of thin ironstone beds throughout the Grebes Nest Point Formation, the Scotia orebody, as well as the upper orebodies and the intervening lagoonal facies, could all be considered as a part of a single episode of ironstone formation.

The similarities that exist between the two main episodes of ironstone formation can be summarized as follows: (1) They both begin as minor ironstone beds within an intertidal facies. (2) The main ore beds probably represent a bar facies. (3) Both main ore beds are overlain by dark shales and dark siderite beds containing chamosite oolites, apparently a lagoonal facies. (4) Both contain thin but extensive phosphatic shale pebble conglomerates. (5) Both of these iron-forming episodes are overlain by dark, pyritic, apparently deep-water shales and silty shales.

Environment of Formation

The following interpretation is suggested for the environment of formation of the ironstones, disregarding for the moment the question of the source of the iron. The ironstones may have formed as chamosite oolites in semi-restricted and perhaps slightly reducing zones within a lagoon. The lagoon probably was protected behind an offshore barrier or tidal bar. The tidal flat facies containing the oolitic hematite may have existed adjacent to, and along-shore from, the barrier bar-lagoon system, thus reflecting lateral migration of environments. The oolites making up the bar and tidal flat sands could have been chamosite oolites that were washed out of the lagoon and up onto the barrier bar or tidal flat and into tidal channels. There they would be oxidized, probably to goethite, forming hematite after diagenesis. In recent sediments of the Niger and Orinoco Deltas, Porrenga (1965) has observed mineralised faecal pellets composed of chamosite with a rim of goethite. The goethite has apparently formed by the oxidation of chamosite in shallow waters. Because of their position within a well-developed intertidal sequence, there is little doubt that some of the oolites were at times subaerially exposed and therefore under highly oxidizing conditions. The idea that the ferric iron oolites formed from the oxidation of chamosite oolites provides a ready explanation for the development of oolites made up of concentric layers of chamosite and hematite. Some of the chamosite oolites that were washed into the oxidizing environment may have been too fine grained to be hydraulically stable in the presumably higher energy zone of the tidal flat or bar. After a short period of time, during which the outer sheath of chamosite had become oxidized, the oolite would have been washed back into the lagoon, where chamosite precipitation recommenced. The cycle could have been repeated several times. This situation may be contrasted with observations on the growth cycle of carbonate ooids, in which periods of precipitation on shallow shoals apparently alternate with periods of rest.

Thin section study of the Bell Island Group sandstones revealed that several contain rare, partially weathered, chamosite oolites as clastic grains. These occur as complete single individuals or as individuals enclosed in shale pebbles. They have been recognized in sandstones that outcrop at the Ore Docks, The Beach, Polls Head and Bell Cove within the Beach Formation and at Scott's Gulch in the Ochre Cove Formation. These sandstones are not in close stratigraphic proximity to known ironstone beds. Although the oolites may be a product of the reworking of underlying ore beds, such a source is considered unlikely. Chamosite oolites and shale pebbles would probably not survive secondary reworking or fluvial transport for even a short distance. Furthermore, in some cases underlying ore beds are more than 100 metres below the sandstones in which oolites have been found. Reworking would therefore probably require uplift or tilting of the beds to near sea level. There is no evidence of such a disturbance.

In light of this, the chamosite oolites within the sandstones are probably not detrital, but have undergone local transport from elsewhere on the shelf. This suggests that ironstones were forming locally at various times and places throughout the deposition of the Bell Island and Wabana Groups. The appearance of the ironstone beds within the exposed strata should probably not be considered as unique episodes, but perhaps simply the lateral migration of a special environment that was a result of, and an integral part of, the overall depositional environment. If the accumulation of the ironstones at a particular locality requires a low sedimentation rate, then a model must be sought that allows regional variation in the sedimentation rate.

The formation of the ironstones may have been related to the migration of major delta distributaries or delta lobes. While a distributary was active, a high rate of sedimentation diluted the available iron preventing the formation of ironstones. Once a particular distributary was abandoned, a slow rate of sedimentation would prevail, depending primarily on longshore currents and the proximity of the newly established distributary. Conditions may then have been favourable for the formation of ironstones on the shallow tidal shelf of the abandoned delta lobe.

There is some stratigraphic evidence that the ironstones formed in an interdistributary environment. The ironstone beds of the Dominion Formation are overlain by pyritic, graptolitic, dark shale and silty shale, evidently a deeper water facies. These are followed by prodelta shales that coarsen upwards into sandy, shallow-water delta front sediments (Fig. 35). This sequence may be interpreted as follows: (1) abandonment of a major delta distributary or delta lobe, accompanied by a major phase of ironstone formation; (2) subsequent transgression and establishment of a deeper water, distal, interdistributary bay environment, followed by (3) lateral migration and re-establishment of a major delta distributary and (4) seaward progradation of the delta and a return to shallow-water tidal shelf conditions.

Significantly, the ironstones of the Scotia Formation and the upper ore beds (considered as a single phase of ironstone formation) are also overlain by dark, pyritic shale and silty shale, indicating a deeper water environment.

Phosphatic Pebble Beds

Phosphate nodules and pebbles occur within flat pebble conglomerate beds and these are generally associated with the lagoonal facies overlying the major ironstone beds. The phosphatic material occurs mostly as structureless pellets or pebbles, but some is also concentrically laminated. Hallimond (1925) recognized intraformational conglomerates as a striking feature of most of the ironstones of England and Wales. He refers to them as submarine breccias resulting from submarine erosion of penecontemporaneous deposits. Phosphate beds have been said to occur at major and minor unconformities (Grabau, 1919; Goldman, 1922), and Pettijohn (1926) suggested that such unconformities are probably submarine surfaces resulting from periods of nondeposition rather than erosion or exposure.

There is no evidence to suggest that the phosphatic pebble beds associated with the Bell Island-Wabana ironstones represent subaerially exposed surfaces; in fact, the presence of fresh-looking chamosite oolites within the pebble beds seems to preclude their exposure to highly oxidizing conditions. Furthermore, the suggestion that these pebble beds indicate minor submarine unconformities due to periods of nondeposition is consistent with the hypothesis that the appearance of the ironstones represents a period of distributary abandonment.

Glauconite

Glauconite sandstones occur within the Ochre Cove Formation. The mineral was identified by x-ray diffraction and is present in quantities of up to 10% of the rock. It occurs as individual microcrystalline aggregates, but also occasionally between cleavage planes in green biotite, expanding the structure into 'accordian' shapes (Fig. 47). Various stages in the alteration of biotite to glauconite were recognized.

Galliher (1935) recognized a similar series of transition stages from biotite to glauconite in bottom deposits of Monterey Bay, California. He concluded that the glauconite was a submarine alteration product of biotite. A similar source for the glauconite from the Ochre Cove Formation seems likely.

It is interesting that glauconite from the Ochre Cove Formation is associated with shallow-water structures and in places is interbedded with thin, silty sandstones, which display runzel marks on flat-topped ripples, indicating subaerial exposure.

Cloud (1955) concluded that glauconite forms in marine waters of normal salinity, 10 to 400 fathoms in depth. On the other hand, Burst (1959) and Wermund (1961) believe that the presence of glauconite is not confined to a specific physical environment and that it will form wherever physico-chemical conditions are favourable, that is, well-oxygenated, normally saline and possibly brackish waters. In light of this, the glauconite from the Ochre Cove Formation may have formed in the shallow subtidal zone and accumulated nearby in the intertidal zone.

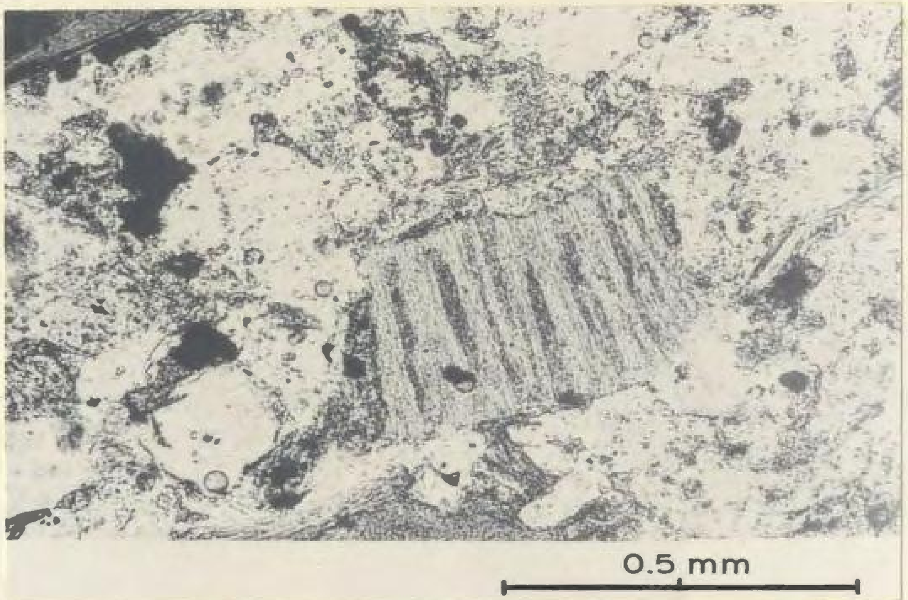


FIGURE 47. Glauconite forming as an alteration of biotite between cleavage planes. Sample BI-64c, Ochre Cove Formation.

Oolitic Pyrite Member

The environment of formation and deposition of the oolitic Pyrite Member remains enigmatic. Stratigraphically, the Pyrite Member overlies dark shales and siderite beds interpreted as a shallow-water lagoonal facies. The Pyrite Member is itself overlain by a deeper water, graptolitic, shale facies however, so that the facies relationships remain unclear. The presence of pyritized graptolite fragments in the Pyrite Member indicates access to open ocean; on the other hand, surface tracks and trails, interference ripples, brachiopod shells, flat pebbles and the oolites themselves are typical of what is recognized as a shallow-water facies elsewhere in the study area. Graded bedding is also common in some of the oolite beds.

The ~~pyrite appears~~ appears to be a secondary replacement of previously existing grains. It replaces graptolite and shell fragments and partially replaces some shale pebbles. Some of the pyrite oolites have an oolitic chamosite core, suggesting incomplete replacement (Fig. 48). Furthermore, it is difficult to conceive of the primary precipitation of pyrite as oolites in the required reducing environment, since the oolitic form implies agitated, and therefore aerated, water.

Pyritization apparently took place before deposition of the Pyrite Member. The pyrite coating on some of the shale fragments appears to have been broken away (Fig. 49),

FIGURE 48. Pyrite Member. (a) Pyritized oolite with chamosite core; (b) unpyritized chamosite oolite. Sample BI-74, Powers Steps Formation.

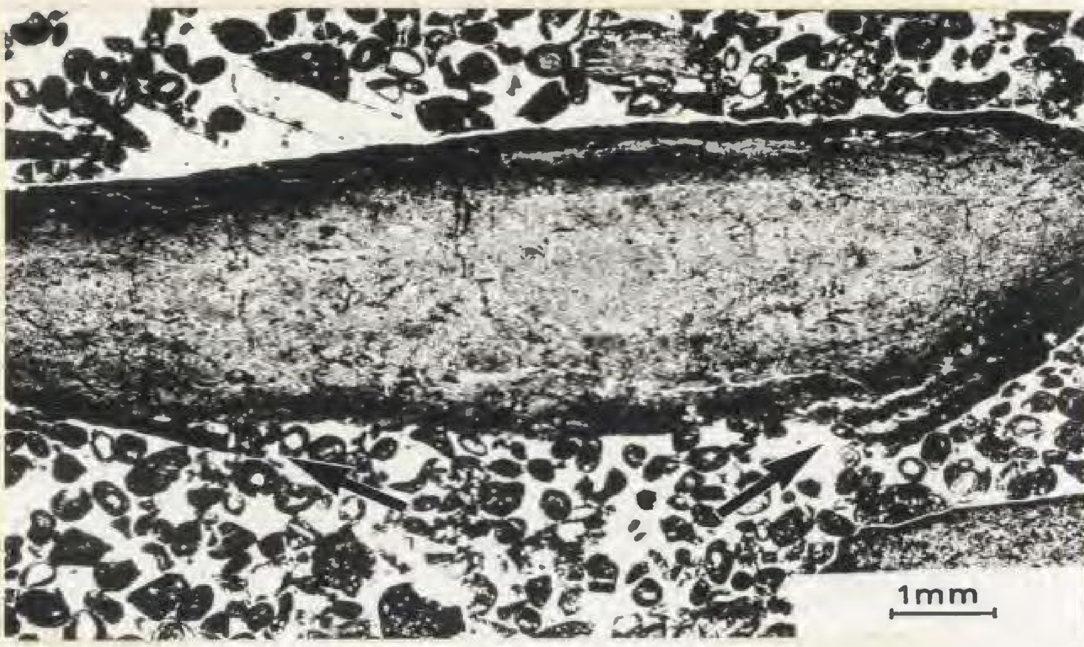


FIGURE 49. Pyrite coated shale pebble in the Pyrite Member. Note break in coating (arrows). Sample BI-74, Powers Steps Formation.

implying some transportation. Rarely, completely unpyritized chamosite oolites are seen in thin section (Fig. 48). If the pyrite is indeed a secondary replacement, then the only way that clastic chamosite oolites could have escaped being replaced is by pyritization taking place before deposition of the bed. Then, during the depositional event, some chamosite oolites were washed in from an adjacent area and deposited along with the pyrite.

CHAPTER 7

DISCUSSION

Comparison of the Bell Island-Wabana Sediments to Other Tidal Flat Environments

The sediments of the Bell Island and Wabana Groups have many features in common with both recent and ancient tidal flat environments documented in the literature.

Klein (1971) lists a number of criterion that are typical features of sediments deposited by tidal currents. A distinct combination of these is required in order to distinguish ancient tidal sequences. Table 6 lists those features recognized in rocks of the Bell Island and Wabana Groups and compares them to features found in several documented examples of ancient tide-dominated sedimentary sequences.

The fining-upwards cycles that are particularly well-developed in the Beach Formation and the Ochre Cove Formation are similar to other examples that have been interpreted as prograding tidal flat sequences (Allen, 1965; Allen and Tarlo, 1962; Smith, 1968; Klein, 1970, 1971, 1975a, 1975b; Klein and Barnes, 1975; Sellwood, 1972). Klein (1971, 1972) has proposed a sedimentary model for such sequences, based on studies of recent tidal flat environments. His model has provided the basis for the tidal flat interpretation in this study (Fig. 5). Klein's model

TABLE 6. Comparison of sedimentary structures in the Lower Ordovician Bell Island and Wabana Groups with other documented intertidal sediments of Paleozoic age.

Unit and Locality / Structure	Herringbone cross-bedding	Multimodal current directions	Flaser bedding	Wavy bedding	Lenticular bedding	Graded bedding	Fining upwards sequences	Shale pebbles and/or shell fragments at base of scours and channels	Mud cracks	Interference ripples	Current ripples	Double crested ripples	Runzel marks	Abundant burrows and/or tracks and trails
Bell Island and Wabana Groups (Lower Ordovician), this study.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Middle Member, Wood Canyon Formation (Late Precambrian), Klein (1975a).	X		X	X			X	X	X	X	X		X	X
Lower Fine-grained Quartzite, Scotland (Precambrian-Dalradian), Klein (1970b).	X	X	X	X	X			X	X	X	X			X
Zabriskie Quartzite (Cambrian), Barnes and Klein (1975).	X		X						X	X	X			X
Potsdam Sandstone (Cambrian), Otvos (1966).	X		X					X	X					
Orville and Barrios Formations, Spain (Cambro-Ordovician), Gietelink (1973).	X		X	X	X			X			X			X
Reedsville and Juniata Formations (Ordovician), A.M. Thompson (1968,1969).									X					X
Eureka Quartzite (Ordovician), Klein (1975b).	X	X	X		X			X	X		X			X
Clinton Formation (Silurian), Smith (1968).					X	X	X	X	X					X
Basal Ringerike Formation, Norway (Silurian), Spjeldnaes (1966).				X		X		X	X		X			X

(Partly compiled and adapted from Kléin, 1970b).

provides criterion for determining the intertidal zone and he concludes that the thickness of this zone in the sequence provides a good estimate of the paleotidal range.

Applying the paleotidal range model to fining-upwards sequences that are particularly well-developed at the Ore Docks and Freshwater Cove (Parsonville) in the Beach Formation, paleotidal ranges were estimated to be approximately 6 and 5.5 metres respectively. At Gull Island North Head in the Ochre Cove Formation, the fining-upwards sequences containing the hematite beds represent an estimated paleotidal range of approximately 3 metres. These estimates indicate a moderate to high tidal range and this probably explains why sedimentation in the Bell Island and Wabana Groups appears to have been dominated so thoroughly by features indicative of tidal processes. Furthermore, if a deltaic system did exist, it is perhaps not surprising that little evidence for it remains, considering the destructive potential of a 3 to 6 metre tidal range.

A comparison of the Bell Island-Wabana stratigraphy with several modern tidal flat environments also shows many features in common.

Tidal flats along the North Sea coast of the United Kingdom, Netherlands and Germany have been well studied (Evans, 1965; Van Straaten, 1954; Reineck, 1963, 1967). These areas are characterized by tidal ranges of 2.4 to 5 metres and the width of the tidal flat varies from 0.5 to

3 kilometres at the Wash (Evans, 1965) and from 7 to 10 kilometres along the Dutch and German coasts (Reineck and Singh, 1975). Longshore barrier bars have developed seaward of the Dutch and German tidal flats.

The characteristic pattern of sediment distribution on the North Sea tidal flats is a gradual change from sand in the lower intertidal zones to mud in the upper mud flats, with a mixed transition zone between the two (Reineck and Singh, 1975). In prograding deposits, the result is a fining upwards stratigraphic sequence.

In the lower sand flats, current crossbedding and occasionally herringbone crossbedding are common. Flaser, lenticular and wavy bedding characterize the middle mixed zone and the upper tidal flats consist of silty clays deposited by suspension settling (Reineck, 1967). In short, a direct comparison can be made between sedimentary features of the modern North Sea tidal flats and features observed in the sediments of the Bell Island and Wabana Groups.

The evidence for a deltaic influence on the overall depositional environment (p. 75) is inconclusive. Several examples of modern, tide-dominated delta systems may be used as possible analogues.

The Klang River delta and the Ord River delta have been described by Coleman and Wright (1975), and the Colorado River delta by Thompson (1968) and Meckel (1975). These systems are characterized by mean spring tidal ranges of 4.3, 5.15 and 7.0 metres respectively. Because of the high tidal ranges, the subaerial delta deposits consist predominantly of tidal flat sediments rather than fluvial sediments. Vertical sequences in the Klang and Ord River deltas are fining-upwards, except for marine shales at the base (Coleman and Wright, 1975). Seaward of the delta, sands are dispersed into coastal barrier or tidal bars, and subaqueous sand ridges and sand waves such as those described by Off (1963). These sands are recognized as a major environment in tide-dominated deltas (Miall, 1967).

All of these features, which are recognized in the Bell Island and Wabana sequences, are diagnostic more of tidal influences than of deltaic processes. Significantly, no well-described examples of specifically tide-dominated deltas in ancient rocks were found in the literature.

Iron Ores

The process by which oolitic chamosite forms is not clear, but it is believed to form either by in situ growth within the sediment or, as in the case of carbonate oolites, by chemical accretion during gentle agitation on the sediment surface (Wilson, 1966; Hallam, 1967). Both of these processes may contribute to the formation of ironstones. In the Wabana iron ores, there is no clear evidence to support either hypothesis; the chamosite oolite beds are often rippled, suggesting agitated conditions, but they are also associated with muddy, shallow-water sediments suggesting a lagoonal environment and low energy conditions.

In the Minette iron ores, limonite laminae within the chamosite oolites are believed to indicate oxidation of the chamosite when washed into an oxidizing region of the sea floor (Brookfield, 1971; Davies and Dixie, 1951). Sheldon (1965) similarly suggests that hematite oolites in the Clinton of Alabama formed from the halmyrolysis of chamosite. This reasoning appears valid for the Wabana ironstones, since the chamosite oolites are associated with apparently lagoonal sediments, probably a reducing or slightly reducing environment, whereas the hematite oolites are in a tidal bar or lower tidal flat facies, presumably an oxidizing environment.

The environment of formation of the Minette chamosite ores is unclear. Due to generally poor exposure, there appears to be some question whether they formed close to old shorelines or within the open sea (Hallam, 1966; Brookfield, 1971). On the other hand, the Silurian Clinton ores of the Eastern United States are undoubtedly near-shore deposits (Hunter, 1960, 1970). Sheldon (1965) concluded that the Silurian Clinton ironstones of Birmingham, Alabama formed in the lagoonward side of a barrier island complex, an environment similar to that proposed in this study for the Wabana ironstones.

The occurrence of the ironstones in a deltaic environment, suggested here for the Wabana ironstones, has been noted in several Minette deposits, among other examples (Chown, 1966). The Jurassic ironstones of Britain may have been formed during the development of a delta (Dunham, 1960; Hallam, 1966). Hallam (1966) suggested that the appearance of the Northampton Sand ironstones was possibly controlled by periodic migration of delta distributaries.

Kimberley (1974) has concluded that ferriferous oolites are calcareous oolites that have been covered by deltaic sediment (or pyroclastics). Weathering and leaching of the deltaic sediment produced solute-rich groundwaters that drained through the oolites replacing aragonite with chamosite. The appeal of this theory is that it explains why no ironstones are seen forming today on the sea floor. There is no real evidence that such a process takes place, nevertheless it is difficult to disprove. Most workers cite the preservation of delicate primary microstructure in the oolites as evidence of the primary precipitation of chamosite. The concentric lamination of chamosite and hematite or limonite is the best example (Hallimond, 1925; Davies and Dixie, 1951; Hunter, 1960; Schoen, 1965). Kimberley (1974) however, contends that after replacement, selected chamosite layers were oxidized, possibly due to differences in the content of organic matter.

The presence of rare chamosite oolites as clastic grains or within shale pebbles in the sandstones of the Bell Island Group provides further evidence of the primary nature of the chamosite. It is unlikely that the oolites have been reworked from underlying ore beds (p. 117) and they have probably been transported and deposited soon after formation. Furthermore, in the Pyrite Member some of the pyritized oolites have an oolitic chamosite core (Fig. 48). Since it appears that the pyrite is a secondary replacement and that pyritization took place before deposition of the Pyrite Member, then it seems likely that the chamosite is the unpyritized remains of a primary chamosite oolite.

Source of the Iron

The source and transportation of the iron in most of the Phanerozoic ironstones remains a subject for speculation. The Devonian Lahn-Dill ironstones of Germany are apparently volcanically derived (James, 1966). In other ironstone types, the lack of evidence for contemporaneous volcanic activity or other extraordinary source of iron has led most workers to believe that continental weathering was the source of the iron. A notable exception is Borchert (1960), who argues that iron was derived from, and concentrated by, sea-bottom reactions. This view is not generally accepted because such processes would seem to be quantitatively inadequate unless sea water chemistry was very different from that of today (James, 1966).

James (1966) and Schoen (1965) have suggested that iron was derived from the leaching of sediments in a large-scale analogy to present-day bog iron ores and transported in bicarbonate groundwaters of low Eh and pH to a restricted basin. Carroll (1958) has shown how bacterial action appears necessary to produce the required chemical environment in which iron oxide can be leached from within crystal lattices or from films on the surface of clay minerals. The common occurrence of bleached biotite in the Bell Island-Wabana rocks may be evidence of this leaching process.

Bogs however, require land vegetation of which there was little if any before the Devonian Period. It may be that supratidal bogs in the lower Ordovician coastal environments were algal marshes. Bacteria acting on decaying organic matter could have produced the necessary low Eh environment in which iron is reduced and mobilized. Transportation could then have taken place by groundwater into shallow restricted ocean lagoons.

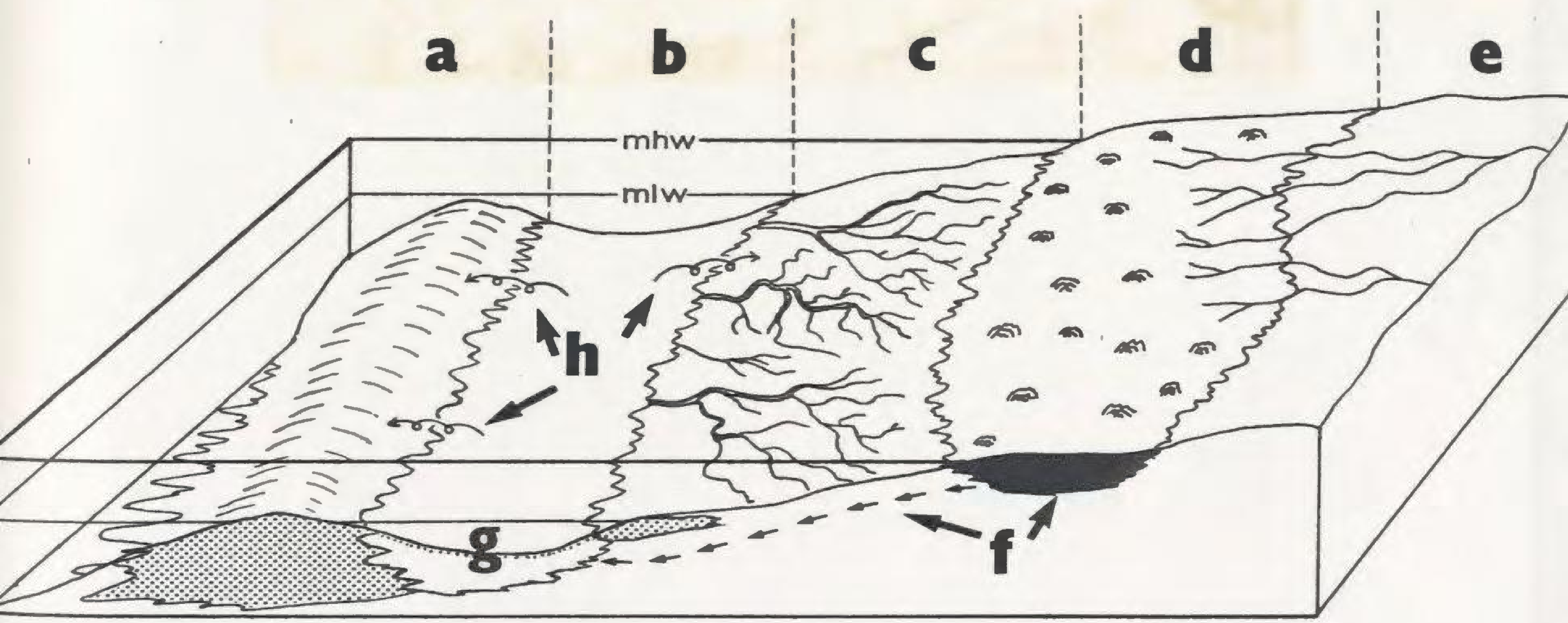
There is evidence for algal activity in the Bell Island-Wabana coastal environment. Chamosite oolites in the upper part of the Scotia ore bed are riddled with Girvanella algal borings (Hayes, 1915). Rippled wash-out structures in an apparently heavily grazed sandstone surface (Fig., 50) may indicate the presence of extensive algal mats in the intertidal zone. Furthermore, the high ichnofaunal content in the rocks indicates a large concentration and variety of marine life and algae would probably have been a low but important link in the food chain. Direct evidence for extensive supratidal algal swamps is, however, lacking. Figure 51 summarizes the possible mechanism for the formation of Wabana-Bell Island ironstones.

If the hypothesis that iron was mobilized in supra-

FIGURE 50. Rippled washout structure in an apparently heavily grazed sandstone surface; Freshwater Cove (north), Bell Island. Hammer is 28 cm long.

FIGURE 51 (below)

Suggested mechanism for the formation and accumulation of the Wabana-Bell Island ironstones: a. tidal or barrier bar; b. lagoon (low Eh sediments); c. tidal flat; d. supratidal algal marsh (low pH and Eh due to bacterial action); e. local drainage from abandoned distributary; f. iron is leached from mineral lattices or from adsorbed films on mineral surfaces, and reduced in the marsh environment, subsequently reaching the water table where it is transported in groundwater; g. iron precipitates as chamosite oolites in lagoon; h. tidal currents or storms wash oolites onto bar and tidal flat, and into tidal channels where iron is oxidized.



tidal bogs is correct, then the problem arises as to why ironstones are not seen to be forming offshore from similar environments at the present time.

Ironstone beds may represent condensed sections (Hallam, 1966). Perhaps then, the accumulation of ironstones requires long periods of stable conditions within the depositional environment. In that case, the accumulation of ironstones in the Quaternary may have been prevented by the frequency of sea level fluctuations associated with cycles of glaciation. It should be noted that ironstones have formed prior to Pleistocene glaciation as recently as the Kimmerian age in the Lower Pliocene (Sokolova, 1964), an epoch during which there appears to have been several prolonged stands of sea level. A less speculative explanation for the apparent lack of formation of ironstones in modern environments must, however, await a better knowledge of the processes which produce ironstones.

Regional Correlation With Other Lower Ordovician Ironstone Deposits

Hayes (1915) noted that the Wabana iron ores were comparable in character and extent with iron ores of similar age in Nova Scotia and Europe. With the advent of the concept of plate tectonics, a close geographic relationship is now generally acknowledged.

Wilson (1966) postulated that a proto-Atlantic ocean of Late Precambrian-Early Paleozoic age might have closed from Ordovician to Devonian times along a line extending through New England, southern New Brunswick and southern Newfoundland. Subsequent rifting of the American-African landmass took place southeast of this suture and is represented approximately by the present shelf edge. Therefore, the early Paleozoic rocks of southeast Newfoundland, Nova Scotia and southeastern New Brunswick are probably exotic to North America (Schenk, 1971).

Pre-drift reconstructions generally place Atlantic Canada opposite the Moroccan coast and west of Spain (Bullard et al., 1965; Dietz and Holden, 1970).

The distribution of Lower Ordovician sedimentary ironstones of Europe, North Africa and Atlantic Canada is plotted on a paleogeographic reconstruction in Fig. 52. The oolitic iron ores of Bell Island, Newfoundland and Arisaig, Nova Scotia can thus be correlated with a broad belt of similar deposits in Europe and North Africa, ranging from Arenigian to Llandeilian in age.

The lower Ordovician iron ores of western France outcrop within the Grès Armorican Formation and succeeding shale formations of the Armorican Massif (C. Babin et al., 1976). In this region, the Ordovician lithologic succession is detrital, consisting of alternations of sandstone and shale and marked by an absence of limestone. Phosphatic pebble beds and conglomerate bands are common. Sedimentary structures include crossbedding, channels, ripple-marks,

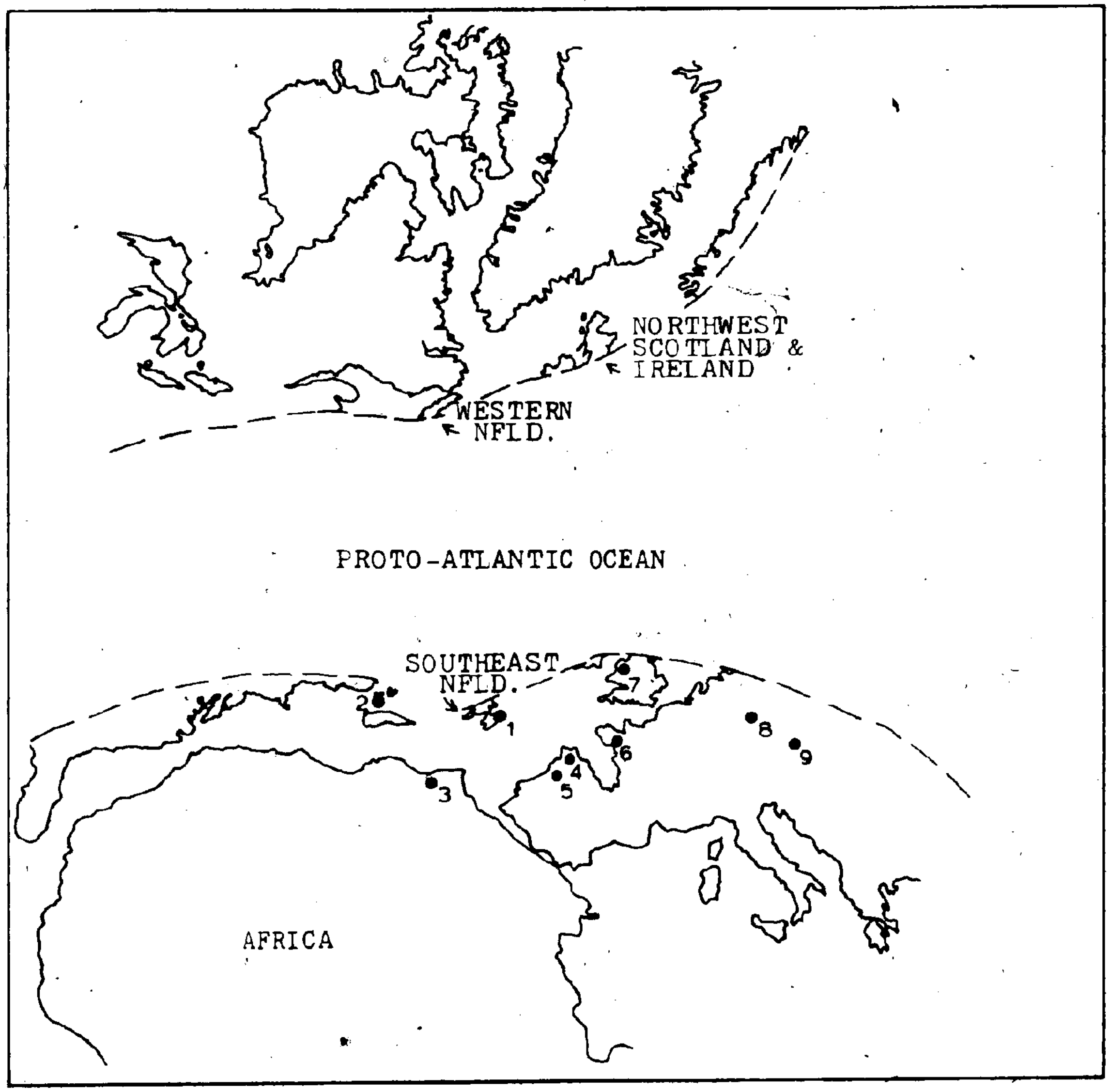


Figure 52.

Generalized map showing the distribution of oolitic ironstone environments during the Lower Ordovician. (Paleogeography adapted from Dean, 1976)

1. Wabana, Newfoundland
2. Arisaig, Nova Scotia
3. Ait Amar, Morocco
4. Coto Wagner, Coto Vivaldi and San Miguel de las Dueñas, Spain
5. Guadramil, Moncorvo and Vila Cova do Marão, Portugal
6. Normandy, Anjou, and Brittany, France
7. Carnarvonshire, Merionethshire and Anglesey, North Wales
8. Thuringia, Germany
9. Barrandienne Basin, Bohemia, Czechoslovakia

Sources: United Nations Publication ST/ECA/113; Blondel and Marvier, 1952; Williams, 1914; Pulfrey, 1933.

load casts, flute casts and numerous tracks and trails, all suggesting epicontinental, shallow shelf conditions (Babin et al., 1976).

In Spain and Portugal, the Lower Ordovician generally shows close stratigraphic affinities with the Lower Ordovician of France. The ironstones occur in the dark shales overlying "Armorican" quartzite of Arenigian age (Hamman, 1976). In the Westasturian-Cantabrian region, the Armorican Quartzite of the Barrios Formation, as well as the underlying Oville Formation, possibly of Tremadocian age, has been interpreted as a linear prograding coastline and high destructive delta complex (Gietelink, 1973). Gietelink recognized several different facies including barrier beach deposits and tidal deposits as well as fluvio-tidal, prodelta, delta slope and shelf deposits, in short, an environment strikingly similar to that proposed for the Bell Island and Wabana Groups in this study.

The shallow-water, epicontinental nature of the Ordovician of the Moroccan Anti-Atlas in which the Ait Amar ironstones occur has also been noted (Destombes, 1962, 1976). The Moroccan succession shows many general similarities to the French-Spanish Armorican and younger successions (Babin et al., 1976; Hammann, 1976).

Of the other Lower Ordovician ironstones occurring within the belt, both the Arisaig deposits of Nova Scotia (Hayes, 1919) and the Barrandienne deposits of Bohemia (Petranek,

1960) are known to represent shallow-water environments.

Petranek (1964) has noted the genetic features of these deposits, emphasizing their shallow-water origin. Following is a point summary of his conclusions: (1) The orebodies are lenticular and elongated. Their narrow width and relatively small size does not suggest a deep water origin. (2) The paleogeographic setting of the deposits indicates that they were deposited close to shore in shallow flats, bays or even littoral and deltaic environments, thus following ancient coastlines. (3) Most of the ores show only coarse bedding or none at all, suggesting shallow-water, high energy conditions. (4) The early Paleozoic oolitic iron ores belong to the oxidic type, implying that these ores were deposited in relatively well-aerated, shallow-water environments, preventing the reducing activity of organic matter. (5) Clastic rocks associated with the ores are chiefly shales, siltstones and orthoquartzitic to subgreywacke sandstones, suggesting a shelf or at most marginal miogeosynclinal environment.

Within this environment, the development of wide tidal flats apparently played a role in the accumulation of economic quantities of iron ore in the Wabana deposits. In light of the work done on the recognition of ancient tidal flat deposits in the last decade, perhaps a detailed re-examination of the other Lower Ordovician iron ore deposits in the North Africa-European belt would reveal a tidal influence on the accumulation of many of these ores as well.

CHAPTER 8

CONCLUSIONS

The rule of priority requires that the division into two groups of the Lower Ordovician stratigraphy of Conception Bay (Van Ingen, 1914, Rose, 1952) should remain in a formal description of the stratigraphy. Much of Van Ingen's (1914) formational subdivisions of the Bell Island and Wabana Groups is still acceptable with minor changes to some inappropriate nomenclature and outdated terminology. Nine formations can be distinguished.

Sediment distribution in the Bell Island and Wabana Groups was controlled dominantly by tidal processes. High to moderate tidal ranges produced regressive, fining-upwards sequences, recording a range of environments from shallow subtidal to upper tidal flat.

Massive quartzites of the Redmond Formation, as well as those of Little Bell Island and Kellys Island, are interpreted to be a shallow-water tidal or barrier bar environment seaward of the intertidal mud flats.

Dark, silty shales and overlying coarsening- and shoaling-upward sequences in the lower part of the Beach Formation and the lower part of the Powers Steps Formation are interpreted as prograding deltaic cycles. The overall environmental control of the Bell Island and Wabana Groups may have been that of a high-destructive, tide-dominated delta system.

A comparison of these sediments to other documented examples of tidal flat environments shows many features in common.

Paleocurrent direction patterns support the hypothesis that the Bell Island and Wabana Groups represent a tidal flat and probably deltaic environment. However, because of the multi-modal nature of the patterns, the source direction cannot be definitely determined. Other evidence, in the form of prodelta sediments with a primary dip towards approximately 320^{0}, could indicate that the modal class oriented in a west-northwest direction represents the seaward direction and that the source lay to the east-southeast, at least during the deposition of the Wabana Group.

Provenance studies show that the source terrain of the Bell Island-Wabana sediments was probably the Precambrian rocks of the Harbour Main, Conception and Cabot Groups as well as the Holyrood Plutonic Series. Detrital garnet, muscovite and metamorphic rock fragments may be derived from a postulated Precambrian crystalline basement underlying the Avalon Zone.

The chamosite oolites are interpreted to be primary precipitates that formed in shallow lagoons. The oolites accumulated in the lower intertidal and shallow subtidal zone of both the tidal flat and tidal bar environments where they became oxidized. The hematite is probably diagenetic after ferric hydroxide. The ironstones may have formed during periods of distributary abandonment.

The Pyrite Member seems to be a secondary replacement of oolitic chamosite, organic material and shale pebbles. The exact nature of the environment of formation and deposition of the Pyrite Member remains problematic, but there is evidence that pyritization took place before final deposition.

A general correlation of the Wabana iron ores can be made with Lower Ordovician iron ores of Nova Scotia, North Africa and Europe. All of these deposits are known to represent shallow-water,/epicontinental, coastal environments and they probably developed as a belt along a slowly subsiding, marginally miogeosynclinal shelf. The sedimentology of the host rocks, where studied, appears to be similar to that of the Bell Island and Wabana Groups.

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APPENDIX

DESCRIPTION OF STRATIGRAPHIC SECTIONS

LEGEND FOR STRATIGRAPHIC SECTIONS

BEDDING STRUCTURE

- small-scale current cross-bedding
- large-scale, parallel cross-bedding
- herringbone cross-bedding
- planar laminated bedding
- large-scale, low angle cross-bedding
- megaripple bedding
- trough cross-bedding
- flaser bedding
- lenticular bedding, sandy
- " " silty
- " " shaley
- " " oolitic
- scours or minor erosion surfaces
- shale pebble conglomerate or lag deposit

BIOTURBATION

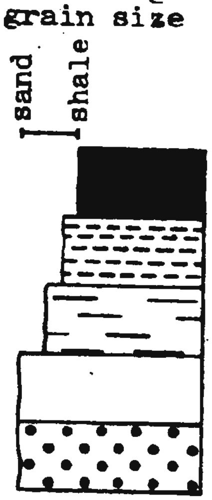
- weak
- moderate
- strong

MISCELLANEOUS FEATURES

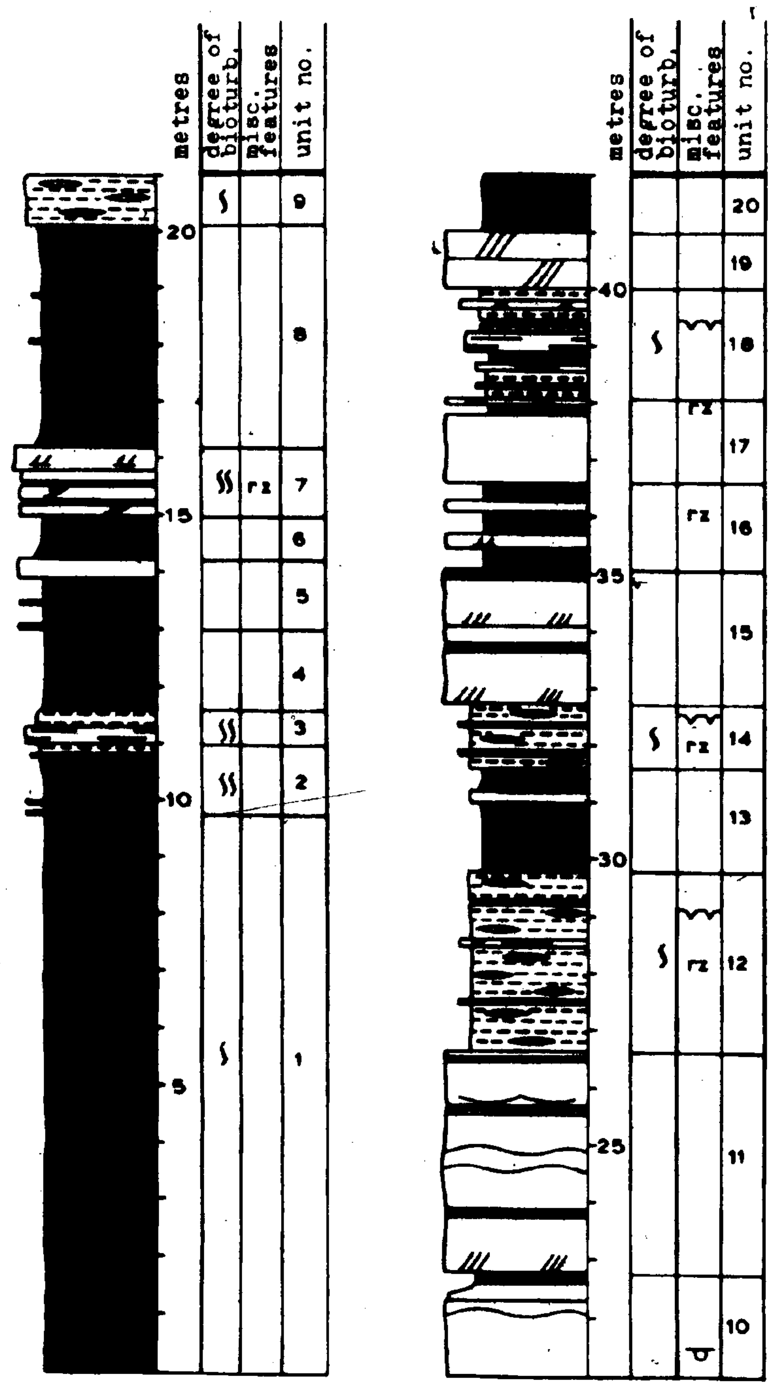
- mud cracks
- channels
- load casts or ball and pillow structure
- rz runzel marks
- rl rill marks
- sw swash marks
- Fe ironstone
- P phosphate
- Py pyrite

ROCK TYPE

field estimate of average grain size



- shale
- silty shale
- siltstone
- sandstone
- oolitic ironstone



LOCALITY A
KELLYS ISLAND

LOCALITY A

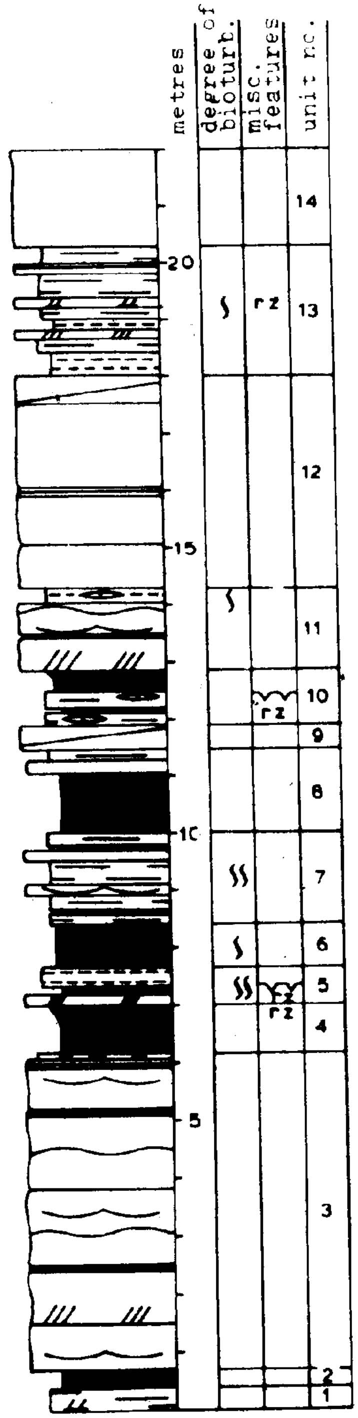
KELLYS ISLAND

UNIT		THICKNESS (METRES) unit	from base
20	Shale, fissile, dark grey, weathering reddish brown.	1.0	41.9
19	Sandstone, massive, light grey, weathering light yellow, some large-scale parallel crossbedding.	1.0	40.9
18	Siltstone, interbedded with light grey silty sandstone lenses, silty shale and dark fissile shale, light yellow, yellowish brown and dark grey, weathering reddish brown and light grey; sandstones are current-ripple and crossbedded, bedding 2 to 25 cm thick, mudcracks; weak bioturbation.	1.8	39.9
17	Sandstone, massive, medium to fine grained, interbedded with fissile shales towards top; megarippled with faint, large-scale parallel crossbedding, low-angle planar-laminated towards top with some flaser bedding and runzel marks.	1.5	38.1
16	Sandstone, fine grained, interbedded with fissile, dark shales containing white siltstone lenses, light yellow and dark grey, weathering light to dark brown; sandstone beds are massive, up to 50 cm thick, with rippled surfaces, runzel marks.	1.5	36.6
15	Sandstone, fine to medium grained with some		

UNIT		THICKNESS (METRES) unit	from base
	silty partings, light grey, weathering light yellowish brown; massive, megarippled with some large-scale parallel crossbedding and low-angle, planar laminations towards the top.	2.3	35.1
14	Shale, fissile, silty, interbedded with sandy siltstones and fine-grained sandstone lenses, light to dark grey and light brown, weathering light to dark brown; bedding 2 to 30 cm, current ripples, lenticular bedding, mudcracks, runzel marks; weak bioturbation.	1.1	32.8
13	Shale, fissile, dark grey, interbedded with silty sandstones up to 10 cm thick; grey and light yellow, weathering dark grey and brownish; sandstones are massive, shales are structureless.	1.8	31.7
12	Shale, fissile, silty, interbedded with fine-grained sandstone lenses and sandy siltstones, light brown and light grey, weathering brownish; sandstones are 5 to 50 cm thick, wavy, lenticular and flaser bedding, current ripples, mudcracks, runzel marks; weak to moderate bioturbation.	3.2	29.9
11	Sandstone, fine grained, light grey, weathering light yellow, bedding 1 to 2 m; megarippled with large-scale parallel crossbedding, low-angle parallel crossbedding towards top of bed, scours filled		

UNIT		THICKNESS (METRES) unit.	from base
	with silt.	3.9	26.7
10	Sandstone, fine grained, light grey, weathering light yellow, bedding 1 to 2 cm thick; massive, faint megaripples, planar horizontal towards top, base contains large slumps, roll-up structure and ball-and-pillow.	1.8	22.8
9	Shale, silty, interbedded with silty sandstone lenses, yellowish brown, weathering dark brown; bedding 1 to 5 cm, lenticular and wavy bedding, runzel marks; weak bioturbation.	0.9	21.0
8	Shale, fissile, interbedded with rare, fine-grained sandstone and siltstone beds; dark grey, weathering dark brown; becoming siltier towards top.	3.9	20.1
7	Sandstone, silty, interbedded with silty shales and dark, fissile shales, light brown, weathering light to dark brown; bedding 1 to 30 cm thick, current ripples, interference ripples, many lenticular and flaser bedding, runzel marks; moderate bioturbation.	1.2	16.2
6	Shale, fissile, dark grey, weathering light brownish grey.	0.8	15.0
5	Shale, fissile, interbedded with fine-grained sandstone and siltstone lenses 1 to 10 cm thick, dark grey and yellowish brown, weathering dark brown; ripple marks		

UNIT		THICKNESS (METRES) unit	from base
	and current ripple crossbedding.	1.2	14.2
4	Shale, fissile, dark grey, weathering light brownish grey, interbedded with rare, thin, silty lenses.	1.4	13.0
3	Shale, silty, fissile, interbedded with massive siltstones 10 to 15 cm thick, light grey, weathering light yellowish brown; moderate bioturbation.	0.6	11.6
2	Shale, fissile, interbedded with silty sandstone lenses 3 to 4 cm thick; becoming siltier towards top; light grey, weathering medium grey and brownish, wavy bedding, interference ripples; weak to moderate bioturbation.	1.2	11.0
1	Shale, fissile, interbedded with rare, thin siltstones toward the top, dark grey, weathering medium grey and rusty; weak bioturbation.	9.8	9.8



LOCALITY B
LITTLE BELL ISLAND

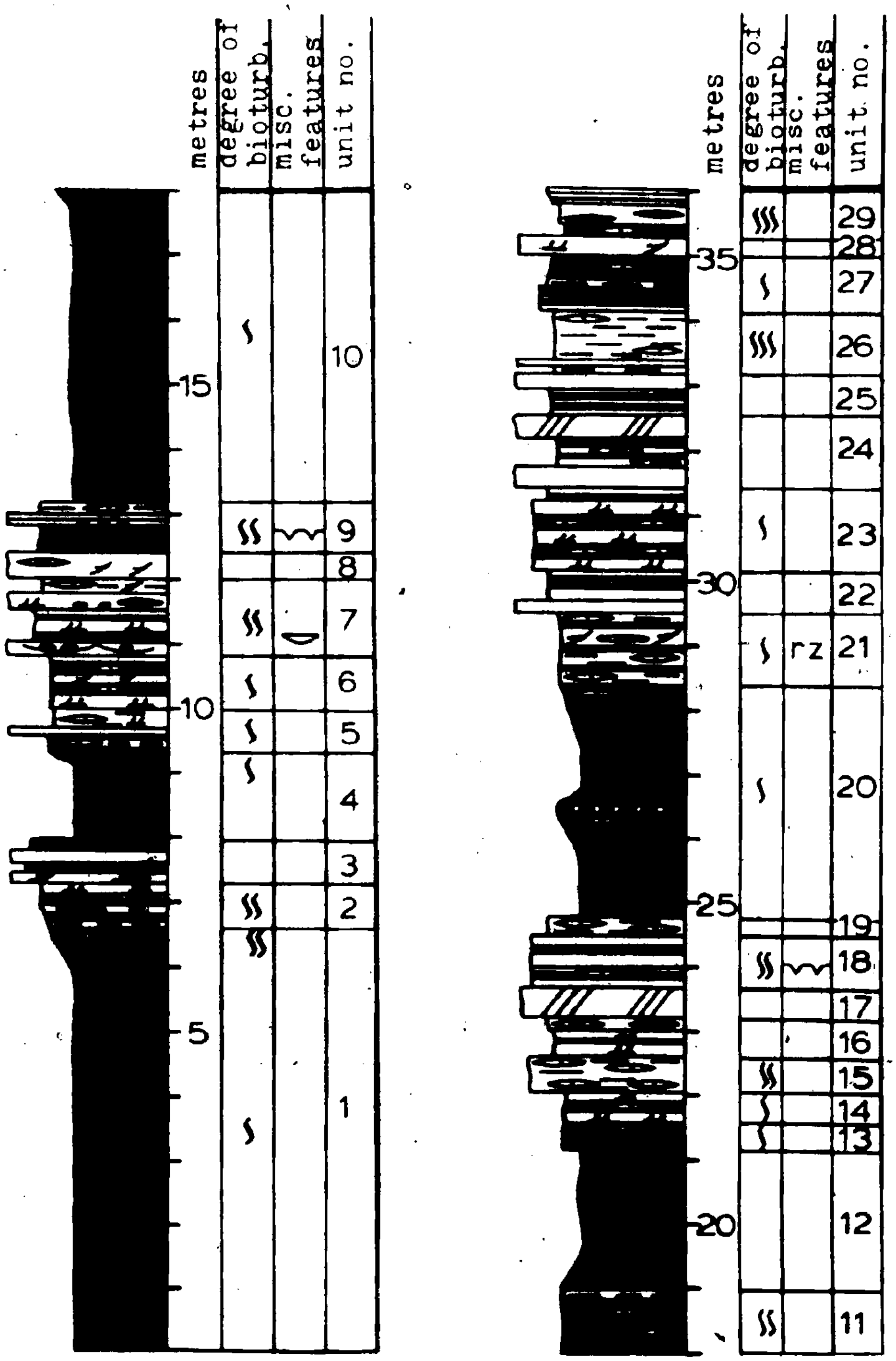
LOCALITY B

LITTLE BELL ISLAND

UNIT		THICKNESS (METRES) unit	from base
14	Sandstone, massive, fine grained, light brownish grey, weathering light grey; structureless, rare silty partings.	1.7	22.0
13	Siltstone, interbedded with fine-grained sandstones and silty shales, light brown and light grey, weathering light yellowish brown; sandstones show large- and small-scale bedding or are horizontal planar laminated, thin bedded, runzel marks; weak bioturbation.	2.2	20.3
12	Sandstone, fine to medium grained, light grey, weathering light brown; structureless or shallow dipping, large-scale parallel crossbedding.	3.6	18.1
11	Sandstone, massive, fine grained, silty shale towards top, light grey, weathering brownish; megarippled, shallow dipping, large-scale parallel crossbedding or current crossbedded, scours, silty partings; weak bioturbation, tracks and trails.	1.4	14.5
10	Siltstone, interbedded with fine-grained sandstone lenses and shale, light grey and light yellow, weathering brownish yellow; ripple marks, wavy bedding, mudcracks, runzel marks.	1.0	13.1
9	Sandstone, massive, light grey, weathering light yellow, large-scale, low-angle crossbedding.	0.5	12.1

UNIT		THICKNESS (METRES) unit	from base
8	Shale, massive, interbedded with sandstone and siltstone towards top; medium grey, weathering rusty brown and fissile; wavy bedding towards top.	1.5	11.6
7	Siltstone, interbedded with fine-grained sandstone lenses and dark shales, light to dark grey, weathering yellow to dark brown; sandstone lenses are up to 15 mm thick, scours; moderate bioturbation.	1.6	10.1
6	Shale, massive with siltstone lenses, medium grey, weathering rusty brown and fissile; weak bioturbation.	0.8	8.5
5	Siltstone, interbedded with fine-grained sandstone and dark shales, light yellow and light to dark grey, weathering light grey and yellowish brown; sandstone are up to 30 cm thick with large-scale parallel crossbedding, runzel marks, mudcracks; moderate bioturbation.	0.7	7.7
4	Shale, fissile, with siltstone lenses towards top, black to light grey, rusty weathering; ripple marks and runzel marks at top.	0.9	7.0
3	Sandstone, massive, with rare silty partings, light grey, weathering brownish; fine-grained, structureless or di playing mega-ripple bedding, faint planar laminated bedding or large-scale parallel crossbedding, scour-and-fill.	5.2	6.1
2	Shale, dark grey, fissile, weathering dark brown.	0.4	0.9

UNIT		THICKNESS (METRES) unit	from base
1	Siltstone, shaly, light grey, weathering medium grey and rusty; thick bedded, some current crossbedding.	0.5	0.5



LOCALITY C
LANCE COVE

LOCALITY C

LANCE COVE

UNIT		THICKNESS (METRES) unit	from base
29	Sandstone, silty and shaly, with interbedded shales, dark to medium grey, and light brownish yellow, weathering to yellowish brown and reddish brown; bedding is highly variable in composition, generally finely laminated, becoming coarser and sandier towards the top of the unit, wavy, lenticular and current ripple crossbedded, fine grained, rare pseudopellet horizons in limy mud; highly bioturbated.	0.8	36.1
28	Sandstone, white to light yellow, weathering light yellow and light brownish yellow; massive bedded with some wavy and flaser bedding, parallel crossbedding, fine grained.	0.3	35.3
27	Siltstone, shaly, sandy with interbedded shales and laminated sandstones, dark grey, yellowish brown and light yellow, weathering brownish yellow and medium grey; thin bedded, 0.3 to 1 cm thick, wavy and lenticular bedding, becoming shalier towards the top of the unit; weak bioturbation.	0.9	35.0
26	Siltstone, with minor interbedded shales, sandstones and sandstone lenses, light grey to brownish grey, weathering medium brownish grey; wavy, laminated, thin		

UNIT		THICKNESS (METRES) unit	from base
	bedded, 0.5 to 1 cm thick, rippled throughout, some flaser bedding, exposure badly weathered; many highly bioturbated zones.	0.9	34.1
25	Sandstone, interbedded with shale, light yellow, medium to dark grey, weathering brownish yellow and brownish grey; sandstones are current ripple crossbedded and 3 to 20 cm thick, some interference ripples.	0.6	33.2
24	Sandstone, interbedded with silty sandstones and minor shales, light to medium grey, light yellow and brownish yellow, weathering to brownish yellow and brownish grey, fine grained; sandstones are massive bedded but lensoid and pinching out, silty sandstones are wavy bedded with shales, in places almost grading to flaser bedding, and containing sandstone and siltstone lenses.	1.1	32.6
23	Sandstone, interbedded with wavy sandstones and shales, light yellow, yellowish brown and medium grey, weathering to brownish yellow and dark brownish grey; sandstones are fine grained, massive bedded, 10 to 15 cm thick and current ripple crossbedded with some thin shale partings, interference ripples, shales are wavy bedded with fine-grained sandstone; weak bioturbation.	1.3	31.5

UNIT		THICKNESS (METRES) unit	from base
22	Sandstone, interbedded with wavy, silty sandstones and shales, light yellow, yellowish brown and dark grey, weathering brownish yellow and dark grey, fine grained; sandstones are massive bedded and laminated from 3 to 15 cm thick, interbedded silty sandstones and shales are finely laminated and lenticular bedded, runzel marks.	0.6	30.2
21	Siltstone, interbedded with sandstones, silty sandstones and shales, white, buff, brownish yellow, light to dark grey, weathering brownish yellow and dark brownish grey, sandstones are fine grained; bedding is highly variable in composition and generally finely laminated, wavy, lenticular and flaser bedding, small-scale scour-and-fill, rare pseudopellet horizons in limy mud; weak to moderate bioturbation.	1.2	29.6
20	Shale, dark, papery, medium to dark grey, weathering dark brownish grey; very thin bedded, becoming sandier and siltier towards the top of the unit, with a few wavy, sandy and silty interbeds; weak bioturbation.	3.6	28.4
19	Siltstone, shaly, with minor sandstone lenses, light brownish grey, weathering to dark brownish grey, sandstones are fine grained; wavy and lenticular bedding, 1 to 3 cm thick.	0.3	24.8

UNIT		THICKNESS (METRES) unit	from base
18	Sandstone, interbedded with shales and shaly siltstones, light yellow, light grey and brownish yellow, weathering to brownish yellow and dark, brownish grey, fine grained; sandstones are massive bedded from 10 to 20 cm thick, shales and shaly siltstones are wavy and lenticular bedded with some sandstone lenses, rare mudcracks; moderate bioturbation.	0.8	24.5
17	Sandstone, with thin shale partings, light grey, weathering yellowish grey, fine grained; massive bedded, variable in thickness to 1 m, large-scale parallel crossbedding, runzel marks.	0.5	23.7
16	Sandstone, silty, interbedded with shales and shaly siltstones, light yellow, brownish yellow and medium grey, weathering brownish yellow and dark brownish grey, fine grained; wavy and lenticular bedding from 1 to 8 cm thick, sandstones are current ripple crossbedded, interference ripples.	0.6	23.2
15	Siltstones, shaly with sandstone lenses, light yellow, light brownish yellow and light grey, weathering to brownish yellow and brownish grey; wavy and lenticular bedding, 0.5 to 3 cm thick; moderately bioturbated.	0.6	22.6
14	Shale, interbedded with sandstone lenses, dark grey and greyish white, weathering		

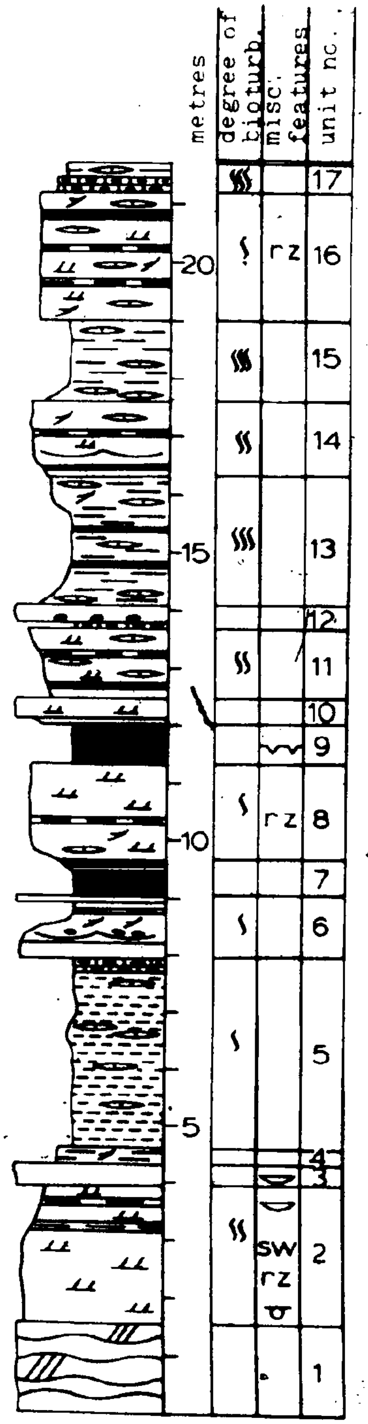
UNIT		THICKNESS (METRES) unit	from base
	to dark brownish grey and light yellow, sandstones are fine grained; sandstone lenses are current ripple crossbedded, 5 to 8 cm thick, wavy and lenticular bedding; weak bioturbation.	0.5	22.1
13	Shale, interbedded with thin sandstones, very light grey and dark grey, weathering to dark brownish grey, reddish grey and light yellow; interbedded sandstones are fine grained and planar laminated from 1 to 8 cm thick with occasional current ripple surfaces; weak bioturbation.	0.4	21.6
12	Shale, dark, papery, dark grey, weathering dark reddish brown; finely laminated, exposure is deeply weathered; bioturbation not discernible.	2.2	21.2
11	Shale, dark, papery, silty, interbedded with some sandstones and siltstones, light to dark grey and brownish yellow, weathering brownish grey and dark rusty grey, sandstones are fine grained; shales are finely laminated and sandstones are current ripple crossbedded but planar laminated towards the bottom of the unit, wavy bedding, interference ripples; moderately bioturbated.	1.0	19.0
10	Shale, dark, papery and silty, dark grey, weathering rusty grey; finely laminated, exposure is deeply weathered; weak bioturbation.	4.7	18.0

UNIT		THICKNESS (METRES) unit	from base
9	Shale, papery, silty, interbedded with sandstones, dark grey, light grey and yellowish grey, weathering brownish grey and brownish yellow, sandstones are fine grained; shales are very thin bedded, sandstones are massive, wavy or horizontally planar laminated, 8 to 20 cm thick, herringbone crossbedding, some scour and shale chip horizons; moderate bioturbation, <u>Cruziana</u>.	0.8	13.3
8	Sandstone, with thin shale partings, light grey to light yellow, weathering light yellow to brownish yellow, fine to medium grained; wavy and flaser bedded, sets 8 to 20 cm thick, shallow tidal channel horizon; rare trace fossils, <u>Cruziana</u>, telopodite scratches, surface scratches.	0.4	12.5
7	Sandstone, interbedded with dark shales and shaly siltstones, light to dark grey and yellowish brown, weathering light to dark brownish grey and brownish yellow, fine to medium grained; sandstones are ripple crossbedded, wavy, lenticular and flaser bedding, variable from 0.5 to 15 cm thick, shales and siltstones are horizontally planar laminated with some lenticular bedding, interference ripples, rare pseudopellet horizons in limy mud, small scour-and-fill with shale chip horizons, bottom of unit is a sandstone zone		

UNIT	THICKNESS (METRES) unit	from base
containing assymetric sand-filled channels up to 1.5 m in width, incorporating large scours and shale chip horizons, and showing small-scale point bar cross-stratification, load casts; moderate bioturbation.	1.2	12.1
6 Shale, dark, interbedded with thin- to medium-bedded sandstones, medium to dark grey, weathering yellowish brown and dark brownish grey, sandstones are fine grained; shales are finely laminated with thin sandstone beds and lenses, a few sandstone beds up to 8 cm thick current ripple crossbedded, flaser, lenticular and wavy bedding; weak bioturbation.	0.8	10.9
5 Siltstone, shaly, sandy, buff to light grey, weathering yellowish brown; horizontally planar laminated, wavy and lenticular bedding, some lenticular sandstones are ripple crossbedded, unit becomes sandier towards top; weak bioturbation.	0.7	10.1
4 Shale, dark, papery, dark grey, weathering dark brownish grey, thin bedded, becoming siltier towards the top of the unit, exposure is deeply weathered; weak bioturbation.	1.4	9.4
3 Sandstone, interbedded with shales and shaly and sandy siltstones, light to dark grey, light yellowish brown and buff,		

UNIT		THICKNESS (METRES) unit	from base
	weathering brownish yellow and dark brownish grey, fine grained; composition and bedding are highly variable, thin horizontally planar from 0.5 cm thick to massive sandstones of up to 40 cm thick, ripple crossbedding, wavy, lenticular and flaser bedding, slumped bedding, ball-and-pillow structure.	0.7	8.0
2	Siltstone, sandy, shaly, interbedded with sandstone lenses and dark shales, light to dark grey, buff and brownish yellow, weathering dark brownish grey and brownish yellow, sandstones are fine grained; composition and bedding are highly variable, 0.5 to 8 cm thick, sandstones are horizontally planar laminated or current ripple crossbedded, lenticular and wavy bedding, small scour-and-fill; moderately bioturbated.	0.7	7.3
1	Shale, dark papery, dark grey, weathering dark brownish grey; finely laminated, deeply weathered, becoming siltier and sandier towards the top, rare small sandstone nodules 10 to 15 cm in diameter; weakly bioturbated, increasing towards the top. Bottom of unit not exposed.	6.6	6.6

THE ORE DOCKS
LOCALITY D



LOCALITY D

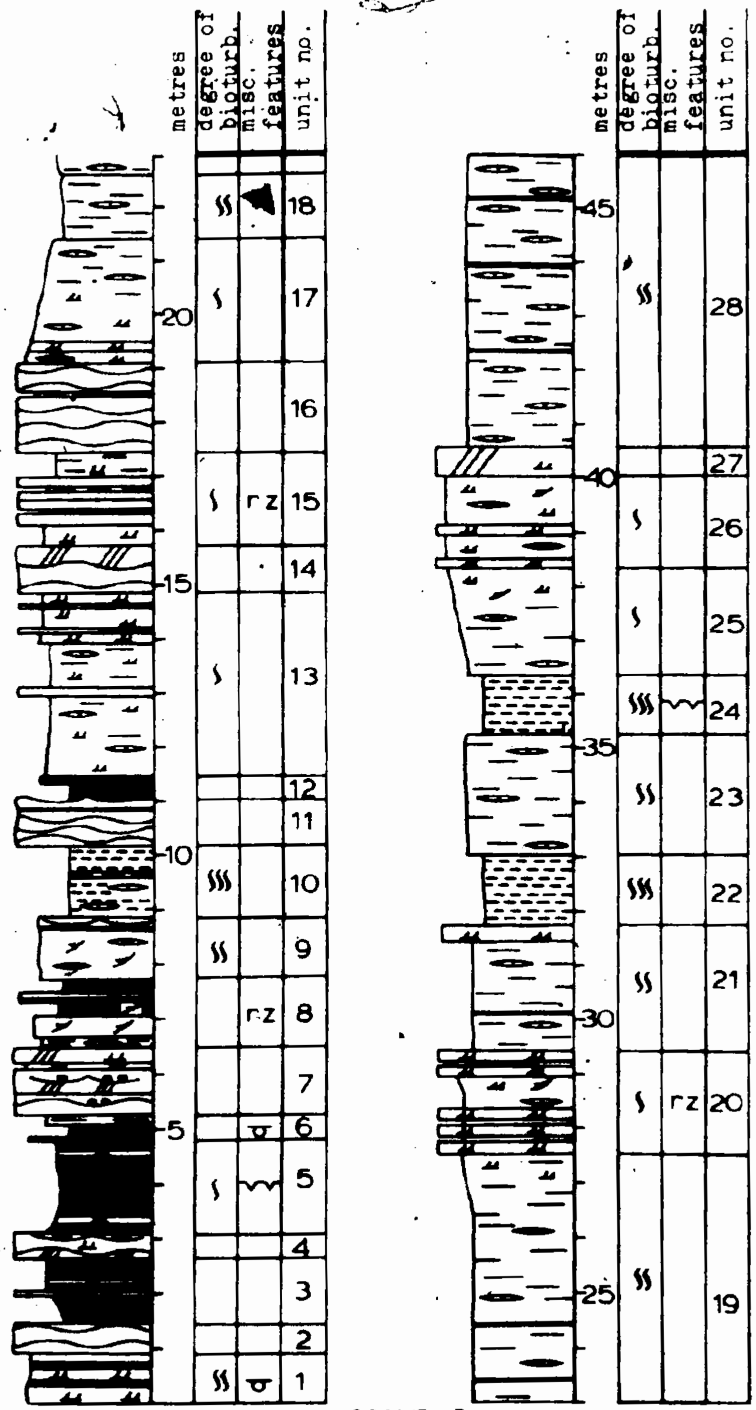
THE ORE DOCKS

UNIT		THICKNESS (METRES) unit	from base
17	Siltstone, shaly, interbedded with sandy lenses, light grey to buff, weathering brownish grey, lower half of unit consists of limy sandstones and limy mud, pseudo-pellet beds in limy mud; highly bioturbated.	0.5	21.4
16	Sandstone, silty interbedded with siltstones and shales, light grey, buff, dark brownish grey, weathering to yellowish brown, fine grained; sandstones are thin bedded, 1 to 5 cm thick, and current ripple crossbedded, flaser, wavy and lenticular bedded with siltstones and shales, runzel marks; weak to moderate bioturbation.	2.2	21.1
15	Shale, silty, interbedded with fine-grained sandstone lenses, buff to light grey, weathering light yellow; thin bedded, sandstone lenses are current ripple cross-bedded; highly bioturbated.	1.4	18.9
14	Sandstone, silty, interbedded with siltstones and shales, light grey, buff and dark brownish grey, weathering to yellowish brown, fine grained; sandstones are thin to medium bedded, 1 to 20 cm thick and current ripple crossbedded, sometimes planar laminated, wavy and flaser bedded with siltstones and shales, some scour-		

UNIT		THICKNESS (METRES) unit	from base
	and-fill; moderately to highly bioturbated, sandstones contain escape burrows.	1.3	17.5
13	Siltstone, shaly, interbedded with silty shales, dark shales and sandstone lenses, buff to light grey, weathering light yellow; thin bedded, but bedding is almost obliterated due to bioturbation, wavy and lenticular bedding are evident, becoming sandier with flaser bedding towards the top; extreme bioturbation.	2.2	16.2
12	Sandstone, with limy mud horizon at base, light grey, weathering light yellowish grey, medium to fine grained; massive bedded with scour and shale chip horizons.	0.4	14.0
11	Sandstone, interbedded with shales and shaly siltstones, light to dark brownish grey, weathering yellowish brown, fine grained; current ripple crossbedded, lenticular and wavy bedded with shales and siltstones, 1 to 8 cm thick; siltstones and shales are moderately bioturbated.	1.2	13.6
10	Sandstone, white to light yellow, weathering light brownish yellow, fine grained; ripple crossbedded, brachiopod shell fragments common.	0.5	12.4
9	Shale, dark, papery, dark grey, weathering dark brownish grey; finely laminated, fresh rock is massive looking and structureless.	0.7	11.9

UNIT	THICKNESS (METRES) unit	from base
8 Sandstone, interbedded with shaly siltstones, light to dark grey, yellowish brown, weathering light brownish yellow to dark brown, fine grained; sandstones are ripple crossbedded and lenticular in places, 2 to 10 cm thick, siltstones are lenticular bedded with some flasers, runzel marks; weak bioturbation.	1.7	11.2
7 Shale, dark, papery, dark grey, weathering dark brownish grey; finely laminated, fresh rock is massive looking.	1.1	9.5
6 Sandstone, silty, interbedded with shaly siltstones; light grey to dark yellowish brown, weathering light brownish yellow to dark brown, fine grained; thin bedded, 0.5 to 2 cm thick, wavy bedded with mud drapes on some sandstones, several scour surfaces and shale chip horizons; weak bioturbation.	1.1	8.9
5 Shale, silty, interbedded with a few fine-grained sandstone lenses, dark to light grey, weathering to dark brownish grey; finely laminated, limy mud horizon at top of unit; weak bioturbation.	3.2	7.8
4 Siltstone, interbedded with sandstones and silty shales, light grey, buff and yellowish brown, weathering light brownish yellow and dark brown; composition and bedding highly variable, wavy and flaser		

UNIT		THICKNESS (METRES) unit	from base
	bedding.	0.3	4.6
3	Sandstone, light grey, weathering to light yellow, fine grained; massive, structureless, contains some sand-filled channels.	0.4	4.3
2	Sandstone, interbedded with sandy siltstones, light grey to light yellowish grey, weathering light brownish yellow, fine grained; ripple crossbedded, 2 to 20 cm thick, mud drapes on some sandstones, interference ripples, swash marks, runzel marks becoming more common towards the top of the unit, scour-and-fill; weak bioturbation but tracks and trails common.	2.4	3.9
1	Sandstone, white to light grey, weathering light yellow to light brownish yellow, fine grained; megaripple morphology and steep crossbedding, 10 to 60 cm thick, many scour surfaces with shale chip and brachiopod fragments as scour lag.	1.5	1.5



LOCALITY E
THE BEACH

LOCALITY E

THE BEACH

UNIT		THICKNESS (METRES) unit	from base
28	Siltstone, sandy, shaly, interbedded with sandstone lenses and shales, medium to dark grey, weathering light brownish grey, sandstones are fine grained; horizontally planar laminated and wavy thin bedded, sandstone lenses are current ripple cross-bedded, broad and thin, 1 to 5 cm thick; moderately bioturbated.	5.5	46.0
27	Sandstone, silty, light to medium grey, weathering yellowish grey, fine grained; parallel crossbedded and current ripple crossbedded, 10 to 20 cm thick, thin silty partings, runzel marks are common.	0.5	40.5
26	Sandstone, silty, with shaly lenses, light to medium grey and yellowish brown, weathering light to dark brown, fine grained; current ripple crossbedded with silty lenses, flaser and lenticular bedding; weak bioturbation.	1.7	40.0
25	Siltstone, sandy, shaly, interbedded with sandstones towards the top, and sandstone lenses, light to dark grey, weathering light brownish grey; sandstones are fine grained and current ripple crossbedded, siltstones are planar laminated or wavy thin bedded, some flasers towards the top, runzel marks; weak to moderate bioturbation.	2.0	38.3
24	Shale, silty, with some minor siltstones, buff, weathering to light yellow and		

UNIT		THICKNESS (METRES) unit	from base
	brownish yellow; bedding obliterated; very highly bioturbated.	1.1	36.3
23	Siltstone, shaly and sandy, with fine-grained sandstone lenses, light grey, brownish grey and yellowish grey, weathering to light brownish yellow and reddish brown; wavy and lenticular bedded, sandstone lenses are 0.5 to 3 cm thick; moderately bioturbated.	2.2	35.2
22	Shale, silty, buff to yellowish brown, weathering to light brownish yellow; bedding obliterated by bioturbation, a few fine-grained sandstone lenses; highly bioturbated.	1.3	33.0
21	Siltstone, shaly, interbedded with silty shales, dark shales and sandstone lenses, buff to light grey, weathering light yellow; thin bedded, 0.5 to 2 cm thick, wavy and lenticular bedding, becoming sandier towards the top; moderate bioturbation.	2.3	31.7
20	Siltstone, sandy, interbedded with sandstones and some sandstone lenses, light yellowish grey and dark brownish, weathering light to dark yellowish brown, sandstones are fine grained; thin wavy bedded with some flasers, sandstones are ripple crossbedded, 5 to 20 cm thick, some runzel marks; weak bioturbation.	1.9	29.4

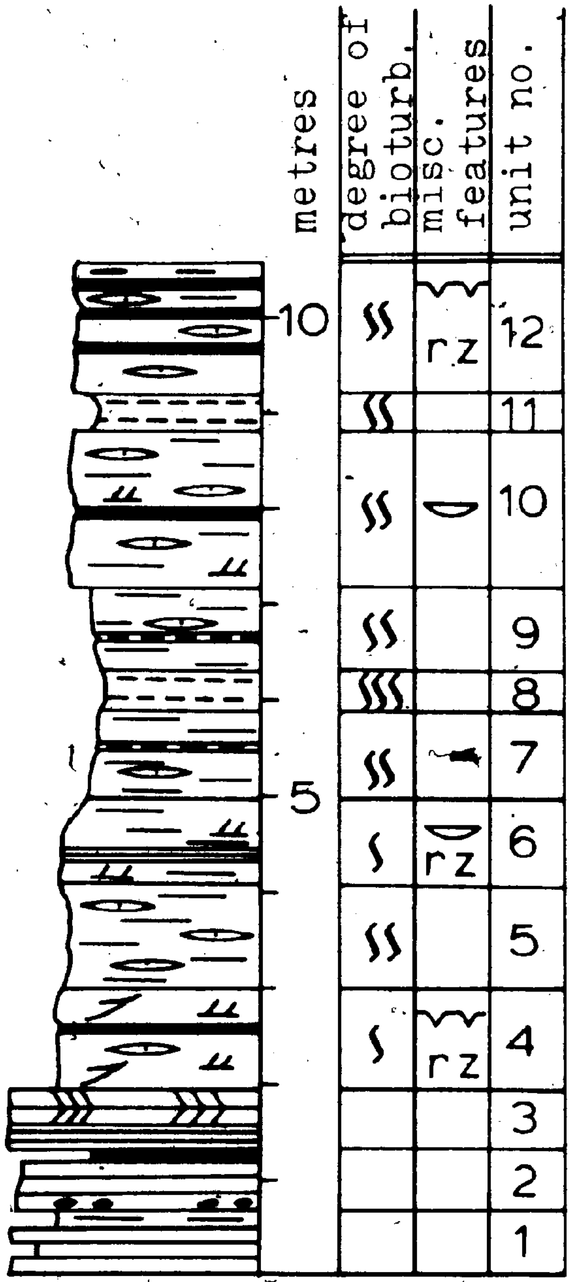
UNIT		THICKNESS (METRES) unit	from base
19	Siltstone, shaly, sandy, interbedded with sandstone lenses and shales, buff, light yellowish brown and dark brown, weathering brownish yellow; thin bedded, wavy and lenticular, sandstone lenses are current rippled; moderately bioturbated.	4.9	27.5
18	Siltstone, shaly, with minor fine-grained sandstones, buff to light grey, weathering brownish yellow; lenticular and wavy bedded; moderately bioturbated.	1.2	22.6
17	Sandstone, silty, interbedded with sandstone lenses and becoming siltier towards the top, light grey and light to dark yellowish brown, weathering dark brown, fine grained; sandstones are current ripple crossbedded, and wavy bedded with the siltstones, runzel marks are common; weak bioturbation.	2.3	21.4
16	Sandstone, very light yellow to light grey, weathering light brownish yellow, medium to fine grained; bedding is massive but shows megaripple morphology and some distinct large-scale crossbedding, scour surfaces are common, often filled with dark, finely laminated, shaly siltstones.		
15	Sandstone, with thin silty partings, interbedded with sandy siltstones, light yellowish grey to dark brownish grey, weathering to yellowish brown, fine		

UNIT		THICKNESS (METRES) unit	from base
	grained; sandstones are thin bedded planar laminated or ripple crossbedded, silt-stones are wavy bedded, some runzel marks; weak bioturbation.	1.7	17.4
14	Sandstone, white to light grey, weathering light yellow to light brownish yellow, fine grained; megaripple morphology and large-scale parallel crossbedding, 10 to 50 cm thick.	0.9	15.7
13	Siltstone, sandy, interbedded with sand-stones and sandstone lenses, light yellowish grey to light brown, weathering light yellowish brown, sandstones are fine grained; wavy and lenticular bedding, sandstones are ripple crossbedded or planar laminated, thin bedded; weak bioturbation.	3.4	14.8
12	Shale, dark, papery, dark grey, weathering black; finely laminated, fresh rock is massive looking.	0.4	11.4
11	Sandstone, carbonate cemented, light grey weathering light yellow, fine to coarse grained; planar laminated or parallel megaripple crossbedded, many scour surfaces, thin shale partings.	0.9	11.0
10	Shale, dark, interbedded with siltstones and thin sandstone lenses, light to dark grey, weathering black and light yellow-ish; finely laminated, wavy and lenticular		

UNIT	THICKNESS (METRES) unit	from base
bedding; highly bioturbated.	1.3	10.1
9 Sandstone, silty, interbedded with shaly siltstones; light grey to dark yellowish brown, weathering light brownish yellow to dark brown, fine grained; thin bedded, 0.5 to 2 cm thick, wavy bedded with flasers, several scour surfaces with shale chip lag deposits; moderate bioturbation.	1.1	8.8
8 Sandstone, silty, interbedded with dark shales and sandy siltstones, light to dark grey and dark brownish grey, weathering black and light to dark yellowish brown, fine to coarse grained; flaser, wavy and lenticular bedding, sandstones are planar laminated or ripple crossbedded, runzel marks common.	1.3	7.7
7 Sandstone, with some silty drapes, light yellowish grey, weathering light yellowish brown, fine to coarse grained; megarippled, with small- to large-scale parallel crossbedding, rare flaser bedding, some runzel marks, scour surfaces are common with a coarse shale chip lag.	1.2	6.4
6 Shale, dark, papery, dark grey, weathering black; finely laminated, fresh rock is massive looking, contains sandstone ball-and-pillow structures.	0.5	5.2

UNIT	THICKNESS (METRES) unit	from base
5 Shale, dark, interbedded with thin sandstones and siltstones, light to dark grey and light yellowish grey, weathering black, light grey and light yellowish brown, sandstones are fine to medium grained; shales are massive looking, very finely laminated, siltstones are massive and graded, sandstones are thin bedded, 1 to 5 cm thick and ripple crossbedded, wavy and lenticular bedding at the top and bottom, mudcracks are common, slightly bioturbated.	1.7	4.7
4 Sandstone, with some silty drapes, light yellowish grey, weathering light yellowish brown, fine to coarse grained; megarippled with small- to large-scale parallel crossbedding, interference ripples, scour surfaces are common.	0.4	3.0
3 Shale, dark, interbedded with silty sandstones towards the top, light to dark grey and light yellowish grey, weathering black and light yellowish brown, sandstones are fine to medium grained; lenticular and wavy bedding, shales are structureless, sandstones are ripple crossbedded, rare flasers.	1.2	2.6
2 Sandstone, white to light grey, weathering light yellow to light brownish yellow, fine grained; megarippled with large-scale parallel crossbedding, 10 to 30 cm		

UNIT		THICKNESS (METRES) unit	from base
	thick, many scour surfaces.	0.5	1.4
1	Sandstone, interbedded with dark shales, light to dark grey, weathering light, yellowish brown and black, fine to medium grained; wavy bedded, small ball-and-pillow structures, sandstones are ripple crossbedded, flasers and mudcracks are common; moderate bioturbation.	0.9	0.9



LOCALITY F
FRESHWATER COVE
(PARSONVILLE)

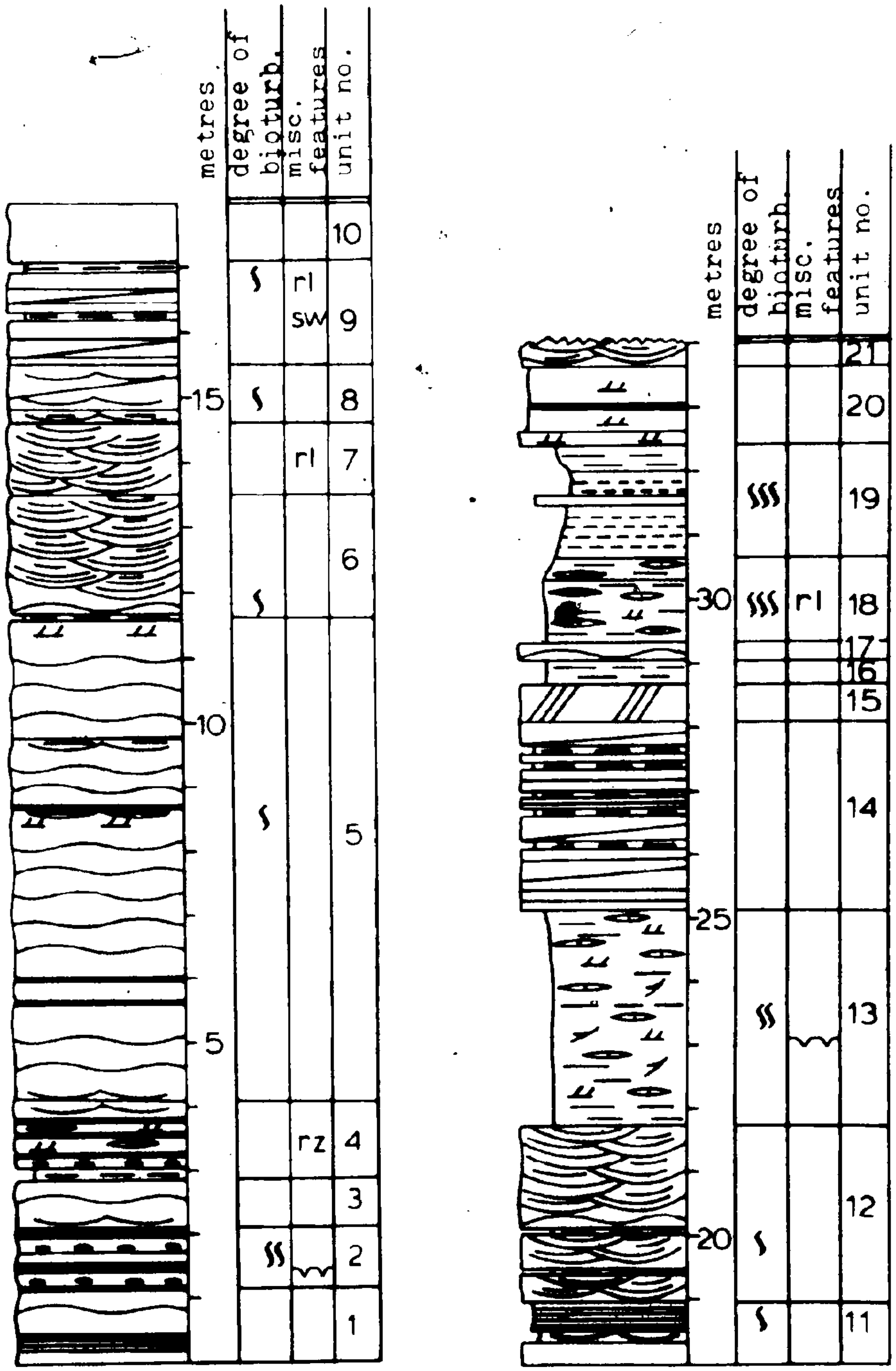
LOCALITY F

FRESHWATER COVE (PARSONVILLE)

UNIT		THICKNESS (METRES) unit	from base
12	Siltstone, sandy, interbedded with shales and fine-grained sandstone lenses, yellowish grey, weathering yellowish brown and reddish brown; wavy and lenticular bedded, sandstone lenses are 1 to 8 cm thick and are current ripple crossbedded, interference ripples, runzel marks, and mudcracks; silts and shales are moderately bioturbated, some blue phosphatic lingulid brachiopod fragments are common in the sandstones.	1.4	10.6
11	Shale, silty, interbedded with minor siltstones, buff to dark grey, weathering brownish yellow; bedding obscured; moderate bioturbation.	0.4	9.2
10	Siltstone, sandy, interbedded with fine-grained sandstone lenses and minor shales, dark yellowish brown and greyish brown, weathering yellowish brown and reddish brown; wavy and lenticular bedded, sandstone lenses are 2 to 5 cm thick and interference rippled, sand-filled tidal channels 30 to 60 cm wide; moderately bioturbated, lenses of brachiopod fragments are common.	1.6	8.8
9	Siltstone, shaly, sandy, buff to light grey, weathering yellow and reddish brown; wavy and lenticular bedding towards top;		

UNIT		THICKNESS (METRES) unit	from base
	moderately to highly bioturbated, some large lenses of blue brachiopod fragments.	0.9	7.2
8	Shale, silty, with some minor siltstones, buff, weathering to light yellow and brownish yellow; bedding obliterated; very highly bioturbated.	0.4	6.3
7	Siltstone, shaly, with minor fine-grained sandstones, buff to light grey, weathering brownish yellow; lenticular and wavy bedded with some black shale interbeds; moderately bioturbated.	0.9	5.9
6	Siltstone, sandy, with fine-grained sandstone lenses, light grey and light yellowish grey, weathering brownish yellow and reddish brown; sandstone lenses are 3 to 15 cm thick and laminated or current ripple crossbedded, interference ripples, runzel marks and rare raindrop impressions; low bioturbation.	0.9	5.0
5	Siltstone, shaly and sandy, with fine-grained sandstone lenses, light grey, brownish grey and yellowish grey, weathering to light brownish yellow and reddish brown; wavy and lenticular bedded, sandstone lenses are 0.5 to 3 cm thick; moderately bioturbated.	1.1	4.1
4	Sandstone, silty, interbedded with fine-grained sandstone lenses and some dark shales, light to dark grey, brownish grey		

UNIT		THICKNESS (METRES) unit	from base
	and greenish grey, weathering to brownish grey and reddish brown; sandstone lenses are 3 to 20 cm thick and are laminated or parallel crossbedded, wavy and flaser bedding, runzel marks and some mudcracks, shallow scours to 2 m wide; low bioturbation but increasing upwards, large <u>Cruziana</u> at top.	1.1	3.0
3	Sandstone, light grey, light yellow or pinkish, weathering medium grey; herringbone crossbedding, laminated or current ripple crossbedding, sets are 10 to 15 cm thick; no fossils.	0.6	1.9
2	Sandstone, some interbedded dark siltstones, light grey to light pinkish grey, weathering medium grey, fine grained; parallel and wavy laminated bedding, laminae are 2 to 4 cm thick, some shale chip conglomerate and brachiopod fragment horizons.	0.6	1.3
1	Sandstone, interbedded siltstones, light grey and yellowish brown, weathering medium grey, fine grained; laminated or current ripple crossbedding, laminae are 2 to 4 cm thick.	0.7	0.7



LOCALITY G
FRESHWATER COVE
(NORTH)

LOCALITY G

FRESHWATER COVE (NORTH)

UNIT		THICKNESS (METRES) unit	from base
21	Sandstone, white to light grey, weathering light brownish yellow, medium to fine grained; trough crossbedded, top of unit is either inaccessible or not exposed. This is the topmost unit of the Redmond Formation.	0.4	35.3
20	Sandstone, silty, interbedded with shales, white to light grey, and dark brownish grey, weathering light brownish yellow to dark brown, fine to medium grained; silty sands are thin bedded up to 6 cm thick and ripple crossbedded, interference ripples.	1.2	34.9
19	Shale, silty with a few thin sandstone lenses, buff to dark yellowish brown, weathering dark brown; finely laminated, becoming siltier towards the top of the unit; highly bioturbated.	1.8	33.7
18	Siltstone, shaly, sandy, interbedded with fine-grained sandstone lenses, dark grey and dark brownish grey, weathering yellowish grey and dark yellowish brown; siltstones are wavy and lenticular bedded, sandstone lenses are planar to wavy bedded, up to 8 cm thick, interference ripples, often planed off, runzel marks common; bioturbation high, surface tracks and trails common.	1.3	31.9

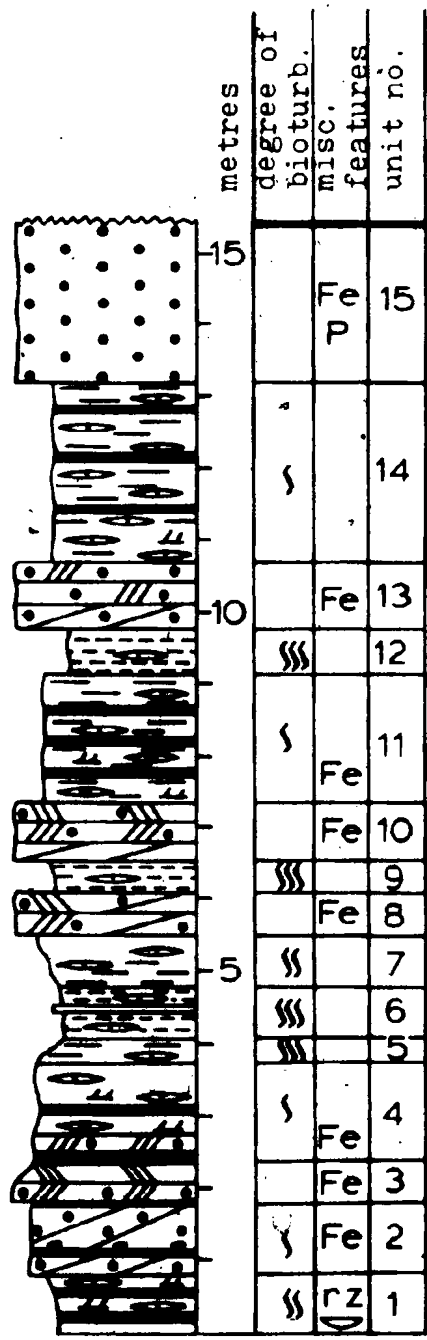
UNIT		THICKNESS (METRES) unit	from base
17	Sandstone, light grey to light yellowish grey, weathering light brownish yellow, fine to medium grained; large-scale mega-rippled, wave length greater than 2 m, thick bedded.	0.3	30.6
16	Siltstone, sandy, yellowish brown, weathering to buff; finely laminated; bioturbation rare.	0.4	30.1
15	Sandstone, light grey to light yellow, weathering light brownish yellow, fine grained; steep parallel crossbedding, thick bedded, rill marks, megascopic stylolites.	0.5	29.7
14	Sandstone, with thin silty partings, light yellowish grey to dark brownish grey, weathering to yellowish brown, medium to fine grained; sandstones are thin bedded, planar laminated with some very shallow large-scale crossbedding, increasing in steepness towards the top of the unit, silty partings are wavy bedded, interference ripples, possibly poorly preserved raindrop impressions, megascopic stylolites.	3.0	29.2
13	Siltstone, sandy, shaly, with interbedded sandstone lenses, yellowish brown to dark brown and light grey, weathering light brownish yellow to buff; flaser, wavy and lenticular bedded, sandstone lenses are		

UNIT		THICKNESS (METRES) unit	from base
	ripple crossbedded, 2 to 25 cm thick, interference and longitudinal ripples often with scoured and bioturbated surfaces, runzel marks, possibly poorly preserved mudcracks or desiccation cracks; moderate bioturbation, tracks and trails common, brachiopod shell fragments common.	3.4	26.2
12	Sandstone, with thin, silty and shaly partings, light grey, weathering light greenish brown, fine grained; massive, steep trough crossbedding, some interference ripples on megarippled surfaces, silty partings are wavy bedded, some megascopic stylolites; rare bioturbation but tracks and trails are common on some surfaces, brachiopod shell fragments increasingly common towards the top of the unit.	2.8	22.8
11	Sandstone, silty, dark brown, weathering yellowish brown, fine grained; shallow dipping to horizontal planar bedded, 1 to 3 cm thick, some interbedded, finely laminated sandy siltstones, scour-and-fill surfaces, megascopic stylolites; weak bioturbation.	1.0	19.0
10	Sandstone, light grey to light yellow, weathering light brownish yellow, fine grained; massive, very homogeneous, bedding absent or obscure, planar, almost horizontal at the top, with some faint, very shallow-dipping, large-scale cross-		

UNIT	THICKNESS (METRES) unit	from base
bedding.	0.8	18.0
9 Sandstone, with silty partings, white to light yellow, weathering light brownish yellow, medium to fine grained; horizontally planar laminated, 2 to 5 cm thick, with some very shallow crossbedding, a few shallow scour surfaces, rill marks, current crescents, swash marks and possibly wind blown foam prints; weak bioturbation, tracks and trails.	1.5	17.3
8 Sandstone, interbedded with a few thin siltstone lenses, light yellow to light yellowish brown, weathering to brownish yellow and dark brown, fine grained; horizontally planar laminated bedding with some very shallow, large-scale crossbedding, 2 to 5 cm thick, many erosional surfaces, interference ripple surfaces on silty lenses; weak bioturbation, tracks and trails.	0.9	15.7
7 Sandstone, light grey, weathering light brownish yellow, fine grained; trough crossbedded, beds 1 to 5 cm thick.	1.1	14.8
6 Sandstone, light grey, weathering light brownish yellow, fine grained; trough crossbedded, beds 1 to 5 cm thick; some silty erosional partings thickening in places to thin, dark greenish silty sandstone laminae, some megaripple		

UNIT		THICKNESS (METRES) unit	from base
	morphology and megaripple crossbedding; tracks and trails common in silty partings.	1.9	13.7
5	Sandstone, very light yellow to light grey, weathering light brownish yellow, medium to fine grained; bedding is massive but shows megaripple morphology and some indistinct large-scale crossbedding, scour or erosional surfaces are common, often filled with dark greenish, finely laminated, shaly siltstones, scour horizons appear to be developed over zones of small-scale current ripple crossbedding in the megarippled sandstones; tracks and trails are common in the silty sandstones.	7.6	11.8
4	Sandstone, interbedded with some greenish silty sandstone lenses and shales, light grey to light yellowish grey, weathering to light brownish yellow, fine grained; sandstones are ripple crossbedded, 2 to 15 cm thick, interference ripples, runzel marks, scour and shale chip horizons, rill marks.	1.2	4.2
3	Sandstone, light grey, weathering light yellowish grey, fine grained; megaripple morphology and crossbedding, scours are common.	0.8	3.0
2	Sandstone, light grey to light yellow, weathering light brownish yellow, medium		

UNIT		THICKNESS (METRES) unit	from base
	to fine grained; horizontally planar laminated, bedding averages 1 cm in thickness, a few scour and shale chip horizons, runzel marks, mudcracks, megascopic stylolites; some weak bioturbation, many tracks and trails.	1.0	2.2
1	Sandstone, massive, light grey, weathering light yellow, fine grained; some mega-ripple morphology, indistinct planar laminations at the bottom of the unit.	1.2	1.2



LOCALITY H
GULL ISLAND NORTH HEAD

LOCALITY H

GULL ISLAND NORTH HEAD

UNIT		THICKNESS (METRES) unit	from base
15	Sandstone, hematite oolitic, dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive bedded, exposure is weathered, obliterating structure; this unit is the remnant of the Dominion ore body which has been exhausted by strip mining in this area; phosphate nodules are common as well as medium-grained phosphatic lingulid brachiopod fragments.	2.2	15.4
14	Siltstone, shaly, sandy, interbedded with sandstone lenses and shales, buff, light yellowish brown, dark brown, weathering brownish yellow; thin bedded, wavy and lenticular, bedding and texture are highly variable, sandstone lenses are current rippled; moderately bioturbated.	2.5	13.2
13	Sandstone, hematite oolitic, dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive and large-scale steep to shallow dipping crossbedding; abundant medium-grained phosphatic brachiopod fragments.	0.9	10.7
12	Shale, silty, buff to yellowish brown, weathering to light brownish yellow; bedding obliterated by bioturbation, a few fine-grained sandstone lenses; highly bioturbated.	0.6	9.8

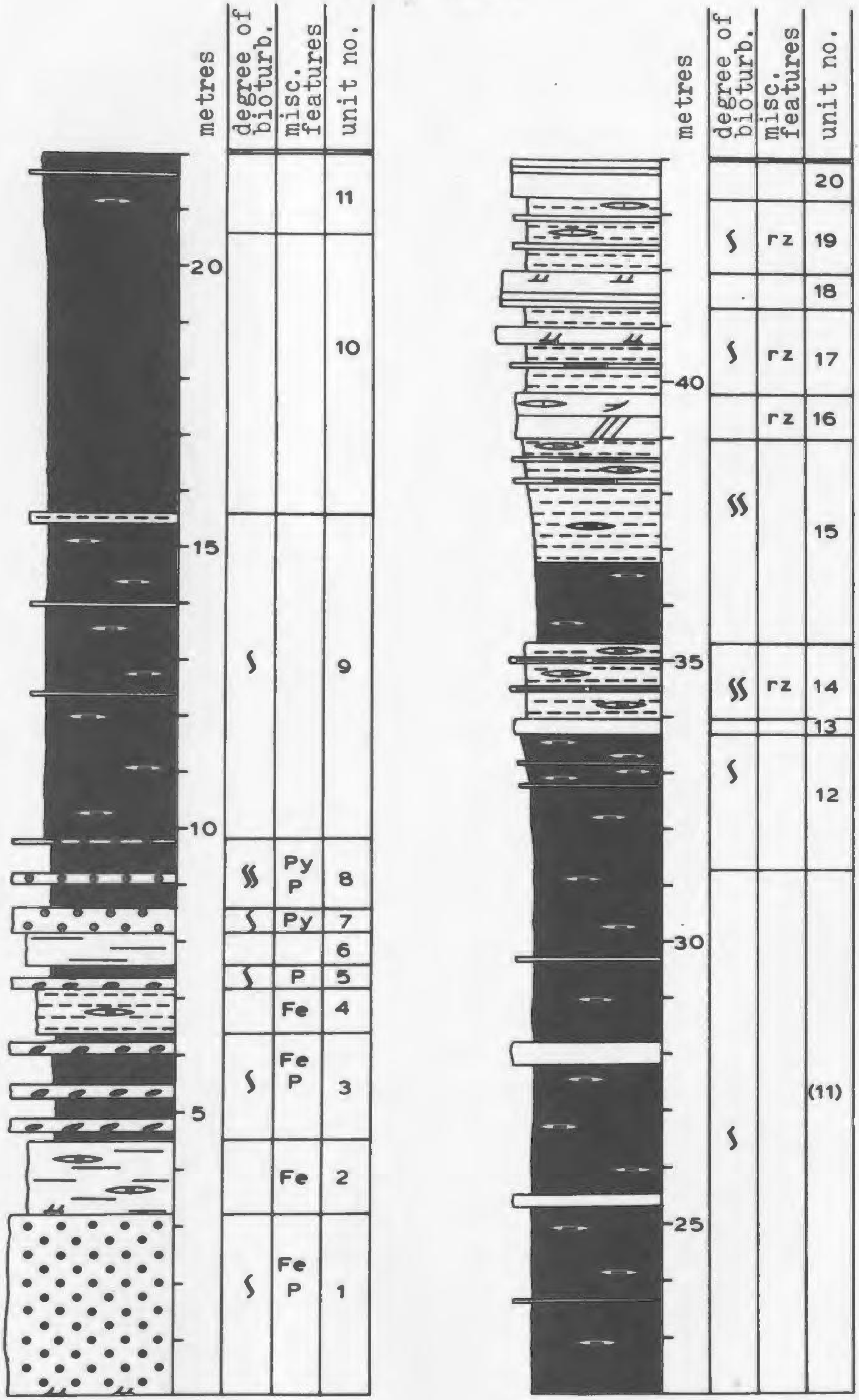
UNIT		THICKNESS (METRES) unit	from base
11	Siltstone, sandy, shaly, interbedded with sandstone lenses and oolitic hematite, light yellowish brown, dark brown and purplish red, weathering brownish yellow and brownish red; bedding and texture are highly variable, wavy and lenticular bedding, medium to thin bedded, quartz sandstone and oolitic hematite lenses are current ripple crossbedded, there is an upwards gradation in the composition of the lenses from oolitic hematite at the bottom to quartz sand at the top of the unit; moderately bioturbated.	1.8	9.2
10	Sandstone, hematite oolitic, dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive, with some large-scale crossbedding and probable herringbone crossbedding; phosphatic brachiopod fragments are common.	0.8	7.4
9	Shale, silty, buff to yellowish brown, weathering to light brownish yellow; very thin bedded, a few sandstone lenses; highly bioturbated.	0.5	6.6
8	Sandstone, hematite oolitic, dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive with some large-scale crossbedding and probable herringbone crossbedding; phosphatic brachiopod fragments are common.	0.6	6.1

UNIT		THICKNESS (METRES) unit	from base
7	Sandstone, silty, lenticular, interbedded with siltstones, light grey and light to dark yellowish brown, weathering dark brown, fine grained; lenticular and wavy bedding, thin bedded; moderate bioturbation.	0.7	5.5
6	Shale, silty, interbedded with sandstone and sandstone lenses, light grey, buff and light brown, weathering to light yellowish brown, sandstones are fine grained; thin bedded, sandstones are current ripple crossbedded, some shallow sand-filled channels; highly bioturbated.	0.7	4.8
5	Siltstone, sandy, interbedded with lenticular sandstones, light to dark yellowish brown, weathering to light brown, sandstones are fine grained; lenticular and wavy bedding, thin bedded, some shallow sand-filled channels; highly bioturbated.	0.3	4.1
4	Sandstone, silty, interbedded with siltstones and shales, light grey, light yellowish brown and dark brown, weathering to brownish yellow, fine grained; thin to medium bedded, lenticular and wavy bedding, thicker sandstones are large-scale crossbedded, a few hematite oolite lenses; bioturbation is moderate.	1.4	3.8

3

UNIT		THICKNESS (METRES) unit	from base
3	Sandstone, hematite oolitic, dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive bedded, with some large-scale cross-bedding and herringbone crossbedding, some shaly interbeds.	0.6	2.4
2	Sandstone, silty, hematite oolitic, interbedded with shales and quartz sand, dark purplish red, yellowish brown, weathering reddish brown and light yellowish brown, fine grained, sandstones are medium bedded to 10 cm thick and large-scale crossbedded, several scour and shale chip horizons; weak bioturbation.	1.0	1.8
1	Shale, silty, interbedded with sandstone lenses, dark grey, yellowish brown, weathering light to dark brown, sandstones are fine grained; thin to medium bedded, wavy and lenticular bedding, sandstones are ripple crossbedded, runzel marks are common, shallow sand-filled channels; moderate bioturbation.	0.8	0.8

LOCALITY I
POWERS STEPS



LOCALITY I

POWERS STEPS

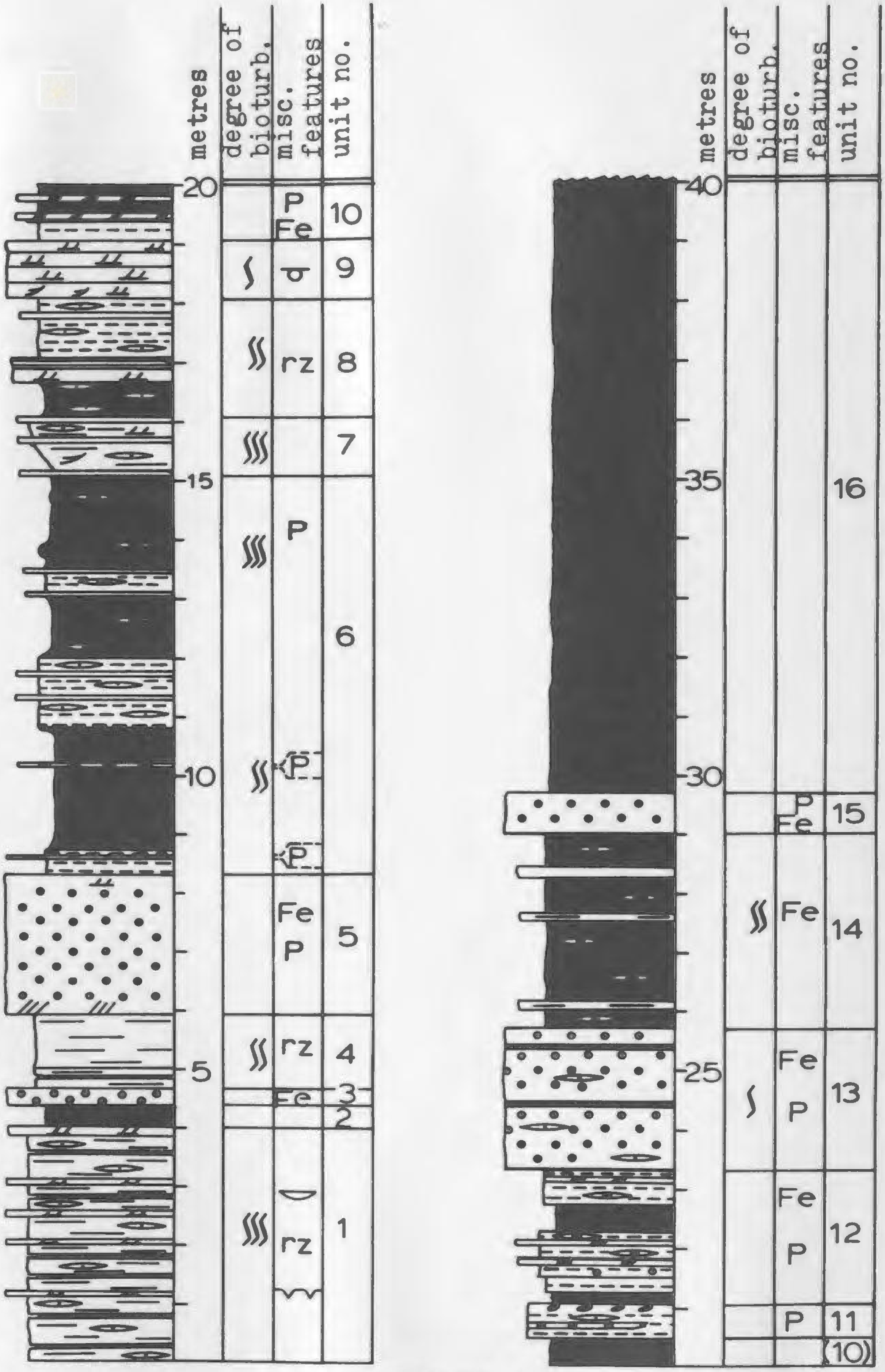
UNIT		THICKNESS (METRES) unit	from base
20	Sandstone, silty, light grey, weathering light to medium grey, fine grained; horizontal planar bedded or massive, becoming thin bedded towards the top, generally structureless.	0.7	43.8
19	Siltstone, shaly, interbedded with fissile silty shales and fine-grained sandstones, light to dark grey, weathering light grey or brownish; sandstones are up to 10 cm thick, and horizontal planar or ripple bedded, siltstones are wavy bedded, runzel marks, interference ripples; weak bioturbation.	1.3	43.1
18	Sandstone, fine grained, massive, white to light grey, weathering light grey; horizontal planar bedded with interference-rippled surface.	0.6	41.8
17	Siltstone, shaly, interbedded with fissile silty shales and fine-grained sandstones, light to dark grey, weathering light grey and reddish brown; sandstones are up to 10 cm thick, planar or ripple bedded, siltstones are wavy bedded, runzel marks, interference ripples; little bioturbation, many tracks and trails.	1.5	41.2
16	Siltstone, massive, interbedded with fine-grained sandstone lenses, light to medium		

UNIT		THICKNESS (METRES) unit	from base
	grey, weathering light grey or reddish brown; sandstone lenses are up to 30 cm thick and display large-scale crossbedding, some carbonate-cemented sandstones weather reddish brown, flaser and wavy bedding, interference ripples, runzel marks.	0.8	39.7
15	Shale, silty, interbedded with some siltstones, light grey, weathering light grey or brownish; massive to medium bedded, siltstones are ripple crossbedded and become abundant towards the top of the unit; bioturbation is generally weak but strong in some beds, many tracks and trails.	3.7	38.9
14	Shale, silty, fissile, interbedded with siltstones, light grey, weathering light grey to light brown; siltstone beds are 1 to 5 cm thick, runzel marks; poor to moderate bioturbation.	1.3	35.2
13	Siltstone, limy, interbedded with carbonate-cemented, fine-grained sandstones, light grey, weathering dark reddish brown; massive bedded up to 40 cm thick, a few longitudinal ripples, septarian nodules and cone-in-cone structure is very common; (trilobite, orthocone cephalopods).	0.3	33.9
12	Shale, silty, fissile, interbedded with siltstones towards the top of the unit,		

UNIT		THICKNESS (METRES) unit	from base
	light to medium grey, weathering light grey to dark brown; siltstones are very thin bedded, increasing upwards to 3 or 5 cm thick, planar or ripple bedded; bioturbation weak, increasing upwards, graptolites, <u>Didymograptus</u> <u>nitidus</u>.	2.4	33.6
11	Shale, dark, fissile, interbedded with some siltstones, light grey, weathering light to dark grey or brownish; siltstones are planar or ripple bedded, generally less than 5 cm thick, a siltstone bed at 24.3 m is approximately 3 m thick, bedding is at an angle of repose of 12° to the primary horizontal; bioturbation is weak.	10.7	31.2
10	Shale, dark, fissile, dark grey, weathering light to dark grey or brownish; very rare siltstone beds.	5.0	20.5
9	Shale, dark, fissile, silty, interbedded with some siltstones and fine-grained sandstones, light to dark grey, weathering light grey or brownish; sandstone and siltstone beds vary from 1 to 5 cm thick, planar or ripple bedded, abundant limy septarian nodules surrounded by cone-in-cone structures along some horizons; bioturbation is nil to weak, graptolites, <u>Didymograptus</u> <u>nitidus</u>.	5.8	15.5
8	Shale, dark, fissile, intercalated with		

UNIT	THICKNESS (METRES) unit	from base
oolitic pyrite beds, light to dark grey, weathering dark brown and light greenish yellow; oolitic pyrite beds are 3 to 7 cm thick and ripple bedded, they also contain pyritized graptolite fragments, phosphatic shell fragments and pyrite-coated shale pebbles; weak to moderate bioturbation, tracks and trails, graptolites, <u>Didymograptus</u> <u>nitidus</u>.	1.2	9.7
7 Ironstone, oolitic pyrite, light grey and light yellow, weathering light greenish yellow; oolitic pyrite also contains pyritized graptolite fragments, phosphatic shell fragments and pyrite-coated shale pebbles in a siliceous matrix, graded bedding with a rippled surface; tracks and trails common, graptolites, <u>Didymograptus</u> <u>nitidus</u>.	0.4	8.5
6 Siltstone, light grey, weathering dark brown; massive, structureless.	0.6	8.1
5 Shale, massive, black, weathering dark brown; interbedded in places with phosphatic shelly and shale pebble conglomerate beds.	0.4	7.5
4 Shale, silty, containing a few hematite streaks, light grey and reddish brown, weathering dark brown; massive, structureless.	0.8	7.1
3 Shale, black, massive, interbedded with		

UNIT		THICKNESS (METRES) unit	from base
	iron-rich red shales and pebble beds, black, dark grey and reddish brown, weathering dark grey or dark reddish brown; pebble beds contain mostly phosphatic shell fragments and shale chips with some oolitic hematite and coarse sand, many erosion and scour surfaces; weak bioturbation.	1.8	6.3
2	Siltstone, hard, black, with some streaks of hematite ore, weathering light reddish brown; massive, but with occasional small-scale ripples.	1.3	4.5
1	Ironstone, hematite oolitic, fine grained, bright purplish red, weathering reddish brown or bright rusty orange; massive bedded with some small-scale current ripples and raindrop impressions at the base, weathering obliterates most structure; contains phosphatic nodules and shell fragments, *Lingula hawkei*, boring algae, some weak bioturbation.	3.2	3.2



LOCALITY J
UPPER GREBES NEST POINT
& GRAVEL HEAD

LOCALITY J

UPPER GREBES NEST POINT AND GRAVEL HEAD

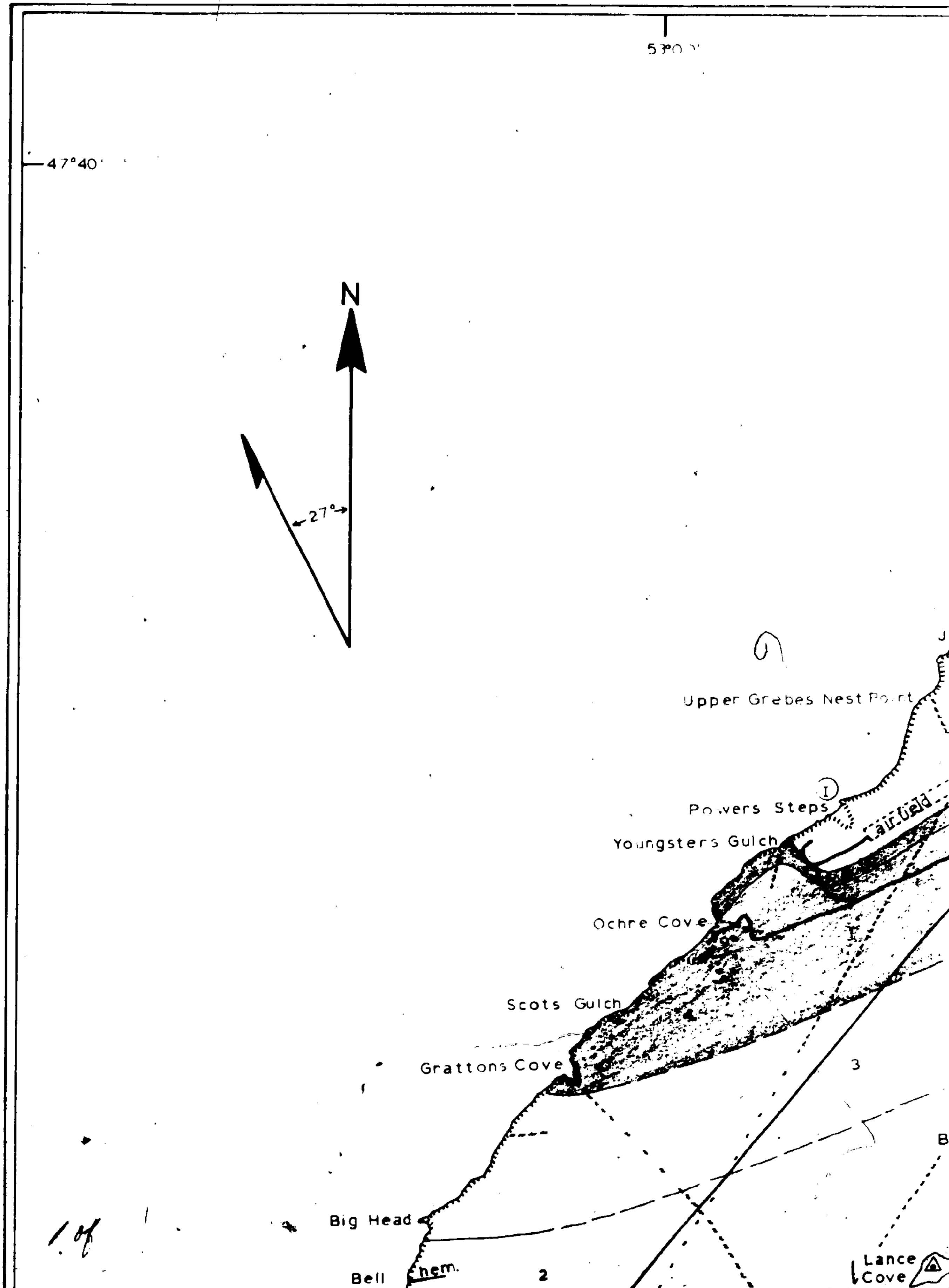
UNIT		THICKNESS (METRES) unit	from base
16	Shale, dark, pyritic, dark grey to black, weathering light grey and brownish yellow; fissile; bioturbation is rare.	10.3	40.0
15	Sandstone, hematite and chamosite oolitic, dark red to dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive; contains some medium-grained phosphatic brachiopod fragments.	0.7	29.7
14	Shale, dark, with silty partings and hematite streaks, interbedded with some sandstones; light to dark grey or reddish, weathering dark brown to black, sandstones are fine grained; shales are massive, sandstones are rippled and crossbedded, 0.5 to 3 cm thick; weak to moderate bioturbation.	3.3	29.0
13	Sandstone, hematite and chamosite oolitic, with many shale and sandstone lenses and phosphate nodules, dark red to dark purplish red, weathering bright reddish brown and rusty orange, fine grained; massive with some small-scale ripple crossbedding; some weak bioturbation evident including telopodite scratches.	2.4	25.7
12	Shale, dark, massive, interbedded with fissile shales and fissile silty shales,		

UNIT		THICKNESS (METRES) unit	from base
	some thin beds of greenish fine-grained sandstone with phosphate nodules and shell fragments, often streaked with hematite, light to dark grey and reddish, weathering light grey to black and brownish; bedding varies from thin and fissile to massive, up to 40 cm thick; bioturbation is rare.	2.2	23.3
11	Shale, silty, massive, streaked with hematite and chamosite oolites, and with some beds of fine-grained sandstone containing phosphate nodules and brachiopod shell fragments, light to dark grey and reddish, weathering black and purplish brown.	0.6	21.1
10	Shale, massive dark, streaked with hematite, intercalated with phosphatic pebbles, dark grey to black, weathering black to dark brown; pebbles are of various shapes but rounded, up to 2 cm in length and consist of phosphate nodules, shale, and shell fragments with some hematite streaks and pyrite spherules.	1.4	20.5
9	Sandstone, with some thin shale partings, white to light greenish grey, weathering reddish brown, fine to medium grained; current and interference rippled with some flaser and wavy bedding, beds are 3 to 15 cm thick, ball-and-pillow structure at base; poor to moderate		

UNIT		THICKNESS (METRES) unit	from base
	bioturbation.	1.0	19.1
8	Shale, dark, silty, interbedded with many sandstone lenses and dark, fissile shales, white to light greenish or dark grey, weathering light to dark brownish grey, sandstones are fine grained; lenticular and wavy bedded, sandstones are current and interference ripple crossbedded or horizontal planar laminated, beds vary from 0.5 to 3 cm in thickness, runzel marks; bioturbation varies from poor to moderate in shales and silty shales to extreme through the sandstones.	2.0	18.1
7	Sandstone, interbedded with siltstones and sandy siltstones becoming sandier upwards, white to light yellow, weathering brownish yellow, fine grained; current rippled, flaser, wavy and lenticular bedding, sandstone beds are up to 15 cm thick; extreme bioturbation including mud-filled <u>Skolithos</u>.	1.0	16.1
6	Shale, dark, fissile, interbedded with silty shales, siltstone lenses, silty sandstone and phosphatic pebble beds, white and light to dark grey, weathering brownish yellow amd medium to dark grey, sandstones are fine grained; sandstone and siltstone beds and lenses vary from 0.5 to 5 cm in thickness, and are horizontal planar laminated or ripple		

UNIT		THICKNESS (METRES) unit	from base
	crossbedded, wavy and lenticular bedding, pebble beds consist of phosphatic nodules and shale fragments, and shale chips; moderate to high bioturbation.	6.7	15.1
5	Sandstone, hematite and chamosite oolitic, dark purplish red and dark green, weathering bright reddish brown and rusty orange, fine grained; chamosite occurs in a 5 to 15 cm thick bed at the top of the unit, highly weathered but displays faint large-scale parallel crossbedding and some small-scale ripple crossbedding.	2.4	8.4
4	Siltstone, shaly, interbedded with some fissile shale, dark grey, weathering light grey; massive but in places displaying some faint ripple crossbedding, runzel marks; moderate bioturbation.	1.3	6.0
3	Sandstone, hematite oolitic with many shaly lenses, dark purplish red, weathering bright reddish brown, fine grained.	0.3	4.7
2	Shale, silty, dark greenish grey, weathering very dark brown, massive bedded; rare bioturbation.	0.4	4.4
1	Siltstone, sandy, interbedded with sandstones, silty shales and dark, fissile shales, light to dark grey, weathering reddish brown and light grey; sandstones are fine-grained lenses, 3 to 25 cm thick, silts and shales occur in beds 0.1 to 2 cm		

UNIT	THICKNESS (METRES) unit	from base
thick, with bedsets up to 10 cm thick, wavy and lenticular bedding, runzel marks, mudcracks and large scour-and-fill structures up to 2 m in width; moderately or occasionally highly bioturbated.	4.0	4.0


47°40'
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2
Lance Cove
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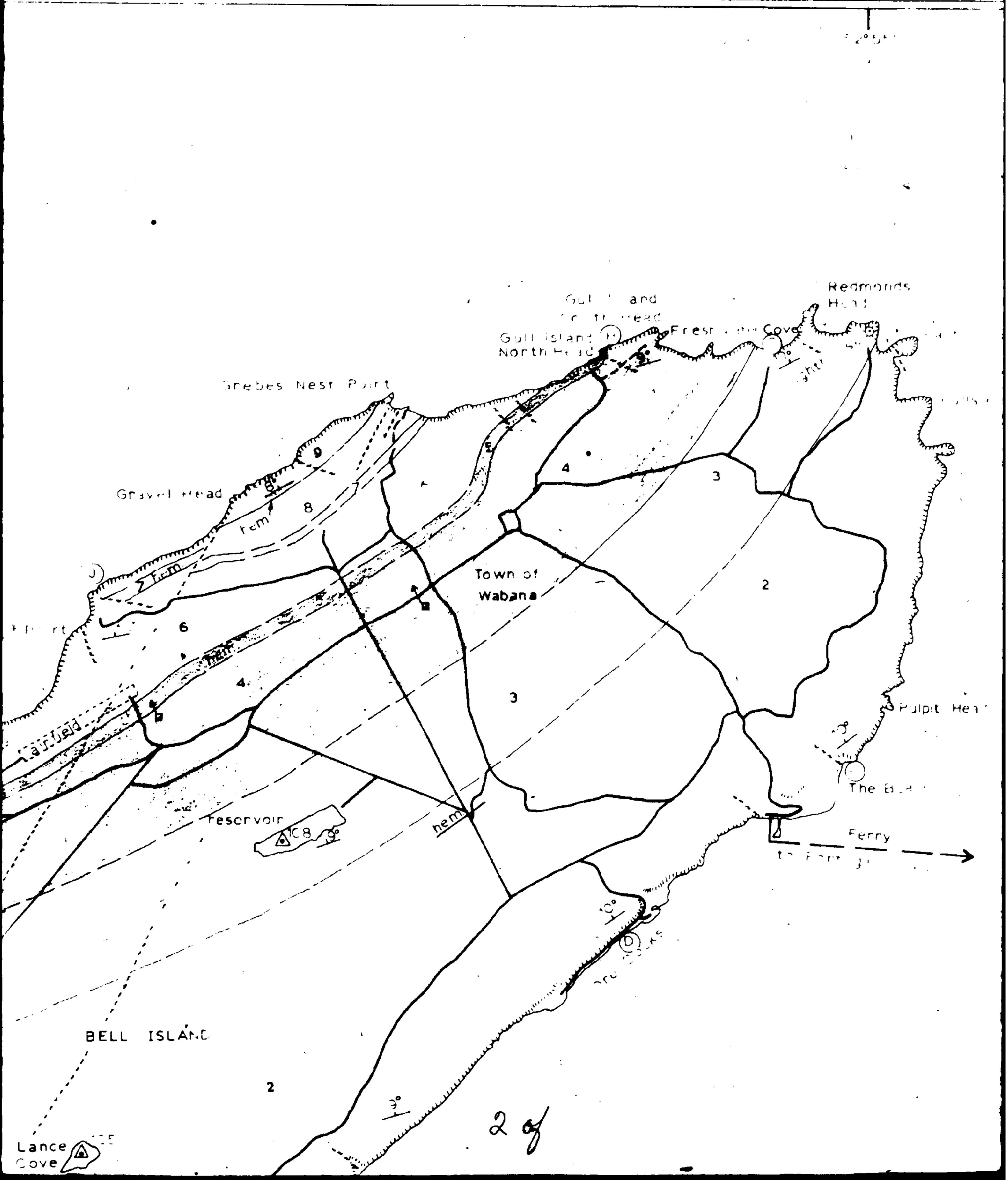
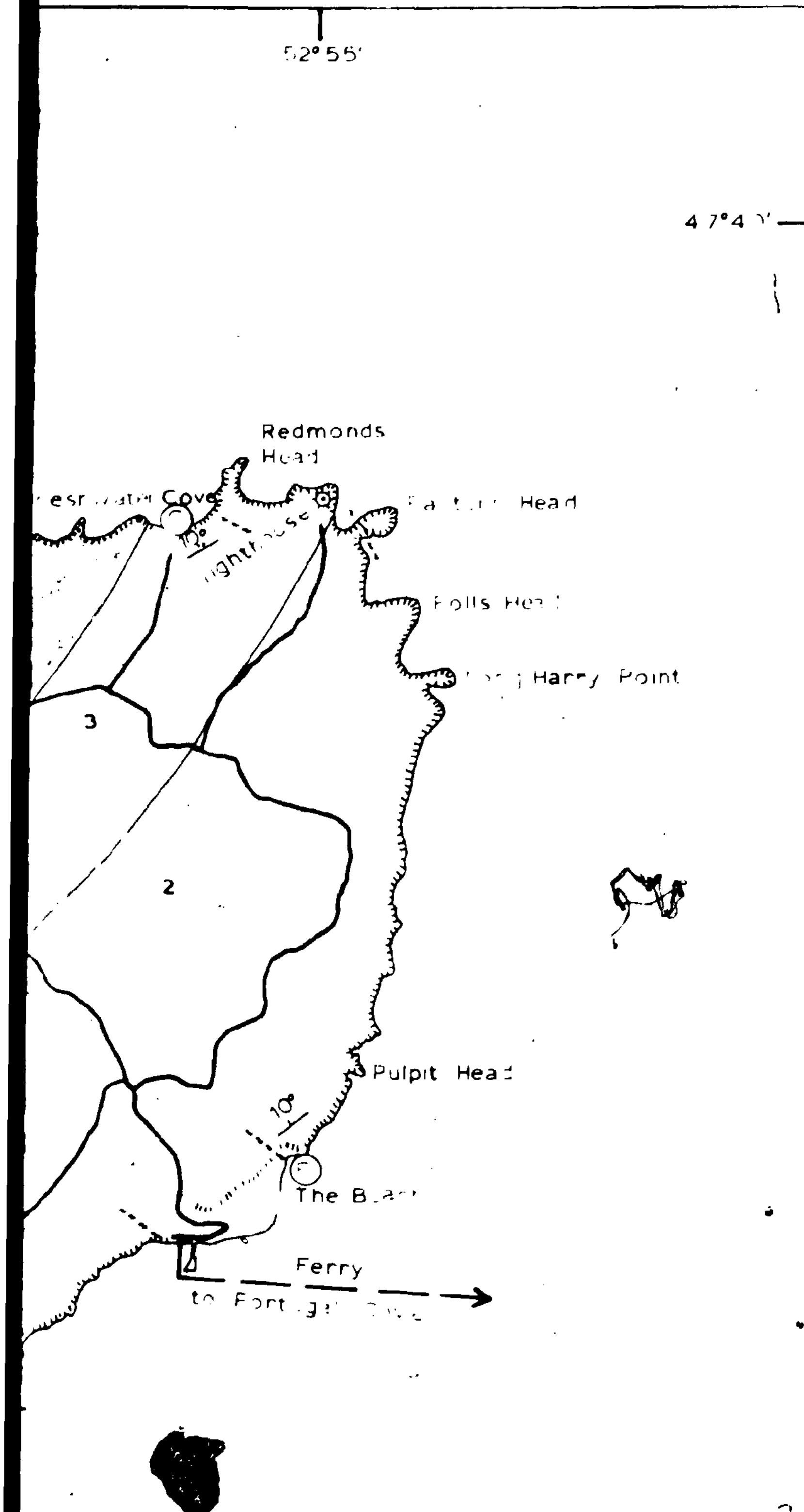


Redmonds
Gull Island North Head
Grebes Nest Point
Gravel Head
Town of Wabana
Fairfield
reservoir
Pulpit Head
Ferry
BELL ISLAND
Lance Cove
2 of



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BELL ISLAND,
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AND
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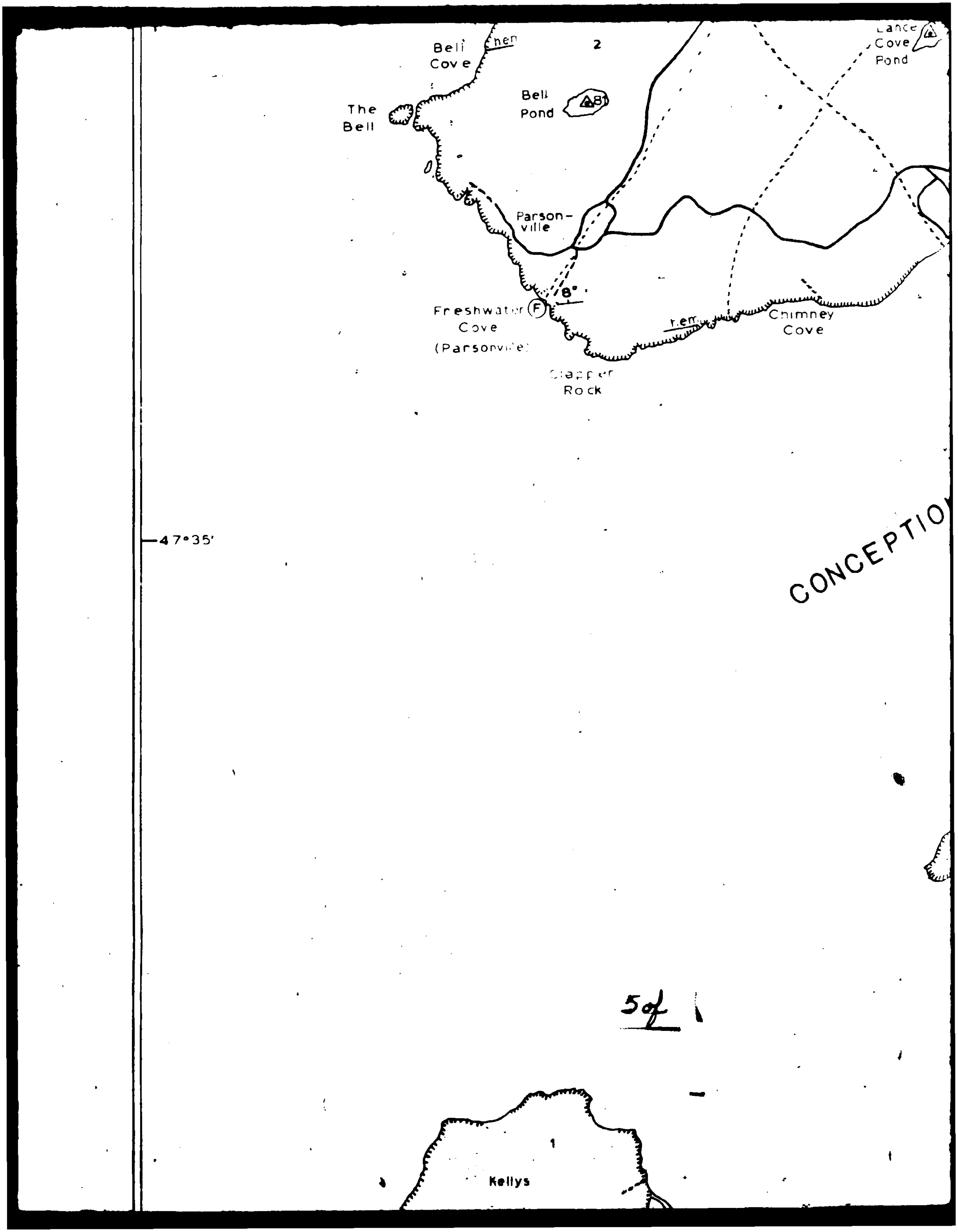
CONCEPTION BAY, NEWFOUNDLAND

4 of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Freshwater Cove (Parsonville)
Chimney Cove
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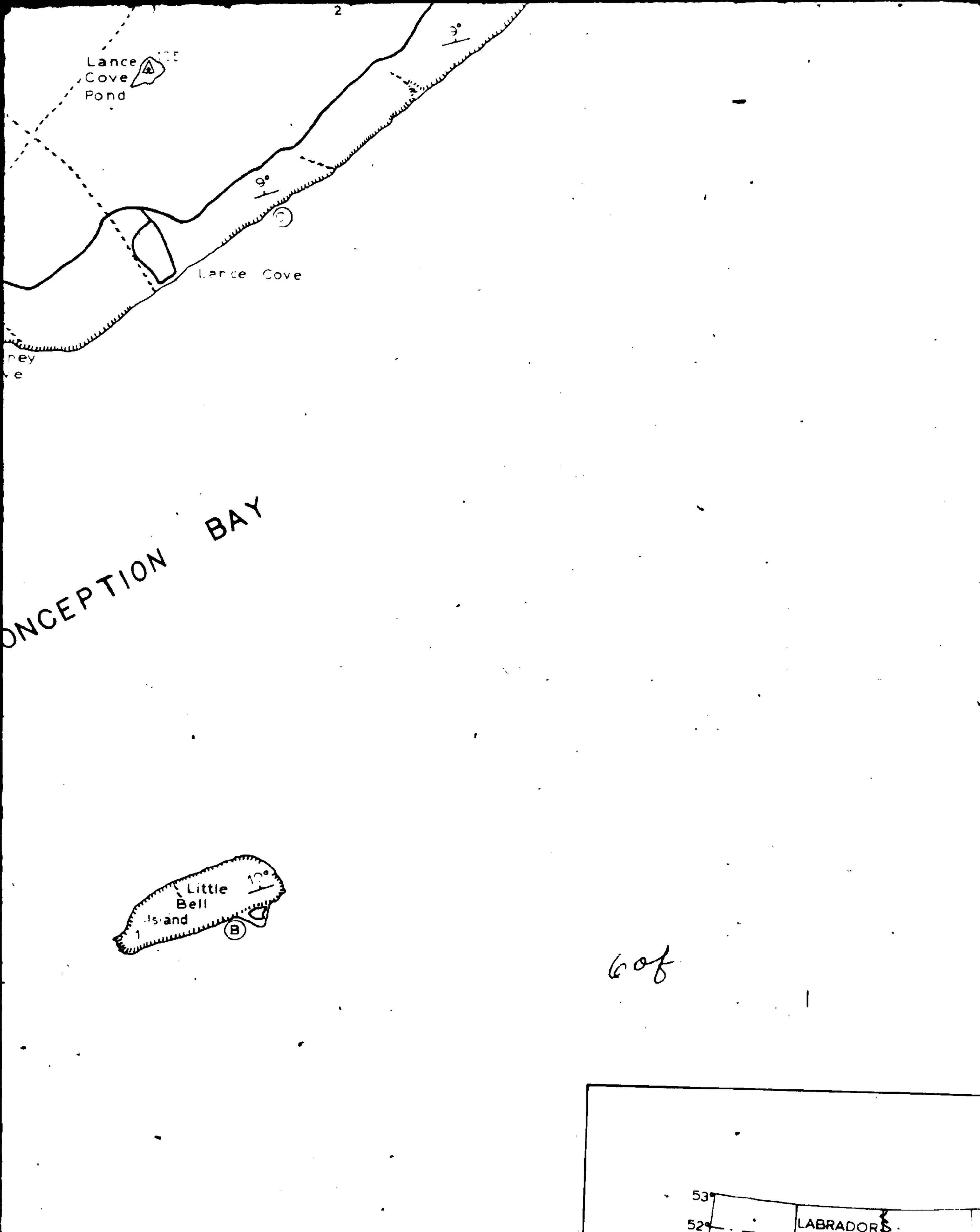
Kellys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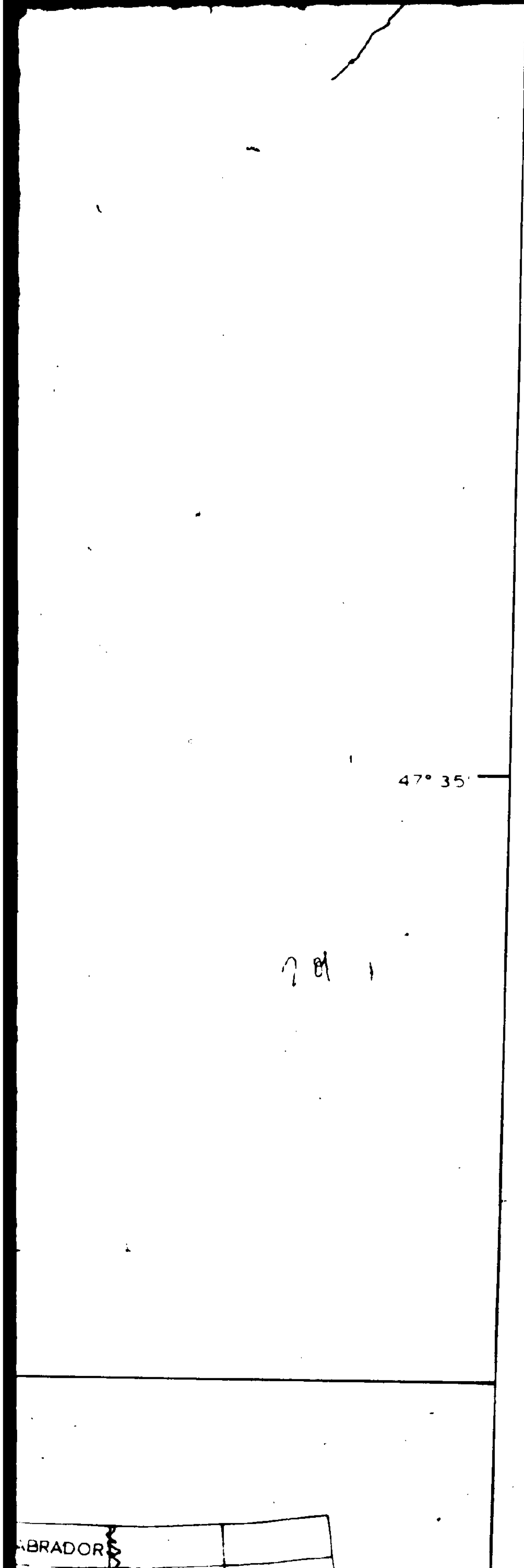
LABRADOR



LEGEND

WABANA GROUP

9 GRAVEL HEAD FORMATION shale.

8 GREBES NEST POINT FORMATION shale, siltston

7 SCOTIA FORMATION oolitic ironstone.

6 POWERS STEPS FORMATION shale, siltstone, sar

BELL ISLAND GROUP

DOMINION FORMATION oolitic ironstone

OCHRE COVE FORMATION shale, siltstone, sandst

3 REDMOND FORMATION massive sandstone

2 BEACH FORMATION shale, sandstone, siltstone, a

1 KELLYS ISLAND FORMATION shale, siltstone and

Road, trail

Coastal cliffs (outcrops)

Geological contact (located, assumed)

Fault (located, assumed)

Strike and dip of bedding

Locality reference for detailed measured sections

Oolitic hematite mineralization

Lighthouse

Mine head and bearing of slope (abandoned)

Elevation (metres)

LEGEND

WABANA GROUP

9	GRAVEL HEAD FORMATION shale
8	REBES NEST POINT FORMATION shale, siltstone, sandstone and oolitic ironstone
7	SCOTIA FORMATION oolitic ironstone
6	POWERS STEPS FORMATION shale, siltstone, sandstone and oolitic ironstone

BELL ISLAND GROUP

	DOMINION FORMATION oolitic ironstone
	OCHRE COVE FORMATION shale, siltstone, sandstone, and oolitic ironstone
3	REDMOND FORMATION massive sandstone
2	BEACH FORMATION shale, sandstone, siltstone, and oolitic ironstone
1	KELLYS ISLAND FORMATION shale, siltstone and massive sandstone

Road, trail	
Coastal cliffs (outcrops)	
Geological contact (located, assumed)	
Fault (located, assumed)	
Strike and dip of bedding	9°
Locality reference for detailed measured sections	(A)
Oolitic hematite mineralization	hem.
Lighthouse	
Mine head and bearing of slope (abandoned)	
Elevation (metres)	125

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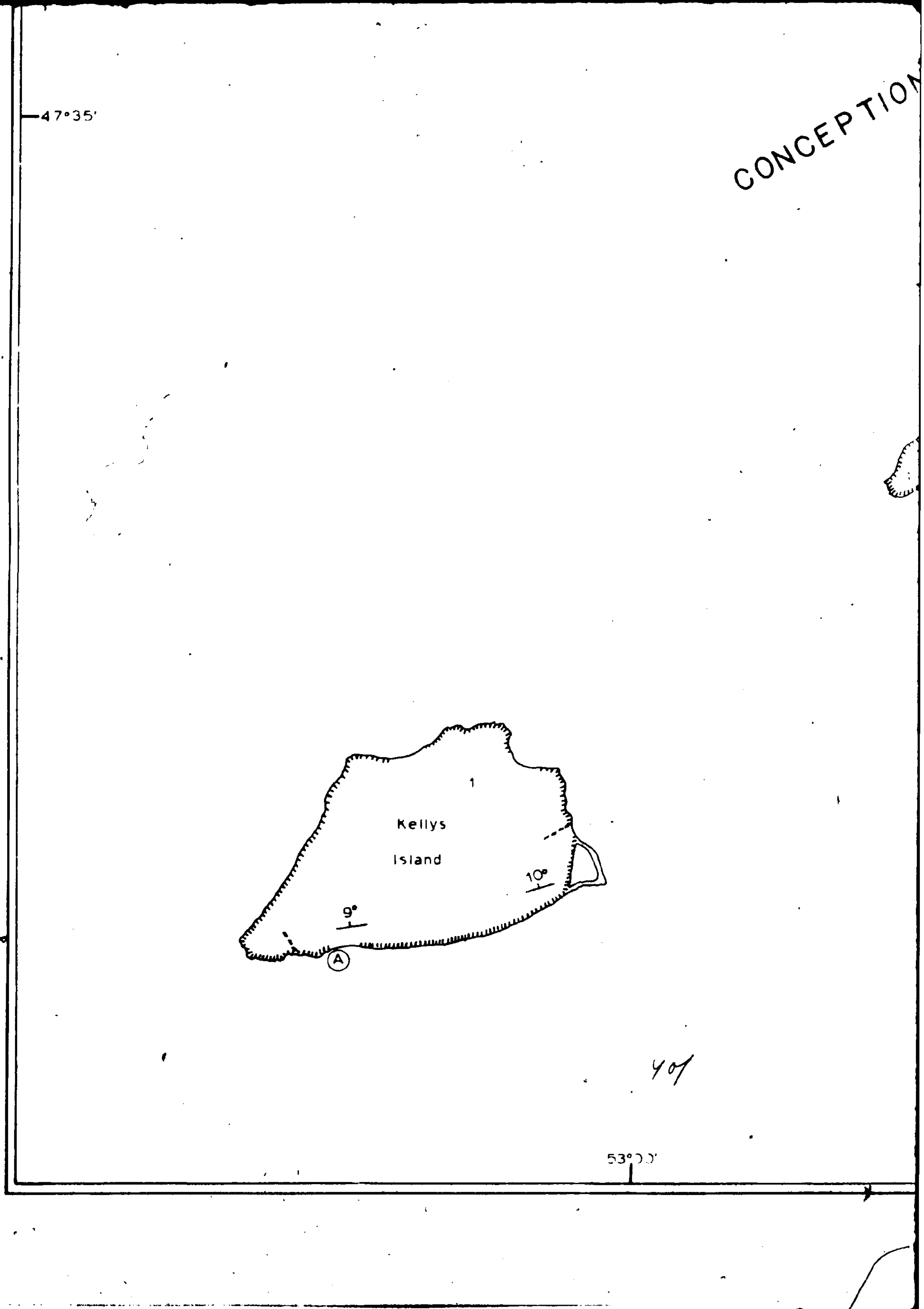
Geology by M.J. RANGER



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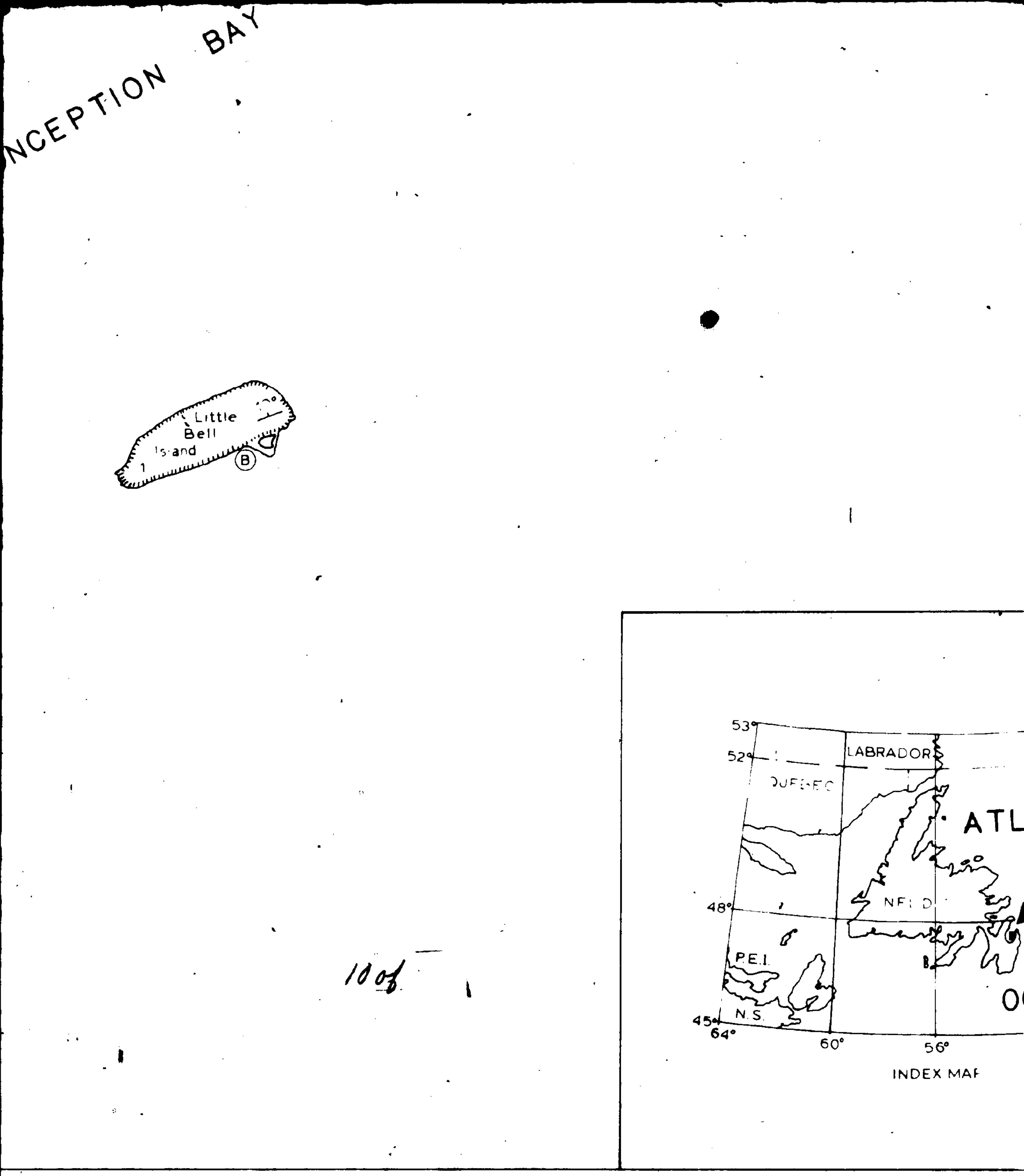
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INDEX MA

10 of

47° 35'

4 OCHRE COVE FORMATION shale, siltstone, sandstone,

3 REDMOND FORMATION massive sandstone

2 BEACH FORMATION shale, sandstone, siltstone, and oo

1 KELLYS ISLAND FORMATION shale siltstone and massiv

Road, trail

Coastal cliffs (outcrops)

Geological contact (located, assumed)

Fault (located, assumed)

Strike and dip of bedding

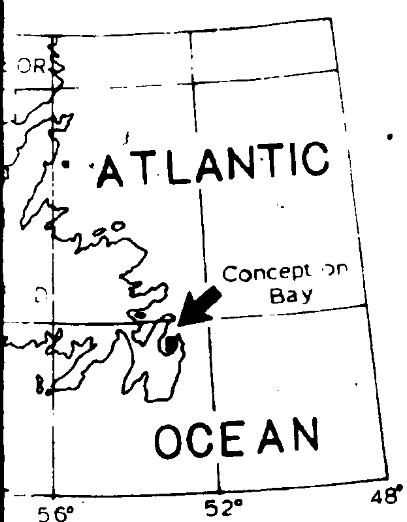
Locality reference for detailed measured sections

Oolitic hematite mineralization

Lighthouse

Mine head and bearing of slope (abandoned)

Elevation (metres)



INDEX MAP

11 of

Ge

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miles

1 0 1

4 OCHRE COVE FORMATION shale, siltstone, sandstone, and oolitic ironstone.

3 REDMOND FORMATION massive sandstone

2 BEACH FORMATION shale, sandstone, siltstone, and oolitic ironstone.

1 KELLYS ISLAND FORMATION shale, siltstone and massive sandstone.

Road, trail

Coastal cliffs (outcrops)

Geological contact (located, assumed)

Fault (located, assumed)

Strike and dip of bedding 9°

Locality reference for detailed measured sections (A)

Oolitic hematite mineralization hem.

Lighthouse

Mine head and bearing of slope (abandoned)

Elevation (metres) 125

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12J/12

SCALE 1:25,000

metres

1000 500 0 1000 2000

miles

0 1 2