HUDSON BAY PLATFORM:

SILURIAN SEQUENCE STRATIGRAPHY AND PALEOENVIRONMENTS

by

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ABSTRACT

Trends in relative sea-level change, shown by curves drawn from drill core and outcrop sections in Llandoverian carbonates of the Hudson Bay Platform, were used to correlate individual parasequences among widely separated localities. Two sequences, bounded by regional disconformities, include: (1) the Severn River Formation, and (2) the Ekwan River, Attawapiskat, and Kenogami River Formations. Initial onlap of marine facies at the base of the Severn River Formation progressed from north to south, occurring first in the Hudson Bay Basin, then in the Moose River Basin; final retreat of the seas at the end of Attawapiskat time was in the opposite direction. The most extensive inundations occurred during Ekwan River and Attawapiskat depositional times. Large-scale trends in the curves delineate four major Early Silurian sea-level highstands also recognized in other basins.

Reefs in outcrops along the Attawapiskat River represent one interval of reef growth, had a syndepositional relief of 8-10 meters, and were terminated by a relative sea-level fall. Their present distribution is controlled by variously uplifted fault blocks.

The most important diagenetic processes were early marine cementation and shallow burial diagenesis, and in the southwestern Moose River Basin early secondary dolomitization.

RÉSUMÉ

Les tendances des fluctuations du niveau relatif de la mer, enregistrées dans les carbonates d'âge Llandovérien de la plate-forme de la baie d'Hudson, sont illustrées par des courbes dessinées à partir de carottes de forage et de sections d'affleurement. Ces courbes sont utilisées pour corréler des "paraséquences" individuelles établies à des sites séparés par de très grandes distances. Deux séquences, délimitées par des discordances régionales, sont reconnues: 1) la formation de Severn River et 2) les formations de Ekwan River, Attawapiskat et Kenogami River. La transgression marine initiale a progressée du nord vers le sud au début de la période de Severn River, se produisant en premier lieu dans le bassin de la baie d'Hudson et ensuite dans celui de Moose River. Le retrait final des mers, à la fin de la période d'Attawapiskat, s'est fait dans la direction opposée. Les innodations les plus étendues se sont produites durant les périodes de déposition des formations d'Ekwan River et d'Attawapiskat. Les courbes généralisées soulignent quatre périodes de niveaux de mer élevés durant le Silurien inférieur, qui sont reconnues aussi dans d'autres bassins.

Les affleurements de récifs le long de la rivière Attawapiskat représentent un seul intervalle de croissance qui s'est terminé par un abaissement du niveau relatif de la mer. Leur relief durant la période de déposition était de 8-10 mètres. Leur distribution actuelle est contrôlée par des blocs faillés rehaussés à des niveaux variables.

Les processus de diagénèse les plus importants sont les suivants: cimentation marine précoce, diagénèse d'enfouissement peu profond et, dans le bassin de Moose River, dolomitisation secondaire précoce.

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Yang made and photographed some of the thin sections. George Panagiotidus also made some of the thin sections. I thank Richard Yates for developing some of the photographs, making presentation slides of some of the figures, and for offering guidance and support in drafting of figures. I am grateful to Eric Prosh for making and developing some of the thin section photographs, and for developing some outcrop photographs. Gratitude is extended to Nicole Gonthier Suchy for translating the thesis abstract into French, and to Eva Drivet for revisions of the same.

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PREFACE

STATEMENT OF ORIGINALITY

Sequence stratigraphy has been successfully used in other areas to establish detailed correlation among siliciclastic and mixed siliciclastic-carbonate deposits (e.g., Van Wagoner *et al.*, 1990), but has rarely been used to analyse stratigraphic problems in platform rocks composed only of carbonates. This study is one of the first to test the applicability of these allostratigraphic methods to a carbonate province in which outcrop and well sections are widely separated. However, it takes the concepts of sequence stratigraphy a step further by focussing on correlation of individual parasequences, and demonstrates that the methods of sequence stratigraphy can be used to decipher correlation problems and to establish the Early Silurian geological history of the Hudson Bay region in greater detail than by standard lithostratigraphic or biostratigraphic methods.

This study is the first to examine in detail the Early Silurian stratigraphy of the Hudson Bay Platform, and to interpret the depositional history of the reefs of the Attawapiskat Formation within a scheme of relative sea-level change. It is the first study to recognize that the distribution of the Attawapiskat reefs along the Attawapiskat River in northern Ontario is controlled by their positions on separate fault-blocks, and it is the first to make basinwide comparisons of the diagenetic history of the Attawapiskat reefs.

The four main chapters of the thesis each represent an original contribution to scientific knowledge in terms of study design, analyses, and conclusions. Collectively, the chapters contribute new knowledge on the applicability of sequence stratigraphy to the study of cratonic basins in general, and specifically to an understanding of the Silurian depositional history of the Hudson Bay Platform.

HISTORICAL BACKGROUND OF PREVIOUSLY RELEVANT WORK

An extensive historical background can be found in the the General Introduction.

THESIS FORMAT

The thesis consists of a series of four chapters on relevant topics, plus a general introduction chapter and a general conclusions chapter. Chapter 2 has been written in a format suitable for publication in a refereed scientific journal and will be submitted for publication later. Therefore Chapter 2 necessarily repeats some information that is included in the general introduction chapter and other parts of the thesis. Chapter 2 contains its own Introduction, Previous Work, Regional Geology, Methods, Results, Discussion, and Conclusions. References cited in Chapter 2 have been included in the list of references cited at the end of the thesis. The Previous Work section of Chapter 2 is brief, but an extensive Previous Work section is included in the general introduction chapter. The

Regional Geology section of Chapter 2 is comprehensive and is therefore not repeated in the general introduction chapter.

The connections between the chapters of the thesis are implicit in the text.

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CHAPTER 1

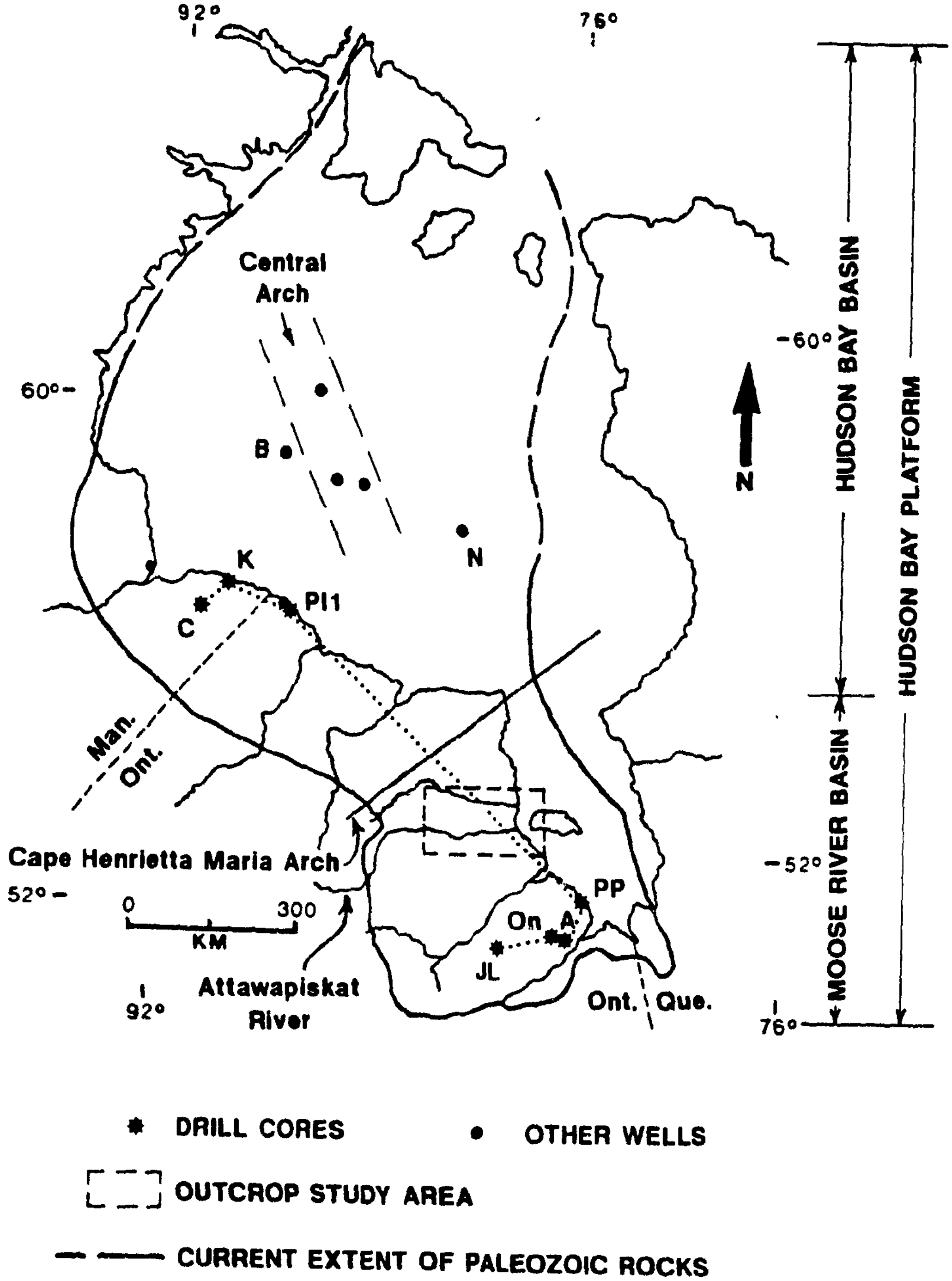
GENERAL INTRODUCTION

Sedimentary strata of the Hudson Bay and Moose River Basins are predominantly carbonate rocks, but include minor beds of evaporites, shales, and sandstones. This sequence encompasses rocks of Ordovician, Silurian, Devonian, Middle Jurassic, and Early to Late Cretaceous ages (Sanford and Grant, 1990). The present study will focus on the 300-400 m (980-1300 ft.) of Silurian rocks on the Hudson Bay Platform, particularly the Lower Silurian (Llandoverian) strata (Figures 1, 2, and 3). The general geology and stratigraphic relationships are discussed in more detail in Chapter 2.

OBJECTIVES

This project examines the Llandoverian strata of the Hudson Bay Platform in drill cores and well cuttings from the area (Table 1 and Figure 1), and from outcrop exposures along the Attawapiskat River in northern Ontario (Figure 4).

Figure 1. Locality map for drill cores and outcrop exposures on the Hudson Bay Platform examined for this study. Letters labelling the wells (identified more fully in Table 1) are as follows: B = Beluga, N = Narwhal, C = Comeault, K = Kaskattama, PI1 = Pen Island No. 1, PP = Puskwuche Point, A = Ardagh, On = Onakwahegan, and JL = Jaab Lake. Dashed outline is the outcrop study area and is the subject of the map of Figure 4. Dotted line is the line of section of Figure 8.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76°
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Attawapiskat
River
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A
JL
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Que.
-60°
-52°
76°
N
HUDSON BAY BASIN
MOOSE RIVER BASIN
HUDSON BAY PLATFORM
DRILL CORES
OTHER WELLS
OUTCROP STUDY AREA
CURRENT EXTENT OF PALEOZOIC ROCKS

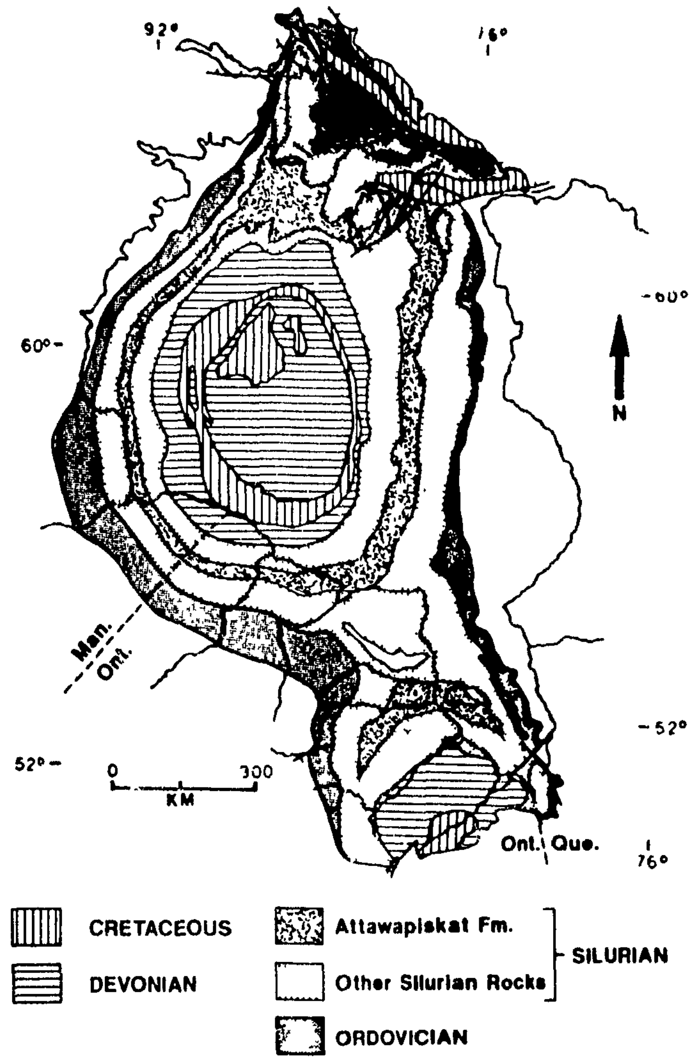


Figure 2. General geology of Paleozoic strata of the Hudson Bay Platform. A limited occurrence of Jurassic rocks along the western edge of Cretaceous rocks in the southern Moose River Basin is too small to be shown here. Areas in white are underlain by Precambrian rocks. (Geology after Sanford and Grant, 1990).

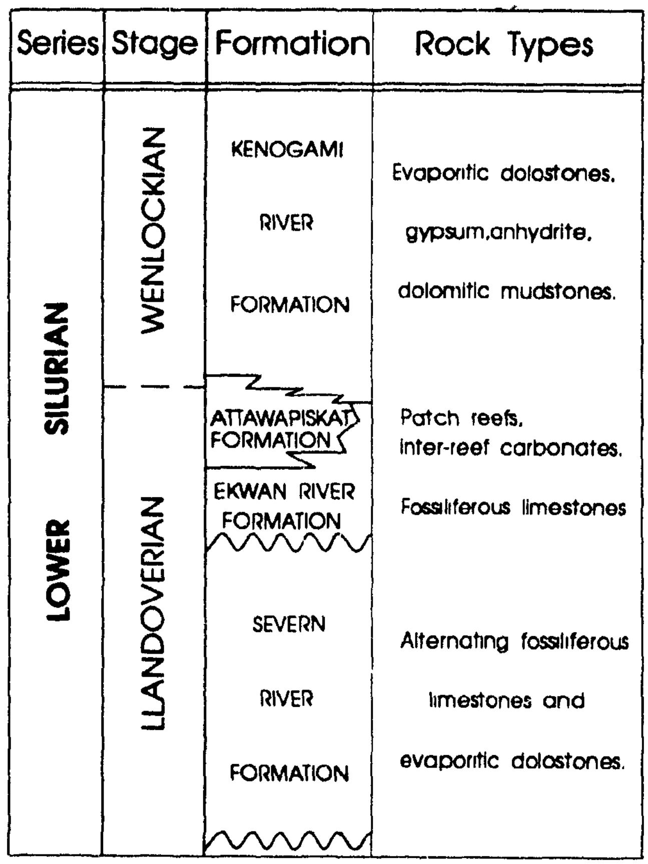


Figure 3. Silurian formations of the Hudson Bay Platform.

TABLE 1

WELL NAME	WELL LOCATION (Lat. & Long.)	1)INTERVAL CORED 2)INTERVAL STUDIED	STORAGE LOCATION
DRILL CORES			
Houston *et al.* Comeault Prov. No. 1.	56-40 N., 90-50 W.	1) 200-2125 ft. 2) 200-1450 ft.	Manitoba Dept. of Energy and Mines, Winnipeg, Manitoba.
Sogepet-Aquitaine Kaskattama No. 1.	57-04-18.487 N., 90-10-29.408 W.	1) 540-2913 ft. 2) 540-2210 ft.	Manitoba Dept. of Energy and Mines, Winnipeg, Manitoba.
Aquitaine Sogepet *et al.* Pen Island No. 1.	56-45-07 N., 88-45-15 W.	1) 713-3393 ft. 2) 713-2775 ft.	Atlantic Geosci. Ctr., Dartmouth, Nova Scotia. and Ont. Min. of Nat'l Res., Petroleum Res. Lab., London, Ontario.
Ont. Dept. of Mines Puskwuche Point No. 1.	51-46-30 N., 80-39-30 W.	1) 22-1535 ft. 2) 22-1535 ft.	Atlantic Geosci. Ctr., Dartmouth, Nova Scotia. and Ont. Min. of Nat'l Res., Petroleum Res. Lab., London, Ontario.
Consumers *et al.* Ardagh No. 1.	51-17-14 N., 81-14-05 W.	1) 194-709 ft. 2) 520-621 ft.	Ont. Min. of Nat'l Res., Petroleum Res. Lab., London, Ontario.
Consumers Onakwahegan No. 2.	51-19-18 N., 81-26-38 W.	1) 141-694 ft. 2) 574-686 ft.	Ont. Min. of Nat'l Res., Petroleum Res. Lab., London, Ontario.
Ont. Dept. of Mines Jaab Lake D.D.H. No.1.	51-10-45 N., 82-56-30 W.	1) 147-1810 ft. 2) 1549-1810 ft.	Ont. Min. of Nat'l Res., Petroleum Res. Lab., London, Ontario.
WELL CUTTINGS ONLY			
Trillium Soquip Onexco *et al.* Beluga 0-23.	59-12-54.4 N., 88-33-26.6 W.	1) none 2) 1500-1895 m	Atlantic Geosci. Ctr., Dartmouth, Nova Scotia.
Aquitaine *et al.* Narwhal South No. 1.	58-07-56.28 N., 84-08-16.78 W.	1) none 2) 1700-3300 ft.	Atlantic Geosci. Ctr., Dartmouth, Nova Scotia.

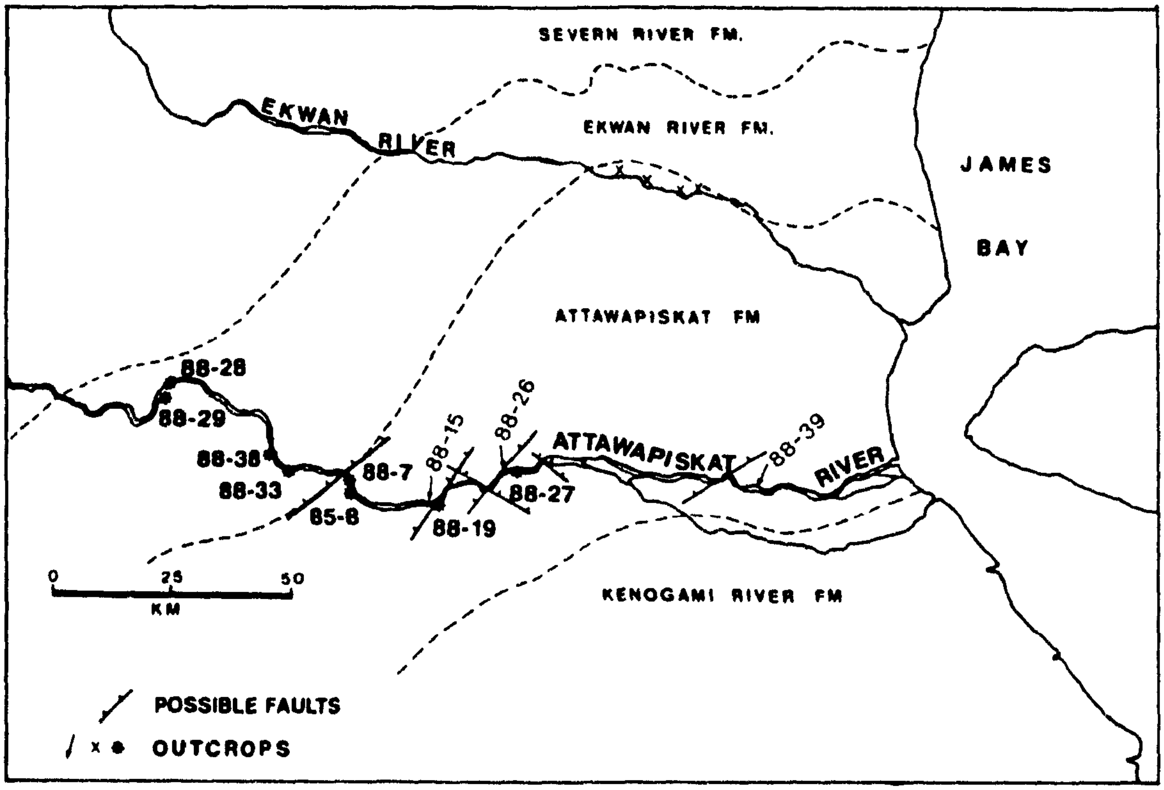


Figure 4. Locality map of measured outcrop sections along the Attawapiskat River in northern Ontario. Of the 21 outcrop sections measured, only those used for correlations in Figure 13 (starred) or those mentioned elsewhere in the text (arrowed) are shown here. Localities of outcrops of the Attawapiskat Formation along the Ekwan River are taken from Sanford *et al.* (1968). Faults are inferred from field data and aerial photo interpretation.

Special emphasis has been placed upon the Attawapiskat Formation (Figures 2 and 3) because it contains well-developed stromatoporoid/coral/algal/cement reefs. The strata were examined on a regional and local scale, with the following questions in mind:

(1) Can relative sea-level changes recorded in the rocks be recognized, from large scale to the smallest scale observable in outcrops and drill cores?

(2) Can changes observed in cores and changes observed in outcrops be correlated from one locality to another within the basin and from one basin to another across North America?

(3) What do the observed relationships tell us about the depositional history of the basin?

  (a) What paleogeographic changes occurred during the depositional history?

  (b) What were the facies distributions?

(4) How do the Attawapiskat reefs fit into the regional scheme of relative sea-level change and the larger geologic framework (i.e., in relation to basin configuration, different facies, and paleotopography)?

  (a) What are the parameters of reef development (syndepositional relief; depositional environment; water depth, energy, and circulation; relative sea-level changes)?

  (b) What are the reef builders (organic, inorganic, cement)?

(5) What controls the regional localization of the reefs?

(a) Are several generations of reefs stacked stratigraphically upsection, or eastward, along the Attawapiskat River, or is their current distribution the result of some other control?

(b) Why do they not occur in the southern part of the Moose River Basin?

(c) What other factors may be involved in their localization (substrate control, paleotopography, paleoceanography, faulting)?

(6) What does diagenetic overprinting tell us about the depositional and burial history of the strata?

(a) What diagenetic features were early marine and which came later?

(b) How do the diagenetic features relate to the scheme of relative sea-level change, basin configuration, paleotopography, and paleoceanography?

METHODS

Seven drill cores from the area were logged in detail over the course of two summers (1988 and 1989), and well cuttings from two wells in the center of Hudson Bay were also examined. In August, 1987, a four-day reconnaissance of exposures along the Attawapiskat River was undertaken, and in the summer of 1988, seven weeks were spent measuring and describing 21 outcrop sections along the river, collecting samples, and making field sketches and taking photographs of the stratigraphic relationships. Access to the outcrop exposures was by helicopter and motorized rubber raft, and topographic control was achieved with the use of aerial photographs and topographic maps. More details about the methods of the drill core and outcrop studies are given in Chapter 2.

In both the drill core and outcrop studies, all stratigraphic changes, however minor, were recorded, and each stratigraphic unit was interpreted in terms of its depositional environment and relative water depth. These interpretations were used to compile relative sea-level curves for each locality, and the curves were then used to make correlations among the localities and to determine regional stratigraphic relationships (explained in more detail in Chapter 2).

Field data coupled with aerial photo interpretations were used to examine the distribution of the reefs in outcrop, to map the positions of faults, and to explain the relationship between reef distribution and fault-block positions (explained more fully in Chapter 4).

Sixty three rock samples for thin sections were taken from the drill cores listed in Table 1. A total of 285 outcrop samples from the Attawapiskat Formation and 92 outcrop samples from the Ekwan/Severn River formations were taken: at least one, and usually several, samples were taken from each stratigraphic unit at each locality. Additionally, seven one-inch (2.5 cm) cores, 5 to 17 feet (1.5 to 5.1 m) long, were taken from the Attawapiskat Formation at different outcrop localities using a portable, hand-held core drill. Thin sections from 51 of the outcrop samples, 35 of the portable core drill samples, and all 63 samples from the drill cores listed in Table 1 were examined in detail with a polarizing petrographic microscope. The hand samples from which the thin sections were made, along with other non-sectioned samples, were examined under a binocular microscope. Fifteen thin sections were stained with alizarin red, and twenty six thin sections were examined for cathodoluminescence.

PREVIOUS WORK

Work on the Silurian rocks of the Hudson Bay region was very limited before 1967. Bell (1887) was the first to describe rocks in the Hudson Bay Lowlands and the first to recognize the reefal origin of the units exposed along the Attawapiskat River; he called these rocks the Attawapiskat Coral Reef. Low (1887) reported flat-lying limestones of Silurian age along the Severn and Fawn Rivers, and Savage and Van Tuyl (1919) proposed the formal names Port Nelson Limestone, Severn River and Ekwan River Limestones, and Attawapiskat Coral Reef for the rock units in the Hudson Bay Lowlands. Dyer (1930) introduced the name Kenogami River Formation for the red and gray mudstones exposed along the Kenogami and Albany Rivers in northern Ontario. He also described rocks along the Pagwachuan River, naming them the Pagwa River Formation; he considered them to be equivalent to the Ekwan River Limestone and the Attawapiskat Coral Reef of Savage and Van Tuyl (1919).

Martison (1953) conducted a geological reconnaissance of the James Bay Lowland for the Ontario Government in search of petroleum. He studied the same section as Dyer along the Pagwachuan River, but he also described the Silurian section along the Albany, Kenogami, Little Current, Kapiskan, and Atikameg Rivers. Hogg *et al.* (1953) described Silurian rocks from the Puskwuche Point drill core. Remick *et al.* (1963) studied Silurian strata in the Quebec portion of the Hudson Bay Lowlands. Nelson and Johnson (1966), after several summers of field work, outlined the stratigraphy of the Hudson Bay Platform and revised some of the work of Savage and Van Tuyl (1919).

The extensive reconnaissance study of the Hudson Bay Lowlands by the Geological Survey of Canada in 1967, called Operation Winisk, and reported in Sanford, *et al.* (1968), marked the beginning of a flurry of activity in the Hudson Bay region, including the drilling of several exploratory wells and subsequent reports thereof. The Kaskattama Province No. 1 well, drilled in 1967 and 1968, provided a key stratigraphic section for Paleozoic rocks of the region. Other wells soon followed. Reports on drilling history, geophysics, stratigraphy, and biostratigraphy resulting from these activities included those of Norris and Sanford (1968), Nelson and Johnson (1968), Johnson and Nelson (1969a and 1969b), Norford (1970), Sanford and Norris (1973 and 1975), and numerous company well reports and studies.

Flower (1968) studied the Silurian cephalopod fauna of the Hudson Bay Lowlands, and Norford (1971) reviewed the Silurian stratigraphy of northern Manitoba. The Paleozoic stratigraphy of Southampton, Coats and Mansel Islands in the northern part of the Hudson Bay Platform was studied by Sanford (1970) and Heywood and Sanford (1976). Sanford (1974) reviewed the Paleozoic geology of the Hudson Bay region. A more specific study on the trilobite fauna of the Attawapiskat Formation was conducted by Norford (1981). LeFevre *et al.* (1976) interpreted sedimentary environments and conodont biofacies in the Kaskattama Province No. 1 well and the Pen Island No. 1 well to make correlations between the wells and to draw generalized relative sea-level curves.

More recently, Cowell (1981) studied modern karst features along the Attawapiskat River, and Chow (1986) and Chow and Stearn (1988) studied the reefal facies on a limited stretch of the Attawapiskat River. Larsson (1984) and Larsson and Stearn (1986) examined the Silurian Hudson Bay platform rocks that extend into Quebec southeast of James Bay. The Ordovician and Silurian stratigraphy on Southampton and Coats Islands in northern Hudson Bay was studied by Dewing (1988). Norford (1988) discussed the Ordovician-Silurian boundary on the Hudson Platform. The Paleozoic rock sequence on the Hudson Platform was summarized by Norris (1986), and further refinements to the geological mapping, stratigraphy, and structure of the Hudson Platform were provided by Sanford (1987), Grant and Sanford (1988), and Sanford and Grant (1990). Recent papers by Jin and Copper (1986) and Jin and Caldwell (in press) have improved our understanding of brachiopod systemetics in the Hudson Bay Lowlands and consequently of the age of the strata there.

CHAPTER 2

SILURIAN SEQUENCE STRATIGRAPHY AND SEA-LEVEL HISTORY OF THE HUDSON BAY PLATFORM

INTRODUCTION

The Hudson Bay Platform is one of the least known areas of Paleozoic rocks in North America owing to its distance from centers of population and transportation routes. Much of the platform is covered by the waters of Hudson Bay, and outcrops on the land area are confined to widely separated river valleys in one of the largest swamps in the continent. The lack of any petroleum finds to date provides no economic incentive for detailed studies in the area. Consequently, previous biostratigraphic and lithostratigraphic studies have allowed only broad-scale correlation of strata within the platform and left many stratigraphic problems unsolved.

Sequence stratigraphy has been successfully used in other areas to establish detailed correlation among siliciclastic and mixed siliciclastic-carbonate deposits (e.g., Van Wagoner *et al.*, 1990), but has rarely been used to analyse stratigraphic problems in platform rocks composed only of carbonates. This study tests the applicability of these allostratigraphic methods to a carbonate province in which outcrop and well sections are widely separated. However, it takes the concepts of sequence stratigraphy a step further by focussing on correlation of individual parasequences, and demonstrates that the methods of sequence stratigraphy can be used to decipher correlation problems and to establish the Early Silurian geological history of the Hudson Bay region in greater detail than by standard lithostratigraphic and biostratigraphic methods.

Curves that show relative water depth, based on interpretations of environments of deposition, were drawn for stratigraphic sections in drill cores and outcrops at individual localities. Correlations based on these relative sea-level curves allowed individual parasequences to be distinguished within the sections and their lateral distribution and facies variations to be mapped.

The purposes of this chapter are 1) to elucidate the methods by which the individual parasequences were distinguished and correlated, and 2) to discuss the stratigraphic relationships and geological history of the Silurian rocks of the Hudson Bay Platform as interpreted from these methods.

Previous Work

The Silurian limestones of the Attawapiskat River were recognized as of reef origin by Robert Bell as early as 1887. The work of the many geologists who established the major stratigraphic units was summarized by Larsson and Stearn (1986). Paleontological studies of the trilobites (Norford, 1971, 1981), cephalopods (Flower, 1968), brachiopods (Jin and Copper, 1986; Jin and Caldwell, in press) and conodonts (LeFevre *et al.*, 1976) have established broad biostratigraphic correlations of the carbonate rocks on the Hudson Bay Platform within various stages of the Lower Silurian. LeFevre *et al.* (1976) correlated the Kaskattama Province No. 1 well and the Pen Island No. 1 well, interpreted the sedimentary environments and conodont biofacies, and drew generalized relative sea-level curves. More recently, Chow and Stearn (1988) studied the reefal facies on a limited stretch of the Attawapiskat River. Larsson and Stearn (1986) examined the Hudson Bay platform rocks that extend into Quebec. The Ordovician and Silurian stratigraphy on Southampton and Coats Islands in northern Hudson Bay was studied by Dewing (1988). Norford (1988) discussed the Ordovician-Silurian boundary on the Hudson Bay Platform. The Paleozoic rock sequence on the Hudson Bay Platform was recently summarized by Norris (1986), and further stratigraphic and structural data were provided by Sanford (1987), Grant and Sanford (1988), and Sanford and Grant (1990).

Regional Geology

The Hudson Bay Platform consists of two roughly dish-shaped basins (Figures 1 and 2), the Hudson Bay Basin in the north and the Moose River Basin in the south, separated by the Cape Henrietta Maria Arch. A north- and northwest-trending basement high in the subsurface (labelled 'Central Arch' in Figure 1) is located in the center of the Hudson Bay Basin (Grant and Sanford, 1988). The sedimentary strata are predominantly carbonate rocks but include minor beds of evaporites, shales, and sandstones. This succession encompasses rocks of Ordovician, Silurian, Devonian, Middle Jurassic, and Early to Late Cretaceous ages (Sanford and Grant, 1990). As interpreted from geophysical data, the Phanerozoic strata exceed 2,000 m (6500 ft.) in thickness in the center of the Hudson Bay Basin (LeFevre, *et al.*, 1976) and unconformably overlie Precambrian basement rocks.

The Silurian section (300 to 400 m; 980-1300 ft.) is divided into four formations: in ascending order, the Severn River, Ekwan River, Attawapiskat, and Kenogami River Formations (Figure 3). This study is concerned primarily with the three lower formations. The Severn River and Ekwan River Formations consist of well-bedded alternating fossiliferous limestones and barren dolostones. These shallow-marine and supratidal carbonate facies were sensitive to recording relative sea-level fluctuations.

Reefs and associated carbonates of the Attawapiskat Formation (Figure 2) completely encircle the Hudson Bay Basin, forming thick bank and barrier-reef deposits (Sanford, 1987; Sanford and Grant, 1990). Seismic sections indicate that patch reefs are also present in the central part of the basin where they are associated with blocks uplifted along faults in the central arch (Sanford, 1987). In the Moose River Basin, reefs occur only in the northern part, on the flanks of the Cape Henrietta Maria Arch. The Llandovery/Wenlock boundary is at the top of the Attawapiskat Formation (Jin and Caldwell, in press; Lefevre, *et al.*, 1976; Norford, 1981). Where the Attawapiskat reef facies is absent, evaporites of the Kenogami River Formation directly overlie the Ekwan River limestones.

The Kenogami River Formation contains only supratidal evaporitic facies and dolomitic mudstones, indicating that relative sea-level was very low at the time of its deposition. This Late Silurian regression was responsible for widespread evaporitic conditions over eastern North America.

STRATIGRAPHIC PROBLEMS

Correlation between data points separated by great distances is a major problem in stratigraphic studies in the Hudson Bay region. The distance between the wells in the southwestern Hudson Bay Basin and those in the southern Moose River Basin (Figure 1) is approximately 750 km (470 mi.). A lack of precision in biostratigraphic control adds to the problem. As a result, it is difficult to make detailed correlations, to determine the time equivalency of individual rock units, and to unravel the basin history as a whole.

On a more specific note, placement of formation boundaries in the wells by previous workers has not been consistent, particularly the Ekwan River and Severn River boundaries, because the rock types of the two formations are similar. A means of positively identifying the formation boundaries is needed.

Deciphering the stratigraphic relationships among outcrop exposures is another problem. In the bogs that cover nearly all the land area of the Hudson Bay Lowland, the best exposures are along the Attawapiskat River where the Ekwan River and Attawapiskat Formations are exposed (Figures 1 and 4). However, even there the regional attitude of the Attawapiskat Formation cannot be determined owing to the draping and depositional dip of the beds associated with the reefs. Additionally, the reefal outcrops are grouped in certain reaches of the river that are separated by reaches several kilometers long without any rock exposures. Standard lithostratigraphic and biostratigraphic methods have not allowed correlations to be made between these outcrop areas at a sufficiently detailed scale to establish whether the same, relatively thin, reef interval is repeatedly exposed along the river for 100 km (60 mi.), or whether a regional dip basinwards introduces several distinct intervals of reef growth downstream. The Attawapiskat River is flowing subparallel to, or at an oblique angle to, the regional strike on the southern flank of the Cape Henrietta Maria Arch (Figures 1 and 2), and so either scenario is possible.

Another question is whether the upper part of the Ekwan River Formation in the southern Moose River Basin (where the Attawapiskat reefal facies is absent) is time-equivalent to the Attawapiskat reefs in the northern part of the basin. If so, what is the relationship between exposures of the two formations along the Attawapiskat River? The contact between the two formations is not exposed in outcrop, but the reefs end abruptly in cliffs at locality 88-7 (Figure 4), and a few kilometers upstream river bank outcrops are of the Ekwan River Formation. Are exposures of the two formations along the river time-equivalent, and if not, what can explain the close juxtaposition of such stratigraphically separate rock units?

METHODS

In addition to the detailed study of outcrops, seven drill cores from the area, three from the Hudson Bay Basin and four from the Moose River Basin (Figure 1 and Table 1), were logged in detail for this study. These are the only drill cores of Silurian rocks available from the Hudson Bay Platform. Cuttings from two other wells in the center of Hudson Bay were also examined (Figure 1 and Table 1), but the data is much less precise than that obtained from drill cores. Twenty one outcrop sections along the Attawapiskat River, in the Hudson Bay Lowlands west of James Bay (Figure 4), were measured, sampled, and described in detail.

Copies of the core descriptions will be deposited at the separate facilities where each particular core is stored (Table 1), and the complete package of core descriptions for all the wells studied will be deposited at the Geological Survey of Canada Library, 3303 - 33rd Street N.W., Calgary, Alberta, T2L 2A7. The lithofacies are discussed in more detail in a subsequent chapter on petrography.

Construction of Relative Sea-Level Curves

For each locality, a curve was drawn to represent interpreted changes in water depth (i.e., changes in relative sea-level) that are recorded by the changing facies of the stratigraphic succession (Figure 5). The interpreted environments of deposition ranged from supratidal to deep subtidal (i.e., below normal wave base). The sedimentary features listed in Figure 5 are some of the main criteria that have been widely used for inferring environments of deposition of carbonate rocks (James, 1984; McIlreath and James, 1984; Kendall, 1984; Wilson, 1975; Shinn, 1983; and Enos, 1983).

Small-scale changes within each depositional environment were also interpreted in terms of relative sea-level changes (Figures 6 and 7). The effects of such small-scale changes were easiest to detect in facies that were deposited at or near the surface of the water, that is, in facies that alternated between shallow subtidal and supratidal. The effects were more difficult to detect in wholly subtidal (especially deep subtidal) (Figure 6) or wholly supratidal deposits (Figure 7). Although the supratidal environment was generally outside the reach of normal marine waters, changes in the Silurian supratidal facies in the Hudson Bay region were probably caused by base-level changes (i.e., relative sea-level changes). The changing base-level affected the groundwater table and the percolation of marine and/or meteoric waters into supratidal ponds and sabkha environments; as base-level lowered, evaporative conditions intensified.

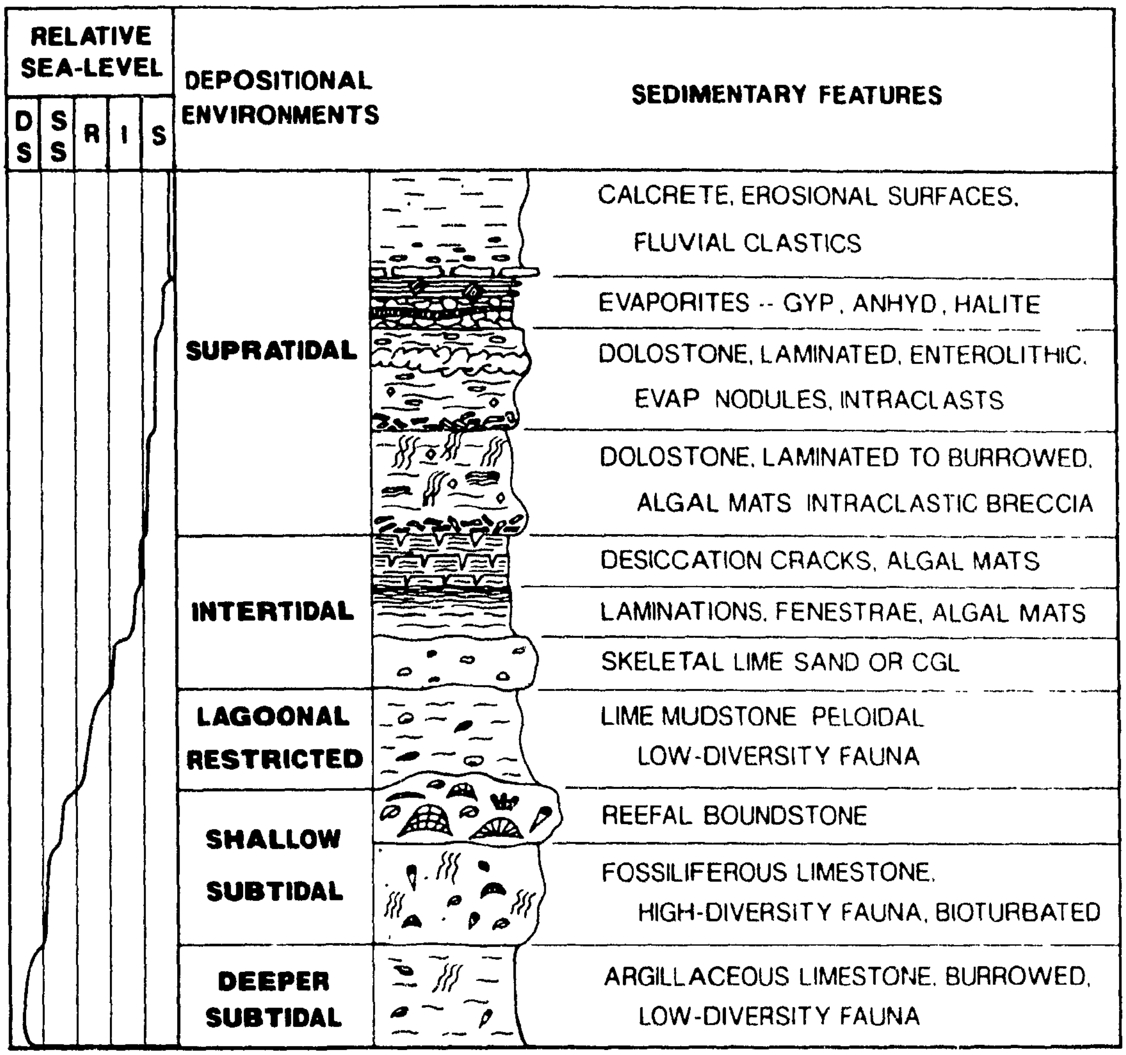
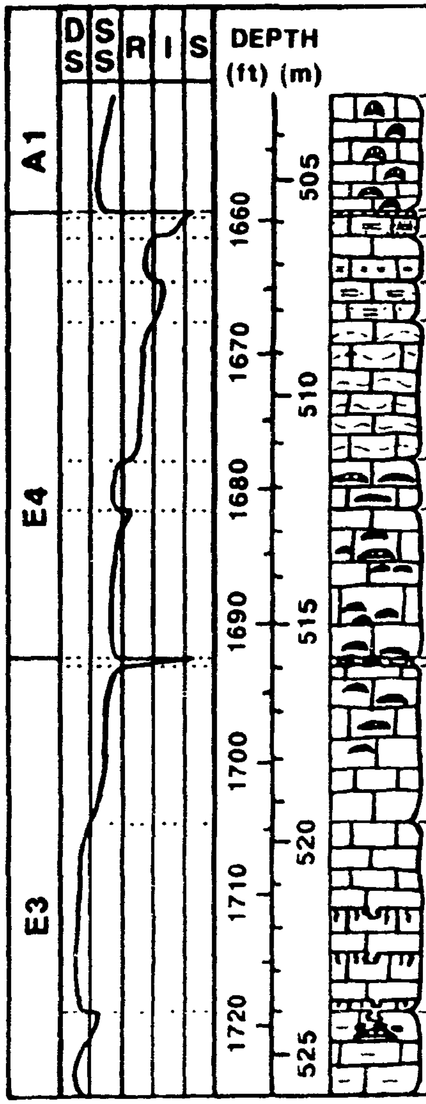


Figure 5. Hypothetical, idealized stratigraphic section to demonstrate how the relative sea-level curves were drawn. The curve is based on interpretations of facies, and shows increasing water depth to the left. Some of the many criteria used to interpret depositional environments are shown on the right. The five depositional environments in the column on the left are: S = supratidal, I = intertidal (or littoral), R = restricted marine, SS = shallow subtidal (above normal wavebase), and DS = deeper subtidal (below normal wavebase).

Figure 6. A portion of the stratigraphic section from the Pen Island No. 1 core and the corresponding relative sea-level curve, showing changes within predominantly marine facies. E3, E4, and A1 are labels for individual parasequences recognized in the upper Ekwan River and lowest Attawapiskat Formations. See Figure 5 for other symbols.

PEN ISLAND NO.1 CORE



DESCRIPTION

Reefal boundstone, abundant stromatoporoids, corals (favositids, rugose, *Halysites*, *Heliolites*), brachiopods, crinoids, and gastropods. Some peloidal calcilutite, minor coquina and calcarenite.

Siltstone (0.5-0.75 in; 1.3-1.9 cm), pale brown, with scattered sand-sized skeletal fragments. Homogeneous, sharp upper & lower contacts

Coarse to fine skeletal wackestone, light gray, with dark, irregular horizontal films. Sharp basal contact.

Lime mudstone (fine micrite mud), pale brown mottled with grayish brown, bioturbated, 0-10% sand-sized fossil fragments (crinoids, brachiopods, one stromatoporoid fragment, broken and rounded). A 1.5 in (3.8 cm) bituminous layer at 1663.8 ft

Bituminous wackestone to lime mudstone, dark grayish brown, finely cross-laminated, nodular, with dark brown to black organic films, sand-sized fossil fragments (crinoids, brachiopods, corals, broken & abraded)

Lime mudstone to wackestone, skeletal & peloidal(?), grayish brown mottled with gray, bioturbated, scattered brown organic films as fine cross-laminae, 5-25% sand-sized fossil fragments [common crinoids, very common ostracodes, spongiostromid algae, rare brachiopods and stromatoporoids (broken, rounded, & overturned, a few small stromatoporoids may be in place), small gastropods (<2mm)]

Lime mudstone to wackestone, similar to above interval, but with larger fossil fragments [up to 1.5 in (3.8 cm)] and several laminar stromatoporoids attached on hardground surfaces

Lime mudstone, burrow-mottled, skeletal & peloidal, grayish brown to light gray, 5-10% fossil fragments, primarily sand-sized [mostly crinoids (rarely up to 1 cm), some brachiopods and small laminar stromatoporoids (rarely up to 1 cm X 2 cm)]

Dolomitic lime mudstone (6 in., 15cm), nodular, small anhydrite nodules (1-7 mm) & minor stromatolites

Lime mudstone, burrow-mottled, 5% sand-sized skeletal fragments (crinoids, brachiopods, ostracodes, a few small laminar stromatoporoids)

Lime mudstone, mottled gray and grayish brown, somewhat nodular, rare sand- to granule-sized fossil fragments (1-2%, mostly crinoids), several burrowed firmgrounds lined with black pyritic mud

Fine lime mudstone, mottled gray and light gray, similar to above interval, but upper 1.5 ft (45cm) contains a laminar stromatoporoid, abundant echinoid fragments, ostracodes, minor *Vermiporella* fragments, and small gastropods (<1 mm). Burrowed firmground marks its base

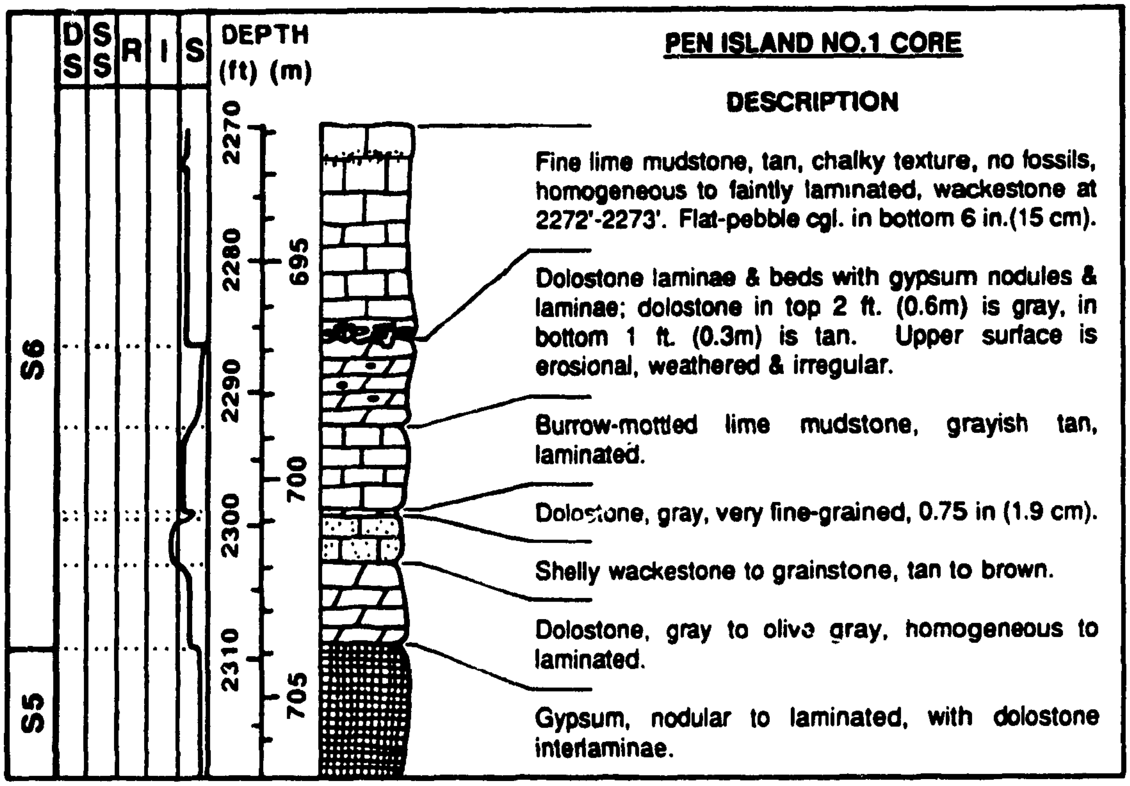


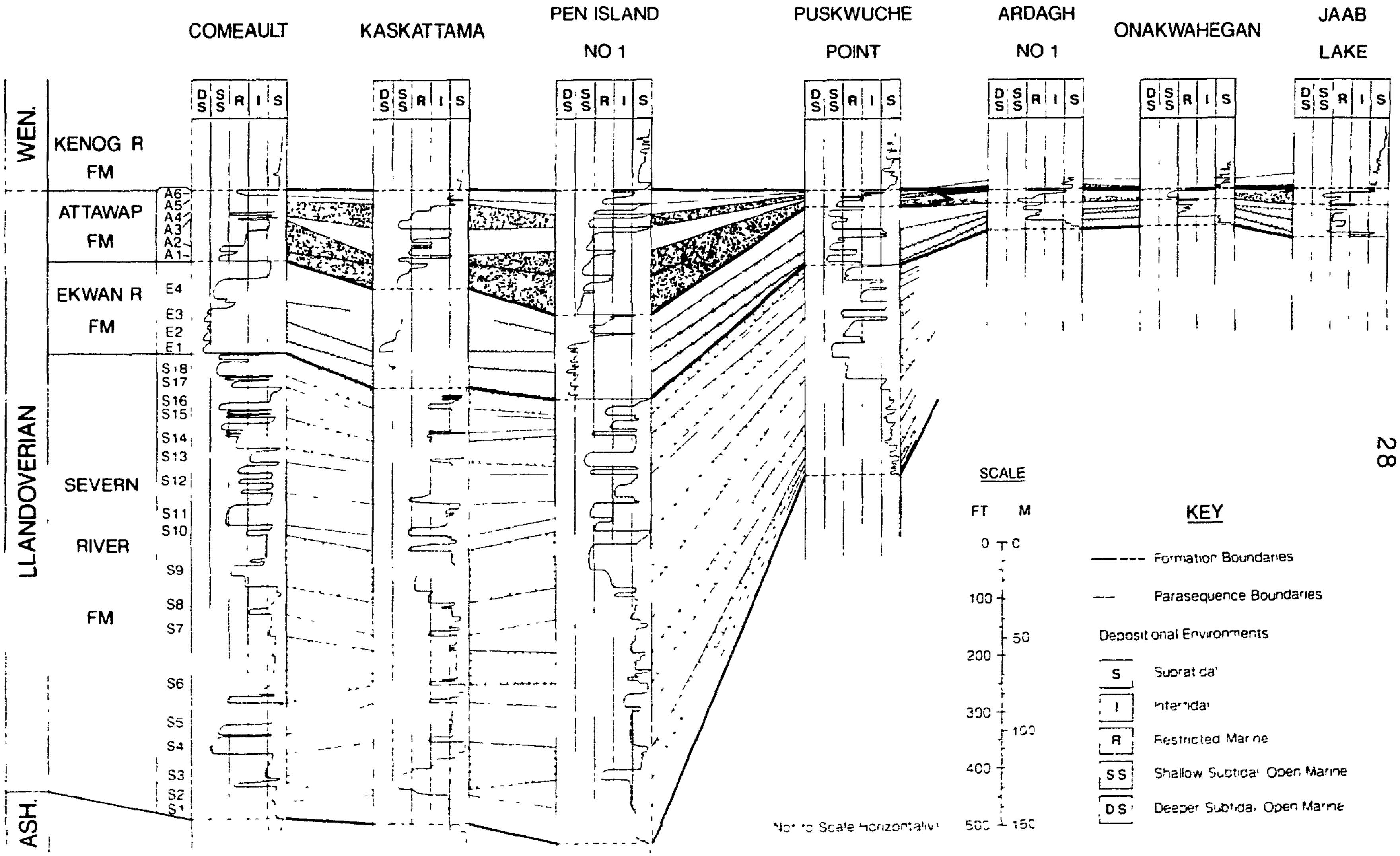
Figure 7. A portion of the stratigraphic section from the Pen Island No. 1 core and the corresponding relative sea-level curve, showing changes within predominantly supratidal facies. S5 and S6 are labels for individual parasequences recognized in the Severn River Formation. See Figure 5 for other symbols.

Correlation of Relative Sea-Level Curves

Comparisons of the relative sea-level curves among the different localities permitted the identification of certain shallowing-upward facies sequences (or parasequences) that displayed similar trends in sea-level change from one locality to another (Figure 8). Van Wagoner *et al.* (1990, p. 8) defined a parasequence as "a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces." As used in this study, individual parasequences extend from the base of one correlatable relative sea-level rise to the base of the next overlying one. The trends in relative sea-level change shown by the curves were the tools that allowed the determination of which shallowing-upward sequences were correlative among the different localities.

An example of how the correlations were made is provided by the Severn River Formation in the three Hudson Bay Basin cores (lower left of Figure 8). Initially, time-stratigraphic markers were needed to delimit the upper and lower limits of specific stratigraphic intervals. In the example cited, regional disconformities (evidence to be discussed later) at the base and top of the Severn River Formation provided the needed markers for such large-scale bracketing. Subsequently, some of the more obvious or important trends in relative sea-level change illustrated by the curves were matched from one locality to another and hence their corresponding parasequences were correlated (emphasized by stippled patterns in Figure 8). For example, the overall trend of the curves illustrating

Figure 8. Chart showing relative sea-level curves for stratigraphic sections in each of the seven cores and the correlations of individual parasequences based on matching trends of relative sea-level change. Locations of the wells are shown in Figure 1. Stippled patterns emphasize some of the more obvious or important correlations. Letters and numbers along left edge of the Comeault column (S1-S18, E1-E4, A1-A6) refer to individual parasequences.


COMEAULT
KASKATTAMA
PEN ISLAND NO 1
PUSKWUCHE POINT
ARDAGH NO 1
ONAKWAHEGAN
JAAB LAKE
DS SS R I S
WEN.
LLANDOVERIAN
ASH.
KENOG R FM
ATTAWAP FM
EKWAN R FM
SEVERN RIVER FM
A6 A5 A4 A3 A2 A1
E4 E3 E2 E1
S18 S17 S16 S15 S14 S13 S12 S11 S10 S9 S8 S7 S6 S5 S4 S3 S2 S1
SCALE
FT M
0 100 200 300 400 500
0 50 100 150
Not to Scale Horizontally
KEY
Formation Boundaries
Parasequence Boundaries
Depositional Environments
S Supratidal
I Intertidal
R Restricted Marine
SS Shallow Subtidal Open Marine
DS Deeper Subtidal Open Marine

relative sea-level change for parasequences S1 through S3 is distinctive in shape and position and can be matched in the three wells easily. Also, the trend displayed for parasequence S9, that is, a rapid rise in relative sea-level after a long period of relative sea-level lowstand, stands out as an event that had a major effect on the types of facies deposited across the basin.

Once the major shifts in relative sea-level were recognized and the corresponding parasequences were correlated, the patterns of change recorded by the intervening parasequences became easier to compare and correlations could be made (Figure 8).

Correlation of individual parasequences depended primarily upon the shape of the relative sea-level curves and the number and stratigraphic positions of the leftward deviations of the curves. It depended much less upon the magnitude of deviation to the left, and any one correlative parasequence may be represented by different lithologies at different localities, e.g., by supratidal facies at one locality, intertidal at another, and subtidal at others (e.g., S6 in Figure 8).

In the Puskwuche Point well (Figure 8), the first stratigraphic unit containing marine sediments in the middle of the Severn River Formation is correlated to parasequence S9 in the Hudson Bay Basin cores. This was done because the trends in relative sea-level change illustrated by their curves match well, and because these sediments record the first extensive marine inundation to affect the Hudson Bay Platform generally. Some of the other parasequences apparently pinched out or merged between the two areas (e.g., S12 and S13).

The trends in relative base-level change interpreted from the supratidal facies below parasequence S9 in the Puskwuche Point well are similar to the trends in relative sea-level change recorded in marine facies below parasequence S9 in the Hudson Bay Basin cores, and justify the correlation of these sections as shown in Figure 8. The facies changes in both environments were probably related to the same relative sea-level changes, as explained above.

Construction of a Composite Core Curve

A composite relative sea-level curve for the Hudson Bay Basin (shown in later figures) was constructed by taking the curves drawn for each of the three measured cores, averaging the thicknesses of each individual parasequence, averaging the values of the curve's deviation to the left for each parasequence, and plotting the averaged values.

Construction of a Composite Outcrop Curve

The stratigraphic sections of the Ekwan River Formation in outcrops were correlated by tracing highly persistent beds from outcrop to outcrop along the Attawapiskat River. By combining the stratigraphic sections from the different localities linked by these beds, a composite section of the entire formation was compiled and a relative sea-level curve was constructed from it. A composite relative sea-level curve for the Attawapiskat Formation was compiled by comparing the curves from all the measured outcrop sections and combining them. The composite outcrop curve for both formations is used in figures later in this chapter.

SEQUENCE STRATIGRAPHY

Unconformities

As previously mentioned, regional disconformities mark the base and top of the Severn River Formation and define the boundaries of a sequence (Van Wagoner *et al.*, 1988 and 1990). A disconformity for which there is only local evidence at the top of the Attawapiskat Formation may make the Ekwan River and Attawapiskat Formations another sequence (Figure 6), but because the evidence occurs only locally, the top of the Attawapiskat Formation does not strictly fit the definition of a sequence boundary. Perhaps a sequence boundary is present slightly higher in the Kenogami River Formation, but that portion of the section was not investigated in detail.

The unconformity at the Ordovician-Silurian boundary (i.e., at the base of the Severn River Formation) in the Hudson Bay region is well-documented (Sanford *et al.*, 1968; Norris and Sanford, 1968; Norford, 1970; Norford, 1988; Jin and Caldwell, in press). This unconformity is underlain in the three Hudson Bay Basin cores by evaporites [either gypsum, or, in the Pen Island No. 1 core, by a 32 ft. (9.8 m) thick bed of halite]. It is overlain by mudstones that grade upward to dolostone containing flat-pebble breccias, which are then overlain by fossiliferous limestones.

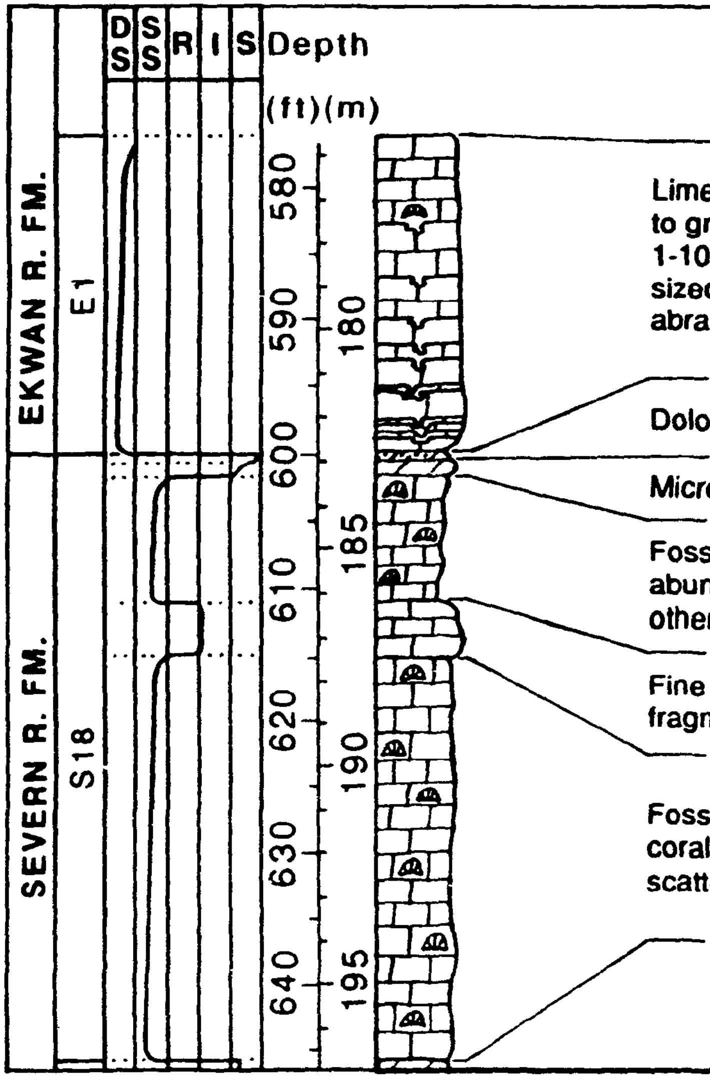
The disconformity between the Severn River Formation and the overlying

Ekwan River Formation has largely gone unrecognized by previous workers. In this study, it has been recognized in all the cores, and appears as a weathered, irregular surface at the top of a weathered, chalky, nodular to vuggy limestone or dolostone interval in the Hudson Bay Basin cores and the Puskwuche Point core (Figure 9). In the three southwestern Moose River Basin cores, where the Severn River Formation is absent, a coarse sandstone-clast conglomerate at the top of the basal siliciclastics may represent a combination of both the basal and post-Severn River unconformities. In cuttings from the Beluga well, evidence of subaerial exposure (white, chalky, apparently weathered, bioclastic limestone) occurs at the level of the Severn River/Ekwan River Formation boundary (Figure 10). In outcrop, the disconformity is exposed near the base of the sections at localities 88-28 and 88-29 (Figure 4) and is marked by a slightly irregular surface and small (1-2 cm; 0.4-0.8 in.) weathered vugs in the underlying interval.

Because the disconformity has not been recognized by previous workers, and rock types of the Severn River and Ekwan River Formations are similar, placement of the boundary between the two formations has not been consistently done. However, on the grounds that the disconformity is recognized in all the subsurface sections and in outcrop exposures, and because it marks a significant break in deposition, it is proposed here as the formation boundary.

Although the basis for placement of the boundary in this study is different from that of previous workers, its stratigraphic position must be revised in only two of the seven wells. In the Puskwuche Point well, the boundary is placed 22 feet

Figure 9. A portion of the stratigraphic section from the Comeault Province No. 1 core and the corresponding relative sea-level curve, showing changes surrounding the disconformity between the Severn River and Ekwan River Formations. S18 and E1 are parasequence labels. See Figure 5 for other symbols.



COMEAULT PROVINCE NO.1 CORE

DESCRIPTION

Lime mudstone, bioturbated, grayish brown mottled with light gray to gray, hard, dense, with abundant hardgrounds (as shown), with 1-10% fossil fragments (mostly sand to granule sized, some pebble sized; crinoids, brachiopods, corals, stromatoporoids; broken and abraded; floating in the micrite matrix).

Dolostone, chalky, nodular, weathered.

Microcrystalline dolostone, soft, yellow, laminated to homogeneous.

Fossiliferous wackestone, nodular, chalky, weathered, with abundant stromatoporoids and favositids, also brachiopods and other unidentified fossil fragments.

Fine wackestone to lime mudstone, algal (much is sand-sized algal fragments in clear spar matrix), white to light tan, clotted texture.

Fossiliferous wackestone, nodular, chalky, with stromatoporoids, corals, brachiopods, and other unidentified fossil fragments, scattered chert nodules (up to 4 cm).

lower than that of Larsson (1984) and 35 feet higher than that of Hogg *et al.* (1953). In the Jaab Lake well the boundary is placed 56 feet lower than that of Hogg *et al.* (1953) and of the Ontario Department of Mines well report. These two reports place the lower 56 feet of the Jaab Lake core in the Severn River Formation, but they express uncertainty about that placement, implying that the beds may be part of the Ekwan River Formation. The boundary, as defined by the disconformity, is at the top of the quartz-rich fluvial sandstones in the bottom of the hole, at the base of the limestone interval, and no strata of the Severn River Formation are present in the Jaab Lake well.

Evidence for local subaerial exposure at the top of the Attawapiskat Formation includes weathered, chalky intervals in the Pen Island No. 1 core and in some outcrop exposures. Because such evidence was not recognized in all cores, the existence of a disconformity of regional extent is questionable.

Sequence I: Severn River Formation

Marine facies occur periodically from the base to the top of the Severn River Formation in the Hudson Bay Basin cores (Figure 8). These facies consist primarily of bioturbated lime mudstones and wackestones containing scattered fossils. They are interspersed throughout the section with intertidal, supratidal, and evaporite facies.

In the Puskwucte Point well (Figure 8), only supratidal facies are present below parasequence S9 in the Severn River Formation. Marine facies interspersed with supratidal facies, similar to those in equivalent beds in the Hudson Bay Basin cores, make up the remainder of the Severn River Formation in this core.

In the three southwestern Moose River Basin wells, no marine facies occur below the base of the Ekwan River Formation and beds equivalent to the Severn River Formation are missing from these three wells. Instead the Ekwan River Formation rests directly on fluvial sandstones of undetermined age.

Because only a preliminary company well report is available for the Beluga well in the center of Hudson Bay (Figure 10) as a guide to the position of formation boundaries, and placement of the lower boundary of the Severn River Formation is uncertain, no attempt was made to compare the trends of relative sea-level change in the Severn River Formation in the Beluga well to those of the other wells.

Outcrop exposures of the Severn River Formation were not examined for this study.

Sequence II: Ekwan River, Attawapiskat, and Kenogami River Formations

Ekwan River Formation in Subsurface Sections.--In the Ekwan River Formation in the drill cores (Figure 8), the disconformity at its base is immediately overlain by deeper subtidal facies. Burrowed firmgrounds occur in this interval in all the cores examined (Figures 6 and 11A). The burrows and the firmground surfaces are lined with black pyritic mud.

Figure 10. Silurian stratigraphic section and corresponding relative sea-level curve from the Beluga well (Figure 1), drawn from observations of well cuttings. Key to depositional environments and labelling of parasequences is as used throughout this paper (Figures 5 & 8).

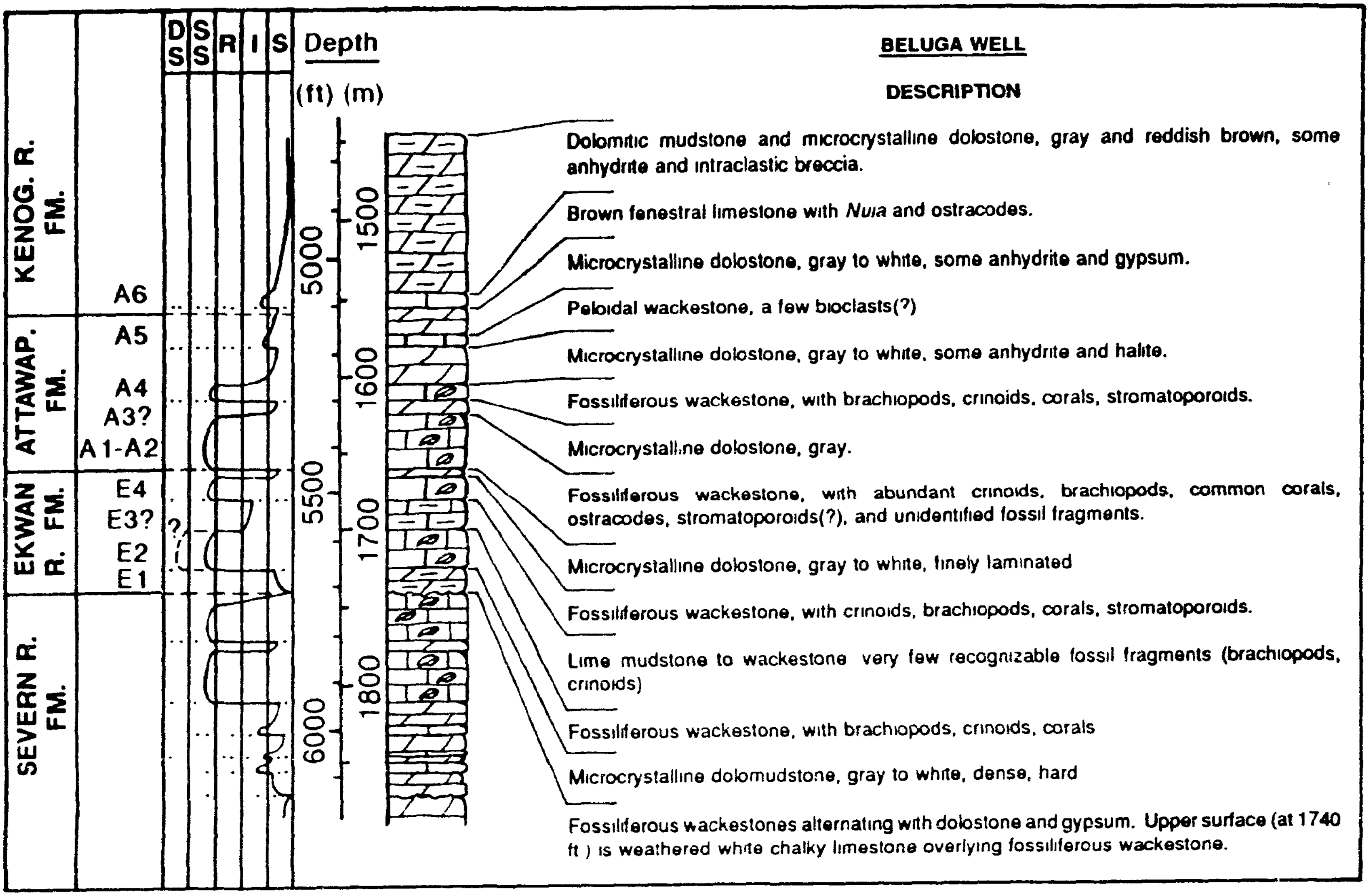
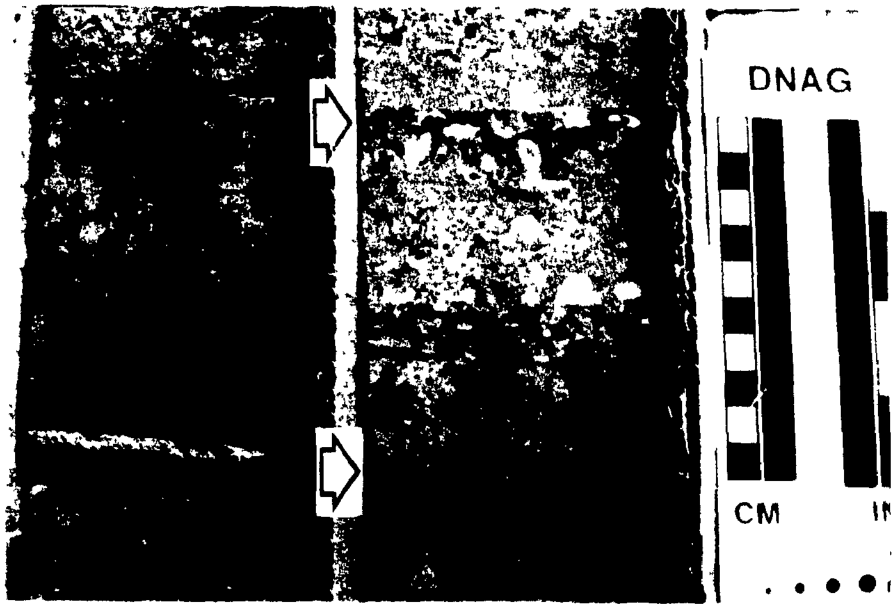

KENOG. R. FM.
ATTAWAP. FM.
EKWAN R. FM.
SEVERN R. FM.
A6
A5
A4
A3?
A1-A2
E4
E3?
E2
E1
DS
SS
R
I
S
Depth
(ft) (m)
5000
5500
6000
1500
1600
1700
1800
BELUGA WELL
DESCRIPTION
Dolomitic mudstone and microcrystalline dolostone, gray and reddish brown, some anhydrite and intraclastic breccia.
Brown fenestral limestone with *Nuia* and ostracodes.
Microcrystalline dolostone, gray to white, some anhydrite and gypsum.
Peloidal wackestone, a few bioclasts(?)
Microcrystalline dolostone, gray to white, some anhydrite and halite.
Fossiliferous wackestone, with brachiopods, crinoids, corals, stromatoporoids.
Microcrystalline dolostone, gray.
Fossiliferous wackestone, with abundant crinoids, brachiopods, common corals, ostracodes, stromatoporoids(?), and unidentified fossil fragments.
Microcrystalline dolostone, gray to white, finely laminated
Fossiliferous wackestone, with crinoids, brachiopods, corals, stromatoporoids.
Lime mudstone to wackestone very few recognizable fossil fragments (brachiopods, crinoids)
Fossiliferous wackestone, with brachiopods, crinoids, corals
Microcrystalline dolomudstone, gray to white, dense, hard
Fossiliferous wackestones alternating with dolostone and gypsum. Upper surface (at 1740 ft) is weathered white chalky limestone overlying fossiliferous wackestone.

Figure 11. Drill core photos from some of the wells. A. Burrowed firmgrounds (indicated by arrows) in lower part of Ekwan River Formation. B. Reefal boundstone of the Attawapiskat Formation; note the abundant favositids (F), stromatoporoids, and other fossils, and its light color.

A.



B.

The Ekwan River Formation in the drill cores contains two main marine intervals (Figures 6 and 8): 1) the burrowed firmground interval noted above (parasequences E1 to E3), and 2) a bioturbated fossiliferous limestone interval which overlies it (parasequence E4). These two intervals are separated in the Pen Island No. 1 core (at 1693.6-1693.8 ft.; 516.2-516.3 m) and the Puskwuche Point core (at 992-1006 ft.; 302.4-306.6 m) by a layer of dolomitic lime mudstone with anhydrite nodules, and in the Comeault core (at 505-511.5 ft.; 153.9-155.9 m) by cross-bedded, fossiliferous, crinoidal packstone. In the three southwestern Moose River Basin cores, the entire section has been secondarily dolomitized, thus obscuring sedimentary features, but two separate intervals of bioturbated, fossiliferous, muddy limestones with burrowed firmgrounds are recognizable in the Ekwan River Formation, and are separated by beds containing cross-bedded fine wackestones. In the Beluga well in the center of Hudson Bay (Figure 10), the Ekwan River Formation contains two fossiliferous limestones separated by a microcrystalline dolostone layer.

Ekwan River Formation in Outcrop Sections.--Beds of the Ekwan River Formation in outcrop along the Attawapiskat River contain flat-lying fossiliferous limestones that have great lateral continuity (Figure 12). This lateral continuity is demonstrated at localities 88-28 and 88-29 (Figure 4), which show exactly the same stratigraphy, the same succession of facies, at localities 3 km apart. This same succession can be followed several more kilometers downriver from these

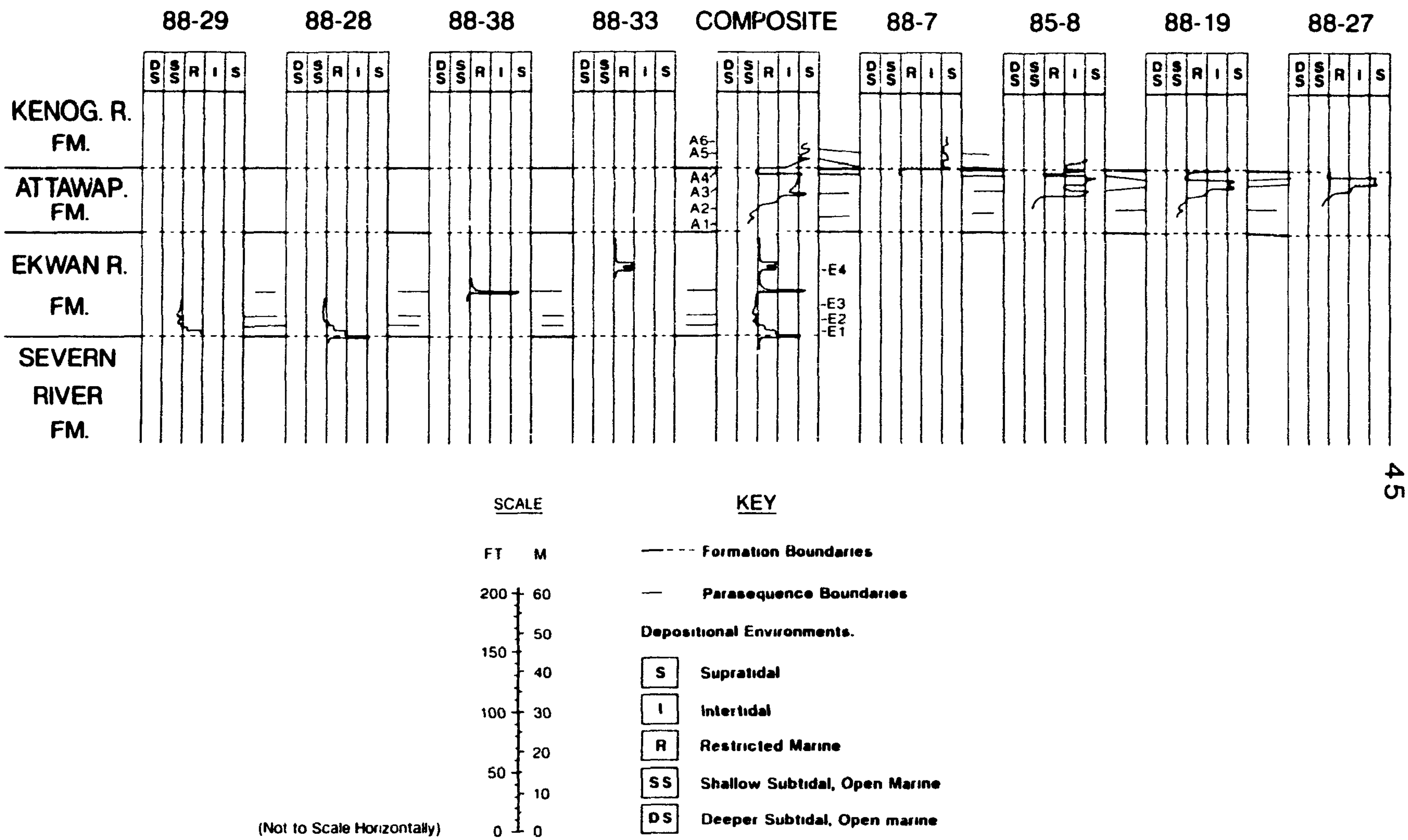
Figure 12. Flat-lying, laterally continuous beds of the Ekwan River Formation in outcrop along the Attawapiskat River. The upper two-thirds of the outcrop in the foreground, at locality 88-29, is fossiliferous, cherty, nodular limestone of the lower Ekwan River Formation; it is underlain by burrow-mottled dolostones and various other facies. The contact with the Severn River Formation is just below the top of the talus pile here. In the background, 3 km away at locality 88-28, is exactly the same succession of facies.

localities.

The disconformity between the Severn River and Ekwan River Formations, exposed near the base of the section at localities 88-28 and 88-29, is immediately overlain by a thin (0.5 m; 1.6 ft.) burrow-mottled dolostone (base of parasequence E1 in Figure 13). This is overlain by fossiliferous and burrow-mottled lime mudstones and wackestones (parasequence E1; 2.75 m or 9.0 ft. thick). However, the major portion of the Ekwan River Formation in outcrop consists of two marine intervals (parasequences E2-3 and E4 in Figure 13) separated by a thin microcrystalline dolostone unit (base of parasequence E4). The lower half of the Ekwan River Formation in outcrop (parasequences E2 and E3) (at least 8 m thick) contains fossiliferous, cherty, nodular limestone exhibiting evidence of shallow-water, high-energy conditions (e.g., cross-bedding and overturned stromatoporoids). The upper half of the formation (parasequence E4) is 10 to 12 m (33-39 ft.) thick and contains thin-bedded limestone with a low-diversity marine fauna. Breaks in deposition or relative sea-level shallowings within these parasequences are evidenced by an extensively bored and cemented layer at the top of parasequence E2, and a muddy interval with a very restricted fauna in the middle of parasequence E4.

<u>Attawapiskat Formation in Subsurface Sections</u>.--The Attawapiskat Formation is usually defined on the basis of the presence of reefal boundstone facies in drill cores or of patch reefs in outcrop or seismic sections (Savage and

Figure 13. Relative sea-level curves for selected outcrop sections along the Attawapiskat River, correlations of parasequences (labelled E1-4 and A1-6) based on matching trends of relative sea-level change, and a composite curve compiled from them. Localities are shown in Figure 4.


88-29
88-28
88-38
88-33
COMPOSITE
88-7
85-8
88-19
88-27
DS SS R I S
KENOG. R. FM.
ATTAWAP. FM.
EKWAN R. FM.
SEVERN RIVER FM.
A6
A5
A4
A3
A2
A1
E4
E3
E2
E1
SCALE
FT M
200 60
50
150 40
100 30
20
50 10
0 0
(Not to Scale Horizontally)
KEY
Formation Boundaries
Parasequence Boundaries
Depositional Environments.
S Supratidal
I Intertidal
R Restricted Marine
SS Shallow Subtidal, Open Marine
DS Deeper Subtidal, Open marine

Van Tuyl, 1919; Nelson and Johnson, 1966; Sanford *et al.*, 1968; Norford, 1970; LeFevre *et al.*, 1976; Grant and Sanford, 1988). In this study, we recognize two distinct facies of the Attawapiskat Formation; 1) the reefal boundstone and associated reef-flanking and inter-reef beds, and 2) an overlying marine facies consisting of fossiliferous packstones to rudstones. These facies are distinctly different from the evaporite facies of the overlying Kenogami River Formation. Therefore, in this study the top of the Attawapiskat Formation is placed at the highest occurrence of marine or restricted-marine fossils or the lowest occurrence of evaporites.

As a result of this usage, the top of the Attawapiskat Formation in the Hudson Bay Basin cores is placed above fossiliferous beds (A5 and A6 in Figure 8) that occur several meters above the reefal interval. These beds contain fragments of normal marine fossils: stromatoporoids, corals, brachiopods, and crinoids in the Pen Island No. 1 well; algae and a few scattered fragments of brachiopods and crinoids in the Comeault and Kaskattama wells.

The typical fossiliferous, vuggy, reefal boundstone of the Attawapiskat Formation was penetrated in the Pen Island No. 1 well (Figure 11B) and in the Comeault and Kaskattama No. 1 wells, all in the southwestern part of the Hudson Bay Basin. It is similar to rocks of the Attawapiskat reefs seen in outcrop along the Attawapiskat River. Cuttings from the Attawapiskat Formation in the Beluga well are richly fossiliferous limestones that contain brachiopods, crinoids, corals, and stromatoporoids. In the Puskwuche Point well, abundant *in situ* corals and stromatoporoids are present in a dark cross-laminated matrix; because the rock approaches a reefal boundstone in composition, it is included as part of the Attawapiskat Formation (Figure 8).

In this interval in the three cores from the southwestern Moose River Basin, only a few scattered corals occur in a medium to dark gray, bioturbated finely crystalline dolostone. Because these dolostones in no way resemble the reefal boundstones nor the overlying marine limestones of the type Attawapiskat exposures, they cannot be placed in the Attawapiskat Formation. They more closely resemble some limestone facies of the Ekwan River Formation and must therefore be placed within that formation (Figure 8).

<u>Attawapiskat Formation in Outcrop Sections</u>.--Many of the riverbanks and islands of the Attawapiskat River are formed by individual patch reefs flanked by beds of coarse bioclastic limestone that dip concentrically away from the reef cores (Figure 14). Post-reef beds drape over the reefs, thinning and locally pinching out above them (Figure 15). Flat-lying beds of fossiliferous wackestones to packstones between the reefs are correlatives of the reefs and post-reef beds; they become finer in texture and thinner bedded away from the reefs. Chow and Stearn (1988) described the succession of facies in the Attawapiskat reefs as a stromatoporoid-coral framework core overlain by a crinoid-rich caprock. Outcrops examined in this study indicate that not all reefs have a crinoidal caprock; some are covered by bioclastic packstones and wackestones to rudstones poor in crinoid

A.

B.

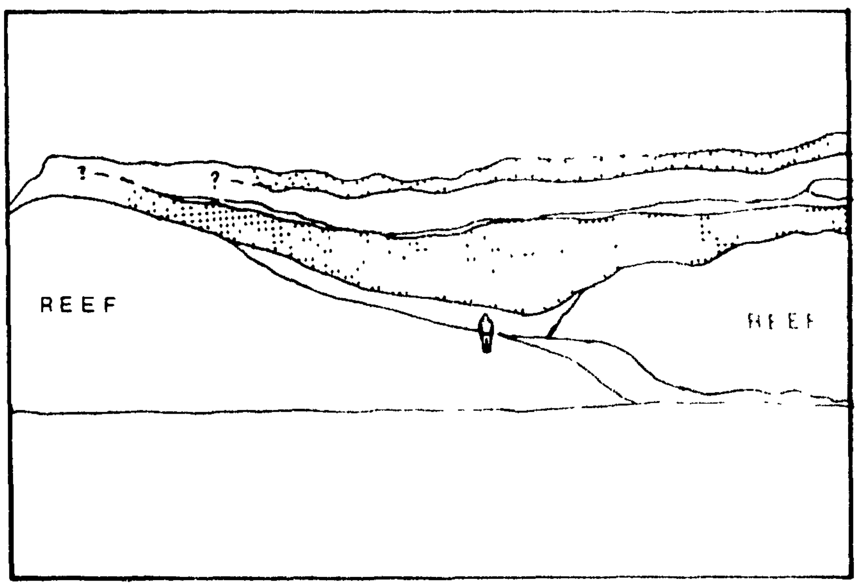


Figure 14. A. Typical outcrop beside the Attawapiskat River (locality 88-15), showing reefs, reef flanking beds, and over-reef beds of the Attawapiskat Formation; person for scale. B. Interpretive drawing of outcrop in above photo; person is standing at position of reef flanking beds, post-reef beds are indicated by alternating stippled and nonstippled patterns

Figure 15. Outcrop in which beds drape over a reef and down its flanks, and pinch out over its crest (locality 88-26).

fragments, but rich in brachiopods and algal fragments.

In outcrop exposures (Figure 16), the main interval of reef growth (A1) is commonly overlain by fossiliferous packstones and rudstones (A2), which give way to a bed (6-24 in. thick; 15-61 cm) of microcrystalline dolostone (top of A2), followed by fenestral limestone (A3) (rich in the alga *Nuia? distincta* and locally containing a few, very small, flat brachiopods), another microcrystalline dolostone unit (top of A3), a thick bed of fossiliferous, shallow-marine to restricted-marine carbonate sediments (A4), and finally by supratidal units of the Kenogami River Formation (post-A4).

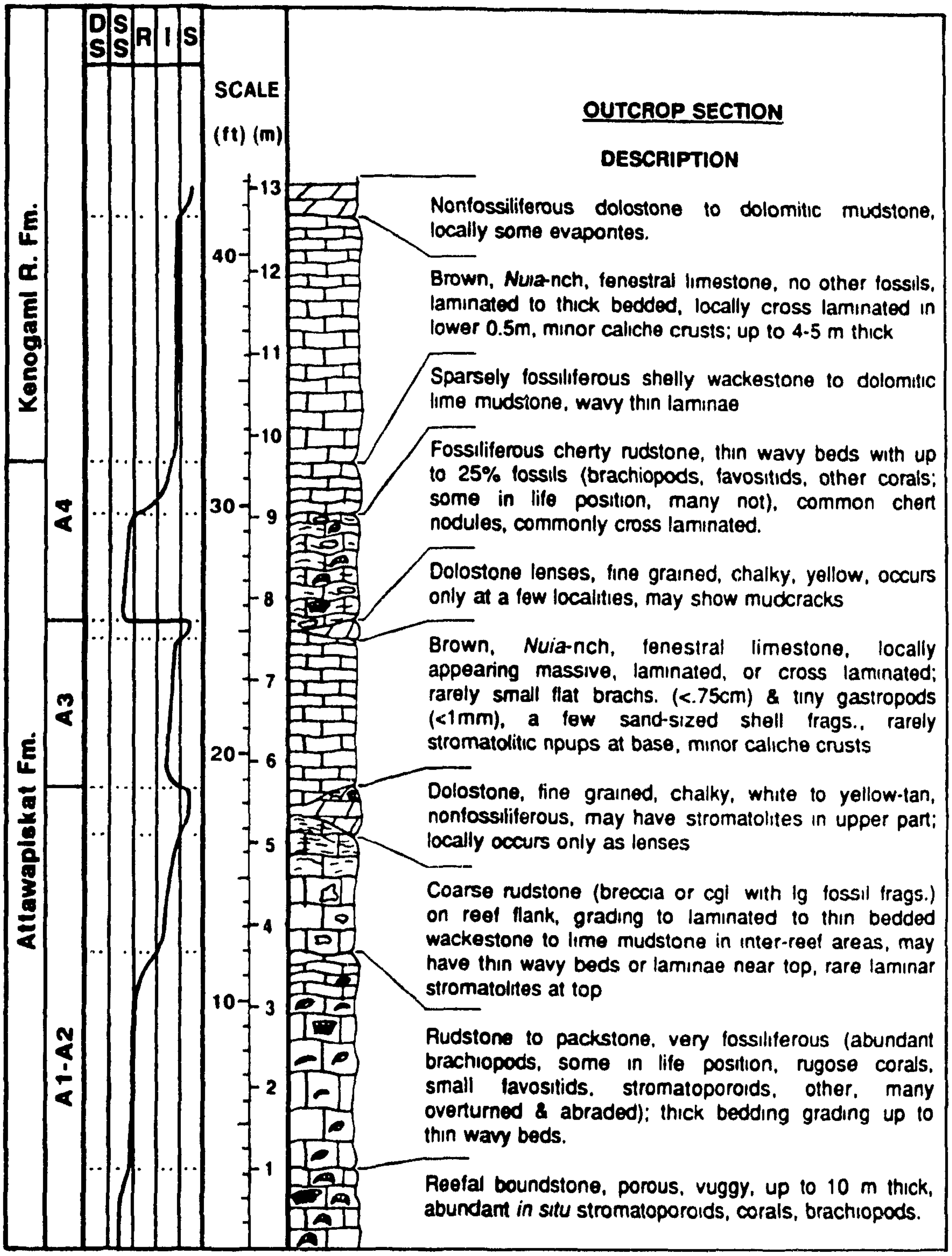
In outcrop sections in the southern part of the Moose River Basin, the Attawapiskat reefal facies has not been recognized and the Ekwan River Formation is directly overlain by the Kenogami River Formation (Figure 3); the Attawapiskat Formation is presumed to interfinger with the top of the Ekwan River Formation somewhere between the Attawapiskat River and the southern Moose River Basin. In the southern Moose River Basin, rocks that are correlatives of the type Attawapiskat are brown bituminous dolomites at the top of the Ekwan River Formation (Sanford *et al.*, 1968).

INTERPRETATIONS

Sequence I: Severn River Formation

Correlation of the parasequences, as discussed above, has elucidated the manner in which marine facies onlapped onto the Hudson Bay Platform during

Figure 16. Generalized composite stratigraphic sequence and the corresponding relative sea-level curve for strata occurring above reefal rocks of the Attawapiskat Formation as exposed along the Attawapiskat River; compiled from sections at localities 88-19, 88-15, and 88-7.


Kenogami R. Fm.
Attawapiskat Fm.
A4
A3
A1-A2
DS
SS
R
I
S
SCALE
(ft) (m)
40
30
20
10
13
12
11
10
9
8
7
6
5
4
3
2
1
OUTCROP SECTION
DESCRIPTION
Nonfossiliferous dolostone to dolomitic mudstone, locally some evapontes.
Brown, *Nuia*-nch, fenestral limestone, no other fossils, laminated to thick bedded, locally cross laminated in lower 0.5m, minor caliche crusts; up to 4-5 m thick
Sparsely fossiliferous shelly wackestone to dolomitic lime mudstone, wavy thin laminae
Fossiliferous cherty rudstone, thin wavy beds with up to 25% fossils (brachiopods, favositids, other corals; some in life position, many not), common chert nodules, commonly cross laminated.
Dolostone lenses, fine grained, chalky, yellow, occurs only at a few localities, may show mudcracks
Brown, *Nuia*-nch, fenestral limestone, locally appearing massive, laminated, or cross laminated; rarely small flat brachs. (<.75cm) & tiny gastropods (<1mm), a few sand-sized shell frags., rarely stromatolitic npups at base, minor caliche crusts
Dolostone, fine grained, chalky, white to yellow-tan, nonfossiliferous, may have stromatolites in upper part; locally occurs only as lenses
Coarse rudstone (breccia or cgl with lg fossil frags.) on reef flank, grading to laminated to thin bedded wackestone to lime mudstone in inter-reef areas, may have thin wavy beds or laminae near top, rare laminar stromatolites at top
Rudstone to packstone, very fossiliferous (abundant brachiopods, some in life position, rugose corals, small favositids, stromatoporoids, other, many overturned & abraded); thick bedding grading up to thin wavy beds.
Reefal boundstone, porous, vuggy, up to 10 m thick, abundant *in situ* stromatoporoids, corals, brachiopods.

Early Silurian time. For example, marine facies occur at intervals from the base to the top of the Severn River Formation (Sequence I) in the Hudson Bay Basin cores (Figure 8), but in the Puskwuche Point well, marine facies do not occur below the middle of the Severn River Formation. In the three southwestern Moose River Basin wells, marine facies do not occur below the base of the Ekwan River Formation (Sequence II). In other words, marine deposition occurred first in the Hudson Bay Basin, later in the vicinity of the Puskwuche Point well, and much later in the vicinity of the Ardagh, Onakwahegan, and Jaab Lake wells. Thus, during the Early Silurian transgression, large scale onlap of marine facies proceeded from north to south, or possibly from northeast to southwest, as suggested by Sanford (1987).

Sequence II: Ekwan River, Attawapiskat, and Kenogami River Formations

Ekwan River Formation.--The burrowed firmground facies in parasequences E1 to E3 (Figures 6 and 8) is platformwide in extent, indicating that conditions for formation of the firmgrounds persisted over the entire Hudson Bay Platform during this time interval. The black pyritic mud linings of the burrows and firmgrounds suggests that conditions at least at the sediment-water interface may have been reducing. This interval represents the first marine incursion onto the southwesternmost Moose River Basin, and it represents some of the deepest-water conditions and the most extensive marine inundation in the region during the Silurian Period.

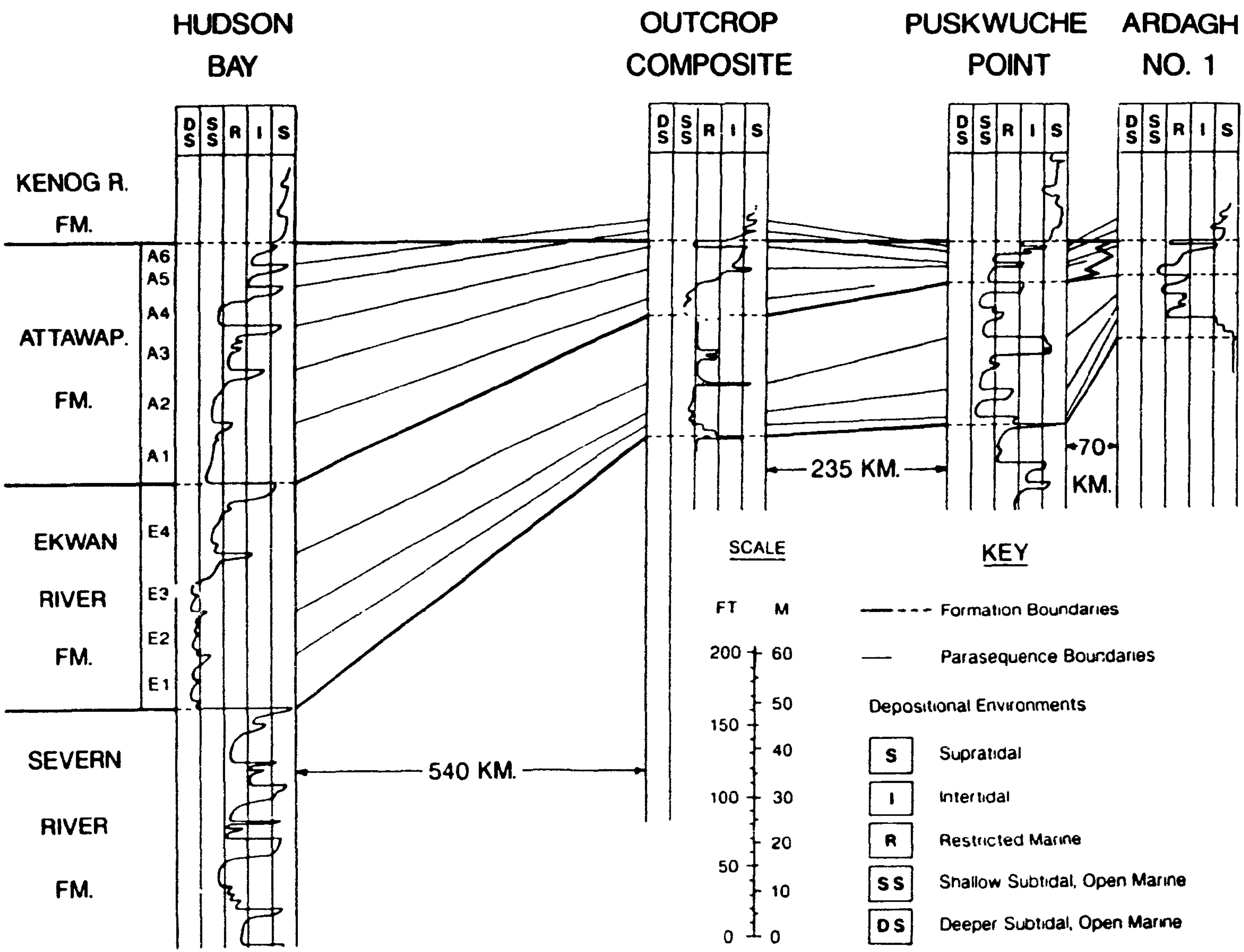
In the drill cores, in outcrop exposures, and in cuttings from wells in the center of the basin, the Ekwan River Formation contains evidence of two main rises in relative sea-level, one represented by the stippled pattern in Figure 8, the other by the unpatterned interval above it (also see Figures 10 and 13). Smaller fluctuations in relative sea-level change were superimposed upon the larger scale changes.

Cuttings of fossiliferous limestones from the Beluga and Narwhal wells only indicate that conditions in the basin center during the deepening events of the Ekwan River Formation were open marine. The data are insufficient to indicate whether conditions were above or below normal wavebase (Figure 10).

The great lateral facies continuity in beds of the Ekwan River Formation in outcrop along the Attawapiskat River indicates that the seabed there must have been very flat when these sediments were deposited. The similarity of trends in relative sea-level change recorded in parasequences correlated among the widely separated drill core localities suggests that the depositional surface over the entire basin was flat; such a flat basin surface made it possible for small-scale sea-level changes to be recorded across the platform.

Attawapiskat Formation.--The Attawapiskat Formation in the drill cores contains evidence of one main interval of reef growth (parasequences A1 and A2 in Figure 17), divided by a relatively minor pause in growth at the top of parasequence A1. The overlying marine facies assigned to the Attawapiskat

Figure 17. Relative sea-level curves for stratigraphic sections from selected localities, including an outcrop composite curve and an averaged curve for the three Hudson Bay Basin cores, and correlation of parasequences. Letters along left edge of Hudson Bay curve refer to individual parasequences.


HUDSON BAY
OUTCROP COMPOSITE
PUSKWUCHE POINT
ARDAGH NO. 1
DS SS R I S
KENOG R. FM.
ATTAWAP. FM.
A6
A5
A4
A3
A2
A1
EKWAN RIVER FM.
E4
E3
E2
E1
SEVERN RIVER FM.
540 KM.
235 KM.
70 KM.
SCALE
FT M
200 60
50
150 40
100 30
20
50 10
0 0
KEY
Formation Boundaries
Parasequence Boundaries
Depositional Environments
S Supratidal
I Intertidal
R Restricted Marine
SS Shallow Subtidal, Open Marine
DS Deeper Subtidal, Open Marine

Formation, which consist of fossiliferous packstones to rudstones, indicate a shallowing event (top of parasequence A2), a minor relative sea-level rise (parasequence A3), another shallowing (top of parasequence A3), then one more significant relative sea-level rise (parasequence A4) before gradual shallowing into the supratidal facies of the Kenogami River Formation. This trend is clearly illustrated by the curve for the Puskwuche Point well (Figure 17). Minor variations on this pattern occurred from one locality to another.

Facies within parasequences A1 and A2 range from open-marine reefal boundstone in the Hudson Bay Basin cores (and in outcrop exposures), to coral- and stromatoporoid-rich rudstone to boundstone with a dark muddy matrix in the Puskwuche Point core, to bioturbated muddy dolostones with only a few scattered corals in the three southwestern Moose River Basin cores. This variability indicates that the environment of deposition ranged from open marine in the vicinity of the Hudson Bay Basin cores or the outcrops, to more restricted in the vicinity of the Puskwuche Point well, to even more restricted in the vicinity of the three southwestern Moose River Basin cores.

In the Beluga and Narwhal wells, the major changes in relative sea-level recorded in the Attawapiskat Formation could be identified (Figure 10). The fossil diversity and rock types were similar to those in the Hudson Bay Basin cores, and the environment of deposition was probably similar.

In outcrop sections along the Attawapiskat River, the trends in relative sea-level change recorded in the rocks are similar to those exhibited by the drill cores

(Figure 17): that is, reef interval (A1-A2), shallowing (top of A2), minor deepening (A3), shallowing (top of A3), significant deepening (A4), and final shallowing (top of A4). The section at locality 88-19 (Figure 13), for which a 5.2-m-long drill core was taken through the reef with a portable drill, suggests a minor disruption of reef growth in the middle of the reef interval that may be correlative to the one shown in the Hudson Bay Basin drill cores (top of unit A1 in Figure 17).

If the outcrop evidence alone is considered (Figure 13), the trends in relative sea-level change recorded at the separate localities along the river could be interpreted to represent repetitions of several episodes of reef growth in the downriver and basinward direction. However, the close match of trends in relative sea-level change in all of the outcrop sections to those recorded in the cores (Figure 17), in which a single major interval of reef growth is clearly identified, is strong evidence that the reefs exposed along the Attawapiskat River all represent a single interval of reef growth.

In general, the Attawapiskat reefs appear to be buried slightly more deeply in a downriver and basinward direction. That is, in upriver sections, the reefs are exposed nearly to their bases in high cliffs (but no reef bases are exposed), whereas downriver progressively less of the reefs are exposed until in the most downriver sections only the tops of the reefs are exposed. This simple scheme is complicated, however, by the presence of a conjugate set of southeast and northeast striking faults (Figure 4). These faults uplift the reefs in tilted fault blocks repeatedly downstream, and cause the areas of reef outcrops along the river to be separated by stretches with no outcrops. Evidence for these faults, and for movement along them at the end of Llandoverian time, are outlined in a later chapter.

Ekwan River-Attawapiskat Relationships.--In the Moose River Basin cores, not only are the overall sections thinner, but each parasequence is very much thinner than in the other cores. Also, the parasequence boundaries between the Puskwuche Point and Ardagh wells cross the Attawapiskat and Ekwan River Formation boundary (Figure 17). As discussed above, beds in the Ardagh well that are correlative with the Attawapiskat reefs are assigned to the upper Ekwan River Formation. These beds were correlated to the Attawapiskat reefs on the basis of matching trends in their relative sea-level curves.

The above evidence suggests that the Attawapiskat reefs are a time-equivalent facies of the upper part of the Ekwan River Formation in the southwestern Moose River Basin, but it does not explain what the relationship is between exposures of the two formations along the Attawapiskat River. That is, are these exposures time-equivalent, and if not, what can explain their close juxtaposition along the river? The trends of relative sea-level change exhibited by the outcrop curves for the Attawapiskat and Ekwan River Formations (Figure 13) are so different that the strata of the two formations exposed along the river cannot be correlative. Furthermore, when the outcrop composite curves of the two formations are compared to curves derived from the wells (Figure 17), the similarity of trends confirms the difference of the outcrop composite curves for each formation. The two main deepening events (E1-2 and E4) are reflected in the Ekwan River Formation in outcrop just as they are in the drill cores and the trends of relative sea-level change illustrated by the Attawapiskat Formation in outcrop are the same as those found in the drill cores.

The above results show that strata of the two formations exposed along the river are not time equivalents. A down-to-basin fault (as described in the previous section) bounds the Attawapiskat reef outcrop belt on its upstream end and explains its abrupt boundary with the Ekwan River Formation outcrops.

In summary, the Attawapiskat reefal episode in the northern Moose River Basin is a correlative of the upper Ekwan River Formation in the southwestern part of the basin, and the beds of the Ekwan River Formation exposed along the Attawapiskat River are correlatives of the lower Ekwan River Formation in the southwestern part of the basin (Figure 17).

Attawapiskat-Kenogami River Relationships.--As stated above, the top of the Attawapiskat Formation is placed at the highest occurrence of marine or restricted-marine fossils in the Silurian section. In the Moose River Basin cores, only burrow-mottled and enterolithic dolostones and interbedded gypsum, anhydrite and siltstone, interpreted as supratidal facies, occur above the last major deepening event (parasequence A4) of the Attawapiskat Formation (and correlative parts of the Ekwan River Formation). In the Hudson Bay Basin cores, however, restricted marine facies are present in parasequences A5 and A6 (Figure 17) and are included within the Attawapiskat Formation because they contain fossils of marine organisms. These parasequences (10-20 ft. thick; 3-6 m) are correlated with the supratidal units (3-20 ft. thick; 1-6 m) of the Moose River Basin on the basis of matching trends in relative sea-level curves and their stratigraphic positions. The relative changes of sea-level recorded by marine facies in the Hudson Bay Basin were also recorded by supratidal facies in the southern Moose River Basin, as discussed previously.

In summary, whereas the Attawapiskat reefal interval is correlated with the uppermost Ekwan River Formation in the southern Moose River Basin, subsequent restricted marine limestones of the Attawapiskat Formation in the Hudson Bay Basin are correlated with the lowermost Kenogami River Formation in the southern Moose River Basin. These interpretations are consistent with the observations of Norford (1970). He suggested on the basis of outcrop relationships that, at the Little Current River in the southwesternmost part of the Moose River Basin, the lower part of the Kenogami River Formation, which directly overlies the Ekwan River Formation there, is equivalent to the Attawapiskat Formation farther north.

The above correlations indicate that at the end of Attawapiskat time the Silurian seas retreated northward. Marine sediments were still being deposited in the Hudson Bay Basin after the Moose River Basin was receiving evaporites and/or was subaerially exposed.

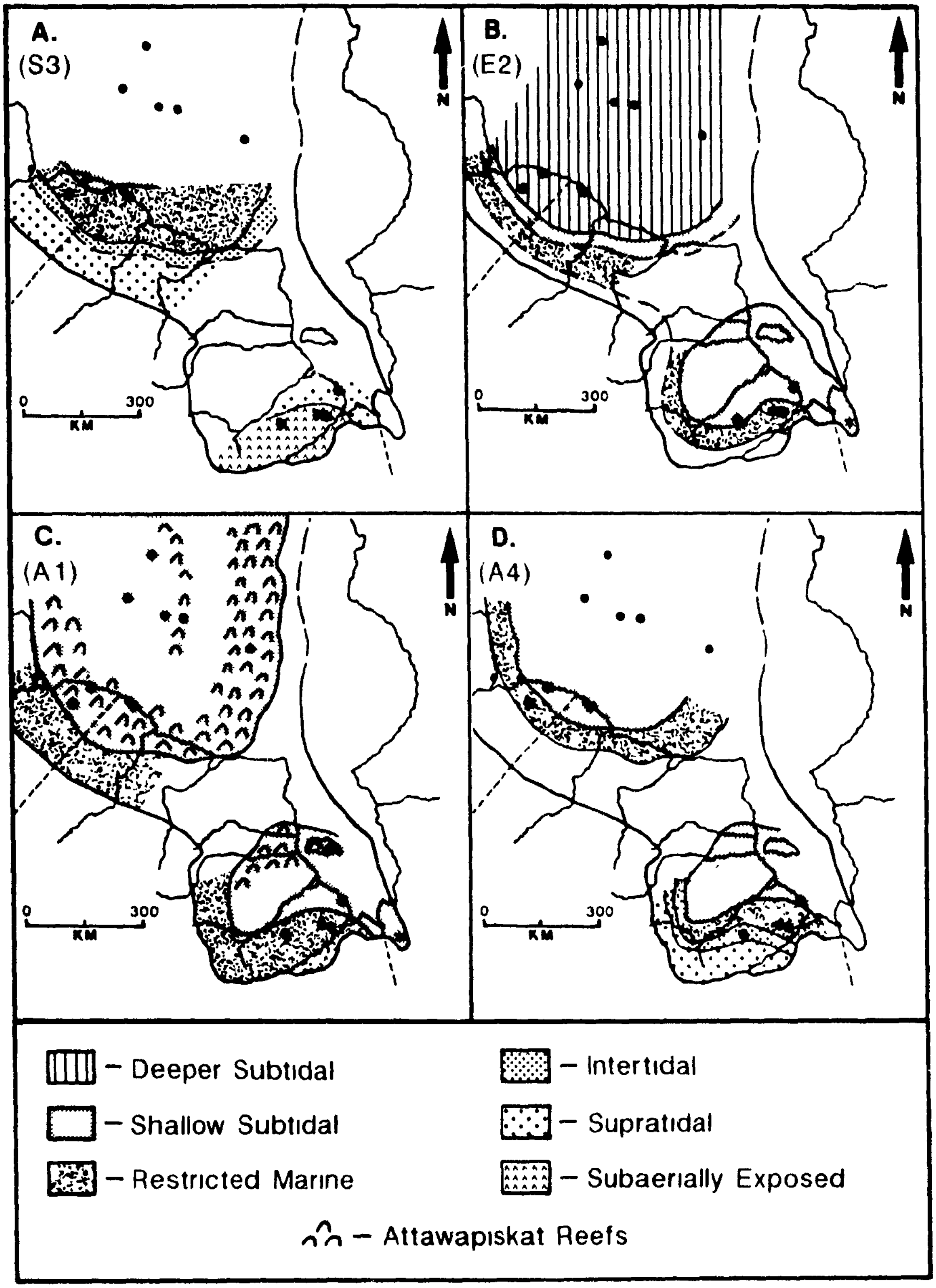
<u>Paleogeography</u>

The initial Silurian transgression began slowly (Figure 18A). It progressed from the north-northeast and gradually inundated the area of the Kaskattama, Pen Island No. 1, and Comeault wells. Sanford (1987) suggested that the connection to the open ocean was probably to the east or northeast. The southern Moose River Basin received primarily supratidal sediments and/or was subaerially exposed at this time.

During the long period of time represented by the lower half of the Severn River Formation, conditions across the basin fluctuated between supratidal and restricted marine environments. The first marine transgression into the Moose River Basin to any extent occurred in middle Severn River time, and resulted in restricted marine facies being deposited in the vicinity of the Puskwuche Point well, while restricted marine to shallow subtidal facies were being deposited in the southwestern Hudson Bay Basin.

During the maximum relative sea-level highstand of the Ekwan River Formation (Figure 18B), the deepest-water conditions of the Silurian prevailed in the southwestern Hudson Bay Basin, and probably in the basin center as well, while shallow to moderately deep, open-marine conditions persisted over most of the rest of the platform. Shallow subtidal facies were deposited in the outcrop study area. Restricted marine facies were deposited in the area of the Ardagh and Onakwahegan wells, while shallow subtidal conditions occurred briefly at the site of the Jaab Lake well. This area was much shallower throughout Early Silurian

Figure 18. Paleogeographic reconstructions of facies distributions for maximum sea level highstands of selected parasequences in the Llandovery Series of the Hudson Bay Platform. The parasequence represented by each map (see Figure 8) is labelled in parentheses in the upper left of the map. Key of depositional environments is as used throughout this paper. Positioning of facies boundaries away from specific datum points is based on present formation boundaries and basement contours shown in the maps of Sanford and Grant (1990); facies boundaries are dashed where inferred. These maps are also based on Sanford's (1987) assumption that the Cape Henrietta Maria Arch was a positive topographic element. Distribution of Attawapiskat reefs is, in part, from Sanford and Grant (1990). For identities of wells, see Figure 1.


A.
(S3)
B.
(E2)
C.
(A1)
D.
(A4)
N
0
300
KM
– Deeper Subtidal
– Shallow Subtidal
– Restricted Marine
– Intertidal
– Supratidal
– Subaerially Exposed
– Attawapiskat Reefs

time than were the rest of the Moose River Basin and the Hudson Bay Basin.

During growth of the reefs of the Attawapiskat Formation (Figure 18C), shallow to moderately deep, open-marine conditions prevailed over most of the Hudson Bay Platform. Conditions in the southwestern Moose River Basin were somewhat restricted.

Subsequent marine inundations were much less widespread, although one short-lived one in the upper Attawapiskat Formation (Figure 18D) did result in deposition of shallow-marine sediments over a wide area. This was the last marine inundation of the Silurian documented in the rock record that deposited subtidal facies in both the Hudson Bay and Moose River Basins. Subsequent marine facies in the uppermost Attawapiskat Formation were deposited only in the Hudson Bay Basin prior to final shallowing, while supratidal facies were being deposited in the Moose River Basin.

These data do not indicate whether the Cape Henrietta Maria Arch was a positive topographic element during Early Silurian time. Sanford (1987) stated that it was a positive element during the Middle Ordovician, and implied that it continued to be so through the Silurian. Sanford and Norris (1973, p. 399) wrote that "during the Early Silurian erosional interval, the Ordovician succession was removed in locally uplifted areas," and "in these localities, Middle Silurian carbonate rocks overlap Ordovician strata to rest directly on the Precambrian." Their list of such localities included some on the Cape Henrietta Maria Arch, suggesting that it was a positive topographic feature during the Silurian. Also, on maps of Early Silurian tectonic elements and Middle Silurian facies distributions, Sanford (1987, Figure 14, p. 494, and Figure 17, p. 497) drew the arch as a positive tectonic element and showed the Attawapiskat reefs as "fringing bank and barrier reef deposits" on the flanks of the Cape Henrietta Maria Arch.

The similarity of the Lower Silurian stratigraphic succession in the Hudson Bay Platform to those in southern Manitoba and the Lake Temiskaming area of eastern Ontario suggests that these areas were part of the same depositional province and were connected by seaways (Johnson and Lescinsky, 1986), but no attempt was made in this study to test this hypothesis.

COMPARISONS WITH OTHER BASINS

Problems

In order to compare the curves from the Hudson Bay Basin with those from other basins, good time control on the stratigraphic section is required. Unfortunately, the biostratigraphic control is imprecise (Figure 19) because no graptolites occur in these rocks and the conodonts are either endemic or they are not biostratigraphically diagnostic (LeFevre *et al.*, 1976; Norford, 1981). Brachiopods are the best biostratigraphic indicators (Jin and Caldwell, in press), but even they give only very broad limits (Figure 19).

Another problem is that Johnson's (1987) curves, which are used for comparison, are very broad and general, unlike the detailed curve developed in this study.

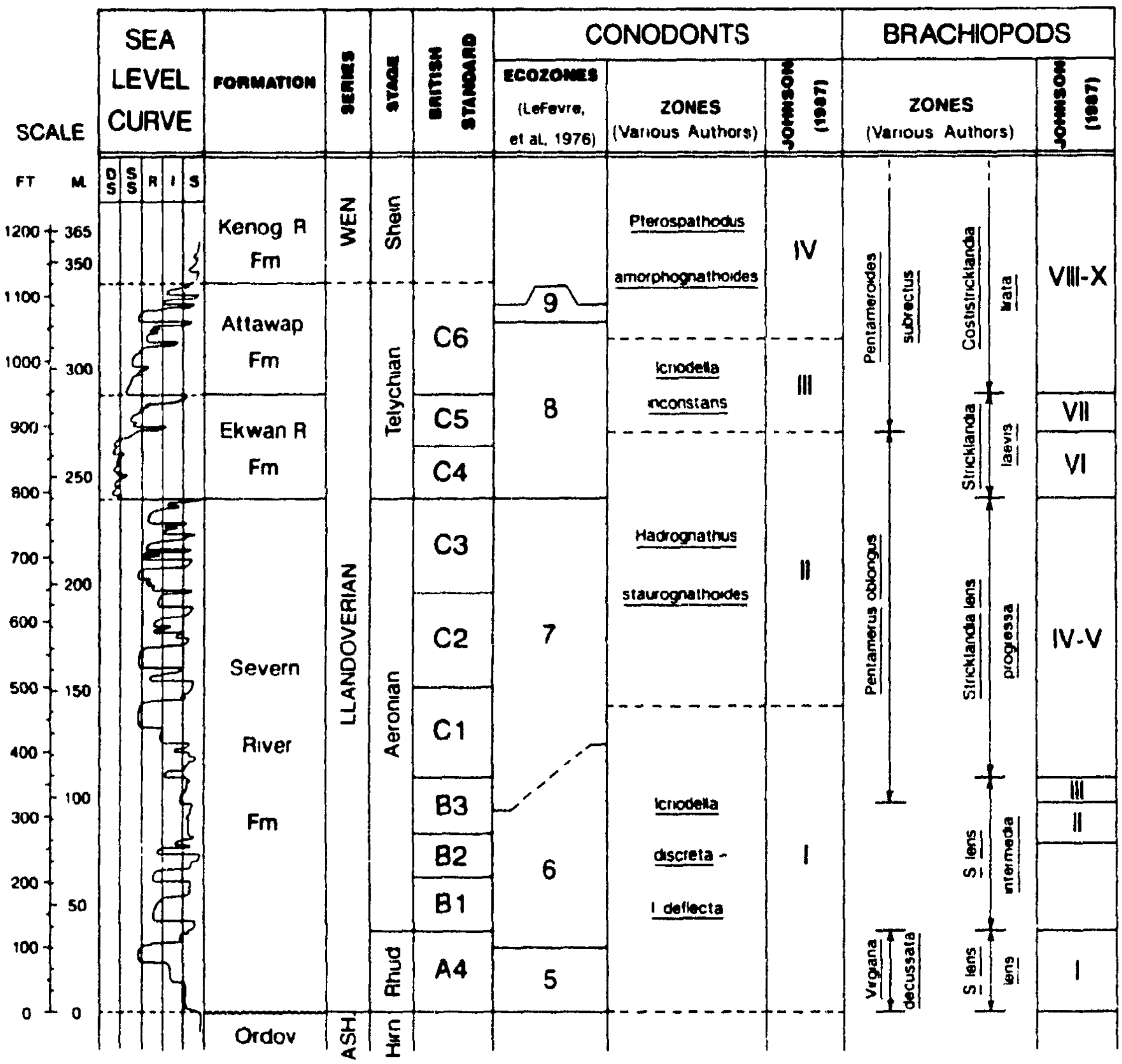


Figure 19. Biostratigraphic chart showing conodont and brachiopod zones of North America coordinated with the Silurian stratigraphic section of the Hudson Bay Basin as represented by an averaged relative sea level curve for that basin. Data is summarized from the studies of LeFevre *et al.* (1976), Norford (1981), Uyeno and Barnes (1983), Johnson *et al.* (1985), Johnson (1987), and Jin and Caldwell (in press). Johnson's (1987) conodont and brachiopod zones and the obsolete British standard time units are shown so that the Hudson Bay Basin curve can be compared with curves for other basins in North America that were presented in earlier publications.

Methods

In order to make a broad general curve from the detailed one of this study, a computer program was used to statistically smooth it. The composite curve for the Hudson Bay Basin was first digitized by measuring its deviation to the left at each 10-foot interval (Figure 20). Subsequently, a SYSTAT software program was used to statistically smooth the digitized curve using a nonlinear smoothing filter (Wilkinson, 1989).

The statistically smoothed curve was then redrawn (Figure 21) so that it could be compared to Johnson's (1987) curves. The Hudson Bay curve had to be squeezed in some places and stretched in others to accommodate the time frame set up by Johnson.

Results

In spite of the poor time control, some correlations are apparent (Figure 21) The four sea-level highstands (indicated by arrows in Figure 21) that Johnson (1987) considered to be significant, and that he correlated among several basins across North America, also correlate with four main sea-level highstands indicated for the Hudson Bay Basin.

The unconformity at the Ordovician-Silurian boundary in the Hudson Bay region (base of Figure 21) coincides with similar hiatuses reported across North America and around the world (Berry and Boucot, 1970, 1973; Trettin, 1976; Vail and Mitchum, 1979; McKerrow, 1979; Lenz, 1982; Barnes, 1986). The lowstand

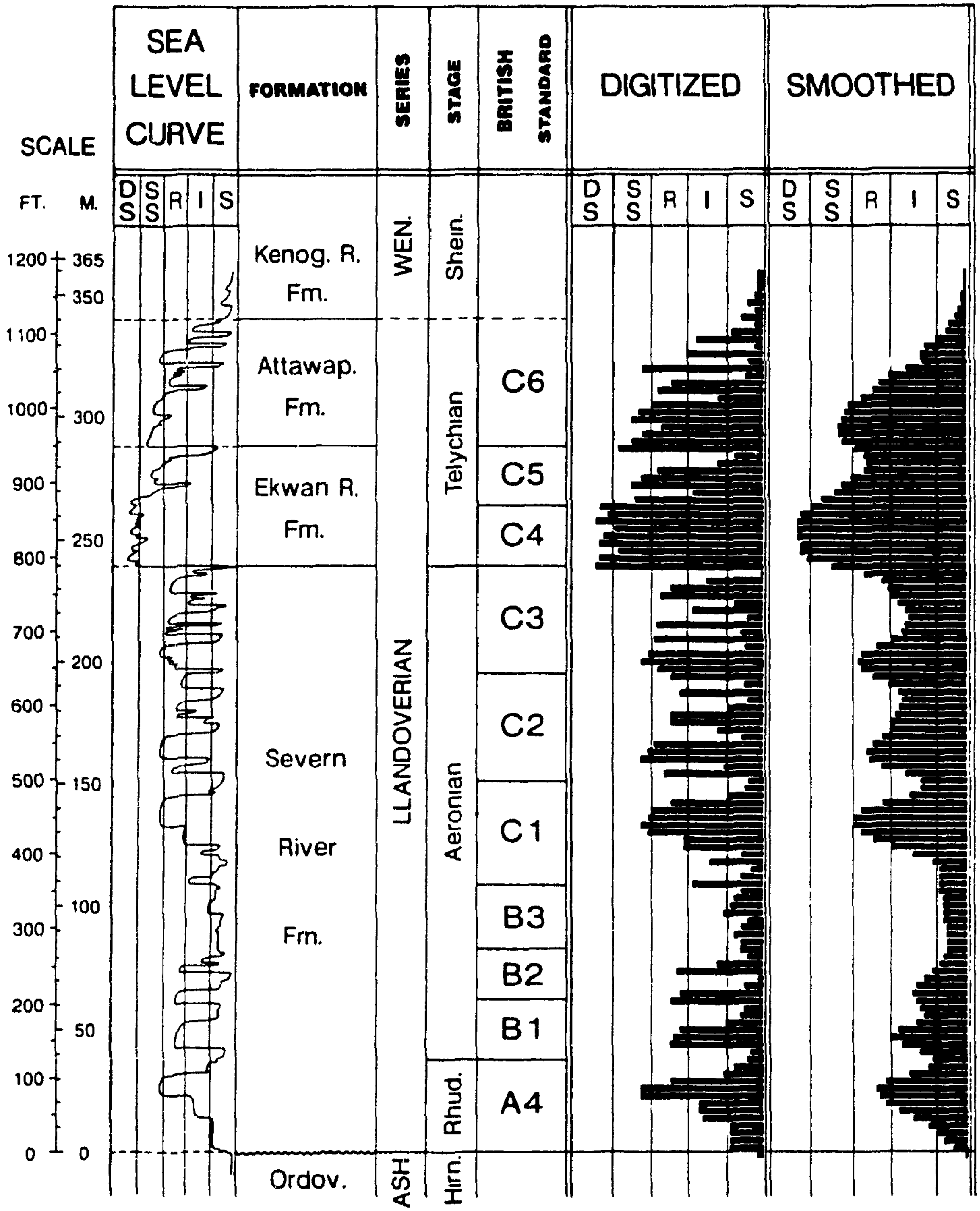


Figure 20. Chart relating computer manipulations of averaged Hudson Bay Basin curve, the digitized version of this curve, and the computer-smoothed version of the same curve.

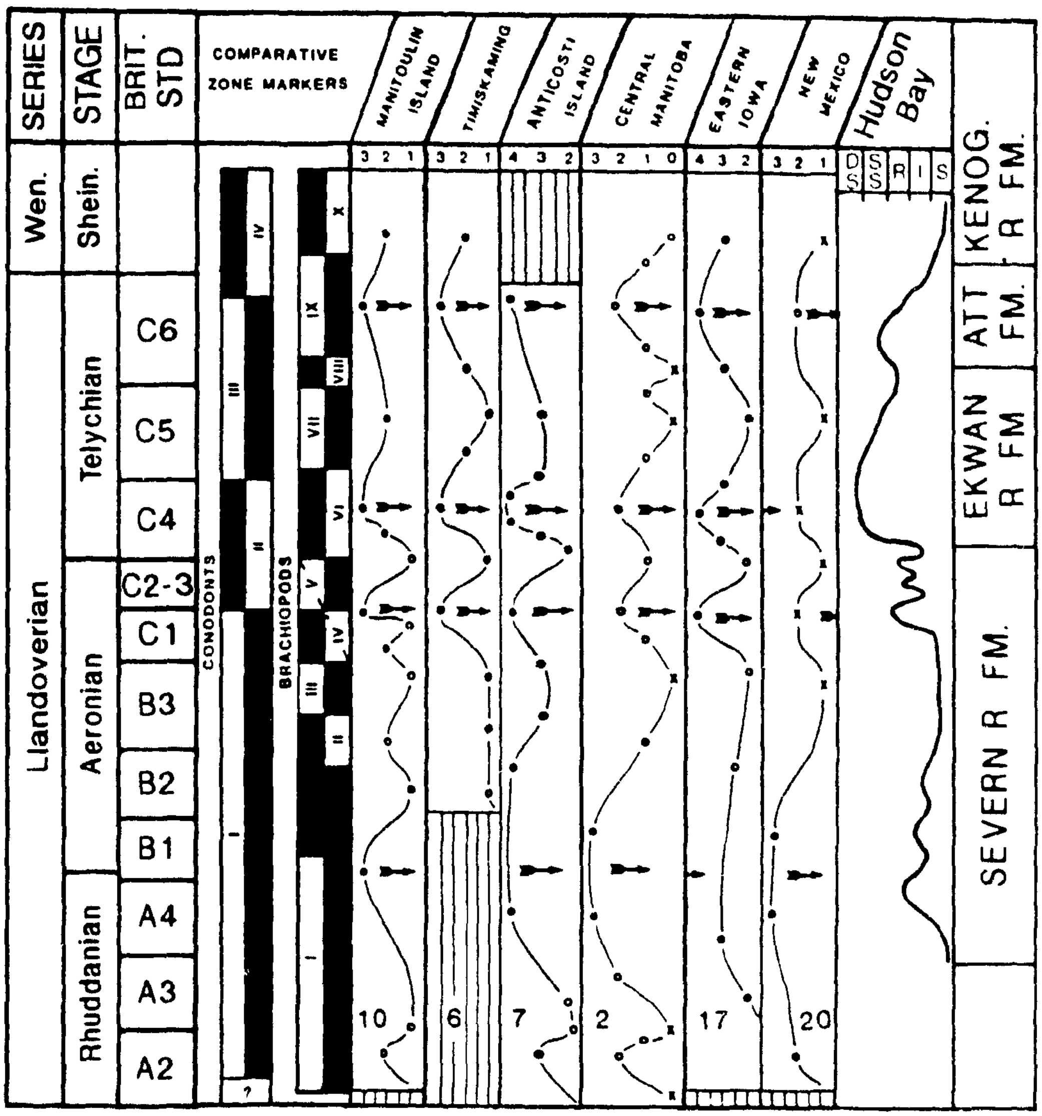


Figure 21. Comparison of Hudson Bay Basin curve with selected curves from Johnson (1987). Arrows indicate Johnson's four major sea level highstands. Base of the figure is base of the Silurian. (Modified from Johnson, 1987, Figure 6, p. 198-199).

in mid-Aeronian time (late middle Llandovery; B3-C1) also correlates across North America (Johnson, 1987). The disconformity at the base of the Ekwan River Formation (base of C4 in Figure 21) may correlate to a reported "widespread break in deposition" recorded in strata across much of the U.S. referred to by Berry and Boucot (1970, p. 67) as "after C1 to C2 time and prior to C5 time."

SUMMARY AND CONCLUSIONS

Relative sea-level curves were constructed for individual localities on the Hudson Bay Platform on the basis of depth-dependent carbonate facies. Changes in those facies reflected the local interplay of subsidence, sedimentation, and eustatic sea-level changes.

Comparison of the Hudson Bay Basin curve with those of other basins suggests that at least the large-scale depositional changes represented by the relative sea-level curves were controlled by eustatic changes in sea-level. That the effects of the small-scale relative sea-level changes can be traced for hundreds of kilometers across the Hudson Bay Platform suggests that these changes were also largely eustatically controlled. Subsidence rates were relatively uniform within each of the two basins (although greater in the Hudson Bay Basin) through most of Llandoverian time. Only at the end of Llandoverian time did major faulting occur.

Application of sequence stratigraphic methods to the carbonates of the Hudson Bay Platform has demonstrated:

1. the details of relative sea-level changes in the two basins,
2. that onlap at the base of the Silurian succession progressed from north to south,
3. that sea-level retreat at the base of the Kenogami River Formation was from south to north,
4. that the boundaries of the Severn River, Ekwan River, and Attawapiskat Formations can be redefined on the basis of objective criteria,
5. that marine carbonates can be correlated with supratidal carbonates based on matching trends in relative sea-level curves,
6. that beds in the upper Ekwan River Formation in the southern part of the Moose River Basin correlate with the Attawapiskat reefs of the northern margin of this basin,
7. that beds at the top of the Ekwan River Formation on the Attawapiskat River are not correlative of the Attawapiskat reefs downstream,
8. that only a single episode of reef growth is represented by outcrops on the Attawapiskat River,
9. that facies distributions of individual parasequences can be plotted on paleogeographic maps for small intervals of geologic time.

CHAPTER 3

MORPHOLOGY OF THE ATTAWAPISKAT REEFS AND DEPOSITIONAL HISTORY OF THE ATTAWAPISKAT FORMATION IN OUTCROP

INTRODUCTION

In Chapter 2, the basinwide geologic setting of the Attawapiskat Formation was explored, and the Attawapiskat reefs were placed within a scheme of relative sea-level change for the Silurian in the Hudson Bay region. Such a large-scale study has provided a broad perspective in which to view smaller-scale relationships within the Attawapiskat Formation itself. In this chapter, the focus turns to local relationships in the outcrop study area (Figures 1 and 4), in particular to the morphology of the Attawapiskat reefs and the depositional history of the Attawapiskat Formation.

The morphology of Silurian reefs cannot always be determined from outcrop relationships. For example, Shaver and Sunderman (1989) critically reviewed Silurian reef models, including shallow- and deep-water models, and they discussed the proposed relationships between reef core and reef-flanking beds. They attacked particularly those authors who have supported a concept of wave-swept benches and clinothems to explain steeply dipping reef-flanking beds exposed in outcrops where no reef core is exposed. The problem is primarily one of incomplete exposures: in outcrops where only reef-flanking beds are exposed, they cannot be related to a reef core; at some localities the relationship between reef core and flanking beds is obscured by cover or weathering; in other outcrops, subsequent erosion has planed off portions of the reef core and reef-flanking beds. These problems force workers to speculate as to original reef morphology.

In contrast, the Silurian reefs of the Attawapiskat Formation are well exposed in outcrops along the Attawapiskat River in the Hudson Bay Lowlands of northern Ontario (Figures 1 & 4), and they clearly reveal the morphology of the reefs and the relationship between the reef cores and flanking beds and the post-reef beds. They also provide evidence to indicate the amount of syndepositional relief on the reefs during their growth.

MORPHOLOGY AND SYNDEPOSITIONAL RELIEF OF ATTAWAPISKAT REEFS

Several lines of evidence in outcrop exposures indicate that the Attawapiskat reefs had considerable relief during their development.

Reef Mounds

The most obvious evidence is in the morphology of the reefs in outcrop

(Figure 14; for position of locality 88-15, see Figure 22). Reef-flanking beds dip at high angles on the sides of the reef cores (up to 35 degrees at this locality), and gradually become horizontal in inter-reef areas (not seen in Figure 14). Post-reef beds drape over reef topography and fill in low places between the reefs. The reef-rock itself is primarily a stromatoporoid-coral boundstone to framestone, and the reef-flanking beds are very fossiliferous, particularly brachiopod-rich, rudstones. The overlying beds are sparsely fossiliferous to nonfossiliferous wackestones grading upsection to oolitic grainstones, which are overlain by lenses of microcrystalline dolostone, followed by fenestral limestone, more dolostone, another fossiliferous wackestone unit, and finally evaporitic dolostones. From the relationships shown here (Figure 14), the original depositional relief can be inferred to have been at least 8 meters.

Just around the corner to the left of the exposure at locality 88-15, and perpendicular to it, is another reef exposure (Figure 23). The two exposures together allow a good 3-dimensional view of the stratigraphic relationships. Dips of the reef-flanking and post-reef beds between the two reef knobs in Figure 23 are as much as 60 degrees; geopetal studies by Chow (1986) indicated that 6 to 25 degrees of the dip of flanking beds on Attawapiskat reefs is compactional in origin. This locality is one of many examples in which the hill or island behind reef exposures is believed to represent reef topography. That is, the two reef mounds shown in Figure 23 are actually reef knobs protruding outward from the main reef represented by the hill behind.

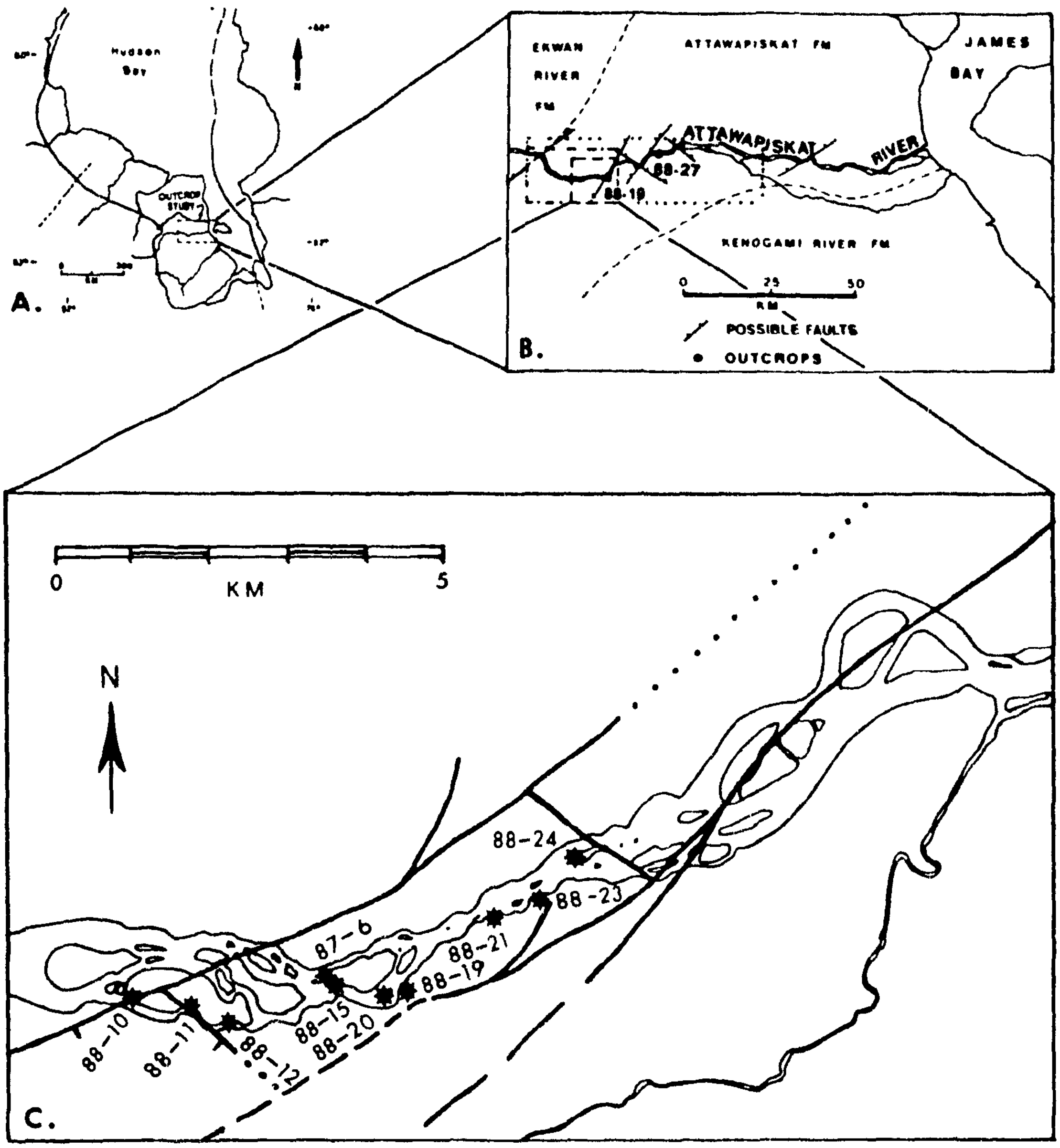


Figure 22. Locality map showing position of outcrop study area along Attawapiskat River west of James Bay (Figs. 22A & 22B), and a short section of the river (Fig. 22C) in which specific localities cited in the text are shown. In Fig. 22B, the dashed outline indicates the area of Fig. 22C, the dash-dot outline is the area of Fig. 30, and the dotted outline indicates the area of Fig. 31. In Fig. 22C, faults are shown by heavy dark lines and locality positions are shown by stars.

Figure 23. Reef outcrops exposed just around the corner to the left of locality 88-15 (Figure 22). The reef seen on the right here (10 m high) is the same one seen on the left in Figure 14. Another reef knob appears on the left, and between the two reef knobs are reef-flanking and post-reef beds that dip steeply toward the river.

One island, 60 m across and 10-12 m high (locality 88-20; see Figure 22) has flanking and draping beds dipping off the reef all the way around the island. Apparently, that island in the river represents one small individual reef, with original depositional relief of at least 10 meters.

Debris Flows

The presence of debris flows on the flanks of the reefs also indicates considerable depositional relief.

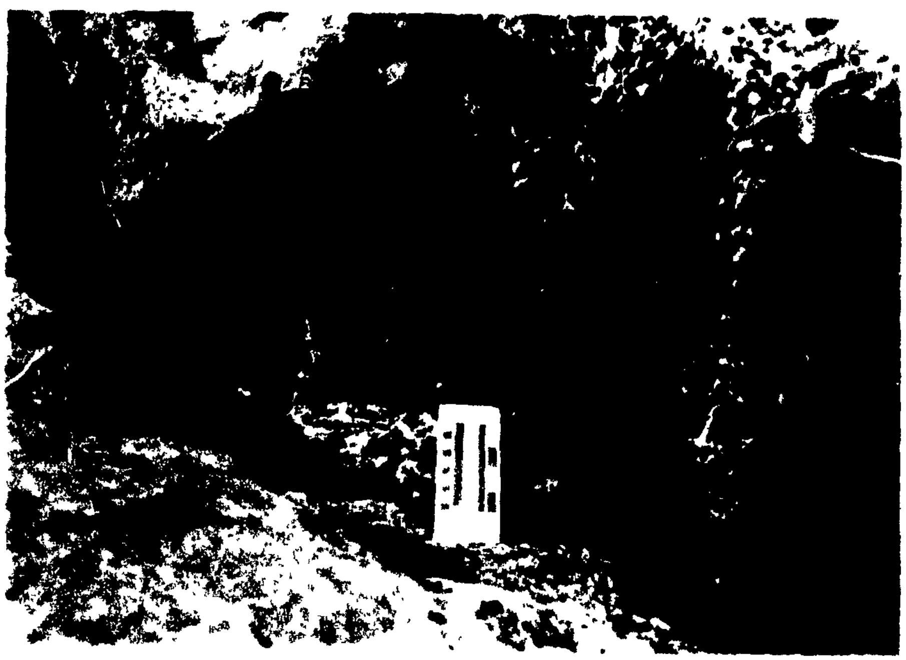
Lens-shaped Pods.--The lens-shaped pod in Figure 24A (locality 88-21; see Figure 22) is part of a debris flow deposit encased in reef-flanking beds that dip steeply toward the river. A small exposure of *in situ* reef rock was found in the woods about 5 m above and 20 m behind this outcrop, verifying that the hill behind the outcrop represents a reef. The lens, 5 m high and 14 m across, consists of rudstone to wackestone, with abundant, angular fossil fragments and rock fragments. The dipping, layered beds above and below the lens are typical of flanking beds found on all the reefs along the river. They are fossiliferous rudstones and wackestones, rich in brachiopods (many *in situ*) and other fossil debris (e.g., stromatoporoid and coral fragments, with some specimens in life position). Similar lens-shaped pods were found in reef-flanking beds at other localities along the river. The lens shape of the pods and deformation of the enclosing beds is probably due to later compaction.

Figure 24. A. Lens-shaped pod of debris-flow material encased in stee ›ly dipping beds on the flanks of a reef represented by the hill behind the outcrop exposure. The outcrop is 8 m high. (Locality 88-21).

B. Large *in situ* favositid (circular feature above and to left of scale) in bed immediately above the debris-flow lens (visible below and to left of favositid) in Fig. 24A.

A.

B.



The lens in Figure 24A represents a debris flow that occurred on the flanks of the reef while the reef was still actively growing. Further evidence for this is a large *in situ* favositid coral in the bed immediately overlying the lens (Figure 24B), suggesting that the reef was actively growing even after deposition of the debris flow. The flanks of the reef were steep, and judging from the outcrop relationships, the reef had a relief of at least 8-10 m.

Debris Flow Tongue.--The lower end of a debris flow is shown in Figure 25A. This debris flow "tongue" fanned out at the base of a slope. Its upper end is narrow and encased in reef-flanking beds that dip off the reef in the hill behind. A knob of reef rock protruding from the main reef is exposed beside the debris flow "tongue." The "tongue" extends further than the river bank shown in Figure 25A (remnants of it can be recognized in the river), but much of it has been broken and eroded away by river ice.

Beneath the broken front of the "tongue" is a group of *in situ* corals (*Pycnostylus*?) and stromatoporoids that apparently were living there before being covered by the debris flow (Figure 25B). The debris flow material itself (Figure 25C) consists of angular limestone clasts and broken fossils floating in a lime mudstone matrix. The clasts also contain fossils similar to those in the matrix. Enclosure of the neck of the debris flow "tongue" within reef-flanking beds, coupled with the presence of *in situ* corals directly beneath the debris flow, suggests that the debris flow occurred while the reef was still active. Outcrop relationships

Figure 25. A. Debris flow fan at the base of a slope; it has a narrow neck encased in layered reef-flanking beds (near right edge of photo). Reef knob in upper right protrudes from main reef in hill to the right. (Locality 88-23).

B. *In situ* corals and stromatoporoids (lower three-fourths of photo) beneath the broken edge of the debris flow "tongue" (upper one-fourth of photo).

C. Broken edge of debris flow "tongue," revealing angular limestone clasts and broken fossils in lime mudstone matrix. Clast at left center is 22 cm long. Light colored limestone in lower left is beneath the debris flow.

A.

B.

C.

suggest at least 6-8 m of relief on the reef.

Reef-flanking Beds Against Vertical Reef Face

At locality 88-27 (Figure 22B), nearly horizontal reef-flanking beds rest directly against a vertical reef face (Figure 26). These beds are clearly a continuation of reef-flanking beds that dip off the main part of the reef in the hill behind, and that were deposited against this spur of the main reef. The beds drape over irregularities in reef rock below them, and laminae of the beds trend directly into small irregularities in the vertical reef face beside them; this evidence precludes the possibility of the beds having been juxtaposed against the reef by faulting. Additionally, at the top of the outcrop, stratigraphically higher beds can be seen to drape over the reef rocks on the left and the flanking beds on the right.

Here we have clear evidence of syndepositional relief of the reef of at least 6 meters.

Geometry of Reef-Flanking Beds

The geometry of the reef flanking beds at many localities reveals that brachiopod communities existed on the flanks of the reefs penecontemporaneously with the reef crests. The flanking bed in Figure 27 (locality 88-24; see Figure 22) dips at 20-25 degrees off the side of the reef, and it contains a rich *Pentameroides* assemblage that apparently had lived there (abundant articulated, hollow brachiopod specimens in life position are present). This bed grades into and

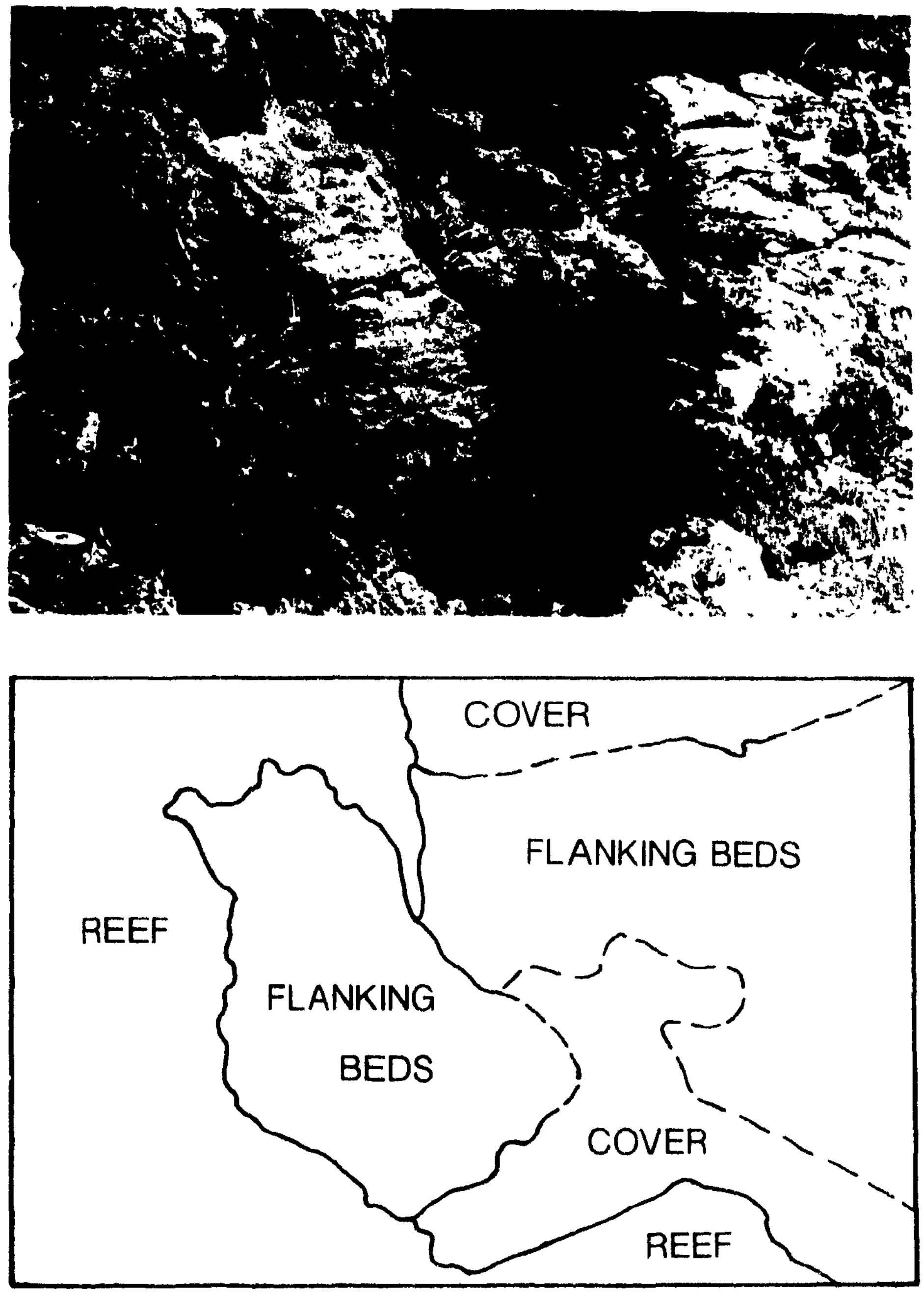


Figure 26. A. Remnant of reef-flanking beds (center and left-center of photo) that had been deposited against a previously-existing vertical reef face (exposed below, to left of, and above flanking-beds remnant). Reef-flanking beds dip off reef behind the beds shown in right half of photo. (Locality 88-27) B. Interpretive drawing of outcrop in above photo.

Figure 27. Reef-flanking bed beneath the person dips at 20-25 degrees off the side of the reef, and it contains *in situ* fossils of a rich *Pentameroides* community (locality 88-24; Fig 22). Reef rock is exposed beneath the bed and in the foreground. This flanking bed interfingers with the reef crest, which is exposed to the right of the photo view and is 4 m vertically higher than the brachiopod bed. Overall height of the outcrop is 8 m.

interfingers with reefal boundstone at the crest of the reef, thereby verifying the penecontemporaneity of the brachiopod bed and the reef crest. The reef crest is 4 m higher vertically than the brachiopod bed, indicating that the reef had an original relief of at least 4 m, and probably more.

Large Slide Blocks

Three large blocks at locality 88-19 have apparently slid down the flanks of a reef (Figure 28A). The question is: when were the blocks emplaced, soon after the reefs formed or much later?

The rocks on the left in Figure 28A are reef flanking beds draped over a reef beneath them. A small drill core was taken to a depth of over 5 m here, revealing reefal boundstone to the bottom of the hole beneath the flanking beds. The three blocks are labelled #1, #2, and #3, from left to right, as they successively overlie each other. Block #1 consists primarily of cobble to boulder breccia overlain by fenestral limestone. Block #2 is nearly all fenestral limestone. Block #3 is white nonfossiliferous fine-grained lime mudstone (probably supratidal) at its base, overlain by brown fenestral limestone. A fragment of the white lime mudstone of block #3, found near the toe of the block, contains hopper-shaped crystal voids, suggesting a hypersaline supratidal environment of deposition. Overall, the succession of facies in the blocks suggests they were superimposed vertically before sliding in the same sequence as they now occur.

In all 3 blocks, the fenestral limestone shows obscure laminations that are

Figure 28. A. Three large slide blocks at locality 88-19. The mass of rocks in the left third of the photo consists of reef-flanking beds overlying reef rock. In the center of the photo is block #1, which is overlain by block #2 to the right, which in turn is overlain by block #3 visible in the trees near the right-hand margin of the photo. Note life jacket [very light colored; approximately 0.45 m (1.5 ft.) tall] tied to a small tree near lower left side of block #1 for scale.

B. Small tight folds in dolostone laminae at the toe of block #2 at locality 88-19. The folds have been highlighted with a marking pen.

A.

B.

disrupted and deformed as if the rock was semi-consolidated at the time of its movement. Relationships between the blocks are obscured by cover. At the bases of blocks #1 and #2 are lenses of soft yellow microcrystalline dolostone that apparently have been deformed by downslope movement of the blocks; they are internally deformed and in places pushed into overthickened lenses. All along the base of block #2 is a soft yellow dolostone "flour" that may have acted as a lubricating cushion upon which the block slid.

At the toe of block #2 are dolostone laminae exhibiting small tight folds that apparently resulted from movement of the block downslope (Figure 28B). These folded laminae suggest that the rocks were plastic and pliable when the blocks slid.

It is difficult to determine the timing of movement of the blocks down the flanks of the reef, but outcrop evidence indicates considerable tectonic activity closely following Attawapiskat reef time (to be discussed in Chapter 4; also see Sanford, 1987). Perhaps an earthquake associated with this faulting triggered movement of the blocks down the flanks of the reef. The apparently semi-consolidated nature of the blocks at the time of their movement suggests that they slid downslope early in their history, perhaps after early partial cementation, but before burial and later diagenesis indurated them into the hard rock they are now. If so, there must have been considerable relief over the side of the reef at the time.

DEPOSITIONAL HISTORY

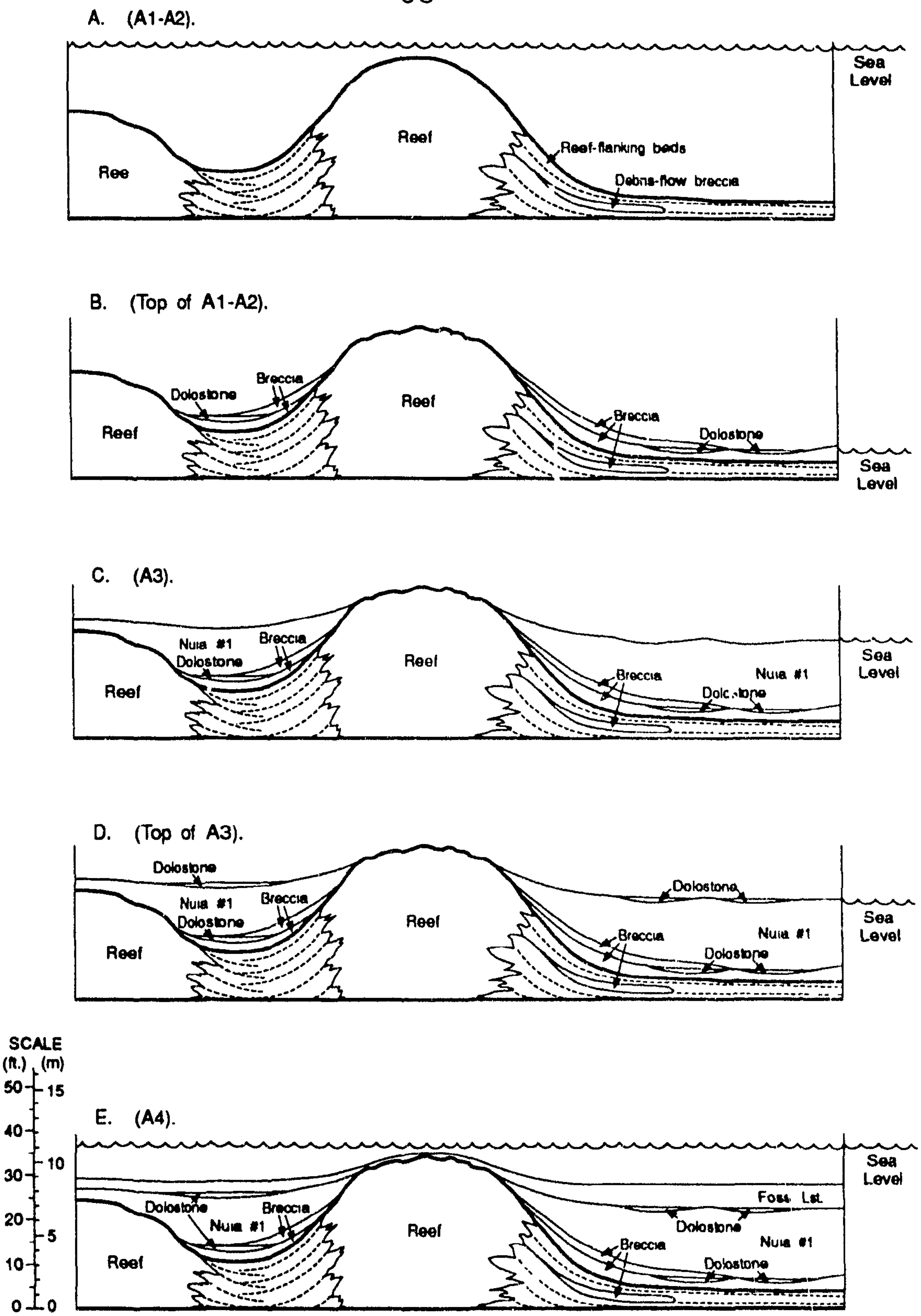
The depositional history of the Attawapiskat Formation proceeded as follows (Figure 29):

Interval A1-A2

As discussed above, the Attawapiskat reefs had a syndepositional relief of at least 8-10 m and the coarse-grained reef-flanking beds dipped steeply off their sides (Figure 29A). The contact between reef core and flanking-beds is irregular, gradational, and indistinct, but generally the reefs appear to be wider at their tops than at their bases. Debris flows shed from the reefs are encased within the reef-flanking beds at some localities, and brachiopod assemblages are present on the flanks of the reefs. The reefs grew in open-marine waters within normal wavebase. They represent a maximum highstand of relative sea-level during the depositional intervals labelled A1 and A2 in Figure 8 (Chapter 2).

At the end of interval A2 time, relative sea-level fell and exposed the reefs to local erosion (Figure 29B), which resulted in the deposition of breccias at some localities (e.g., localities 88-10, 88-15, 88-19, and 88-27 shown in Figure 22); these breccias contain angular fragments of reef rock on the flanks of the reefs and into inter-reef areas. One such breccia at locality 88-10 is highly weathered, crumbly, and bleached, and its uppermost parts approach a paleosol in composition and texture; it is also partially dolomitic and is overlain by a primary dolomicrite that is, in turn, overlain by stromatolites and stromatolite ripups; all of which is evidence

Figure 29. Schematic reconstructions of depositional history of Attawapiskat Formation in outcrop. Letters and numbers in parentheses refer to depositional intervals labelled in Figures 8, 13, and 17 (Chapter 2). Effects of progressive compaction have not been taken into account.



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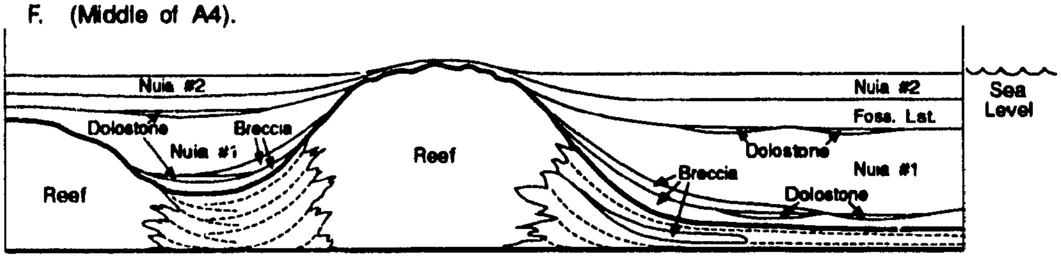
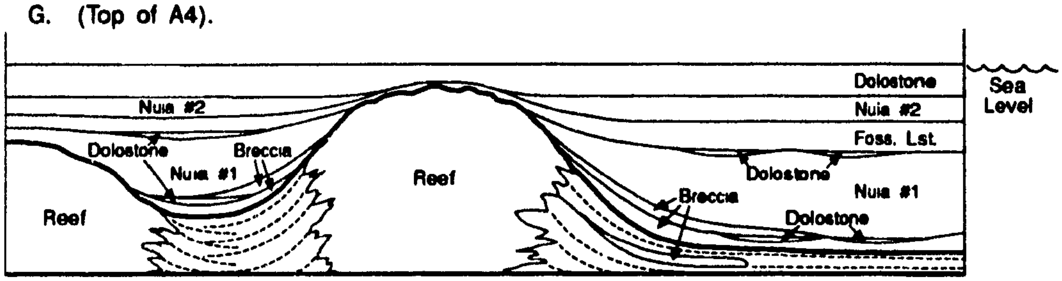
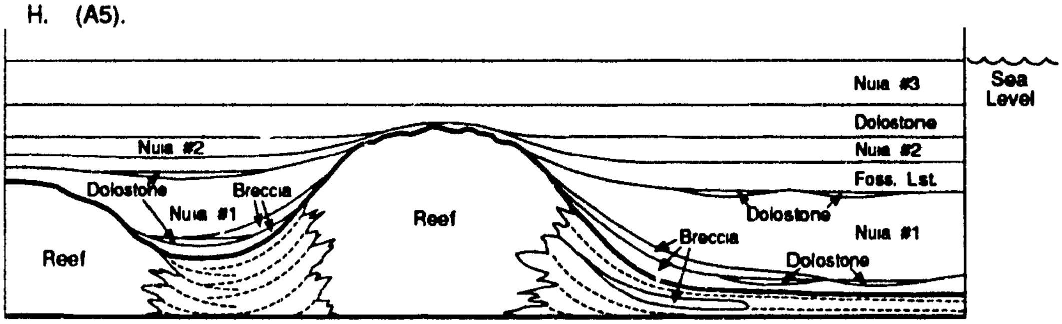
F. (Middle of A4).



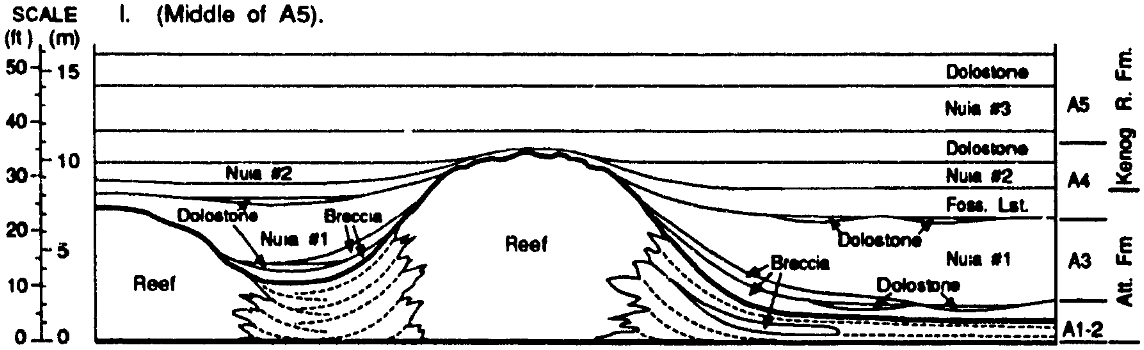
G. (Top of A4).



H. (A5).



I. (Middle of A5).



of subaerial exposure and hence a minor disconformity at this stratigraphic level. The rocks at this level at locality 85-8 are also weathered and vuggy, indicating subaerial exposure. Exposure must have been short-lived, however, because virtually no vadose cements are present in the underlying beds (Chapter 5). In the Hudson Bay Basin cores, the top of interval A2 consists either of white supratidal limestone containing only sand-sized algal debris or of algal micrite mud the upper surface of which is a bored hardground; no evidence of prolonged subaerial exposure occurs in these cores. In the Puskwuche Point well, a weathered irregular surface is present at the top of interval A2.

At most outcrop localities studied, primary dolomicrite lenses are present above the breccias (Figure 29B). A similar dolomicrite also occurs at this stratigraphic level in the Comeault well. Evidence that these dolostones are primary will be discussed in more detail in a subsequent chapter on petrography, but the evidence includes: 1) stratigraphic positions at the tops of shallowing-upward sequences (occur as dolostone lenses encased within limestones and they have sharp upper contacts and gradational lower contacts, indicating a depositional origin); 2) common association with stromatolites; 3) very finely crystalline fabric; 4) absence of fossils; and 5) no evidence of secondary recrystallization and no replacive fabrics. At a few localities [88-15 and 88-26 (near locality 88-27 in Figure 22)], breccias are present both below and above the dolostone lenses, testifying to the penecontemporaneity of the two facies. Many of the dolostone lenses contain stromatolites or stromatolite rip-ups near their tops. Relative sea-level was low and the dolostones may have been deposited in local supratidal ponds (Friedman, 1980).

Interval A3

A small rise in relative sea-level (A3; Figure 29C) gave rise to widespread supratidal ponds or hypersaline lagoons in which the alga *Nuia distincta?* flourished as a monoculture (discussed in detail in Chapter 5). Thick [up to 3.2 m (10.5 ft.)], laterally extensive *Nuia* grainstones with fenestral porosity were deposited in depressions between the reefs, and in a few places these grainstones were deposited over the tops of the smaller reefs or reef spurs. The tops of the taller reefs are not exposed in outcrop and therefore relationships between the *Nuia* beds and these reefs are unclear, but in some outcrops the *Nuia* beds may pinch out against the reef crests. A similar, 0.46 m (1.5 ft) thick *Nuia* grainstone bed occurs at this level in the Comeault well, but the Kaskattama and Pen Island No. 1 wells contain limestones with marine to restricted-marine fossil faunas at this stratigraphic level.

A drop in relative sea-level resulted in renewed deposition of dolomicrite lenses on top of the *Nuia* grainstone beds in the outcrop area (Figure 29D). These lenses are similar to those deposited beneath the *Nuia* grainstones. In the Pen Island No. 1 well, weathered chalky limestone that contains caliche crusts occurs at the top of interval A3.

Interval A4

A significant rise in relative sea-level (interval A4; Figure 29E) resulted in open marine conditions across much of the platform, and coarse-grained limestones with a diverse marine fauna were deposited. Evidence of shallow water and high energy conditions includes common overturned stromatoporoids, corals, and brachiopods, broken and abraded shell fragments, wavy beds, and cross laminations. This fossiliferous bed does not represent a rejuvenation of reef growth because no reefal boundstone is present and there is evidence for significant relative sea-level lowstands, subaerial exposure, and termination of reef growth in strata between this fossiliferous bed and the underlying reefs (see above). This bed drapes over the tops of reefs in outcrop.

As relative sea-level began to drop during interval A4 time, conditions again became favorable for *Niua* grainstone beds to be deposited over much of the outcrop area (Figure 29F). In the Pen Island No. 1 well, another weathered chalky limestone interval is present at the top of interval A4, and a soft, yellow, dolomicrite occurs at this level in the Comeault well.

Post A4

In most outcrop exposures, only a small portion of the beds overlying interval A4 remain (Figures 29G, 29H, and 29I). Where present, they are evaporitic dolostones which commonly contain stromatolites and intraclastic breccias. At localities 88-7 and 88-16 (near 88-15) (Figure 4), a third *Nuia* grainstone bed (A5) occurs above these dolostones and is, in turn, overlain by more dolostones. In the Hudson Bay Basin cores, two more minor restricted-marine intervals occur above interval A4, and the upper part of each one is a weathered caliche interval.

The top of the Attawapiskat Formation was defined in this study (Chapter 2) as the highest occurrence of marine or restricted-marine fossils in the Silurian section. No fossils other than *Nuia* were identified in the upper two *Nuia* grainstone beds in outcrop exposures, and so these beds are interpreted to have been deposited in supratidal ponds (discussed in Chapter 5). Therefore, the boundary between the Attawapiskat Formation and the Kenogami River Formation in the outcrop sections is placed at the top of the fossiliferous marine limestone of interval A4 (Figure 29I). In the Hudson Bay Basin cores, this boundary is above interval A6 (Chapter 2).

SUMMARY AND CONCLUSIONS

The outcrop evidence cited above clearly reveals the relationships between reef cores and flanking beds, and the syndepositional relief of the Attawapiskat reefs. The evidence includes the morphology of the reefs and flanking beds, breccia lenses within reef flanking beds, the debris flow "tongue" at the base of a reef flank, thin reef-flanking beds truncated against a vertical reef face, penecontemporaneous brachiopod beds on the flanks of reefs, and the large slide blocks. The Attawapiskat reefs evidently had an original syndepositional relief of at least 8-10 meters.

Schematic reconstructions of the depositional history of the Attawapiskat Formation in outcrop portray a stratigraphic sequence that was controlled by relative sea-level changes during Late Llandoverian time. The high-relief Attawapiskat reefs were terminated by a relative sea-level fall, which resulted in erosion of the reefs and deposition of primary dolostone lenses and limestone breccias. A minor relative sea-level rise made conditions favorable for the deposition of thick *Nuia* grainstone beds, which filled depressions between the reefs and draped over the tops of the smaller reefs. More primary dolostone lenses were deposited on top of the *Nuia* grainstone beds when relative sea-level dropped to a low level. One more significant relative sea-level rise resulted in the deposition of a coarse fossiliferous limestone, which gave way to another *Nuia* grainstone bed as relative sea-level again began to fall. Subsequent deposition of dolostones of the Kenogami River Formation occurred as relative sea-level continued to fall, but this was interrupted by the deposition of one more *Nuia* grainstone bed before relative sea-level fell for the last time in the Silurian.

CHAPTER 4

REGIONAL DISTRIBUTION OF REEFS AND FAULTS

INTRODUCTION

A question was raised in Chapter 2 as to whether the distribution of reefal outcrops along the Attawapiskat River represents one or several intervals of reef growth. It was determined that the reefs so exposed represent a single interval of reef growth, and that, generally speaking, the reefs are progressively buried beneath the Kenogami River Formation in a downstream direction. However, this scheme of things is complicated by faulting (Figure 22). It was suggested that the periodic occurrence of reefal outcrops along the river separated by stretches of the river with no outcrops could be explained as a result of block faulting. This chapter will develop those concepts and show how the interpretations were made.

The outcrops along the Attawapiskat River are the major exposures of the reefs in the Moose River Basin, although some reefs also crop out along the

Ekwan River (Figures 2 & 4). No Attawapiskat reefs have been found in the southern Moose River Basin, but they completely encircle the Hudson Bay Basin as thick bank and barrier reef deposits (Figure 2) (Sanford, 1987).

The Attawapiskat Formation contains well-developed stromatoporoid, coral, and algal patch reefs and associated "off-reef" or inter-reef, shallow-water carbonate sediments. It overlies the Ekwan River Formation and is, in turn, overlain by the Kenogami River Formation (Figure 3). It is correlative to parts of the upper Ekwan River Formation in the southern Moose River Basin, but along the Attawapiskat River the two formations are not lateral facies equivalents (see Chapter 2). The Attawapiskat Formation represents the last open-marine incursion in the region during the Silurian. The evaporite facies of the overlying Kenogami River Formation indicate that relative sea-level was very low throughout the time of its deposition, and suggest that the Attawapiskat reefs were terminated by this relative sea-level drop (see Chapter 2). The distribution of the reefs in the outcrop study area will be discussed in this context.

AERIAL PHOTO AND OUTCROP RELATIONSHIPS

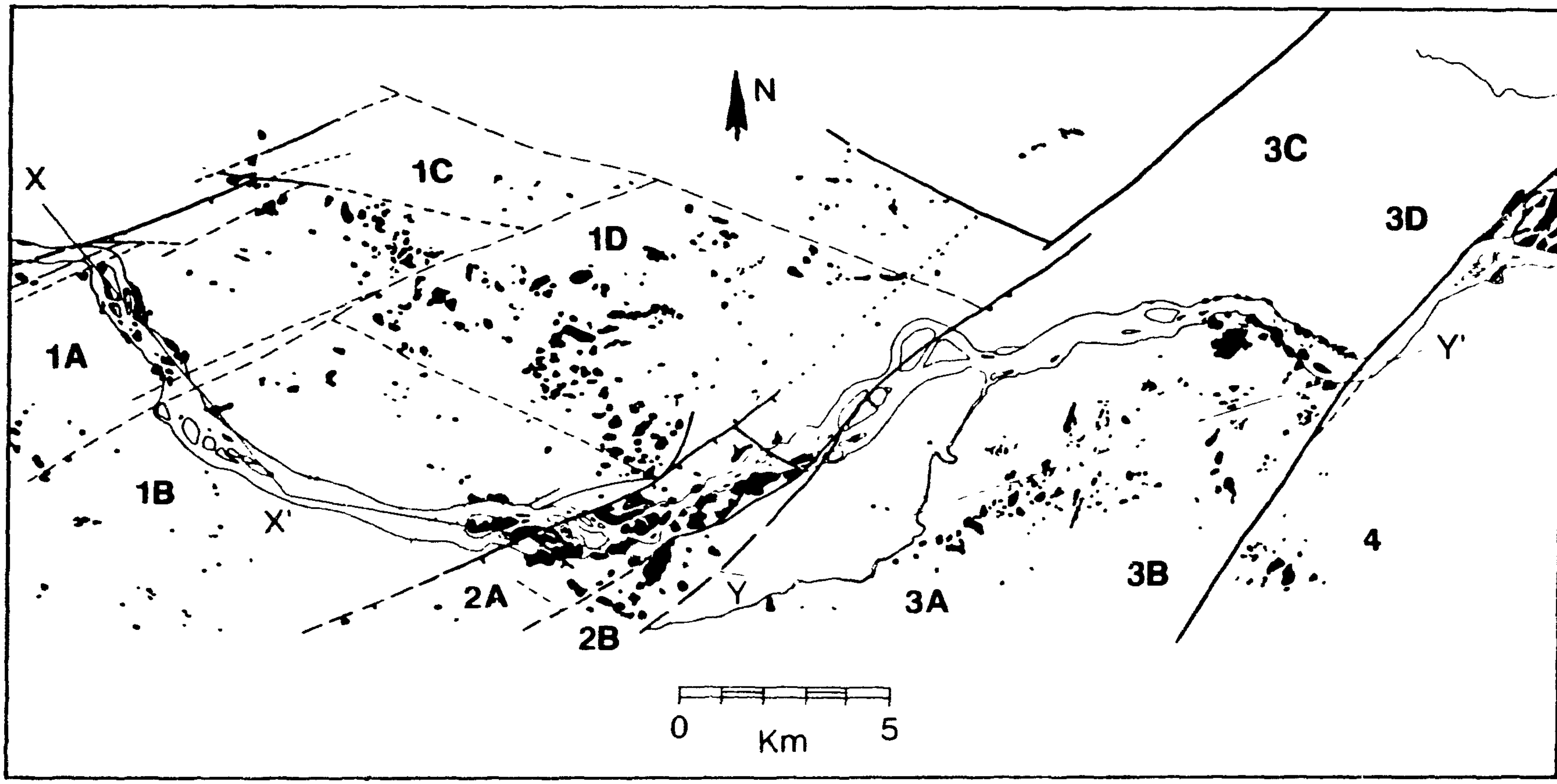
Evidence

Aerial photos and field data were used to interpret reef distribution and to determine the presence and positions of faults in the outcrop study area (Figures 22, 30, and 31). The positions of reefs along the river are certain, as they were mapped in detail in the field. Additionally, some localities within a few hundred

Figure 30. Aerial photo of area outlined in Figure 22. Rocks of the Ekwan River Formation underlie the area in the upper left corner of the photo (above and to the left of the fault). Known or inferred reefs are outlined in red, and known or inferred faults are shown as blue lines (dashed or dotted where less certain). [Composite of air photos A24036-145 and A24036-147; these aerial photographs, © 1975 Her Majesty the Queen in Right of Canada, reproduced from the collection of the National Air Photo Library with permission of Energy, Mines and Resources Canada].


0
5
Km

Figure 31. Map showing distribution of Attawapiskat reefs and faults along the Attawapiskat River, as traced from aerial photos. Left two-thirds of Figure 31A is the area shown in Figure 30. See Figure 22 for location of these maps. Faults shown by solid lines are certain or obvious, whereas those shown by dashed to dotted lines are increasingly less certain. Major fault blocks are numbered, and smaller fault blocks within the major ones are additionally assigned letters (e.g., 1A, 1B, etc.). Line XX'YY' is position of cross section shown in Figure 33.



A.

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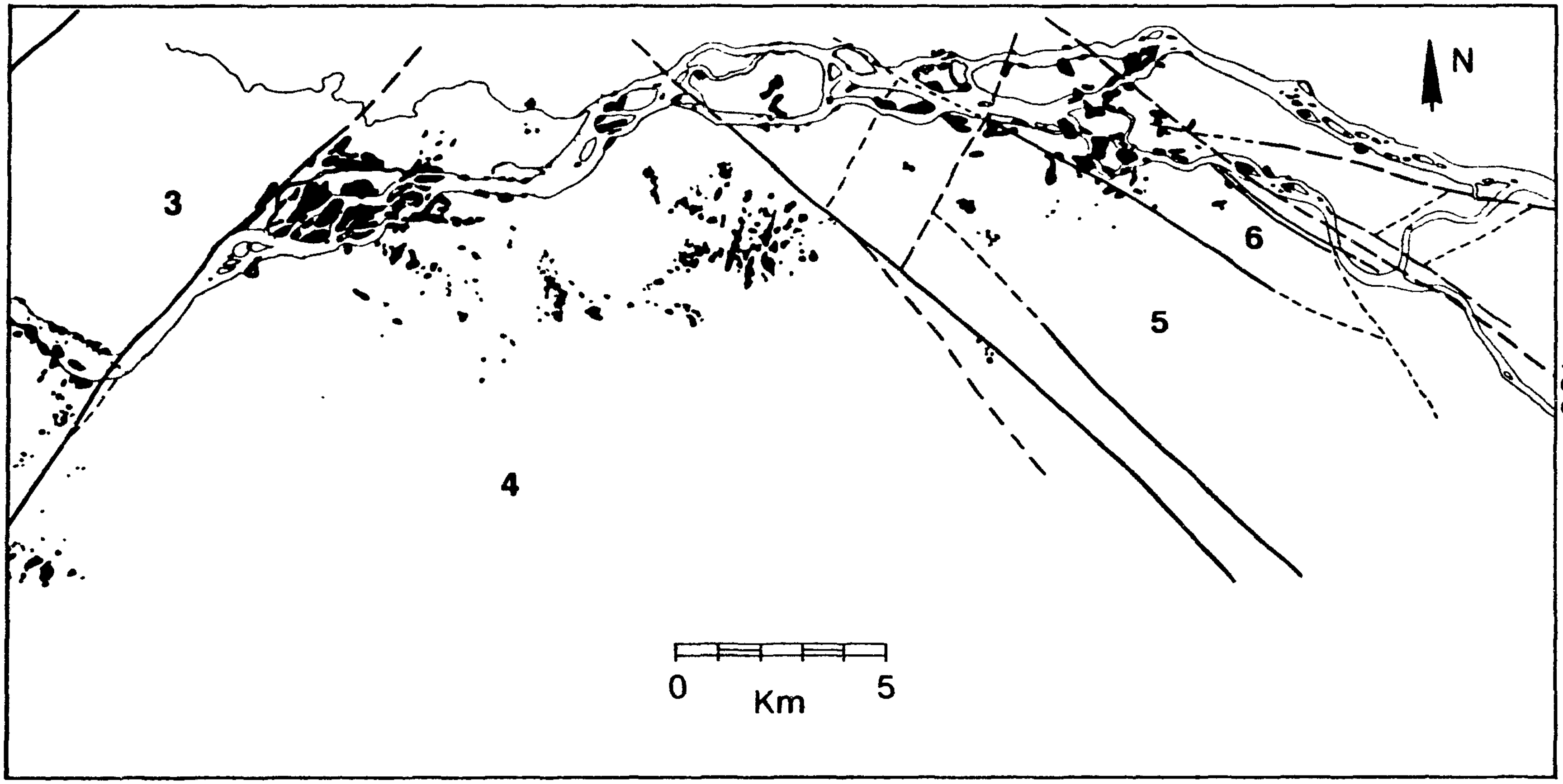


B. (Continued from previous page)

meters of the river were accessed by foot, and several reefal exposures protruding above the muskeg swamp away from the river south and north of locality 88-19 (Figure 22) were visited by helicopter.

Farther away from the river, certain topographic highs were inferred to be reefs on the basis of aerial photo interpretation only. Some of the criteria used for these interpretations include: abrupt protrusion above the muskeg swamp, especially where the protrusion appears to be exposed rock; apparent association with and similarity to known reef exposures; and the presence of recent karstic "moats" surrounding some reefs (Cowell, 1981). A reefal interpretation is less certain at localities farther from the river and where the relief of the topographic high is less abrupt. It is also less certain in the vicinity of raised beaches near the coast (not shown in Figures 30 and 31).

Peat islands within the muskeg swamp can also create topographic highs, but their characteristics are different from those created by reefs. Their relief is lower, less abrupt, and more subdued. They are more rounded or tear-drop shaped, as opposed to the irregular shapes of reefs, and they do not show evidence of being obstacles in the regional movement of swampy vegetative material downslope as do reefal bedrock protrusions (J. Parry, pers. comm). Many peat islands also have collapse scars in their centers as a result of degradation of permafrost lenses beneath them (Hustich, 1957; Sjors, 1959; Zoltai, 1972; Prest, 1983; Zoltai *et al.*, 1988).

Some faults were identified in outcrops and their attitudes were measured (localities 88-10 and 88-11; Figure 22). These fault locations and their attitudes correspond well to certain lineaments seen in aerial photos (Figure 30). Major lineaments were also verified on landsat photos of the area; the faults between blocks 1 and 3 and blocks 3 and 4 (Figure 31) were especially obvious on landsat photos.

The fault between the Ekwan River Formation and the Attawapiskat Formation (Figure 30) was initially inferred in order to explain outcrop relationships (i.e., the juxtaposition of the Ekwan River Formation against the stratigraphically higher Attawapiskat Formation; see Chapter 2) and was subsequently related to lineaments seen on aerial photos. For example, aligned oriented lakes, other subtle linear trends, and an abrupt change in the river course are all evidence of the presence of a fault here. Also, upstream from the fault no reefs occur, but immediately adjacent to the fault, on its downstream side, very high (10-12 m) reef exposures occur in abundance.

In a like manner, the presence of two subparallel faults between blocks 1A and 1B (Figures 30 and 31) was initially suspected because many large reefal outcrops occur upstream from the faults, but immediately downstream no reefs occur, only low mud banks. Subsequently, subtle lineaments on the aerial photos could be traced through this locality.

Other faults were inferred on the basis of aerial photo interpretation alone, taking into account visible lineaments, changes in topographic expression across linear trends, changes in the course of the river, long linear stream channels, and abrupt changes in reef distribution. Lineaments seen on the aerial photos ranged from the obvious to the subtle (Figures 30 and 31). In places (e.g., the dashed faults shown in block 1 of Figure 31A), apparent to subtle lineaments and their relationships to reef distribution were used as evidence for the presence of faults. The faults between the Ekwan River and Attawapiskat formations, between blocks 1 and 3, and between blocks 3 and 4 are also accompanied by abrupt changes in the course of the river.

Fault Complexity

Many of the faults in the outcrop area are not simple linear faults, but complex fault zones. The best example of this is in fault block #2 (Figures 30 and 31). Lineaments on aerial photos here show complex relationships, as do outcrop exposures.

At locality 87-6 (Figure 22), several large blocks of rock are tilted on their sides (Figure 32), which can only be explained as resulting from tectonic activity. This locality is in the center of a large complex fault zone (Figure 31), and is not far from locality 88-19, where the 3 large slide blocks discussed in Chapter 3 are located (see Figures 22 and 28).

At locality 88-10 (Figure 22), a fault is present in which reef-flanking and post-reef beds on the southeastern side of the fault are juxtaposed against reef rock on the northwestern side of the fault, with no interfingering, and with fault slickensides exposed. Between the bedded rocks and the reef, a 1-m thick fault

Figure 32. In center of photo, large block of bedded limestone (reef-flanking to post-reef beds) is tilted on its side, with the bedding planes perpendicular to the plane of the photo. In the left part of the photo is reef rock, possibly in original position. In the right third of the photo is another tilted block of reef rock and associated bedded limestones tilted on its side, with bedding planes parallel to plane of photo. To the right of the photo view are 3 other large blocks tilted on their sides at disparate attitudes. Note person for scale in center of right block. (Locality 87-6; Fig. 22).

gouge occurs; and the fault undulates within 1-2 m of the fault "plane." The fault had a general orientation of 70 degrees E. of N., it dipped 80-90 degrees E., and it was downdropped to the southeast. Movement on the fault at this locality was apparently only a few meters at most. Nearby, at locality 88-11, two parallel vertical faults 2-3 m apart are oriented at 15-20 degrees W. of N., and each is downdropped 1.5-1.7 m to the southwest, for a total of at least 3 m of movement along the fault zone. Therefore, the faults at localities 88-10 and 88-11 are a conjugate pair in which the block south of their juncture is downdropped.

Complex faulting has also affected the reefs and stratified rocks at locality 88-12 (Figure 22), but the relationships could not be determined due to inaccessibility resulting from steep cliffs and swift currents.

The evidence cited above indicates that much of fault block 2 has been affected by complex faulting, which has disrupted the stratigraphic relationships.

Timing of Faulting

Faults, once initiated, often remain the focus of subsequent tectonic adjustment throughout the geologic history of a region. Faults and arches on the Hudson Platform have been periodically reactivated from Proterozoic to present times (Sanford, 1987).

The complex fault zone in the vicinity of fault block 2, and the large blocks of rock tilted on their sides at locality 87-6, indicate that a major faulting and earthquake event occurred in this region at some time in the past. The closely associated slide blocks at locality 88-19 were probably emplaced during the same event, and the evidence cited in Chapter 3 suggests that these blocks slid down the flanks of the reef a short time after Attawapiskat reef time.

Additionally, seismic sections across the central uplift in Hudson Bay indicate a major tectonic event subsequent to Attawapiskat Formation time but prior to Kenogami River Formation time. Sanford's (1987; also see Grant and Sanford, 1988, and Sanford and Grant, 1990) structural cross sections showed strata of the Severn River, Ekwan River, and Attawapiskat formations on the tops of uplifted fault blocks on the central uplift, which are directly overlain by Devonian rocks. In the sub-basins beside the uplifted blocks, Kenogami River Formation sediments were deposited directly against the sides of the uplifted fault blocks. The seismic sections from which these interpretations were made clearly show the relationships; seismic reflectors of the Kenogami River Formation trend directly into the uplifted fault blocks, indicating that the Kenogami River Formation sediments were deposited after uplift of the fault blocks (A. Grant, pers. comm., 1988). The total displacement on some of these faults in the center of Hudson Bay is 500 meters; movement along faults in the Attawapiskat River area was certainly much less, probably less than 20 meters.

Apparently a major earthquake and faulting event occurred soon after deposition of the Attawapiskat Formation, at a time when only the first few beds of the Kenogami River Formation had been deposited. Sanford (1987) suggested that intensive tectonic movements during this time corresponded to similar events across North America, and he (p. 488) linked them to "Caledonian events in progress at the same time in the East Greenland and Appalachian orogens."

Relatively minor movement along these faults could also have been occurring since the last deglaciation as a result of isostatic uplift of the region. According to Dredge and Cowan (1989), the area of the Hudson Bay Lowlands west of James Bay has been uplifted 180 m in the past 8,000 years, 130 m of which occurred between 8,000 and 4,000 years ago. Their sea-level emergence curves suggested initial isostatic rebounds of at least 7.5 m/century, and they estimated present-day emergence rates of 0.9 to 1.2 m/century. This magnitude of movement of the crust certainly must have required some readjustment along many pre-existing faults in the area. Such readjustment would account for the relatively "fresh" appearance of some faults in outcrop and in aerial photos (particularly the faults between blocks 1 and 3, and between blocks 3 and 4; Figure 31). Other faults may not have been recently reactivated, for example the less apparent ones in the outcrop study area (shown by dashed and dotted lines in Figure 31).

Distribution of Reefs Relative to Faulting

Distribution of the reefs in outcrop along the Attawapiskat River is strongly influenced by a complex system of conjugate faults with vertical displacements (Figures 30, 31, and 33). The northeasterly and northwesterly orientation of these conjugate faults coincides with a similarly oriented, continent-wide system of

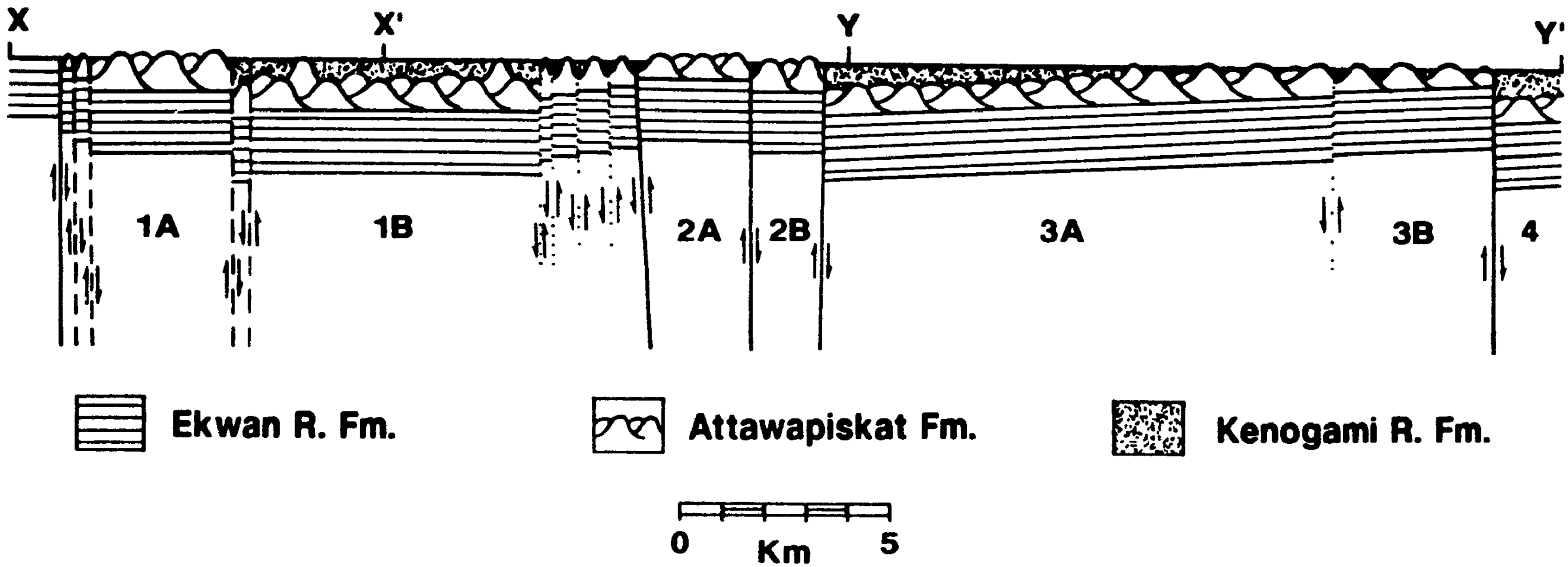


Figure 33. Schematic drawing of vertical profile XX'YY' from Figure 31A. No vertical scale implied.

arches and basins discussed by Sanford *et al.* (1985). According to these authors, the arches and their attendant faults criss-cross the continent as a result of tectonic stresses induced at the continental margins throughout geological time. They claimed (p. 54) that the most intensive and widespread regional stresses were "associated with principal orogenic events ... during Taconian, Acadian (Caledonian) and Alleghenian orogenies," and that "the most intensive arch movements were along the southeast and northeast margins of the craton bordering the Appalachian and East Greenland orogens respectively."

In the outcrop study area, the system of conjugate faults defines a series of individual fault blocks (Figure 31). In fault block #1, an apparent trend of reef occurrences extends in a northwest-southeast direction, and it is terminated by the fault between blocks 1 and 2 (Figure 31A). However, complications within the block also seem to have uplifted block 1D relative to the other blocks, and blocks 1B and 1C are downdropped relative to the others (also see Figure 33). The downdropped position of block 1B relative to block 1A accounts for the 10-m-high reefs exposed along the river on block 1A, whereas virtually no reefs occur on block 1B (only 2 or 3 very low (<1m) reef-rock exposures).

Fault block #2 is uplifted as a horst, exposing many reefs to a low level. However, as previously discussed, the faulting is complex and many fault splays and fault block splinters occur. In the fault block splinter just west of the main fault between blocks 1 and 2, the reef exposures are small and low, whereas reef exposures within block 2 are high and extensive.

Fault block #3 appears to be tilted, exposing progressively more reefs in a downstream direction (Figures 31A and 33). Apparently no reefs are exposed in fault blocks 3C and 3D, suggesting that they are downdropped; the Kenogami River Formation, which is easily weathered and forms no outcrops, underlies the surface here.

Fault block #4 is tilted so that its northern corner is uplifted relative to its southern portion (Figure 31B). As such, the fault between blocks 3 and 4 is a scissor fault. Subtle lineaments within block 4 suggest the presence of other, less active faults. Complex faulting occurs in the vicinity of blocks 5 and 6, but block 6 is apparently uplifted relative to other blocks around it.

In the remaining 50 km of the river downstream from block 6, only 3 small, very low reef outcrops occur. The last one is 15 or 16 km upstream from the mouth of the river. Only the top few centimeters of these reefs are exposed, indicating that the overall trend is for the reefs to be progressively buried beneath the Kenogami River Formation downstream.

SUMMARY AND CONCLUSIONS

Evidence from aerial photo interpretation and field data was used to make inferences about reef distribution and faulting. Some of the faults are complex fault zones with numerous fault splays and fault-block splinters. The faults have been reactivated periodically since Proterozoic times, and a major tectonic event occurred just after the close of Attawapiskat Formation time, resulting in considerable uplift of the central Hudson Bay arch and a major earthquake event in the vicinity of the present-day Attawapiskat River. Minor movement on some of the faults has also taken place within the last 8,000 years. The positions of the faults and fault blocks presently control the distribution of reefal outcrops along the Attawapiskat River. Reefs are exposed only where the Attawapiskat Formation is uplifted to the surface, and no reefs occur where the blocks are downdropped and the easily-weathered Kenogami River Formation underlies the surface.

CHAPTER 5

PETROGRAPHIC ANALYSIS OF FACIES, CEMENT, AND DIAGENETIC FEATURES

INTRODUCTION

This chapter focusses on the petrography of the Silurian (Llandoverian) rocks on the Hudson Bay Platform, especially those of the Attawapiskat Formation, and examines the vertical and regional distribution of facies, fossils, and cements, and briefly discusses diagenetic overprinting and local dolomitization. This information casts additional light upon the depositional and diagenetic environments. The diagenesis discussion is brief because diagenesis of the Attawapiskat carbonates has been discussed by Chow (1986). The geochemistry of these carbonates is beyond the scope of this study.

DATA TABULATION

Figures A-1 to A-11 in Appendix A show stratigraphic sections, rock types, and the distribution and abundance of fossils and cements at drill core and outcrop localities in the study area (for map of localities see Figures 1 and 4). The rock types are tabulated by circles and fossil abundances are depicted as histograms. These data were obtained primarily from thin section study, but outcrop and hand sample data were also incorporated.

The main focus of Figures A-1 to A-10 is the Attawapiskat Formation, but part or all of the Ekwan River Formation is shown in the drill core sections and part of the Severn River Formation is shown in the Puskwuche Point well section.

Most of outcrop section 85-8 (Figure A-6) consists of post-reef beds. Outcrop relationships reveal that the lowest 8.5 ft. (2.6 m) shown in Figure A-6 are reef-flanking beds that are time equivalent of the reef core; all overlying beds are post-reef. Also shown below the stratigraphic section in Figure A-6 are data from a sample of the reefal boundstone at this locality, taken from the reef core next to the reef-flanking beds, and data from a brachiopod coquina (or brachiopod wackestone) lens high on the flank of the reef.

At locality 88-19 (Figure A-7), 21 ft. (6.4 m) of outcrop section were measured, and a 17-ft. (5.2 m) drill core was taken with a portable drill. All the strata shown are part of the Attawapiskat Formation (see relative sea-level curve in Figure 13). Only the lowest 8 ft. (2.4 m) contain reefal boundstone, but some of the immediately overlying beds may be time equivalent to the latest stages of reef growth.

Locality 84-2 (Figures A-8 through A-11) is a low outcrop of the surface of a reef. Its surficial facies were mapped in detail by Chow (1986). For the present study, 3 small drill cores were taken through the reef with a portable drill to examine its internal facies. The cores did not penetrate to the bottom of the reef.

FACIES AND FOSSIL CONTENT

Seven different rock types (most of which are limestones, except for rocks designated specifically as dolostones) are depicted in Figures A-1 to A-10, but they will be grouped for discussion in the following order: (1) reefal boundstones; (2) skeletal wackestones, grainstones, rudstones, and coquinas; (3) lime mudstones; (4) fenestral limestones rich in the alga *Nuia? distincta*; and (5) dolostones (primary and secondary).

(1) Reefal Boundstones

Reefal boundstones of the Attawapiskat Formation in the Hudson Bay Basin cores and in outcrop exposures along the Attawapiskat River contain an abundant fauna of high diversity. This facies is well represented in the Pen Island No. 1 core (intervals A1 through mid-A2 in Figure A-1) and the three small drill cores taken at locality 84-2 (Figures A-8 through A-11), but the facies has also been examined in detail at outcrop locality 85-8 (Figure A-6) and the lower part of section 88-19 (Figure A-7).

The cores from locality 84-2 are primarily reefal boundstone throughout their lengths, with the exception of the top 1.8 ft. (.55 m) of core 84-2-10,20E (Figure A-8), which contains crinoidal wackestone [Chow's (1986) "crinoidal caprock"].

Additionally, the boundstone at this locality is interrupted in its upper part by a 1-ft. (0.3 m) thick skeletal wackestone to rudstone (Figures A-8, A-9, and A-11). A similar coarse skeletal wackestone to rudstone interrupts the boundstone at locality 88-19 and in the Pen Island No. 1 core (upper interval A1 in Figures 8, A-1, and A-7); this interruption in boundstone production probably represents a shallowing event (top of A1) that affected all of these widely separated localities (Chapter 2).

Chow (1986) described a "sparse fossil zone" between the crinoidal caprock and the boundstone at locality 84-2, but he stated (p. 67) that this facies is "not easily distinguishable from the stromatoporoid coral framestone facies" and that crinoid fragments are absent or scarce within it. Core 20,10E (Figure A-9) was drilled in rock mapped by Chow (1986) as the "sparse fossil zone," and this rock type may constitute the upper 1 ft. (0.3 m) of the core, but little difference can be detected between this facies and the boundstone in the remainder of the core, and crinoids are common in all the samples from the core.

The reef rock at locality 84-2 has a number of different compositions: stromatoporoid/cement boundstone, stromatoporoid/algae/cement boundstone, algae/cement boundstone, and algae/skeletal-clast/cement boundstone. In rocks of the last category, skeletal clasts are coated and bound by algae (mostly *Sphaerocodium* and spongiostromatids) and micrite to microspar cement, and larger pores and vugs are filled with radial calcite cement; this rock type and the similar algae/cement boundstone may be equivalent to Chow's (1986) "sparse fossil zone." Locally within the reefs stromatoporoids and radial calcite cement are the major constituents, but by and large, algae and cement make up the bulk of the reef rock; in places the rock is greater than 50% cement (to be discussed later).

The paucity of corals at locality 84-2 is apparently peculiar to this reef; at other localities stromatoporoids and corals are both important framebuilders (e.g., locality 38-19 and Pen Island No. 1 core). Brachiopods and crinoids are common to abundant throughout, and ostracodes are common. A wide variety of other fossils are locally common to abundant in the reef rock. Algae (predominantly spongiostromatids) tend to dominate the upper parts of the reefs at localities 84-2, 88-19, and in the Pen Island No. 1 core (Figures A-1 and A-7 to A-10) and stromatoporoids are more abundant downsection, but the trend is not obvious.

The most common stromatoporoids in the Attawapiskat reefs include clathrodictyids, labechiids, *Ecclimadictyon*, and *Parallelostroma*. Corals include tabulates, colonial rugosans, and solitary rugosans: *Favosites*, *Halysites*, *Catenipora*, *Heliolites*, *Strombodes*, *Pycnostylus*, *Cystiphyllum*, *Subalveolites*, and syringoporids. The most common brachiopods are *Pentameroides*, *Lissatrypa*, *Atrypa*, *Whitfieldella*, *Ancillotoechia*, *Camarotoechia*, *Brachyprion*, *Fardenia*, *and Clorinda*. Spongiostromatids and *Sphaerocodium* are by far the most abundant of the algae, but the following are also common: *Renalcis*, *Epiphyton*, *Vermiporella*, *Girvanella*, *Hedstroemia*, *Halyses*, and *Parachaetetes*. For a complete list of fossils in the Attawapiskat reefs in outcrop, see Chow (1986, Table 4, p. 83-84). See Norford (1970) for a list of fossils in the Kaskattama No. 1 well.

Porosity in the reefal boundstones at some localities is generally low due to the large quantities of cement which occlude pore spaces, but intergranular porosity can be up to 50% within the skeletal wackestones to rudstones, and porosity may be high in weathered or vuggy intervals.

The Attawapiskat Formation in the Puskwuche Point core consists primarily of coral-rich, slightly bituminous, muddy rudstone, which approaches a boundstone composition in the lower half of the formation (Figure A-2). Fossil diversity is fairly high, but less than in the Pen Island No. 1 core. Corals and stromatoporoids predominate, and brachiopods become more common downsection. The algal content is lower than in the Pen Island No. 1 core, presumably because the waters were more turbid and unfavorable to algae growth, as indicated by the higher clay content. Porosity is low but increases in the more fossiliferous parts.

Conditions at the Puskwuche Point well site were apparently more restricted than in the vicinity of the Hudson Bay Basin cores and the outcrop exposures, but the fossil content in the three southwestern Moose River Basin cores is even more diminished, no boundstone occurs, and the matrix is muddier than in the Puskwuche Point well. Similar relationships apply to the Ekwan River Formation strata.

(2) Skeletal Wackestones, Grainstones, Rudstones, and Coquinas

Much of the Attawapiskat Formation consists of skeletal wackestones, grainstones, and rudstones. These facies represent reef-flanking beds (Figures

A-6 & A-7), some post-reef beds (especially those deposited during brief deepening events subsequent to reef demise; see Chapter 2; interval A4 in Figures A-1, A-6, & A-7), and pockets and admixtures within the reefs (Figures A-6 to A-10). Also, some of the strata in the three southwestern Moose River Basin cores that are time-equivalent to the Attawapiskat Formation elsewhere are wackestones and floatstones (intervals A1-A3 in Figures A-3, A-4, and A-5).

Generally, this facies is very coarse grained and contains an abundant and diverse fossil fauna. Many of the fossil fragments are broken and overturned, and some are abraded. Post-reef fossiliferous wackestone and rudstone beds are flat-lying, but reef-flanking beds commonly dip 25-35 degrees and can dip up to 65 degrees locally. Variable amounts of fine-grained admixtures are present within the coarse-grained beds, and minor fine-grained, but otherwise similar, interbeds are present. The fossil content is dominated by brachiopods, crinoids, and spongiostromatid algae, but stromatoporoids and corals are also very common (interval A4 in Figures A-6 & A-7). Any of the other fossils listed above for the reefal boundstone can also occur, especially on the flanks of the reefs.

Porosity in these coarse skeletal limestones ranges from low to moderately high, depending upon the percentage of fine-grained constituents which form the matrix and occlude pore space. Porosity is highest in the rudstones due to the coarse grain size and sparsity of cement and fine-grained matrix, and lowest in the finer-grained beds.

On the flanks of some reefs are local coquina lenses, which consist primarily of the small brachiopod *Whitfieldella* n. sp. (Jin, pers. comm., 1989); at other places on some reef flanks, assemblages of *Pentameroides septentrionalis* are common. Intergranular and intraskeletal porosities in these beds can be high.

Crinoidal wackestone beds at the top of core 84-2-10,20E (Figure A-8) (Chow's, 1986, "crinoidal caprock") consist of sand- to granule-sized skeletal fragments in a micrite mud matrix. Crinoids are by far the most abundant fossil (>15%), but brachiopods and ostracodes are common, and other fossils are present as well. This facies occurs locally at the tops of some reefs (Figure A-8) and as minor interbeds within the reefs or in the Ekwan River Formation (Figures A-1 & A-2).

(3) Lime Mudstones

Lime mudstones occur commonly as post-reef beds (upper intervals in Figures A-1, A-6, & A-7), or as the predominant reef-equivalent facies in regions where no Attawapiskat reefs grew (Figures A-3, A-4, & A-5), and as the predominant facies in the Ekwan River Formation in some areas (Figures A-1 and A-3 to A-5).

Post-reef lime mudstones in the Pen Island No. 1 well (intervals A5-A6 in Figure A-1) are sparsely fossiliferous, locally peloidal, with scattered sand-sized skeletal clasts. Brachiopods and crinoids are the most common fossils. Porosity is generally low due to the fine grain size and low fossil content.

The Ekwan River Formation in the Pen Island No. 1 core and the

Puskwuche Point core (Figures A-1 & A-2) consists predominantly of skeletal lime mudstones with some skeletal wackestones. The fossil fauna is less diverse and less abundant than in the Attawapiskat Formation and it is dominated by crinoids and brachiopods, but corals and stromatoporoids are common in some intervals. Low-diversity burrowed-firmground intervals are common in the lower part of the Ekwan River Formation. Porosity is generally low due to the fine grain size and low fossil content, but it increases in some of the more fossiliferous and coarser-grained intervals.

The upper Severn River Formation in the Puskwuche Point core is also primarily skeletal lime mudstones, but contains some interbedded oolite and dolomite intervals. Fossil diversity and abundance is low, but burrows and echinoids are common. Porosity is very low.

Secondary dolomitization has affected all of the rocks of the Ekwan River Formation in the three southwestern Moose River Basin cores, and has obscured original textures and features, but the original rock type and fossil diversity can still be ascertained (Figures A-3 to A-5). Originally, most of the rocks were fossiliferous lime mudstones with low fossil diversity and abundances, but some of the Attawapiskat-equivalent strata were wackestones and floatstones with common corals and stromatoporoids. Any algal remains that may have been present have been totally obscured by recrystallization. Porosity is low but increases locally in some of the more fossiliferous intervals.

(4) Fenestral Limestones (*Nuia* Grainstones)

Fenestral limestones are present in the upper Attawapiskat Formation and the lower Kenogami River Formation in the Pen Island No. 1 well (Figure A-1), in the Kaskattama and Comeault wells, and in most outcrop sections (Figures A-6 & A-7). These fenestral limestones are similar in appearance to the loferites of the Alpine Triassic described by Fischer (1964), but the ones in the Silurian of the Hudson Bay Platform are grainstones consisting primarily of fragments of the alga *Nuia*? *distincta*.

Fossil content in these beds is overwhelmingly dominated by *Nuia*, but there are local minor occurrences of small flat brachiopods (*Plectodonta*? or *Protomegastrophia*?), spongiostromatid algae, ostracodes, and/or crinoids. Some interstitial fine micrite mud occurs. Minor interbedded algal laminites, weathered dolomitic intervals, and minor calichification are also present. Porosity is usually at least 20-30% and locally approaches 50% due to the sparsity of pore-filling cement.

The *Nuia* grainstones are common in areas where open-marine conditions existed prior to their deposition, e.g., in outcrop sections along the Attawapiskat River and in the Pen Island No. 1 core; they do not occur in the Puskwuche Point well or the other three southwestern Moose River Basin cores. Along the Attawapiskat River, some outcrops of *Nuia* grainstone beds 6-10 ft. (2-3 m) thick are exposed for several hundred meters between reefal outcrops; outcrop relationships clearly reveal the *Nuia* beds to be post-reef in age.

(5) Dolostones

Two types of dolostones are recognized in the study area: primary and secondary. Primary dolostones are presumed to be evaporitic (Friedman, 1980) and are interpreted as being primary on the following criteria: stratigraphic position at the tops of shallowing-upward sequences (commonly as dolostone lenses encased within limestones), common association with stromatolites and sabkha-type evaporite minerals [gypsum, anhydrite (locally enterolithic), and local halite], very finely crystalline fabric [dolomicrite; sometimes inferred to represent aragonite mud that was replaced before burial (Morrow, 1990)], absence of marine fossils, good preservation of sedimentary and organic fabrics (commonly burrow-mottled) with no evidence of secondary recrystallization and no replacive textures.

Secondary dolostones in the study area are more coarsely crystalline (>20 microns) than the primary dolostones and they are clearly replacive: matrix and marine fossils are all recrystallized to coarse, euhedral dolomite, and original sedimentary textures and fabrics are obscured to nearly obliterated by dolomitization.

Primary dolostones occur locally in the upper Attawapiskat Formation (Figures A-6 & A-7) and they make up the bulk of the lower Kenogami River Formation (Figures A-1 to A-5). Secondary dolomitization has affected all of the Ekwan River Formation in the three southwestern Moose River Basin cores (Figures A-3 to A-5) and a few beds in the upper Ekwan River Formation in the Puskwuche Point well (Figure A-2). Secondary dolomitization and the presence of gypsum and anhydrite pore fillings in these intervals will be discussed later.

CEMENTS

Cements in these rocks are primarily early marine: radial-fibrous calcite, clear to dusty prismatic calcite, and micrite to microspar. Shallow burial cements (clear blocky spar and microspar) are common to abundant in some intervals, and rare vadose cements (meniscus, gravitational, caliche) are present locally, but deep burial cements (e.g., saddle dolomites) are absent.

Distribution

In the Attawapiskat Formation of the Pen Island No. 1 well (Figure A-1), the most abundant marine cement is radial-fibrous calcite, but it decreases downsection. The other types of marine cements are common to very common, and they also decrease downsection. In the Ekwan River Formation, marine cements are uncommon to absent. Rare vadose cements and minor calichification are present only in weathered intervals at the top of A5 and in the Kenogami River Formation. Blocky calcite cement is most abundant in porous skeletal wackestones to rudstones, and syntaxial cement is most common in crinoid-rich sediments.

Marine cements in the Puskwuche Point core are uncommon to rare, especially in the Ekwan River and Severn River formations. Blocky calcite is common in some of the coarser grained intervals, and in the sample at the bottom of the Ekwan River Formation, in which the abundant brachiopod specimens are nearly all dissolved away and replaced by clear blocky spar. Syntaxial overgrowths are common to abundant in a few crinoid-rich or oolitic beds.

In the three southwestern Moose River Basin cores, recognizable marine cements are virtually absent, with the possible exception of micrite cement, which is difficult to recognize as such in the muddy sediments. Rare prismatic calcite crystals line a few pores in the uppermost Ekwan River Formation of the Jaab Lake core.

Radial-fibrous calcite cement is present in limited quantity in the rocks at locality 85-8, and it is rare to absent at locality 88-19, even in the reefal boundstone. Other marine cements at these two localities are rare to fairly common. Blocky calcite is most common in the coarse-grained fossiliferous units. Syntaxial cement is common where crinoids are common.

At locality 84-2, radial-fibrous calcite cement is ubiquitous; it is abundant at all levels in the reef. In fact, the reef could be considered a cement reef in places. Other marine cements are also very common. Where the rock is reefal boundstone, nearly 50% is radial-fibrous calcite and the major fossils are stromatoporoids and algae. Where the rock is wackestone or rudstone, blocky spar to microspar and bladed spar are more common, but radial-fibrous calcite cement remains a major constituent. As at the other localities, the quantity of syntaxial cement in the rocks is proportional to the number of crinoid fragments present.

Cement Relationships and Timing

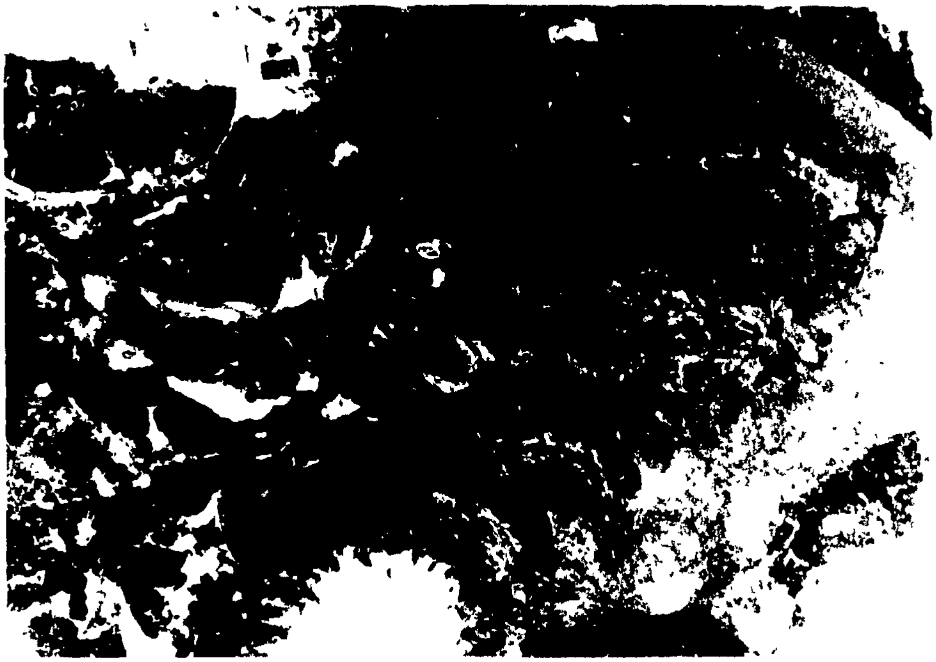
Radial-fibrous calcite cement, as used herein, was well-described by Davies and Nassichuk (1990) and includes three specific cement fabrics: radiaxial fibrous calcite, fascicular-optic, and radial-fibrous (*sensu strictu*). They are all inclusion-rich (cloudy), multiple generation, commonly isopachous (very thick in places), and they are preserved as elongate crystals oriented approximately normal to the substrate. They line or fill primary and secondary (but penecontemporaneous) reef cavities such as shelter voids (commonly beneath stromatoporoids and beneath and within brachiopods) and large borings or solution cavities. In a sample from locality 84-2 (Figure 34A), fossil fragments protrude into a large pore space that was subsequently lined with *Sphaerocodium* algae, indicating that the sediments were cemented and vugs were dissolved in the marine environment, and then they were filled with marine radial-fibrous calcite cement.

In places, the radial-fibrous calcite has a replacive relationship with the matrix and fossil fragments, similar to that described by Davies and Nassichuk (1990) for the Carboniferous to Permian carbonates of Ellesmere Island (Figure 34B). The cement fan has a feather edge where it replaces peloidal or micritic sediment, and some bioclasts are preferentially preserved within the cement. In places bioclasts serve as barriers to growth of the fan: cement growth is terminated against the bioclast but continues into the matrix on both sides of the clast. The replacive nature of the cement is shown by truncation of primary sediment fabrics and the incorporation of skeletal clasts (and "ghosts") within the

Figure 34. A. Photomicrograph of sample taken at the -3.3 ft. (-1 m) level in core 84-2-0,10W (Figure A-10), showing a vug (in right half of photo) lined with the alga *Sphaerocodium* (indicated by arrows) and subsequently filled with radial-fibrous calcite cement. (X 5.9).

B. Photomicrograph of sample taken at the -11.8 ft. (-3.6 m) level in core 84-2-0,10W (Figure A-10), showing an example of radial-fibrous calcite replacing sediment matrix. Note cement that has grown around resistant objects (e.g., crinoid fragment in lower center). (X 6.9).

A.



B.

fans. Davies and Nassichuk (1990, p. 47) listed several examples of modern and ancient sediments which contain similar radiating, replacive cement fabrics that developed within the marine environment.

A few samples reveal ostracodes and bryozoan fragments that are encased as sedimentary particles within radial-fibrous calcite cement that fills vugs (i.e., the cement is not replacive), indicating that the cement and marine fossils were penecontemporaneous. In a sample from the Pen Island No. 1 core (Figure 35A), ostracodes are encased within the latest growth stages of radial-fibrous cement, and ostracodes which protruded into the remaining pore space were subsequently coated with clear prismatic calcite cement; the remaining pore space was then filled with clear blocky calcite. Davies and Nassichuk (1990) also found ostracodes and bryozoans within the radial-fibrous cements in their rocks, and they claimed (p. 29) that the ostracodes "form part of the cavity-dwelling (coelobite) community".

Prismatic or bladed calcite cements, some dusty, some clear, predate and postdate radial-fibrous cements. In many samples, they are best developed as thick palisades on the undersides of brachiopod shells, in shelter voids. In a sample from the Pen Island No. 1 core, small vugs are filled with several generations of cement (Figure 35B): (1) micrite, (2) clear bladed cement, (3) dusty fibrous cement, (4) zoned prismatic calcite crystals, and (5) equant, clear blocky spar. Blocky calcite and syntaxial overgrowths are in all cases the final cements to form in these rocks. The origin of the microspar is unclear; it could have formed in the marine, early burial, and/or meteoric environment (Frykman, 1986; James

Figure 35. A. Photomicrograph of sample taken at -1440 ft. (439 m) in the Pen Island No. 1 core (Figure A-1), showing ostracodes encased within the latest growth stages of radial-fibrous cement. (X 20.2).

B. Photomicrograph of sample taken at -1536 ft. (468 m) in the Pen Island No. 1 core (Figure A-1), showing small vugs filled with several generations of cement. (X 8.9).

A.

B.

and Choquette, 1990a&b).

Cathodoluminescence and Staining Results

Twenty six thin sections were examined for cathodoluminescence. In most samples, nothing luminesced. In a few samples, there was minor dull orange luminescence of the latest stages of the blocky calcite crystals, of a few crinoid fragments (syntaxial overgrowths do not luminesce), of small patches of micrite matrix (where it appeared to be algal peloids or bituminous), in two samples as very small patches (2-3 mm in diameter) near the outer edges of thick fibrous cements, and in minor patches of chalky dolomitized micrite.

Fifteen representative thin sections were stained with alizarin red. Results indicate that all these cements are non-ferroan calcite. No ferroan calcites nor late stage ferroan dolomites were revealed.

NEOMORPHIC FABRIC

In hand sample, all the fossils in the Attawapiskat Formation in both core and outcrop appear to be well preserved. However, in thin section, nearly all of the fossils and much of the micrite matrix have been neomorphosed to finely crystalline calcite or microspar, in which the skeletal fabric is in different states of preservation depending upon the fossil type (Figure 36).

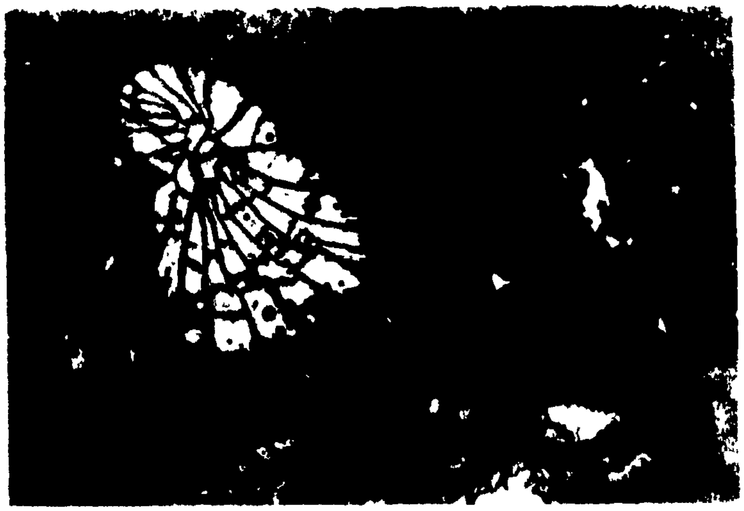
Stromatoporoids are usually the most poorly preserved; some are nearly unrecognizable. Certain types of brachiopod shells are the best preserved and

Figure 36. A. Photomicrograph in plane light of sample taken at -1633 ft. (-498 m) in the Pen Island No. 1 core (Figure A-1), showing a solitary coral encased within a stromatoporoid; stromatoporoid fabric is obscured by recrystallization. (X 7.8).

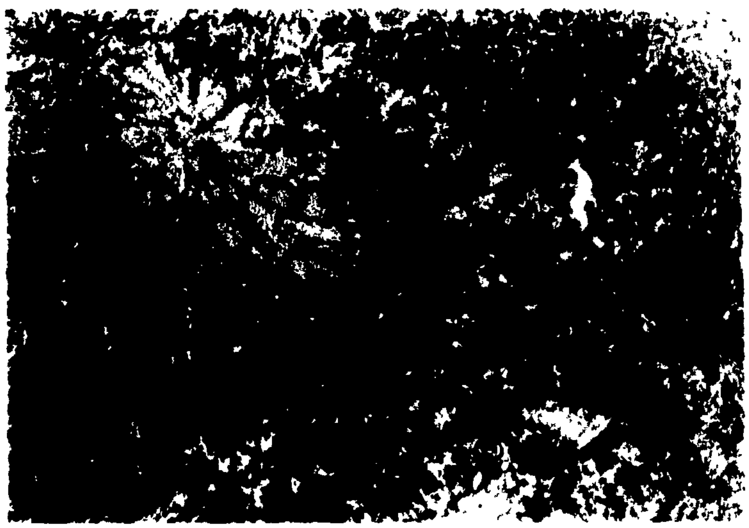
B. Photomicrograph of same sample as in A, but under crossed polars, showing pervasive recrystallization, especially of the stromatoporoid; coral is better preserved. (X 7.8).

C. Photomicrograph under crossed polars of well-preserved pentamerid and rhynchonellid shells, from skeletal wackestone sample at 18.8 ft. (5.7 m) in section 85-8 (Figure A-6), showing fine internal fabric of the shells. (X 9.7).

A.



B.



C.

show fine internal fabric: rhynchonellids, atrypids, and especially pentamerids (some of which appear to retain original shell material). Preservation of most other fossils ranges between these two end members, i.e., the fossils are micritized to recrystallized to varying degrees. The skeletal walls of rugose and favositid corals, for example, are commonly neomorphosed to microspar, which contains a micritic ghost of the original microstructure, and the walls are coated with a thin layer of clear dogtooth spar; the remaining void space is empty. Intraskeletal porosity is commonly the predominant porosity remaining in some reefal boundstones and skeletal wackestones.

SECONDARY DOLOMITIZATION, GYPSUM, AND ANHYDRITE

The rocks in the three southwestern Moose River Basin cores are all recrystallized to dolostone (Figures A-3 to A-5). The only other secondary dolomitization recognized in this study is in two minor intervals in the Ekwan River Formation in the Puskwuche Point core (Figure A-2); one is overlain by primary dolomite, the other by a sharp, irregular exposure surface.

Gypsum and anhydrite nodules, pore fillings, and replacements of fossil fragments are also common to abundant in the three southwestern Moose River Basin cores. Many skeletal chambers (especially of corals) are filled with gypsum and clear, euhedral quartz crystals; cross-cutting relationships indicate that the quartz crystals formed last. The only other place gypsum and anhydrite are present in minor amounts is in the two dolomitic intervals in the Ekwan River

Formation of the Puskwuche Point well.

In the Jaab Lake core, virtually no gypsum and anhydrite nodules and pore fillings are present below about 1750 ft (533 m); this is about 60 ft (18 m) below the nearest evaporites (dolostone with gypsum nodules, stringers, and veins) and 90 ft. (27 m) below the nearest gypsum bed. In the Ardagh well, only one sample shows minor pore fillings of gypsum and anhydrite below 586 ft. (179 m); this is approximately 40 ft. (12 m) below the nearest evaporites and 50 ft. (15 m) below the nearest gypsiferous bed. No gypsum or anhydrite is present below 682 ft. (208 m) in the Onakwahegan core; this is 40 ft. (12 m) below the nearest evaporites and 70 ft. (21 m) below the nearest gypsiferous bed.

DISCUSSION

Rock Type and Fossil Distribution

Depositional Environment.--The rock types and fossils present in the Attawapiskat Formation in the southwestern Hudson Bay Basin and in the Attawapiskat River area indicate that conditions were open marine, generally within normal wavebase (Chapter 2), with clear, well-oxygenated waters of normal marine salinity. However, the sediment types and lower diversity fauna in equivalent strata in the Puskwuche Point well indicate less favorable conditions for growth of marine organisms. Conditions in the southwesternmost Moose River Basin were even more restricted, and resulted in a low-diversity, low-abundance fauna and more clay and organic carbon in the sediments.

The southwestern Moose River Basin could have been a lagoon during Attawapiskat Formation time, but no clear evidence of a barrier exists. Instead the seafloor may have been so flat, extensive, and shallow in this area that circulation was restricted and hence the southwesternmost parts, farthest from open marine waters, became more saline, less oxygenated, and less favorable for organisms. Carbonate sediments would have been deposited more slowly, resulting in a condensed section and permitting greater dilution by terrigenous clays. Terrigenous source areas to the south and southwest were closer as well (Sanford, 1987). Additionally, if the waters were restricted and poorly oxygenated, a greater proportion of organic carbon would be preserved.

Vertical Faunal Zonation.--Chow (1986) discussed in detail the fossils and the depositional environments of individual reefs along the Attawapiskat River. However, because his study encompassed only the surfaces of exposed reefs, he could only speculate about the possibility of vertical faunal zonation. The present study reveals a weak vertical trend in the reefs from stromatoporoid-dominated in the lower portions to algae-dominated boundstone in the upper parts (Figures A-1 and A-8 to A-10). The lower stromatoporoid-dominated portions could be considered to represent the early diversification stage, and the upper algae-dominated intervals may represent the domination stage of ecological succession in the reefs, as outlined by Walker and Alberstadt (1975). Alternatively, vertical zonation could simply reflect growth of the reef into shallower water where conditions were more favorable for algae and less favorable for other organisms.

Nuia Grainstones.--Grainstone beds comprised primarily of fragments of the alga *Nuia? distincta* (Figure 37) are present within the shallowing-upward intervals above the Attawapiskat Formation in the southwestern Hudson Bay Basin and the Attawapiskat River area, wherever open-marine conditions prevailed just prior to their formation (Figures A-1 to A-10; Chapter 2). The fact that *Nuia* is usually the only fossil and locally the only grain type present in these rocks, coupled with the stratigraphic positions of the beds near the tops of shallowing-upward intervals, suggests a very restricted environment, probably supratidal or intertidal ponds or very restricted lagoons that existed in the area as marine waters were retreating at the end of Attawapiskat time. The local occurrence of small brachiopods, spongiostromatid algae, ostracodes, and crinoids indicates at least limited marine influence. Fischer (1964) interpreted the similar loferites of the Alpine Triassic to be of intertidal origin.

The *Nuia* grainstone beds are commonly 2-3 m (6-10 ft.) thick and laterally very extensive. An outcrop on the south bank of the Attawapiskat River, approximately 1 km (0.6 mi.) upriver from locality 85-8 (Figure 4), revealed a flat-lying, 3-m (10 ft.) thick *Nuia* grainstone bed that extended 275-300 m (900-985 ft.) between reefal outcrop exposures. Outcrop relationships revealed it to be post-reef, but it had filled in the depressions between reefs. The depositional environment for these beds was flat, extensive, very shallow, probably hypersaline

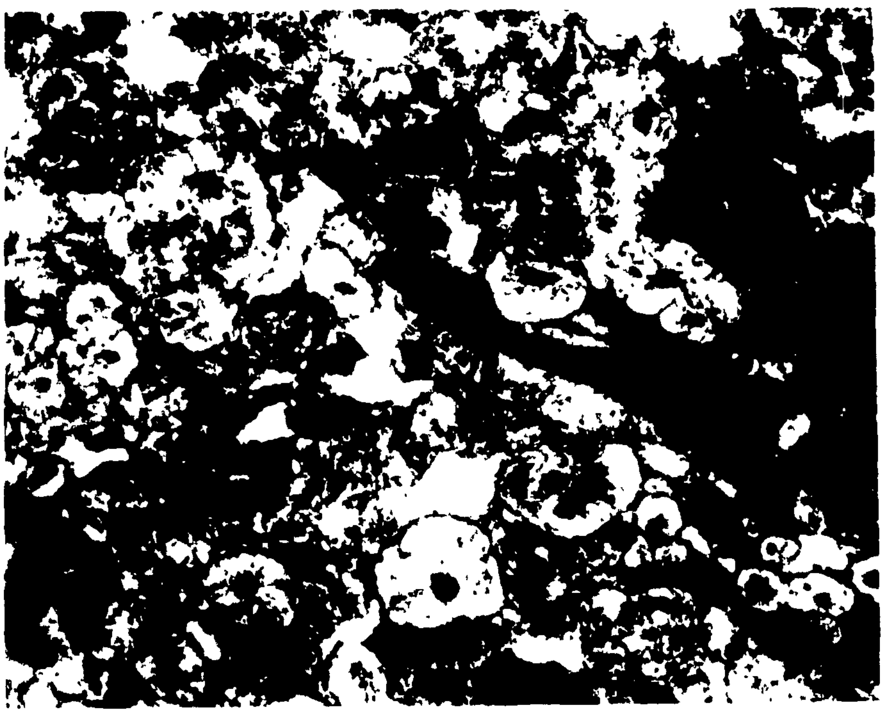


Figure 37. Photomicrograph in plane light, from sample at 23 ft. (7 m) in section 85-8 (Figure A-6), showing *Nuia* grainstone that contains a few spongiostromatid algae fragments (dark). *Nuia* grains show a radial fabric, usually with dark micrite cores, and are sometimes clumped together in grapestone-like forms. (X33.7).

(but not to the point of evaporite deposition), and favorable for the growth of a *Nuia* monoculture.

Nuia? distincta may not be identical with the Cambrian *Nuia* (B. Mamet, pers. comm, 1991). It has many of the same growth forms, but it rarely exhibits the elongate form typical of the Cambrian *Nuia* (Mamet and Roux, 1982). More commonly, it has the branching, clumping (grapestone-like) form (Figure 37), and sometimes forms a coating on other skeletal fragments (Figure 38), typical of the Devonian *Paleomicrocodium.* Taxonomically, it may lie somewhere between the Cambrian *Nuia* and the Devonian *Paleomicrocodium* (B. Mamet, pers. comm., 1991).

Marine Cement Distribution

Marine cements, especially radial-fibrous calcite, are most abundant in reefs of the Attawapiskat Formation (Figures A-1 to A-10). They are much less common in skeletal wackestones or rudstones, and they are absent in the southwestern Moose River Basin cores. However, even within the reefal interval, the distribution of marine cements from one locality to another appears to be erratic: radial-fibrous cement is ubiquitous at locality 84-2, abundant in the Pen Island No. 1 core (but decreases downsection within the reef), present at locality 85-8, and nearly absent at locality 88-19 (Figures 1 and 4). What can account for this distribution?

According to Bathurst (1975) this type of cementation requires pore-water exchange on the order of 50,000 to 100,000 pore volumes. In other words, it

Figure 38. Photomicrographs in plane light, from sample at 15.2 ft. (4.6 m) in section 85-8 (Figure A-6), showing *Nuia* coatings on shell fragments. A. Elongate *Nuia* specimen coating a brachiopod(?) fragment. (X 42.8). B. *Nuia* coating an ostracode, a fairly common occurrence. (X 53).

A.

B.

requires pumping of large volumes of water through porous and permeable rocks, such as those in a reef. Davies and Nassichuk (1990, p. 58) wrote that these cements are best developed "in porous carbonate sediments that projected above the surrounding basin floor, facing an open seaway." Possible pumping mechanisms that could assert the necessary pressure gradients within the reefs include storm surges, wave pulses, and tidal fluctuations. Other factors may be involved as well, including "non-seasonal convergence or setup by wind..., interacting with local submarine topography or conduit flow..." within the reefs (Davies and Nassichuk, 1990, p. 59). In any case, Davies and Nassichuk (1990, p. 59) argued that "submarine cementation may be more the result of high-volume throughflow of oversaturated surface seawater, rather than the product of chemical or microbiochemical processes within the reef cavity system."

The bedded skeletal wackestones and rudstones on the platform and the fine-grained sediments in the restricted environment of the southwestern Moose River Basin would not have undergone adequate pore-water exchange to effect much cementation. On the other hand, reefs in the open marine environments of the southwestern Hudson Bay Basin and the Attawapiskat River area could have been subject to pressure surges caused by large waves that were generated by winds having a fetch of hundreds of kilometers. The Hudson Bay Platform was situated well within the tropics, practically on the equator, during Silurian time (Scotese and McKerrow, 1990), and thus would have been within the zone of prevailing easterly winds (i.e., winds analogous to the modern northeasterly or southeasterly trade winds, depending upon the precise latitudinal position of the platform at the time). These winds and their consequent waves and swells would have travelled long distances across the Hudson Bay Platform intracratonic sea before reaching the reefs of the study area. Furthermore, if the connection to the open ocean was to the east or northeast, as suggested by Sanford (1987), swells on the open ocean created by the northeasterly trade winds may have entered the Hudson Bay Platform sea via this connection.

Perhaps the reef at locality 84-2 was in such a position as to catch the brunt of such wave activity, whereas the reefs at localities 88-19 and 85-8 were in more protected surroundings. The reef at the Pen Island No. 1 locality became more highly cemented in its upper portions after it grew into the zone of greater wave activity.

Diagenesis

The rocks of the study area have undergone a typical shallow burial diagenetic sequence as outlined by Longman (1980). No evidence of deep burial exists. That is, physical compaction, fracturing, and pressure solution features are minimal, there appears to be no deep subsurface dolomitization or deep burial cements (such as saddle dolomite or ferroan calcite), and hydrous minerals have not been altered to anhydrous minerals to any extent (i.e., gypsum to anhydrite).

Chow (1986) identified nine phases of diagenesis in rocks of the outcrop area: (1) micrite cement, (2) marine cement, (3) syntaxial cement, (4) blocky calcite, (5) neomorphism of fossils, (6) dissolution, (7) fracturing, (8) fracture filling cement, and (9) microspar. This diagenetic sequence also applies to rocks in the cores from the southwestern Hudson Bay Basin and to some degree to those of the Puskwuche Point well. Rocks in the three southwestern Moose River Basin cores underwent a slightly different diagenetic history which led to their pervasive dolomitization and the precipitation of gypsum and anhydrite in void spaces.

Micrite cement was one of the first cements formed while the sediments were being deposited in the marine environment. This is shown by relationships in which: 1) solution voids formed in previously indurated sediments, 2) their margins were micritized and coated with *Sphaerocodium* algae, and then 3) they were infilled with marine cements, all while still in the marine environment. Cementation was probably patchy, which allowed formation of the voids and permitted growth of intrasediment replacive radial-fibrous cements.

The volumetrically abundant marine cements (primarily radial-fibrous) began forming soon after the first marine sediments were deposited. They continued to form in shelter voids, intraskeletal chambers, and solution cavities within the sediments and reefal boundstone throughout the submarine history of the rocks, as evidenced by the incorporation of marine fossils that settled as sedimentary particles within the radial-fibrous cements. Where the reefs have a great abundance of these cements, they may be similar to the pelletal mud and cement reefs described by Schwarzacher (1961) in the Carboniferous of northwestern Ireland. The bladed or prismatic cements formed during this time as well, in shelter voids and intraskeletal pores, between sediment grains, and in solution voids. In some voids that were not completely filled by the radial-fibrous cement, bladed cements formed a thin layer on the surface of the radial-fibrous cement .

The original mineralogy of the radial-fibrous cement is believed to have been high-Mg calcite, as evidenced by the presence of microcrystalline dolomite rhombs (by exsolution) within the cements (Lohmann and Meyers, 1977; Davies and Nassichuk, 1990). Additionally, where crystal terminations are visible, they are pyramidal in form, typical of high-Mg calcite, and the crystal sizes are the same as those of bladed high-Mg calcite in modern reefs (James *et al.*, 1976). The radial-fibrous cements do not show any of the criteria listed by Sandberg (1985) as being indicators of original aragonite mineralogy. This is consistent with Sandberg's (1983) contention that the Silurian was a time of "calcite seas."

Syntaxial cements and blocky calcite were emplaced after the marine cements in remaining pore spaces. In some large pore spaces, the blocky calcite crystals increase in size toward the centers. These are burial cements (Choquette and James, 1990), but because no evidence of deep burial was found, they must have formed in a shallow burial environment. Longman (1980, p. 461) suggested that these types of cement "are typical of cementation in the active freshwater phreatic zone." However, some of the earliest blocky calcite may also have formed locally in the marine environment (James and Choquette, 1990a).

Dissolution and neomorphism of unstable grains most often occur in the meteoric diagenetic environment (i.e., vadose, meteoric phreatic, and mixing zone environments) (Longman, 1980; James and Choquette, 1990b). The marine rocks of this study were subject to meteoric influences soon after they were deposited, as evidenced by closely overlying subaerial exposure surfaces, supratidal sediments and evaporites, and weathered intervals with minor calichification. This is consistent with an interpretation of fluctuating sea-levels and an overall relative drop in sea-level at the close of Attawapiskat time (Chapter 2).

Differences in degrees of dissolution and neomorphism of fossil clasts are highly dependent upon original mineralogy of the clasts. Stromatoporoids are the most highly altered, suggesting they were originally aragonite. Brachiopods are the best preserved, which is consistent with an original calcite mineralogy, and corals are less well preserved than brachiopods, suggesting an original high-Mg calcite mineralogy (Brand and Morrison, 1987).

Fracturing and fracture-filling cement are minor local features in the rocks of this study. Some fracturing may have occurred in the reefs while they were growing, but most occurred later in the shallow burial environment. Most fractures contain no marine sediments and they were filled during the latest diagenetic stage with clear, coarse blocky spar.

The timing of microspar formation is difficult to determine, and some microspar in these rocks is difficult to distinguish from blocky calcite because they grade into each other. The microspar occurs primarily as a pseudosparite replacement of a micritic matrix. Bathurst (1975, p. 513) stated that microspars are largely "the products of neomorphism of a pre-existing micrite," which is consistent with Choquette and James' (1990) suggestion that microspar can form in shallow burial or meteoric diagenetic environments. However, James and Choquette (1990a) suggested that blocky spar crystals less than 50 micrometres in size [which is within the defined microspar size range (Bathurst, 1975)] may also form locally in the marine environment. Therefore, microspar may have formed episodically in these rocks from early in their depositional history to relatively late in their diagenetic history.

Secondary Dolomitization, Gypsum and Anhydrite

All the evidence cited above points to a very flat, restricted depositional environment for the southwestern Moose River Basin during Late Llandoverian time. The fact that the strata there are the only ones on the Hudson Bay Platform to be secondarily dolomitized is a direct result of that depositional setting. The area was the most restricted during relative sea-level highstands, and it became the most intensely hypersaline during relative sea-level lowstands (Chapter 2).

Two models may be invoked to explain the secondary dolomitization of carbonates in the southwestern Moose River Basin. One is the sabkha model with seepage reflux, and the other is the 'shallow subtidal' or hypersaline lagoon model (Machel and Mountjoy, 1986; Morrow, 1990).

Beds of evaporitic dolostones, anhydrite, and gypsum directly overlie the marine sediments in the area, a relationship which supports the sabkha model. According to this model, storm-driven flood tides inundate the sabkha periodically.

In the sabkhas of the Persian Gulf, Morrow (1990, p. 127) wrote "the frequency of flooding decreases landward across the sabkha but the Mg/Ca ratio of the floodwaters rises uniformly landward by means of gypsum precipitation so that the zone of optimum dolomite formation is less than a kilometre wide straddling the boundary between high intertidal and supratidal areas...," and "the dense Mg^{2+}-bearing hypersaline floodwater brines sink downward and flow seaward through the sediment by seepage refluxion." A variant of this model calls upon "evaporative pumping," a process whereby seawater continually flows landward through the sediments to replace groundwater lost by evaporation on the sabkha surface; the direction of flow is the reverse of that in seepage refluxion.

One problem with invoking this model is the limited volume of sediments dolomitized by this process. The dolomite-forming zone is only 1-1.5 km wide, and dolomitization takes place "only in the upper 1-1.5 m of the sediment and is mostly incomplete and variable across the area" (Machel and Mountjoy, 1986, p. 201-202), which makes pervasive dolomitization to the extent observed in the three cores difficult to explain. However, the zone of dolomitization can move fairly rapidly across a given point, tracking the strandline during relative sea-level fluctuations (Machel and Mountjoy, 1986), which could explain horizontally extensive dolomitization. To explain vertically extensive dolomitization, Morrow (1990) claimed that successive regressions on a subsiding platform could build thick vertical sequences of peritidal dolomite.

Alternatively, the dolomites could have formed in a very shallow subtidal or hypersaline lagoon environment, in which salinities increased with increasing isolation of the system (Machel and Mountjoy, 1986; Morrow, 1990). "The resulting increase in density of these evaporated waters causes them to infiltrate the underlying sediment and to move seaward by seepage (i.e., reflux) through the seaward-dipping beds," and "the cycle of fresh marine replenishment of lagoon waters and seaward seepage of brines is the mechanism by which Mg^{2+} is continually transported to the sediment" (Morrow, 1990, p. 125-127). The southwestern part of the Moose River Basin was so flat over such great distances that, during relative lowerings of sea-level, very shallow marine waters (less than a few meters) could have been present over wide areas. The water would have been increasingly shallow and hypersaline in a landward direction, and would have become even more so as sea-level continued to drop.

Either or both of the above mechanisms may have dolomitized the sediments in the southwestern Moose River Basin. In any case, dolomitization occurred early in the diagenetic history and refluxing evaporated seawater was the source of the Mg^{2+}.

The evaporating brines eventually became supersaturated with respect to gypsum and anhydrite and resulted in precipitation of these minerals in beds and laminae approximately 10 ft. (3 m) above fossiliferous beds in the Ardagh and Onakwahegan cores, and 33 ft. (10 m) above fossiliferous beds in the Jaab Lake core. Gypsum and anhydrite also occur as fillings in vugs and pore spaces and as replacements of fossils in these cores to a maximum depth of 40-60 ft. (12-18

m) below the nearest evaporites (dolostone with gypsum and anhydrite nodules, veins, and stringers), and 50-90 ft. (15-27 m) below the nearest pure gypsum or highly gypsiferous beds (Figures A-3 to A-5). Apparently these are the depth limits to which the gypsum-precipitating fluids percolated into the sediments. Dolomitization, on the other hand, affected the sediments below the gypsum levels all the way to the basal clastics.

The disparity between the depth of dolomitization and of gypsum precipitation argues for two separate processes or events. Gypsum precipitation may have occurred during a later remobilization of soluble salts, perhaps after or during some meteoric diagenetic event (i.e., related to fossil dissolution and replacement).

Porosity

Porosity in the Attawapiskat reefs as they were growing was initially very high. It consisted of intergranular, intraskeletal, and shelter voids. Solution porosity also became important after initial micrite cementation of the sediments. However, in some of the Attawapiskat reefs, submarine cementation eventually became so extensive that little porosity now remains. Patches of high [illegible] rosity are present locally, particularly as intergranular voids in more packstone- to grainstone-rich intervals, and in reefs with low overall cementation, vuggy reef porosity can be greater than 50%.

Although neomorphism has affected nearly all of the fossils in these rocks, the low volume of meteoric syntaxial and blocky calcite cements and only minor evidence of weathering and calichification suggest that residence time in the meteoric environment was short-lived. Consequently, secondary solution porosity is minimal. Therefore, porosity in these rocks is predominantly controlled by original submarine cementation: where it occurred, porosity is low, where it did not occur, porosity is high.

Porosity is highest in the skeletal grainstones and rudstones, as intergranular, intraskeletal, and shelter voids, because cementation is low. During deposition the sediments were probably moved around too much by wave activity to allow cementation, and after deposition the pumping mechanisms were inadequate to exchange enough pore water through these flat-lying beds.

Porosity in the three southwestern Moose River Basin cores is generally low due to the fine-grained character of the sediments, secondary dolomitization, and filling of intergranular and intraskeletal pores by gypsum and anhydrite. The little secondary solution porosity tnat formed in these sediments was also filled with gypsum and anhydrite.

SUMMARY AND CONCLUSIONS

Reefs of the Attawapiskat Formation have a wide range of compositions from stromatoporoid-, coral-, and cement-rich to algae- and cement-rich boundstones, the latter making up the greater proportion. Within the reefs, there is some suggestion of a vertical zonation in which stromatoporoids are most common in the lower part and algae predominate in the upper parts. The reefal facies developed in clear, well-oxygenated, open-marine conditions in the Hudson Bay Basin and the northern part of the Moose River Basin, but time-equivalent facies in the southwestern Moose River Basin developed in a flat, restricted environment, resulting in a low-diversity fauna and fine-grained, muddy limestone.

Thick, laterally extensive *Nuia* grainstone beds are present in the shallowing-upward intervals above the reefs. This facies is a product of widespread *Nuia* monocultures which proliferated in supratidal ponds left scattered over the area as marine waters retreated during relative sea-level falls.

Radial-fibrous calcite cement (originally high-Mg calcite) is the most abundant cement in the reefs, locally constituting up to 50% of the rock. It is most abundant in reefs that were exposed to wave surges approaching generally from the east, which provided the mechanism to pump adequate quantities of pore waters through the system. Other types of marine cements are more common in the flat-lying, bedded fossiliferous limestones. Marine cements are largely absent in the southwestern Moose River Basin cores.

The rocks of this study were subjected to shallow-burial diagenesis. No evidence of deep burial exists. The main diagenetic features include early marine cementation and solution, and later shallow burial and meteoric overprinting, including pervasive neomorphism of skeletal clasts and matrix.

Secondary dolomitization of the rocks in the three southwestern Moose River Basin cores can be explained by a sabkha and/or hypersaline lagoon model of dolomitization with seepage refluxion. The precipitation of gypsum and anhydrite in pore spaces to depths of 50-90 ft. (15-27 m) below gypsiferous beds may have been caused by a later remobilization of soluble salts.

Intergranular, intraskeletal, shelter, and solution porosity in rocks of the Attawapiskat Formation may initially have been high. However, the percentage of remaining porosity is largely dependent upon the degree of early marine cementation: where the rocks were cemented, porosity is now low, where they were not cemented, remaining porosity can be very high.

CHAPTER 6

GENERAL CONCLUSIONS

LOWER SILURIAN OF THE HUDSON BAY PLATFORM

Application of the methods of sequence stratigraphy on a fine scale to Llandoverian carbonate rocks of the Hudson Bay Platform has demonstrated that individual parasequences can be correlated basinwide. Relative sea-level curves were constructed on the basis of depth-dependent carbonate facies, and changes in those facies reflect the local interplay of subsidence, sedimentation, and eustatic sea-level changes. At least two sequences, bounded by regional disconformities, occur in these rocks: one includes all of the Severn River Formation, the other includes the Ekwan River, Attawapiskat, and possibly part of the Kenogami River Formation.

The Early Silurian seas transgressed from north to south, inundating first the Hudson Bay Basin and later the Moose River Basin, which was always shallower than the Hudson Bay Basin; however, both basins were remarkably shallow and flat. Depositional environments oscillated between shallow subtidal and supratidal. The most extensive marine inundations occurred during deposition of the Ekwan River Formation and again during growth of the Attawapiskat Formation reefs. The marine facies of the Attawapiskat Formation, which represent the last Silurian marine inundation recorded in the rocks of the Hudson Bay Platform, were succeeded by the supratidal evaporitic facies of the Kenogami River Formation, which indicate a low relative sea-level for the remainder of the Silurian. The seas retreated northward at the end of Attawapiskat time, but some marine sediments were still being deposited for a short time in the Hudson Bay Basin after the Moose River Basin was receiving only evaporites and/or was subaerially exposed.

Correlations show that strata of the upper Ekwan River Formation in the southern Moose River Basin were time equivalents of the Attawapiskat reefs in its northern margin and that reefal outcrops along the Attawapiskat River represent one interval of reef growth, not several stacked facies sequences. Additionally, the beds at the top of the Ekwan River Formation on the Attawapiskat River are not correlatives of the Attawapiskat Formation reefs downstream. The boundaries of the three carbonate formations were redefined on the basis of objective criteria, and some marine carbonates were correlated with supratidal carbonates on the basis of matching trends in relative sea-level curves. Facies distributions of individual parasequences were plotted on paleogeographic maps for small intervals of geologic time.

Large-scale trends in the relative sea-level curves delineate four major sea-level highstands (late Rhuddanian, late Aeronian, early Telychian, and late Telychian) that are equivalent to Early Silurian sea-level highstands recognized elsewhere in North America and on other continents.

Outcrop evidence cited in Chapter 3 clearly reveals the relationships between reef cores and flanking beds, and shows that the syndepositional relief of the Attawapiskat reefs was at least 8-10 meters. Schematic reconstructions of the depositional history of the Attawapiskat Formation in outcrop portray a stratigraphic sequence that was controlled by relative sea-level changes during Late Llandoverian time. The Attawapiskat reefs were terminated by a relative sea-level fall, and the immediately overlying facies record 3 subsequent minor rises and falls in relative sea-level.

Evidence from aerial photo interpretation and field data (Chapter 4) suggests that faults presently control the distribution of reefal outcrops along the Attawapiskat River. Reefs are exposed by the river only where the Attawapiskat Formation is uplifted on fault blocks, and no reefs crop out on the river where the blocks are downdropped and the easily-weathered Kenogami River Formation underlies the surface. A major tectonic event occurred just after the close of Attawapiskat time, and minor movement on some of the faults has also taken place within the last 8,000 years.

Examination of the vertical and regional distribution of fossils, cements, and diagenetic features (Chapter 5) has revealed that reefal boundstones of the Attawapiskat Formation have a wide range of proportions of stromatoporoids, corals, cement, and algae, but cement and algae are the most important constituents. The reefal facies developed in clear, well-oxygenated, open-marine conditions in the Hudson Bay Basin and the northern part of the Moose River Basin, but time-equivalent facies in the southwestern Moose River Basin developed in a flat, restricted environment. Thick, laterally extensive *Nuia* grainstone beds are present in the shallowing-upward intervals above the reefs.

The rocks of this study were subjected to shallow-burial diagenesis. No evidence of deep burial exists. The main diagenetic features include early marine cementation and solution, and later shallow burial and meteoric overprinting, including pervasive neomorphism of skeletal clasts and matrix. Early marine cements, the most abundant of which is radial-fibrous calcite, locally constitute up to 50% of the reef rock. Other types of marine cements are more common in the flat-lying, bedded fossiliferous limestones. Marine cements are largely absent in the southwestern Moose River Basin cores.

Secondary dolomitization of the rocks in the southwesternmost Moose River Basin can be explained by a sabkha and/or hypersaline lagoon model of dolomitization with seepage refluxion. Precipitation of gypsum and anhydrite in pore spaces to depths of 50-90 ft. (15-27 m) below gypsiferous beds may have occurred during a later remobilization of soluble salts.

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APPLICABILITY OF METHODS

The methods employed in Chapter 2 of this thesis, that is, basinwide correlation of individual parasequences, can be applied to stratified sedimentary rocks of any age in any depositional basin that contains marine strata. Potentially, detailed comparisons of relative sea-level curves among separate basins may be used to distinguish the effects of subsidence and sedimentation from the effects of eustatic sea-level change on the depositional history of individual basins.

The methods of this study take the sequence-stratigraphic approach to basin analysis a step further. Sequence stratigraphy, usually based on seismic data, brackets the stratigraphic units between basinwide unconformities on a large scale, and in that manner deciphers the basin configuration and the history of advance and retreat of relative sea-level. Biostratigraphy and stratigraphic markers are also important in bracketing depositional units between tie-points of time-stratigraphic significance and in assigning absolute ages to stratigraphic sequences, but in these methods the temporal resolution is usually poor and placement of geologic boundaries may be uncertain. Fine-scale sequence stratigraphy, on the other hand, based on drill core and outcrop data (which may be available where seismic data is not), gives a finer resolution of temporal correlations, defines stratigraphic and temporal boundaries more clearly, and thus provides an improved framework for paleoenvironmental, paleogeographic, and basin history analyses. It also allows recognition of subtle lateral differences in depositional conditions for specific time intervals.

Sequence stratigraphy is most often applied, with the use of seismic profiles, to continental margins. It is more difficult to apply to cratonic Paleozoic strata due to "1) limited accommodation potential on platform areas; 2) slow, episodic sediment-accumulation rates and limitations in sediment preservation; and 3) difficulty in establishing independent methods of correlating parasequences" (Watney *et al.*, 1989, p. 38). However, as Watney *et al.* (1989) wrote, sequence stratigraphic methods can be applied on cratonic platforms without seismic profiles by examining the strata in detail, describing it in terms of depositional environment and relative water depth, identifying surfaces (bedding planes, exposure surfaces, and hardgrounds), drawing profiles, and correlating between localities. Chapter 2 of this thesis has done exactly those things, but the task has been made easier by the use of relative sea-level curves.

Goldhammer *et al.* (1990) discussed cycle stacking patterns (that is, stratigraphic stacking of carbonate facies in cyclic patterns) in platform carbonates from the Alpine Triassic and the Pleistocene of Florida. They concluded (p. 561) that an understanding of "composite eustasy" (superimposed third, fourth, and fifth order sea-level changes) "provides a link between meter-scale cyclostratigraphy and kilometer-scale sequence stratigraphy." Furthermore, they stated (p. 561) that, on flat-topped platforms and banks that contain transitional stratigraphic boundaries that are not detectable in seismic profiles, "the stacking patterns of the high-frequency depositional cycles may be the only means of identifying sequences." The methods of this thesis provide a further means by which sequences and parasequences can be identified in cratonic basins and correlated on a fine scale over great distances.

Most workers, when correlating strata on such a fine scale, have attempted to trace individual stratigraphic cycles across and between basins without the use of curves (Connolly and Stanton, in press; Osleger, 1991; Suchy and West, in press; Goldhammer *et al.*, 1990; Busch and West, 1987; Brett and Baird, 1986), but such a method can quickly become unwieldy when comparing thick sections that contain numerous thin cycles. The advantage of using relative sea-level curves, such as the ones used herein, is that they provide a highly visual means of making correlations and of distinguishing small-scale changes from large-scale changes. Additionally, basinwide breaks in deposition are more apparent, and correlations from one depositional environment to another (supratidal to shallow subtidal to deep subtidal) are facilitated.

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APPENDIX A

Vertical profiles showing distribution of rock types, fossils, and cements in drill cores and outcrops.

(For locality maps, see Figures 1 and 4 in text).

(For key to symbols, see next page).

KEY TO SYMBOLS USED IN FIGURES A-1 TO A-11

Rock Types

B = Boundstone

R = Rudstone

S = Skeletal wackestone to grainstone

C = Crinoidal wackestone

M = Lime Mudstone

N = *Nuia* grainstone

D = Dolostone

Ool = Oolite

● = main rock type

O = subsidiary rock type

⊗ = original rock type

Fossils

S = Stromatoporoids
Corals:
T = Tabulate
RC = Rugose, Colonial
RS = Rugose, Solitary
B = Brachiopods
Cr = Crinoids
A = Algae
O = Ostracodes
Bry= Bryozoans
T = Trilobites
Ce = Cephalopods
G = Gastropods
Sp = Spicules
AC = Algal Crusts
N = *Nuia*
Ech= Echinoids
Bur= Burrows

Abundances

■ = Abundant (>15%)
■ = Very Common (5-15%)
▬ = Common (2-5%)
— = Present (<2%)

Cements

R = Radial-fibrous
P = Prismatic, bladed
B = Blocky spar, & microspar
M = Micrite

S = Syntaxial

V = Vadose

Other

Bit = Bitumen
Pe = Peloids

Anhyd. & Gyp. = Anhydrite and Gypsum

Qtz. Xls = Quartz Crystals

Dolo. & Gyp. = Dolostone and Gypsum

Att. equiv. = Attawapiskat equivalent

S15-S18, E1-E4, & A1-A6 = parasequence numbers

Note 5 different scales, one for each of the following groups of figures:

1) Figure A-1
2) Figures A-2 to A-5
3) Figures A-6 to A-7
4) Figures A-8 to A-10
5) Figure A-11

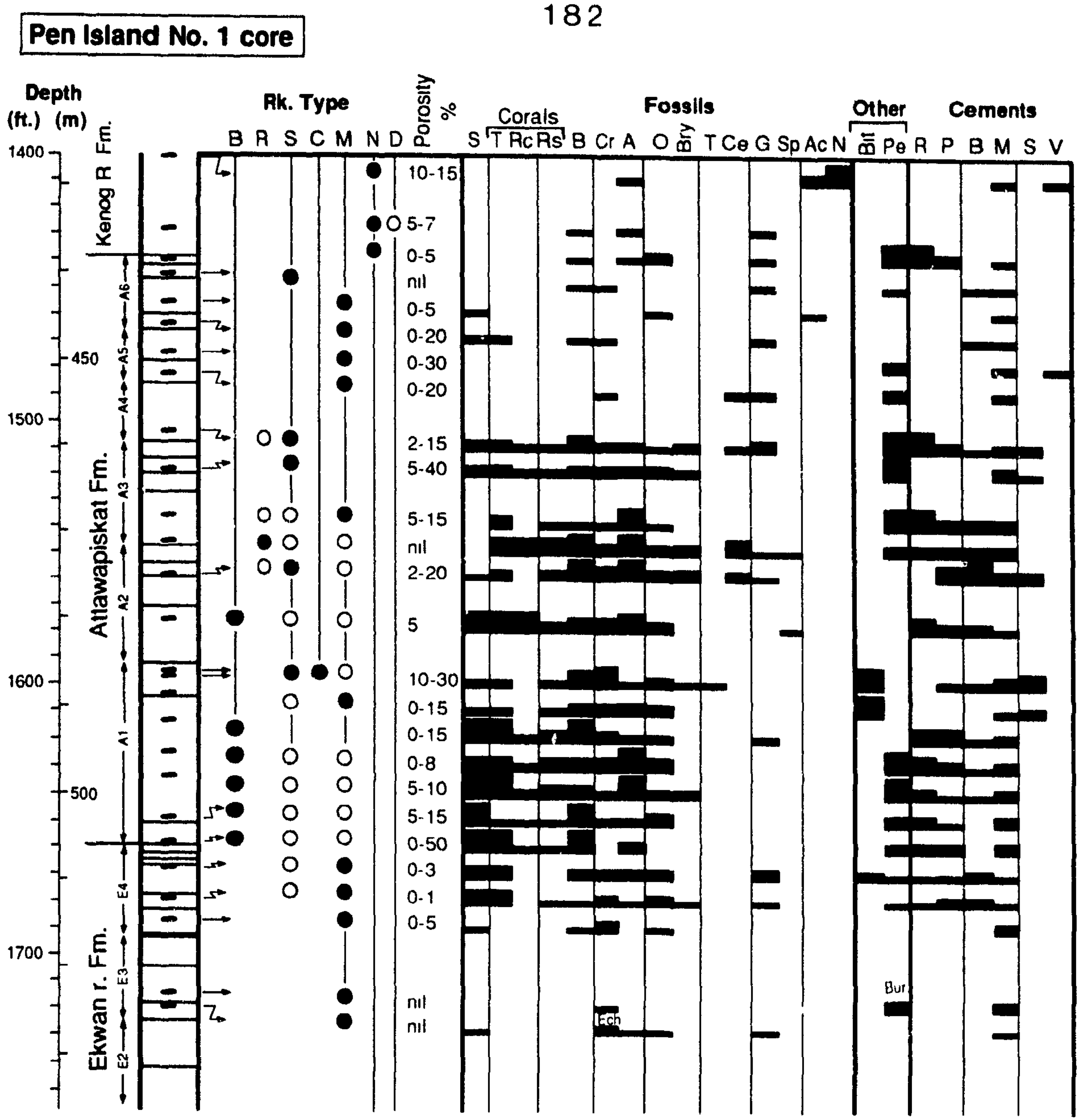

Figure A-1. Vertical profile of fossil and cement distributions in the Pen Island No. 1 core. See Key for meanings of letters, symbols, and abundance bars.

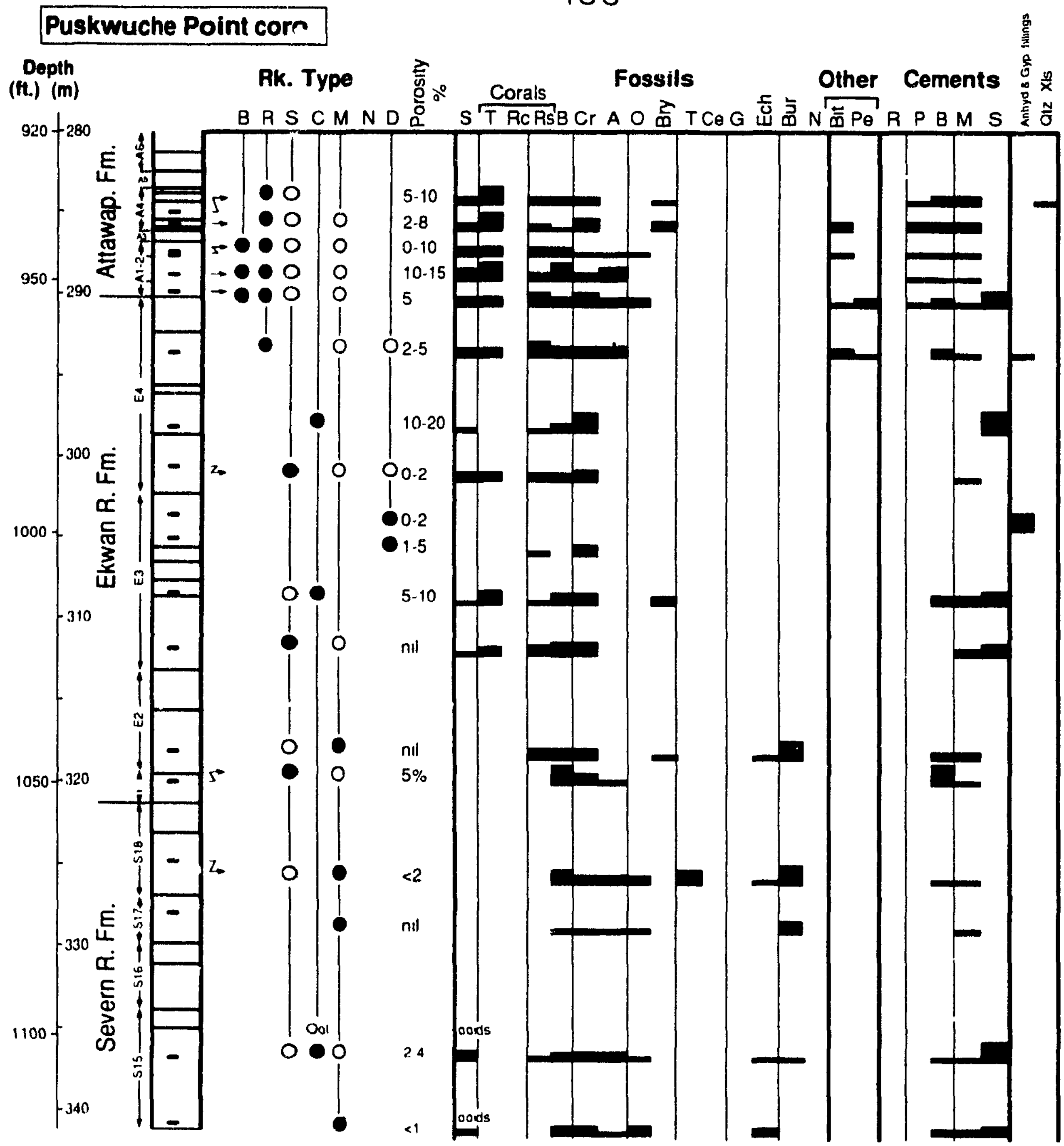

Figure A-2. Vertical profile of fossil and cement distributions in the Puskwuche Point No. 1 core. See Key for symbols.

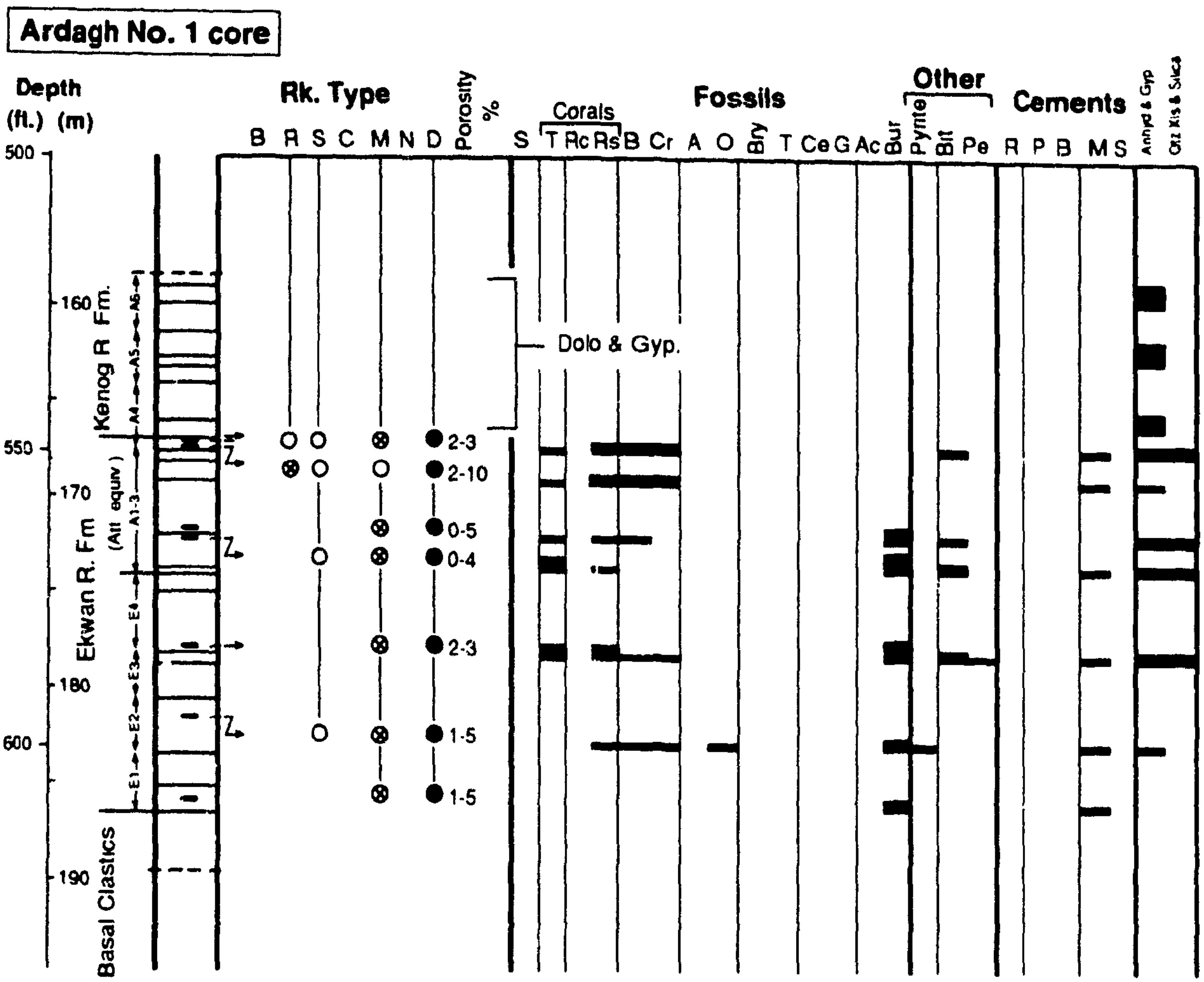

Figure A-3. Vertical profile of fossil and cement distributions in the Ardagh No. 1 core. See Key for symbols.

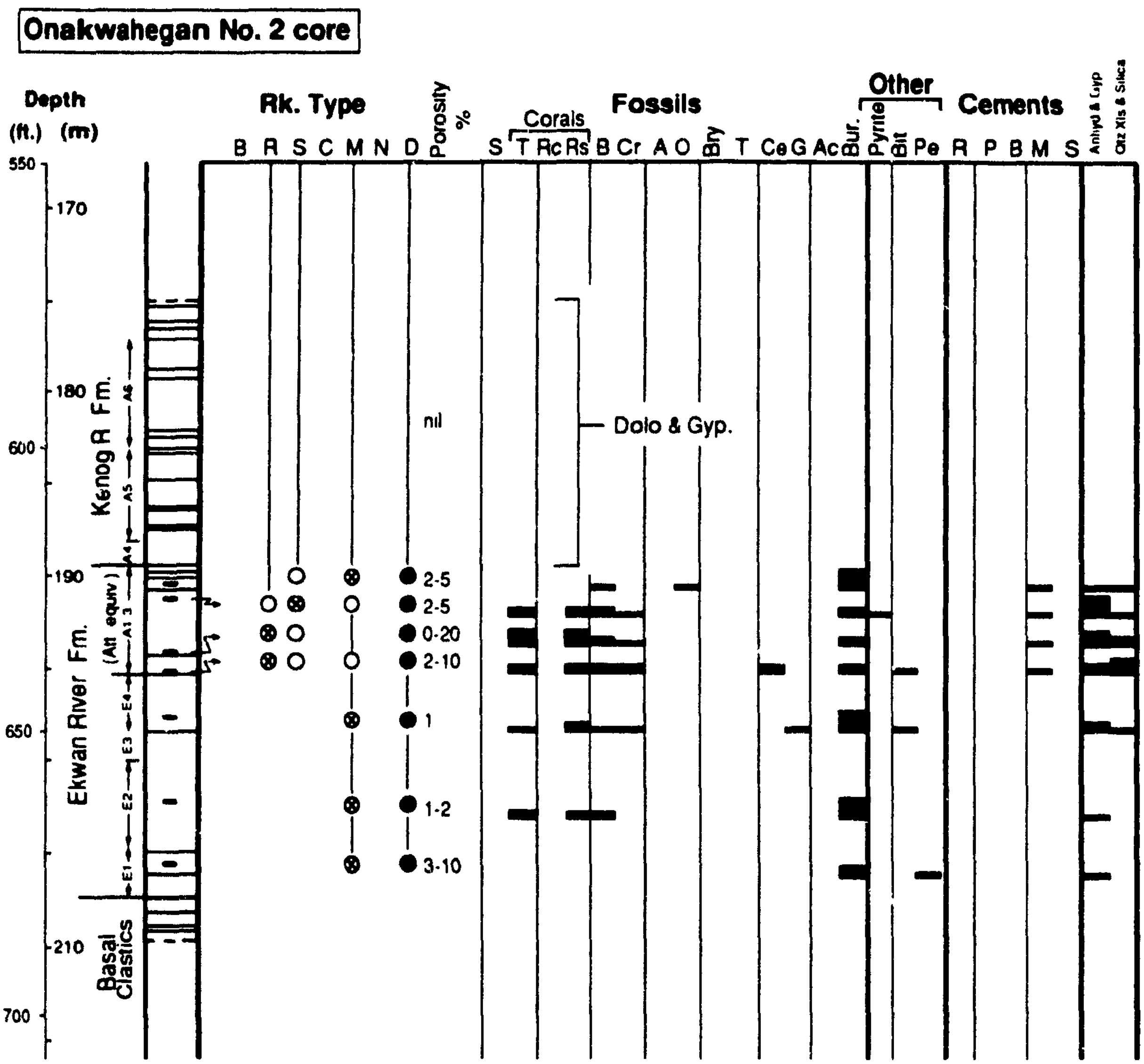

Figure A-4. Vertical profile of fossil and cement distributions in the Onakwahegan No. 2 core. See Key for symbols.

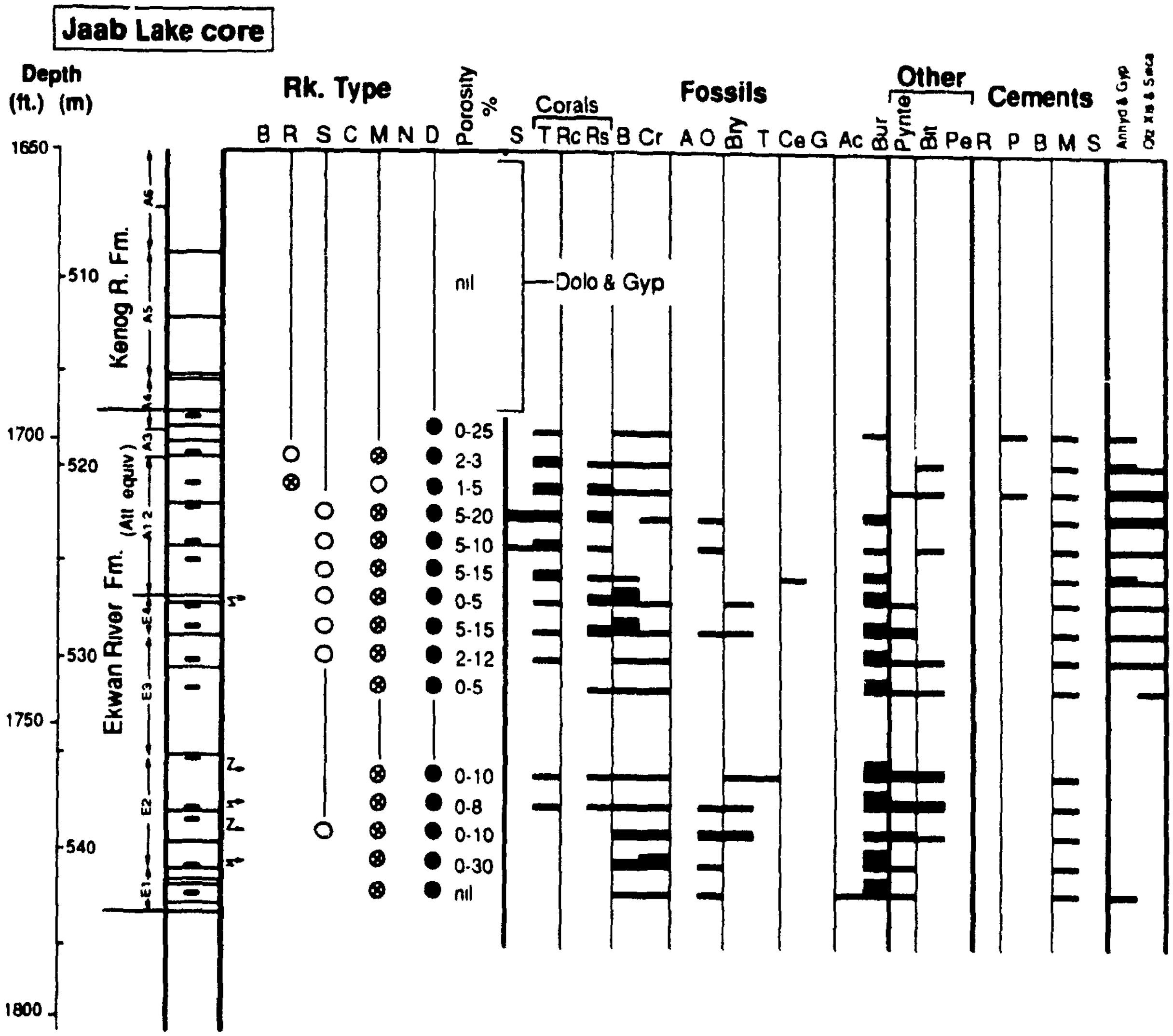

Figure A-5. Vertical profile of fossil and cement distributions in the Jaab Lake No. 1 core. See Key for symbols.

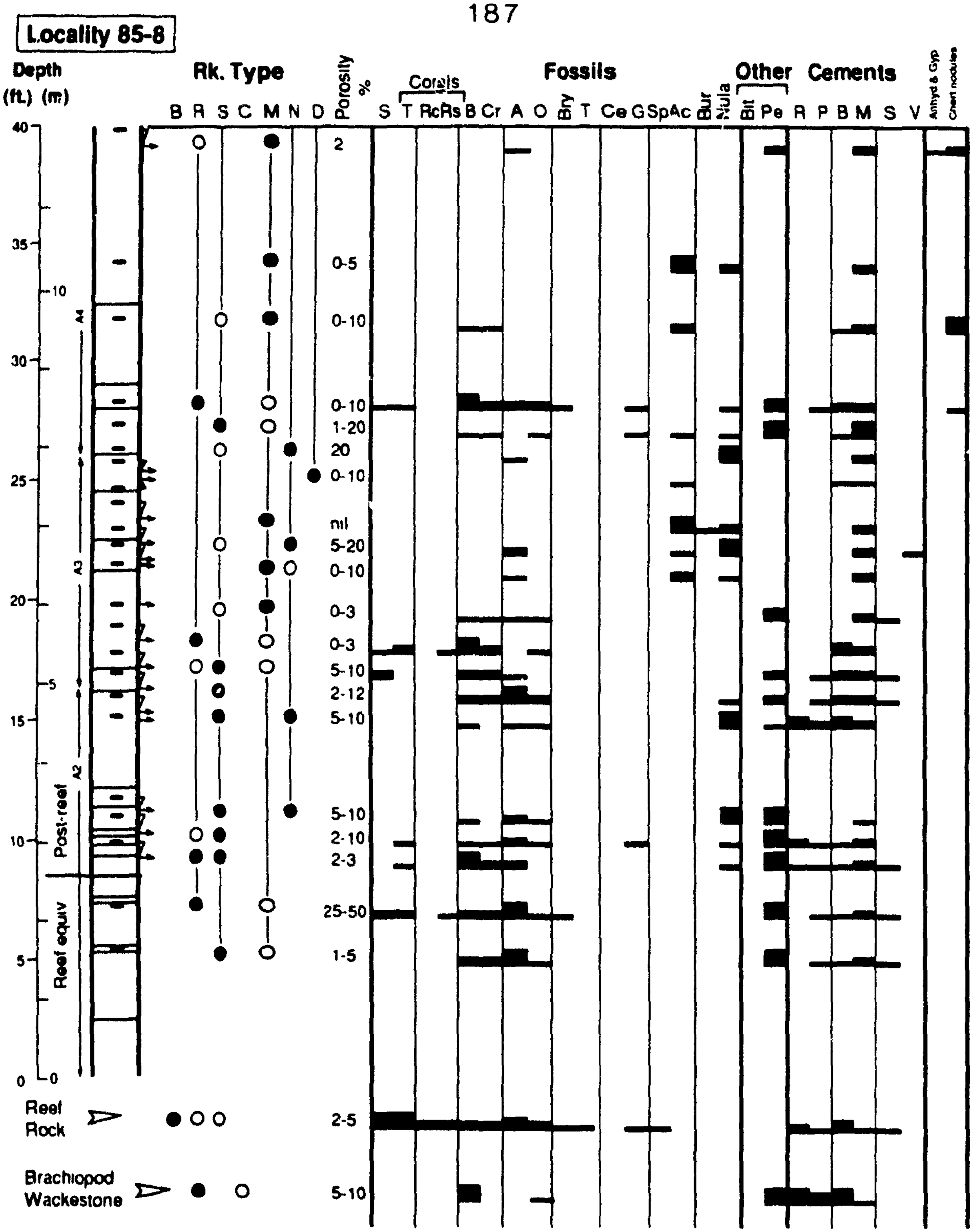

Figure A-6. Vertical profile of fossil and cement distributions at outcrop locality 85-8. Post-reef beds are above the 8.5 ft. (2.6 m) level, reef equivalent beds below this level. The two samples shown below the stratigraphic section include one of reef rock collected to the right of the section, and one of a brachiopod-rich lens on the flanks of a reef to the left of the section. See Key for symbols.

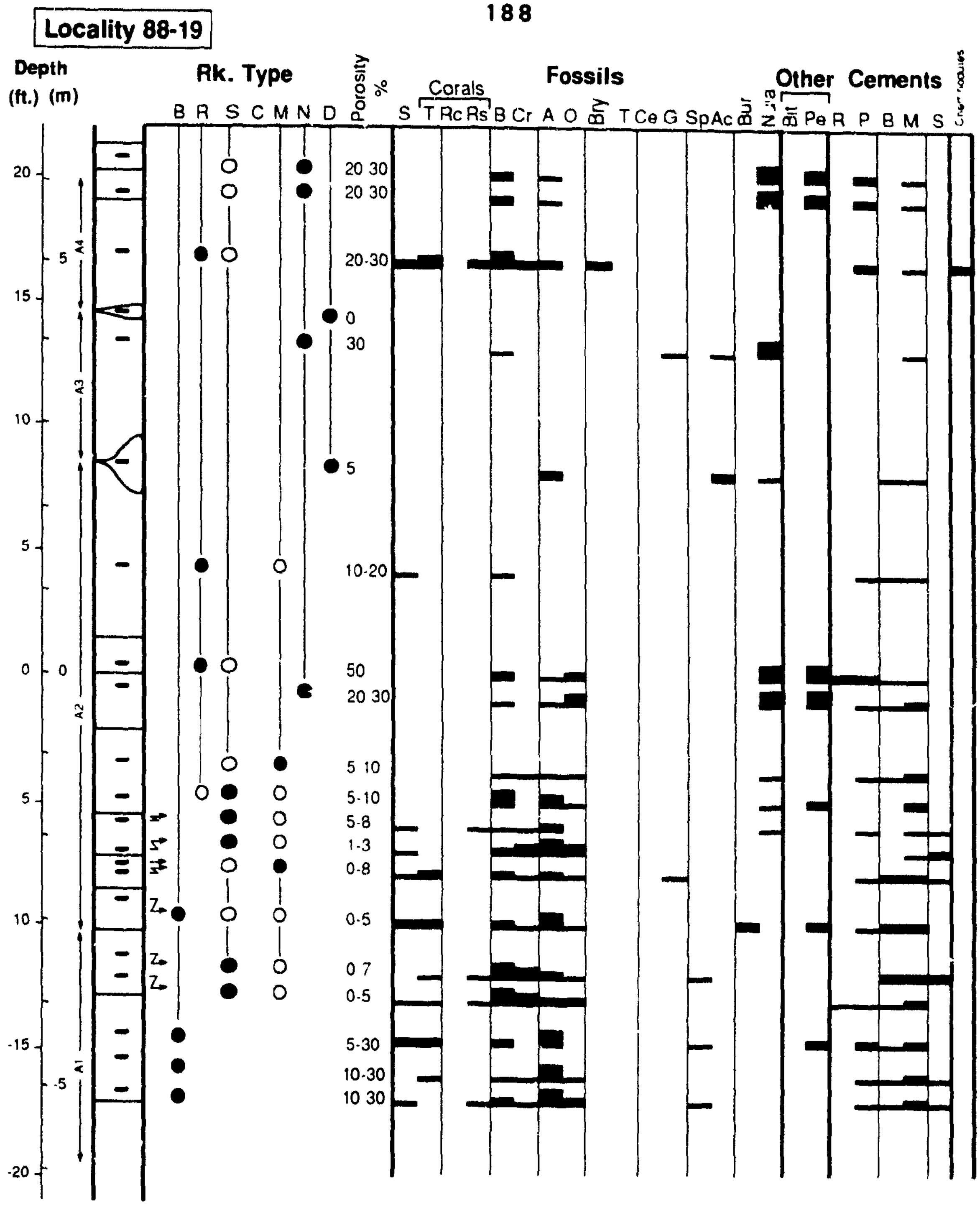

Figure A-7. Vertical profile of fossil and cement distributions at outcrop locality 88-19. Interval above 0 on the scale is outcrop exposure, below 0 is drill core. See Key for symbols.

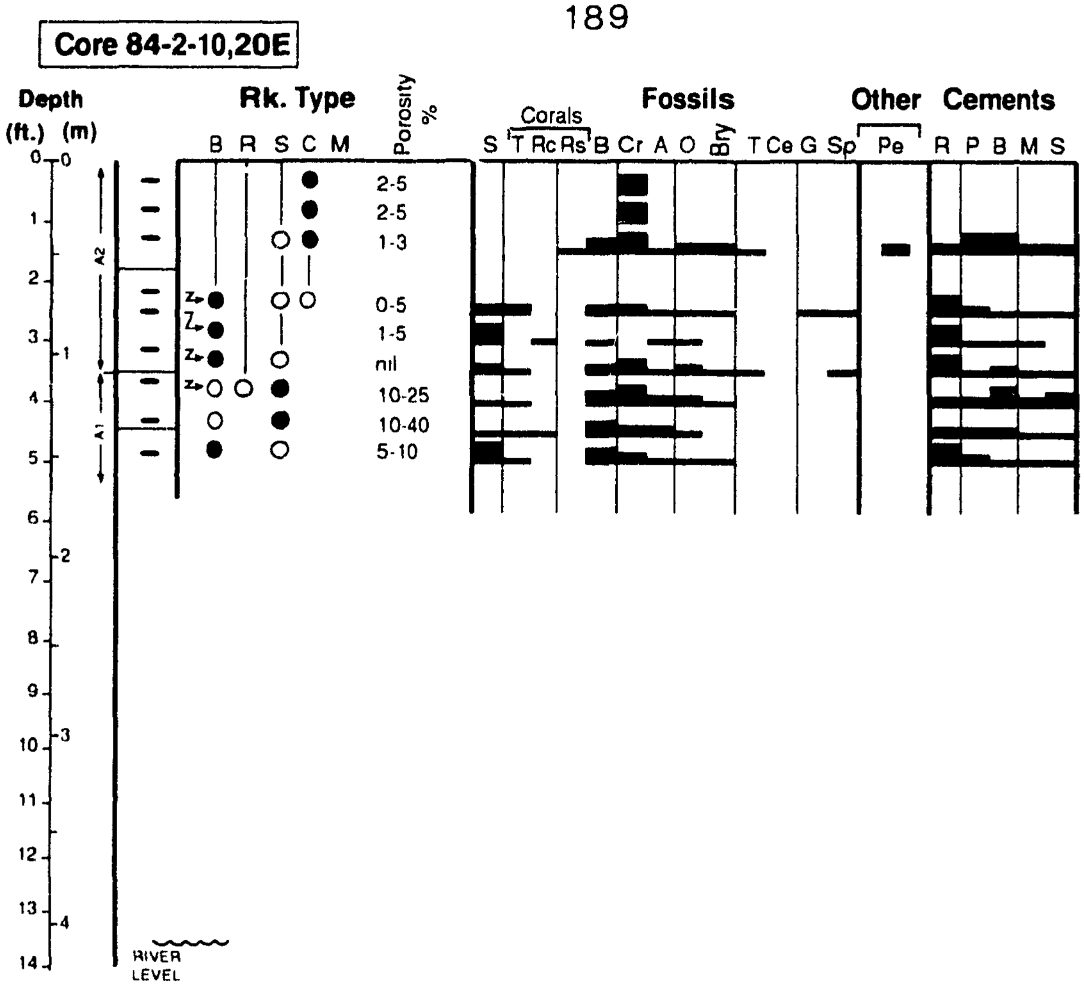

Figure A-8. Vertical profile of fossil and cement distributions in small drill core (no. 84-2-10,20E) taken in reef at outcrop locality 84-2. See Key for symbols.

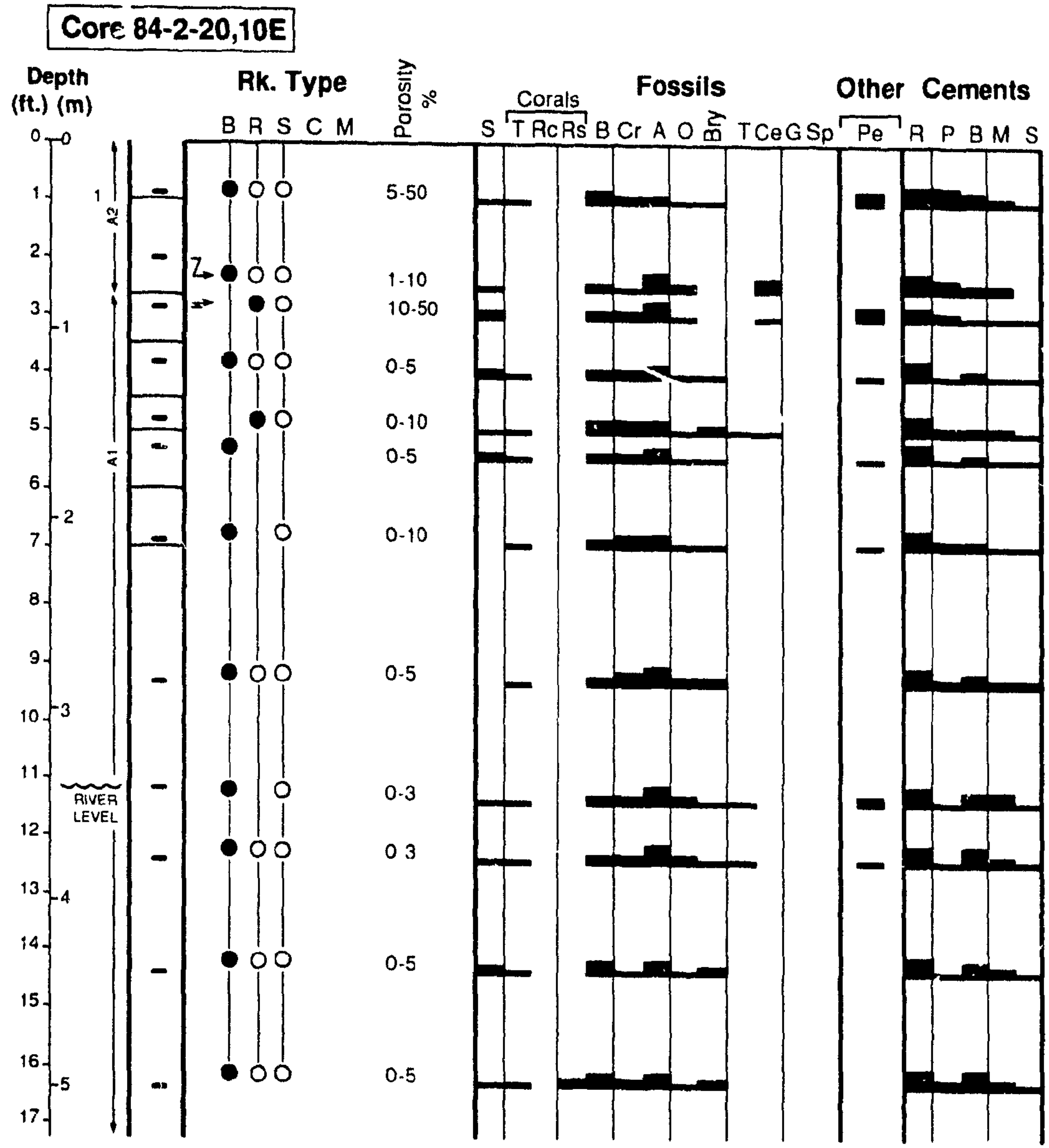

Figure A-9. Vertical profile of fossil and cement distributions in small drill core (no. 84-2-20,10E) taken in reef at outcrop locality 84-2. See Key for symbols.

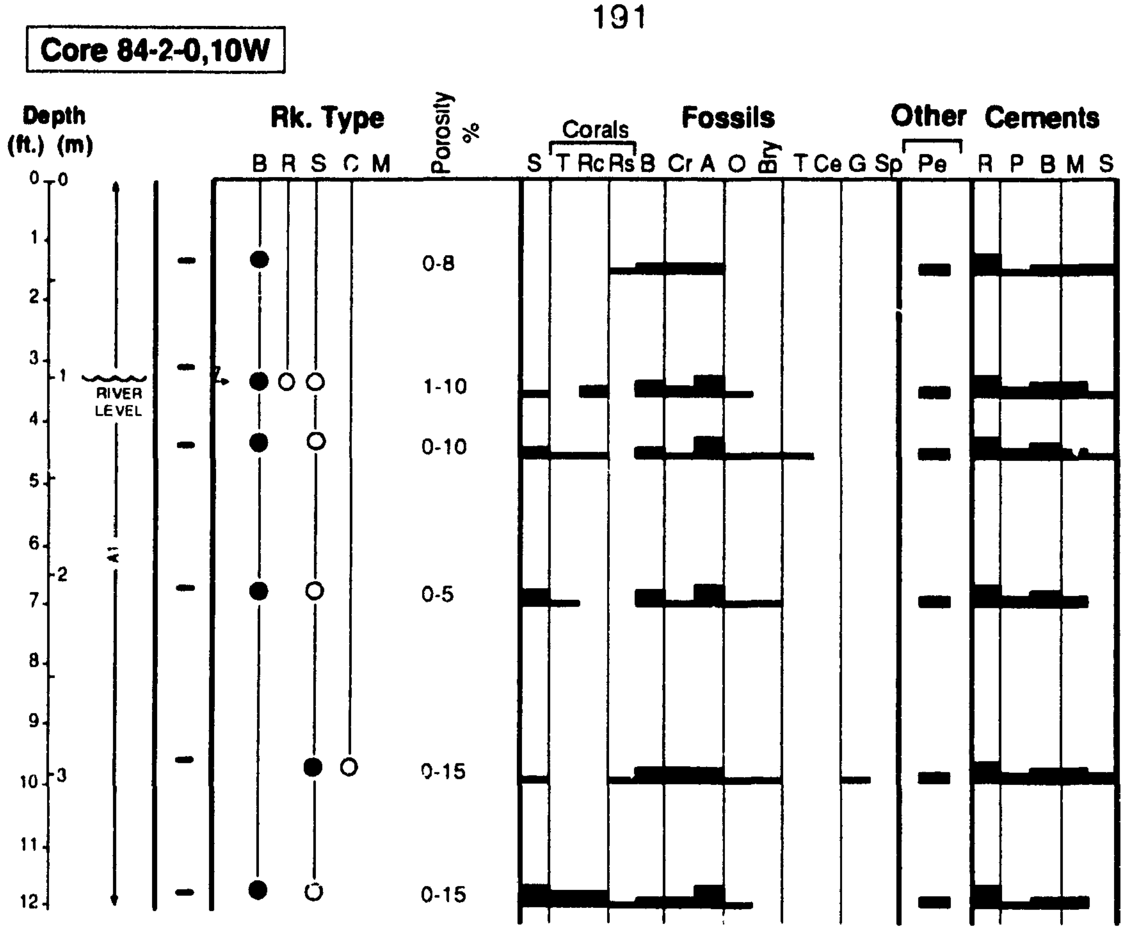

Figure A-10. Vertical profile of fossil and cement distributions in small d[illegible] core (no. 84-2-0,10W) taken in reef at outcrop locality 84-2. See Key for symbols.

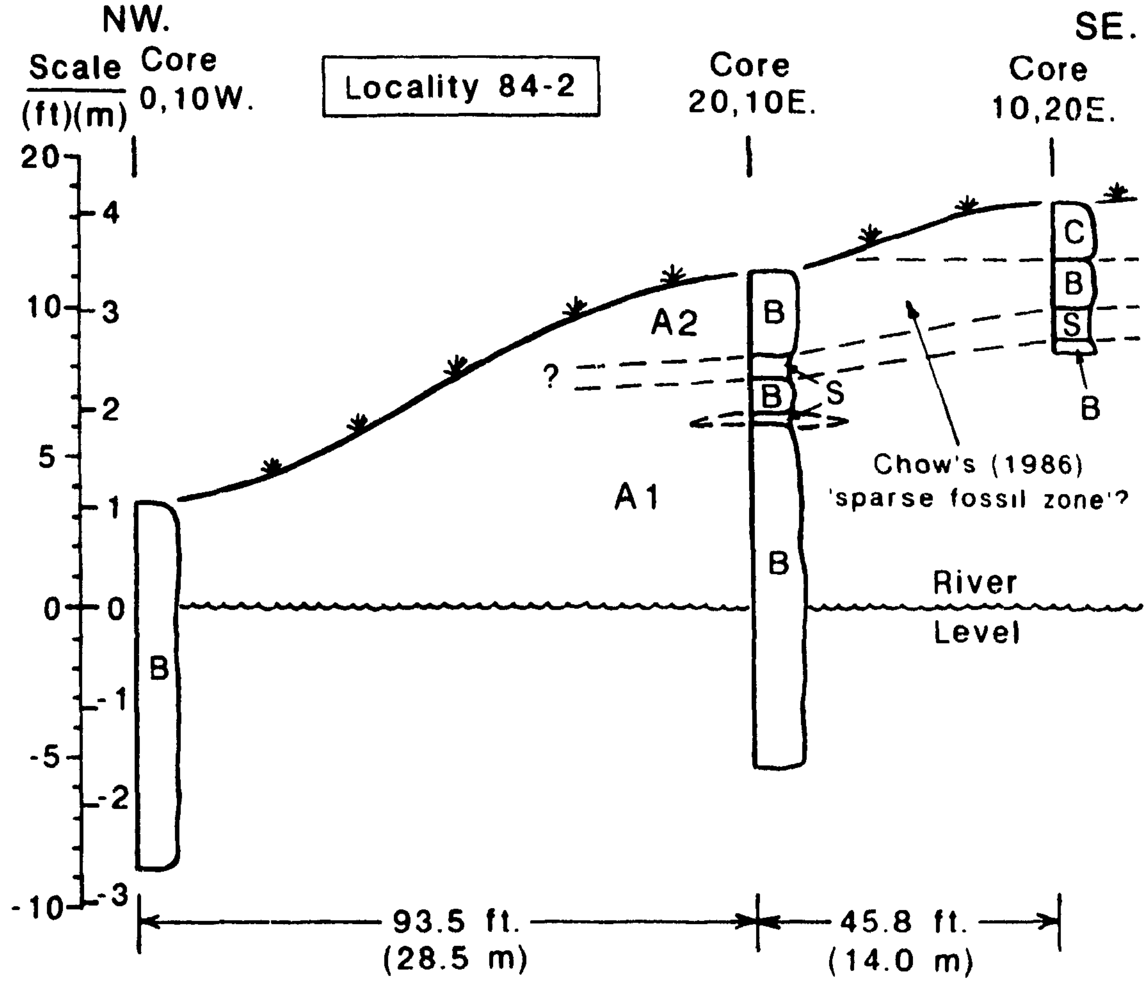

Figure A-11. Schematic drawing showing vertical and lateral relationships of three small drill cores taken at locality 84-2. Letter symbols are as follows: B = reefal boundstone, S = skeletal wackestone to grainstone, C = crinoidal wackestone, and A1 & A2 = parasequence numbers (Figure 8).