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DEVONIAN HARE INDIAN AND RAMPARTS FORMATIONS,
MACKENZIE MOUNTAINS, N.W.T.: BASIN-FILL,
PLATFORM AND REEF DEVELOPMENT

by

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INCEPTION, DEVELOPMENT, AND TERMINATION OF THE
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5.1 INTRODUCTION

The reef facies association consists of facies deposited in a spectrum of depositional environments. Cycle boundary correlation (see Chapter 2) and lithofacies analysis (in this chapter) resulted in grouping of subfacies into three broad facies, designated the reef interior-, the reef margin/shoal-, and the reef foreslope to basin facies.

Reef second-order cycles terminated with tidal flat or reef flat lithofacies at, or near, sea level, as indicated by near-parallel tops on reef cycles 1-5 in PL. 5-1. This is in sharp contrast to ramp and platform second-order cycles on which depositional topography was more pronounced, and was an important factor, along with sea-level change, in affecting lithofacies distribution. Since second-order cycle boundaries in the reef margin to interior facies approximate time-synchronous sea levels, it is possible to estimate and to consider the significance of accommodation for each time interval. Accommodation refers to water depth created by eustasy and subsidence (relative sea-level change) in addition to water depth remaining after deposition during the previous time interval (negligible where cycles terminated near inferred sea level). The thickness and disposition of facies that are accommodated reflect the history of relative sea-level change. Furthermore, if relative sea-level change was the overriding control on reef development in the study area, then

correlative sequences should be present in the time-equivalent Norman Wells buildup (Muir et al., 1984).

The reef facies association is distinguished from the platform association by the following principal characteristics:

- (1) Geometry: Second-order, upward-shoaling cycles in the reef facies association are areally less extensive than the underlying platform cycles (FIG. 3-2). Furthermore, second- and third-order cycle boundaries in the reef interior show little evidence of topographic relief, and are parallel to inferred sea level (FIG. 2-3).
- (2) Litho- and Biofacies: Reef margins in the reef facies association sheltered a restricted interior lagoon in which shallow water Amphipora rudstone, floatstone, and sparsely fossiliferous tidal-flat sediments were deposited (Muir et al., 1984; Muir and Dixon, 1984). Platform interior facies are generally more open marine, and contain more diverse assemblages of corals, brachiopods, crinoids, and stromatoporoids (Muir and Dixon, 1984).

This chapter is organized in a "building block" manner in order to meet the following objectives:

- (1) Discussion of factors controlling reef inception.
The nature of platform-reef transitions is commonly

poorly described in ancient reef studies. This chapter examines the factors that appear to have controlled the time and place of reef margin development on the underlying carbonate platform.

- (2) Description and interpretation of depositional environments of reef and related facies.
- (3) Discussion of facies variations through time, as defined by second-order cycle boundaries, and their relationships to a relative sea-level change/sedimentation model.
- (4) Comparison of stages of development in the Mackenzie Mountains buildup and Norman Wells subsurface buildup. This final aspect of the study represents the combined work of the author in the Mackenzie Mountains, and P.K. Wong and J.C. Wendte in the Norman Wells area. Preliminary results were presented in Muir et al. (1984, 1985).

5.2 TERMINATION OF PLATFORM AND INITIATION OF REEF CYCLE 1

The upper platform cycle was terminated by a significant rise in relative sea level, and hardgrounds developed on buildup tops. Initiation of margin/shoal facies of reef cycle 1 was restricted to these drowned platform highs (FIGS. 3-2, 4-1). These were likely areas of good circulation, and nutrient upwelling favorable for reef growth. Reef margins of reef cycle 1 prograded 800-1000 m

in the area of sections 23 to 04, and sediments of the reef interior infilled antecedent lows on the drowned platform interior, such as the embayment-fill at section 08 (PLS. 5-2 to 5-4). This embayment-fill is represented diagrammatically in FIG. 3-2 and PL. 5-5, and is an upward-shoaling sequence composed of the following facies in ascending order:

- (1) Dark, argillaceous, laminated, crinoidal lime mudstone and interbedded shale. These are interpreted as deep water laminites deposited in anoxic waters at depths of about 35 m.
- (2) Dark brown, wafer stromatoporoid floatstone, bindstone, and interbedded shale. These were deposited in calm, open marine waters at depths of 10-25 m. Channel-fills of robust cylindrical stromatoporoid rudstone occur rarely in this depositional setting (PL. 5-4b).
- (3) Fragmented wafer-tabular-robust cylindrical stromatoporoid floatstone and rudstone.
- (4) Abraded stromatoporoid breccia and robust cylindrical stromatoporoid rudstone. This 5 m thick unit is characterized by high interparticle porosity (occluded by calcite cement), common robust cylindrical stromatoporoid rudstone lithoclasts and a shallow water allochthonous assemblage of Amphipora, algae, and robust

cylindrical stromatoporoids. The facies shows evidence for high energy deposition, such as fragmentation and disorientation of allochems; grain-support; high initial porosity; and early marine cement. It is interpreted as a shallow water shoal facies, formed at depths of 0-5 m, which caps the embayment-fill sequence.

The shoal margin facies lacks the thick, encrusting stromatoporoid fauna observed in the reef margin facies at sections 04 and 18. These more consistently growing reef margin facies eventually became well-established during reef cycle 1 time, and the irregular depositional profile inherited from the upper platform cycle became nearly flat in the reef interior. This resulted in greatly restricted water circulation and the deposition of distinctive facies in the reef interior.

It appears that reef initiation during Ramparts time was controlled by two major factors:

- (1) Formation of discrete accretionary platform highs in the vicinity of the upper platform margin provided the topographic relief necessary for recolonization by reef organisms. Platform interior depressions were too deep to be colonized by reef formers and were initially depositional sites for deep water, open-marine laminated lime mudstone and shale (FIG. 3-2).

- (2) Progradation of the first reef cycle (FIG. 5-1) implies prolonged relative stillstand. This would have permitted rapid infilling of depressions, as well as progradation of reef margins. Soon after, severe restriction of water circulation in the reef interior resulted in deposition of shallow-water, faunally-impooverished facies.

5.3 FACIES ANALYSIS OF REEF MARGIN/SHOAL FACIES

5.3.1 General Statement

The distribution of reef margin/shoal facies in the study area is represented in PL. 5-1. Unfortunately, the present erosion surface and overburden allow only a tentative delineation of reef margin facies in reef cycle 5, although there is some evidence of backstepping from the margin positions of reef cycle 4 (see section 5.6). In the eastern portion of the study area, reef margin facies were probably never wider than 10's-100's of m at any time. Reef cycle 1 is characterized by progradational margins. Closely spaced sections indicate that both reef cycles 2 and 3 typically had more aggradational margins, although the latter appears to have been somewhat more progradational in the western portion of the study area. The culminating shoal sequence (subfacies 2) outcrops only at sections 20 and 31 (PL. 5-1).

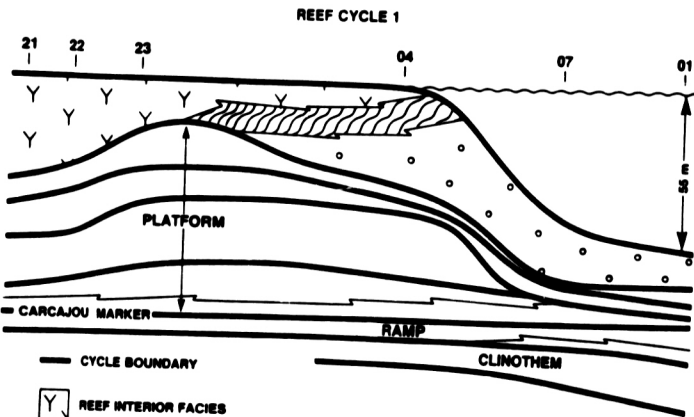


FIG. 5-1 Distribution of reef facies in reef cycle 1, eastern portion of study area.

Similar areally localized sequences lacking reef margins have been observed capping the Swan Hills-Judy Creek reef complex (Wendte and Stoakes, 1982).

5.3.2 Reef Margin/Shoal Subfacies 1

5.3.2.1 Description

Reef margin subfacies 1 mainly comprises massive to thickly bedded, thick tabular stromatoporoid boundstone (PL. 5-6a) and minor interbedded abraded stromatoporoid-robust cylindrical stromatoporoid rudstone (PL. 5-6b). The boundstone matrix is typically light tan colored, grain-supported, abraded stromatoporoid rudstone with calcite-occluded interparticle porosity. Allochems are micritized to various degrees. The margins are generally sparse to dense reef structures (15-35% in situ "massive" stromatoporoids; Riding, 1977) and tabular stromatoporoids are commonly not in contact, although they are typically less than one unit distance apart.

Reef margin facies in reef cycles 1 and 3 were examined in the eastern (sections 04, 24) and western portions of the study area, and TABLE 5-1 summarizes their major characteristics. At these localities, reef margin subfacies gradationally overlie reef foreslope subfacies 1 (PL. 5-7) and exhibit an upward increase of in situ, thick, tabular

TABLE 5-1

CHARACTERISTICS OF REEF MARGIN/SHOAL SUBFACIES 1		
	<u>West Margins</u>	<u>East Margins</u>
Average Thickness	3-4 m	6-8 m
Primary Matrix	robust cylindrical stromatoporoid rudstone with "muddy" peloidal lime packstone matrix support	robust cylindrical stromatoporoid-abraded stromatoporoid rudstone with peloidal lime grainstone matrix support
Interparticle Porosity	estimated 1%	estimated 2-3%
<u>Macrofauna</u>		
- thick, encrusting tabular stromatoporoid	common	common
- low extended hemispherical stromatoporoid	rare	common
- robust cylindrical stromatoporoid	common	common
- encrusting stromatoporoid	common	common
- bulbous stromatoporoid	--	rare
- <u>Amphipora</u>	rare	rare
- atrypid brachiopod	rare	rare
- crinoid columnals	common	rare
- ramose corals (thamnoporoid, <u>Coenites</u>)	rare	rare
- solitary rugose coral	rare	--

and low hemispherical stromatoporoids. The reef margin subfacies grades into reef interior subfacies 1 (mainly robust cylindrical stromatoporoid rudstone with high primary interparticle porosity occluded by calcite).

Faunal composition varies insignificantly from one cycle to another and from western to eastern margins. Stromatoporoids tend to be small and of low diversity in western margin localities, compared to eastern margin localities. In situ, thick, tabular stromatoporoids and low, extended, hemispherical stromatoporoids are commonly up to 100 cm in diameter and 30 cm thick at section 04 (reef cycle 1; PL. 5-8a). However, tabular stromatoporoids are smaller, averaging 20-25 cm in diameter and 3-10 cm thick at section 18, reef cycles 1, 3 (PL. 5-8b).

5.3.2.2 Interpretation

Reef margin facies reported in other ancient buildups are thought to be the end product of constructional processes, including reef-building and baffling of sediment by in situ benthos and destructional processes such as physical and bioerosion (Schoeder and Zankl, 1974). In the study area, physical erosion and minor bioerosion accounted for the abraded skeletal rudstone matrix and interbeds. There is little evidence that early marine cementation significantly affected the reef margin facies.

The predominance of tabular and thick tabular-encrusting, reef-building stromatoporoids suggests adaptation to moderate to intense wave action, but slow sedimentation (James, 1979). However, constant wave agitation possibly continually winnowed debris from the stromatoporoid growing surfaces. Low profile forms would have been least affected by pressure drag in turbulent zones (Bjerstedt and Feldman, 1985). At the same time, there is evidence to suggest that some stromatoporoids were attached to the substrate. Robust cylindrical stromatoporoid rubble was commonly encrusted by other stromatoporoids which, in turn, evolved into tabular forms. Firm anchoring on the substrate could have been another adaptation to high energy conditions. Vertical zonation of stromatoporoid morphotypes is evident only in the eastern margin localities where hemispherical and tabular forms are succeeded upward by thick, encrusting, tabular forms.

Although the two-dimensional transect of the reef complex makes it difficult to distinguish windward margins from leeward margins, there is evidence to suggest that the eastern margins developed in better circulated waters under higher energy conditions. Reef margins are better developed and abraded stromatoporoid rudstone (reef interior subfacies 1) more extensively distributed behind the eastern margins. In the western portion of the study area (section 18), marginal facies are thin and reefs developed poorly. Thin

(<2 m thick) sequences of reef interior subfacies 1 fringe the western margins and are capped by a megalodont-Amphipora lime floatstone, the culmination of reef cycles 1 and 3.

Hine (1983) noted that windward margins in the Bahamas show the best reef development. He attributed this to exposure to wave currents of well-oxygenated, agitated, nutrient-bearing water. Also, because the net energy flux is greater from east to west, the western margins are subject periodically to inimical bankwater, varying in salinity, temperature, oxygen content, and turbidity. This component of offbank transport probably accounts for the poorer reef development and progradation of the western margins of reef cycles 1 and 3.

5.3.3 Reef Margin/Shoal Subfacies 2

5.3.3.1 Description

Subfacies 2 is a 29 m-thick succession that constitutes reef cycle 6 at section 20. It is composed mainly of ramose coral-robust cylindrical stromatoporoid-brachiopod rudstone and bulbous-encrusting-robust cylindrical stromatoporoid rudstone (PL. 5-9a) with minor Amphipora rudstone and packstone.

The cycle thins eastward over 5 km to an equivalent 0.5 m thick section of slightly nodular, pyritiferous, atrypid

brachiopod lime mudstone and floatstone at section 31. Subfacies 2 is not exposed anywhere else in the study area and, therefore, its geometry cannot be ascertained. However, local "shoal"-like accumulations capping other Ramparts buildups have since been recognized on regional seismic sections (D. Bowen, Esso Resources Canada Ltd., pers. comm., 1985).

The base of the sequence is planar and abrupt on reef interior subfacies 3 of reef cycle 5. The basal 50 cm is dark brown, pyritiferous, Coenites floatstone and wackestone. Imperial clinotherm facies sharply overlie the subfacies at both localities (PL. 5-1). Unfortunately, the exposures are within stream cuts where it is difficult to determine if the apparent smooth truncation of allochems at the top of the sequence was due to prolonged hardground development or to recent erosion. An irregularly distributed, thin (2 cm) iron "slag" derived from water runoff through the Imperial shale and siltstone further obscures contact relationships. Compared to the lower cycle contact, presumed to have been approximately parallel to sea level, the upper cycle contact has an average depositional slope of 6.2 m/km.

5.3.3.2 Interpretation

In section 20, there is abundant evidence for persistent current agitation:

- (1) Allochems are commonly oriented in east-west and northeast-southwest directions (FIG. 5-2).
- (2) Interbedded, graded calcarenite to calcisiltite beds (average 15 cm thick) dominated by horizontal stratification and low angle cross-stratification are present rarely, and probably represent storm-emplaced sediments.
- (3) Grain-supported fabrics predominate. Allochems are commonly fragmented and partially micritized.
- (4) Interparticle porosity is ubiquitous (~1%; occluded by calcite cement).

Relatively unrestricted circulation permitted a diverse stromatoporoid-ramose coral fauna to flourish through much of reef cycle 6 time (FIG. 5-2). Reef margins were apparently absent. The paucity of lime mud reflects effective current winnowing, probably in water depths of 2-7 m.

Wendte and Stoakes (1982) documented isolated stromatoporoid shoals as the last reefal stage of the Swan Hills-Judy Creek buildup. The shoal units typically exhibit ramp-like, presumably windward profiles (northeast) and more steeply dipping southwest slopes. Reef cycle 6 in the study area possibly has similar shoal geometry.

The top of the shoal unit in reef cycle 6 shows no evidence of subaerial solution, such as scalloped microtopography and sediment-infilled pits, caliche, vadose

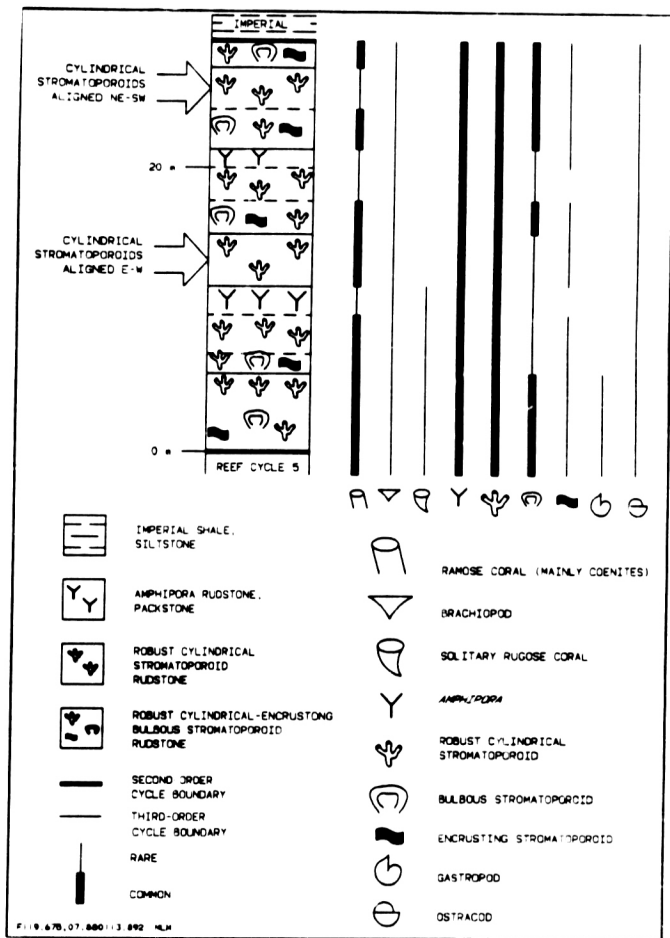


FIG. 5-2 Macrofossil distribution in shoal subfacies of reef cycle 6, Ramparts Formation (section 20).

diagenetic features, etc. Drowning, caused by another pronounced sea-level rise, terminated the shoal phase before reef margins could be established. Features interpreted as a hardground at section 31 suggest current winnowing of the Ramparts buildup before downlap of Imperial clinotherm sediments. However, because of the somewhat obscured Imperial-Ramparts contact (PL. 5-1), this hypothesis is tentative.

Minor third-order cycles (average 4 m thick, FIG. 5-2) can be discerned on the basis of the following shallowing-upward criteria:

- (1) Upward decreasing faunal diversity and stromatoporoid morphotype diversity.
- (2) Upward thinning and lightening of beds with concomitant decrease of the lime mud component in the rudstone matrix.
- (3) Upward increase in calcite-occluded interparticle porosity, ratio of fragmented to whole fossils, and degree of allochem micritization.

5.4 FACIES ANALYSIS OF REEF INTERIOR FACIES

5.4.1 General Statement

The reef interior facies has been subdivided into three major subfacies. Subfacies 1 occurs immediately behind the

reef margins and consists of abraded stromatoporoid rudstone with high (5-15%) calcite-occluded, primary interparticle porosity. This subfacies is a laterally fringing belt (FIG. 5-3) that passes into reef interior subfacies 2 and 3. Subfacies 2 typically occurs in the basal portions of reef interior third-order cycles and is generally muddier and more carbonaceous than overlying subfacies 3. Subfacies 3 consists of Amphipora floatstone, rudstone, and packstone, and commonly becomes grainier towards the tops of third-order cycles. Some of these beds are abruptly capped by light-colored fenestral lime mud and peloidal mudstone.

5.4.2 Reef Interior Subfacies 1

5.4.2.1 Description

The distribution of reef interior subfacies 1 is best observed in the eastern part of the study area (FIG. 5-3). The subfacies is composed of light-colored, abraded stromatoporoid rudstone (PL. 5-10a) and minor fragmented skeletal lime grainstone. Detailed examination of sections and reconnaissance traverses suggest that this facies belt is typically 100-400 m wide (FIG. 5-3) and occurs immediately behind the reef margins. Beds 10-20 cm thick are defined by variations in matrix/cement content, and (rarely) normal grading. Bedding contacts are commonly

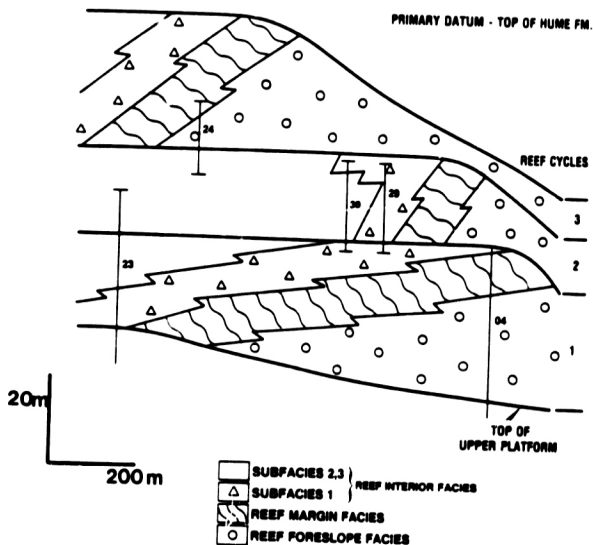


FIG. 5-3 Distribution of reef interior subfacies 1 and associated rocks in reef cycles 1-3 at sections 04, 23, 24, 29, and 30.

stylolitized. Allochems are invariably fragmented, disoriented, and commonly intensely micritized. Encrusting algae are common (TABLE 5-2), and robust cylindrical stromatoporoids are abundant (PL. 5-10b) throughout this subfacies. Some allochems are current-oriented (PL. 5-11a) and paleocurrent data acquired from them are summarized on FIG. 5-4. Rudstone lithologies generally contain a peloid skeletal grainstone matrix, and blocky cement-occluded interparticle porosity of 5-15% (PL. 5-10b).

5.4.2.2 Interpretation

Reef interior subfacies 1 represents aprons of coarse reef flat sediments that extended from behind the reef margins 100-400 m into the reef lagoon. Deposition would have been affected by waves breaking over the reef crest at high tide and by periodic storm waves (indicated by graded bedding). This possibly accounts for the common bimodality of paleocurrent data in the subfacies (FIG. 5-4).

The reef flat was probably inhospitable to most organisms due to shifting, unstable substrates, very high energy conditions, and periodic exposure at low tide. Rarely occurring aggregate grains and stromatoporoid-encrusted abraded allochems are indicative of intermittent grain movement. Allochems tend to be well-washed, lack delicate surface structures, and show extensive cortoid development. The extensive micritization probably resulted from infilling

TABLE 5-2

MACROFOSSILS OF REEF INTERIOR SUBFACIES 1

Common Constituents

robust cylindrical stromatoporoids: average 3-5 mm diameter, 10-40 mm long; stachyoditid average 2 mm diameter, 20 mm long

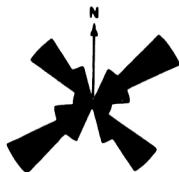
Amphipora

encrusting algae
crinoid columnals

Rare ConstituentsThamnopora

solitary rugose coral
atrypid brachiopod
ostracod
bulbous stromatoporoid: abraded, encrusted;
actinostromatid
encrusting stromatoporoid: stromatoporellid

GROUPED PALEOCURRENT DATA - REEF INTERIOR SUBFACIES 1

ALIGNED ROBUST CYLINDRICAL
STROMATOPOROIDS

SECTION 18 UNIT 034

SED 1	SED 2
060/230°	146/320°
060/230°	130/310°
030/110°	130/310°
044/220°	060/230°
040/230°	130/300°
060/270°	117/300°
070/280°	107/320°
130/310°	040/220°
	004/040°
	171/300°
	171/300°

FIG. 5-4 Paleocurrent data in reef interior subfacies 1.

of endolithic algae borings by micritic calcite cement (Bathurst, 1966).

Robust cylindrical stromatoporoids are volumetrically predominant in the subfacies and were evidently better adapted to stronger wave and current action. Abraded bulbous stromatoporoids, encrusting stromatoporoids, and Amphipora are more common in distal reef flat facies, possibly reflecting a preference for calmer conditions. Kobluk (1975) suggested that Amphipora was more tolerant of slightly higher sedimentation rates and lower nutrient concentrations. The rarely occurring, but ubiquitous, atrypids, solitary rugose corals, and thamnoporoids in the fauna are possibly allochthonous or inhabited niches on the reef flat where waters were better circulated and open marine.

5.4.3 Reef Interior Subfacies 2

5.4.3.1 Description

Subfacies 2 typically consists of medium olive-brown, bulbous-encrusting-robust cylindrical stromatoporoid-Amphipora floatstone and rudstone (PL. 5-11b). Allochems are supported by microstylolitized, peloidal, lime mudstone to skeletal wackestone matrix which coarsens-upward in some third-order cycles to light brown, peloidal packstone.

The subfacies is generally thickly bedded (30-40 cm average) at the base of third-order cycles, thinning- and lightening-upwards into reef interior subfacies 3. Associated with this upward trend is abrupt increase in the ratio of cylindrical stromatoporoids to total stromatoporoid content; decrease in bulbous stromatoporoid size; and sharp decrease in Coenites-brachiopod content.

Reef interior subfacies 2 is not restricted to any portion of the reef interior in the east-west transect exposed in the study area. However, several relationships were noted that helped to predict its occurrence and thickness variations with respect to the established stratigraphic framework:

- (1) Antecedent topographic depressions on the drowned upper platform became the sites of thick accumulations of subfacies 2 (e.g. in section 28, FIG. 3-2).
- (2) The subfacies occurs as sheet-like bodies at the bases of third-order cycles (PL. 5-12a).
- (3) Reef interior subfacies 2 thickens towards the reef flat settings of subfacies 1 and commonly contains a megalodont bivalve fauna (PL. 5-12b).

Reef interior subfacies 2 contains a more diverse fossil assemblage than the other reef interior subfacies (TABLE 5-3). Coenites, brachiopods, crinoids, and solitary rugose corals occur rarely in the basal beds of subfacies 2.

TABLE 5-3

MACROFOSSILS OF REEF INTERIOR SUBFACIES 2

Common Constituents

- bulbous stromatoporoid: clathrodictyid, stromatoporel-
lid; actinostromatid; commonly
overturned
- encrusting stromatoporoid: stromatoporid; commonly asso-
ciated with encrusting algae
- robust cylindrical stromatoporoid: 3-5 mm diameter, sub-
ordinate to Amphipora towards top of subfacies
- Amphipora
- megalodont bivalve: commonly articulated and in situ

Rare ConstituentsCoenitesThamnopora

crinoid columnals
solitary rugose coral
brachiopod
encrusting bryozoan

Restricted to basal portion of
subfacies 2. Coral fragments
commonly encrusted by
stromatoporoids.

encrusting algae
gastropod
ostracod

ubiquitous

Lamination is generally indistinct and burrows common. Nests of round fecal pellets are common in the bioturbated matrix.

5.4.3.2 Interpretation

Dark-colored, micritic limestone lithofacies of reef interior subfacies 2 were deposited in low energy settings, but in somewhat more open marine conditions than subfacies 3 (see following section). These conditions were essentially met adjacent to the reef flat depositional environment of subfacies 1. However, the occurrence of subfacies 2 at the base of third-order cycles and the associated more open marine fauna (diverse stromatoporoid assemblage; corals and brachiopods rare) suggest that areal distribution of these facies expanded during relative rise in sea level.

Cylindrical-bulbous stromatoporoid-branching coral biostromes have been described by Burchette (1981) as commonly occurring behind reef margins in Devonian reef complexes. Havard and Oldershaw (1976) reported similar facies in back reef cycles proximal to reef margins in the Swan Hills-Snipe Lake reef complex (Middle Devonian). Megalodonts occur in shallow subtidal facies (1 - a few m depth) in the Upper Devonian Miette reef complex in the Canadian Rockies (Mountjoy and Burrowes, 1982) and in proximal back reef facies of Silurian buildups in Arctic Canada (Packard, 1985). Kobluk (1975) documented a

hemispherical-irregular-bulbous-tabular-encrusting stromatoporoid-Stachyodes assemblage in the proximal lagoon sediments of the Miette buildup.

The extensive distribution of subfacies 2 across the entire complex in reef cycles 1-5 possibly indicates the east-west array of stratigraphic sections crosses a portion of the complex nearer to the reef margin than to the central reef interior (see Section 5.6 for comparison to Norman Wells buildup). Bulbous stromatoporoids would have been adapted to rapid sedimentation and soft substrates, but evidently were frequently overturned by periodic increases in water movement. This is particularly true in areas closer to the reef flat settings of subfacies 1 (e.g. in section 28), where bulbous stromatoporoids tend to be smaller and characterized by continuous outer growth surfaces. Upwardly increasing Amphipora/robust cylindrical stromatoporoid ratios, and decreasing coral-brachiopod fauna in subfacies 2 reflect shallowing under progressively more restrictive conditions. Robust cylindrical stromatoporoids, such as Stachyodes, were apparently less tolerant of higher salinities and lower nutrient concentrations, compared to Amphipora (Klovan, 1964; Kobluk, 1975; Wong and Oldershaw, 1980).

5.4.4 Reef Interior Subfacies 1

5.4.4.1 Description

Subfacies 3 comprises three major lithofacies groups that occur together in some reef interior third-order cycles. Typically these lithofacies occur in these minor shallowing-upward cycles in the following upward sequence:

- (1) Medium brown, carbonaceous Amphipora floatstone with ostracod-gastropod, microstylolitized wackestone matrix.
- (2) Medium to light brown Amphipora rudstone and peloidal lime packstone and grainstone.
- (3) Medium olive-brown, peloidal, laminoid lime mudstone and packstone.

The relative proportions of these reef interior lithofacies are discussed in terms of their spatial and temporal distribution in section 5-5. Fossil content is summarized in FIG. 5-5. Faunal diversity sharply decreases towards the top of subfacies 3, particularly within lime mudstone lithofacies. The sequence becomes lighter-colored upward, reflecting an overall decrease in carbonaceous lime mudstone content (except for the capping lime mudstone lithofacies).

In the Amphipora floatstone lithofacies, allochems are typically well-preserved and rarely pyritized. Beds average

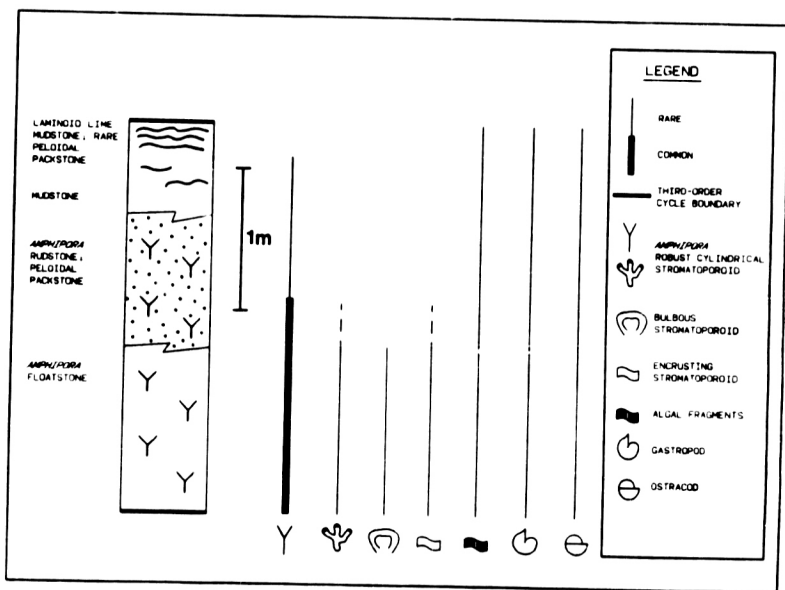


FIG. 5-5 Typical macrofossil distribution in reef interior subfacies 3, section 20.

10 cm thick, are extensively bioturbated, and generally have stylolitized contacts.

Amphipora rudstone and peloidal packstone lithofacies are characterized by a less diverse fauna, grain-supported fabrics, and more intensely micritized allochems. Peloids are commonly subangular, average 0.2 mm in diameter, and are poorly sorted. Bedding contacts are invariably stylolitized.

Medium olive-colored, bioturbated lime mudstone (PL. 5-13a) abruptly overlies the Amphipora rudstone lithofacies, and is gradational into laminoid lime mudstone (PL. 5-13b) and rarely into peloidal packstone. Bedding typically thins upward in this portion of the sequence, and horizontal stylolites are common. Blocky calcite cement-occluded open space structures are sparse and irregular in the bioturbated lime mudstone lithofacies. In the laminated mudstone lithofacies, stratification is more obvious and defined by alternating light and dark laminae averaging 1-2 mm thick, which pinch and swell slightly. Open space structures are laminoid and more continuous (PL. 5-13b). Beds of cylindrical stromatoporoid packstone and rudstone 5-10 cm thick are interbedded rarely with these laminated lime mudstone lithofacies in section 20 (units 028 and 029). These beds show sharp, slightly scoured, lower contacts, and sharp, planar, upper contacts.

Evidence for prolonged subaerial exposure occurs rarely at the tops of third-order reef interior cycles. In section 31 (PL. 5-13c), an emersion surface at the top of reef interior subfacies 3 (laminated lime mudstone) marks the boundary of reef cycles 1 and 2 (see also PL. 5-12a) in this area; however, this emersion surface could not be correlated into slightly deeper water, reef interior lithofacies (subfacies 3) in adjacent sections (08, 20). The emersion surface is orange-red, due to oxidation, in section 31. It shows irregular karst pits with 5-10 cm of relief, infilled by peloidal lime sand, laminoid fenestral limestone intraclasts, and vadose pendant cements.

5.4.4.2 Interpretation

Subfacies 3 was deposited apparently in a shallow, restricted reef lagoon and can be interpreted in terms of the relative positions of component lithofacies in third-order shallowing-upward cycles (FIG. 5-6).

The dark carbonaceous Amphipora floatstone lithofacies contains abundant micrite and is interpreted as deeper, restricted lagoonal sediment that gradationally overlies reef interior subfacies 2 (FIG. 5-6). Delicate cylindrical Amphipora thrived in a calm to slightly agitated lagoon floored by soft mud, and tolerated extremes in salinity, temperature, and Eh that few other organisms could withstand (Jamieson, 1971).

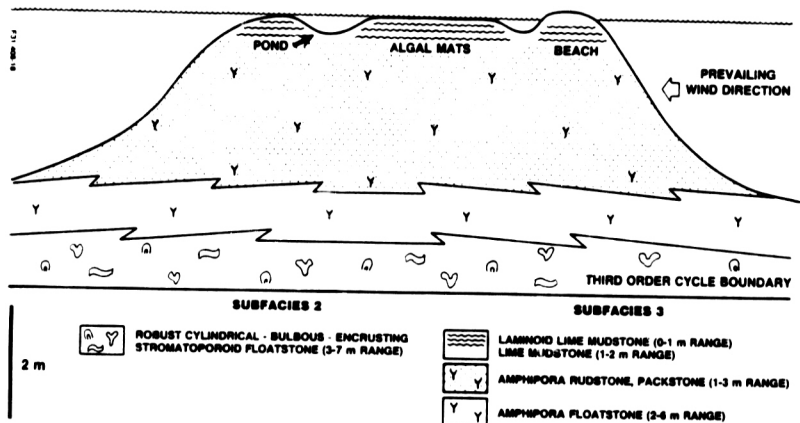


FIG. 5-6 Interpreted paleobathymetry of reef interior subfacies 2 and 3.

These facies coarsened-upwards as Amphipora rudstone and peloidal packstone were deposited in slightly shallower, more agitated waters 1-3 m deep (FIG. 5-6). Dasycladacean and codiacean algal fragments and calcispheres are much more abundant than in subfacies 2, or in the Amphipora floatstone of subfacies 3. The Amphipora rudstone is commonly capped by lime mudstone in the uppermost portions of third-order reef interior cycles. Fossils are extremely rare, and constitute a eurytopic Amphipora-ostracod-gastropod-alga assemblage that was able to withstand fluctuations in salinity, temperature, Eh, and nutrient supply. Water circulation became progressively more restricted and sluggish as Amphipora mounds built toward sea level. The bioturbated lime mudstone was deposited probably just below tide level in 1-2 m water depths. Ginsburg and Hardie (1975) documented bioturbated pelletal lime mud with minor admixed skeletal debris just below low tide level off northwestern Andros Island. Stratified muds and algal mats occur through the intertidal and supratidal zones where surfaces were periodically flooded and exposed. The laminoid lime mudstone in reef interior subfacies 3 probably formed in a similar tidal flat setting (0-1 m depth range) with lime mud being sporadically introduced by storms and derived from offshore mud reservoirs (cf. Hardie, 1977).

In reef cycle 3 (section 20; units 028, 029) interbedded cylindrical stromatoporoid rudstone appears to represent

storm beach accretion, based on the following characteristics:

- (1) Sharp, scoured lower contacts; sharp upper contacts.
- (2) Grain-to-grain contact of randomly oriented, fragmented, micritized allochems with high (average 5%) primary interparticle porosity occluded by blocky calcite and microstalactitic cements.
- (3) Allochthonous fossils (robust cylindrical stromatoporoids, bulbous stromatoporoids) that would not have thrived in juxtaposition to tidal flat environments.

Folk and Robles (1964) documented deposits of fragmented ramose corals stranded in high intertidal to supratidal zones on Isla Perez off the Yucatan Peninsula. They suggested that these sediments accumulated during abnormally high tides or storm events. The cylindrical stromatoporoid rudstone possibly represents analogous storm beach accretion on Amphipora mounds (FIG. 5-5) in the Devonian.

5.5 FACIES ANALYSIS OF REEF FORESLOPE AND BASINAL FACIES

5.5.1 General Statement

The reef foreslope and basinal facies can be subdivided readily into allochthonous foreslope subfacies 1 and 3;

autochthonous foreslope subfacies 2; and foreslope "toe" to basinal subfacies 4. These are well-exposed in both western (sections 15, 18) and eastern (sections 07, 01, 25) portions of the study area.

Shallowing-upward trends are indicated by the following combined textural, sedimentological, and paleoecological evidence:

- (1) Reef foreslope facies grade up into reef margin/reef interior facies that are abruptly overlain by reef foreslope facies at cycle boundaries (e.g. reef cycles 1, 3 in section 18; PL. 5-1).
- (2) The foreslope facies generally coarsens-, thickens-, and lightens upward. Primary interparticle porosity (partially occluded by blocky calcite cement) and sorting of the matrix both increase upward. Wilber (1985) reported shallowing-upward, coarsening-upward sequences along the leeward margins of the Western Bahama Banks. These sediments tend to be more winnowed and well-washed with hardgrounds commonly developed towards the tops of the sequences.
- (3) The ratio of allochthonous cylindrical stromatoporoids to corals and brachiopods increases towards the tops of the sequences. This appears to

indicate increasing input from shallow water source areas.

The foreslope and basinal subfacies will be interpreted below in the context of their positions in second-order shallowing-upward cycles. Sequence analysis also permits some interpretation of depositional slopes and paleobathymetric constraints for facies deposition.

5.5.2 Reef Foreslope Subfacies 1

5.5.2.1 Description

Reef foreslope subfacies 1 consists of medium-bedded (average 15 cm), light brown, abraded stromatoporoid rudstone and subordinate interbedded skeletal lime grainstone (PL. 5-14a). Where reef cycle 1 foreslope facies are exposed in the eastern portion of the study area (section 04), the subfacies grades upwards into reef margin facies. Basinward (sections 07, 01) reef foreslope subfacies 1 grades into, and is interbedded with, finer-grained, allochthonous reef foreslope subfacies 3 (FIG. 4-1). The western foreslope facies show similar relationships at section 18, as reef foreslope subfacies 3 and 1 constitute coarsening-upward, allochthonous, foreslope successions. These grade into poorly defined reef margin facies in reef cycles 1 and 3 (PL. 5-1).

Beds are horizontally stratified (PL. 5-14a), with either stylolitized or planar-abrupt to slightly scoured basal contacts (PL. 5-14b, c). Fining-upward from rudstone to grainstone is common in subfacies 1 (PL. 5-14b), although not always expressed in each bed. Primary interparticle porosity (2-15% visual estimate) is mainly occluded by blocky calcite cement.

Allochems (fossils listed in TABLE 5-4) show abundant evidence for physical abrasion and reworking: most are fragments with broken margins and display loss of fine detail, rounding of skeletal parts, and common encrustation by epibionts (PL. 5-15a). Apparently some larger allochems periodically came to rest downslope and temporarily provided a suitable substrate for encrusting organisms before being transported further downslope.

Intraclasts occur rarely in the subfacies and are mainly subrounded, tabular, lime mudstone clasts, 1-2 cm long. Aggregate grains are slightly more common and are predominantly robust cylindrical stromatoporoids encrusted by stromatoporoids and algae. The grainstone matrix is moderately to well-sorted, with little preserved lime mud. Grains are typically subrounded to subangular, and comprise nearly equal proportions of peloids (average 0.1-0.3 mm diameter) and partly micritized skeletal fragments.

TABLE 5-4

MACROFOSSILS OF REEF FORESLOPE SUBFACIES 1

Common Constituents

robust cylindrical stromatoporoid: shows weak current alignment in some beds
tabular stromatoporoid: mainly disoriented (flipped over, imbricate) with respect to bedding
hemispherical stromatoporoid: average 15 cm diameter
encrusting stromatoporoid: including clathrodictyid
Amphipora: more abundant component in western foreslope (section 18)

Rare Constituents

atrypid brachiopod
encrusting bryozoan
thamnoporoid coral
crinoid columnals
wafer stromatoporoid
bulbous stromatoporoid
solitary rugose coral
algal fragments

5.5.2.2 Interpretation

Much of allochthonous reef foreslope subfacies 3 was deposited as coarse-grained turbidites derived from an upper foreslope-reef margin source, based on the following evidence:

- (1) Common sharp to slightly eroded basal contacts and the incorporation of broken abraded allochems point to erosive turbulent flow.
- (2) Distinct stratification and upward-fining in many beds show that tractional and suspension sedimentation from turbulent flows were locally important.

These carbonate turbidites do not display sole markings, presumably due to the relative incohesiveness of the coarse-grained sediment and/or to removal by post-depositional pressure solution (cf. Hopkins, 1977; McIlreath and James, 1979). Bouma sequences are not well-developed. Robertson (1976) suggested that the scarcity of well-developed Bouma sequences in coarse-grained carbonate turbidites could be due to bimodality, or extremely variable size, volume and density of carbonate particles. Furthermore, because these beds were presumably formed by the sudden surge of density currents (McIlreath and James, 1979), other sediment gravity flow mechanisms could have acted in conjunction with turbulent flow. Grain-support could have been enhanced by dispersive

pressure, escaping pore fluid, and buoyancy forces. All these factors might be expected in high concentration turbidity flow and could account for the common occurrence of non-graded, sharp-based, horizontally-stratified rudstone beds.

Early-lithified clasts are notably absent from the subfacies. This apparent lack of pervasive early marine cementation could have been primarily a function of low foreslope inclination (48 m/km from section 03 to 01 in reef cycle 1) and, hence, slower rates of water movement through the sediment.

Sediment was mainly derived from the reef margin-upper foreslope environments as indicated by the common, allocthonous, thick tabular-hemispherical stromatoporeid fauna. The presence of abraded grains, algal fragments, and strictly shallow water fossils in resedimented flows also suggests that the source was relatively shallow.

Sediment gravity flows are generated when shear stress exerted by gravity exceeds the shear strength of the sediment, which is mainly a function of cohesion and intergranular friction (Allen, 1970; Rupke, 1978). In shallowing-upward foreslope sequences, shear stress would have increased with increasing slopes. Sediment movement downslope could also have been prompted by thickening of the sediment pile and storm wave activity. Both would have served to increase pore fluid pressure and thus decrease the

shear strength of the sediment, leading to sediment fluidization.

5.5.3 Reef Foreslope Subfacies 2

5.5.3.1 Description

Reef foreslope subfacies 2 is composed of dark brown, wafer-robust cylindrical stromatoporoid-ramose coral floatstone, bindstone, and interbedded calcareous shale. Allochems are supported by a microstylolitized, fragmented skeletal, lime wackestone matrix (PL. 5-15b, c), and are rarely pyritized or silicified. Fine-grained pyrite is more commonly disseminated in the dark brown carbonaceous wackestone matrix.

Most wafer stromatoporoids appear to be autochthonous and in life positions (PL. 5-15b). However, in some beds, the stromatoporoids are fragmented, extensively bored, and disoriented (PL. 5-15c) with respect to bedding. Peloidal mudstone intraclasts occur rarely in the subfacies.

Beds are typically 10-20 cm thick and show stylolitized contacts. The subfacies was observed only in reef cycle 1 foreslope facies, where it is stratigraphically bounded by upper foreslope subfacies 1 and lower foreslope subfacies 3. The upper subfacies boundary is gradational; the lower boundary is not exposed in the area.

Faunal diversity decreases from subfacies 1 to subfacies 2 (TABLES 5-4, 5-5). Stromatoporoid growth forms are also less diverse, and robust cylindrical and wafer forms predominate. Thamnoporoid corals are ubiquitous in the subfacies, but are particularly abundant in shale interbeds. Amphipora notably occurs very rarely in this subfacies compared to reef foreslope subfacies 1.

5.5.3.2 Interpretation

Reef foreslope subfacies 2 represents autochthonous, micritic sediment deposited in calm, open-marine waters characterized by slow sedimentation. Wafer stromatoporoids would have been well adapted to this environment as broad forms presumably both maximized feeding area and enhanced stability on a muddy substrate (Kershaw, 1984). The estimated paleobathymetric upper limit for this subfacies was ~14 m (FIG. 4-1). This value compares closely to the upper limit (15 m) determined for in situ, wafer stromatoporoid floatstone in upper platform subfacies 3 (Chapter 4). A lower paleobathymetric limit could not be ascertained due to incomplete exposure, but is tentatively estimated at 22-28 m (cf. Wendte and Stoakes, 1982). The paleogeographic extent of the subfacies would have varied according to the following factors:

- (1) Hydrographic position (especially circulation).

TABLE 5-5

MACROFOSSILS OF REEF FORESLOPE SUBFACIES 2

Common Constituents

wafer stromatoporoids: actinostromatid, stromatoporid;
5-20 mm height; 100-300 mm
diameter
robust cylindrical stromatoporoid: Stachyodes
crinoid columnals
thamnoporoid coral

Rare Constituents

Amphipora
encrusting stromatoporoid
tabular stromatoporoid
atrypid brachiopod
bryozoan
encrusting alveolitid coral
solitary rugose coral
ostracod

- (2) Slope - steeper slopes could have promoted more allochthonous transfer of sediment (i.e. expansion of subfacies 1, 3 belts).
- (3) Accretion style - progradation tends to produce more debris.
- (4) Relief - depth constrains where organisms can live.

5.5.4 Reef Foreslope Subfacies 3

5.5.4.1 Description

Reef foreslope subfacies 3 consists of thin to medium, horizontally bedded (average 5-10 cm thick), peloidal calcisiltite and calcarenite, with subordinate interbedded robust cylindrical stromatoporoid rudstone and dark grey slightly calcareous shale (PL. 5-16a). In reef cycle 1 at section 01, the subfacies constitutes the entire sequence and its beds generally thicken-, coarsen-, and lighten-upward overall (PL. 5-16b). At section 18, the subfacies typically occurs at the base of allochthonous foreslope sequences (reef cycles 1-4) and grades upwards into reef foreslope subfacies 1. Thickening- and coarsening-upward trends are not evident in all reef cycles. At section 01, reef cycle 2 is composed entirely of reef foreslope subfacies 3, which shows soft sediment deformation and submarine erosion at its upper contact (PL. 5-16c).

Orientations of minor slump fold axes tentatively suggest a northwest to southeast paleoslope. Within the slumped unit, lithofacies show truncated, microfaulted, and microfolded (recumbent) laminae (PL. 5-17a), dewatering structures (PL. 5-17b), and load structures.

Bedding contacts are planar-sharp or stylolitized, and some show faint sole markings that indicate off-reef derivation. The calcisiltite and calcarenite beds commonly fine upward (PLS. 5-17c, 18a). Bioturbation is typically restricted to upper contacts, and escape burrows occur rarely throughout subfacies 3 in sections 01, 07, 18. Biogenic structures are not evident in subfacies 3 at section 25. Pyrite occurs as fine disseminations and replacement mineralization of skeletal fragments. Nodular, slightly layered chert occurs as selective replacements primarily of coarser-grained calcarenite. Formation of the chert nodules apparently precluded plastic compaction. Pyrite-infilled peripheral fractures in the chert nodules indicate that these beds behaved brittly during compaction, whereas finer-grained calcareous muds were compacted around the chert layers (PL. 5-17a). Chert nodules are not apparent in reef foreslope subfacies 1 and 2. Furthermore, chert in subfacies 3 appears to be restricted to more basinward sections (01, 25) that were temporally and spatially proximal to Canol deposits of black siliceous shale.

Fossils occur rarely in reef foreslope subfacies 3, and represent a greater proportion of nekctic-planktic organisms than in other foreslope subfacies (TABLE 5-6). A higher ratio of skeletal fragments to peloids appears to characterize the western exposures (section 18) of subfacies 3 compared to sections 01, 07, 25 in the eastern foreslope depositional setting.

5.5.4.2 Interpretation

Reef foreslope subfacies 3 consists of fine-grained carbonate turbidites derived from the upper foreslope or reef margin and deposited on the lower foreslope. The turbidite origin is supported by the following evidence:

- (1) Wide, lateral continuity of beds.
- (2) Sharp basal contacts with faint sole markings.
- (3) Upward-fining and upward-gradation into interbedded shale.
- (4) Association with a foreslope depositional setting; common gradation into reef foreslope subfacies 2.

Partly analogous are turbidites cored on the deep bank margin of Little Bahamas Bank (Mullins and Neumann, 1979) that are dominated by Bouma A-intervals. These laterally continuous beds were most likely derived from a "line-source" on the shelf margin (Crevello and Schlager, 1980). It is likely that a line source supplied debris for the carbonate turbidites of subfacies 3. These could have

TABLE 5-6

MACROFOSSILS OF REEF FORESLOPE SUBFACIES 3

Rare Constituents

styliolinid: rare to common

crinoid columnals: rare to common

thin-shelled brachiopods: including Leiorhynchus
hippocastanea, atrypidAmphipora: 3-5 mm diameter

robust cylindrical stromatoporoid

wafer stromatoporoid

fish fragments

nautiloid

ostracod

solitary rugose coral

thamnoporoid coral

been distributed downslope through small gullies oriented perpendicular to the depositional margin and, thus, foreslope allochthonous debris could have bypassed sites of in situ foreslope facies deposition. Unfortunately, the east-west orientation of available outcrop is nearly parallel to the probable orientation of these gully-fill structures, and this interpretation must be considered tentative.

Rapid emplacement of turbidites during shoaling-upward phases of reef cycle development probably caused slope instability and sediment fluidization (PL. 5-17b). This is substantiated by evidence of periodic slumping downslope (PL. 5-16a).

In section 01, reef foreslope subfacies 3 of reef cycle 2 comprises 6-8 m of incoherently bedded slide and slump sheets that are variably deformed internally. The evidence of slumping includes the following:

- (1) Smooth, curving, concave-upwards surfaces that are interpreted as slump scars.
- (2) Unlike channels, the interpreted slump scars have one steep side (PL. 5-16a) that may be subparallel to paleobathymetric contours.
- (3) Depositional conditions were unaltered following slumping events, and later sediments (e.g. reef cycle 3 in PL. 5-16a) draped and gradually eliminated the topography of the slump scars. In

contrast, channel cutting involves current action that should be reflected in an erosional surface being overlain by coarse lag sediments. This was not observed in the reef foreslope slump unit (section 01, unit 031).

Formation of nodular chert in lower foreslope calcisiltite and calcarenite probably was related to upwelling of nutrient-rich water along the foreslope. Associated high biological productivity (e.g. radiolarians - see following section on basinal facies) could, in turn, have supplied abundant biogenic silica to lower foreslope and basinal sediments (MacKenzie, 1973; Muir and Dixon, 1984). Chert nodules formed in these facies apparently during burial and compaction. Evidence of early replacement includes:

- (1) Lamination that continues from chert nodules into surrounding rock (PL. 5-17a), indicating that the nodules replaced original sediment.
- (2) Primary textures and sedimentary structures preserved in the nodules. Laminae are typically 2-5 times as thick as those outside the nodules. This demonstrates early formation of chert.
- (3) Very irregular shapes of some chert nodules and enclosed patches of limestone that suggest a replacement origin.

(4) Association of silicified allochems in juxtaposed carbonate lithofacies.

Earlier workers (e.g. Braun, 1966; MacKenzie, 1970; among others) postulated that subfacies 3 at section 01 represented sediments derived from mechanical erosion of a lithified buildup ("Allochthonous Beds" in Chapter 1). However, in this study, sedimentological evidence points to slope failure of incoherent margin and upper foreslope material concurrent with the cyclic evolution of the reef complex.

5.5.5 Reef Foreslope Subfacies 4

5.5.5.1 Description

Subfacies 4 is only exposed in the basal portion of reef cycle 1 at section 07 (FIG. 4-1). At this locality, the subfacies is typically thinly-bedded (3-5 cm thick), medium-dark brown, nodular, lime mudstone and wackestone interbedded with shale (PL. 5-18b). Bedding contacts are diffuse to sharp, and shales show compressed biogenic structures (mainly small Chondrites, average diameter 1-2 mm) more commonly than does the nodular limestone. Pyrite is ubiquitous as framboidal disseminations and replacement mineralization of allochems. Faunal diversity and abundance are low, and the fossil assemblage includes allochthonous

crinoid columnals, styliolinids, fish fragments, and robust cylindrical stromatoporoids. An unidentified, small (average 0.8 cm long), subcircular, smooth-shelled impunctate brachiopod is locally abundant in some shale interbeds. Valves are commonly disarticulated, but show little evidence of transport.

5.5.5.2 Interpretation

Sediments in reef foreslope subfacies 4 were deposited in calm to slightly agitated, dysaerobic conditions. The muddy nature of the subfacies indicates low turbulence. Remains of epifaunal organisms were mainly transported to this site, and low infaunal diversity attests to poorly oxygenated depositional environments. The brachiopods present possibly were epipelagic organisms or an opportunistic species that intermittently exploited a substrate where ecologic stresses would have been inhospitable to most other organisms.

Paleodepths estimated for reef foreslope subfacies 4 (at section 07) are ~40-55 m (FIG. 4-1). Burrowing and possible episodic current activity possibly enhanced early cementation and contributed, along with burial diagenesis (pressure-solution phenomena), to the development of nodular bedding. Syndimentary lithification is also suggested by the presence of intrastratal fracturing in the limestone. This indicates brittle and plastic response to loading by cemented and unlithified sediment layers, respectively.

5.5.6 Basinal Facies

5.5.6.1 Description

The basinal facies consists of black, even-laminated shale with minor limestone interbeds. Limestone is increasingly subordinate to shale basinward. Graded crinoidal grainstone beds (average 5-10 cm thick, PL. 5-19a) are present in sections 01, 07, 18, 15, but are not evident in the subfacies at section 25. However, sharp-based, peloidal calcisiltite beds (PL. 5-19b) are interbedded rarely with shale at all localities in the study area. Carbonate content varies in the shale, and generally decreases basinwards and upwards in Canol stratigraphic sections.

At section 01, in unit 028 (basal reef cycle 2), megacrasts of tabular-wafer stromatoporoid floatstone are supported by black, slightly calcareous shale (PL. 5-20a), and peripheral fractures in the lithoclasts are filled with black shale.

The basinal facies thickens downslope (PL. 5-1) and is gradationally overlain by Imperial clinotherm facies (PL. 5-20b). Paleocurrent data in the lowermost Imperial Formation, -60 m above top of the Canol Formation, indicates southward transport (PL. 5-21).

The limestone lithofacies within the basinal facies are faunally impoverished (TABLE 5-7) and contain only

TABLE 5-7

A. MACROFOSSILS IN THE BASINAL FACIES - LIMESTONE

Rare Constituents

crinoid columnals: common in graded grainstone beds
Amphipora
 robust cylindrical stromatoporoid
 fish fragments
 sponge spicules
 styliolinids
 plant fragments
 indeterminate brachiopod fragments
 solitary rugose coral

B. MACROFOSSILS IN THE BASINAL FACIES - SHALE

Rare Constituents

styliolinids	-	locally common on bedding planes
tentaculitids	-	
sponge spicules	-	
fish fragments		
plant fragments		
radiolarians:		spherical, less than 0.5 mm diameter, microcrystalline quartz composition; commonly contain framboidal pyrite in cavities

allochthonous elements. Allochems are fragmented and commonly pyritized. Upward-fining, crinoidal grainstone beds, with planar-abrupt basal contacts, contain tabular, laminated lime mudstone intraclasts oriented subparallel to bedding in their middle portions. The crinoidal grainstone units grade into horizontally laminated lime mudstone, some of which contain current-oriented crinoid pluricolumnals. the peloidal calcisiltite beds show similar sharp-based contacts and upward fining. Beds are typically 2-5 cm thick, with continuous, horizontal, graded laminae (1-3 mm thick). Low angle climbing ripples are present rarely near the tops of some of these beds. Peloids are subangular (0.1-0.2 mm diameter) and commonly coated by dark brown organic films. The calcisiltite beds pinch and swell in the upper Canol Formation (PL. 5-20b) and commonly are replaced by chert along bedding contacts.

Shale lithofacies make up most of the basinal facies. Even horizontal lamination (average 1-3 mm thick) typifies the lithofacies and is primarily controlled by compositional variations in the carbonate and clay contents. Disseminated pyrite is locally preferentially concentrated in the organic-rich laminae. The relatively high pyrite content in the basinal facies (2-5% visual estimate) is reflected by its weathering product, jarosite (sulphate mineral), pervasive through much of the Canol Formation. FIGURE 5-7 shows the weight percentage of total organic carbon for

basinal facies in the western (section 15) and eastern (section 25) portions of the study area. The average weight percentage TOC is slightly higher in section 25 (4.32) than in section 15 (3.13).

5.5.6.2 Interpretation

The basinal depositional environment was characterized by slow sedimentation and anoxic conditions, as indicated by the following:

- (1) Pyrite as disseminated euhedral-framboidal grains and replacement mineralization of shells is ubiquitous. Pyrite formation is favored by slow bacterial decomposition of organic matter in anoxic environments during slow sedimentation (Curtis, 1980; Blome and Albert, 1985; Carstens, 1985).
- (2) Fossils representing infaunal and autochthonous benthic epifaunal biota are absent, and this permitted preservation of horizontal even lamination without disruption (Cluff, 1980).
- (3) Total organic carbon content is high in the basinal facies, and this would have been favored by slow sedimentation under anoxic conditions (Rhoads and Morse, 1971). The average of 3-4% compares well with an average of 3.2% TOC reported by Curtis (1980), based on 800 North American black shale

samples. He suggested that the average shale contains only 0.33% TOC.

The well-laminated nature of the shale lithofacies reflects compositional variations, possibly due to fluctuations in sediment supply. Laminae characterized by higher ratios of organic material and clay/carbonate are commonly much more enriched in pyrite than the carbonate-rich laminae. Carstens (1985) suggested that abundance of pyrite crystals can be related to slow sedimentation. This would permit the sulphate ion content of pore water to be renewed by diffusion from sea water. The well-laminated muds likely resulted from both dispersal of carbonate mud-rich turbidity flows into a well-stratified water mass and slow accumulation of hemipelagic muds.

Graded peloidal calcisiltite beds and crinoidal grainstone beds represent carbonate material transported from the foreslope environment by discrete turbidity events. Deposition occurred during flow deceleration and resulted in sharp-based, graded units. The greater extent of interbedded calcisiltite beds along the eastern foreslope-to-basin profile (sections 01, 25) possibly reflects better circulation and more intense wave reworking of the eastern reef-platform margins than those to the west (sections 18, 15). Preliminary evidence suggests that basinal facies in the upper disparilis zone are much thicker in section 25 (Appendix A) than in section 15. The rocks in

section 15 of this age are a highly condensed sequence representing significantly less input of carbonate debris than in section 01 east of the platform-reef complex.

5.6 CYCLICITY IN THE REEF FACIES ASSOCIATION

5.6.1 Introduction

The previous facies analysis is a basis for identifying cycle boundaries in the reef facies association. Each shallowing-upward cycle begins where shallower water sediments are overlain by relatively deeper water sediments. Because many carbonates are deposited within their environment of formation, external sources of sediment are not needed for accumulation to keep pace with rising sea level. However, if relative sea-level rise is very rapid and/or the carbonate factory is stressed, the production of skeletal and nonskeletal carbonate sediments can diminish or cease, and a cycle of sedimentation terminated.

In Chapter 2, it was noted that reef margin facies rarely show third-order cyclicity because reefs can grow rapidly and keep pace with frequent minor changes in relative sea level. Conversely, reef interior facies show less growth potential and are more likely to be drowned by smaller increments of relative sea-level rise. However, this is not the only mechanism by which third-order cyclicity can be

developed in the reef interior. Ginsburg (1971) suggested that carbonate production rates eventually fall behind subsidence rates as progradation decreases the size of the subtidal shelf lagoon where most carbonates are produced (Schlager, 1981). There is a certain lag time, controlled by the depth of the subsiding lagoon (Ginsburg, 1971; Hardie and Shinn, 1986). This results in subtidal sediments overlying supratidal sediments and the development of a new cycle of reef interior sedimentation.

Attempts at correlating third-order cycles in the reef interior facies were not successful, quite probably due to this autocyclic variation in carbonate production.

However, second-order reef cycles can be correlated from foreslope to reef interior depositional settings (see PL. 5-1). Basinal facies tend to show no distinct second-order cyclicity because environments and deposits at such depths were not sensitive to similar changes in relative sea level.

This part of the chapter outlines the characteristics of second-order reef cycles in the reef facies association. These shallowing-upward cycles can be discussed in terms of the initiation and direction of growth of reef margins following a pronounced rise in relative sea level, as follows:

- (1) Progradational - Reflects an overall basinward shift of cyclic shallow water facies. Reef

foreslope debris contributes significantly, and the reef flat facies belt expands.

- (2) Aggradational - Positions of the margins are essentially stationary through time. The reef foreslope steepens and foreslope debris can be less significant downslope than in progradational cycles. The reef flat facies belt is narrow.
- (3) Retreating/Backstepping - Backstepping refers to an abrupt landward shift of shallow carbonate facies following a relative rise in sea level. Retreating refers to a lesser magnitude backstep such that, in some portions along the cycle boundary, similar facies are present both below and above. Significantly less reef debris is shed into the depositional basin.

The nature of second-order cyclicity can be examined within a time-stratigraphic framework. Reef cycles 1-6 will be described in terms of reef evolution. Assuming that these cycles of sedimentation were controlled by an allocyclic mechanism, facies shifts on the reef margin and foreslope should also be reflected in the reef interior.

5.6.2 Second-Order Cyclicity in the Reef Margin/Shoal and Reef Foreslope Facies

Reef cycle 1 is the most progradational depositional stage in the evolution of the reef complex (PL. 5-1, TABLE

5-8). The top of the reef cycle built close to sea level before being terminated by a pronounced rise in sea level. This is indicated by presence of culminating tidal flat lithofacies in the reef interior sequence. Embayments and other topographic depressions in the drowned platform were quickly infilled during reef cycle 1 time, as sediment accumulation outpaced sea-level rise and the reef margins prograded basinwards (FIG. 4-1, PL. 5-1). Reef flat facies are more extensively developed in this sequence than in reef cycles 2 and 3 (FIG. 5-3). Allochthonous foreslope debris is thicker, coarser, and more widely distributed downslope than in the overlying reef cycles in the eastern portion of the study area (TABLE 5-8).

Reef cycles 2 and 3 are considered to represent aggradational reef development for the following reasons:

- (1) Lithofacies indicate that the tops of the reef cycles terminated in water depths near sea level (see section 5.6.3) similar to reef cycle 1.
- (2) Only minor backstepping (retreating) of the reef margins is evident, and the reef margins grew upward in the same general positions. Reef margin facies of reef cycles 1 and 3 both overlie foreslope subfacies 3 at section 18. Reef margins of cycles 2 and 3 were initiated probably a few 100 m at most toward the reef interior from the position of the margin in reef cycle 1 (FIG. 5-2).

- (3) Reef flat facies in reef cycle 2 (sections 29, 30) are more areally restricted than in reef cycle 1 (FIG. 5-3).
- (4) Each of reef cycles 2 and 3 in section 01 (TABLE 5-8) contain thinner accumulations of foreslope debris than in the preceding cycle. In reef cycle 3, foreslope limestones are interbedded with Canol basinal shale.

This last point reflects decreasing rates of progradation as the foreslope became steeper for reef cycles 2 and 3. Continued progradation would have required ever-increasing volumes of sediment on the flanks (Schlager, 1981). Hence, to keep pace with rising sea level, the reef margins became more aggradational, while maintaining a well-established restricted reef interior.

A slightly more progradational style might be expected for leeward margins, as wind-driven currents could have helped move sediments across the shallow reef interior onto the foreslope. This could account for reef cycles 2 and 3 being more progradational in section 18. Reef interior-derived Amphipora fragments comprise a substantially higher proportion of transported allochems in western foreslope facies than in the east (sections 01, 04, 07).

Reef cycle 4 began with backstepping of the reef margins toward the reef interior (PL. 5-1). To the east, Canol

basinal sediments abruptly overlie reef cycle 3 allochthonous foreslope facies. At section 18 to the west, distal allochthonous foreslope subfacies 1 overlies reef cycle 3 reef interior facies. Accelerated sea-level rise terminated reef cycle 4, but reef cycle 5 shows only minor reef margin backstepping. Although foreslope debris is absent from sections 18 and 01, reef interior facies present are grossly similar, lithologically and paleoecologically to the underlying reef cycle (see section 5.6.3). This suggests aggradational development of the reef margins for reef cycle 5.

Reef cycle 6 represents the establishment of an areally restricted shoal (PL. 5-1) lacking reef margins (TABLE 5-8). Relatively unrestricted circulation permitted the accumulation of grainy sediments which contain a mixed robust cylindrical stromatoporoid-~~Amphipora-Coenites~~-brachiopod fauna. The presence of a well established coral-brachiopod fauna possibly reflects the lack of a restricting reef margin.

5.6.3 Second-Order Cyclicity in the Reef Interior Facies

Since reef margin development and termination are primarily controlled by rates of relative sea-level rise, reef interior second-order cycles should mirror their response. This part of the study examines the reef interior

sequences in light of the evidence put forth in the previous section (5.6.2).

Because cycle boundaries within the reef interior are approximately parallel to inferred sea levels, lithofacies constituents within the cycles will vary due to changing rates of sediment supply and relative changes of sea level. Although climatic changes can also cause variations within the carbonate sequences, a humid, warm climate is inferred for much of Ramparts deposition because of the lack of evaporite lithofacies in the carbonate succession. Third-order cycles in reef cycles 1-5 (FIG. 5-8) average 3-4 m thick, with reef cycle 5 the thickest (4.3 m). These third-order cycles are only locally correlatable due to the combined effects of autogenic and allogenic controls (see Chapter 2). However, second-order reef interior cycles can be recognized and correlated. Their attributes permit some interpretation about water circulation. The latter would have been controlled by proximity to, and continuity of, reef margins and their varying restrictions on water exchange.

In reef interior sections, shallowing-upward, second-order reef cycles are recognized by the following criteria:

- (1) Successive third-order cycles generally culminate with progressively shallower water subfacies. Younger cycles typically begin with reef interior

REEF INTERIOR FACIES VARIATIONS (SECTION 20)

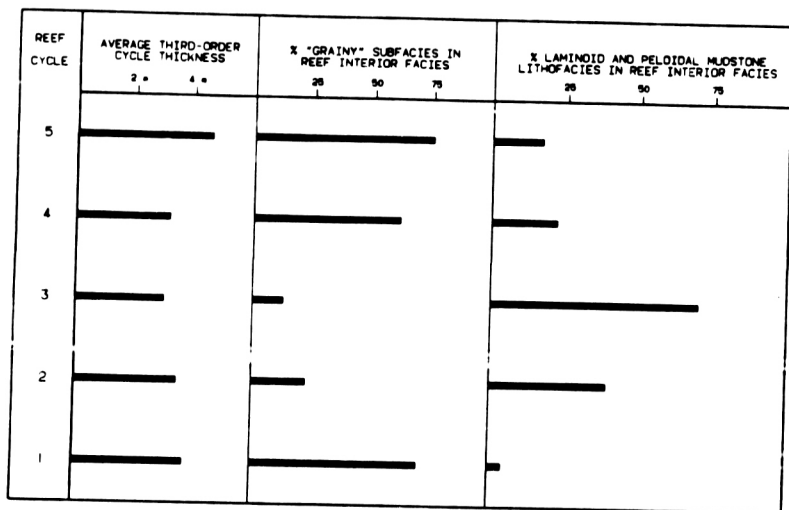


FIG. 5-8 Reef cycle facies variation in a reef interior depositional setting (section 20).

subfacies 2, rather than reef interior subfacies 3, which begins older cycles.

- (2) Abrupt shifts in reef interior facies result from backstepping of reef margin facies. Two features in particular can be used to interpret associated changing water circulation.

a) Higher percentage of "grainy" lithofacies (packstone, grainstone, rudstone) within reef cycles is an indicator of higher current energy.

b) Higher percentage of laminoid and peloidal lime mudstone lithofacies is an indicator of more restricted water circulation.

- (3) The presence of fossils representing stenohaline organisms can be used to interpret water circulation, in particular the improvement of water quality, near reef margins, and during sea-level rises (e.g. reef cycle 6 in FIG. 5-9).

Reef cycles 1 through 3 show a dramatic decrease in percentage of grainy lithofacies and proportional increase in laminoid and peloidal lime mudstone lithofacies (FIG. 5-8). Remains of stenohaline organisms are rare to absent.

Conditions in the reef interior during reef cycle 1 time were probably less restricted than during the overlying reef cycles due to initial bathymetric relief on the drowned

SECTION 20

REEF CYCLES

FAUNA	1	2	3	4	5	6
CORALITES						
CRINOID						
BRACHIOPOD						
SOLITARY RUDDER CORAL						
BRYOZOA						

SECTION 31

FAUNA	1	2	3	4	5	6
CORALITES						
CRINOID						
BRACHIOPOD						
SOLITARY RUDDER CORAL						
BRYOZOA						

RARE - < 1% OF TOTAL ALLOCHENS

OBSERVED IN < 50% OF UNITS

RARE TO COMMON - 1-5% OF TOTAL ALLOCHENS

OBSERVED IN > 50% OF UNITS

COMMON - > 5% OF TOTAL ALLOCHENS

OBSERVED IN > 50% OF UNITS

FIG. 5-9 Macrofaunal abundance and diversity in reef interior and shoal facies, sections 20 and 31.

upper platform and the temporary maintenance of open-marine embayments along the periphery of the reef complex.

The substantial increase in tidal flat lithofacies and decrease in grainy lithofacies in reef cycles 2 and 3 are suggestive of more restricted water circulation, with the reef interior more protected from wave action.

These changes are in accordance with the change from progradational to aggradational reef margins, interpreted for reef cycles 1 through 3 (section 5.6.2).

An abrupt shift in reef interior facies occurred with backstepping of the reef margin to begin reef cycle 4. The percentage of grainy lithofacies in the reef interior increased substantially from the underlying cycle and there is a corresponding decrease in lime mudstone lithofacies (FIG. 5-8). This character is maintained in reef cycle 5. Corals and brachiopods occur rarely to commonly, but ubiquitously in both reef cycles. The disposition of these reef interior facies reflects agitated, better-circulated water conditions that followed pronounced backstepping of the reef margins (section 5.6.2). Aggradational growth typifies both reef cycles, as demonstrated by the minor compositional change in reef interior facies across the cycle boundary. Reef interior facies disappeared from the Mackenzie Mountains buildup, with the major backstepping that led to reef cycle 6.

Wendte and Stoakes (1982) noted that grainier facies characterized the reef interior after pronounced reef margin backstepping in the Swan Hills-Judy Creek reef complex. They attributed the coarser reef interior facies to better circulation and/or slower rates of sea-level rise. The latter would have permitted extensive fragmentation and reworking of backstepped reef margin material to form finer sands.

Reef-derived sand is transported into and across the narrow lagoon on the Eleuthera Bank in the Bahamas (Dravis, 1977). The Eleuthera Bank is subjected to stronger wave surge from oceanic swells than the South Florida reef tract. The South Florida back-reef lagoon is more isolated from wave action, and two to four times the width of the Eleuthera Bank (Dravis, 1977). Consequently, lagoonal sediments tend to be much muddier in the South Florida lagoon.

By analogy, lagoon size and rates of sea-level rise probably controlled the disposition of reef interior sediments in reef cycles 1-5 of the Ramparts reef facies association.

In summary, second-order reef cyclicity can be documented in the reef interior and substantiates evidence for the style of reef cycle development observed in the reef margin-foreslope facies (section 5.6.2).

5.7 RAMPARTS PLATFORM AND REEF EVOLUTION:

A COMPARISON BETWEEN ISOLATED BUILDUPS

5.7.1 Introduction

The remainder of this chapter reviews the controls on second-order cyclicity, and then compares and contrasts Ramparts platform and reef evolution in the Mackenzie Mountains study area and in the subsurface at the Norman Wells oil field, ~100 km to the east (FIG. 1-1).

The composition of any section through a second-order platform or reef cycle is primarily determined by position relative to reef margin/shoal facies, and by oscillations of relative sea level. Distance from margin/shoal facies will affect sediment supply and composition, and these also depend on location of the margin/shoal with respect to predominant wind and current direction. In the reef interior, proximity to islands would influence the deposition of tidal flat facies. Finally, carbonate sedimentation rates are depth-dependent, with rates sharply decreasing below 10 m water depth (Schlager, 1981). In the absence of evidence to the contrary, subsidence rates are considered to have been uniform during deposition of the Ramparts platform and reef carbonates. No sedimentologic evidence for falls in relative sea level is apparent in either complex (Muir et al., 1985, 1986). Thus the cyclic nature of the platform and reef successions in the two areas

reflects episodically rising sea level. Each second-order cycle began with a marked increase in the rate of sea-level rise, such that carbonate production was outpaced by rising sea level. Kendall and Schlager (1981) noted that a relative deepening is accentuated by a lag (100's-1000's years) in carbonate production following an accelerated rise in relative sea level. Carbonate-producing biota take time to re-establish before carbonate production catches up and keeps up at times of lower sea-level rise (often termed stillstand). This results in characteristic upward-shoaling cycles of sedimentation. Longer lags permit more time for deepening while sediment accumulation is reduced (Read et al., 1986). In reef interior settings, this results in cycles having thicker subtidal bases and thinner tidal flat caps. Longer lag times might be expected for third-order reef interior cycles within the basal portions of second-order reef cycles.

Smaller increments of relative sea-level rise probably account for some of the third-order cyclicity observed in each second-order reef cycle. Read et al. (1986) suggested that high amplitude sea level oscillations result in thick subtidal facies and thinner capping tidal flat facies in each cycle. Rates of shoreline migration landward generally exceed maximum progradation (typically several km/1000 years) and tidal flat facies would be thin or absent, particularly further seaward.

The thickness of a cycle is determined by accommodation. Accommodation for each cycle time interval is the sum of water depth created by eustasy and subsidence (relative sea-level change) and water depth remaining after deposition during the previous cycle time interval. For purposes of comparison, cycle thicknesses should be measured where cycle boundaries terminated close to inferred sea level (e.g.: platform/reef margin facies; reef interior tidal flat facies).

Equivalent cycles between the two complexes should show similar thicknesses relative to a regional marker, and display a consistent style or reef/platform margin development (progradation, aggradation; backstepping, forestepping) if sea-level oscillation was the primary mechanism controlling carbonate sedimentation.

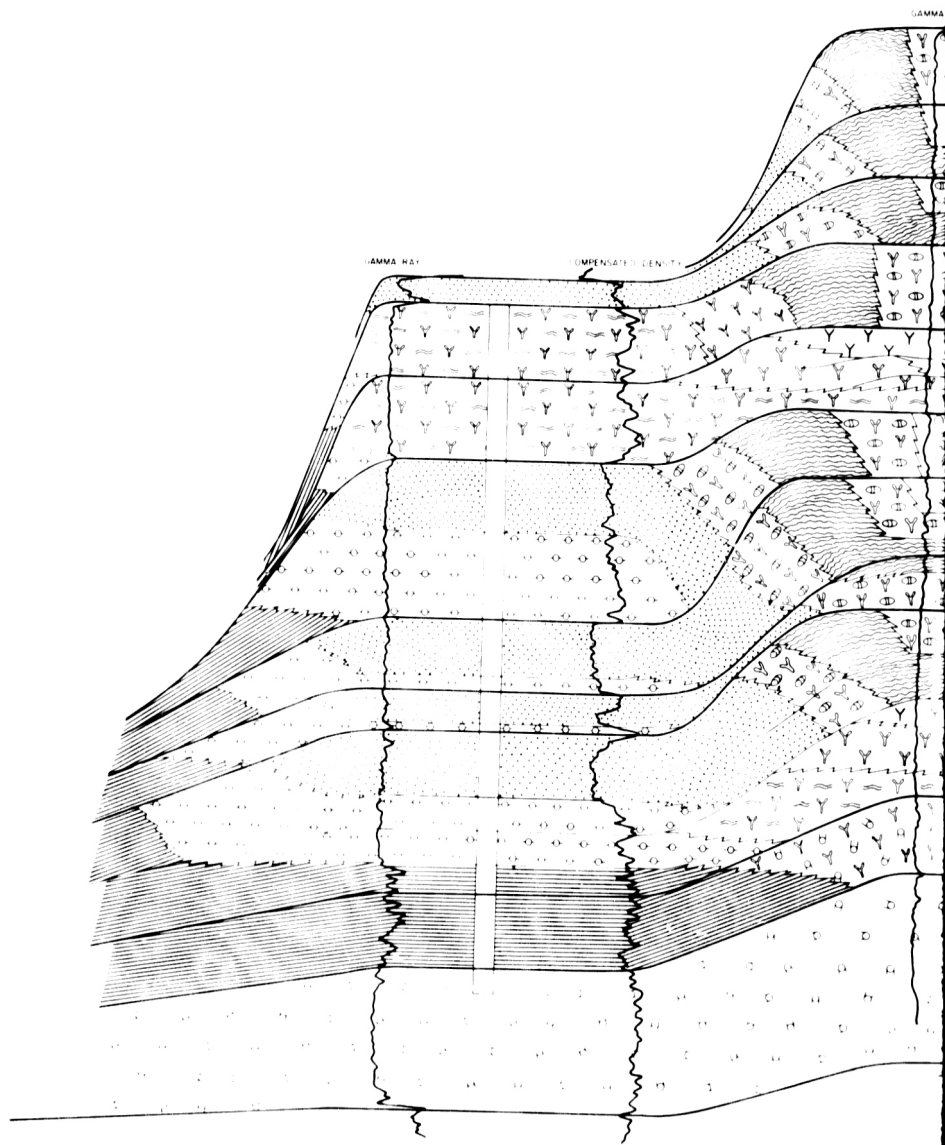
5.7.2 Observations and Interpretations

Eleven second-order cycles are recognized in the subsurface Ramparts platform-reef facies at Norman Wells (FIG. 5-10). These are labelled K1A through K4, and form the basis for reservoir zonation in the complex (Muir et al., 1984, 1985).

Cycle tops have been correlated on the basis of their positions relative to the Carcajou Marker and to the top of the first reef cycle (K2B at Norman Wells) in FIGS. 5-11 and 5-12. Comparison of the cross-sections shows that only

FIG. 5-10 Stratigraphic cross-section of the Ramparts (Kee Scarp) platform-reef complex at Norman Wells (after Muir et al., 1984).

P-9x

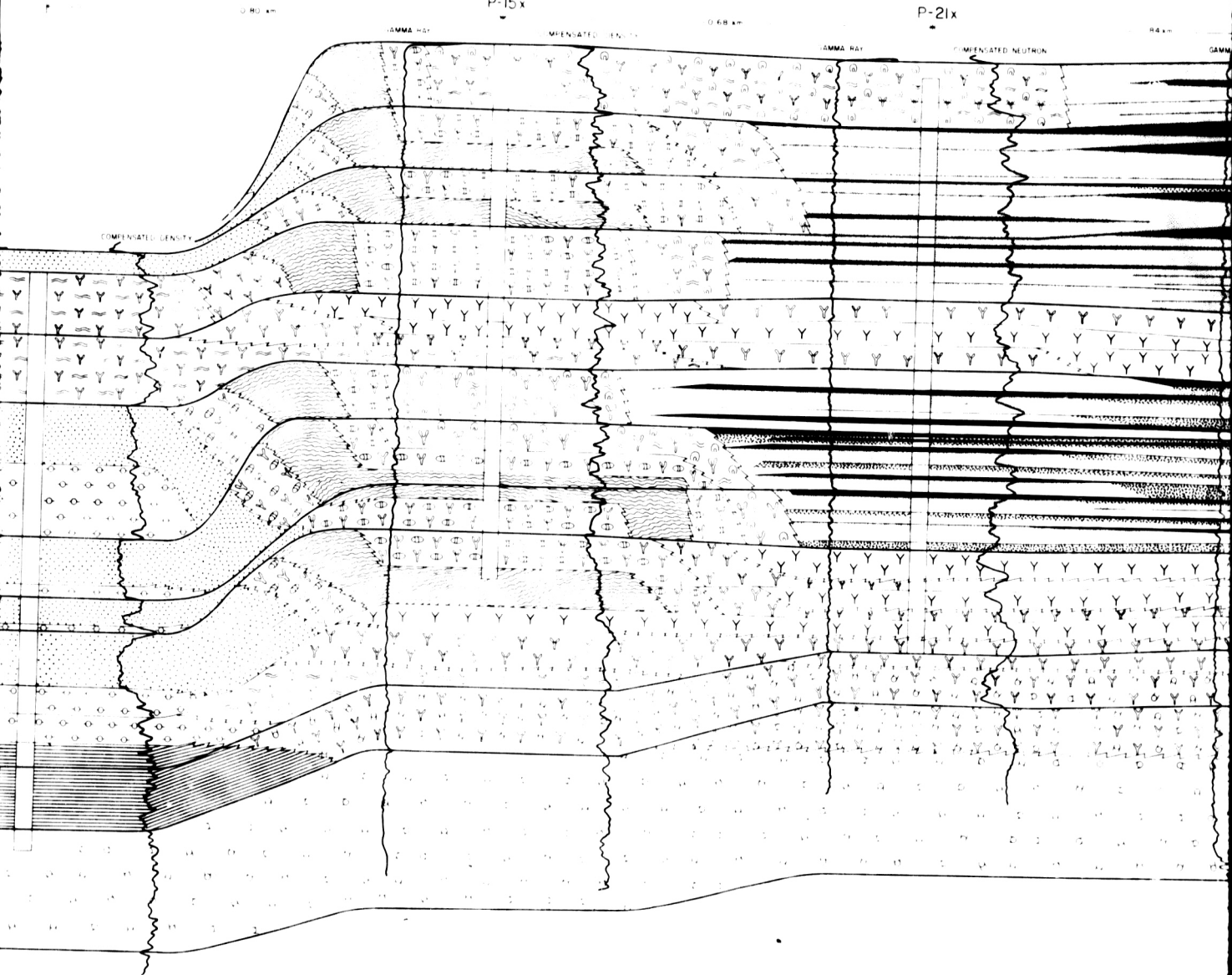


STRATIGRAPHIC CROSS SECTION

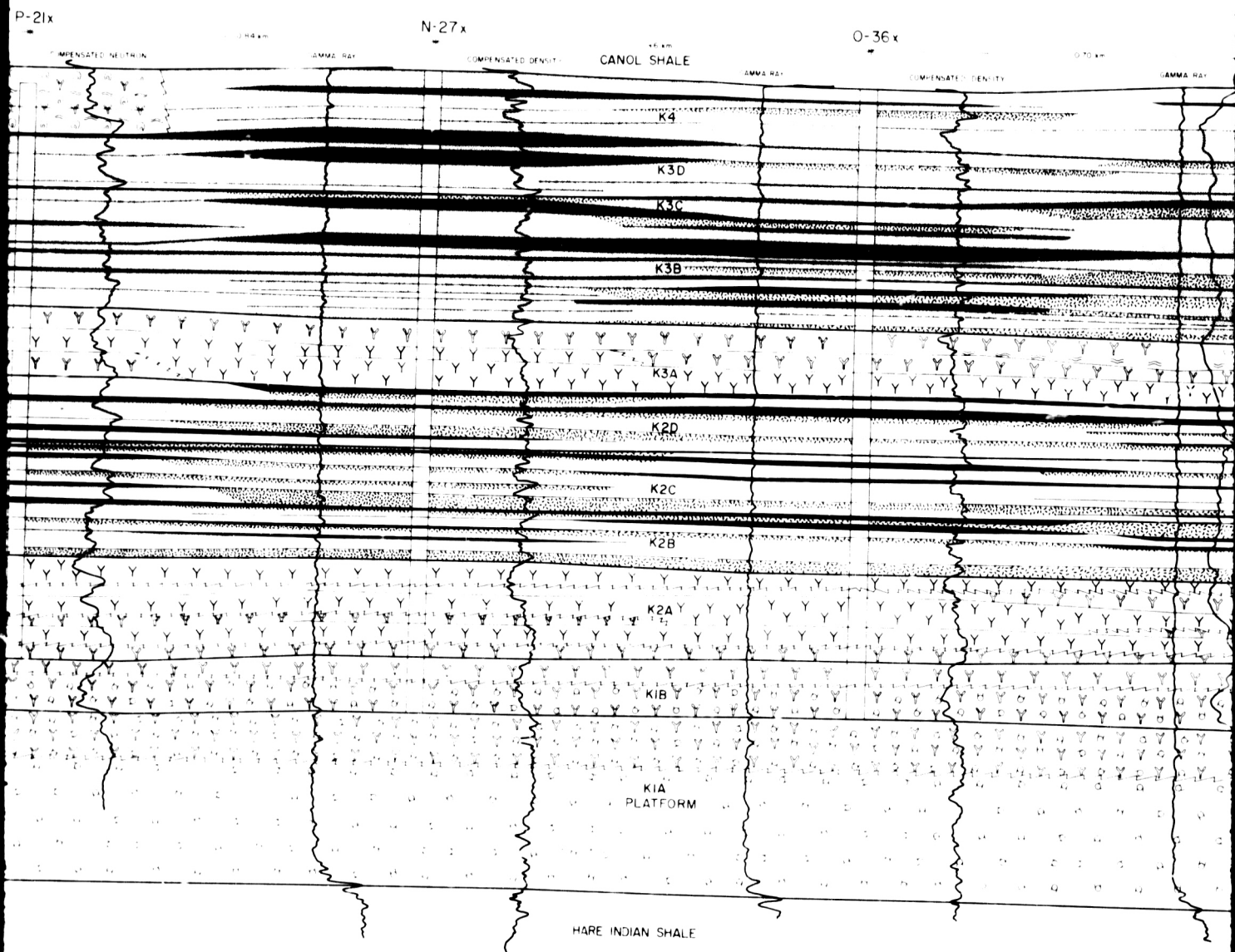
P-9x

P-15 x

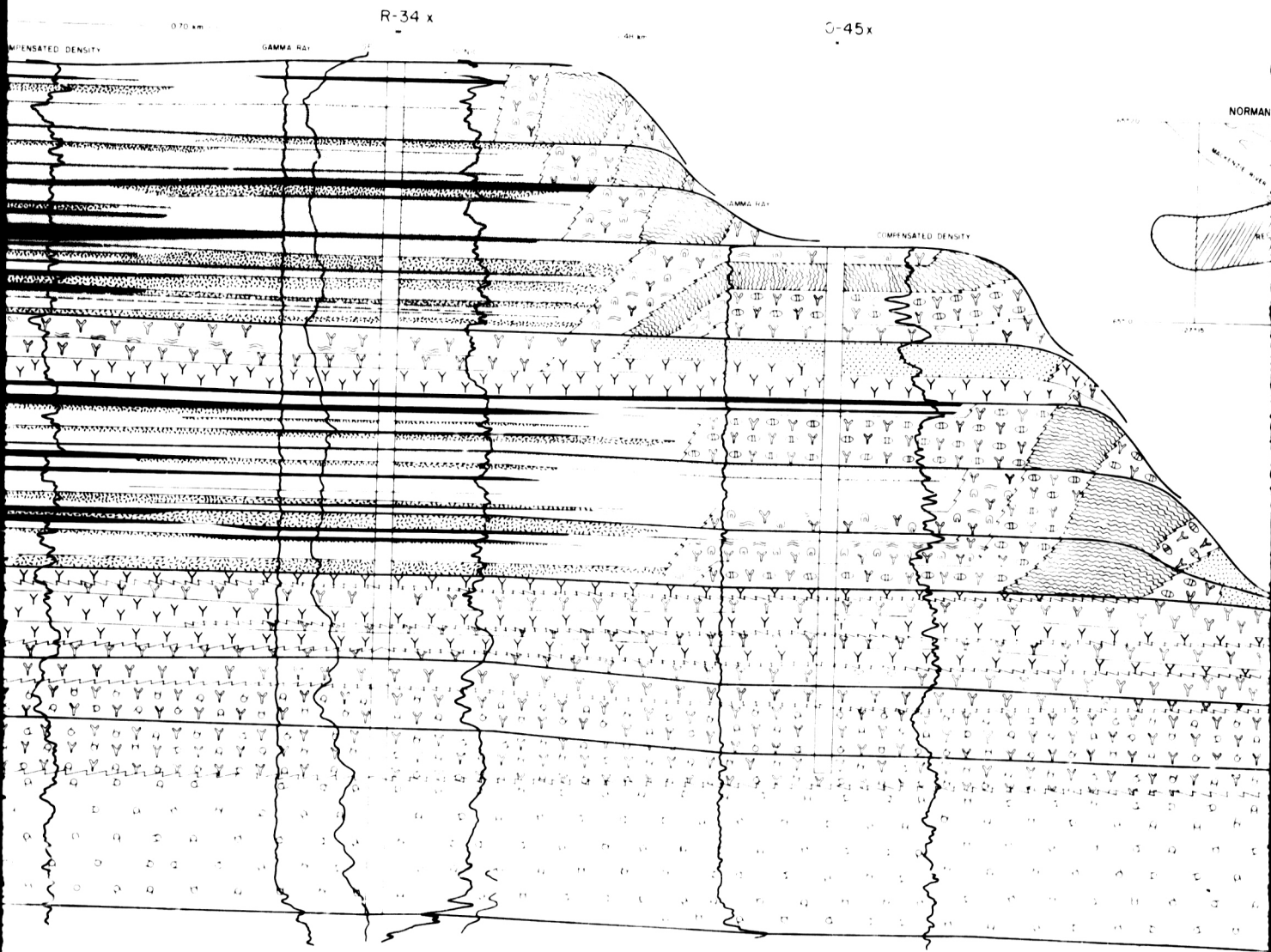
P-21x

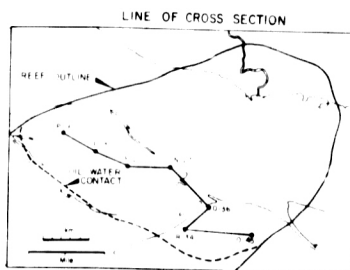


STRATIGRAPHIC CROSS SECTION-UPPER DEVONIAN KEE SCARP REEF AT NORMAN WELLS



NORMAN WELLS





LEGEND
RAMPARTS (KEE SCARP) CARBONATE
PLATFORM - REEF FACIES
SHOAL LIMESTONE FACIES

-  CYLINDRICAL STROMATOLITE FACIES
-  CYLINDRICAL STROMATOPOROID CORAL SHOAL SURFACES
-  BRANCHING CORAL SHOAL SURFACES
-  SMALL CYLINDRICAL STROMATOPOROID SURFACES
- BASIN - FORESLOPE TOE LIMESTONE AND SHALE FACIES**
-  NODULAR PALE STONE SURFACES
-  BASINAL LAMINITE SURFACES
- FORESLOPE LIMESTONE FACIES**
IN SITU FORESLOPE LIMESTONES
-  CYLINDRICAL STROMATOPOROID FORESLOPE SURFACES
-  WATER CYLINDRICAL STROMATOPOROID MIDDLE FORESLOPE SURFACES
- ALLOCHTHONOUS FORESLOPE LIMESTONES**
-  STROMATOPOROID RUBBLE SURFACES
-  DARK NATE SAND SURFACES
- REEF MARGIN FACIES**
-  THIN TABULAR STROMATOPOROID SURFACES
- REEF FLAT FACIES**
-  STROMATOPOROID RUBBLE SURFACES
-  RUBBLED ENCRUSTING CYLINDRICAL STROMATOPOROID SURFACES
- REEF INTERIOR FACIES**
-  TIDAL FLAT SURFACES
-  AMPHIPORA SURFACES
-  AMPHIPORA, RUBBLES, AND THIN TABULAR STROMATOPOROID SURFACES
-  GRAINY SHALLOW WATER POOL
-  MUD CYCLE TOP
-  MUD CYCLE TOP
-  FREE INTERVAL
-  DATUM
- TOE - BASIN JUNCTION**
- VERTICAL SCALE**
- DEPTH**
- FEET**
- METERS**

FIG. 5-11 Correlation of platform and initial reef cycles in the Mackenzie Mountains and Norman Wells buildups (left and right, respectively).

PLATFORM

REEF
CYCLE
1

UPPER

MIDDLE

LOWER

W

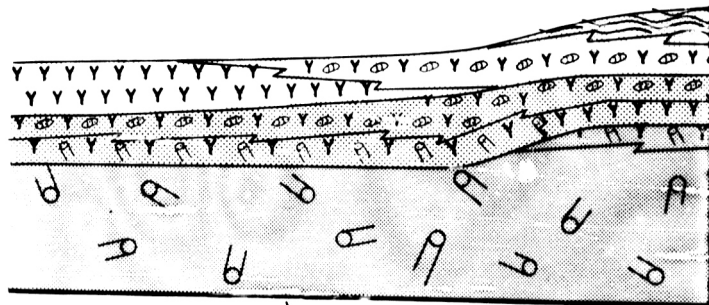
28

75 km

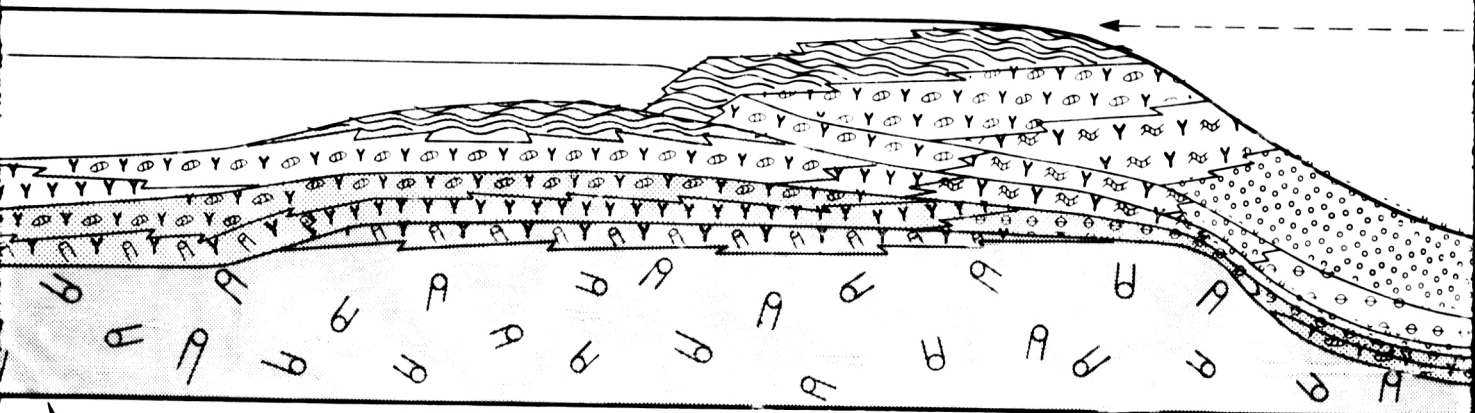
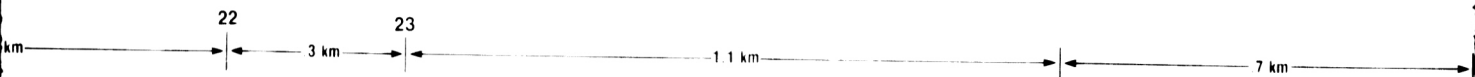
22

.3 km

23



BASE OF CARCAJOU SUBFACIES
(CARCAJOU MARKER)



BASE OF CARCAJOU SUBFACIES
(CARCAJOU MARKER)

E

NW

7 km

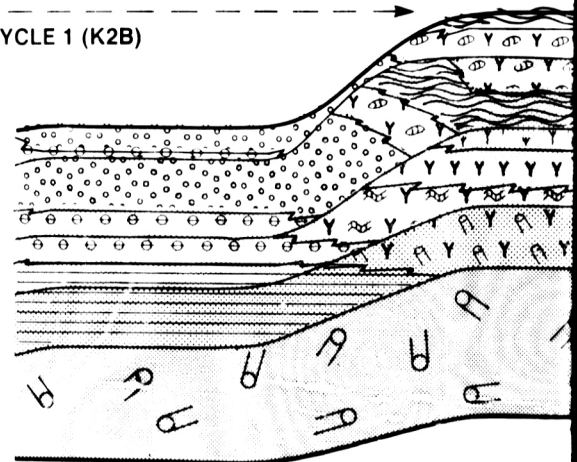
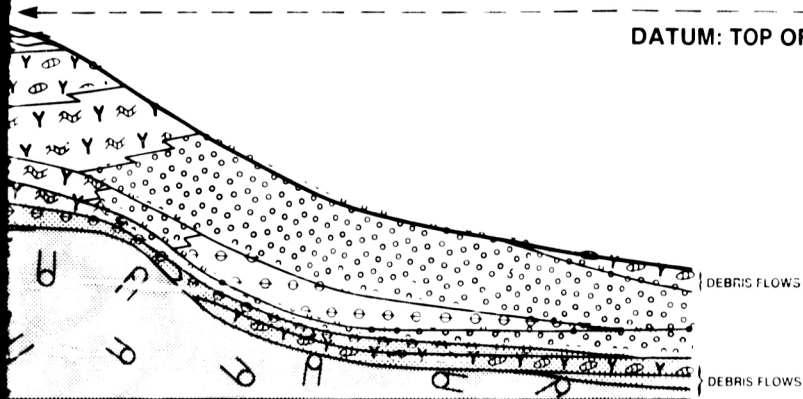
5 km

P-21x

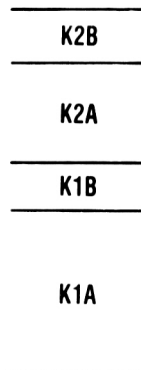
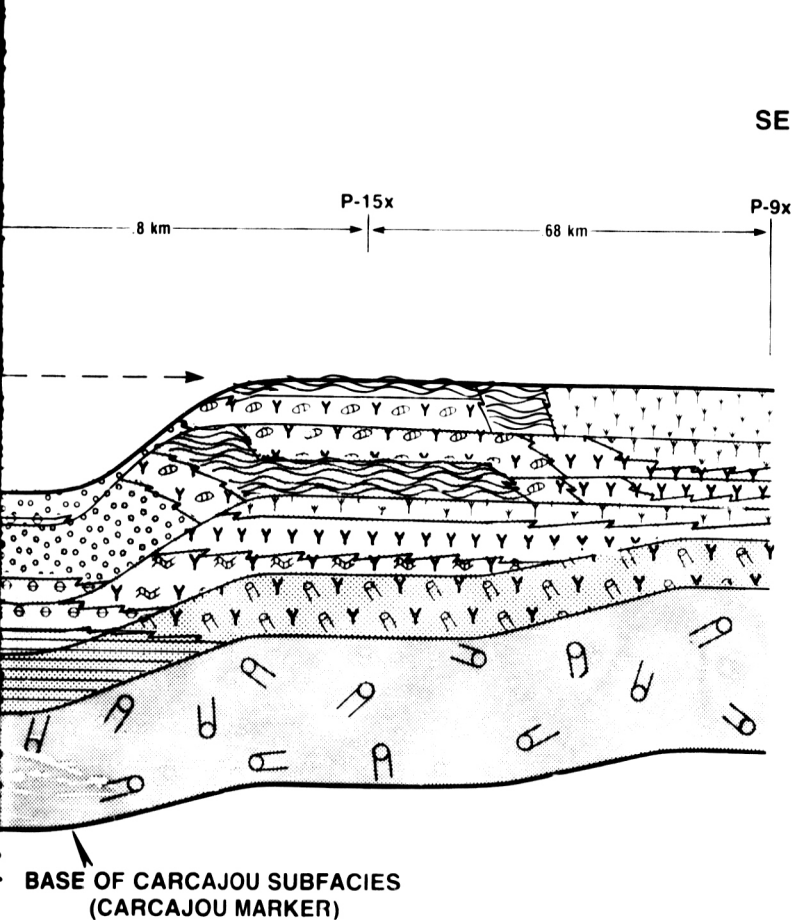
8 km

P-1

DATUM: TOP OF REEF CYCLE 1 (K2B)



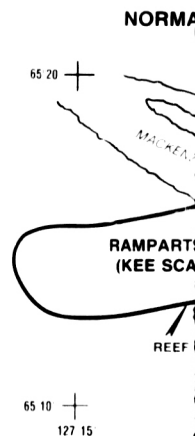
BASE OF CARCAJOU SUBFACE
(CARCAJOU MARKER)



PLATFORM

20 m

- UNDIFFERENTIATED REEF IN
- SMALL CYLINDRICAL STROM
- THICK TABULAR STROMATO
- ROBUST CYLINDRICAL STRO
- ABRADED STROMATOPORO
- LIME GRAINSTONE
- CYLINDRICAL STROMATOPO
- RAMOSE CORAL RUDSTONE
- WAFER STROMATOPOROID
FLOATSTONE, RUDSTONE, B
- NODULAR LIME MUDSTONE.
- LAMINATED SHALE, LIME MU
- MAJOR CYCLE BOUNDARY



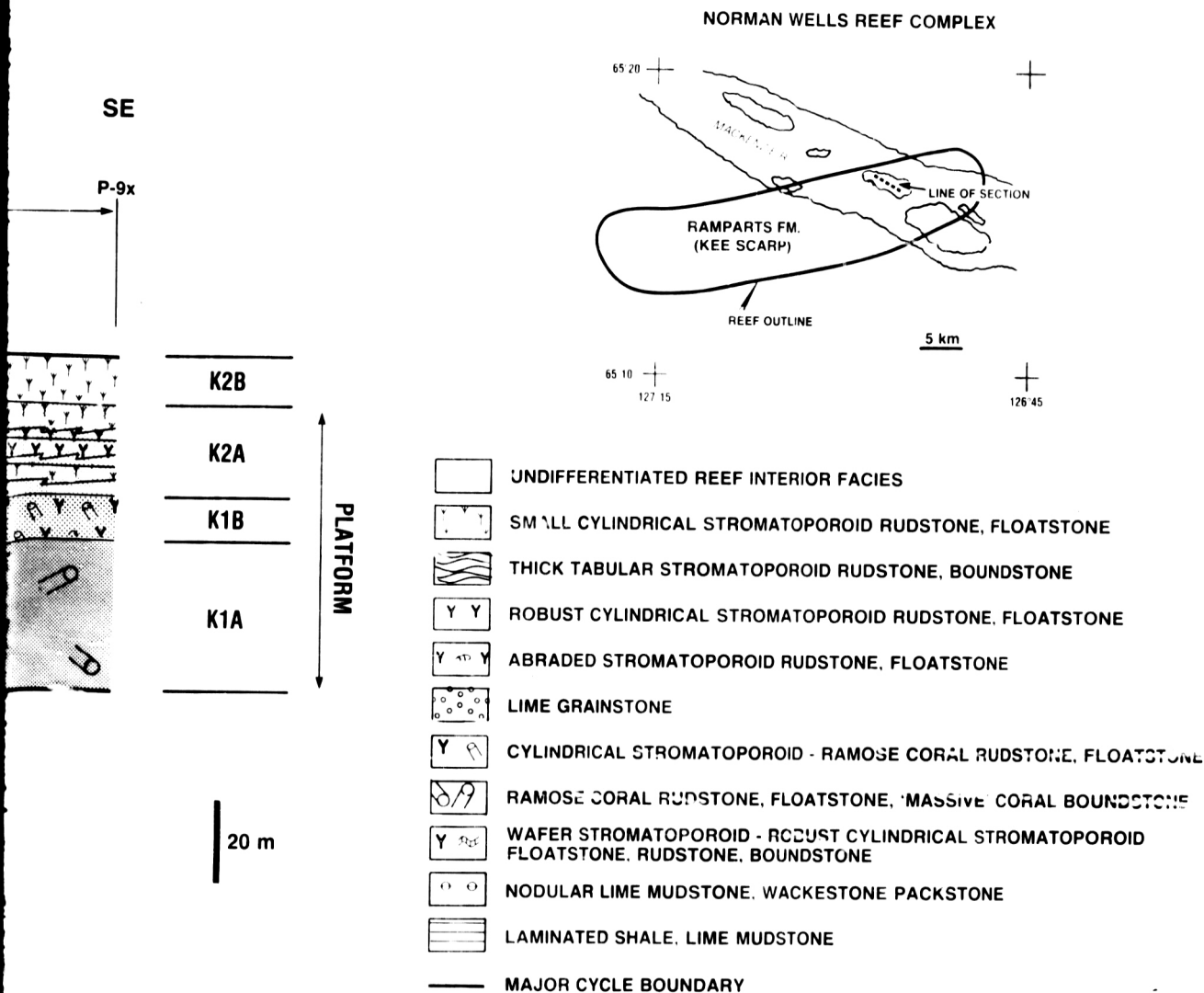


FIG. 5-12 Correlation of reef cycles in Mackenzie Mountains and Norman Wells buildups (left and right, respectively).

IMPERIAL FM.

W

4.6 km

REEF CYCLES

6 29 m

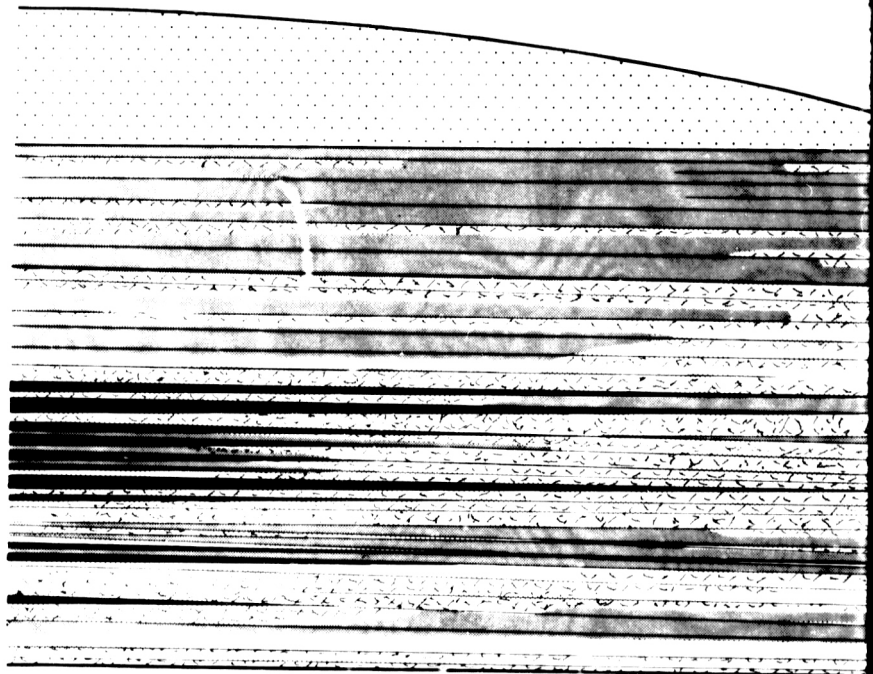
5 26 m

4 26 m

3A 34 m

3B

2 26 m



IMPERIAL FM.

E

4.6 km

CANOL

NE

.7 km

K3C-D
K4

K3A-B

K2C-D

DATUM: TOP OF REEF CYCLE 1 (K2B)

CANOL FM.

NE

SW

.7 km

K3C-D
K4

K3A-B

K2C-D

32 m

29 m

22 m

REEF CYCLE 1 (K2B)

UNDIFFERENTIATED SHOAL
STROMATOPOROID RUDESTONE
ENCrustING AND CYLINDRICAL

SHOAL SUBFACIES; ROBUST
RUDESTONE

SHOAL SUBFACIES; SMALL
RUDESTONE

TIDAL FLAT SUBFACIES, FINE

LIME MUD-RICH AMPHIPORA
LIME MUD-RICH AMPHIPORA
STROMATOPOROID FLOATSTONE

GRAINY SUBFACIES; AMPHIPORA
AMPHIPORA BULBOUS-CYLINDRICAL

MINOR CYCLE BOUNDARY

MAJOR CYCLE BOUNDARY

20 m

NORMAN

65° 20'

MACKEENZIE

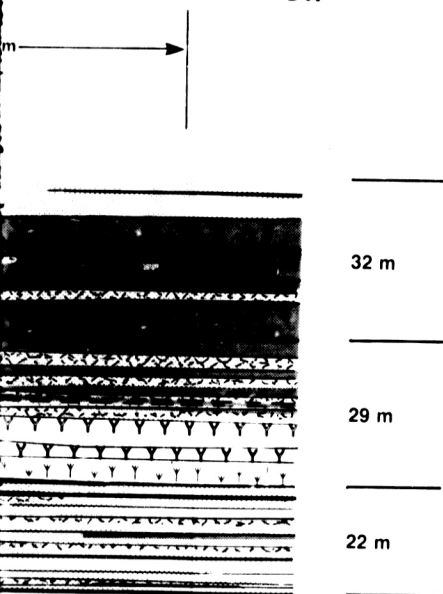
RAMPARTS F
(KEE SCARP)

REEF OUT

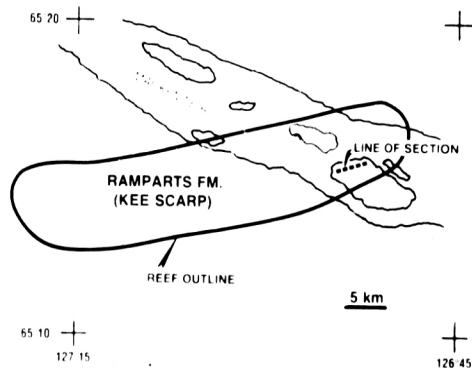
65° 10' 127° 15'

FM.

SW



NORMAN WELLS REEF COMPLEX



UNDIFFERENTIATED SHOAL SUBFACIES; ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE; LIME PACKSTONE; BULBOUS, ENCRUSTING AND CYLINDRICAL STROMATOPOROID RUDSTONE.



SHOAL SUBFACIES; ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE



SHOAL SUBFACIES; SMALL CYLINDRICAL STROMATOPOROID RUDSTONE



TIDAL FLAT SUBFACIES, FENESTRAL LIME MUDSTONES



LIME MUD-RICH *AMPHIPORA*-BEARING MUDSTONE, WACKESTONE
LIME MUD-RICH *AMPHIPORA*-BULBOUS CYLINDRICAL STROMATOPOROID FLOATSTONE



GRAINY SUBFACIES; *AMPHIPORA*-BEARING PACKSTONE, RUDSTONE;
AMPHIPORA BULBOUS-CYLINDRICAL STROMATOPOROID RUDSTONE

MINOR CYCLE BOUNDARY

MAJOR CYCLE BOUNDARY

20 m

those subsurface cycle boundaries marked by the greatest lateral shift of facies can be correlated with the Mackenzie Mountains complex. In addition, the Mackenzie Mountains reef complex (FIG. 5-12) contains two second-order cycles of reef growth (cycles 5 and 6) not present in the subsurface Norman Wells reef complex. These additional cycles account for the reef section in the Mackenzie Mountains being appreciably thicker than that at Norman Wells. Subfacies have been grouped in the Mackenzie Mountains buildup to simplify comparisons to the Norman Wells buildup in FIGS. 5-11 and 5-12.

The recognition of equivalent cycles in the two complexes, and observation of gross facies characteristics, allow distinct stages of platform and reef growth to be defined. These stages are discussed sequentially above the regionally correlatable Carcajou Marker.

5.7.2.1 Lower Platform (K1A) Stage

The lower platform cycle represents the most extensive depositional environments of both the Norman Wells and Mackenzie Mountains buildups. Similar thicknesses accumulated in platform margin settings of the lower platform cycle (32 m at P-21X, Norman Wells; 35 m at section 04, Mackenzie Mountains). In both study areas, the resulting sequence is dominated volumetrically by ramose coral floatstone and rudstone, which are overlain by

lighter-colored ramose coral-robust cylindrical
stromatoporoid rudstone. In the Mackenzie Mountains, the top of the lower platform achieved a greater relief, with maximum accumulation in the vicinity of the platform margins. In contrast, the top of the Norman Wells lower platform cycle had relatively little topographic relief (FIG. 5-10).

5.7.2.2 Middle (K1B) and Upper (K2A) Platform Stages

Subsequent rises in sea level resulted in progressively more localized platform upbuilding in both complexes (FIG. 5-11). The resulting middle platform cycle is thin (10-12 m thick at Norman Wells; 10-14 m thick in the outcrop study area), and represents the accumulation typically of ramose coral-cylindrical stromatoporoid floatstone and rudstone that pass upward into abraded stromatoporoid-robust cylindrical stromatoporoid rudstone. In situ, thick, tabular, stromatoporoid boundstone lithofacies were not developed in the middle platform sequence, but locally along platform margin highs during deposition of the overlying upper platform cycle (20 m thick at Norman Wells; 15 m thick in the outcrop study area).

In the Mackenzie Mountains area, the top of the platform developed greater paleotopographic relief (FIG. 5-11), although correlative stacked platform cycles display comparable shallow-water facies distributions, cycle

thicknesses, and overall backstepping. The reason for this is unclear. It appears that antecedent topography, combined with relatively poor circulation in the platform interior (possibly related to greater platform size and orientation with respect to prevailing winds), restricted optimum growth rates to the platform margins. Circulation in the Norman Wells area was sufficient to permit carbonate benthos to catch up and keep pace with sea-level rise through much of the platform interior. Consequently, most platform cycle boundaries in the Norman Wells succession are nearly planar, and are considered to define sea-level positions.

5.7.2.3 Reef Cycle 1 (K2B): Inception and Progradation

Accelerated sea-level rise terminated this cyclic platform development. Carbonate-forming reef benthos soon colonized the margins of previous platform highs and, thus, initiated reef growth (FIG. 5-11). During this time, the reefs quickly prograded and filled adjacent lows in the platform in the Mackenzie Mountains area. Reef growth was also predominantly progradational in the correlative K2B cycle at Norman Wells. Reef margins in both complexes sheltered an interior lagoon, in which *Amphipora* rudstone, floatstone and packstone, and tidal-flat sediments were deposited. Reef cycle 1 is slightly thicker (18 m) than the K2B cycle (12 m). Upper platform buildups were terminated in waters possibly slightly deeper (~5 m) in the outcrop

study area than in the Norman Wells area, hence allowing for greater accommodation of sediment. However, the sediment accumulated between the Carcajou Marker and the top of reef cycle 1/K2B is remarkably similar in both complexes: 77-80 m in the Mackenzie Mountains and 74-81 m in the Norman Wells subsurface (FIG. 5-11).

5.7.2.4 Reef Cycles 2 and 3 (K2C through K3B)

Aggradation

Successive sea-level rises following K2B time produced only minor increments of backstepping so that reef margins grew upwards in essentially the same positions (FIGS. 5-10, 5-12). In both complexes, tidal flat deposition was most extensive during this period (FIG. 5-12). The K3A-B cycle began with a widespread, cylindrical stromatoporoid shoal, reflecting good circulation temporarily following the termination of the K2C-D cycle. A shoal apparently did not initiate deposition of reef cycle 3 in the outcrop study area, possibly due to larger lagoon size and, hence, poorer circulation. Nonetheless, the initial deposits of reef cycle 3A in FIG. 5-12 were typically grainy, reef-interior lithofacies, and not tidal flat lithofacies.

5.7.2.5 Reef Cycle 4 (K3C-D, K4):

Reef Backstepping and Subsequent Aggradation

A relatively pronounced rise in sea level led to appreciable backstepping of the reef margins of both reef complexes following reef cycle 3/K3A-B. Subsequently, the reef margins aggraded, and deposition of peloidal carbonate sand in shallower, but higher energy, environments characterized the reef interiors of both reef complexes (FIGS. 5-10, 5-12). Tidal flat deposition was notably reduced in both areas. The thicknesses of sediment that accumulated in reef cycles 2, 3, and 4 (K2C to K4) are approximately the same in the two complexes (86 m in the Mackenzie Mountains buildup; 83 m in the subsurface Norman Wells buildup).

5.7.2.6 Reef Cycles 5 and 6: Backstepping and Aggradation; Drowning of the Norman Wells Reef Complex

Another pulse of accelerated sea-level rise drowned the Norman Wells buildup and resulted in backstepping of the reef margins in the Mackenzie Mountains area (reef cycle 5). The initial sedimentation of reef cycle 5 (reef interior section 31) was associated with an open marine fauna including atrypid brachiopods, alveolitid and thamnoporoid corals, robust cylindrical stromatoporoids, and bulbous stromatoporoids. This fauna suggests that reef margins were

poorly developed during initial reef cycle 5 time. Circulation became slightly more restricted towards the close of reef cycle 5 time. However, the high percentage of peloidal carbonate sand lithofacies (FIG. 5-12) and ubiquitous cylindrical stromatoporoid-ramose coral fauna reflect improved circulation in the reef interior compared to the underlying reef cycles. A deepening at the end of reef cycle 5 time led to formation of reef cycle 6, an areally restricted, cylindrical stromatoporoid-ramose coral shoal lacking reef margins.

5.7.3 Summary

In conclusion, study of two widely separated Ramparts buildups indicates that distinct cycles of sedimentation can be correlated based on style of sediment accumulation, facies distribution, and thickness of sediment accommodated. The correlation and the small-scale periodicity of the second-order cycles suggest that eustasy produced the accelerated sea-level rises that terminated cycles of sedimentation and led to initiation of new cycles. Alternative mechanisms, such as changes in rates of either tectonic subsidence or subsidence due to compaction of underlying shale, operate over much longer intervals and, consequently, are less likely to have initiated the observed cycles of sedimentation. This successful correlation of second-order shallowing-upward cycles suggests that

application of similar procedures could aid in understanding the evolution of platform-reef complexes elsewhere.

PLATE 5-1

Second-order cycle boundaries
in the reef facies association.

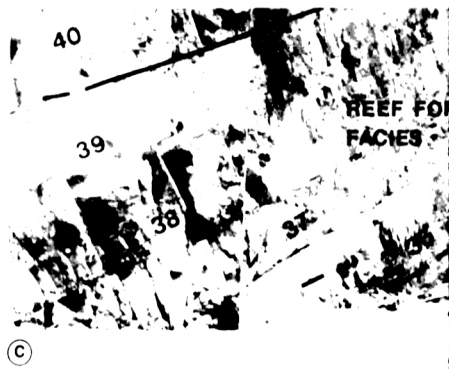
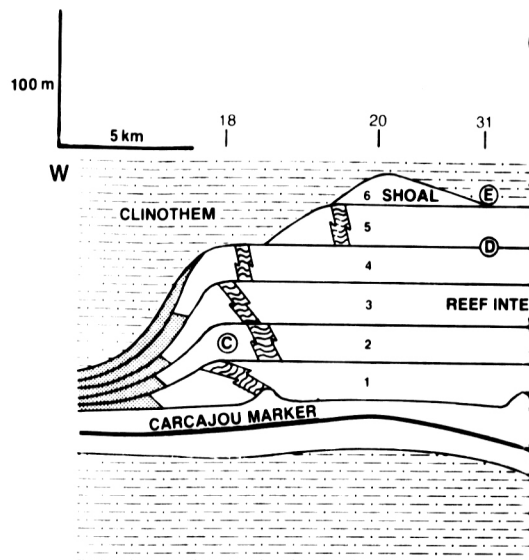
Second-order cycle boundaries in the reef facies association. Aerial view of lowermost three reef cycles in 5-1a. Reef cycle 1 is ~30 m thick. In 5-1b, a dark brown, laminated shale unit (arrows) occupies the basal portion of reef cycle 2 in a foreslope depositional setting. Shallowing-upward trends in allochthonous foreslope sequences (e.g.: 5-1c) reflected by overall lightening- and thickening-upwards bedding, with a corresponding decrease in lime mud content and increase in abraded skeletal debris. Figure (arrow) is 2 m high. Cycle boundaries in the reef interior correspond to brief interruptions in continuity of reef margin facies (drowning), and are recognized by slightly more open marine lithofacies in the reef interior. In 5-1d, thickly-bedded, light-colored, atrypid-bulbous stromatoporoid-robust cylindrical stromatoporoid rudstone (cycle 5) sharply overlies dark, thinly-bedded Amphipora lime mudstone (cycle 4). Pogo stick is 2 m high. Imperial clinothem shale and siltstone sharply overlie reef cycle 6 in 5-1e. Resistant weathering siltstone bed is ~4 m above the top of the Ramparts Formation.



(E)



(D)



(C)

PLATE 5-2

Reef cycle 1 embayment-fill, section 08.

Reef cycle 1 embayment-fill succession in the vicinity of section 08. Note clinoform geometry of bedding at site 3. Plates 5-3 and 5-4 show details at sites 1, 2, and 4. Embayment-fill succession at site 4 is 36 m thick.

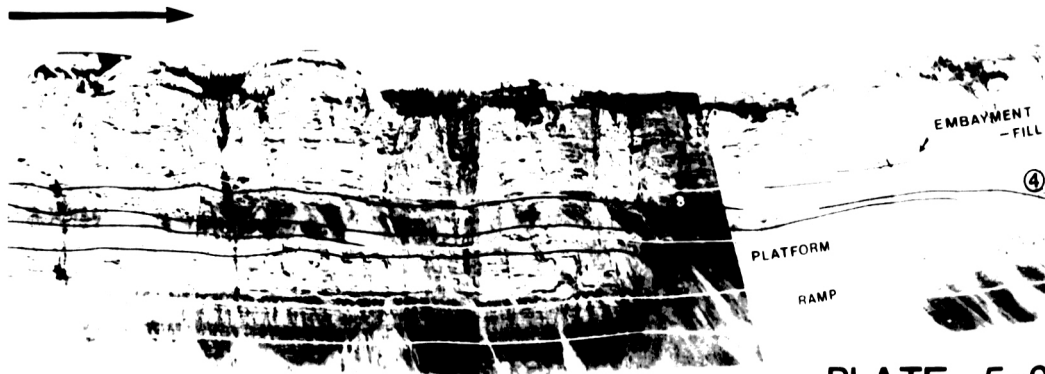


PLATE 5-2

PLATE 5-3

Upper platform buildup and embayment-
fill succession, section 08.

- a Upper platform buildup (15 m relief) at embayment margin (site 1 in PL. 5-2). Platform top indicated by arrows.
- b Sigmoidal clinoform bedding in embayment-fill succession (site 2 in PL. 5-2). Embayment-fill succession ~30 m thick.

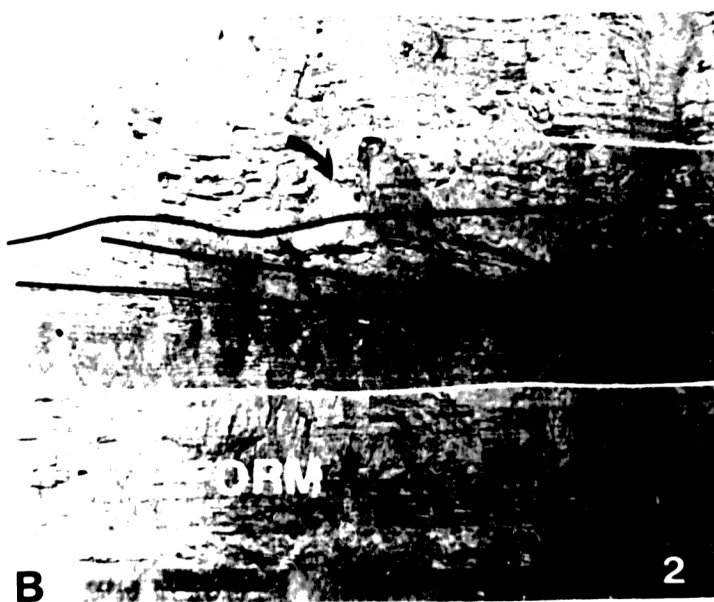


PLATE 5-3

PLATE 5-4

Typical lithofacies within embayment-fill succession, section 08.

- a Embayment-fill succession at section 08 (site 4 in PL. 5-2) showing ramp-platform-reef transition. The platform top (B) and upper embayment-fill succession (A) are enlarged in PL. 5-4b, c, respectively. Units 10-14 constitute the 22 m thick platform facies association.
- b Top of platform at section 08 (site B in PL. 5-4a). Basinal laminites and small, thamnoporoid coral floatstone-occupied gully-fills characterize the base of the embayment-fill succession. Gully-fill unit is 1.5 m thick.
- c Top of embayment-fill succession at section 08 (site A in PL. 5-4a). Basinal laminites in unit 17 pass upwards into lower foreslope wafer stromatoporoid boundstone with robust cylindrical stromatoporoid rudstone-occupied channel-fills (units 18-20). 5 m thick robust cylindrical shoal unit caps the succession, and is overlain by restricted reef interior sediments.

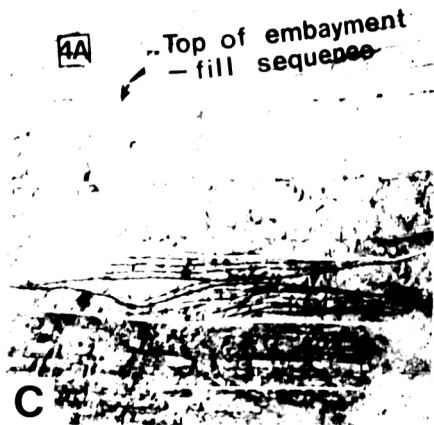
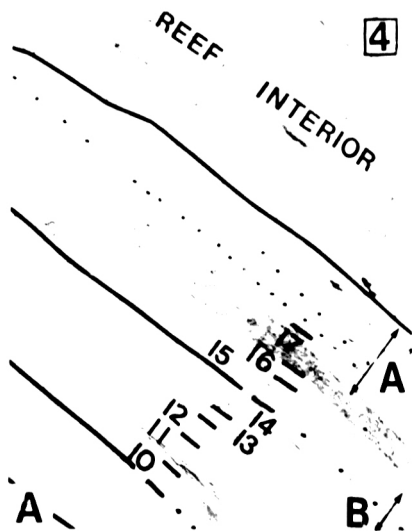


PLATE 5-4

PLATE 5-5

Schematic representation of embayment-fill facies of reef cycle 1, section 08.

Schematic representation of embayment-fill facies of reef cycle 1 at section 08. Scale bars in b-e are 2 cm long. Macrofossil symbols are same as in figures for Chapters 4, 5.

- a Dark, argillaceous, laminated lime mudstone near base of embayment-fill succession.
- b Wafer stromatoporoid floatstone in lower foreslope facies.
- c Robust cylindrical stromatoporoid rudstone from the channel-fill sequence, lower foreslope facies. Note calcite-occluded interparticle porosity.
- d Fragmented wafer-tabular stromatoporoid floatstone, middle foreslope facies.
- e Abraded stromatoporoid breccia from the shoal facies capping the embayment-fill succession. Note calcite-occluded interparticle porosity between intraclasts.

EMBAYMENT - FILL FACIES (REEF CYCLE 1)



SHOAL



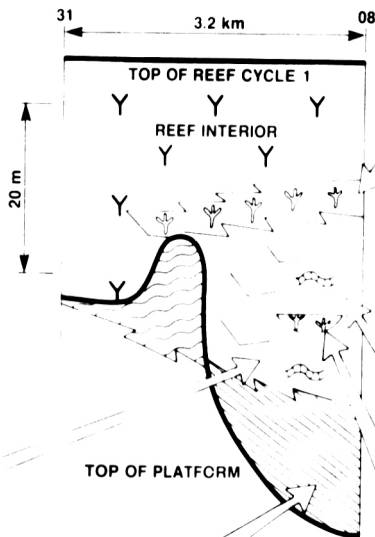
CHANNEL-FILL



LOWER-MIDDLE FORESLOPE



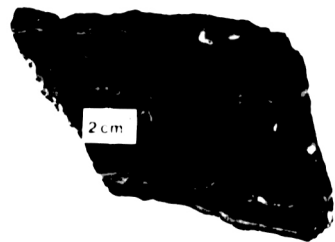
BASINAL LAMINITES



E



D



B



A



C

PLATE 5-6

Typical lithofacies in reef margin subfacies 1.

- a Light-colored robust cylindrical stromatoporoid rudstone and large, thick tabular and hemispherical stromatoporoids (section 04). Hammer is 20 cm long.
- b Abraded stromatoporoid rudstone (section 24).

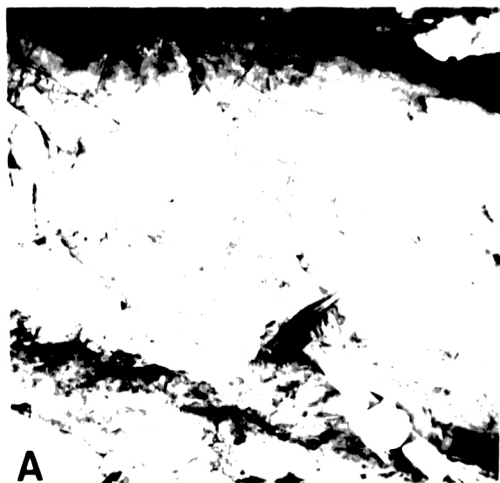


PLATE 5-6

PLATE 5-7

Reef cycle 1 at section 04.

Reef cycle 1 (section 04). Bedded foreslope facies pass upward into massive reef margin facies which, in turn, are overlain by bedded reef flat facies (white dashed lines mark bedding traces). Sense of reef progradation is both towards the right (north) and out towards the viewer (basinward, east). Units 008 and 009 are ~8 m thick.

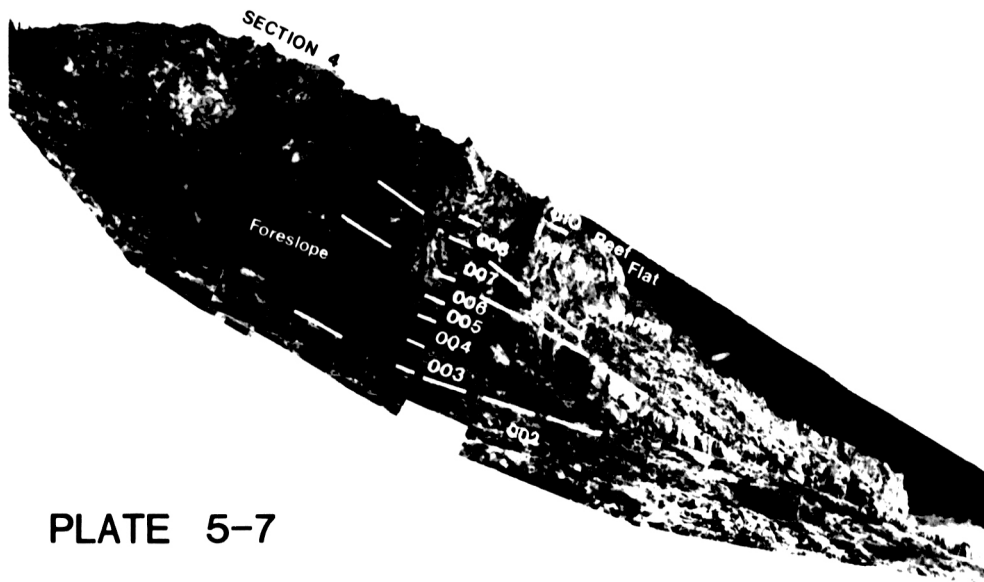


PLATE 5-7

PLATE 5-8

Macrofauna in reef margin facies.

- a Large, thick, tabular stromatoporoids in eastern reef margin facies (section 04). Scale is 15 cm.
- b Encrusting and tabular stromatoporoids in the western reef margin facies (section 18, reef cycle 1). Scale shows 10 cm increments.



PLATE 5-8

PLATE 5-9

Reef cycle 6 at section 20 and
foreslope equivalent at section 31.

- a Bedding plane surface of robust cylindrical-encrusting-bulbous stromatoporoid rudstone of reef margin/shoal subfacies 2 in reef cycle 6 (section 20, unit 047 - top of reef complex). Iron oxides on bedding plane were deposited by present stream runoff from the overlying Imperial Formation. Scale is in cm.
- b Pyritiferous, atrypid brachiopod lime mudstone and floatstone representing the distal foreslope equivalent of reef cycle 6 (section 31). Note slightly nodular structure outlined by carbonaceous microstylolites. Scale is 2 cm.

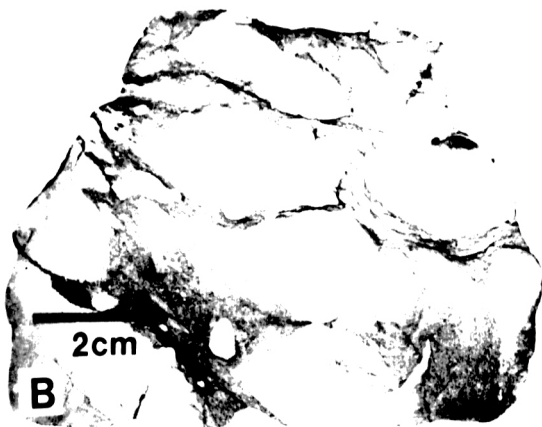
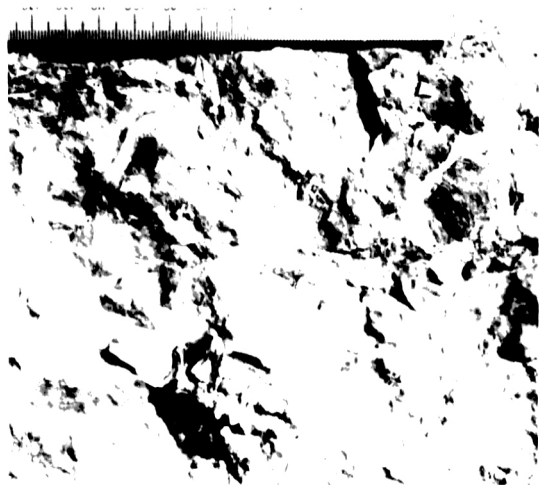


PLATE 5-9

PLATE 5-10

Typical lithofacies in reef interior subfacies 1.

- a Abraded stromatoporoid rudstone (section 29). Scale is in cm.
- b Polished slab of robust cylindrical stromatoporoid-encrusting algae rudstone showing high initial interparticle porosity completely occluded by blocky calcite cement (section 30).



A



2 cm ↑

B

PLATE 5-10

PLATE 5-11

Macrofauna in reef interior subfacies 1 and 2.

- a Branching, robust cylindrical stromatoporoids in reef interior subfacies 1 (section 04, unit 010). Note slight alignment of allochems, possibly indicating current orientation. Pen is 13 cm long.
- b Reef interior subfacies 2 (section 28). Bulbous stromatoporoids supported by dark micritic matrix.

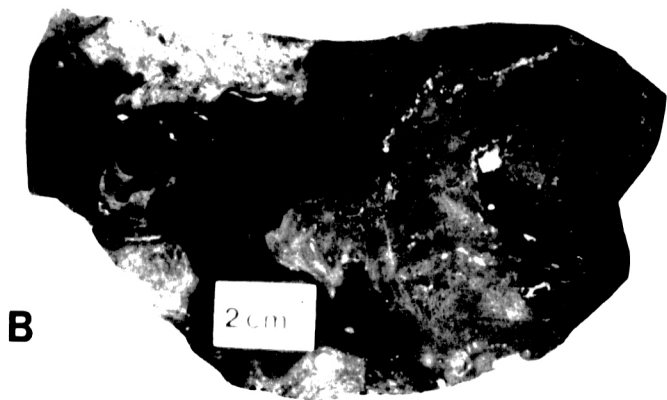
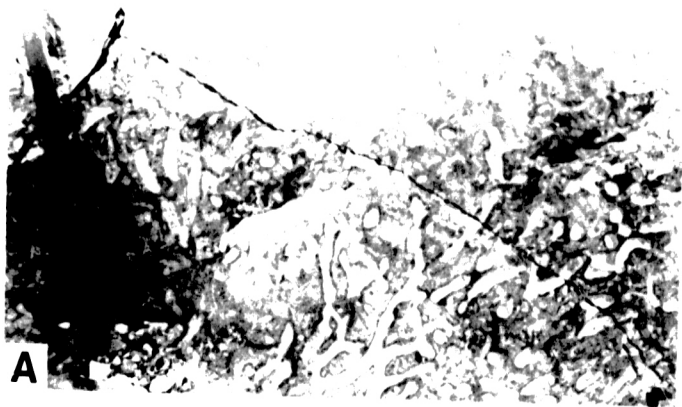


PLATE 5-11

PLATE 5-12

Macrofauna in reef interior subfacies 2.

- a Reef interior subfacies 2 of reef cycle 2 abruptly overlying reef interior subfacies 3 of reef cycle 1 (section 20, unit 023). Note tabular mudstone lithoclasts derived from subfacies 3 and encrusting tabular stromatoporoid on cycle boundary surface. Cylindrical stromatoporoids are mainly Amphipora.
- b Megalodont bivalves, robust cylindrical stromatoporoids, and encrusting stromatoporoids supported by lime mudstone matrix (section 30, 100 m west of reef flat facies in section 29).



A



B

PLATE 5-12

PLATE 5-13

Typical lithofacies in reef interior subfacies 3.

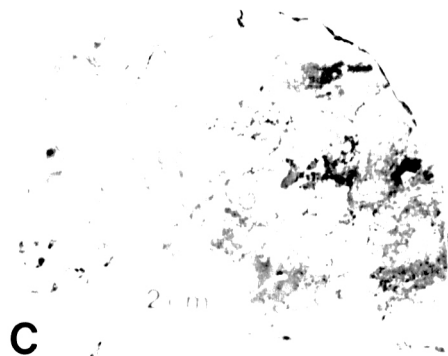
- a Non-laminated lime mudstone (section 31). Note large blocky calcite pore-fillings.
- b Laminoid fenestral lime mudstone (section 31). Scale is 2 cm.
- c Polished slab showing emersion surface on reef interior subfacies 3 at top of reef cycle 1 (section 31).



A



B



C

PLATE 5-13

PLATE 5-14

Reef foreslope subfacies 1 at section 18.

- a Horizontal stratification (average 10 cm thick) defined by interbedded, coarse-grained lime grainstone and abraded stromatoporoid rudstone. Scale is in dm.
- b Abraded stromatoporoid rudstone. Note weak upward-fining and scoured basal contact (arrows). Scale is in cm.
- c Sharp, planar, basal contact of a robust cylindrical stromatoporoid-crinoid rudstone.



A



B



C

PLATE 5-14

PLATE 5-15

Reef foreslope subfacies 1 and 2.

- a Coarse, fragmented skeletal lime grainstone in reef foreslope subfacies 1 (section 18). Note paucity of lime mud within matrix and stromatoporoid-encrusted allochems.
- b Wafer stromatoporoid-thamnoporoid coral floatstone in reef foreslope subfacies 2 (section 04). Wafer stromatoporoids 5-10 mm thick, but >150 mm diameter. Scale is in cm.
- c Polished slab of wafer stromatoporoid-Coenites floatstone from reef foreslope subfacies 2 (section 04). Note dark micritic supporting matrix and common biogenic encrustation of allochems. Scale is in cm.



A



B



C

PLATE 5-15

PLATE 5-16

Second-order cyclicity in
reef foreslope facies.

- a Reef cycles 2 (unit 31) and 3 (unit 32) consisting of reef foreslope subfacies 3 (section 01). Note basal dark shale bed at base of reef cycle 2. Top of cycle 2 shows slump scars and relief produced by slumping. Site B shown in PL. 3-11. Unit 31 6-8 m thick.
- b Reef cycle 1 consisting of reef foreslope subfacies 3 (section 01). Bedding thickens- and lightens-upward overall. Knapsack beside figure (1.8 m high) marks top of upper platform cycle.
- c Reef cycle 2 consisting of reef foreslope subfacies 3 (section 01). Thickening-upward trends in sequence not observed, probably obscured by soft sediment deformation and submarine erosion at top of cycle. Figure is 1.8 m high.

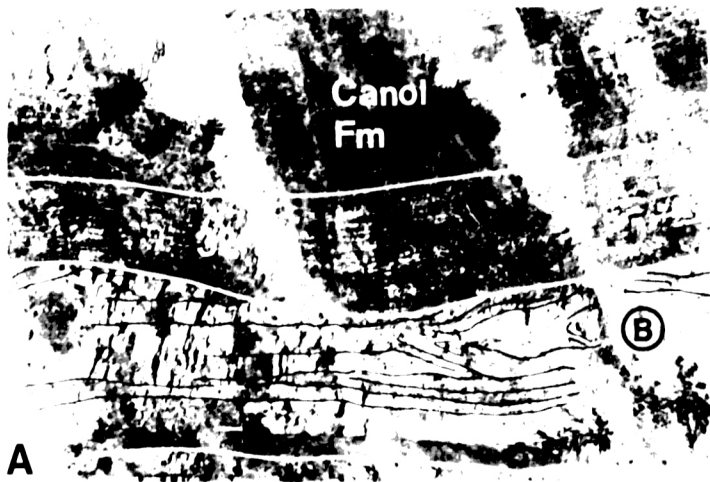


PLATE 5-16

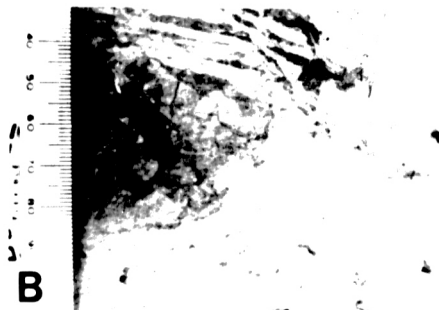
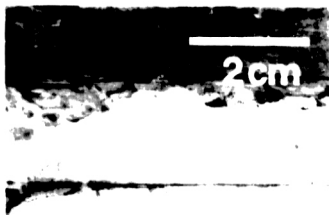
PLATE 5-17

Sedimentary structures in
reef foreslope subfacies 3.

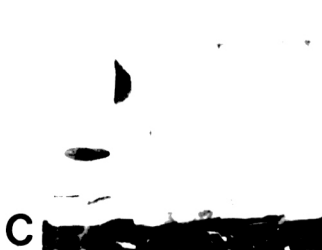
- a Soft sediment deformation (recumbent folding) (section 01, unit 031). Note chert-replaced portion of polished slab was not as compacted as enclosing sediment.
- b Dewatering structure (section 01, unit 031). Scale is in cm.
- c Stacked, sharp-based, upward-fining calcisiltite beds (section 25, unit 019). Amalgamated beds 30 cm thick. Note undisturbed nature of laminae.



A



B



C

PLATE 5-17

PLATE 5-18

Reef foreslope subfacies 3 and 4.

- a Upward-fining calcisiltite beds in reef foreslope subfacies 3 (section 25, unit 019). Note that beds thin-upward. Scale is in cm.
- b Nodular lime mudstone and wackestone in reef foreslope subfacies 4 (section 07). Scale is 15 cm.

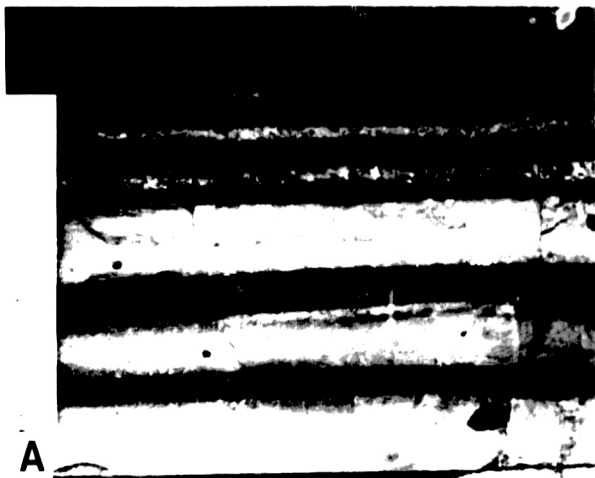
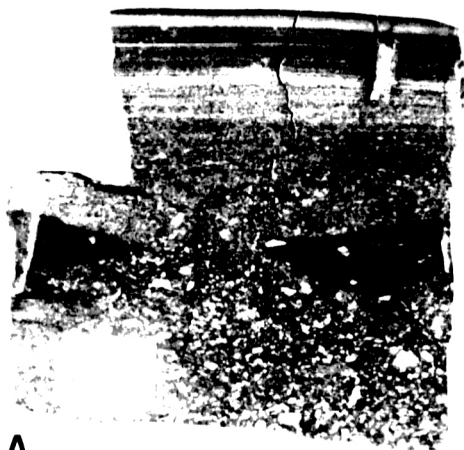


PLATE 5-18

PLATE 5-19

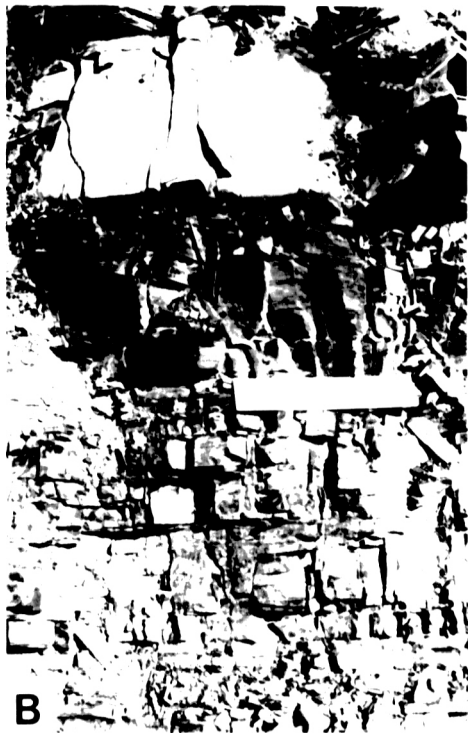
Limestone lithofacies in basinal subfacies.

- a Graded, crinoidal grainstone (section 01). Note tabular, laminated mudstone lithoclasts.
- b Horizontally-laminated peloidal calcisiltite unit interbedded with siliceous, even-laminated shale (section 25). Scale is 15 cm.



A

PLATE 5-19



B

PLATE 5-20

Canol basinal facies at section 01.

- a Tabular lithoclast of wafer stromatoporoid floatstone encompassed by black, slightly calcareous shale. Base of reef cycle 2, basinal facies (section 01, unit 028). Scale is 1.5 m.
- b Canol Formation consisting of reef foreslope-basinal subfacies 4 (section 01). Note large carbonate concretions. Figure (1.8 m high) standing close to Imperial-Canol contact where dark recessive argillaceous shale overlies resistant, jarosite-coated, siliceous shale.

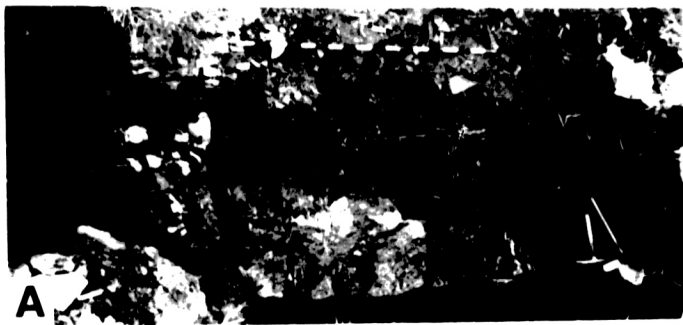


PLATE 5-20

PLATE 5-21

Lowermost Imperial clinothem facies.

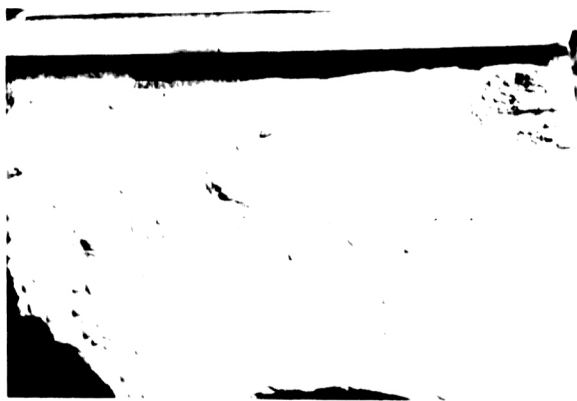
Lowermost Imperial clinothem facies and paleocurrent data.

- a Coarsening-upward cycles 20-30 m thick (section 01).
- b Furrowed sole markings in horizontally laminated siltstone bed (section 01, unit 046). Scale is 15 cm.
- c Current crescents around slightly more resistant-weathering vertical burrows (section 01, unit 044). Pen is 12 cm long.
- d Paleocurrent data (section 02, unit 008).



(B)

(A)



(C)

(D)

F31-406-20

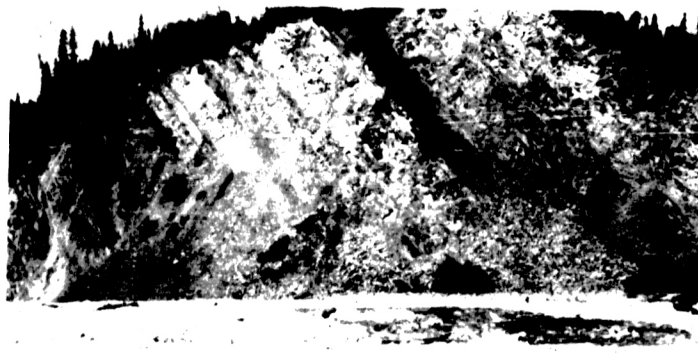


(B)



(C)

11 406-20



(A)

SECTION 02 UNIT 008

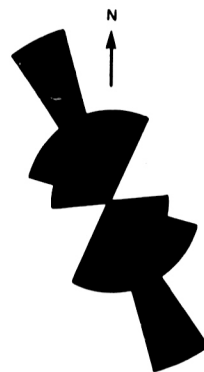
- GROOVE CASTS

- SKIP MARKS

n = 20

O = 139 319°

P = 1.3 x 10⁻³



(D)

VI

SUMMARY

6.1 CYCLICITY: RECOGNITION AND USE

Cycle boundaries represent ancient depositional surfaces produced during periods of non-deposition or by abrupt changes in depositional conditions associated with relative rises in sea level. Although these surfaces can take years to form, they are essentially synchronous, representing instants of geologic time (Purser, 1969). Therefore, cycle correlation can be used to establish a regional chronostratigraphic framework in which detailed facies analysis can be conducted. This idea is not new. It has been evident for many years that cycle correlation provides a powerful tool for the stratigrapher. Yet, despite ample documentation, its routine use has been extremely limited in ancient basin-fill, platform and reef studies.

A hierarchy of shallowing-upward cycles is evident in the Hare Indian-Ramparts succession. First-order cycles tend to be 100's of m thick, and are regionally correlatable. The lower portion of a first-order cycle is characterized by carbonate platform development, with mainly backstepping and aggradational margins, and by condensed basinal sedimentation. The backstepping style of platform development is shown by the Hume Formation, although the base of this first-order cycle was not established in the study area. The upper portion of this first-order cycle is characterized by prograding basin-fill facies representing ramp, clinothem, and basinal sedimentation. A first-order

cycle boundary (Carcajou Marker) separates the basin-fill strata of the Hare Indian and lower Ramparts Formations from strata of the backstepping platform-reef complex in the upper Ramparts Formation. Second-order cycles, averaging 10-25 m thick, can be correlated regionally, both in basin-fill and platform-reef strata, for 10's of km. This regional persistence of cycles into the basin argues for relative sea-level control. Accelerated rise of sea-level influenced deposition across the basin, although cycle boundaries are difficult to recognize in basinal settings where there was little sedimentological change in response to abrupt deepenings. Third-order cycles (2-5 m thick) are apparent only in reef interior, ramp and platform facies. These resulted from autogenic and/or allogenic control, and can be correlated only locally (100's-1000's of m).

6.2 EVOLUTION OF THE HARE INDIAN-RAMPARTS SEQUENCE

The Hare Indian and Ramparts Formations show evidence of distinct evolutionary stages in their succession. FIGURES 6-1 through 6-8 schematically depict successive depositional phases from the end of Hume sedimentation to the end of Ramparts reef development. These stages are summarized on the following pages.

6.2.1 Stages 1 and 2

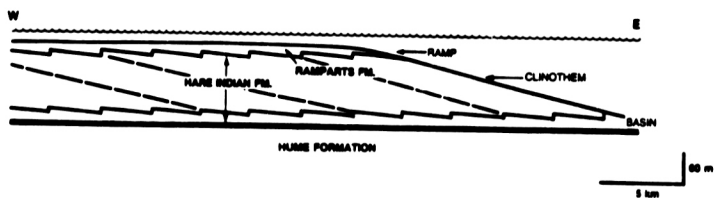
(1) Drowning of the Hume Platform (FIG. 6-1)

A pronounced and rapid sea-level rise near the beginning of Givetian time caused drowning of the Hume carbonate platform. Sea level continued to rise, leading to water depths in excess of 185 m in the Mackenzie Mountains area.

(2) Progradation of the Hare Indian Clastic Wedge and Ramparts Ramp Facies (FIG. 6-1)

As sea-level rise diminished, clastic wedges of the Hare Indian Formation built out into the density-stratified, deep-water basin. The Hare Indian Formation and overlying lower member of the Ramparts Formation accumulated episodically as progradational basin-fill. The ramp succession shows evidence for active sediment bypassing down the ramp mainly by storm winnowing and generation of low-density turbidity currents. Sediments in the clinotherm succession represent both episodic turbidite deposition and background deposition of hemipelagic shale. The basin facies association is represented by sediments of the Hare Indian Bluefish Member. Black, organic-rich laminated shale and minor peloidal calcisiltite turbidites accumulated under anaerobic conditions.

2. PROGRADATION OF HARE INDIAN CLASTICS WEDGE AND RAMPARTS RAMP FACIES



1. DROWNING OF THE HUME PLATFORM, MACKENZIE MOUNTAINS REGION.

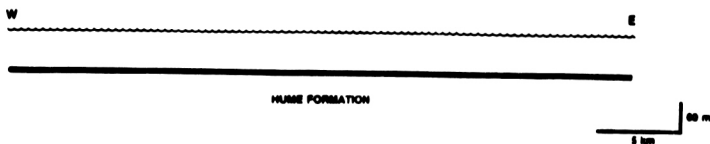


FIG. 6-1 (1) Drowning of the Hume platform.
 (2) Progradation of the Hare Indian clastic wedge and Ramparts ramp facies.

6.2.2 Stages 1 and 4

(3) Termination of Clastic Wedge Progradation - The Carcajou Marker (FIG. 6-2)

Another pulse of accelerated relative sea-level rise led to cessation of clastic wedge progradation. This rapid deepening is represented by the Carcajou Marker at the base of the Carcajou subfacies. This marks a first-order cycle break, ending basin-fill conditions prior to mainly aggradational, backstepping, cyclic, platform-reef development.

(4) Inception of the Lower Carbonate Platform (FIG. 6-2)

Following the Carcajou drowning event, poorly oxygenated conditions persisted over much of the ramp and led to widespread deposition of the organic-rich, shaly Carcajou subfacies. Local banks with cylindrical stromatoporoids, ramose corals, crinoids, and brachiopods became established on topographic highs on the underlying ramp, and in the vicinity of the ramp-clinothem transition. Sea-level rises during lower platform time resulted in a more aggradational style of platform development with third-order platform cycles thickening over antecedent topographic highs. Pronounced lower platform relief played a significant role in determining the nature of subsequent cyclic platform-lower reef (reef cycle 1) development.

4. INCEPTION OF LOWER CARBONATE PLATFORM (L).

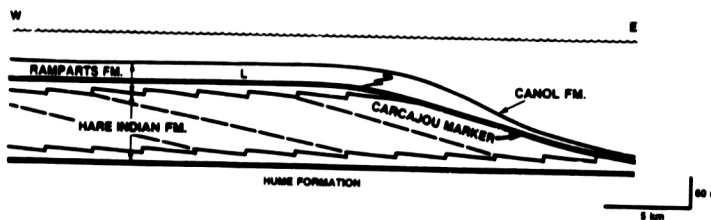
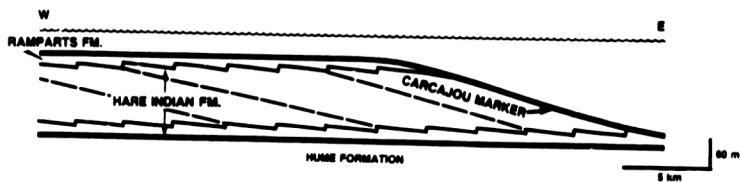
3. TERMINATION OF CLASTIC WEDGE PROGRADATION
— THE CARCAJOU MARKER

FIG. 6-2 (3) Termination of clastic wedge progradation
— the Carcajou Marker.
(4) Inception of the lower carbonate platform.

6.2.3 Stages 5 and 6

(5) Localized Upbuilding of the Carbonate Platform (FIG. 6-3)

A pulse of accelerated relative sea-level rise initiated middle platform cycle development on previous lower platform depositional highs. Although margins backstepped relative to the underlying lower platform margins, the sequence apparently represents deposition under more prolonged relative stillstand conditions. The middle platform cycle is composed of grainy, abraded stromatoporoid-bearing lithofacies, which thicken into adjacent depositional lows in the platform interior. This is in marked contrast to the overlying upper platform cycle which typically built up locally in areas of good water circulation and antecedent middle platform highs. Overall this produced more areally restricted highs surrounded by deeper water on the carbonate platform.

(6) Reef Inception and Progradation (FIG. 6-3)

A subsequent rise in sea level terminated the upper platform cycle as indicated by the presence of hardgrounds on buildup tops. Margin/shoal facies of reef cycle 1 were initiated preferentially on these drowned buildup highs, and prograded during reef cycle 1 time. Embayments and paleodepressions inherited from the drowned platform were

5. LOCALIZED UPBUILDING OF THE CARBONATE PLATFORM (U).
 6. REEF INCEPTION AND PROGRADATION (1).

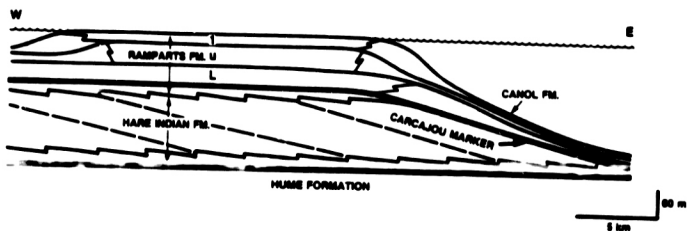


FIG. 6-3 (5) Localized upbuilding of the carbonate platform.
 (6) Reef inception and progradation.

quickly infilled, and the stromatoporoid reef margins eventually sheltered an interior lagoon in which restricted tidal flat and Amphipora-bearing lithofacies accumulated.

6.2.4 Stage 7

(7) Aggradation of Second and Third Reef Cycles (FIG. 6-4)

Successive sea-level rises following reef cycle 1 time produced only small increments of backstepping, and the reef margins grew upwards in essentially the same positions. Shallow-water lagoonal and tidal-flat deposits continued to form in the reef interior.

6.2.5 Stage 8

(8) Backstepping and Subsequent Aggradation of Fourth Reef Cycle (FIG. 6-5)

A relatively pronounced rise in sea level led to appreciable backstepping of the reef margins. Following this rise, the reef margins sheltered higher energy peloidal carbonate deposition in the reef interior.

7. AGGRADATION OF SECOND AND THIRD REEF CYCLES.

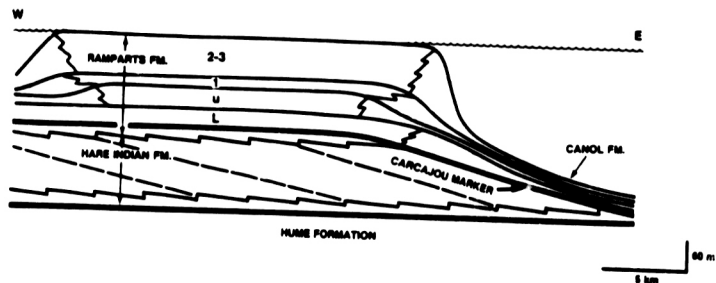


FIG. 6-4 (7) Aggradation of second- and third-order reef cycles.

8. BACKSTEPPING AND SUBSEQUENT AGGRADATION OF FOURTH REEF CYCLE.

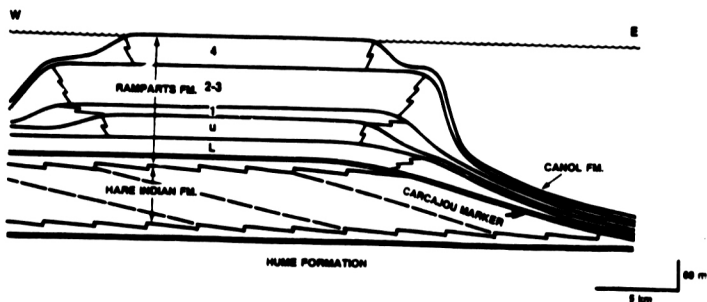


FIG. 6-5 (8) Backstepping and subsequent aggradation of fourth reef cycle.

6.2.6 Stage 9

- (9) Drowning of the Norman Wells Reef Complex;
Backstepping and Aggradation of the Fifth Reef Cycle
in the Mackenzie Mountains Reef Complex (FIG. 6-6)

Regional correlation of depositional sequences showed that a relative sea-level rise terminated the Norman Wells buildup and led to backstepping of the reef margins of the Mackenzie Mountains buildup. During reef cycle 5 time, slightly more open marine, "grainy" sedimentation characterized the reef interior.

6.2.7 Stage 10

- (10) Aggradation of Shoal Cycle (FIG. 6-7)

A pulse of accelerated sea-level rise terminated reef cycle 5 and led to the formation of an areally restricted, cylindrical stromatoporoid-ramose coral shoal lacking reef margins. Open marine conditions with good water circulation prevailed during deposition of reef cycle 6.

9. BACKSTEPPING AND AGGRADATION OF THE FIFTH REEF CYCLE.

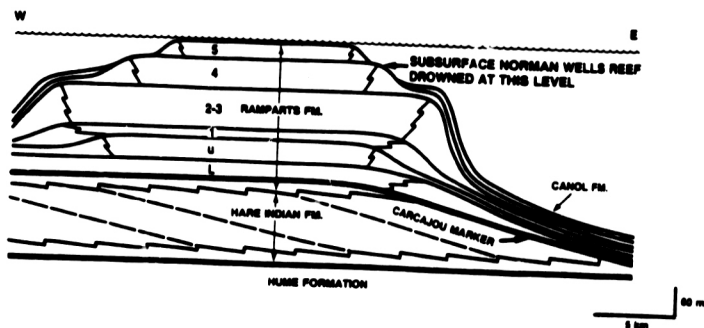


FIG. 6-6 (9) Drowning of the Norman Wells reef complex; backstepping and aggradation of the fifth reef cycle in the Mackenzie Mountains reef complex.

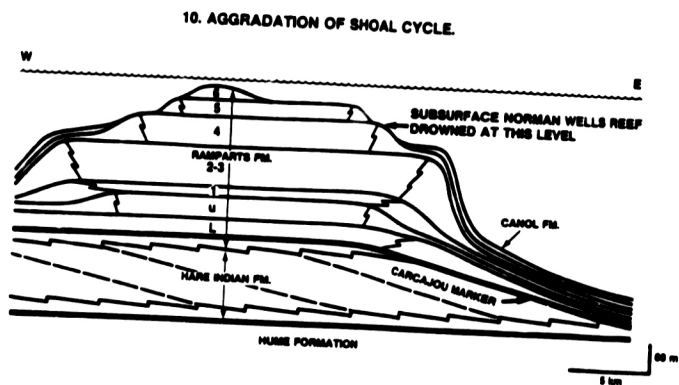


FIG. 6-7 (10) Aggradation of shoal cycle.

6.2.8 Stage 11(11) Drowning of the Mackenzie Mountains Reef Complex

(FIG. 6-8)

Another rapid rise of sea level caused the ultimate drowning of the Mackenzie Mountains reef complex. Following cessation of reef growth, the complex remained uncovered by sediments for a considerable period of time. Eventually prograding clinotherm sediments of the Imperial Formation downlapped onto the buildup. Basinal sediments of the Canol Formation did not accumulate on top of the Mackenzie Mountains complex.

11. DROWNING OF THE MACKENZIE MOUNTAINS REEF COMPLEX.

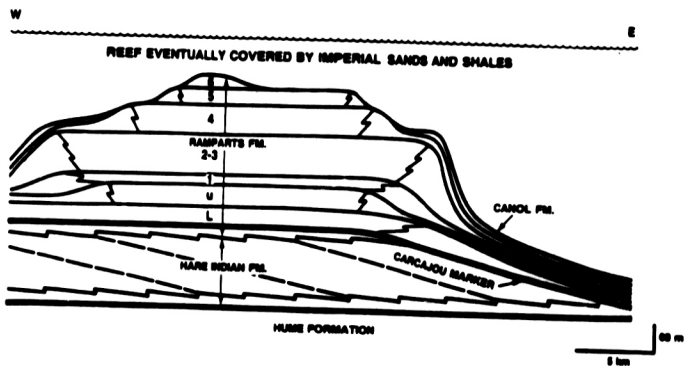


FIG. 6-8 (11) Drowning of the Mackenzie Mountains reef complex.

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APPENDICES

APPENDIX A:

Conodont biostratigraphy. The following conodont identifications and ages were prepared by Dr. T.T. Uyeno using 177 samples from the study area. Heights measured above the top of the Hume Formation unless otherwise noted. Only samples which yield conodonts are listed here.

SECTION 01	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Powell Creek 65° 16' 30" W 128° 46' W	0.3 below Hume top	Hume	c-108351	01-003	735-01	<u>Polynathus parawebbi</u> <u>P. pseudofoliatus</u>	<u>australis</u> zone to lower <u>varcus</u> subzone
	128.5	Hare Indian (upper member)	c-108352	01-006	735-02	<u>Polynathus linguiformis linguiformis</u> <u>P. varcus</u> <u>P. timorensis?</u>	lower <u>varcus</u> to <u>hermanni- cristatus</u> subzones
	133.0	Hare Indian (upper member)	c-108353	01-008	735-03	<u>Polynathus linguiformis linguiformis</u> <u>P. timorensis</u>	lower <u>varcus</u> to <u>hermanni- cristatus</u> subzones
	141.5	Hare Indian (upper member)	c-108354	01-010	735-04	<u>Icriodus brevis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	160.0	Hare Indian (upper member)	c-108356	01-013	735-06	<u>Icriodus brevis</u> <u>Polynathus linguiformis linguiformis</u> <u>P. ansatus</u>	middle <u>varcus</u> subzone
	164.5	Hare Indian (upper member)	c-108357	01-015	735-07	<u>Icriodus brevis</u> <u>Polynathus linguiformis linguiformis</u> <u>P. varcus</u>	probably lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
Base of Ramparts at 165.5 m	168.0	Ramparts (ramp)	c-108358	01-016	735-08	<u>Icriodus brevis</u> <u>Polynathus linguiformis linguiformis</u> <u>P. ansatus</u>	middle <u>varcus</u> subzone
	175.0	Ramparts (lower platform - "Cercajow Marker")	c-108359	01-018	735-09	<u>Icriodus brevis</u> <u>I. cf. I. difficilis</u> <u>Polynathus linguiformis linguiformis</u> <u>P. timorensis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones

SECTION 01 (cont'd) HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
177.5	Ramparts (middle platform)	c-108360	01-020	735-10	<u>Icriodus difficilis</u> <u>Ozarkodina brevis</u> <u>Polyanathus dubius</u> <u>P. xylus xylus</u> <u>Schmidtognathus peracutus</u>	<u>disperilis</u> zone, lower part
181.5	Ramparts (middle platform)	c-108361	01-022	735-11	<u>Elsonella rhenana</u> <u>Palmatolepis disparata</u> <u>P. disperilis</u> <u>Polyanathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u> <u>S. ? sp.</u>	<u>disperilis</u> zone, lower part
184.5	Ramparts (upper platform)	c-108362	01-023	735-12	<u>Elsonella rhenana</u> <u>Ozarkodina semialternans</u> <u>Palmatolepis disperilis</u> <u>Polyanathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u>	<u>disperilis</u> zone, lower part
190.5	Ramparts (reef cycle 1)	c-108363	01-025	735-13	<u>Polyanathus cristatus</u> <u>P. denaleri</u> <u>P. xylus xylus</u>	<u>disperilis</u> zone, upper part
193.5	Ramparts (reef cycle 1)	c-108364	01-026	735-14	<u>Elsonella rhenana</u> <u>Ozarkodina semialternans</u> <u>Polyanathus cristatus</u> <u>P. dubius</u> <u>P. denaleri</u>	<u>disperilis</u> zone, upper part

SECTION 01 (cont'd) HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
197.5	Ramparts (reef cycle 1)	c-108365	01-027	735-15	<u>Ozarkodina brevis</u> <u>Palmitolepis dispersalvea</u> <u>Polynathus cristatus</u> <u>P. denigleri</u> <u>P. dubius</u> <u>P. norrisi</u> <u>P. sp.</u>	lowermost <u>asymmetric</u> zone
199.5	Ramparts (reef cycle 2)	c-108366	01-028	735-16	<u>Ozarkodina brevis</u> <u>Polynathus cristatus</u> <u>P. dubius</u> <u>P. norrisi</u> <u>P. sp.</u>	lower most <u>asymmetric</u> zone
202.5	Ramparts (reef cycle 2)	c-108367	01-030	735-17	<u>Ozarkodina brevis</u> <u>Polynathus dubius</u> <u>P. xylus xylus</u> <u>P. sp.</u>	lower <u>hermanni-cristatus</u> subzone to lower <u>asymmetric</u> zone
207.5	Ramparts (reef cycle 3)	c-108369	01-032	735-19	<u>Polynathus dubius</u> <u>P. xylus xylus</u> <u>P. sp.</u>	probably lower <u>hermanni-</u> <u>cristatus</u> subzone to lower <u>asymmetric</u> zone
Base of Canal at 209.9 m	Canal	c-108372	01-035	735-22	<u>Icriodus</u> sp. <u>Palmitolepis</u> cf. <u>P. transitans</u> <u>Polynathus varcus</u> <u>P. xylus xylus</u>	probably lower <u>asymmetric</u> zone
231.5	Canal	c-108375	01-039	735-25	<u>Ancyrodella</u> (possibly <u>A. nodosa</u>) <u>Ancyronathus</u> ? sp. (possibly <u>A. ancyrognathoides</u>) <u>Palmitolepis subrecta</u> <u>Polynathus</u> sp.	possibly middle <u>asymmetric</u> zone

SECTION 03	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Ridge Section 65° 16' 30" W 128° 47' 30" W. Approximately 1.4 km bearing 290° from Section 01.	123.4	Hare Indian (upper member)	c-108406	03-005	840-02	<u>Icriodus brevis</u> <u>Polynathus linguiformis linguiformis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	138.6	Hare Indian (upper member)	c-108404	03-009	840-04	<u>Icriodus brevis</u> <u>Polynathus linguiformis linguiformis</u> <u>P. varcus</u> <u>P. timorensis</u> ?	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
Base of Ramparts at 163.3 m	171.6	Ramparts (ramp)	c-76900	03-016	840-08	<u>Icriodus</u> sp. <u>Polynathus linguiformis linguiformis</u> <u>P. varcus</u>	<u>ensensis</u> to lower <u>asymmetricus</u> zones
	181.1	Ramparts ("Carcajou Marker")	c-76899	03-018	840-09	<u>Icriodus</u> sp. <u>Ozarkodine brevis</u> <u>Polynathus</u> cf. <u>P. varcus</u>	<u>ensensis</u> to middle <u>asymmetricus</u> zones, possibly middle to upper <u>varcus</u> subzone
	191.3	Ramparts (lower platform)	c-76897	03-021	840-11	<u>Icriodus</u> sp. <u>Polynathus timorensis</u> <u>P. axylus axylus</u>	lower <u>varcus</u> subzone to probably lowermost <u>asymmetricus</u> zone
	203.9	Ramparts (lower platform)	c-76896	03-024	840-12	<u>Icriodus</u> sp. <u>Ozarkodine brevis</u> <u>Polynathus dubius</u> <u>P. varcus</u>	lower <u>hermanni-cristatus</u> subzone to lower <u>asymmetricus</u> zone
	210.1	Ramparts (middle platform)	c-76895	03-025	840-13	<u>Ozarkodine brevis</u>	<u>ensensis</u> to middle <u>asymmetricus</u> zones

SECTION 04	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CNW. NO.	CONODONTS	AGE
Ridge Section 65°16'30"W 128°47'30"W. 30 m distance from top of Unit 03-025 at bearing 289°.	218.1	Ramparts (upper platform)	c 60194	04-003	841-01	<u>Icriodus</u> sp. <u>Ozarkodina brevis</u> <u>Polyanethus axius axius</u> <u>P. sp.</u>	lower <u>varcus</u> subzone to lower: <u>asymmetricus</u> zone
	228.3	Ramparts (reef cycle 1)	c 60195	04-006	841-92	<u>Polyanethus cristatus</u> <u>P. dubius</u> <u>P. varcus</u>	upper <u>hermanni-cristatus</u> subzone to lower <u>asymmetricus</u> zone
	232.9	Ramparts (reef cycle 1)	c 60196	04-008	841-03	<u>Ozarkodina brevis</u> <u>Polyanethus varcus</u>	probably <u>varcus</u> zone undivided to lower <u>asymmetricus</u> zone

SECTION 05	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Ridge Section 65°16'30"W 128°47'30"E. 40 m distance from Section 04 at bearing 290°	213.4	Ramparts (middle platform)	c-60197	05-001	841-04	<u>Icriodus</u> sp. <u>Ozarkodina brevis</u> <u>Polygnathus varcus</u> <u>P. xylus xylus</u>	lower <u>varcus</u> subzone to lower <u>asymmetricus</u> zone
	217.3	Ramparts (upper platform)	c-60198	05-002	841-05	<u>Ozarkodina brevis</u> <u>Polygnathus timorensis</u> <u>P. xylus xylus</u> <u>Schmidiongnathus peracutus</u> ?	probably <u>hermanni</u> - <u>crispatus</u> subzone to <u>asymmetricus</u> zone
	221.1	Ramparts (reef cycle 1)	c-60199	05-003	841-06	<u>Elsonella rhenana</u> <u>Ozarkodina brevis</u> <u>Polygnathus</u> cf. <u>P. collieri</u> <u>P. dubius</u> <u>P. xylus xylus</u>	probably upper <u>disparilis</u> zone to lower <u>asymmetricus</u> zone
	226.3	Ramparts (reef cycle 1)	c-60200	05-004	841-07	<u>Icriodus</u> sp. <u>Ozarkodina brevis</u> <u>Polygnathus dubius</u> <u>P. varcus</u>	probably lower <u>hermanni</u> - <u>crispatus</u> subzone to lower <u>asymmetricus</u> zone

SECTION 06	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Ridge Section 65° 16' 30" W 128° 47' 30" W. 45 m distance from Section 03 at bearing 110°.	185.8	Ramparts (lower platform)	c-108408	06-002	841-08	<u>Icriodus</u> sp. <u>Polygnathus aylus aylus</u> <u>P. ovetinodosus</u>	middle <u>varcus</u> subzone to lower <u>asymmetricus</u> zone
	205.5	Ramparts (middle platform)	c-108-410	06-008	841-10	<u>Icriodus difficilis</u> <u>Ozarkodina brevis</u> <u>O. semialternans</u> <u>Polygnathus dubius</u>	lower <u>hermanni-cristatus</u> subzone to lowermost <u>asymmetricus</u> zone

SECTION 07	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
West Powell Creek 65° 16' 30" W 128° 47' W. Approximately 500 m distance at bearing 290° from Section 01.	0.3 m below Hume top	Hume	c-60179	07-001	736-01	<u>Polyanthus angustipennatus</u> <u>P. linguiformis linguiformis</u> <u>P. parawebbi</u>	<u>australis</u> to <u>ensensis</u> zones
	85.6	Hare Indian (upper member)	c-60180	07-002	736-02	<u>Icriodus brevis</u> <u>Polyanthus varcus</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	95.5	Hare Indian (upper member)	c-60181	07-004	736-03	<u>Icriodus</u> cf. <u>I. brevis</u> <u>Polyanthus linguiformis linguiformis</u> <u>P. varcus</u>	probably lower <u>varcus</u> to lower <u>hermanni-cristatus</u> zones
	108.6	Hare Indian (upper member)	c-60182	07-006	736-04	<u>Icriodus brevis</u> <u>Polyanthus varcus</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	122.0	Hare Indian (upper member)	c-60183	07-008	736-05	<u>Icriodus brevis</u> <u>I. sp.</u> <u>Polyanthus linguiformis linguiformis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u>
	132.4	Hare Indian (upper member)	c-60184	07-010	736-06	<u>Polyanthus linguiformis linguiformis</u> <u>P. varcus</u>	<u>ensensis</u> to questionably middle <u>varcus</u> subzone
	163.2	Hare Indian (upper member)	c-60186	07-014	736-08	<u>Icriodus</u> sp. <u>Polyanthus linguiformis linguiformis</u> <u>P. timorensis</u> ?	probably lower <u>varcus</u> to upper <u>hermanni-cristatus</u> subzones
Base of Ramparts Formation at 166.8 m	173.6	Ramparts (ramp)	c-60188	07-018	736-10	<u>Icriodus brevis</u> <u>I. sp.</u> <u>Polyanthus timorensis</u> <u>P. xylus xylus</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzone*

SECTION 07 (cont'd) Height (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
183.1	Ramparts (middle platform)	c-60189	07-022	736-11	<u>Icriodus difficilis</u> <u>Ozarkodina brevis</u> <u>O. semialternans</u> <u>Polygnathus dubius</u> <u>P. ovatinodosus</u> <u>P. xylus xylus</u> <u>Schmidtognathus peracutus</u>	<u>disparilis</u> zone, lower part
186.4	Ramparts (upper platform)	c-60190	07-024	736-12	<u>Palmitolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u>	<u>disparilis</u> zone, lower part
192.3	Ramparts (reef cycle 1)	c-60191	07-025	736-13	<u>Ozarkodina brevis</u> <u>Palmitolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. timorensis</u> <u>P. xylus xylus</u>	<u>disparilis</u> zone, lower part
206.6	Ramparts (reef cycle 1)	c-60192	07-026	736-14	<u>Ozarkodina brevis</u> <u>O. semialternans</u> <u>Palmitolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. denigleri</u> <u>P. timorensis</u> <u>P. xylus xylus</u> <u>Schmidtognathus peracutus</u>	<u>disparilis</u> zone, upper part
209.6	Ramparts (reef cycle 1)	c-60193	07-027	736-15	<u>Ozarkodina brevis</u> <u>Palmitolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>P. ovatinodosus</u>	<u>disparilis</u> zone, upper part

SECTION 08	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Bell Creek 65° 17' W 129° 04' W	145.0	Hare Indian (upper member)	c-108411	08-002	842-01	<u>Icriodus brevis</u> <u>Polygonathus timorensis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	154.2	Ramparts (ramp)	c-108412	08-004	842-02	<u>Icriodus</u> sp. <u>Polygonathus varcus</u>	<u>ensensis</u> to lower <u>symmetricus</u> zones
Base of Ramparts at 152 m	171.0	Ramparts (ramp)	c-108414	08-008	842-04	<u>Icriodus brevis</u> <u>Polygonathus linguiformis linguiformis</u> <u>P. ensatus</u> ?	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones, possibly middle <u>varcus</u> subzone
	178.6	Ramparts ("Carcajou Marker")	c-108415	08-010	842-05	<u>Icriodus</u> sp. <u>Ozarkodina brevis</u> <u>Polygonathus varcus</u>	<u>ensensis</u> to lower <u>symmetricus</u> zones
	199.2	Ramparts (reef cycle 1)	c-108418	08-016	842-08	<u>Icriodus</u> cf. <u>I. difficilis</u> <u>Polygonathus</u> cf. <u>P. pyatinodosus</u>	probably middle <u>varcus</u> subzone to lower <u>symmetricus</u> zones

SECTION 15	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Gayna River (eastern bank) 65° 18' N 129° 21' W	198.0	Ramparts (ramp)	c-76893	15-017	834-01	<u>Icriodus</u> cf. <u>I. difficilis</u> <u>Ozarkodina brevis</u> <u>Polygonathus axilus axilus</u>	lower <u>varcus</u> subzone to lower <u>asymmetricus</u>
Base of Ramparts at 185 m	198.9	Ramparts ("Carcajou Marker")	c-76883	15-081	834-02	<u>Icriodus</u> sp. <u>Polygonathus linguiformis linguiformis</u> <u>P. varcus</u>	<u>ensensis</u> to lower <u>asymmetricus</u> zones
	199.1	Ramparts (lower platform)	c-76884	15-019	834-03	<u>Icriodus</u> sp. <u>Polygonathus linguiformis linguiformis</u> <u>P. varcus</u>	probably <u>ensensis</u> to lower <u>asymmetricus</u> zones
	205.7	Ramparts (lower platform)	c-76885	15-020	834-04	<u>Polygonathus axilus axilus</u> ?	probably <u>ensensis</u> to lower <u>asymmetricus</u> zones
	215.1	Ramparts (lower platform)	c-76886	15-023-4b	834-05	<u>Polygonathus axilus axilus</u> ?	probably <u>ensensis</u> to lower <u>asymmetricus</u> zones
Base of Canol at 218.0 m	218.4	Canol	c-76888	15-024	834-07	<u>Icriodus difficilis</u> <u>Palmitolepis disparilis</u> <u>Polygonathus cristatus</u> <u>P. cristatus</u> transitional to <u>Palmitolepis disparilis</u> <u>P. denaleri</u> <u>P. dubius</u> <u>P. norrisi</u>	lowermost <u>asymmetricus</u> zone

SECTION 18	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Creek Section 65° 17' W 129° 11' W	170.8	Nere Indian (upper member)	c-76852	GG-01-01-4	830-01	<u>Icriodus brevis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
Base of Ramparts at 175 m	177.8	Ramparts (ramp)	c-76859	GG-01-04-4b	830-08	<u>Icriodus brevis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	184.8	Ramparts (ramp)	c-76866	GG-01-07-4b	830-15	<u>Polyanethus varcus</u>	probably middle to upper <u>varcus</u> subzones
	186.8	Ramparts (ramp)	c-76868	GG-01-09-4a	830-17	<u>Polyanethus anastus</u>	middle <u>varcus</u> subzone
	333.4	Ramparts (reef cycle 4)	c-198381	18-047-c	812-01	<u>Ozarkodina brevis</u>	<u>anastus</u> to middle <u>asymmetricus</u> zones

SECTION 20	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Creek Section 65° 17' N 129° 04' W	189.3	Nare Indian (upper member)	c-99820	GG-02-01-4a	829-01	<u>Icriodus brevis</u> <u>I. difficilis</u> <u>Polyanethus linguiformis linguiformis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
Base of Ramparts at 193 m	194.3	Ramparts (ramp)	c-99825	GG-02-03-4b	829-06	<u>Icriodus difficilis</u> <u>Polyanethus linguiformis linguiformis</u> <u>P. xylus xylus</u> <u>P. sp.</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	199.3	Ramparts (ramp)	c-99830	GG-02-06-4b	829-11	<u>Oxarkodina cf. O. semialternans</u> <u>Polyanethus varcus</u>	possibly middle <u>varcus</u> subzone to lowermost <u>asymmetricum</u> zone
	201.3	Ramparts (ramp)	c-99832	GG-02-07-4a	829-13	<u>Icriodus brevis</u> <u>Polyanethus timorensis</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones

SECTION 25	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Mountain River Distributary 65°14'15"W 128°35'45"W	62.6	Canol ("Carcajou Marker")	c-126424	25-014-5c	895-01	<u>Polyanethus linguiformis linguiformis</u> ? <u>P. yarcus</u> ?	possibly middle and upper <u>yarcus</u> subzones
Top of Hare Indian at 55 m	91.3	Canol	c-126428	25-021-5c	895-05	<u>Elsonella rhenana</u> <u>Icriodus</u> sp. <u>Ozarkodina semialternans</u> <u>Palmitolepis disparilis</u> <u>Polyanethus denaleri</u> <u>P. dubius</u> <u>P. xylus xylus</u> ?	<u>disparilis</u> zone, upper part

SECTION 31	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONODONTS	AGE
Stream Cut 65° 16' 30" W 128° 58' W	363.2	Ramparts (reef cycle 6)	c-126430	31-047-5a	895-07	<u>Icriodus difficilis</u> <u>Ozarkodina brevis</u> <u>Polymaethus avilus avilus</u>	lower <u>Yarcus</u> subzone to lower <u>asymmetricus</u> zone

APPENDIX B:**Paleocurrent data.**

SECTION - 20

UNIT - 013

Facies - platform interior facies (Ramparts Formation)

Structure(s) - aligned thamnoporoids

n = 31 $\theta = 170/350^\circ$ r = 22.81 L = 74% P = 4.2×10^{-8}

SECTION - 20

UNIT - 044

Facies - reef shoal facies, cycle 6 (Ramparts Formation)

Structure(s) - aligned robust cylindrical stromatoporoids

n = 25 $\theta = 96/276^\circ$ r = 16.25 L = 65% P = 2.6×10^{-5}

SECTION - 25

UNIT - 002

Facies - basinal facies (Hare Indian Formation)

Structure(s) - aligned ammonoids, dactyonarids, plant fragments,
crinoid pluricolumnals in current stable positionsn = 37 $\theta = 267^\circ$ r = 22.42 L = 61% P = 1.0×10^{-6}

SECTION - 25

UNIT - 002

Facies - basinal facies (Hare Indian Formation)

Structure(s) - aligned ammonoids, dactyonarids, plant fragments,
crinoid pluricolumnals in current stable positionsn = 34 $\theta = 264^\circ$ r = 22.98 L = 68% P = 1.5×10^{-7}

SECTION - 25

UNIT - 012

Facies - clinothem facies (Hare Indian Formation)

Structure(s) - prod and skip marks, grooves

n = 20 $\theta = 251^\circ$ r = 19.28 L = 96% P = 9.0×10^{-9}

APPENDIX C: Organic carbon contents in shale samples from
the Hume, Hare Indian, Ramparts, Canol, and
Imperial Formations.

SECTION	UNIT	HEIGHT ABOVE TOP OF HUME (m)	WT% TOC	FORMATION
01	004-5	4.6- 6.7	0.43	Hare Indian
01	016-5	168.5-171.3	0.98	Ramparts
01	017-5	171.3-176.6	0.41	Ramparts
01	018	176.6-178.3	0.26	Ramparts
01	018-BOT	176.6-178.3	1.10	Ramparts
01	018-BOT	179.1-181.6	0.03	Ramparts
01	021-5	181.6-183.1	2.54	Ramparts
01	021-SSH	181.6-183.1	1.62	Ramparts
01	025-5c	190.6-194.1	0.36	Ramparts
01	029-5	203.1-204.2	0.44	Ramparts
01	030-5	204.2-207.1	0.53	Ramparts
01	031-5a	207.1-208.8	1.58	Ramparts
01	032-5b	208.8-212.9	0.89	Ramparts
01	033-SSH	212.9-217.4	4.24	Canol
01	039-SSH	230.0-236.6	2.91	Canol
03	002	0.0- 3.6	1.48	Hare Indian
03	002-NOD	0.0- 3.6	0.53	Hare Indian
03	003	3.6- 12.4	1.49	Hare Indian
03	018-C11	178.5	1.57	Ramparts
03	018-C12	178.7	1.40	Ramparts
03	018-C14	179.6	1.23	Ramparts
03	018-C15	180.3	1.51	Ramparts
03	018-VTOP	181.2	0.35	Ramparts
07	007-BJ	113.7	3.16	Hare Indian
07	008-SSH	120.3	3.79	Hare Indian
07	015-5a	165	0.54	Ramparts
07	016-5	170	0.38	Ramparts
07	016-5	166.8-173.5	0.43	Ramparts
07	016-SSH	166.8-173.5	2.15	Ramparts
07	017-5MOT	170.1-172.1	2.60	Ramparts
07	018-5	172.1-173.9	0.36	Ramparts
07	019-5	173.9-177.5	0.19	Ramparts
07	020-5	177.5-180.1	0.83	Ramparts
07	023-5	183.6-186.0	0.32	Ramparts
07	024-5	186.0-187.5	0.06	Ramparts
07	025-5	187.5-193.8	0.32	Ramparts
08	004-5	146.9-149.2	4.07	Ramparts
08	008-5cb	160.3-166.4	0.52	Ramparts
08	014-5	184.8-190.0	0.12	Ramparts
08	016-5	194.1-197.5	0.87	Ramparts
08	017-5	197.5-204.7	1.01	Ramparts
08	019-5	209.3-214.2	1.67	Ramparts
08	020-5c	214.2-221.0	0.03	Ramparts
08	020-5d	214.2-221.0	0.45	Ramparts

SECTION	UNIT	HEIGHT ABOVE TOP OF HUME (m)	WT% TOC	FORMATION
08	021-5c	221.0-229.9	0.15	Ramparts
08	037-5	342.6-352.0	0.02	Ramparts
15	003	0.2	1.30	Hare Indian
15	004-5b	2.0	5.04	Hare Indian
15	004-5c	2.6	5.91	Hare Indian
15	005-5b	4.1	7.09	Hare Indian
15	005-5c	4.5	2.01	Hare Indian
15	005-FIB	4.5	2.31	Hare Indian
15	006-5b	8.8	3.07	Hare Indian
15	006-5c	10.2	3.00	Hare Indian
15	008-5a	14.0	2.41	Hare Indian
15	009-5a	15.3	1.68	Hare Indian
15	013-5a	187.7	0.15	Ramparts
15	014-5c	190.2	4.05	Ramparts
15	015-5a	191.0	1.36	Ramparts
15	015-5b	191.8	0.93	Ramparts
15	016-5a	192.5	2.40	Ramparts
15	016-5c	195.2	0.45	Ramparts
15	017-5a	196.1	1.85	Ramparts
15	017-5b	196.7	0.42	Ramparts
15	018-c1	198.2	1.12	Ramparts
15	018-c3	198.5	0.76	Ramparts
15	018-c4	198.6	8.27	Ramparts
15	018-c5	198.8	5.97	Ramparts
15	018-c6	198.9	3.25	Ramparts
15	018-c8	199.0	1.58	Ramparts
15	018-5a	199.0	0.59	Ramparts
15	018-5b	198.9	2.71	Ramparts
15	020-5	206.0	0.18	Ramparts
15	021-5a	207.7	0.23	Ramparts
15	022-5c	213.0	0.17	Ramparts
15	023-5b	215.1	0.24	Ramparts
15	024-5b	219.2	3.34	Canol
15	024-5c	219.6	0.55	Canol
15	025-5a	219.8	6.03	Canol
15	025-5c	221.7	2.68	Canol
15	026-5a	223.4	2.33	Canol
15	026-5c	226.1	2.32	Canol
15	027-5b	228.4	4.24	Canol
15	028-5a	229.4	1.73	Canol
15	028-5b	230.0	2.34	Canol
17	002-5b	1.0	4.27	Hare Indian
17	002-5c	2.1	5.42	Hare Indian
17	003-5b	2.7	3.47	Hare Indian
17	004-5a	4.2	2.63	Hare Indian

SECTION	UNIT	HEIGHT ABOVE TOP OF HUME (m)	WT% TOC	FORMATION
17	004-5b	6.6	5.09	Hare Indian
17	004-5c	7.4	1.80	Hare Indian
17	005-5a	8.3	4.15	Hare Indian
17	005-5b	9.6	3.00	Hare Indian
17	005-5c	11.5	2.75	Hare Indian
19	001-5b	-2.5	0.22	Hume
19	002-5b	1.0	5.10	Hare Indian
19	003-5c	3.3	6.10	Hare Indian
20	004-5b	195.0	1.73	Ramparts
20	004-5d	198.0	1.35	Ramparts
20	005-5c	203.1	0.92	Ramparts
20	006-5a	204.1	0.21	Ramparts
20	007-5a	204.5	0.26	Ramparts
20	009-5c	208.0	2.89	Ramparts
25	002-5b	0.4	1.99	Hare Indian
25	003-5a	4.0	2.07	Hare Indian
25	003-5b	4.6	3.66	Hare Indian
25	004-5a	6.8	4.13	Hare Indian
25	004-5b	8.2	4.01	Hare Indian
25	004-5c	10.2	3.31	Hare Indian
25	004-5d	12.4	2.87	Hare Indian
25	005-5a	13.7	5.03	Hare Indian
25	005-5b	15.0	2.91	Hare Indian
25	008-5a	34.3	0.44	Hare Indian
25	009-5b	40.0	4.57	Hare Indian
25	010-5a	41.3	4.01	Hare Indian
25	010-5c	46.2	3.88	Hare Indian
25	011-5a	46.4	3.66	Hare Indian
25	011-5d	47.4	6.43	Hare Indian
25	012-5a	51.5	1.18	Hare Indian
25	012-5b	52	1.45	Hare Indian
25	012-5c	52.4	5.29	Hare Indian
25	012-5d	53.0- 55.0	0.27	Hare Indian
25	013-5a	56.7	4.15	Canol
25	013-5b	57.3	4.75	Canol
25	013-5c	57.8	6.21	Canol
25	013-5d	58.2	4.55	Canol
25	013-5a	58.5	4.69	Canol
25	014-5a	61.0	2.54	Canol
25	014-5b	62.1	5.73	Canol
25	015-5a	64.0	4.92	Canol
25	015-5b	65.8	2.64	Canol
25	016-5b	68.3	5.30	Canol
25	016-5c	68.9	3.91	Canol

SECTION	UNIT	HEIGHT ABOVE TOP OF HUME (m)	WT% TOC	FORMATION
25	016-5d	70.6	4.11	Canol
25	017-5a	73.5	5.49	Canol
25	017-5b	74.8	6.41	Canol
25	017-5c	76.0	5.01	Canol
25	017-5d	77.5	5.34	Canol
25	017-5c	78.4	4.68	Canol
25	018-5a	78.6	3.96	Canol
25	018-5b	79.3	5.81	Canol
25	019-5b	81.7	2.57	Canol
25	019-5c	83.3	4.14	Canol
25	020-5b	86.2	5.25	Canol
25	020-5c	87.5	4.63	Canol
25	021-5a	88.6	3.07	Canol
25	021-5b	90.0	2.34	Canol
25	022-5a	93.4	2.88	Canol
25	022-5c	94.7	3.79	Canol
25	023-5a	96.5	3.58	Canol
25	023-5b	98.1	3.48	Canol
25	023-5c	99.8	3.67	Canol
25	023-5d	100.7	2.40	Canol
25	024-5a	101.5	4.64	Canol
25	024-5b	103.9	1.61	Canol
25	025-5a	104.2	4.47	Canol
25	025-5b	106.2	3.12	Canol
25	025-5c	107.2	5.03	Canol
25	026-5b	108.8	3.86	Canol
25	026-5c	111.2	0.91	Canol
25	026-5d	113.2	4.62	Canol
25	027-5a	114.4	3.79	Canol
25	027-5b	116.1	4.36	Canol
25	028-5a	117.1	6.35	Canol
25	028-5b	118.6	1.95	Canol
25	028-5c	120.0	3.66	Canol
25	028-5d	121.5	3.23	Canol
25	029-5a	123.5	5.23	Canol
25	029-5c	126.9	4.79	Canol
25	030-5a	128.2	2.02	Canol
25	030-5b	129.4	3.49	Canol
25	030-5c	130.5	2.02	Canol
25	031-5a	130.9	3.46	Imperial
25	031-5b	132.9	2.59	Imperial
25	032-5a	138.4	4.21	Imperial
31	004-5a	190.9	3.87	Ramparts
31	006A-5a	204.6	0.66	Ramparts
31	006B-5b	209.5	0.13	Ramparts
31	007B-5a	219.8	0.33	Ramparts

SECTION	UNIT	HEIGHT ABOVE TOP OF HUME (m)	WT& TOC	FORMATION
31	009-5a	229.0	4.30	Ramparts
31	009-5b	229.4	3.09	Ramparts
31	009-5d	229.8	1.14	Ramparts
31	047-5a	357.2	0.10	Ramparts