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

by:

IAIN D. MUIR

A thesis
presented to the University of Ottawa
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in
Geology

OTTAWA, Ontario, 1988

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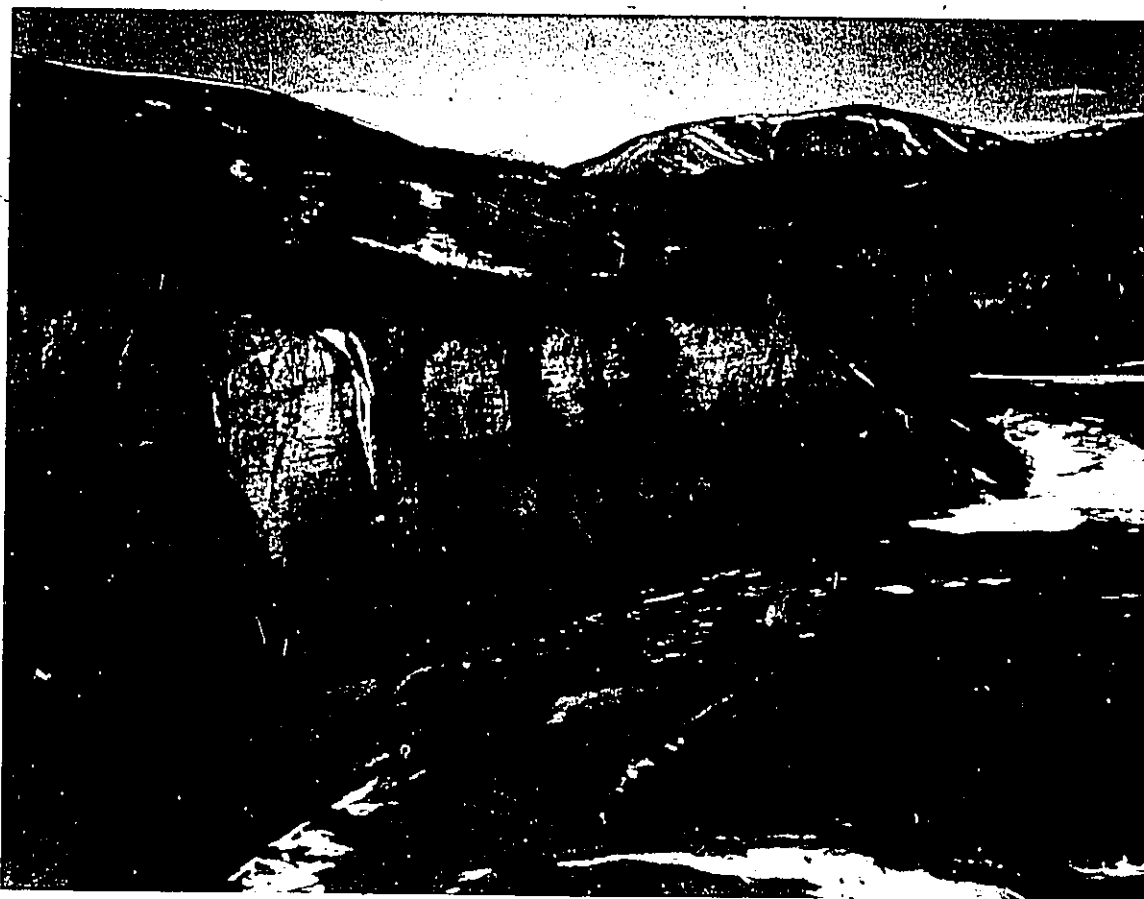
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FRONTISPIECE

View of an abandoned Canol camp (circa 1944-1945) along Dodo Canyon, Mackenzie Mountains, N.W.T.

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ABSTRACT

The Givetian-(?) Frasnian Hare Indian and Ramparts formations are superbly exposed in the Mackenzie Mountains, Northwest Territories. Hare Indian shales, siltstones and limestones and Ramparts limestones collectively represent basin-fill, platform and reef development in the area.

The Hare Indian and Ramparts strata consist of shallowing upward cycles on at least three scales. The cycles are thought to have resulted from accelerated rates of relative sea level rise. Two major first-order cycles (each greater than two hundred metres thick) can be discerned. The lower cycle consists of progradational basin-fill strata (basinal and clinotherm facies) of the Hare Indian Formation and the immediately overlying lower "ramp" member of the Ramparts Formation (ramp facies). A rapid deepening terminated clastic wedge progradation and led to widespread deposition of the organic-rich shaly Carcajou subfacies. The Carcajou Marker (base of Carcajou subfacies) marks a first-order cycle break as the basin-fill conditions reverted to mainly aggradational or backstepping, cyclic, platform and reef development of the upper first order cycle (upper member, Ramparts Formation).

The first-order cycles consist of a number of smaller (10-25 m thick) second-order cycles. These are best defined in the shallow-water platform and reef complex, but also are recognized in the Hare Indian clinotherm facies and, in certain locations, in basinal facies. In platform and reef interior facies and within ramp facies, these second-order cycles are composed of even smaller third-order cycles (2-5 m thick).

Six second order cycles make up the Ramparts buildup. Reef cycle 1 began with local formation of reef margin and shoal facies on drowned highs of the upper platform. These facies are strongly progradational (800-1000 m) compared to margin facies in the overlying reef cycles. This may imply more prolonged relative stillstand. Successive sea-level rises following reef cycle 1 resulted in backstepping or aggradation of the reef margin for each of the succeeding four cycles. Shallow-water lagoonal and tidal-flat deposits continued to form in the reef interior. A pulse of accelerated sea-level rise terminated reef cycle 5 and led to the formation of an areally restricted shoal lacking reef margins. Open marine conditions with good water circulation prevailed during deposition of the shoal sediments. Another rapid rise of sea level caused the ultimate drowning of the Mackenzie Mountains reef complex.

Second-order platform and reef cycles in the Mackenzie Mountains buildup can be correlated to the time-equivalent subsurface buildup at Norman Wells, based on similar thicknesses relative to a regional marker, and on consistent style of reef and platform margin development (progradation, aggradation, backstepping). However, reef cycle 5 and the culminating shoal cycle of the Mackenzie Mountains buildup are evidently not represented in the Norman Wells buildup.

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I

GENERAL INTRODUCTION

1.1 LOCATION OF STUDY AREA

The study area is situated along the Mackenzie Mountains front, 110-150 km west of Norman Wells, N.W.T. (FIG. 1-1a). Twenty-nine stratigraphic sections (1-25; 28-31), totalling in excess of 3000 m thickness, were examined along a discontinuously-exposed escarpment during the course of three field seasons (1982-84). Rocks of the escarpment (stippled area, FIG. 1-1b) are accessible in a number of stream cuts and ridge exposures between the Mountain and Gayna River areas (65°18'N, 124°21'W - 65°14'N, 128°35'W).

Supplementary data were obtained from selected well logs (FIG. 1-2) and reconnaissance of exposures at Ramparts Narrows (section 26 - 66°14'N, 129°41'W), East Mountain (section 27 - 65°42'N, 128°45'W), and the Norman Wells limestone quarry. These additional data help to define regional lithostratigraphic distributions.

1.2 SCOPE AND SIGNIFICANCE OF PRESENT STUDY

The general objectives of the project were to document and interpret lithofacies and biofacies associations in a superbly exposed, Middle Devonian, basin-fill, platform and reef sequence. Detailed study of closely spaced sections along the Mackenzie Mountains front permitted documentation of facies relationships that usually are difficult to

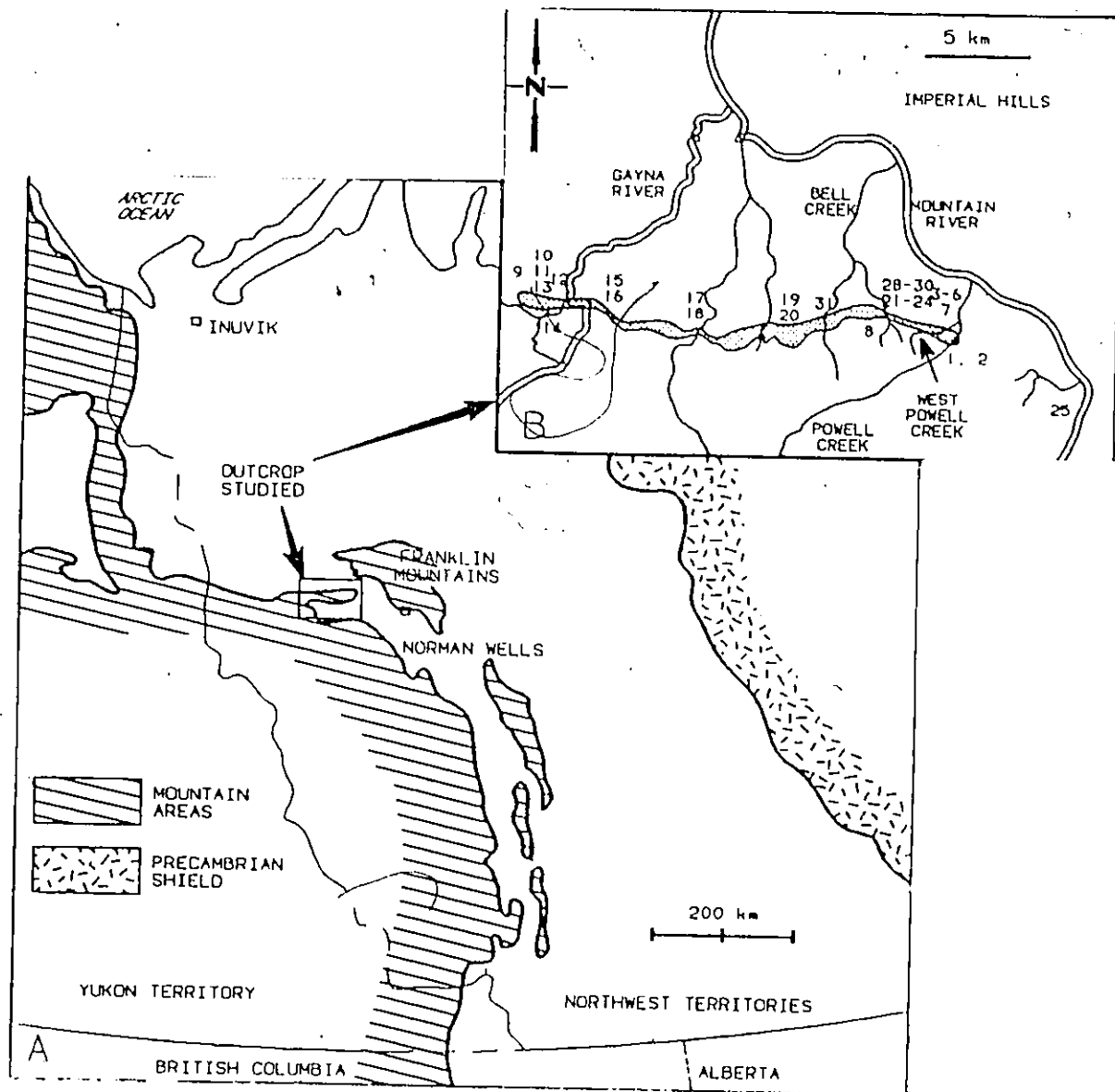


FIG. 1-1 Location of study area (A). Index map (B) showing measured sections (1-25, 28-31). Stippled area marks escarpment where Middle-Upper Devonian strata are exposed.

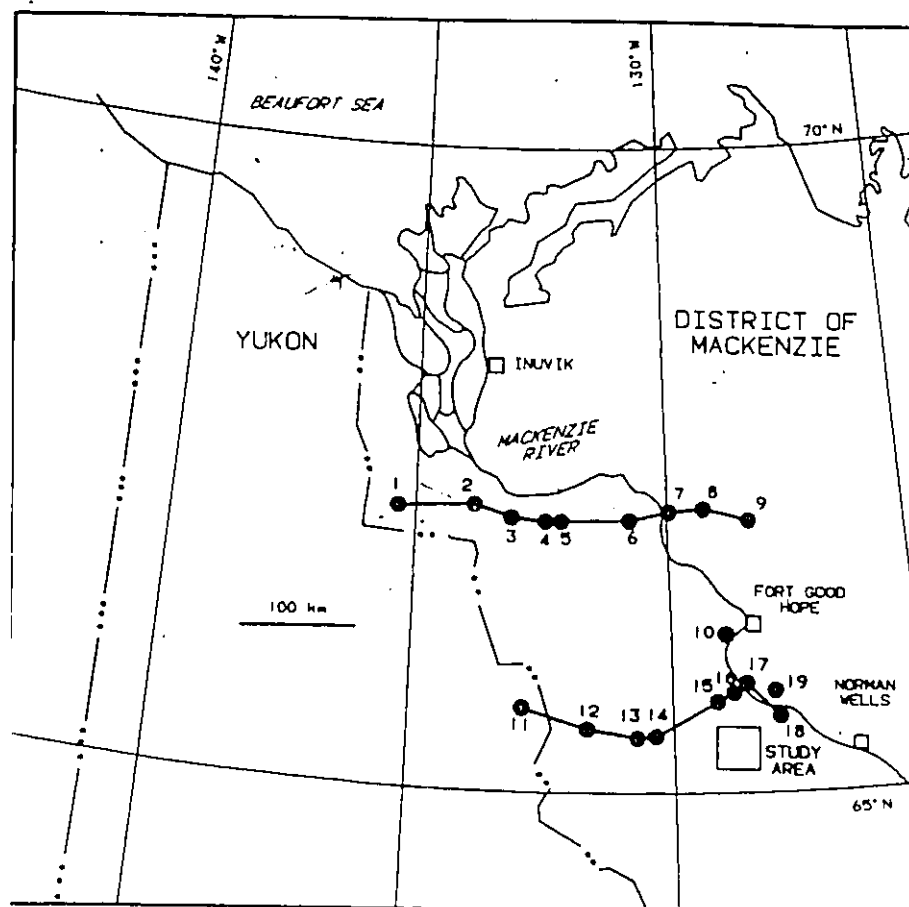


FIG. 1-2 Subsurface and outcrop location sites outside study area, used for supplementary data.

1. Union McPherson B-25
2. I.O.E. Nevejo M-05
3. I.O.C. Clara F-79
4. Shell Tree River F-57
5. Shell Tree River East H-57
6. R.O.C. Grandview Hills No. 1
7. At. Little Chicago No. 32
8. Mobil Manuel Lake J-42
9. Decalta Rond Lake P-75
10. Ramparts Narrows outcrop (section 26)
11. Amoco B-1 Cranswick
12. Amoco A-1 Cranswick
13. Candel South Ramparts I-77
14. Candel North Ramparts A-59
15. Candel Mountain River A-23
16. Arco Mountain River H-47
17. At. Shoals C-31
18. McD. Maida Creek F-57
19. East Mountain outcrop (section 27)

ascertain in subsurface studies. The following aspects of the project were examined in particular detail:

- (1) The lithostratigraphy and conodont biostratigraphy of the Hare Indian, Ramparts, and Canol Formations. Reconnaissance studies only were conducted in the underlying Hume and overlying Imperial Formations.
- (2) The depositional environments and the nature and controls of cyclic basin-fill, platform and reef development during Hare Indian-Ramparts time. Facies models were generated through integrating paleoecological and sedimentological studies.
- (3) The Middle Devonian paleogeography of the study area.

The Ramparts Formation in the Mackenzie Mountains incorporates well-preserved ramp, platform, and reef facies which are superbly exposed along the escarpment (PL. 1-1a). Its study is significant because:

- (1) Surface exposures of the reef and sub-reef facies are essentially unstudied in detail apart from reconnaissance work. An unpublished study of the Ramparts Formation by James (1972) was primarily a petrographic and diagenetic study.
- (2) Surface studies permit a wealth of information to be integrated directly with subsurface information. This larger database enhances the reservoir model

for the hydrocarbon-producing Ramparts Formation in the Norman Wells field (Muir et al., 1984, 1985).

- (3) Faunal and sedimentological studies of the Ramparts Formation are pertinent to reef model studies in Western Canada. In particular, these studies contribute to the understanding of less well-exposed and more diagenetically altered Devonian reef complexes, such as the dolomitized Upper Devonian Leduc Formation in the Alberta Basin.
- (4) Study of the Hare Indian and Ramparts Formations reveals distinct cycles of sedimentation in the time-equivalent Mackenzie Mountains and Norman Wells buildups (Muir and Dixon, 1984, 1985; Wendte and Wong, 1983). Successful correlation of these cycles between the two widely separated reef complexes (110 km) indicates that this may be more widely applicable and aid in understanding the evolution of other Devonian carbonate provinces (Muir et al., 1984, 1985, 1986; Viau, 1984).
- (5) Non-reservoir units such as the Hare Indian and Canol Formations are rarely cored during hydrocarbon exploration/exploitation programs. In this study, data from the enclosing rocks are critical to interpreting the initiation, development, and termination of the Ramparts reef

complex. This methodology differs from that generally used on Canadian Devonian reefs, most of which are known only through subsurface study.

- (6) Systematic lithostratigraphic and biostratigraphic studies of the Hare Indian, Ramparts, and Canol Formations have revealed stratal and temporal relationships that differ from previous interpretations. Some authors (e.g. Warren and Stelck, 1962; Bassett and Stout, 1968; Gilbert, 1973; Braun, 1966, 1977, 1978) have suggested that a significant unconformity separates the Canol and Ramparts Formations. This study, in contrast, reveals that the Canol Formation is partly time-equivalent to, and partly post-dates, the Ramparts Formation.

1.3 METHODOLOGY

Stratigraphic sections were divided into field units averaging 1-3 m in thickness. Each unit is a sedimentary package composed of one or more lithologies, that represents a distinct set of depositional conditions. These units were described on unit cards modified from ones developed by J.D. Aitken of the Geological Survey of Canada. The unit card facilitates rapid recording of field data using numerical codes, and the data can readily be stored on

computer file. Qualitative data that could not readily be entered on a unit card were recorded by section and unit numbers in a field notebook.

At least one lithic sample was obtained from each unit. In addition, 177 samples were submitted to Dr. T.T. Uyeno, Geological Survey of Canada, for conodont separation and identification. The conodont zonation provides the biostratigraphic framework for the study. Organic carbon analyses were conducted by Dr. F. Monnier, Canterra Exploration Ltd., by means of flame photometry.

Approximately 1100 oriented lithic samples were cut, polished, and examined under binocular microscope. Nearly 300 thin sections and 200 acetate peels provided supplementary information, particularly from the finer-grained lithic samples.

Detailed stratigraphic logs of all measured sections are on file with the Department of Geology, University of Ottawa.

1.4 GEOLOGICAL SETTING

4 The eastern margin of the Cordilleran Orogen in northern Canada has a prominent salient directed towards the Canadian Shield (FIG. 1-3). The field area is situated within this salient, in the Mackenzie Foldbelt. En echelon fold bundles and associated strike-slip faults characterize the Mackenzie

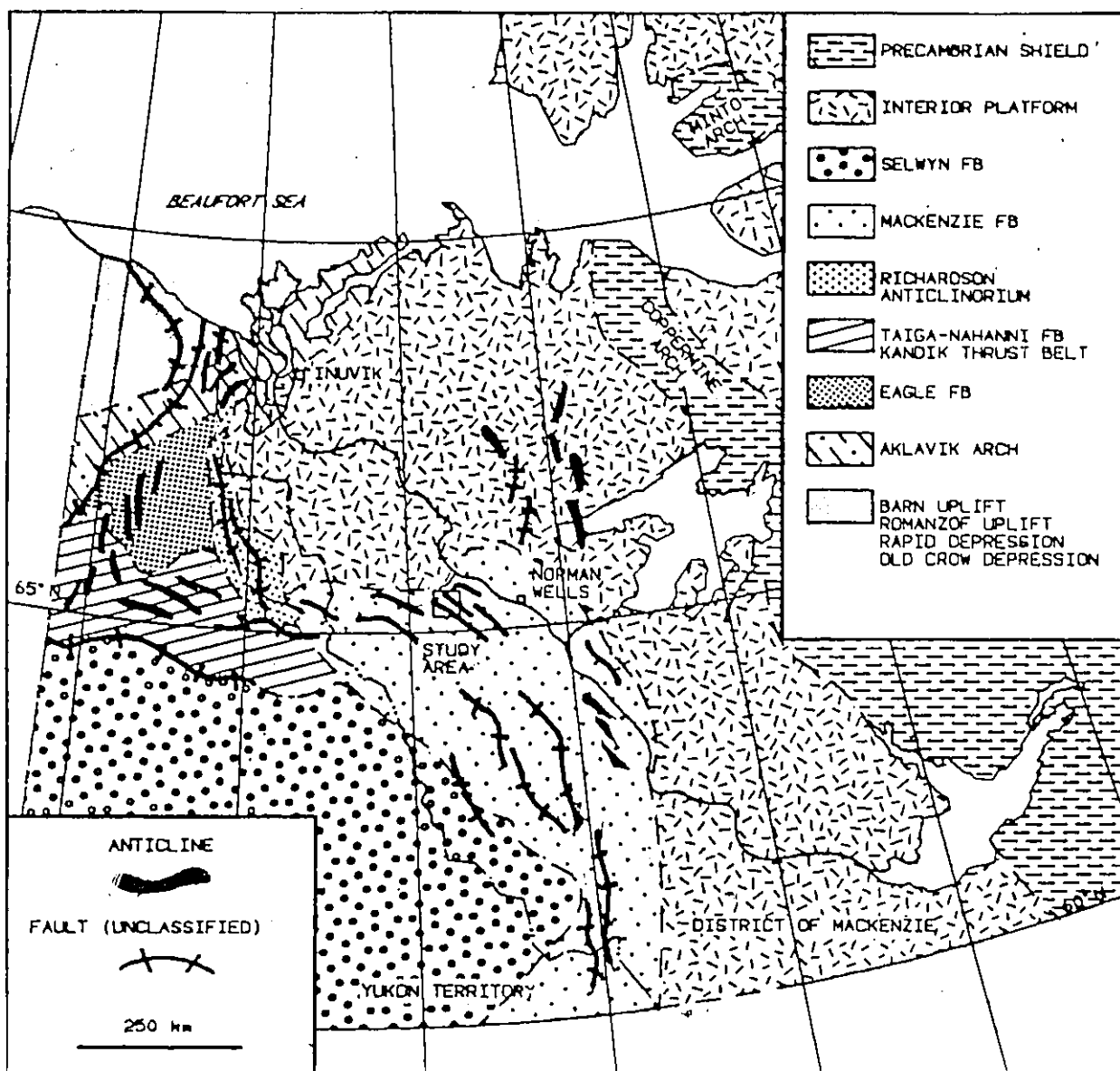


FIG. 1-3 Tectonic elements of the eastern Cordilleran Orogen of northern Canada (modified from Norris, 1985). FB = Foldbelt.

Foldbelt (Norris, 1985). The fold pattern typically displays broad, flat-topped anticlines and steep, narrow synclines up to 225 km long parallel to the Mackenzie Mountains front (Aitken et al., 1982). The exposed strata in the study area are part of the northern flank of one of these broad anticlines (Stony Anticline) in the vicinity of the Gayna Flexure (see Aitken et al., 1982). The Mackenzie Foldbelt was formed during the Late Cretaceous-Paleocene Laramide evolution of the northern Cordillera (Norris and Yorath, 1981) during which open folds and zones of complex folding and thrusting were produced by northeasterly directed compression (Cecile, 1982; Norris, 1985). Norris and Yorath (1981) suggested that the arcuate form of the fold bundles may reflect the initial curvature of the eastern margin of the Mackenzie-Rocky Mountains miogeocline. Shortening due mainly to folding was calculated to be 12.3% in the wider portions of the foldbelt (Aitken et al., 1982). Geological studies in the area of the Misty Creek Embayment approximately 250 km west of the thesis area, indicate minimum northeasterly-directed shortening and minor or no northwesterly strike-slip fault movement (Cecile, 1982). Therefore palinspastic reconstruction would result in little change in the representation of basin-platform geometry.

Regional Devonian paleogeography in the Mackenzie Mountains-Norman Wells area has been summarized by numerous authors (e.g. Hume and Link, 1945; Bassett, 1961; Bassett

and Stout, 1967; Tassonyi, 1969; Law, 1971; Gilbert, 1973; Norris and Yorath, 1981; Aitken et al., 1982; Pugh, 1983). The reader is referred to those papers for more detailed accounts than that presented below.

FIG. 1-4 delineates the major Middle Devonian paleogeographic features near the field area. Shallow water carbonates of Lower-Middle Paleozoic age predominate in the areas of the Mackenzie and Porcupine platforms. From Late Cambrian to Middle Devonian time, these cratonic shelves were tectonically stable (Pugh, 1983). Near the beginning of Givetian time, clastic wedges, represented now by the Hare Indian Formation, prograded westward and aggraded towards sea level on the Mackenzie platform (Muir and Dixon, 1984). Carbonate deposition took place locally in relatively shallow, clear water (lower portion of the Ramparts Formation). Isolated platform-reef complexes of the Ramparts Formation developed on paleotopographic highs of the Hare Indian mudbanks (Muir and Dixon, 1984, 1985).

These platform-reef complexes were terminated by major drowning events during the Late Givetian-Frasnian(?) and overlapped by Canol basinal shales or downlapped by Imperial clinotherm shales (Muir et al., 1984, 1985, 1986). Carbonate sedimentation did not resume during deposition of the remainder of the Mackenzie and Porcupine platform sequences (FIG. 1-5).

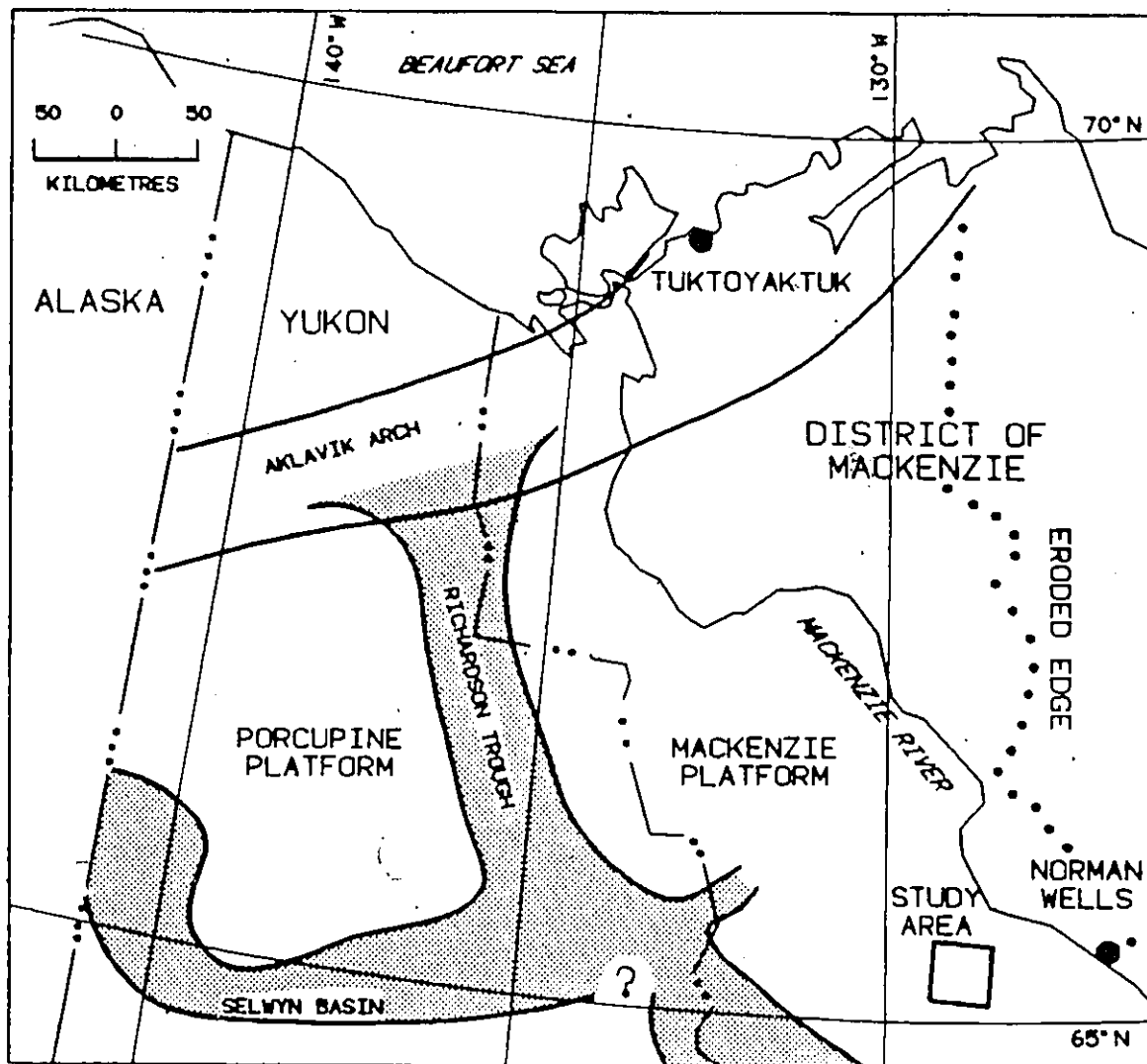


FIG. 1-4 Map showing regional Middle Devonian paleogeography (modified from Pugh, 1983; Williams, 1983; Norris, 1985). Delineation of platform margins is uncertain in the Aklavik Arch area. The Aklavik Arch complex embraces a number of smaller uplifts and structural depressions intermittently active during the Middle Paleozoic to Early Tertiary (Norris and Yorath, 1981).

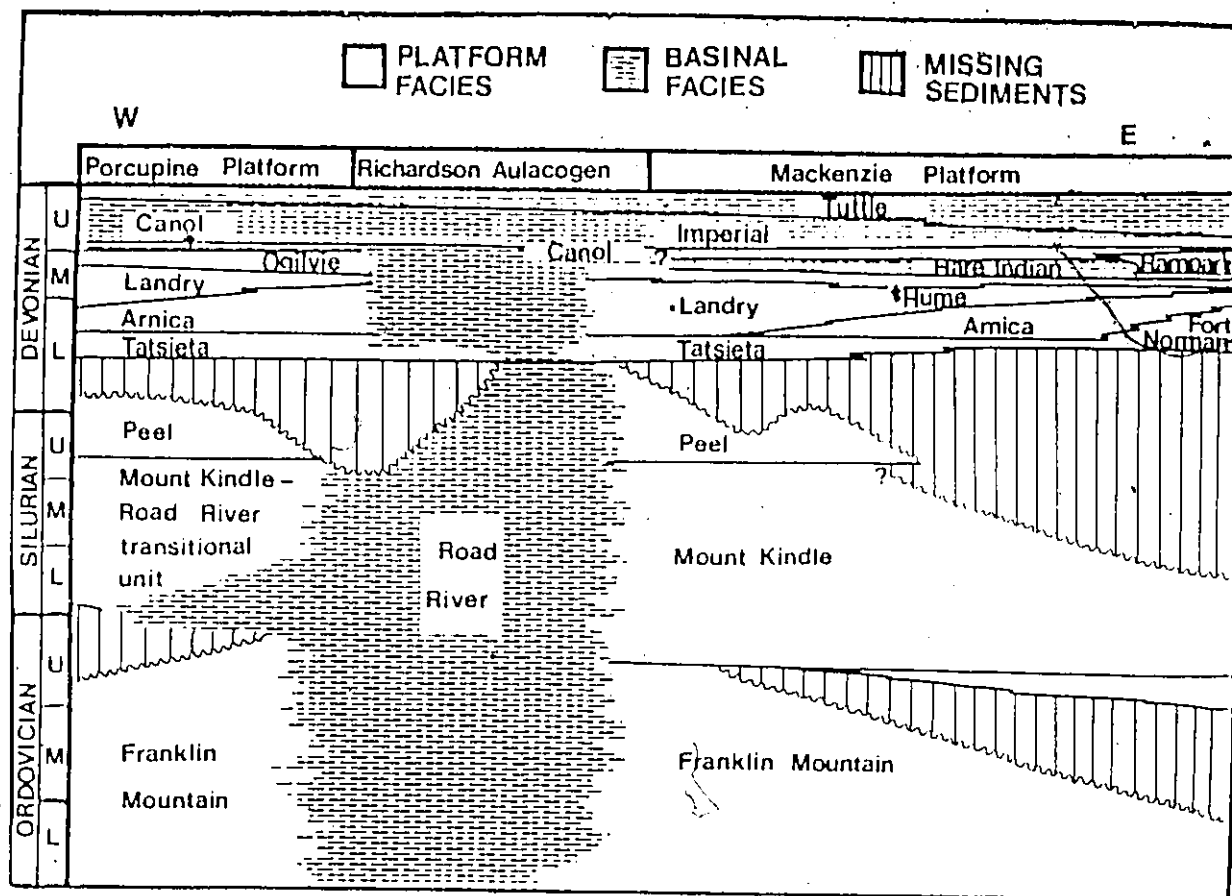


FIG. 1-5 Ordovician-Devonian platform and basin facies distribution in the Mackenzie Mountains-Richardson Mountains (modified from Pugh, 1983).

The platforms are separated by a narrow, north-south, structurally-controlled depression known as the Richardson Trough. Rocks in this structural basin range in age from at least Late Cambrian to Middle Devonian (Pugh, 1983; Norris, 1985). Thick basinal facies of the Road River Formation (Cambrian-Devonian) were deposited contemporaneously with shelf carbonates of the Mackenzie and Porcupine platforms (Pugh, 1983). The platform margin migrated back and forth through time (FIG. 1-5) but these relationships have not been studied in detail. The Richardson Fault Array is a system of mainly vertical strike-slip faults which were periodically active from Late Helikian to beginning of the Carboniferous. The faults can be traced 1000 km from the Beaufort Shelf south of Banks Island, to the southern end of the Richardson Anticlinorium. Norris and Yorath (1981) suggested that the Richardson Fault Array controlled the position, timing, and life span of the Richardson Trough. Because it is a fault-bounded intracratonic depression that persisted for at least 200 ma, the Richardson Trough may be regarded as an aulacogen (Pugh, 1983; Norris, 1985). Southward, the trough opens into the Selwyn Basin (FIG. 1-4). The Selwyn Basin encompasses a large area of Lower and Middle Paleozoic basinal facies that overlie thick successions of Proterozoic sedimentary rocks (Cecile, 1982). Northward, the Richardson Trough widens so that the eastern edge of the Porcupine platform is approximately in the

position of the Aklavik arch complex (Norris, 1985). The western edge of the Mackenzie platform (eastern trough margin) appears to follow a northwest-trending curvilinear fault trace onto the Holocene shelf (Norris, 1985). Some authors have suggested that the Richardson Trough was once linked to the northeast-southwest trending Hazen Trough of the Arctic Archipelago (Miall, 1976; Norris and Yorath, 1981; Pugh, 1983; Norris, 1985). Upper Devonian Canol and Imperial turbidite sequences have been recognized on the northern mainland east of the Mackenzie Delta (Norris, 1985). Coeval nearshore equivalents of the Melville Island Group are exposed on Banks Island. During the Late Devonian, thick basin-fill sequences of the Imperial and Tuttle Formations (FIG. 1-5) prograded southward and southwestward (Pugh, 1983) across the Mackenzie and Porcupine platforms, and a regional south-dipping paleoslope was established.

1.5 REVIEW OF STRATIGRAPHIC NOMENCLATURE

Studies of the Hare Indian and Ramparts Formations are too numerous to document fully here. This section summarizes the development of stratigraphic terms applied to the studied sequences. More comprehensive reviews of the stratigraphic nomenclature can be found in Caldwell (1964),

Tassonyi (1969), Crickmay (1970), Pugh (1983), and Johnson et al. (1985).

Kindle and Bosworth (1921) first used the name Hare Indian in a stratigraphic sense as the "Hare Indian River Shale". They described the uppermost 30 m of the clastic sequence at the north end of the Ramparts Narrows on the Mackenzie River. Unfortunately, the formation is heterogeneous (Muir and Dixon, 1984) and therefore reference sections are required to illustrate features not exposed in the type section.

The Hare Indian sequence tends to weather recessively. It abruptly, but conformably, overlies limestone of the Hume Formation (Bassett, 1961). The lower 2-20 m of the Hare Indian Formation was informally named the "spore-bearing member" by Tassonyi (1969). This lower member is characterized by slightly calcareous, fissile, brown-black bituminous shale (Aitken et al., 1982) which grades into grey-green shale of the upper member (Pugh, 1983). Tassonyi (1969, p. 71) reported that "R.J. Kirker referred to this unit [the lower member] as the 'Bluefish Member' in his presidential address in 1962 to the Alberta Society of Petroleum Geologists. Unfortunately, the type section of this member at Bluefish Creek, a tributary of the Hare Indian River, is a poor exposure. Moreover, in the Norman Wells-Fort Good Hope area there are two Bluefish Creeks." Pugh (1983) reinstated the geographic name for the unit by

proposing the Powell Creek section. He noted that because the Powell Creek section is in the same general area as the two Bluefish Creeks, the name "Bluefish Member" can be applied. However, the ~~proposed~~ type section has not been published and the upper contact of the Bluefish Member is not exposed there.

The upper member ("grey shale member" in Pugh, 1983) generally grades upwards from slightly calcareous, non-silty, green-grey shale at the base, to grey, calcareous, silty shale and calcisiltite at the top of thicker sections (Pugh, 1983; Muir and Dixon, 1984). The top of the member is recognized by the following criteria, outlined by Bassett (1961), Tassonyi (1969), and Pugh (1983):

- (1) Where overlain by Ramparts limestone, the upper boundary is gradational and diachronous, and the contact is arbitrarily placed where limestone becomes predominant up-section (PL. 1-1b).
- (2) Where overlain by Canol black shale, the contact is sharp and obvious, as the underlying Hare Indian sequence is calcareous and grey-green (PL. 1-1c). However, Pugh (1983) noted that the contact may be difficult to recognize where the Hare Indian shale is dark and slightly bituminous.

A few workers have erroneously based the Hare Indian Ramparts boundary on faunal content. Braun (1978) placed

the Hare Indian-Ramparts contact at the bottom of a microfossil (ostracodes) zone slightly below the beds that contain diagnostic brachiopods of the Stringocephalus group. However, lithostratigraphy must be based on rock types rather than fossil indicators. Benthic faunas, in particular, can show marked, ecologically-controlled distribution unrelated to lithology and are, thus, a poor basis for regional lithostratigraphic correlation.

The term "Ramparts" was first used by Isbister (1855, p. 511) to describe "the limestone of the Ramparts" which he noted "...appears again lower down [the Mackenzie River] at a spot called the Narrows and is continued in a westerly direction to the Rocky [Mackenzie] Mountains." Kindle and Bosworth (1921, p. 45B-46B) defined the type section of the Ramparts limestone where there are "...excellent exposures of it in the Ramparts section [Ramparts Narrows]...[lying] between the Hare Indian River shales below and the Cretaceous shales above." Caldwell (1964) and Tassonyi (1969) amended this definition to include the limestones lying above the Hare Indian Formation and below the Canol Formation. Bassett (1961, p. 492) proposed that the term Ramparts be replaced by Kee Scarp as the former had been used to designate a sequence of Mississippian rocks in the Yukon-Alaska area prior to Kindle and Bosworth's (1921) study. Bassett (1961) obtained the name Kee Scarp from a well-known outcrop 10 km east of Norman Wells. Caldwell

(1964) and Tassonyi (1969) rejected Bassett's proposal for the following reasons:

- (1) The Kee Scarp type section was described only in unpublished reports (cf. Caldwell, 1964).
- (2) The Kee Scarp section is incompletely exposed with no formational contacts, and biostratigraphic zonation is poorly established. Lenz (1961) indicated that the Kee Scarp section is younger (based on brachiopod biostratigraphy) and more "reefold" than the Ramparts section.
- (3) There is little justification for dropping the name Ramparts because it was preoccupied. Tassonyi (1969, p. 78) suggested that the Devonian Ramparts Formation is unlikely to be confused with the Mississippian Ramparts group in the U.S.A. despite the similarity of the names.

Kee Scarp has continued to be used as the informal name of the nearby producing Ramparts buildup at Norman Wells (Muir et al., 1984). Tassonyi (1969, p. 80) recognized two informal members within the Ramparts Formation. His lower "platform member" is characterized by well-bedded, brown argillaceous limestone and shale interbeds. Tassonyi (1969) recognized a 6 m thick "sequence of interbedded dark limestone and shale on Carcajou Ridge" (ibid., p. 81) for which he suggested the name "Carcajou Marker". This unit separates the two informal members at that locality and was,

included by Tassonyi in the platform member. The Carcajou Marker has not been recognized in all sections through the Ramparts Formation (e.g. Tassonyi, 1969; Crickmay, 1970; Pugh, 1983). However, Muir et al. (1984) recognized facies changes within what is termed herein the Carcajou subfacies which appear to have been depositionally controlled by antecedent paleotopography. Thus the Carcajou Marker may have been inadvertently missed by previous workers. Pugh (1983, p. 36) rightly points out that a more detailed study of this marker is required to ascertain its stratigraphic significance. Chapter 2 elaborates further on the Carcajou Marker.

The overlying "reef member" consists "...generally of massive, clean, light grey to light buff limestones characterized by digitate and tabular corals and stromatoporoids..." (Tassonyi, 1969, p. 80).

The lower Ramparts contact with the Hare Indian Formation is gradational and conformable. Aitken et al. (1982) observed that the platform member grades laterally into the Hare Indian Formation in the surface and subsurface, whereas this was not observed for the reef member. The upper Ramparts contact has been described frequently as an erosional unconformity formed during brief uplift and erosion (see Warren and Stelck, 1962; Bassett and Stout, 1968; Gilbert, 1973; and Braun, 1966, 1977, 1978). This interprets the Canol shales as entirely post-Ramparts reef.

Most of these authors cited paleontological evidence for Canol sediments directly overlying truncated Lower-Middle Devonian sequences west of the study area.

Braun (1977) reported the Canol Formation resting directly upon the Hume Formation in the vicinity of Snake River. His conclusion was based on missing ostracode faunal zones which he attributed to a pre-Canol erosional truncation of the Ramparts and the Hare Indian Formations. However, Muir and Dixon (1984) observed that Canol shale both intertongues (PL. 1-2a) with, and onlaps (PLS. 1-2b, 2c) the Ramparts Formation in the study area and in the Norman Wells subsurface. These relationships indicate that the Canol Formation is partly time-equivalent to, and partly postdates, the "reef member" of the Ramparts Formation. Evidently the faunal zones reported missing by earlier workers may instead reflect the presence of condensed sequences caused by slow rates of basinal sedimentation. Furthermore, some faunal elements utilized in biostratigraphic studies may have had ecologic constraints which prevented widespread distribution. Braun (1977, p. 71) noted that "...dark-colored shales were deposited over wide areas of the Northwest Territories during the early part of the Givetian [Bluefish Member].... No ostracodes are to be expected in this type of facies, nor have any been found to date, except for dwarfed and pyritized fragments."

Lenz and Pedder (1972), Johnson et al. (1985), and Uyeno (pers. comm., 1986) suggested that there is no evidence for a major hiatus between the Ramparts and Canol Formations in the off-reef section at Powell Creek (01). Thicker sections of Ramparts Formation (Pugh, 1983) may be overlain by the Imperial Formation (sections 08, 31, 20). However, there is no evidence for subaerial exposure (Muir et al., 1984, 1985) at the Ramparts-Imperial contact. Furthermore, Imperial quartz arenite resting on the Ramparts Formation does not contain carbonate clasts. Hills et al. (1984) suggested that the absence of carbonate clasts in the sandstone indicates that little or no erosion took place on the Ramparts high prior to downlapping of Imperial strata.

1.6 HARE INDIAN FORMATION

1.6.1 General Statement

The Hare Indian Formation is a detrital unit composed of mixed siliciclastic and carbonate lithologies. Two members are recognized (see section 1.6.3). The Bluefish Member (FIG. 1-6) abruptly but conformably overlies the limestone-shale sequence of the Hume Formation (PL. 1-2d). The upper part of the Hare Indian Formation, referred to here informally as the "upper member" (Muir et al., 1984, 1985), is gradational from the Bluefish Member into the

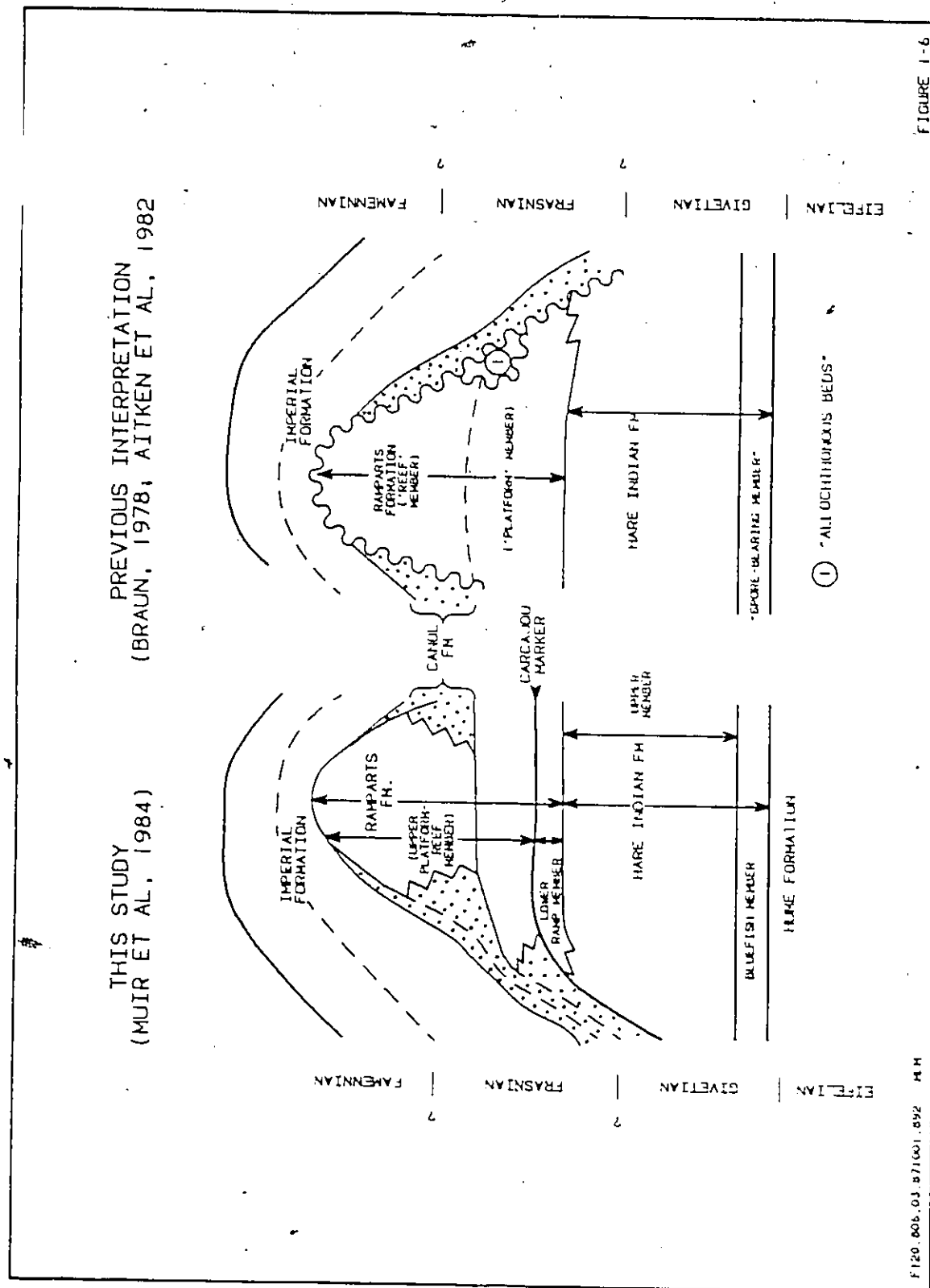


FIG. 1-6 Middle and Upper Devonian stratigraphy in the study area.

Ramparts Formation. The upper contact is arbitrarily placed where limestone becomes predominant up-section. However, where the Ramparts is absent, the upper member is abruptly overlain by Canol shale (PL. 1-1c) or Cretaceous strata.

1.6.2 Distribution and Thickness

The distribution of the Hare Indian Formation is shown in FIG. 1-7. Regionally the formation thins (FIGS. 1-8, 1-9) westward. The Bluefish Member apparently extends westward and southward beyond these limits of upper member distribution. It can be distinguished from the younger Canol shale by the following criteria (Pugh, 1983; Muir and Dixon, 1984, 1985):

- (1) Lithic characteristics - the shales are dark, bituminous, slightly calcareous, and contain little jarosite (a sulphate weathering product after sulphide) compared to siliceous shales of the Canol Formation.
- (2) Electric log character - typically the Bluefish sequence gives higher, much more erratic gamma ray and sonic log responses than the Canol shales.
- (3) Faunal content - fossils are sparse in the Canol Formation, but more abundant and diverse in the Bluefish Member (see Chapter 3).

The Bluefish Member has a probable western limit at approximately 132°W longitude (MacKenzie, 1972) and averages

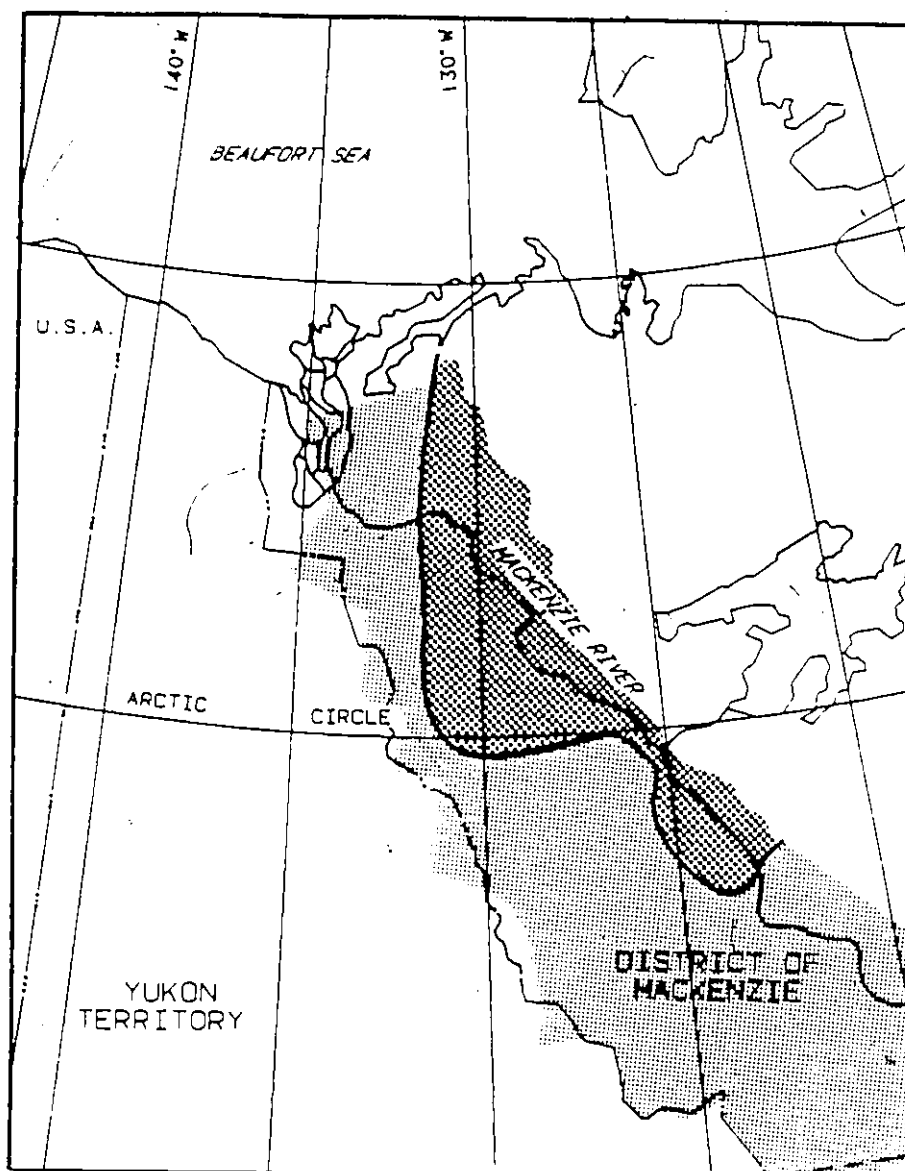


FIG. 1-7 Distribution of the Hare Indian Formation (modified after Williams, 1985). Fine stippled pattern indicates Hare Indian upper member distribution. Coarse stippled pattern indicates undifferentiated Hare Indian Bluefish Member-Canol Formation distribution where Hare Indian upper member-Ramparts succession is absent.

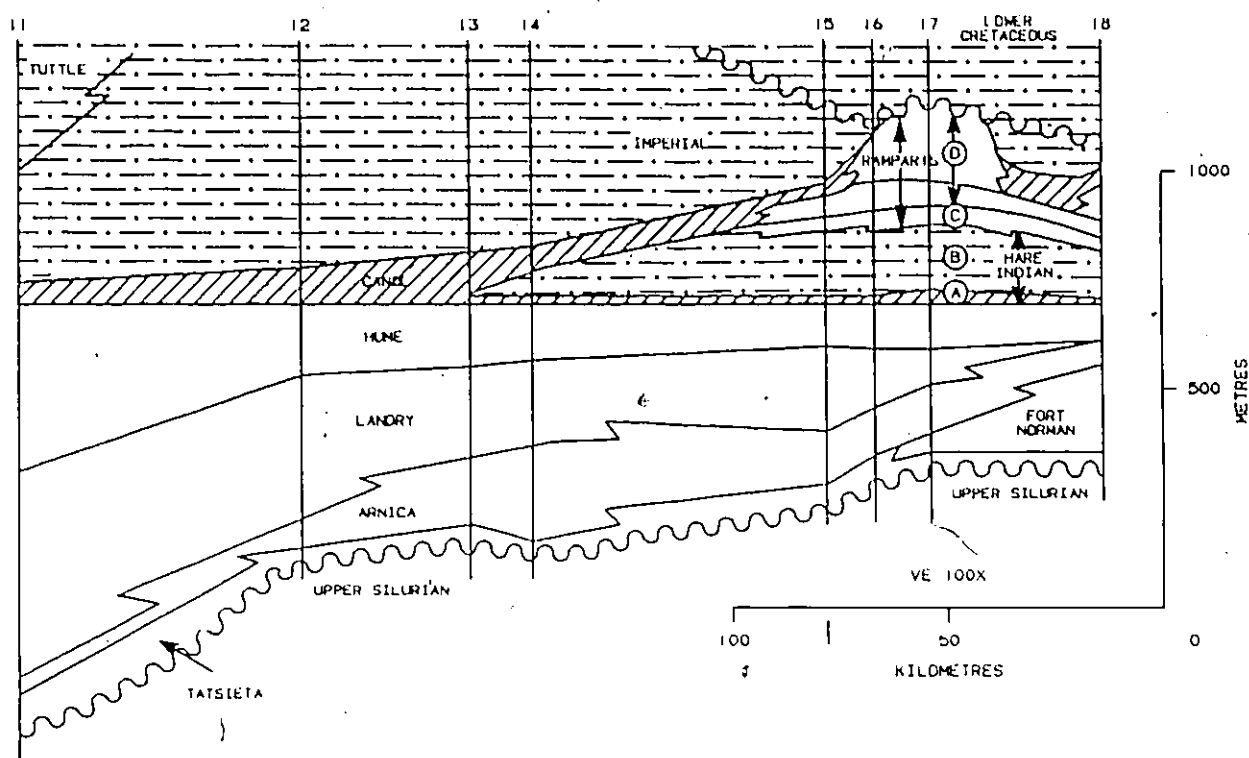


FIG. 1-8 Stratigraphic correlation based on wells (11-18) along an east-west transect approximately 20 km north of study area (see FIG. 1-2).

- (a) Hare Indian Formation, Bluefish Member; thins westward to 8 m at 11 (Amoco B-1 Cranswick A-42).
- (b) Hare Indian Formation, upper member.
- (c) Ramparts Formation, lower "ramp" member.
- (d) Ramparts Formation, upper "platform-reef" member.

Modified after Pugh (1983) using top of Hume Formation as datum instead of base of Canol Formation. Stippled pattern - siliciclastic facies; oblique ruling - organic-rich, laminated shale; blank area - carbonate facies.

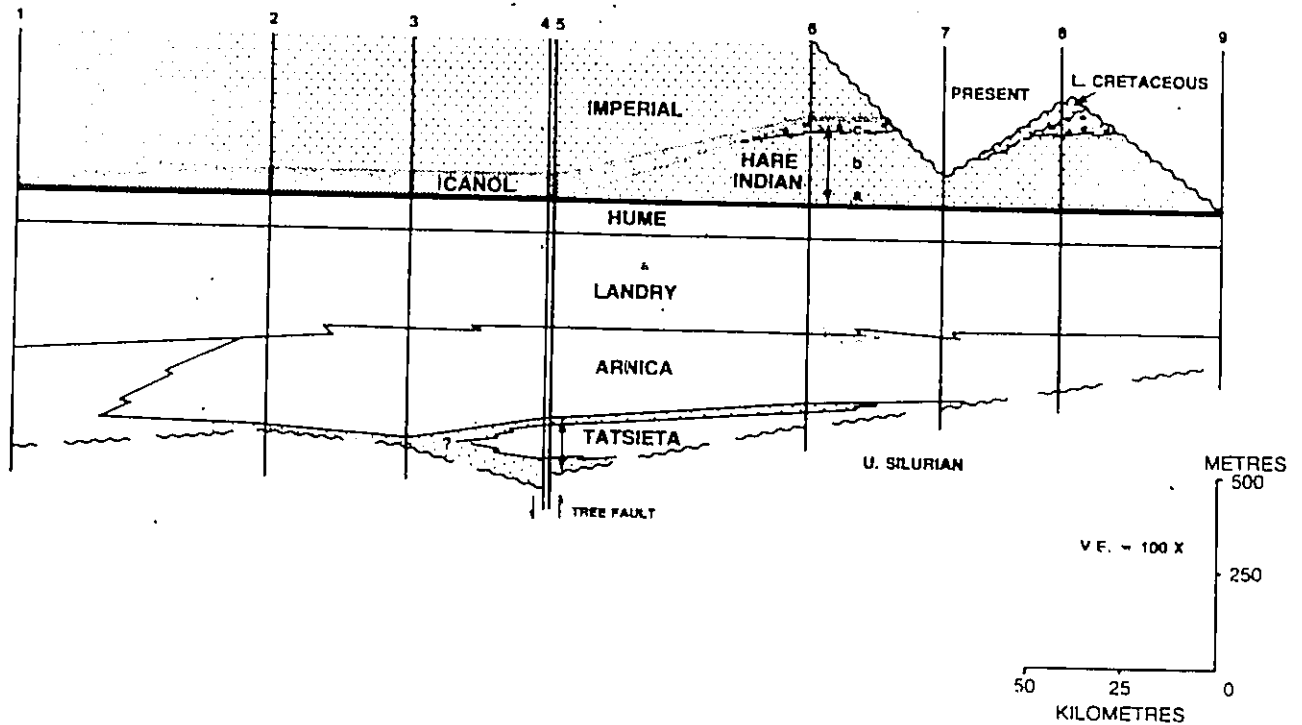


FIG. 1-9 Stratigraphic correlation based on wells (1-9) along an east-west transect approximately 200 km north of study area (see FIG. 1-2).

(a) Hare Indian Formation, Bluefish Member; thins westward to 2 m at 1 (Union McPherson B-25).

(b) Hare Indian Formation, upper member; note westward thinning.

(c) Hare Indian Formation, upper member; quartz arenite unit.

Modified after Pugh (1983) using top of Hume Formation as datum instead of base of Canol Formation. Stippled pattern - siliciclastic facies; dark pattern - organic-rich, laminated shale; blank area - carbonate facies.

roughly 15 m in thickness east of 131°W longitude (Pugh, 1983, p. 33). The member thins westward to 2 m at the Union McPherson (B-25) well (1 in FIGS. 1-2, 1-9), the most westerly indication of Bluefish beds on electric logs, according to Pugh (1983).

In the study area (FIG. 1-10), the Hare Indian Formation attains a maximum thickness of 189 m (section 15) and thins eastward to 55 m (section 25) over a distance of 41 km. Thickness variations in the Hare Indian Formation are primarily a function of:

- (1) depositional thinning westward and southward (Muir et al., 1984, 1985, 1986; Chapter 2 in this thesis).
- (2) facies change of the Hare Indian upper member into the lower "ramp" member of the Ramparts Formation (Aitken et al., 1982).

1.6.3 Lithostratigraphy

The general distribution of lithology types is shown in FIG. 1-11, and the Hare Indian lithofacies are examined in much more detail in Chapter 3.

The Bluefish Member consists of dark brown, slightly calcareous, bituminous shale which tends to be more fissile and recessive towards the top of the member with a concomitant decrease in carbonate content (Muir and Dixon, 1984). Thin (average 2 cm thick), horizontally-laminated

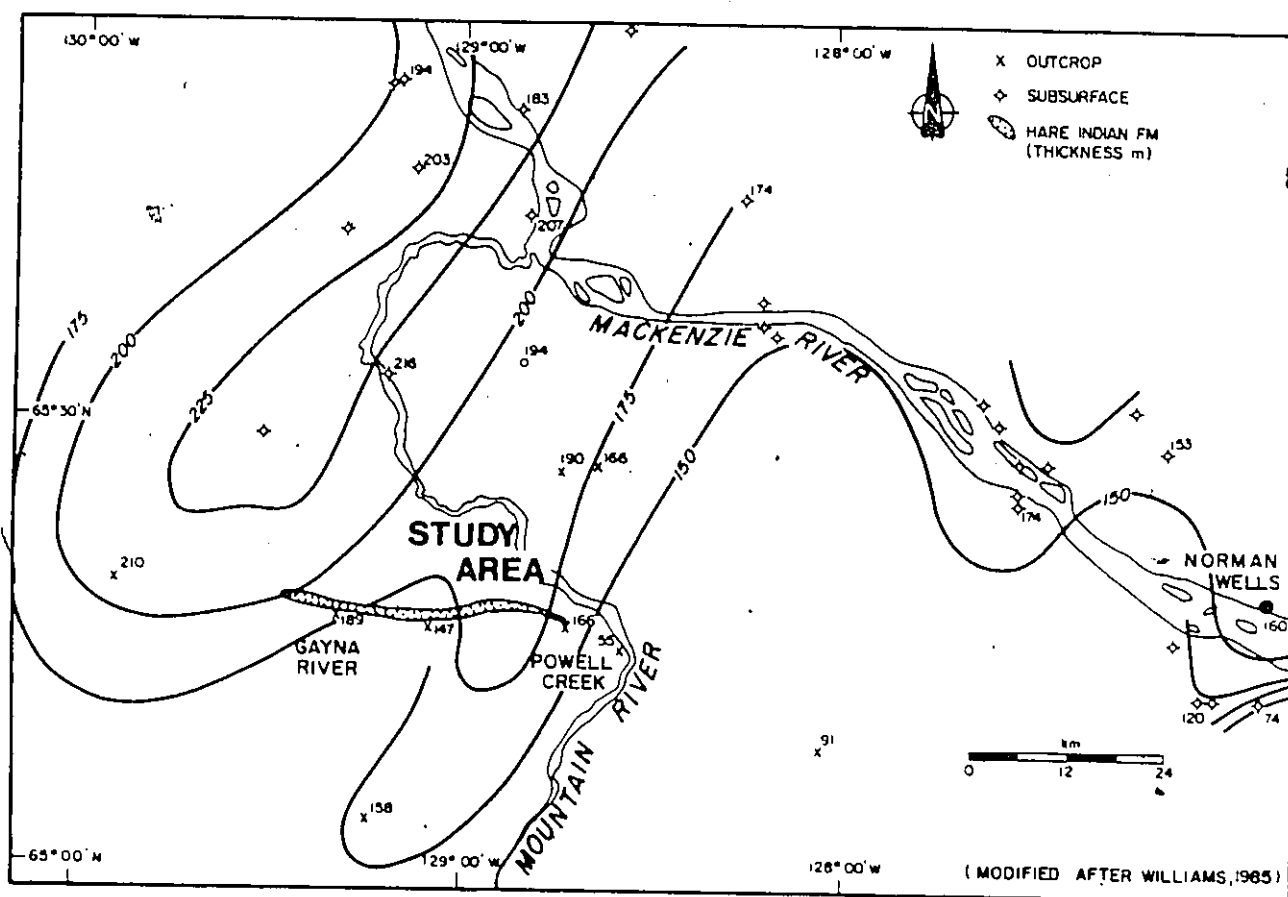


FIG. 1-10 Distribution and thickness of the Hare Indian Formation in the study area.

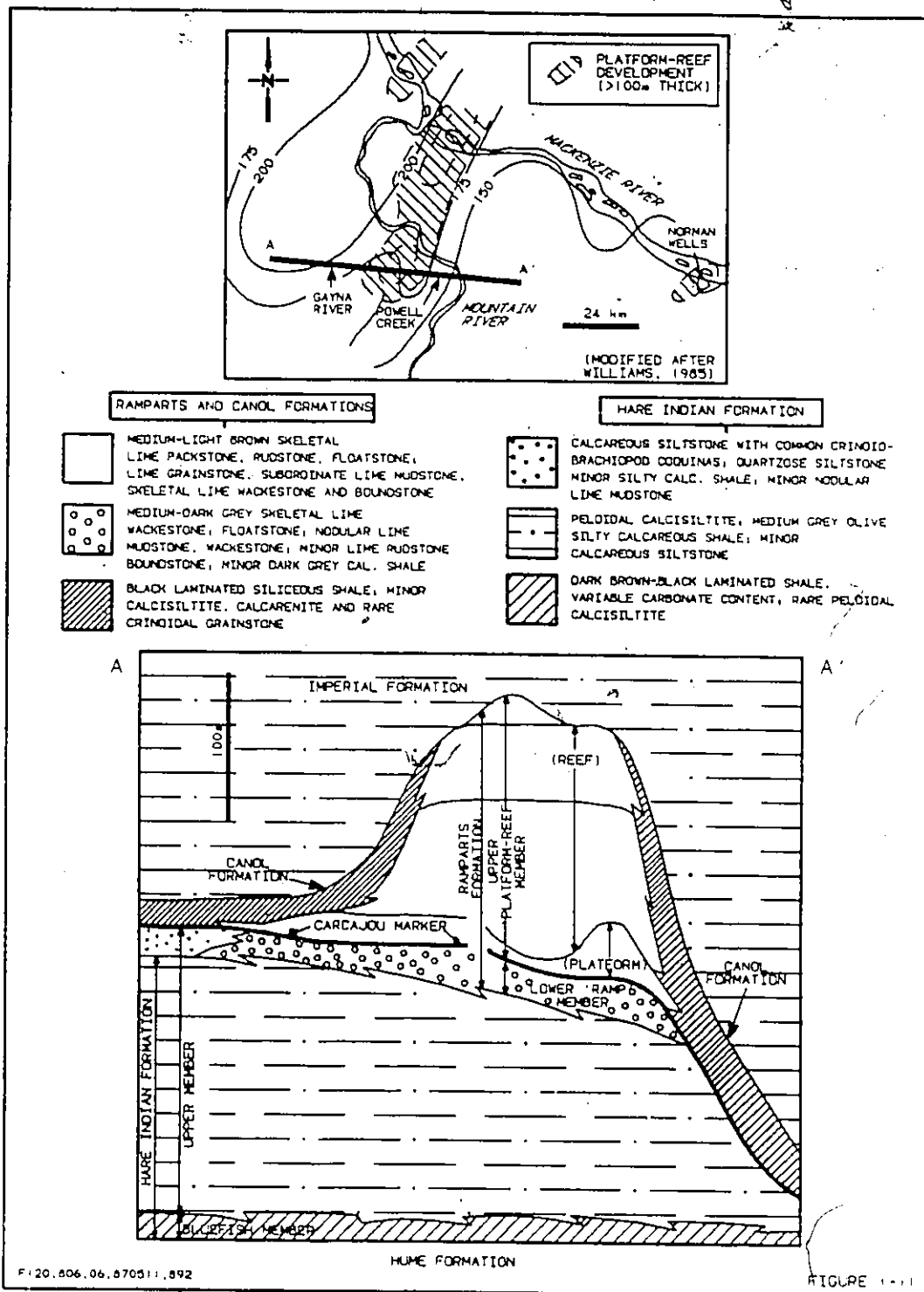


FIG. 1-11 Lithostratigraphic chart showing distribution of major lithologies in study area. Detailed facies distributions are illustrated in relevant portions of this thesis. Hare Indian isopach thick indicated in meters.

calcsiltite beds and concretions are present rarely. In addition, 1-5 cm thick beds of fibrous calcite (MacKenzie, 1972) showing cone-in-cone structure appear to be restricted to the lower portion of the Bluefish Member. Common fossils include: Styliolina, Tentaculites, bivalves, crinoids, ammonoids, and plant debris including the algocysts Leiosphaeridia and Tasmanites. Basal contacts and major lithological and faunal variations in the Bluefish Member are illustrated in FIG: 1-12, a reference section exposed on the Gayna River. Small, coarsening-upward cycles (3 m) composed of shale to silty shale with rare calcsiltite beds and an overall lightening-upward trend characterize the upper portion of the Bluefish Member at this locality (PL. 1-3a).

The upper member of the Hare Indian Formation consists of interbedded, green-grey calcareous shale, marl, grey calcsiltite, rare calcareous siltstone beds, and quartz arenite. The sequence coarsens upward with increasing silt content (Tassonyi, 1969) and a more abundant and diverse fauna towards the top of the formation (FIG. 1-13). Pugh (1983) documented a distinct upward color change for shales from more than 30 borehole sections: from dark brown-grey to grey, green-grey or buff-grey, and then to pale grey shales in thicker Hare Indian sections. He noted (ibid., 1983) that these shales tend to be non-calcareous and non-silty, grading to micaceous, calcareous, silty shales

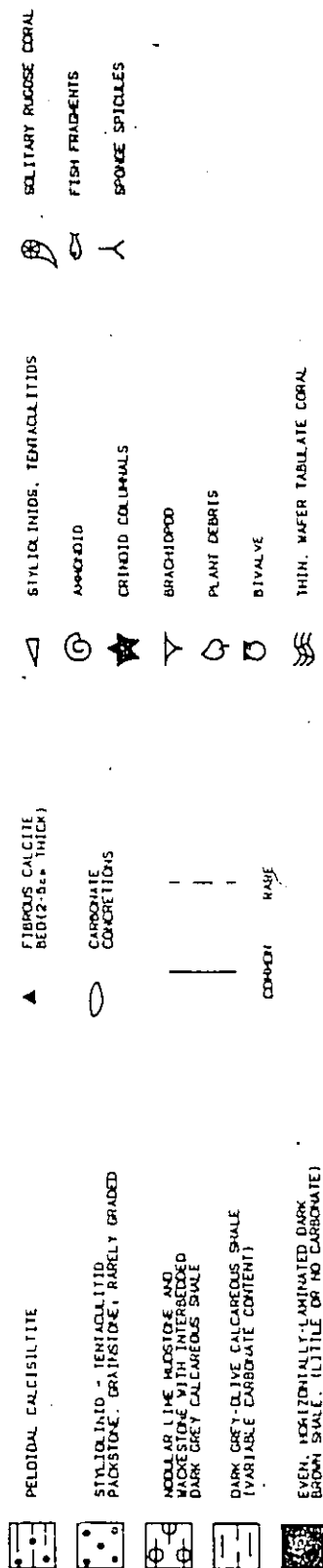
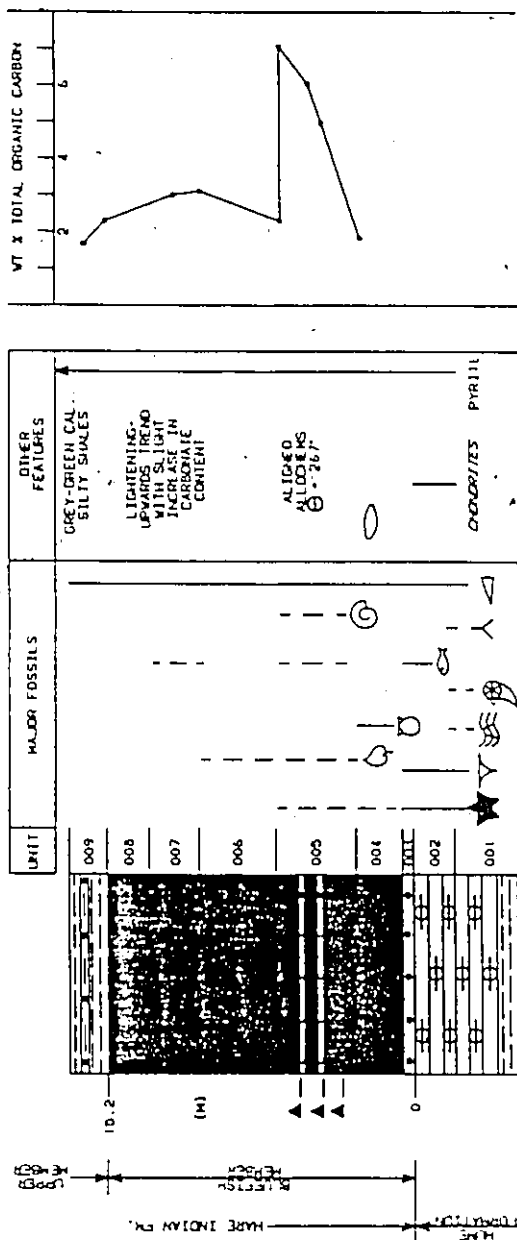


FIG. 1-12 Reference section for the Bluefish Member at Gayna River (section 15).

FIG. 1-13 Reference section for the Hare Indian upper member at West Powell Creek (section 07). Conodont listing in Appendix A.

towards the top. Muir and Dixon (1984) and Muir et al. (1984, 1985) recognized that the upper member is organized in cycles typically 10-25 m thick (PL. 1-3b). Thicker cycles are characterized by a thinner, shaley lower portion and thicker limestone upper portion. The calcisiltite beds are normally 3-10 cm thick and consist of peloidal (altered skeletal) packstone with a high percentage of clay minerals and only rarely occurring identifiable skeletal constituents (mainly a brachiopod-crinoid fauna, TABLE 1-1). Muir and Dixon (1984) observed that these cycles are less obvious towards thicker lobes of the Hare Indian Formation (e.g. sections 15, 16, PL. 1-1b) where shale is more subordinate to silty limestone and calcareous siltstone, and hence lithologic contrasts are not as marked (Pugh, 1983 - siltstone lentil).

Calcareous siltstone, coquinoid lime rudstone, and nodular lime mudstone and wackestone are common towards the top of the Hare Indian Formation. Pugh (1983) observed lateral interfingering or intergrading of siltstone-dominated facies with the lower "ramp" member of the Ramparts Formation (see FIG. 1-11). Pugh (1983) noted that these siltstones grade northward outside the study area into quartz arenite (FIG. 1-9). Tassonyi (1969) recognized this facies (maximum thickness 20 m in the Richfield et al., Grandview Hills No. 1 well) in the Gossage River area where it caps the lower "ramp" member of the Ramparts Formation.

TABLE 1-1.

Macrofossils from uppermost Hare Indian Formation. List compiled from Cook and Aitken, 1971; Pedder, 1975; Aitken et al., 1982; Pugh, 1983; and author's own observations.

BRACHIOPODS	CORALS
<u>Ambocoelia meristoides</u>	<u>Alveolites</u>
<u>Warrenella kirki</u>	<u>Grypophyllum</u>
<u>Leiorhynchus castanea</u>	<u>Tabulophyllum</u>
<u>Schizophoria cf. allani</u>	
<u>Rensellandia</u>	CRINOIDS
<u>"Schuchertella"</u>	columnals and
<u>Atrypa</u>	ambulacral segments
<u>Cyrtina</u>	
<u>Spinatrypa</u>	OTHER
<u>Emanuella</u>	plant fragments, fish
productid spines	fragments, encrusting
	and branching bryozoa,
OSTRACODES	orthoconic nautiloid,
	gastropods
DACRICONARIDS	
<u>Styliolina</u>	
<u>Tentaculites</u>	

The quartz arenite unit is areally restricted to Hare Indian lobe isopach thicks. Pugh (1983) suggested that the quartz arenite unit may be a siliciclastic facies contemporaneous with the lower "ramp" member of the Ramparts Formation based on stratigraphic position and biostratigraphic data (MacKenzie et al., 1975).

1.6.4 Age

Previously, a brachiopod-coral zonal scheme was used for Devonian rocks in the Mackenzie Mountains-Norman Wells area (see Lenz and Pedder, 1972). However, the fact that these faunas are commonly facies controlled limits their reliability for precise, long range correlation. In an attempt to achieve more precise age information, 177 samples from the Hume-Hare Indian-Ramparts-Canol succession were submitted to Dr. Tom Uyeno (Geological Survey of Canada) for conodont identification. His conodont faunal listings and designated conodont zones are tabulated in Appendix A, and the major biostratigraphic zones are shown in FIG. 1-14.

The uppermost beds (6 m) of the Hume Formation (sections 01, 03, 15) contain conodonts assigned to the Polygnathus pseudofoliatus zone (Johnson et al., 1985). This interval also coincides with the brachiopod Leiorhynchus castanea zone which Pedder (in Lenz and Pedder, 1972, p. 35) regarded as Givetian.

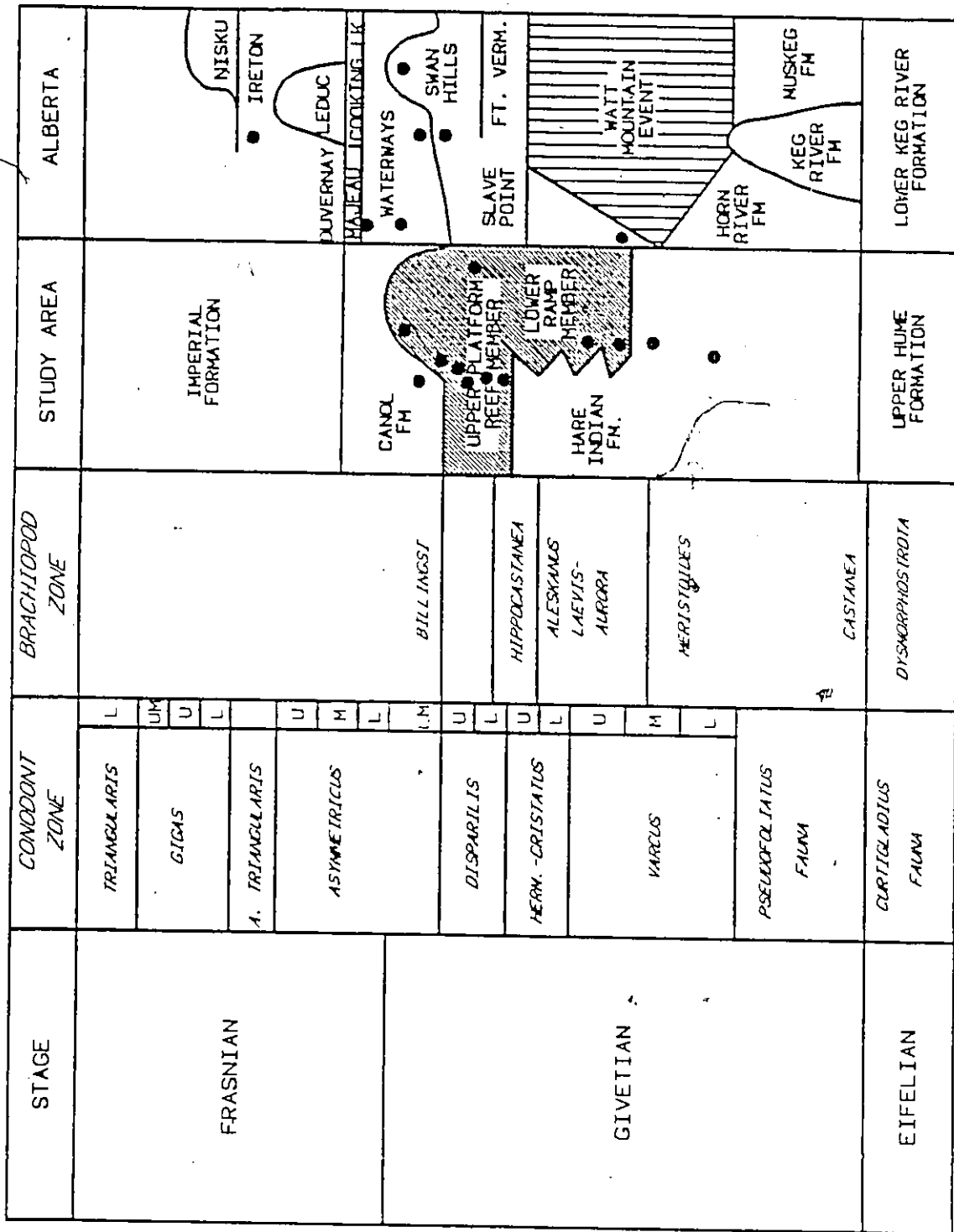


FIG. 1-14 Time-rock transect of some Devonian rocks in northern Alberta and study area. Black dots indicate conodont control (Uyeno, 1985, pers. comm.; Johnson et al., 1985). Modified after Johnson et al. (1985). Erosional Watt Mountain event more fully documented in Williams (1984).

The Bluefish Member of the Hare Indian Formation contains a non-diagnostic conodont fauna in the study area (Uyeno, 1978) including: Polygnathus parawebbi (late form), P. linguiformis linguiformis, P. cf. P. xylus, P. parawebbi, Icriodus sp., and Belodella sp. The ammonoid Cabrieroceras karpinskyi is present in concretions near the base of the Bluefish Member. The ammonoid is considered to be a middle to upper Givetian fossil by House (in House and Pedder, 1963).

The middle portion of the Hare Indian Formation (15-130 m above base at sections 01, 07) is barren of conodonts and zonal megafossils in the study area (Uyeno, 1978, and this study). Conodonts assigned to the middle Polygnathus varcus subzone occur 5.5 m below the top of the 165.5 m thick Hare Indian Formation in section 01, Powell Creek. This subzone corresponds with the brachiopod Rensellandia laevis zone (Pedder, 1975, p. 573) approximately 2 m below the top of the 183 m thick Hare Indian Formation at section 15, Gayna River.

The quartz arenite unit north of the study area in the Grandview Hills represents the youngest Hare Indian strata exposed in the region. Uyeno (in MacKenzie et al., 1975) identified a Polygnathus varcus (undivided) conodont assemblage in the unit based on the presence of: Icriodus eslaenis, Pelekysgnathus n. sp., Polygnathus pseudofoliatus, P. xylus, P. varcus, P. decorosus, P. linguiformis, and P.

pennatus. However, a late Givetian age is suggested by a brachiopod fauna representing the Stringocephalus aleskanus zone and Leiorhynchus hippocastanea zone (Pedder, 1975).

1.7 RAMPARTS FORMATION

1.7.1 General Statement

Two informal members can be recognized and mapped in the Ramparts Formation in the study area. The lower "ramp" (previously the "platform member" in Tassonyi, 1969, and Braun, 1978) is a well-bedded, argillaceous limestone sequence which grades laterally into Hare Indian silty shale, calcisiltite, and calcareous siltstone (FIG. 1-11).

In this study, the Carcajou Marker is the basal portion of a 0-7 m thick dark brown shale-limestone unit informally named the Carcajou subfacies (see Chapter 2). This subfacies sharply overlies the lower member and grades into limestone lithofacies of the upper member. The Carcajou Marker, as identified by Tassonyi (1969), has been difficult to correlate due mainly to the uneven distribution of Carcajou subfacies across the lower "ramp" member, and because their constituent facies vary according to antecedent paleotopography (Muir and Dixon, 1984). The importance of recognizing the Carcajou Marker in the Ramparts succession is elaborated upon in Chapter 2.

The upper "platform-reef" member of the Ramparts Formation here includes platform, reef interior, reef margin, and reef flank facies which are typically less argillaceous than the underlying lower "ramp" member.

Johnson et al. (1985) and conodont work in this study show that there is no break in the conodont faunal succession through the Hare Indian, Ramparts, and Canol successions.

The Ramparts upper contact is abrupt and concordant where overlain by the Canol Formation (PL. 1-3c, 1-4a). The Canol Formation is commonly thin or absent over thicker sections of the Ramparts; in sections 08, 31, 20 the Imperial Formation sharply overlies the Ramparts Formation. Northeast of the study area, the Ramparts Formation is unconformably overlain by Lower Cretaceous sandstone (Aitken et al., 1982).

1.7.2 Distribution and Thickness

The distribution of the Ramparts Formation (FIG. 1-15) is distinctly related to the lobate Hare Indian distribution (cf. FIG. 1-11). The Ramparts Formation is localized on these thicker clastic wedges and is truncated eastward by Lower Cretaceous and present day unconformities. The southward extent of the Ramparts Formation is poorly known (Gilbert, 1973). Thickness variations are primarily depositional and, to a lesser degree, erosional in origin.

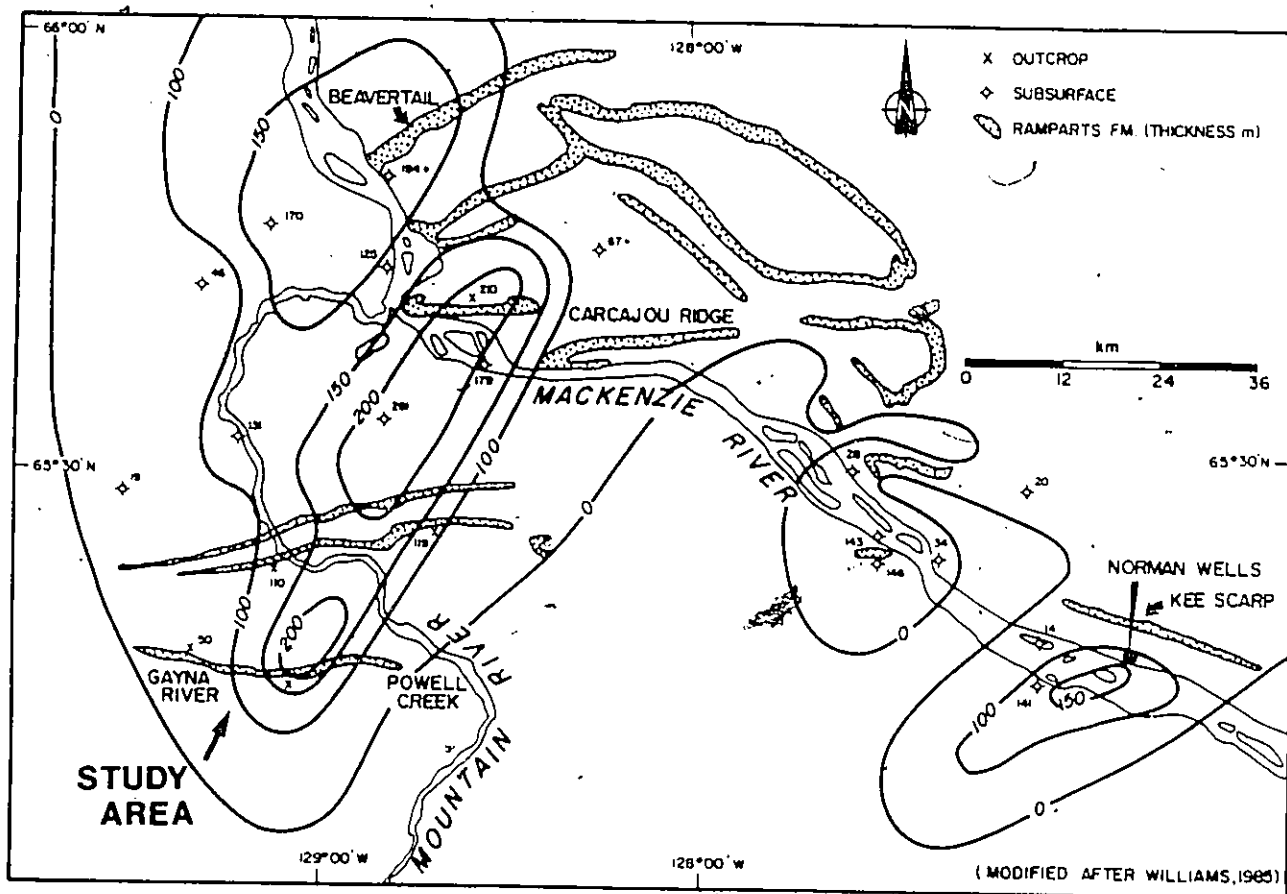


FIG. 1-15 Distribution and thickness of the Ramparts Formation in study area.

Thicker sections are typically isolated Ramparts buildups (Bassett, 1961). In the study area, the lower "ramp" member displays thickness variation from 0 m (in off-reef sections both towards a Hare Indian isopach maximum west of section 11 and basinward towards section 25 to 26 m (directly under thick platform-reef development at section 20)).

The upper "platform-reef" member consists of a lower, widespread, open-marine platform sequence that attains a maximum thickness of 57 m in the study area (Muir and Dixon, 1984). This compares with 63 m in the subsurface at Norman Wells (Muir et al., 1984). The overlying, more areally restricted, reef unit attains a maximum thickness of 160 m in the study area, but is only 90 m in the Norman Wells subsurface (Muir et al., 1985).

1.7.3 Lithostratigraphy

The major Ramparts lithology types are shown in FIG. 1-11. The Ramparts Formation is so heterogeneous lithologically that no one section can be considered representative.

Comprehensive correlations based on both descriptions and sedimentological principles are presented in Chapters 4 and 5. It is generally considered that lithostratigraphy is descriptive and empirical, and should not involve use of genetic modelling. However, Miall (1984) noted that more accurate correlations can be achieved if they are erected on

a sound genetic model. This is particularly true for the complex platform/reef (Ramparts) to basin (Canol) correlations where detailed sedimentology aids in understanding and predicting lithological distribution. The type section of the Ramparts Formation is restricted to ramp and platform facies without buildup facies. The Kee Scarp section appears to be younger (Lenz, 1961) and represents the lower portion of the buildup facies (Bassett, 1961; Caldwell, 1964). Previous difficulties in understanding Ramparts platform and reef development partly account for the confusing array of stratigraphic terms (cf. Tassonyi, 1969; Crickmay, 1970 for review) that evolved over the last 60 years.

The lower "ramp" member is distinguished from the upper "platform-reef" member on the basis of stratigraphic position below the Carcajou Marker (see Chapter 2) and lithology. Bioturbated, nodular, lime mudstone and wackestone with interbedded shale (PL. 1-4b) characterize the lower portion of the member. Limestone bedding tends to thicken upwards in the lower member, with a corresponding decrease in shale interbeds and increase in faunal diversity (Muir and Dixon, 1984). Calcareous quartz arenite and siltstone are common in the lower member, but are also present in the lower portion (lower platform cycles - Chapter 4) of the upper "platform-reef" member. Bedding style and shale content (PL. 1-4c) clearly distinguish the

thinly-interbedded shale-limestone sequence from the more massive, limestone-dominated, upper "platform-reef" member.

Muir et al. (1984, 1985) recognized distinct cyclic organization to Ramparts strata and this will be discussed in detail in the following chapter.

1.7.4 Age

The age of the Ramparts Formation based on brachiopod-coral biostratigraphy is middle to late Givetian (MacKenzie et al., 1975). The lower "ramp" member is associated with the Stringocephalus aleskanus zone (Pedder, in Lenz and Pedder, 1972, p. 35-36; FIG. 1-14). However, the top 2 m of the member shows a late Givetian brachiopod fauna (Leiorhynchus hippocastanea zone) and are time-equivalent to the Hare Indian quartz arenite unit reported north of the study area (Cook and Aitken, 1975). Leiorhynchus hippocastanea has also been reported in basal beds of the Carcajou subfacies by Tassonyi (1969) who noted that this fauna appeared to have favored a quiet (possibly deeper) water, more turbid environment. Lenz and Pedder (1972, p. 37) recognized the Tecnocyrtina billingsi brachiopod zone (FIG. 1-14) in the Ramparts' upper "platform-reef" member at section 01, Powell Creek ("Allochthonous Beds" in MacKenzie, 1970).

Conodonts in the lower "ramp" member belong to the middle Polygnathus varcus subzone of middle Givetian age (T.T.

Uyeno, pers. comm., 1986; see Appendix A). The Carcajou subfacies cannot be dated precisely as it is devoid of diagnostic conodonts. Uyeno^o (pers. comm., 1986) stated that, "In most sections it falls within the gap between the middle Polygnathus varcus subzone and the lower Palmatolepis disparilis zone, and at section 25 (Mountain River tributary) the Carcajou Marker may possibly be of the middle to upper varcus subzones." He (ibid.) noted that at section 01 (Powell Creek) the interval between the lower disparilis zone and the middle varcus subzone is only 9.5 m thick, and possibly represents a condensed sequence. Uyeno (ibid.) suggested that this is not totally unexpected since in the Antelope Range, Nevada, Johnson et al. (1985) found the Schmidtognathus hermanni - Polygnathus cristatus zone to be highly condensed.

Most samples from the upper "platform-reef" member are devoid of conodonts. Only off-reef sections 07, 01 and 25 yielded significant conodont collections. The youngest diagnostic conodont fauna in the Ramparts Formation was obtained in the lower reef foreslope facies at section 01, indicating a lowermost Mesotaxis asymmetricus zone of late Givetian age (see Appendix A). However, Johnson et al. (1985) reported a conodont fauna of the lower asymmetricus zone of early Frasnian age in a stratigraphically higher reef foreslope unit (possibly reef foreslope cycle 3, in Muir et al., 1986). Conodonts from 9.9 m above the base of

the Canol Formation at section 01 probably belong to the lower asymmetricus zone. The youngest conodont fauna, 2 m from the top of the Canol Formation at section 01 (01-039, Appendix A) possibly represents the middle asymmetricus zone. In section 25, approximately 11 km east of section 01, conodonts from 28.7 m above the base of the Canol Formation indicate the Palmatolepis disparilis zone. At this locality, a thick Canol succession (75.1 m) directly overlies a thin Hare Indian succession (55 m). Muir et al. (1984, 1985, 1986) suggested that a basinal depositional setting resulted from accumulation of a condensed sequence distally in the Hare Indian clastic wedge. At this locality (PL. 1-4d, e), sediments derived from Ramparts platform-reef development appear more Canol-like (laminated black siliceous shale and thinly interbedded calcisiltite) than a Ramparts-like succession. However, the Carcajou subfacies can be identified readily (PL. 1-4d).

Although tentative at present, some additional inferences may be drawn about the duration of Ramparts sedimentation in the study area. It is significant that, where the Ramparts is overlain directly by the Imperial Formation (as in section 20), reef cycles 5 and 6 are developed. These two second-order shallowing-upward cycles (see Chapter 2) are not represented in the thinner subsurface buildup at Norman Wells, where cycle 4 is succeeded conformably by Canol shale (Muir et al., 1984, 1985, 1986). Intermediate in position,

the Powell Creek area (section 01) was probably too far removed from reef cycles 4, 5, and 6 (see Chapter 2) to receive significant foreslope debris. However, the presence of these reef cycles (and a presumed topographic high) may be indicated instead by a few thin (5-10 cm) laminated calcisiltite beds distributed through the Canol Formation at Powell Creek. Common sharp-based contacts and rare graded lamination suggest a turbidite origin for these beds (PL. 1-2a, 1-4d).

If the six second-order reef cycles of the Ramparts Formation (discussed in more detail in Muir and Dixon, 1984; Muir et al., 1984; Chapters 2 and 5 in this thesis) were of similar duration, then a very approximate estimate of the duration of reef cycles 5 and 6 may be made using what is known about the duration of the earlier cycles. The Givetian and Frasnian are considered to represent time spans of 6 ma and 5 ma respectively (Harland et al., 1982). At Powell Creek, the first three reef cycles (units 025-033) span the interval from the upper part of the disparilis zone through the lower asymmetricus zone (Johnson et al., 1985, Fig. 8; this study, Appendix A). If these cycles were of similar duration (and they are a similar order of thickness), then their average duration would have been about 460,000 years. The implication, therefore, is that the 55 m of reef cycles 5 and 6 represent a significant period of Frasnian sedimentation in part post-dating the

middle asymmetricus zone and possibly coeval in part with early Imperial sedimentation. The only conodont information available is inconclusive: a sample from reef cycle 6, 363.2 m above the Hume Formation in section 31, yielded the long-ranging, non-diagnostic conodonts Icriodus difficilis, Ozarkodina brevis, and Polygnathus xylus xylus.

PLATE 1-1

Aerial view of principal sections.

- a Aerial view of eastern portion of study area; West Powell Creek (section 07) in foreground. Recessive calcareous shale and calcisiltite of Hare Indian Formation underlain by resistant limestone of Hume Formation (left) and overlain by resistant limestone of Ramparts Formation (right). Hare Indian Formation 165 m thick.
- b Aerial view of section 15, Gayna River. Dark brown, bituminous shale of the Bluefish Member sharply overlie Hume Formation and grade upwards into recessive silty calcareous shale and calcisiltite of upper Hare Indian Formation. Hare Indian grades upward into resistant limestone and minor shale of Ramparts Formation. Hare Indian Formation 189 m thick.
- c Canol siliceous black shale abruptly but conformably overlying silty calcareous shale of Hare Indian Formation. Section approximately 30 m high, on Hume River, 25 km west of section 15.
- d Undifferentiated Bluefish-Canol shales abruptly overlie Hume Formation near Francine Creek, south of Norman Wells.

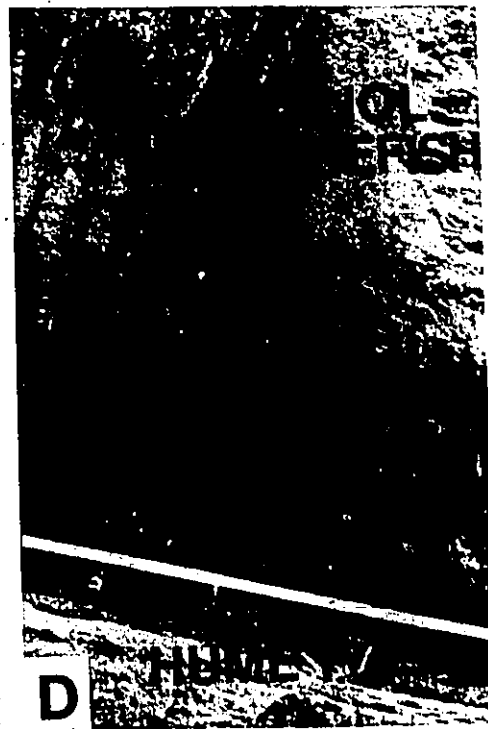


PLATE I-I

PLATE 1-2

Formation boundary relationships.

- a Canol Formation displaying intertonguing and onlapping relationships with Ramparts Formation foreslope facies. Exposure approximately 40 m high in section 01 (Powell Creek). Note thin-bedded calcisiltite bed 2 m from the top of the Canol Formation. Canol Formation overlain by Imperial Formation.
- b Canol Formation abruptly overlying reef interior facies of Ramparts Formation in Norman Wells quarry. Note bed truncation at contact (arrows). Channels floored by lag deposit - discontinuous crinoidal grainstone 5-10 cm thick. Limestone section approximately 3 m high.
- c Canol-Ramparts contact in Norman Wells quarry. Note apparent lack of karst features. Hammer, 15 cm long.
- d Hare Indian Bluefish Member (dark shale sequence) abruptly overlying shale-limestone sequence of Hume Formation (section 03).



A



B



C



D

PLATE I-2

PLATE 1-3

Hare Indian Formation boundary relationships.

- a. Hare Indian Bluefish Member reference section at Gayna River (section 15 - see also PL. 1-1b). Note abrupt basal contact and gradational upper contact. Bluefish Member 15.2 m thick. Upper portion of Bluefish Member and lower portion of Hare Indian upper member show 3-10 m thick coarsening-upward cycles (recessive shale to more resistant silty shale) which are reflected in weathering profile.
- b. Photomosaic of upper part of reference section 07 (FIG. 1-13) at West Powell Creek. Facies described in Chapters 2 and 3. Hare Indian-Ramparts contact at base of 07-016. Note cyclic organization of strata with lower shaley and upper limestone-dominated portions in each cycle. Cycle 012-013 is 17 m thick.
- c. Aerial view of Canol Formation abruptly overlying Ramparts Formation at Gayna River (section 15). Ramparts exposure approximately 30 m thick. Canol Formation grades upward into recessive silty shale of Imperial Formation.

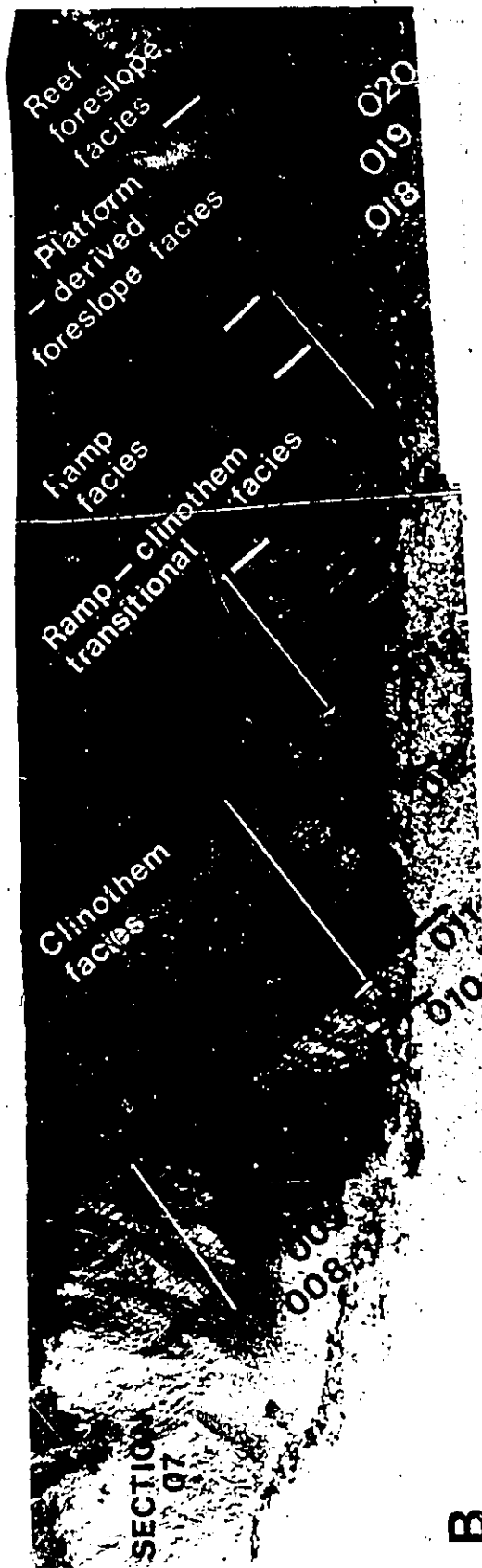


PLATE 1-4

Canol-Ramparts and Ramparts-Hare
Indian contact relationships.

- a Siliceous black shale of Canol Formation abruptly overlying Ramparts Formation at Gayna River (section 15). Bulbous alveolitid tabulate corals account for "knobby" aspect of uppermost Ramparts bedding plane.
- b Lower "ramp" member (lower and upper parts) of Ramparts Formation at Bell Creek (section 08). Note thin, nodular lime mudstone and wackestone passing upwards into thicker, biostromal beds. Sequence (26 m thick) abruptly overlain by Carcajou subfacies.
- c Aerial view of Bell Creek (section 08) exposure shown in PL. 1-4b. Note recessive nature of Hare Indian Formation underlying Ramparts lower "ramp" member. Shaley Carcajou subfacies (6 m thick) separates lower "ramp" member from more massive upper "platform-reef" member.
- d Aerial view of section 25 (Mountain River tributary). Hare Indian Formation 55 m thick. Note well-exposed Bluefish Member, Carcajou subfacies, and thick (75 m) Canol sequence. Rare, thin-bedded (5-10 cm), laterally persistent calcisiltite beds are present through the entire Canol succession.
- e Interbedded laminated siliceous black shale and calcisiltite of Canol Formation at section 25. Calcisiltite beds interpreted as turbidites derived from coeval Ramparts platform-reef. Scale 15 cm.

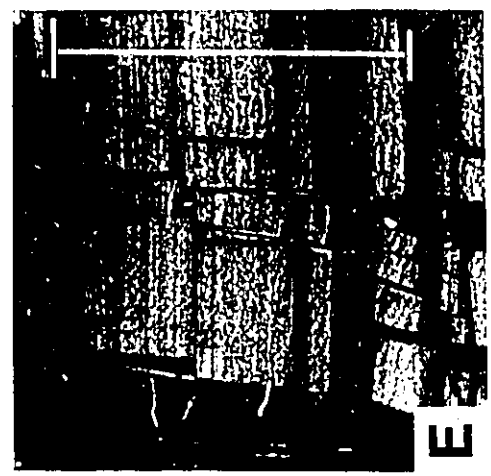
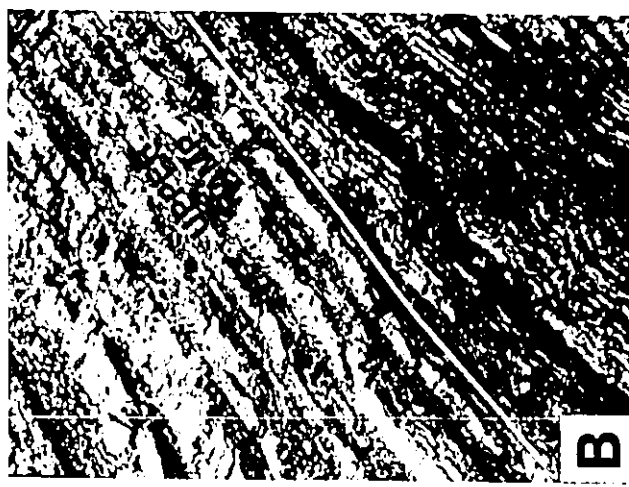
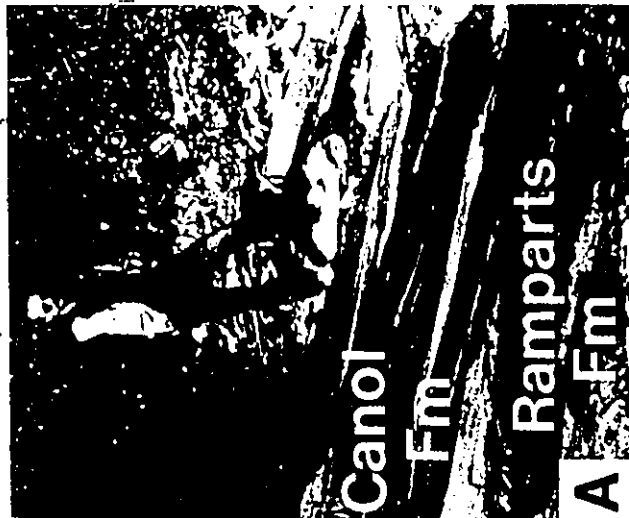


PLATE 1-4

II

SHALLOWING-UPWARD CYCLES IN THE
HARE INDIAN-RAMPARTS SUCCESSION:
A METHOD OF CORRELATING
DEPOSITIONAL FACIES

2.1 INTRODUCTION

2.1.1 Recognition of Cyclicity in Strata

Cyclicity in stratigraphic successions has been well documented (e.g. Duff and Walton, 1962; Wilson, 1975; among others). A cycle is a repetitive group of rock units that reflects a predictable series of depositional events that returns to a starting point (Schwarzacher, 1975). Dott (1983) warned that, because the ancient rock record results primarily from episodic deposition, episodic discontinuities should be considered as the norm in developing facies models and subsequently interpreting paleoenvironments. Wilson (1975) recognized that most carbonate sections are not the result of continuous deposition, but consist of shallowing-upward cycles commonly separated by sharply defined nondepositional surfaces. At a cycle boundary, the rocks overlying the surface represent more offshore or deeper water facies than the underlying rock, irrespective of environmental position.

Most carbonate depositional cycles are asymmetric, with or without thin basal segments, representing deposition during transgression (Goodwin et al., 1985). This is caused mainly by retainment of sediments landward during transgression. The bulk of the cycle consists of an upward-shallowing succession of lithofacies, reflecting progradation or aggradation of shallow-water facies over

more seaward deep water sediment. Carbonate sediments accumulate at rates much greater than the usual rate of subsidence of platforms on which they are deposited (Wilson, 1975; Kendall and Schlager, 1981; James, 1984). Thus the cyclic nature of carbonate successions implies episodic changes in relative sea level. The initiation of each cycle corresponds to accelerated relative sea-level rise and concurrently greatly reduced carbonate production. Purser (1969) suggested that because of very slow sedimentation during these rapid sea-level rises, submarine cementation may occur and result in laterally extensive hardgrounds along the tops of some cycles. Shallowing-upward cycles reflect lower rates of sea-level rise, or stillstands, as carbonate deposition equals or exceeds the rate of rise (Wendte, 1974; Kendall and Schlager, 1981). Progradation and aggradation continue until the cycle is terminated, either by subaerial exposure caused by a relative fall in sea level, or by rapid sea-level rise (Wendte and Stoakes, 1982).

2.1.2 Hierarchy of Cycle Organization

Shallowing-upward carbonate cycles can be recognized at many scales. Anderson and Goodwin (1978) documented 1-5 m thick shallowing-upward cycles (punctuated aggradational cycles) in a Middle Ordovician carbonate succession (Black River-Trenton Group, New York). This succession was shown

to represent stratigraphic accumulation of cycles in successively "deeper" or "more offshore" settings during a marine transgression. Busch and Rollins (1983, 1984) observed Upper Pennsylvanian cycles of similar thickness in the Appalachians, and noted that groups of two to six cycles are commonly arranged to form larger cycles or cyclothems. Typically, these cyclothems (400,000-450,000 years duration) are organized into yet larger cycles (1-10 ma duration), which resemble third-order depositional cycles outlined by Vail et al. (1977).

In this study, the cyclic stratigraphic succession can be discussed in terms of a hierarchy of three orders of cycles (TABLE 2-1) similar to those documented by Busch and Rollins (1983, 1984) and Wendte and Stoakes (1982):

First-order cycles are the largest, and are regionally correlatable. These first-order cycles consist of several depositional cycles of smaller scale (second-, third-order cycles). In the lower portion of a first-order cycle, aggradation and backstepping of the carbonate platform, or reef (i.e. shift of reef margin facies toward the reef interior), as well as condensed sedimentation in the basin, can be attributed to rapid sea-level rise (Wendte and Stoakes, 1982). Wendte and Stoakes (1982) were able to correlate Givetian and Frasnian first-order cycles throughout the Western Canada Sedimentary Basin. They (ibid.) observed that the upper portions of first-order

TABLE 2-1

Hierarchy of shallowing-upward cycles in the study area.

FIRST-ORDER CYCLES

- 100's m thick.
- Regionally correlatable (100's km).
- Lower part:
 - Condensed basinal strata
 - Carbonate platforms show upbuilding and backstepping style of evolution.
- Upper part:
 - Prograding basin-fill strata and forestepping carbonate ramp facies.

SECOND-ORDER CYCLES

- 10-25 m thick.
- Regionally correlatable (10's to >100 km).
- Identified in platform-reef and basin-fill facies.

THIRD-ORDER CYCLES

- 2-5 m thick.
- Locally correlatable (100's m to few km).
- Identified in reef interior, ramp, and platform facies.

cycles tend to be characterized by prograding basin-fill strata and forestepping ramp facies as carbonates built towards sea level with slowing sea-level rise or stillstand.

Second-order cycles (10-25 m thick) and third-order cycles (2-5 m thick) are typically below seismic resolution, but are readily recognizable in outcrops, cores and, commonly, wireline logs (see section 2.3, Application of Cycle Analysis, below). Second-order cycles are more widely correlatable than their component third-order cycles (TABLE 2-1). Third-order cycles are mainly restricted to platform-reef interior settings. Wendte (pers. comm., 1983) suggested that smaller sea-level rises which may, in part, be responsible for third-order cycles, produce no discernible depositional response in faster growing reef or platform margin environments, but can initiate new cycles of sedimentation on sheltered reefs and in platform lagoons.

2.1.3 Significance of Shallowing-Upward Cycles

Cycle boundaries result from accelerated relative sea-level rise. The wide, lateral persistence of second-order and first-order cycles argues for extrinsic or allocyclic control on sea-level fluctuations. Because of basinwide influence of accelerated relative sea-level rise, cycle boundaries can be considered time-synchronous (Wilson, 1975) and, as such, show the following:

- (1) Normal lateral disposition of facies beneath a cycle contact with appropriate bathymetric constraints (Wendte and Stoakes, 1982). The proportion of "deep" water facies within the cycle increases basinward.
- (2) Parallelism to marker beds (e.g. synchronous storm deposits) in the underlying cycle.
- (3) Correlation at similar stratigraphic heights above or below a given datum for those cycles that built to sea level.
- (4) Depositional topography consistent with the type of facies beneath the cycle contact (e.g. a sloping cycle boundary in a basin-fill succession).

Cycle thicknesses are mainly a function of the magnitude of relative sea-level rise, depositional setting and topography, and rate of sediment supply. The rate of sediment accumulation will vary according to the interaction of the following variables:

- (1) Bathymetry and hydrography - higher carbonate production rates characterize shallow water environments (<10 m) (Schlager, 1981). However, the rate of sediment accumulation depends largely on hydrography and topographic relief. For example, some cycles from current-swept "highs" thicken into adjacent paleotopographic "lows". Conversely, some cycles thicken in areas of good

water circulation (e.g. platform-reef margins), but thin due to slower carbonate production in areas of poor water exchange, such as platform interiors.

- (2) Source potential of extrabasinal terrigenous material - the rate of siliciclastic input is greater in depositional settings proximal to a terrigenous source. This will have an adverse effect on carbonate production rate (Wilson, 1975). However, extrabasinal terrigenous supply will be significantly reduced by accelerated sea-level rise (Wilson, 1975; Stoakes, 1980).
- (3) Magnitude and direction of relative sea-level change - carbonates will prograde, aggrade, or be drowned, depending on the interaction of relative sea-level rise with the variables outlined in (1) and (2). Erosion (karsting; soil development) during relative falls of sea level would result in a significantly reduced supply of carbonate detritus to basinal settings due to early cementation (James and Mountjoy, 1983).
- (4) Climatic changes - salinity variations can result from excessive evaporation during arid conditions, or from fresh water input during humid, wet conditions. This, and increased siliciclastic input, could lead to reduction in benthic growth

potential and consequently inhibit carbonate production (Cook, 1983).

2.2 IMPORTANCE OF CYCLE CORRELATION

Second-order cycles are thin (10-25 m thick), regional, time-stratigraphic units bounded by isochronous surfaces and, as such, offer a potential for very detailed chronologic correlation at least on a basinwide scale (Muir et al., 1984; Goodwin et al., 1985). In contrast, correlations based on lithostratigraphic units can be less accurate for establishing a stratigraphic framework. Formations tend to be much thicker than typical second-order cycles, and formation boundaries are commonly diachronous. Goodwin et al. (1985) stated that biostratigraphic control, based on evolutionary change, may be less precise than cycle correlation by perhaps an order of magnitude; Miall (1984) suggested that cycle correlation can be particularly useful in poorly understood areas where biostratigraphic control is meagre.

With their potential for precise and detailed definition of a time-stratigraphic framework, these shallowing-upward cycles also provide a more reliable base for paleoenvironmental and paleoecological analysis. Cycle analysis can help in unravelling the evolution of carbonate successions in frontier areas (e.g. Muir et al., 1984,

1985, 1987). The discernment of cyclicity helps to predict facies distribution according to Walther's Law within each cycle, although the relationships do not extend across cycle boundaries.

At present, there is a need in paleoenvironmental interpretation for precise definition of paleobathymetry of sediments and their contained fossils. Previously, fossils were utilized as relative paleobathymetric indicators because depth-related factors such as pressure, energy, light, substrate, etc., appear to control faunal distribution. However, estimates of the relative depth of a given facies in a stratigraphic cycle (see Lenz, 1982) are complicated by the fact that fossil distribution can also be affected by other factors such as water circulation, temperature variations, nutrient supply, and turbidity levels. Wendte and Stoakes (1982) showed how the correlation of second-order cycle boundaries in the Devonian Judy Creek Reef Complex (Swan Hills Formation) permits semi-quantitative paleobathymetric estimates to be made (FIG. 2-1). Paleoecologic reconstructions of benthic communities, therefore, could benefit significantly from integrating the three following components:

- (1) Cycle analysis of stratigraphic successions to establish spatial and temporal relationships during deposition of component lithologies.

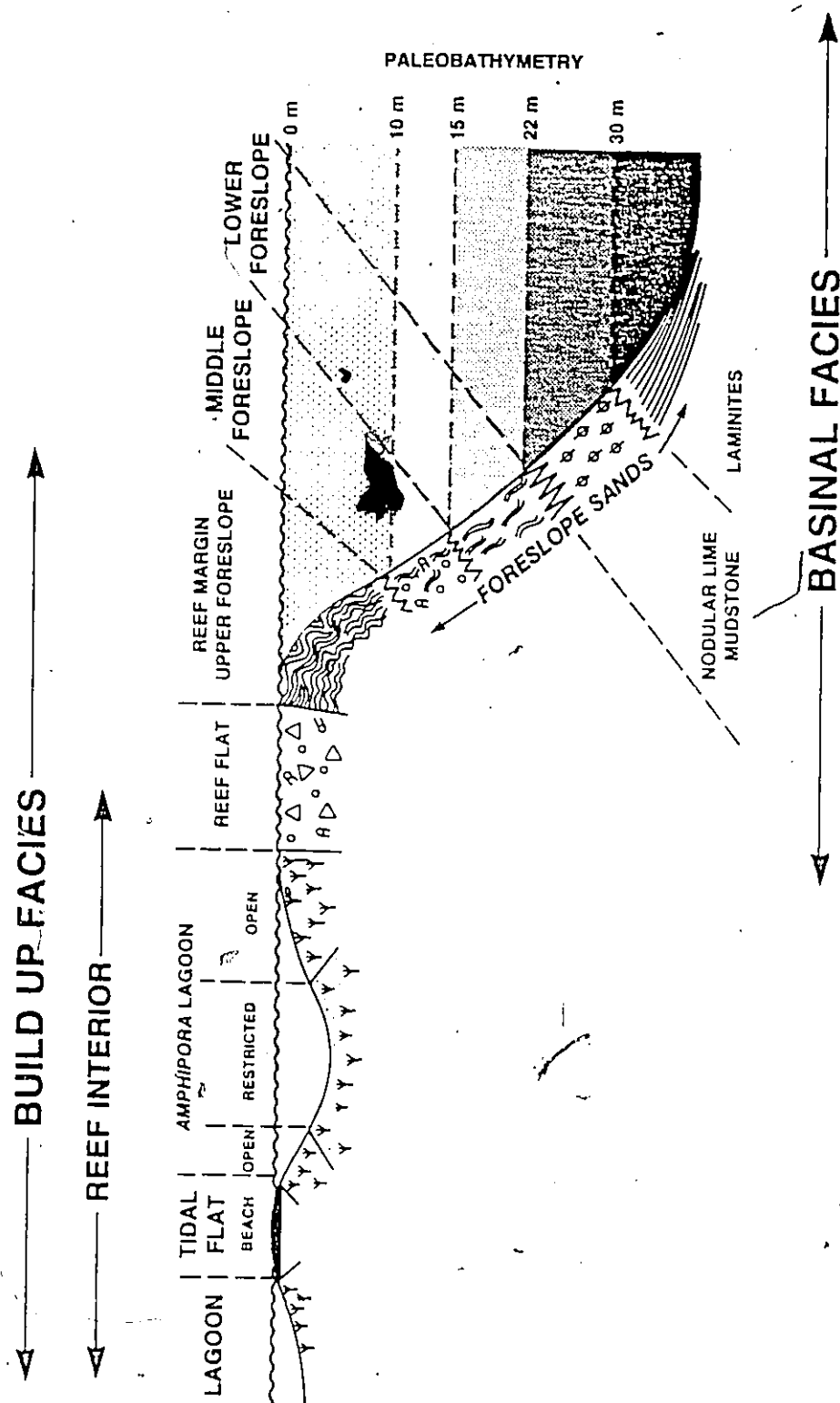


FIG. 2-1. Paleobathymetric profile across the Judy Creek Reef Complex - Swan Hills Formation (after Wendte and Stoakes, 1982).

- (2) Careful systematic and taxonomic analyses of the fossils present.
- (3) Paleoecological interpretation based on methodological uniformitarianism (Dodd and Stanton, 1981) in which growth forms are considered inherently advantageous or disadvantageous in various depositional settings (Bjerstedt and Feldmann, 1985).

Cycle analysis also has important economic implications. Wendte and Stoakes (1982) utilized cycle correlation in the Judy Creek reef reservoir to help determine facies-controlled reservoir continuity and dense permeability barriers. This permitted more complete and efficient field development using an infill pattern waterflood recovery scheme and later a tertiary miscible flood. Cycle analysis also has important potential for exploration in frontier basins (Muir et al., 1984; Miall, 1984).

2.3 APPLICATION OF CYCLE ANALYSIS

2.3.1. General Statement

Although members in the Hare Indian and Ramparts Formations can easily be recognized, they are less significant for detailed sedimentologic study than their

contained sequence of shallowing-upward cycles (Muir and Dixon, 1984; Muir et al., 1984). Cycle correlation was used in this study to build a time-stratigraphic framework that contributes to more complete understanding of the depositional evolution of the Hare Indian-Ramparts succession. An objection to the use of conventional lithostratigraphic methods in reconstructing a depositional framework is the common failure to recognize and accommodate the episodic nature of the stratigraphic record (Ager, 1973; Dott, 1983).

The remainder of this chapter outlines the use of cycle analysis to establish a more refined depositional facies framework for the Hare Indian-Ramparts succession. The nature of relative sea-level fluctuations and their imprint on cycle development will be discussed briefly.

2.3.2 Selection of Regional Geologic Datums

The accuracy of cycle correlation can be verified by relating cycle boundaries to regional geologic datums. Zonal biostratigraphy (Appendix A) and the establishment of these geologic datums also permit a general correlation within the Hare Indian-Ramparts succession.

Three geologic datums (FIGS. 2-2, 2-3) were selected in the study area. Regionally, each datum marks an event of accelerated sea-level rise and, therefore, represents a synchronous cycle boundary.

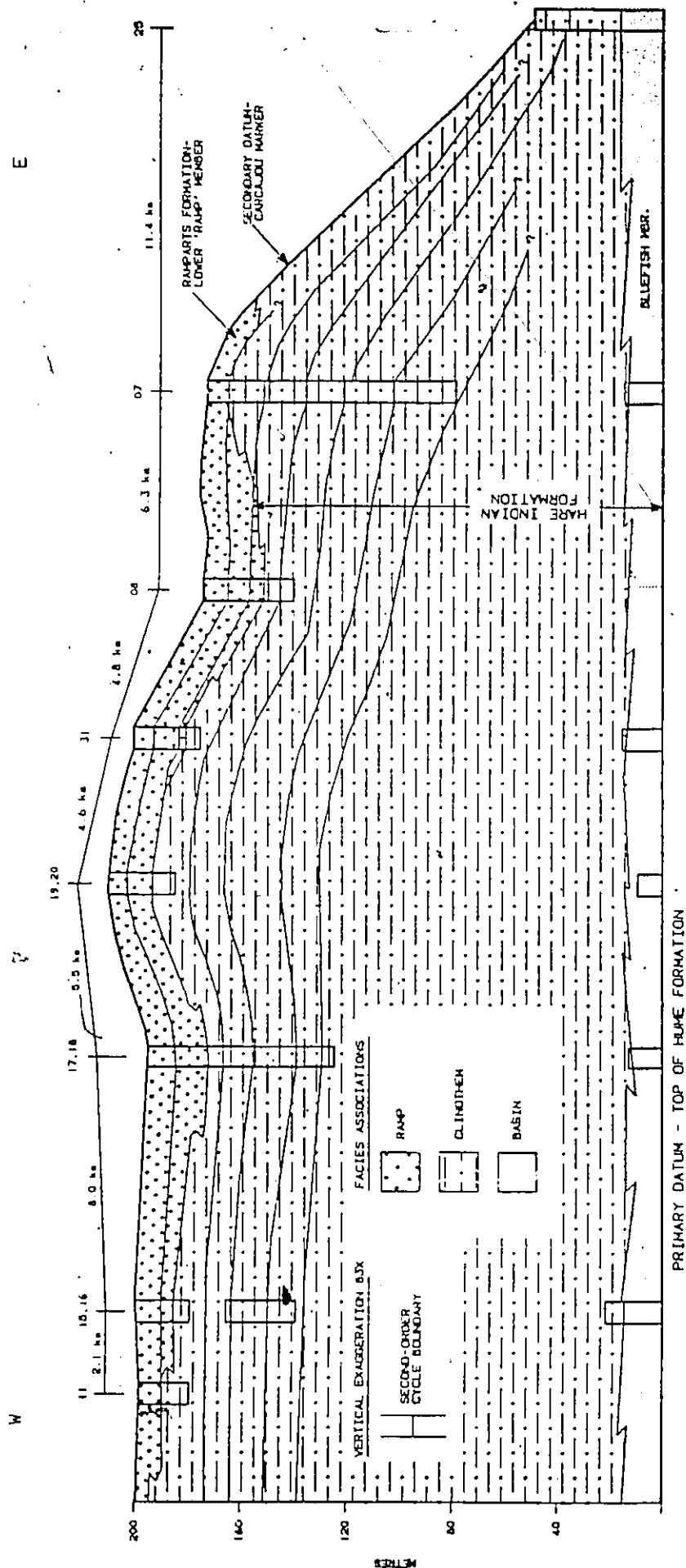


FIG. 2-2 Correlation of second-order shallowing-upward cycles in the Hare Indian Formation and Ramparts lower "ramp" member. The lower portion of the Hare Indian Formation is quite recessive and commonly covered in the study area.

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FIG. 2-3 Correlation of second-order shallowing-upward cycles in the Ramparts upper "platform-reef" member. 1-6 represent reef cycles. Lower, middle, and upper platform cycles are not illustrated (see Chapter 4) for purposes of simplicity. Geologic datums utilized in this study include: (1) top of the Hume Formation, (2) Carcajou Marker, and (3) cycle boundary between reef cycles 3 and 4.

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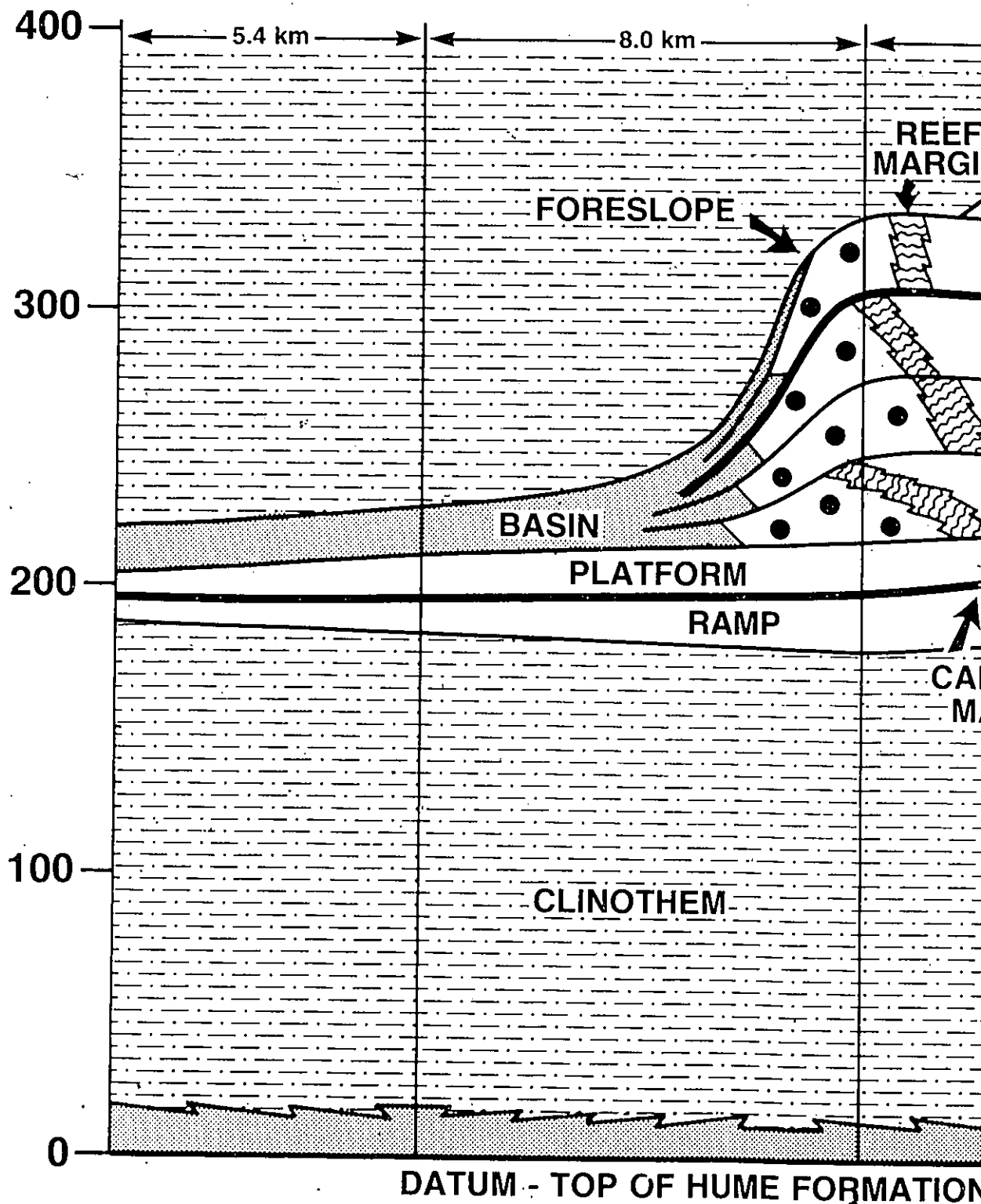
GAYNA RIVER

9,11

15,16

17,18

METRES



BELL CREEK

17,18

20

31

3,

22 23

5.5 km

4.6 km

4.8 km

5.4 km

REEF MARGIN

REEF INTERIOR

6

5

4

3

2

1

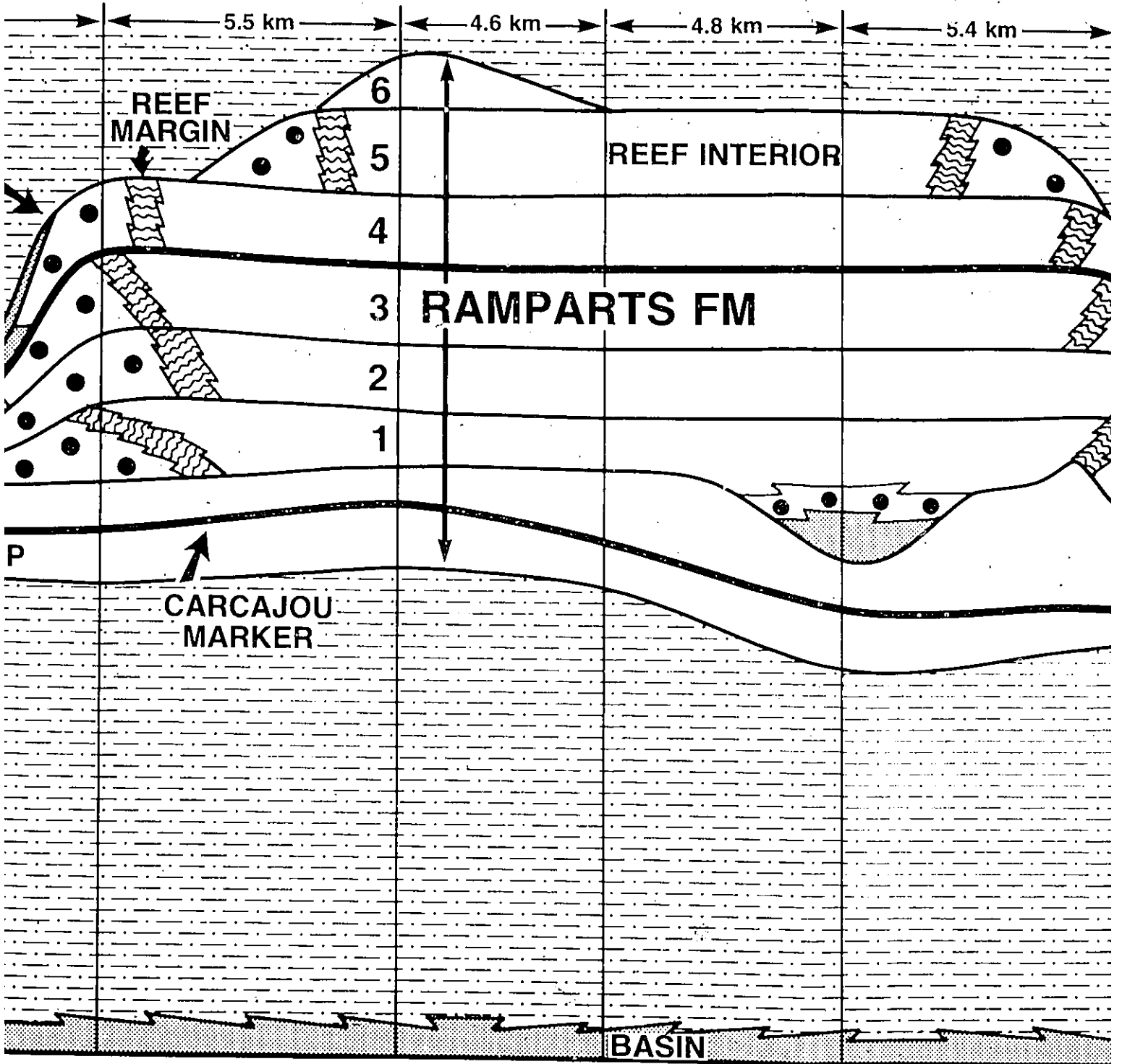
RAMPARTS FM

P

CARCAJOU
MARKER

BASIN

E FORMATION



17,18

20

31

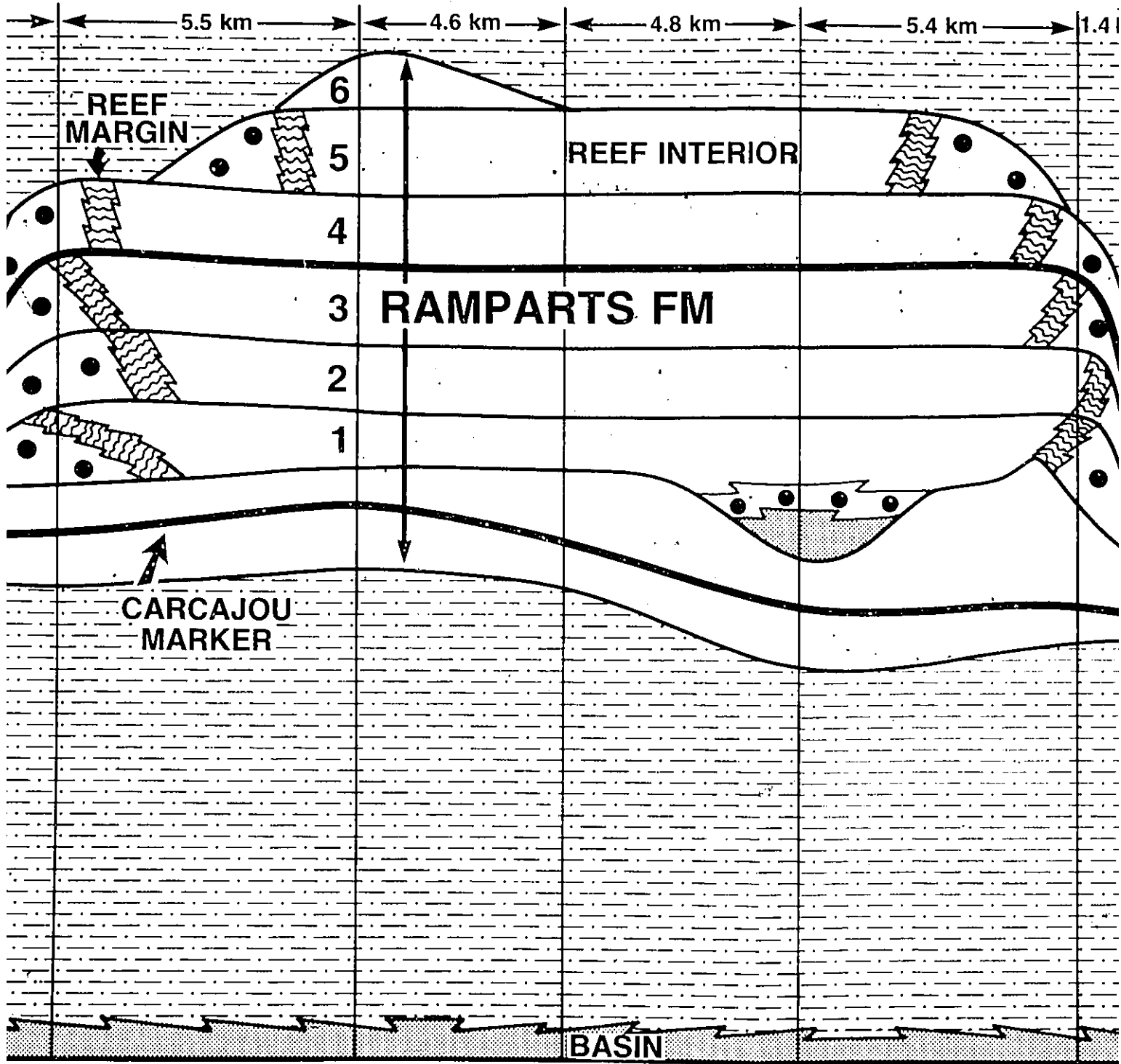
BELL CREEK

8

PO'

3,4,2

22 23



FORMATION

E

POWELL CREEK

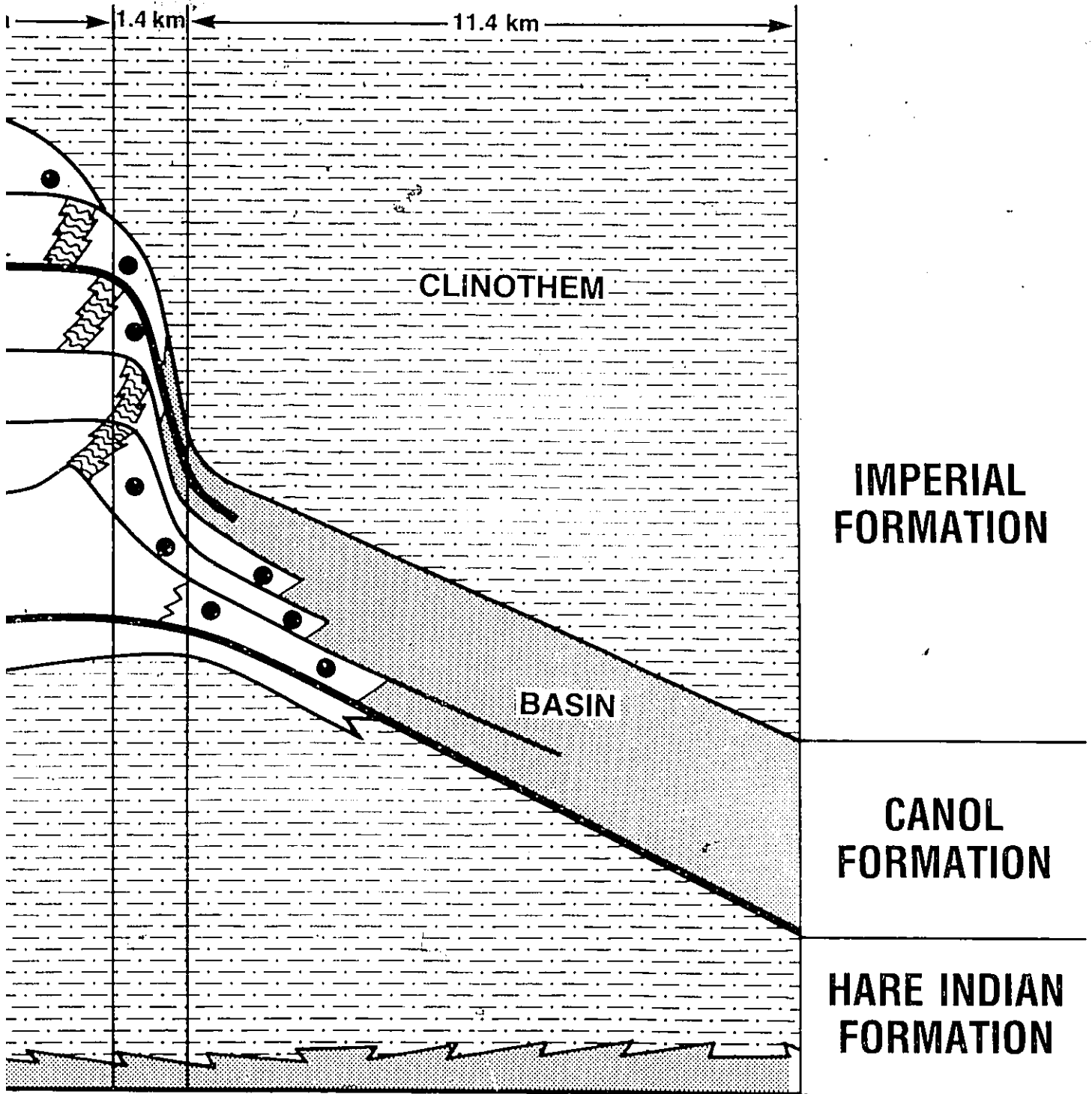
MOUNTAIN RIVER

3,4,24,28

25

22 23

1



The top of the Hume Formation (PL. 2-1a, b, c) is the primary datum used in this study. It is readily identifiable regionally, as carbonate facies of the Hume Formation are abruptly overlain by deeper water black laminated shales of the Hare Indian Bluefish Member (Muir and Dixon, 1984). A datum chosen beneath the cycle of interest avoids errors in cycle correlation introduced by differential compaction (Stoakes, 1980). Furthermore, except for localized buildups, the top of the Hume platform in the study area is taken to be nearly planar, and to have formed essentially parallel to sea level in a few 10's m of water (Muir and Dixon, 1984). However, because of possible errors in measuring these thick stratigraphic successions (maximum 370 m thick) and the detailed nature of cycle analysis, two secondary datums were chosen at higher levels to verify cycle correlations.

The Carcajou Marker (PL. 2-2a, b, c) at the base of the Carcajou subfacies is the lower secondary datum. Its significance in the cyclic evolution of the Hare Indian-Ramparts succession is presented in section 2.3.4, and Chapter 4 contains a more detailed account of the sedimentology of the Carcajou subfacies. Evidence for abrupt deepening and termination of a shallowing-upward cycle is as follows:

- (1) Shallow water "nearshore" benthic communities are abruptly replaced by "offshore" deeper ones.

Analogous change to deeper water communities can be recognized at a similar stratigraphic horizon (middle to upper varcus subzones) in basinal areas.

- (2) Lighter colored coarse-grained limestone and siltstone are abruptly overlain by argillaceous limestone and dark grey calcareous shale. The Carcajou subfacies tends to be pyritiferous with high total organic carbon values (1-8 wt%, see Chapter 4). Localized hardground development marks the top of the Ramparts lower "ramp" member at section 20, and is overlain by the Carcajou subfacies.
- (3) The Carcajou subfacies represents slow sedimentation associated with marked deepening. The subfacies is a condensed cycle (0.5-7.0 m thick) that falls between the middle varcus subzone and the lower disparilis zone. Because the subfacies spans a long period of time, it is important to correlate the base of the cycle (Carcajou Marker), which represents synchronous regional initiation of transgression. The Carcajou subfacies grades upward into limestone facies of the Ramparts upper "platform-reef" member, and the boundary may be markedly diachronous.

The boundary between reef cycles 3 and 4 (FIG. 2-3) is the final secondary datum used in this study. A significant

backstep of the reef margin (reef cycle 4) towards the reef interior is expressed as an abrupt lateral shift of facies across the entire complex (FIG. 2-3). Significantly, the cycle boundary separates tidal flat facies in reef cycle 3 from open lagoonal facies in reef cycle 4 in all measured sections (08, 31, 20) through the reef interior. The presence of intertidal facies at the top of reef cycle 3 in these sections implies a near-horizontal depositional surface approximately at sea level immediately before the regional deepening event. The datum is apparently at the same distance above the top of the Hume Formation in the different sections, which serves to corroborate the stratigraphic control.

2.3.3 Construction of Depositional Facies Framework

The correlation of shallowing-upward cycles and construction of a depositional framework can be accomplished through a series of steps (TABLE 2-2) as follows:

- (1) Determine zonal biostratigraphy and regional geologic datums to establish a general correlation. Conodonts, at present, provide the best resolution for biostratigraphic zonation in the Devonian (average zonal duration of 0.5 ma; Johnson et al., 1985). Samples are selected and located with respect to a regional geologic datum or cycle boundary (see Appendix A). One limitation of

TABLE 2-2

CONSTRUCTION OF DEPOSITIONAL FACIES FRAMEWORK

1. Determine zonal biostratigraphy and regional datums to establish general correlation.
2. Identify cycle boundaries.
3. Correlate cycle boundaries.
4. Determine facies distribution within individual shallowing-upward cycles.

conodont biostratigraphy in the study area is that the conodonts are apparently very poorly represented in reef interior and reef margin depositional settings (Uyeno, pers. comm., 1986). This suggests some paleoenvironmental control on the distribution of the conodont organisms. Post-mortem downslope and episodic reworking may also be problematical in displacing older faunas basinward (Nicoll, 1984). However, the reliability of interpretations can be enhanced by closely coupling conodont biostratigraphy with detailed sedimentology. This is particularly important if the conodont organisms had a depth-related ecologic distribution. For example, Stritzke (1986) noted that icriodids and coarsely-sculptured polygnathids favored a more proximal forereef position, while slenderly-built palmatolepids occupied distal off-reef settings.

- (2) Identify cycle boundaries. The boundaries are delineated where deeper or more seaward facies overlie shallower or more landward facies. Generally, such boundaries are abrupt, although some in foreslope settings are gradational. Comprehensive facies description and interpretation of sections (Chapters 3, 4, 5) revealed a variety

of criteria that indicate shallowing, as outlined in TABLE 2-3.

- (3) Correlate cycle boundaries. This is perhaps the most difficult step because the cycles will vary in thickness and composition with position along a bathymetric profile. Correlated cycle boundaries should be concordant with prominent geologic datums. Beneath the cycle contact, there should be a normal lateral disposition of facies according to bathymetric constraints. Wendte and Stoakes (1982) employed this technique to correlate reef cycles in the Devonian Judy Creek buildup in the Alberta subsurface (FIG. 2-1). Depths for specific facies were estimated by measuring their vertical separation from facies in the same cycle deposited at sea level. They (ibid.) noted that these interpreted facies depth ranges may vary according to compaction and environmental factors such as water circulation and nutrient supply. Second-order reef cycles, which represent shallowing to sea level, should be correlatable at similar stratigraphic heights throughout the reef interior. The thickness of each second-order cycle should be relatively constant (see FIG. 2-3) because relative sea-level rise across the reef interior should accommodate equal increments of

TABLE 2-3

SHALLOWING-UPWARD CRITERIA

Hare Indian Formation (Muir and Dixon, 1984)

- Upward-coarsening of grains, thickening and lightening of calcisiltite beds.
- Increased percentage of proximal fine-grained turbidities towards top of cycle with concomitant increase in carbonate content.
- Reworking by storm wave activity (upper cycles, Hare Indian Formation).
- Increased epifaunal diversity upwards.
- Increase of infaunal diversity, burrow size, and bioturbation intensity upwards.

Ramparts Formation (Muir et al., 1984, 1985)

- Textural parameters and grain size variations which reflect strength and persistence of current and wave action. This is manifested by upward-coarsening of grains, decreased mud content, increased sorting towards tops of cycles.
- Sedimentary structures which can be related to flow regime (e.g. proximal calciturbidites versus distal calciturbidites).
- Biogenic features; particularly stromatoporoid and coral morphotypes (e.g. wafer forms in deeper, less agitated depositional settings versus thick, tabular forms in shallow, agitated depositional settings).

sediment. Finally, correct cycle correlation should result in cycle boundaries being parallel to closely associated storm deposits. Cycle boundaries in the upper Hare Indian Formation, for example, are parallel to storm deposits or tempestites in the Carcajou subfacies (discussed further in Chapter 3).

- (4) Determine facies distribution within individual shallowing-upward cycles. This is attempted only after detailed sedimentological study of the succession is complete and paleoenvironmental settings for each facies have been summarized.

2.3.4 Hierarchy of Cycle Organization

First-order cycles. The criteria used (TABLE 2-1, section 2.1.2) led to the recognition of two first-order cycles in the study area. Backstepping platform development in the Hume Formation characterizes the basal portion of the lower first-order cycle. Reconnaissance work indicated that the Hume Formation is a cyclic succession in which shallowing-upward cycles terminated in progressively deeper water settings during marine transgression. Lenz (1982, p. 1924) noted that "...the basal ostracode-bearing member of the formation appears to have originated in shallower waters than the two overlying, richly fossiliferous members." Unfortunately, the base of this first-order cycle could not

be established in the study area because the evaporite-dolostone-limestone succession of the underlying Bear Rock Formation (Fort Norman, Arnica, Landry Formations in Pugh, 1983) is poorly understood.

In the southern Mackenzie Mountains in the vicinity of the Liard Arch, a widespread, early Eifelian unconformity separates the Arnica and Landry Formations (G.K. Williams, pers. comm., 1986). Similarly, in the Fort Nelson area, northern British Columbia, the Dunedin Limestone is separated from the Stone Dolomite by an unconformity most widespread during earliest Eifelian time (Lenz, 1982). More data is required to determine the significance and correlation of this possible first-order cycle break.

The upper portion of this lower first-order cycle records slowing sea-level rise during early Givetian time (Lenz, 1982; Muir et al., 1984; Johnson et al., 1985). This resulted in progradation of the Hare Indian clastic wedge and forestepping of the ramp facies. The ramp facies are succeeded by a deep-water, condensed cycle, the Carcajou subfacies. A first-order cycle break is indicated by the abrupt change from basin-fill sediments, representing marine regression to backstepping Ramparts platform-reef facies and a condensed basinal cycle (Canol Formation). The top of the upper first-order cycle was not determined. However, the rapid rise in relative sea level eventually was followed by stillstand and prograding of Imperial siliciclastic

basin-fill sediments into the study area during the Frasnian (Muir and Dixon, 1984).

If the proposed lower first-order cycle break is of earliest Eifelian age, then this lower cycle would be of 8-10 ma duration (base of Eifelian to Givetian-middle varcus subzone). Busch and Rollins (1983, 1984) documented similar time spans for large Upper Pennsylvanian cycles in the Appalachians.

The Carcajou Marker, separating the lower and upper first-order cycles, probably corresponds to the Taghanic onlap event recorded by Johnson (1971) in western North America. Brett and Baird (1985) noted that evidence of widespread regression preceding the Taghanic onlap has long been recognized in North America. The lowermost unit (Leicester Pyrite) of the late Middle Devonian Genessee Formation in western New York State (ibid.) is a dark brown pyritiferous, argillaceous condensed cycle similar in age (hermanni-cristatus conodont zone), and geologic setting to the Carcajou subfacies. Johnson et al. (1985, p. 578) suggested that the Taghanic onlap represented the inception of a major transgressive-regressive cycle where the base "...is best dated in the middle varcus subzone. Within the limits of available accuracy, the initial deepening event is evident in all five study areas (Western Canada, Iowa, southwestern Ontario, Ohio, New York)."

It appears that the potential to correlate first-order cycles over significant distances (100's km) may be limited in the future only by the available database. Seismic stratigraphy and biostratigraphy, in conjunction with detailed sedimentology, will help to extend the regional correlation of first-order cycles.

Second-order cycles. The Hare Indian basin-fill succession comprises second-order cycles that successively terminate in shallower water facies (FIG. 2-2). These cycles (10-25 m thick) demonstrate that regression was not continuous, with the rate of sediment supply exceeding relative sea-level rise, but rather episodic, with pulses of accelerated sea-level rise followed by periods of stillstand in which most sedimentation occurred. Cycle boundaries representing sea-level falls were not observed in the study area; no evidence of subaerial exposure was observed in either basin-fill or platform-reef cycles.

While basin-fill cycles can be correlated for 10's of km in the study area (FIG. 2-2), their boundaries are difficult to discern in certain depositional settings. In basinal settings, accelerated rise in sea level would have little sedimentologic effect. Similarly, for some basin-fill cycles, a substantial and a more proximal source of silty sediment may mask the effect of abrupt deepening. Nonetheless, some Hare Indian shallowing-upward cycles can

be correlated in the subsurface using gamma ray and sonic logs (FIG. 2-4) to recognize coarsening-upward trends.

Second-order cycles in the Ramparts Formation (PL. 2-3) show thicknesses (average 10-30 m thick) comparable to those in the Hare Indian Formation. The cycles can be correlated across the platform-reef complex. Muir et al. (1984, 1985, 1986) correlated these depositional cycles over 100 km, from the study area to the time-equivalent Ramparts buildup in the Norman Wells subsurface. They (ibid.) noted that, in cross-section comparisons (see Chapter 5) through both complexes, only those subsurface second-order cycles with the greatest shift in facies could be recognized in the study area. Muir et al. (1984) suggested that this reflected no real difference in the cyclic evolution of the complexes, but rather that the discontinuous nature of surface exposures permitted the delineation only of more prominent cycle breaks. Second-order cycles in the Ramparts upper "platform-reef" member correspond to second-order cycle sets in the Norman Wells subsurface.

In any case, reef cycles 1-6 (FIG. 2-3) show remarkable parallelism and little variance in cycle thickness (average 25 m thick) regionally.

Third-order cycles. Third-order cycles (2-5 m thick) are recognized only in ramp and platform-reef interior facies of the Ramparts Formation. Some ramp cycles appear to be correlatable over a few km (PL. 2-4), but reef and platform

interior third-order cycles cannot be correlated regionally. Cyclicity may be generated both by allocyclic relative sea-level changes and by autocyclic varying carbonate production (James, 1984).

Wong and Oldershaw (1980) suggested that in areas where carbonate sedimentation outpaced relative sea-level rise, a reduction in subtidal areas would occur. As a consequence of poor circulation, reef interior waters would become inimical to marine organisms and carbonate production would decrease. This would permit relative sea-level rise to exceed sediment accumulation and subtidal conditions to replace supratidal and intertidal conditions. This autogenic model applied to a reef interior "island" mosaic could explain the difficulties in correlating third-order reef interior cycles. However, in the Ramparts Formation, each successive third-order reef interior cycle in a second-order cycle appears to show a greater proportion of more restricted lagoonal facies (see Chapter 5). Thus, it would also appear that relative sea-level fluctuation significantly affected third-order cyclicity.

Interestingly, third-order reef interior cycles are not expressed in the reef margins (Muir et al., 1984). Wendte and Stoakes (1982) suggested that smaller increments of sea-level rise would produce no discernible response on the faster-growing reef margins, but could cause abrupt

deepenings of the sheltered reef interior, thus initiating new cycles of sedimentation.

Each second-order reef cycle typically consists of six to nine third-order reef interior cycles. The latter would represent durations of 51,000-77,000 years based on an average 460,000 year second-order cycle (see Chapter 1). The scale (2-5 m thick) and duration of these third-order cycles compare favorably to the punctuated aggradational cycles (1-5 m thick, 10,000's years) reported in Busch and Rollins (1983, 1984) and Goodwin et al. (1985).

2.3.5 Depositional Topography and Major Depositional Environments

Because successive correlated cycle boundaries are taken to represent synchronous horizons, they reflect depositional topography at various stages of basin-fill and platform-reef development. In other words, each cycle boundary approximates the paleotopography prior to a cycle of deposition.

The regional correlation of second-order cycles in the basin-fill succession of the Hare Indian Formation and Ramparts lower "ramp" member indicates three broad depositional environments (FIG. 2-5). These correspond, in general, to the undaform, clinoform, and fondoform physiographic zones defined by Rich (1951). Undathem facies, as originally defined, represent sedimentation under

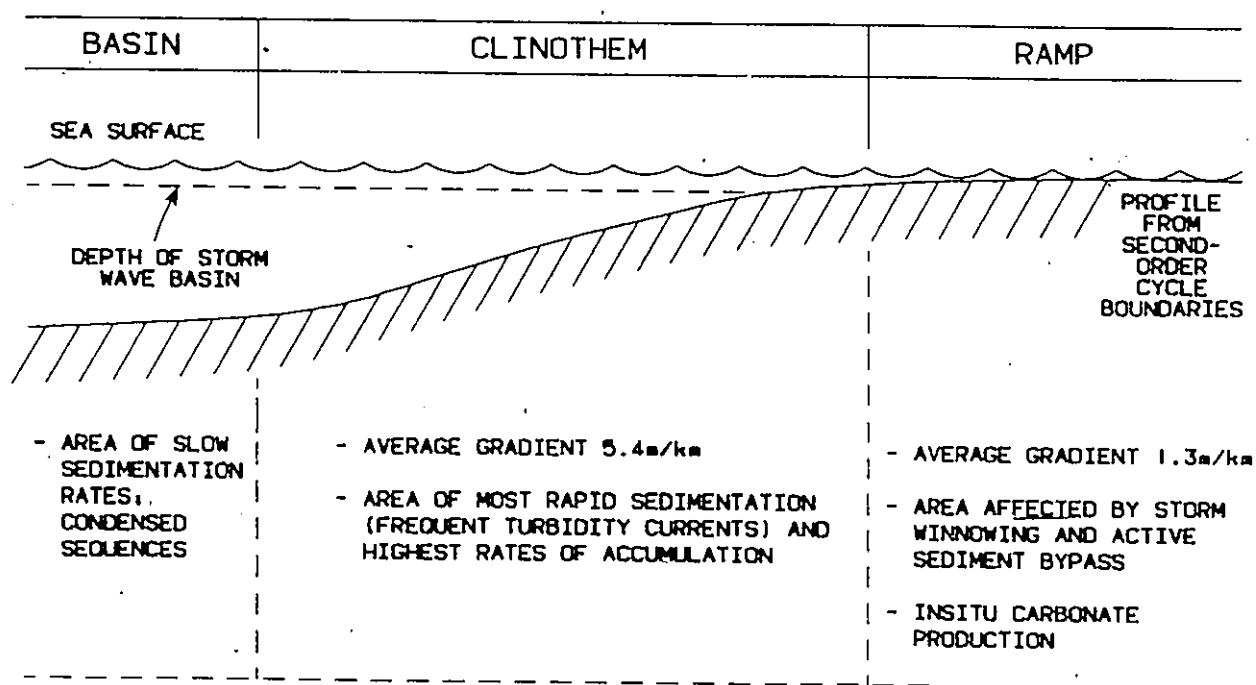


FIG. 2-5 Depositional facies associations in the Hare Indian Formation - Ramparts lower "ramp" member basin-fill succession.

constant wave agitation. In this study, the ramp facies association approximates undathem facies, even though it was deposited between storm and fairweather wave bases, and does not show evidence of constant wave reworking (see Chapter 3). The ramp facies association shows irregular to vaguely concentric facies belts that follow the isopach contours of the associated basin-fill succession (FIG. 2-6). Mixed siliciclastic-carbonate ramp facies west of the study area grade basinward into interbedded shale and biostromal limestone. Shallowing-upward trends in the vicinity of the quartz arenite unit show limestone and shale passing upward into quartz arenite, and rarely bioclastic limestone (MacKenzie et al., 1975). The dual occurrence may reflect progradation of siliciclastic shallow marine-shoreface facies accompanying outbuilding of a carbonate ramp. This will be discussed in more detail in Chapter 3.

The top of the ramp facies association was a shallow, gently dipping surface (average 1.3 m/km; maximum 2.3 m/km or 0.1°) from section 18 to section 07. Precompaction values were probably much higher. Stoakes (1980) estimated gradients of 0.5 m/km for the Upper Devonian Ireton platform facies in southern Alberta.

The clinothem facies of Rich (1951) are represented in the study area by sediments laid down mainly below storm wave base on a sloping surface. An average gradient of 5.4 m/km or 0.2° was obtained for clinoform cycle boundaries

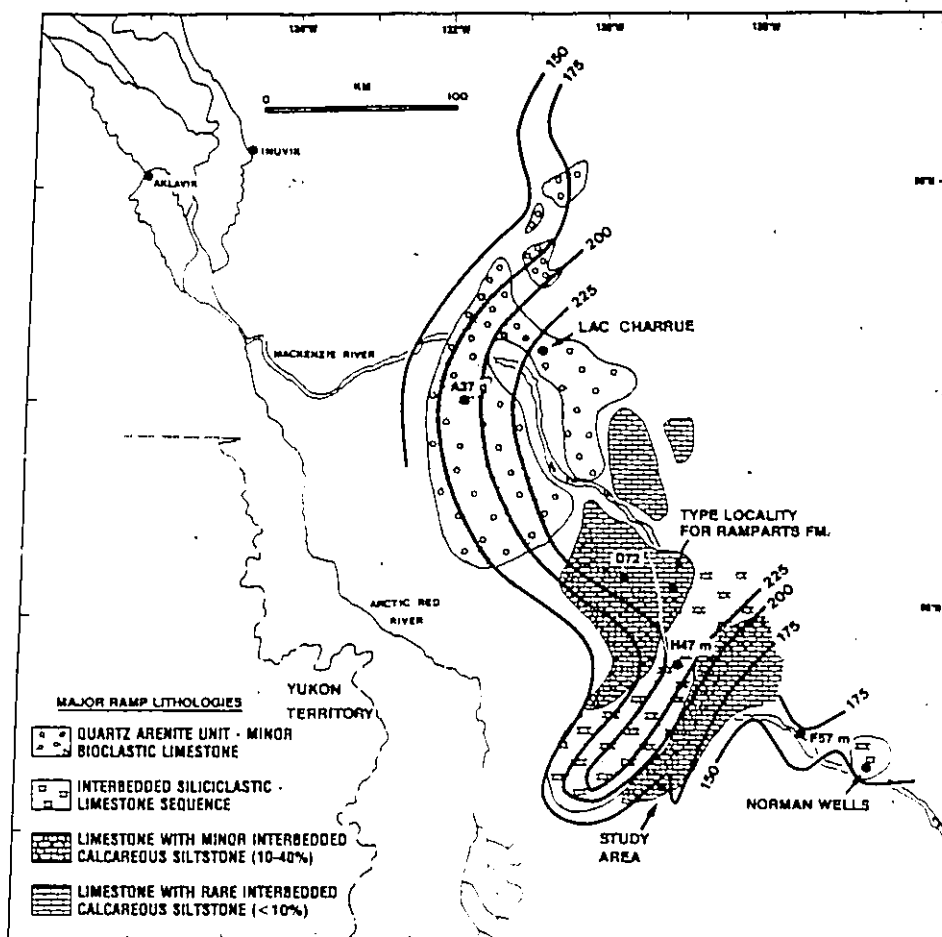


FIG. 2-6 Distribution of major ramp lithologies superimposed on an isopach map (m) for the basin-fill succession between the top of the Hume Formation and the Carcajou subfacies. Stratigraphic cross-section through wells A37g, D72 and H47m, shown in FIG. 2-4. Ramp facies are dominated by siliciclastic lithologies (Hare Indian Formation) or carbonate lithologies (Ramparts lower "ramp" member) depending on proximity to sites of siliciclastic input and redistribution by major currents (see Chap. 3).

between sections 07 and 25. Williams (1977) documented westward-dipping (2-8 m/km) clinoform log markers within the Upper Devonian (Frasnian) Hay River Formation in northern Alberta and southern Northwest Territories.

The fondothem facies of Rich (1951) are referred to as the basin facies association in this study. This portion of the Hare Indian succession shows thin second-order cycles (PL. 1-2d) in condensed cycles resulting from slow sedimentation.

Cycle boundaries in the basin-fill succession are broadly sigmoidal (FIG. 2-2), as indicated by seismic data from the Norman Wells area (G. Klose, Esso Resources Canada Ltd., pers. comm., 1983). Seismic reflections can be generated from stratal surfaces that appear to represent former depositional surfaces. Second-order cycles are imbricate towards the basin (FIG. 2-2), demonstrating the progradational nature of the basin-fill succession.

Four major environments of deposition can be recognized in the Ramparts upper "platform-reef" member. These depositional settings are distinguished on the basis of detailed sedimentology (Chapters 4, 5) and their positions relative to enclosing second-order cycle boundaries (FIGS. 2-3, 2-7):

- (1) Platform or reef interior environment. Third-order cyclicity is common in these environments and cycles are bounded by depositional surfaces which

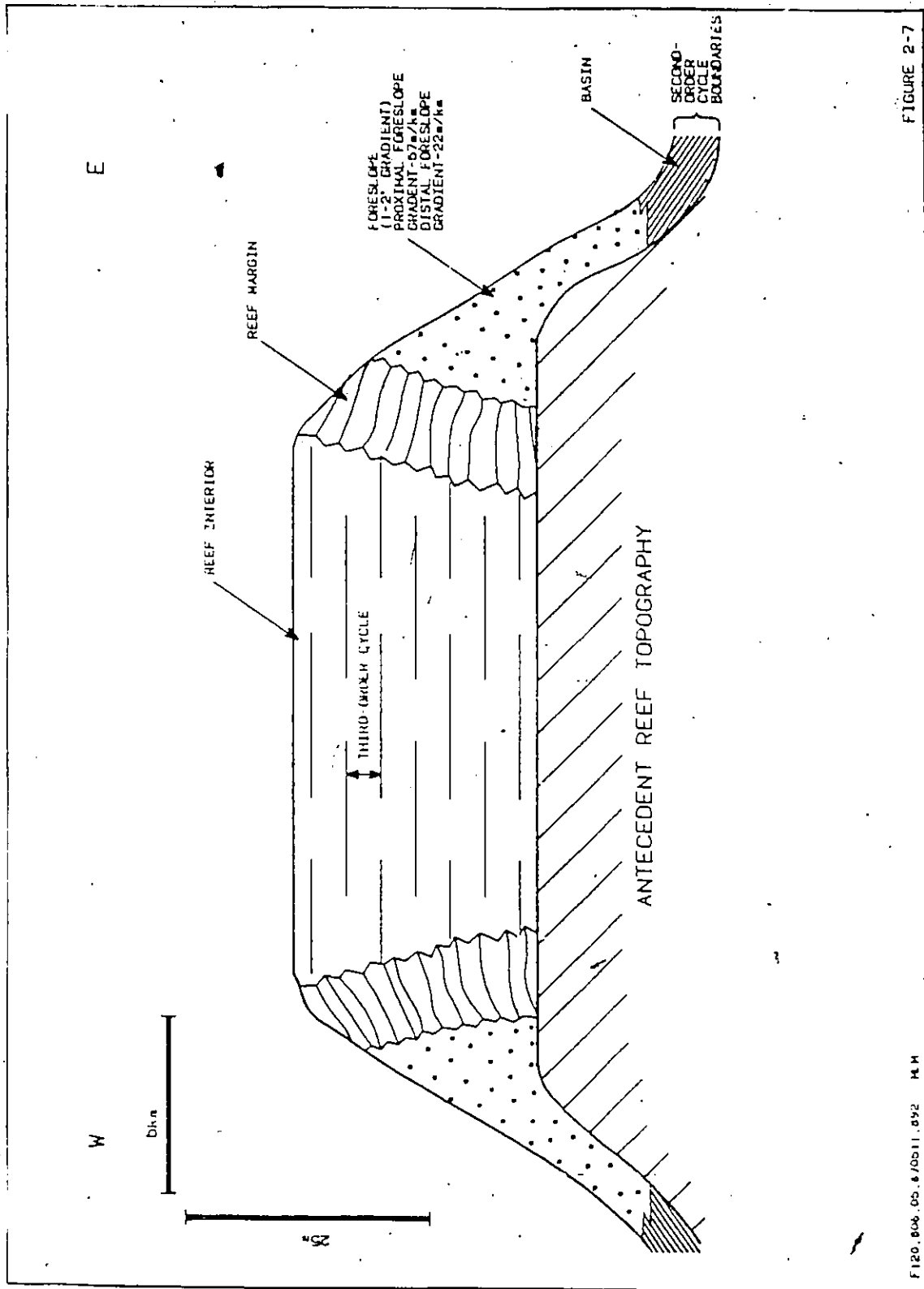


FIG. 2-7 Major facies distribution within a second-order reef cycle.

are subparallel to sea level (FIG. 2-7). In contrast to platform interior facies, reef interior facies contain restricted lagoonal and tidal flat sediments (Muir et al., 1984).

- (2) Platform or reef foreslope environment. Cycle boundaries in this setting indicate post-compaction depositional dips of 1-2°. Facies consist of both allochthonous rubble and dark, micritic autochthonous limestones (Muir et al., 1984, 1985).
- (3) Platform or reef margin environment. The margin is the physiographic shelfbreak between (1) and (2), as defined by geometric inflection of enclosing cycle boundaries. Reef margin facies in reef cycles 1-5 (FIG. 2-3) are characterized by interbedded reef rubble and boundstone of in situ thick, tabular, stromatoporoids (Muir and Dixon, 1984). Platform margin facies are not as clearly defined. However, second-order cycles tend to thicken in the vicinity of the platform margin, presumably due to conditions favoring in situ carbonate production.
- (4) Basinal environment. Dark, bituminous laminites are deposited in deeper, oxygen-depleted waters downdip from the platform, reef and foreslope depositional environments (Muir and Dixon, 1984).

2.3.6 Nature of Relative Sea-Level Fluctuations and the Development of Cyclicity

First-order and second-order shallowing-upward cycles in the Hare Indian-Ramparts succession indicate fluctuating water depths that can be related to allogenic and/or autogenic mechanisms (TABLE 2-4). Sediment supply variations, eustatic sea-level fluctuations, and subsidence probably interacted in a cyclical manner. However, there is substantial evidence to suggest that eustatic sea-level fluctuation was the primary driving mechanism producing cyclicity in the Hare Indian and Ramparts Formations. Different cycles terminate at different points in their shoaling-upward cycles. Complete shoaling to sea level was not always expressed, demonstrating that an autogenic mechanism such as the Ginsburg (1971) model did not induce each submergence and cycle break. Furthermore, autogenic mechanisms should account for different numbers of cycles at different locations. In contrast, allogenic mechanisms would result in a constant number of cycles, correlatable regionally (cf. FIGS. 2-2, 2-3, 2-4). Second-order reef cycles were correlated across the entire reef complex (10's of km) and to time-correlative cycles in the Norman Wells buildup 100 km east of the study area (Muir et al., 1984, 1985, 1986; Chapter 5 in this study). The larger the distance that synchronous cycles can be correlated, the less likely that cyclicity was controlled by local patterns of

TABLE 2-4

CAUSES FOR CYCLICITY

Allogenic Mechanisms: External to the depositional basin, and with a net effect on depositional processes across the basin.

Examples: (a) tectonic subsidence
(b) eustasy
(c) climatic changes.

Autogenic Mechanisms: Internal and inherent within the depositional basin, independent of external influences or variations.

Example: Tidal flat progradation (Ginsburg 1971; Wong & Oldershaw, 1980) with variations in supply of sediment to tidal flats.

sediment supply (e.g. autogenic delta lobe switching that could explain cyclicity in the Hare Indian Formation). Finally, the 10-25 m thick second-order cycles are also persistent temporally and can be recognized through the entire Givetian succession (6 ma) despite local facies variations.

It is unlikely that varying rates of subsidence could provide such regular, laterally extensive shallowing-upward cycles. Basin subsidence rates are more typically smooth and decay with time (Watts et al., 1982). Third-order cycle periodicity (10,000's of years) was unlikely due to tectonic subsidence in an epicontinental basin. According to Bayer et al. (1985), epeirogenic movements are not rapid enough to account for minor cycle development.

The causes of eustatic sea-level variation have been summarized by numerous authors, including Hays and Pitman (1973), Pitman (1978), Turcotte and Burke (1978), Hallam (1980), and Guidish et al. (1984). Some mechanisms are not considered here because they produce cyclicity of inappropriately long duration or are unknown in the Devonian (Johnson et al., 1985). The ones discussed below are more pertinent to Hare Indian-Ramparts cyclicity in having potential for sea-level changes that are relatively rapid in geological terms. Much work remains to be done to verify the various hypotheses:

(1) Plate movement and first-order cycles. Volume

changes of mid-oceanic ridge systems could displace large volumes of water (300-500 m), but only at rates of 1-2.5 cm/1000 years (Miall, 1984; Guidish et al., 1984). This may account for first-order and larger cycles (10-100 ma) of the scale of the unconformity-bound cratonic cycles recognized by Sloss (1963, 1972). Johnson (1971) showed that the Antler, Ellesmerian, and Acadian orogenies of North America coincided with the major transgression of the Kaskaskia cycle (385-325 ma). Highstands of sea level accompany episodes of rapid sea-floor spreading and generation of hot oceanic lithosphere. Miall (1984) suggested that these periods of orogeny were followed by episodes of slow spreading and post-orogenic reordering of spreading axes, which resulted in widespread unconformities associated with falling sea level. However, this mechanism cannot explain the greater frequency of sea-level changes associated with second- and third-order cycles (10,000-100,000's of years).

(2) Milankovitch Insolation Theory: second- and

third-order cyclicity. Variation in stored ice volume within the polar ice caps is probably the only known mechanism capable of causing rapid

fluctuations in eustatic sea level. Increase or decrease of land-based ice sheet volume can account for rapid sea-level fluctuations (probable maximum rate = 1000 cm/1000 years; Pitman, 1978). Pleistocene glaciation at its maximum is considered to have resulted in sea-level fall of approximately 150 m, reduced to 100 m by isostasy (Donovan and Jones, 1979). However, the timing and nature of glaciation in the Paleozoic are poorly known. Many authors such as Anderson and Goodwin (1978), Johnson et al. (1985), and others, suggest that it is difficult to attribute eustatic sea-level changes to fluctuating polar ice budget during periods of equable climate. However, Harland (1981) cautioned that the absence of geological evidence for ice action (e.g. from periods such as the Cretaceous) does not necessarily indicate the absence of ice worldwide for these prolonged periods, during which cyclicity may be developed. Small-scale (1-100 m) shallowing-upward cycles are frequently attributed to climate-controlled eustatic changes at Milankovitch orbital periodicities (Imbrie and Imbrie, 1980). Third-order cycles of 51,000-77,000 years duration in the Ramparts Formation fall within the range (21,000-95,000 years) of the shorter dominant

periods of Earth's orbital cycles (TABLE 2-5) that the Milankovitch insolation theory postulates as controlling the Pleistocene ice ages.

The Milankovitch theory may be tentatively applied to second- and third-order cyclicity in the Ramparts succession. Periodicity of third-order cycles is similar to the cycle of the obliquity of the earth's axis with a present period of 41,000 years. Second-order cyclicity in the Ramparts Formation (estimated to have an average 460,000 years duration) may be controlled by the cycle of the eccentricity of the earth's orbit with the present period of 413,000 years.

Thus it would appear that eustatic sea-level fluctuations associated with climatic changes brought on by variations in the earth's orbit could have played a role in the cyclic development of the Hare Indian-Ramparts succession. However, corroborative evidence is required from other Devonian samples to substantiate the relationship between cyclic sedimentation and orbital parameters.

2.4 MODUS OPERANDI

The recognition of shallowing-upward cycles is critical to interpreting, in detail, the evolution of the Hare Indian-Ramparts succession. The Carcajou Marker separates two first-order shallowing-upward cycles. The upper portion

TABLE 2-5

MAJOR EARTH ORBITAL CYCLES

(after Imbrie and Imbrie, 1980; Moore et al., 1982)

1. Precession of the equinoxes with a period averaging 21,000 years.
2. Obliquity of the ecliptic with a period averaging 41,000 years.
3. Eccentricity of the orbit with three dominant periods:
 - (a) 95,000 years
 - (b) 123,000 years
 - (c) 413,000 years.

of the lower cycle (Hare Indian Formation and Ramparts lower "ramp" member) is a basin-fill succession that represents forestepping and marine regression. Chapter 3 examines the depositional interrelationships of the basin-clinothem-ramp facies associations making up this portion of the cycle.

The lower portion of the overlying first-order cycle, the Ramparts upper "platform-reef" member is a distinctly different backstepping cycle representing marine transgression. The nature of cyclic platform and reef development in this member is documented in Chapters 4 and 5. Finally, in Chapter 5, an attempt is made to correlate second-order shallowing-upward Ramparts cycles regionally between two isolated buildups 100 km apart.

PLATE 2-1

Hume-Bluefish contact relationships.

- a Top of Hume Formation abruptly overlain by dark brown, laminated shale of the Hare Indian, Bluefish Member. Exposure at Gayna River (section 15). Bluefish Member is 15 m thick.
- b Lowermost 30 cm of Bluefish Member is a condensed styliolinid-tentaculitid-fish fragment lime packstone. Note abrupt contact with underlying Hume Formation marked by base of 15 cm scale. Exposure at Gayna River (section 15).
- c Close-up of Hume-Bluefish contact (above 15 cm scale) at section 15. Note common Leiorhynchus valves in the Hume shale.

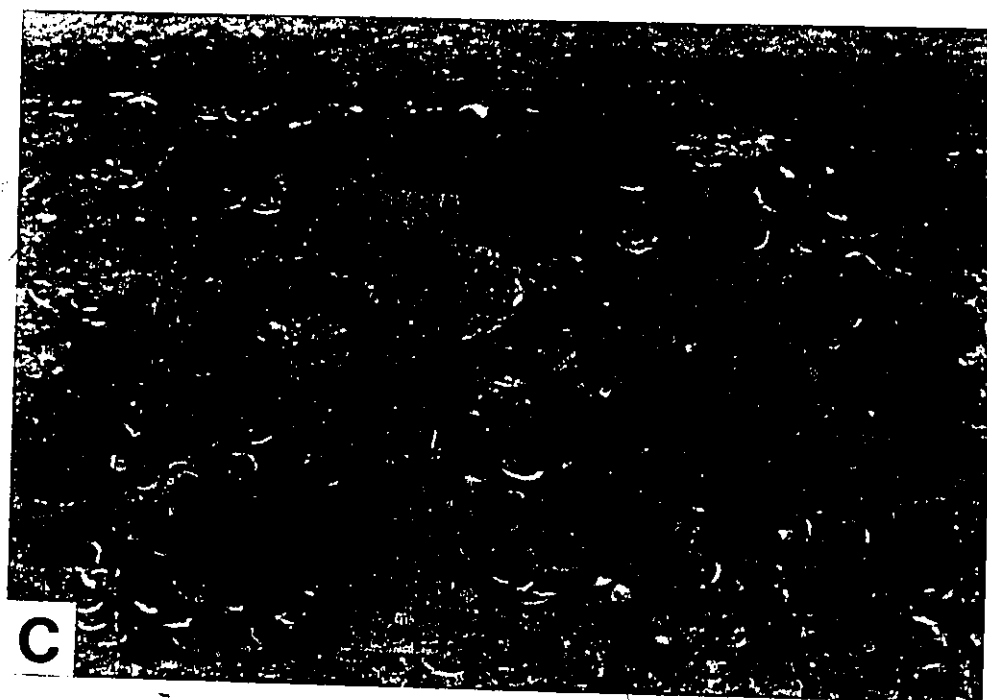


PLATE 2-1

PLATE 2-2

Carcajou subfacies.

- a Carcajou subfacies (0.6 m thick) at section 15. Note that basal portion of Carcajou subfacies is more argillaceous, pyritiferous, and less fossiliferous than the upper portion above the 15 cm scale.
- b Carcajou subfacies (6 m thick) at section 03. Base (Carcajou Marker) at contact with thick limestone bed (uppermost ramp facies). 1.5 m long scale.
- c Carcajou subfacies (7.7 m thick) at Mountain River tributary (section 25). Hare Indian Formation 55 m thick.



PLATE 2-2

PLATE 2-3

Second-order reef cycles in
the Ramparts Formation.

Second-order reef cycles (Ramparts Formation) in the vicinity of West Powell Creek (section 07). FIG. 2-3 diagrammatically illustrates the position of these cycles in the Ramparts platform-reef complex.

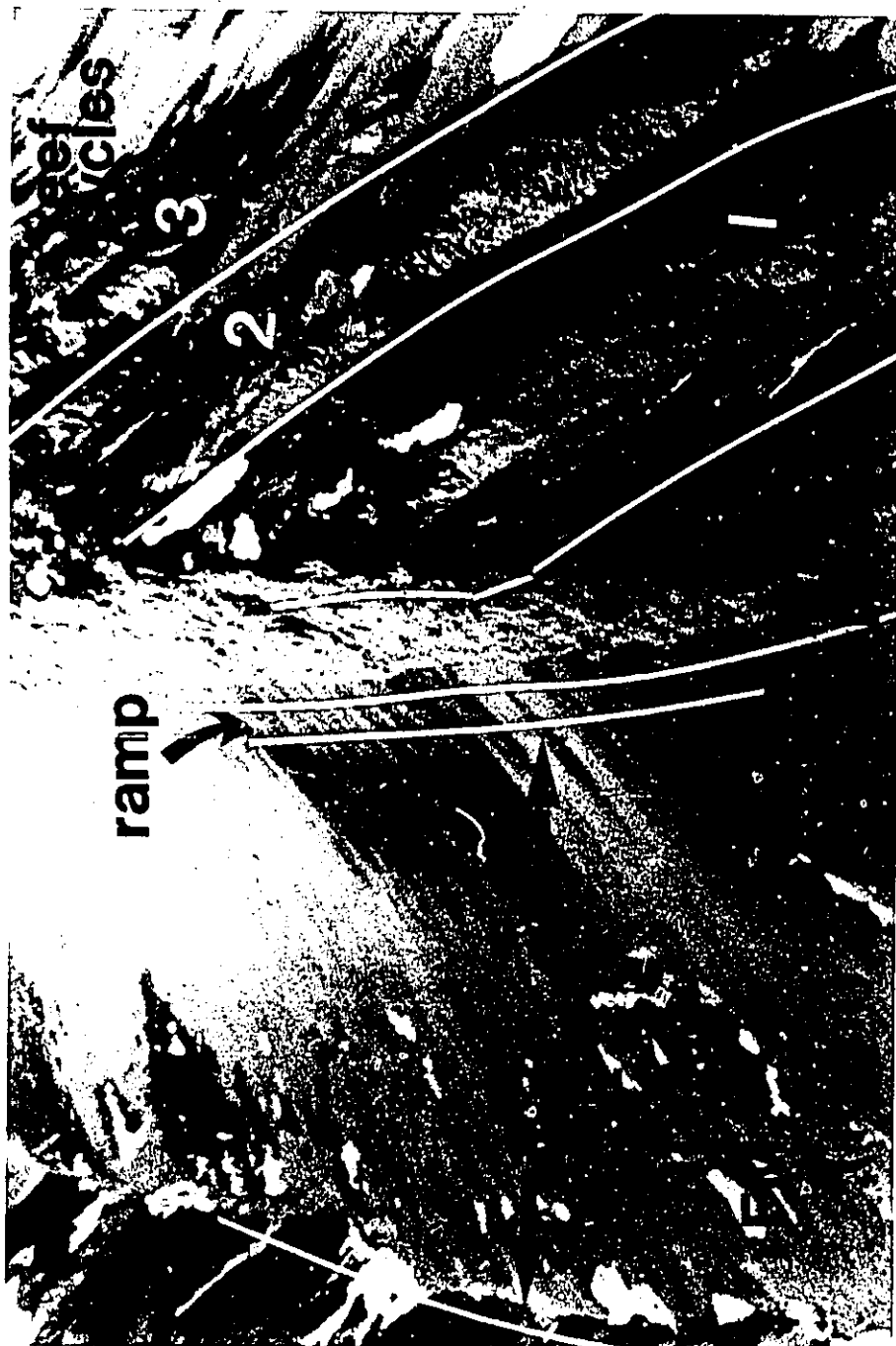


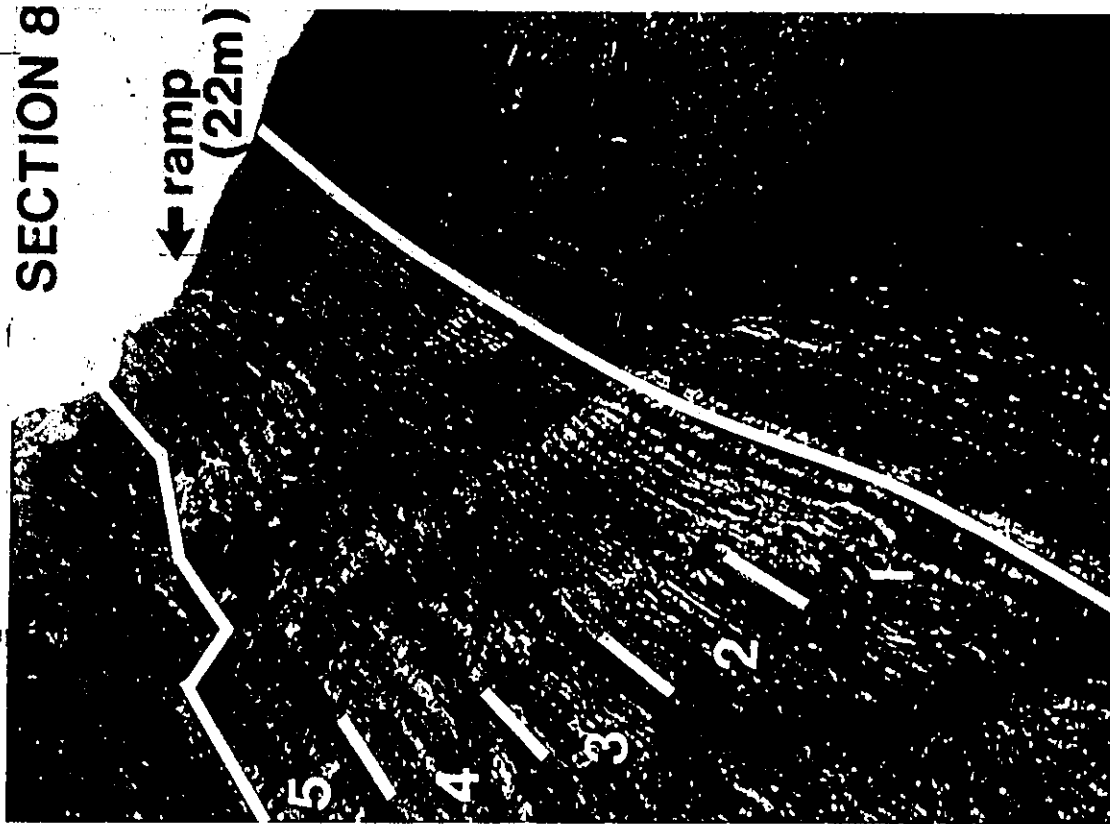
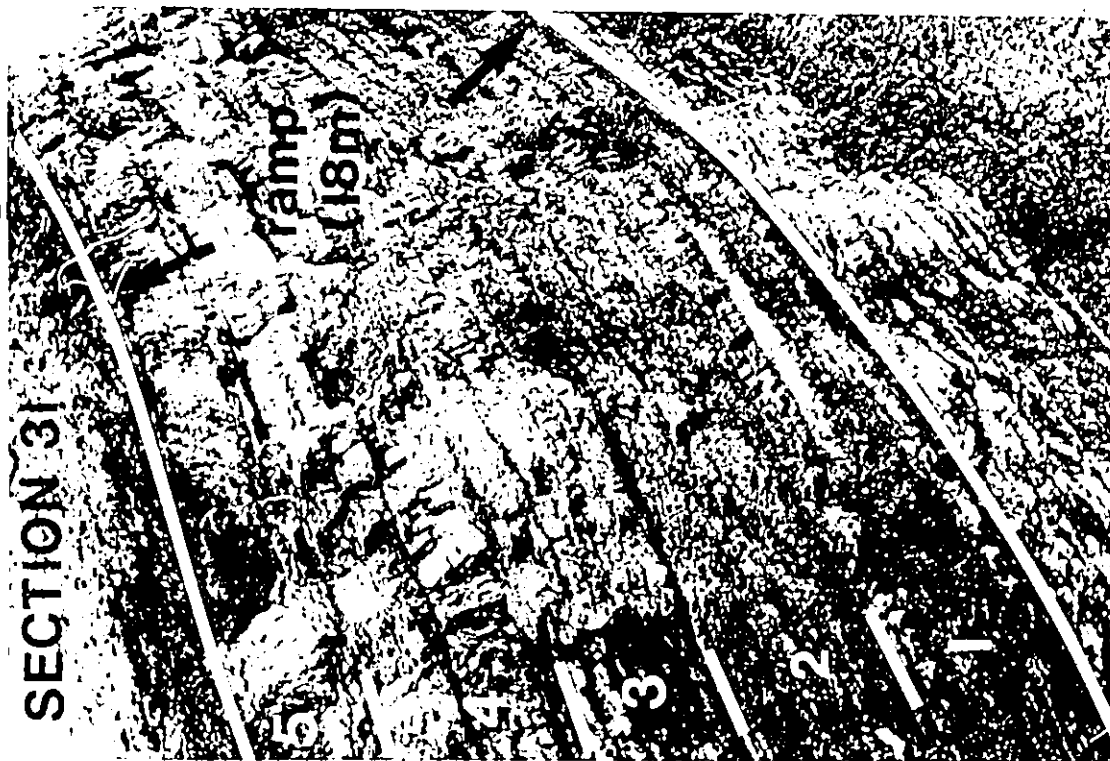
PLATE 2-3

PLATE 2-4

Third-order cycles in the
ramp facies association.

Correlation of third-order cycles in the ramp facies
association (Ramparts Formation). Note shaley lower
portions of cycles and abrupt cycle boundaries.

4.8 Km



III

SEDIMENTOLOGY AND PALEOENVIRONMENTAL
RECONSTRUCTION OF A BASIN-FILL SUCCESSION:
HARE INDIAN FORMATION AND
RAMPARTS FORMATION (LOWER "RAMP" MEMBER)

3.1 INTRODUCTION

Systematic lithostratigraphic analysis should deal with several aspects of basin-fill geology, particularly:

- (1) The framework of the basin, including its size, shape, probable range of water depths, and major sediment sources, and
- (2) Principal depositional units (cf. depo-units in Stoakes, 1979, 1980) and analysis of their depositional architecture.

Shallowing-upward cycles make up the Hare Indian-Lower Ramparts succession (see Chapter 2) and the recognition of cyclicity permits construction of a dynamic model for the evolution of this Middle Devonian basin-fill package. There are only a few detailed accounts of ancient basin-fill successions in the literature (e.g. Woodrow and Isley, 1983). This may be due to the apparent monotony and limited exposure of many such successions. Lithologic heterogeneity of the Hare Indian-lower Ramparts sequence has not been widely appreciated. Consequently, the major objectives in this chapter are the following:

- (1) To determine the origin, mode of transport, and depositional environments of the fine-grained sediments which comprise most of the basin-fill succession.
- (2) To understand the significance of shallowing-upward cycles in the succession.

- (3) To construct a depositional model consistent with the cyclic evolution of the Hare Indian-lower Ramparts stratal assemblage.

Three major facies associations (ramp, clinothem, basin) are recognized in the basin-fill succession using criteria outlined in Chapter 2. The ramp and clinothem facies associations are each subdivided into upper and lower facies using both lithologic attributes and stratigraphic position with respect to certain geologic markers. Finally, the smallest lithofacies groupings, or subfacies, are described and interpreted in the broader context of the facies or facies associations to which they belong.

Study of the Hare Indian-lower Ramparts succession contributes to two areas of research in which little work has been done. Mechanisms for sediment-transport across ancient shelves are still poorly understood, particularly for storm-influenced sequences. In this chapter, it will be shown that storm-deposited carbonates in both the ramp facies association and upper clinothem facies show evidence for spatial and temporal variations in flow conditions with varying water depths. Finally, the nature of transport and deposition of fine-grained carbonate turbidites is a relatively new field of research (see Stow et al., 1984). Most conceptual models interpret carbonate turbidite sequences by analogy with modern canyon-fan turbidites. However, the fine-grained turbidites that comprise most of

the Hare Indian clinotherm facies association do not show evidence for point sources. This also will be addressed in relevant portions of this chapter.

3.2 FACIES ANALYSIS OF THE RAMP FACIES ASSOCIATION

3.2.1 General Statement

Differences between the upper and lower ramp facies are outlined in TABLE 3-1. Four subfacies were recognized in the lower ramp facies, and four in the upper ramp facies (FIGS. 3-1, 3-2). These subfacies are described individually below.

References are made to common shapes or growth forms of corals and stromatoporoids in some subfacies. These growth forms reflect both phylogeny and the adaptation of shape to environment. While a sound taxonomy should be established wherever possible, this study emphasizes the paleoecological cause-and-effect relationship between environmental conditions and organism growth forms. Bjerstedt and Feldman (1985) considered growth forms to be advantageous or disadvantageous in particular paleoenvironments. However, unlike their study, in which paleoecologic interpretations were based on methodological uniformitarianism, this study, using cycle concepts, helps to provide more precise depth-related paleoecologic information. Definitions and

TABLE 3-1

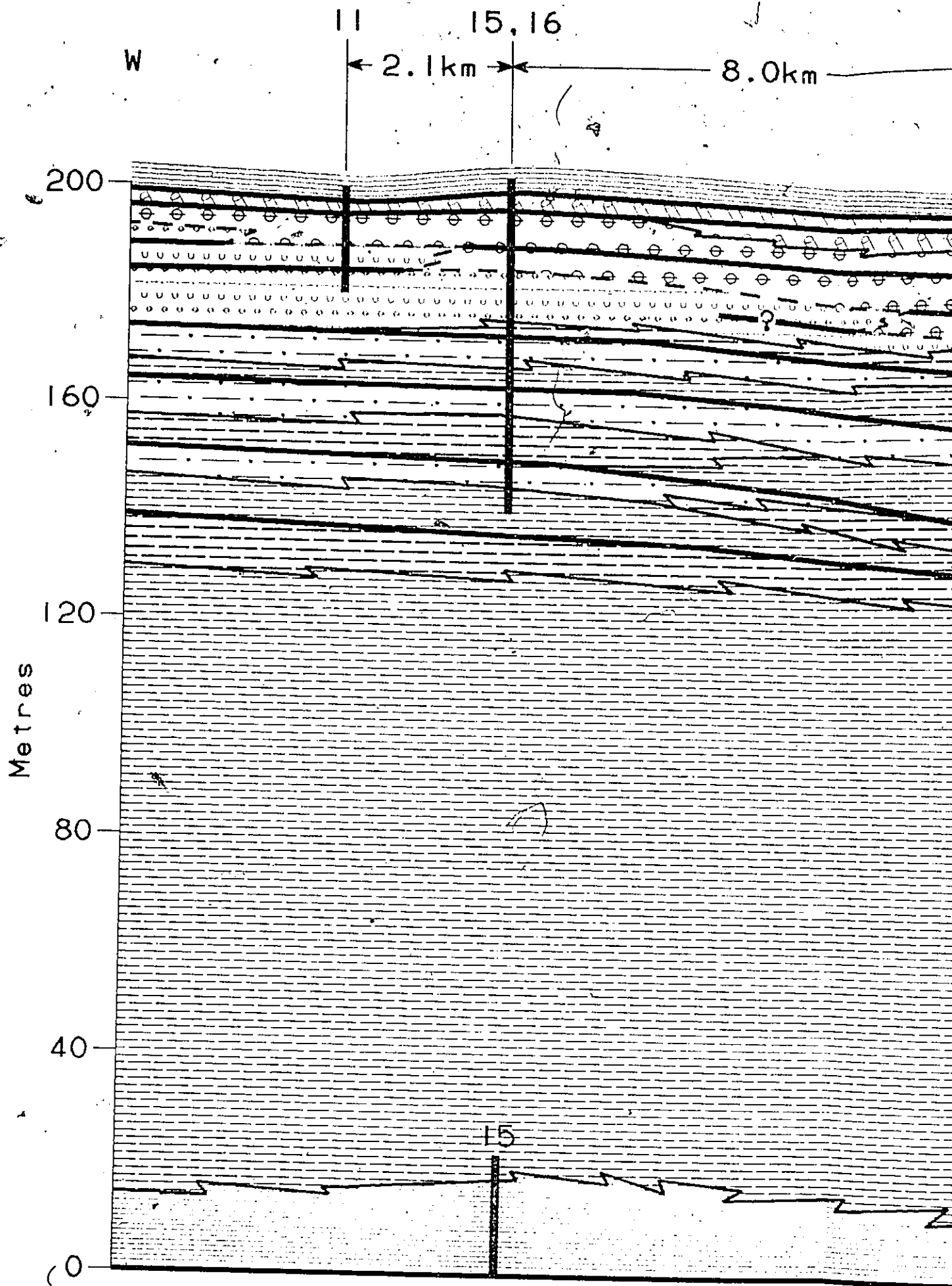
LOWER RAMP FACIES CHARACTERISTICS

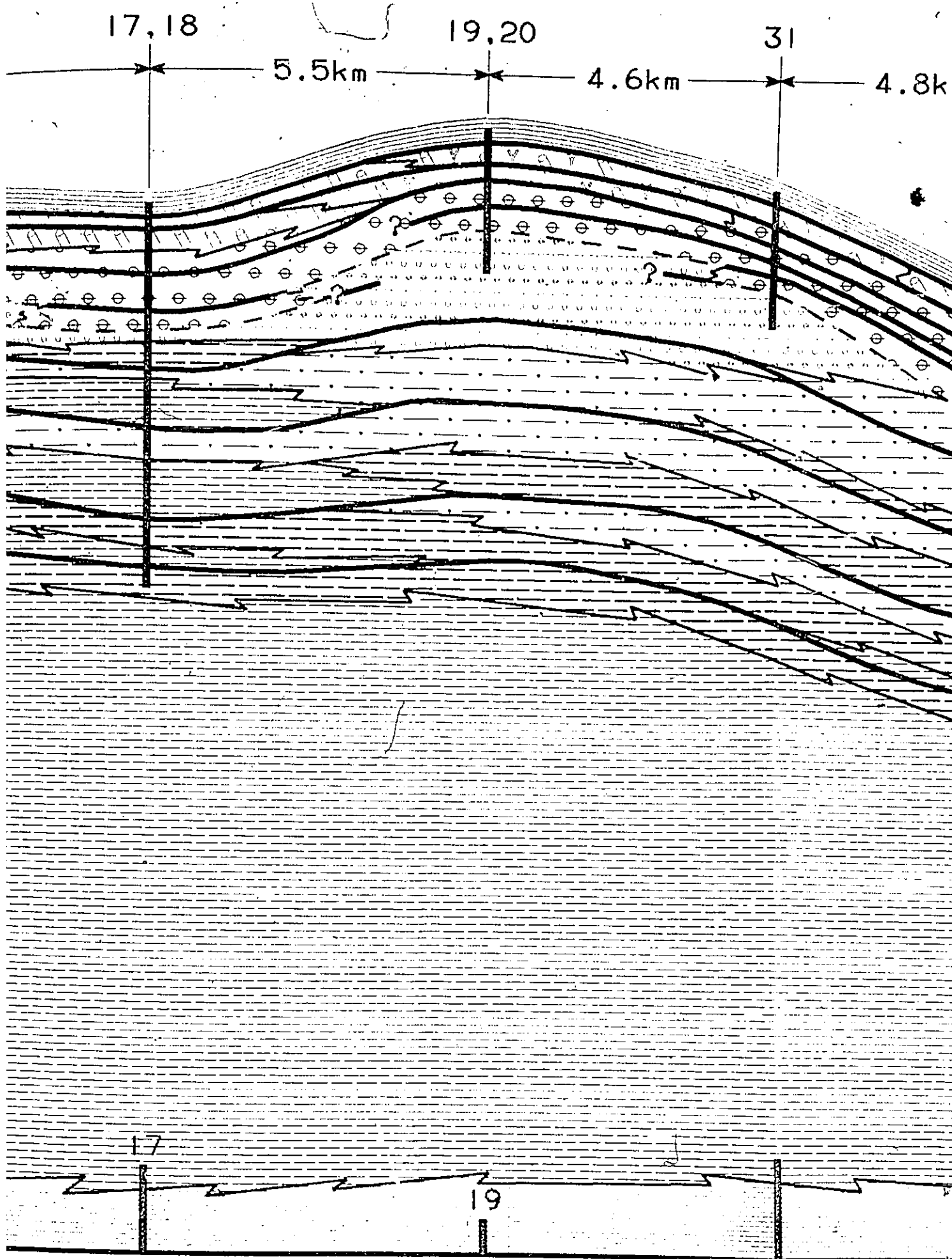
- Mainly interbedded shale and dark, nodular lime mudstone, wackestone.
- Common evidence for storm reworking and deposition (Muir and Dixon, 1984).
- Sparse, low diversity benthic fauna dominated by a brachiopod-crinoid assemblage; moderate bioturbation (Chondrites, Teichichnus, Planolites, Rhizocorallium).

UPPER RAMP FACIES CHARACTERISTICS

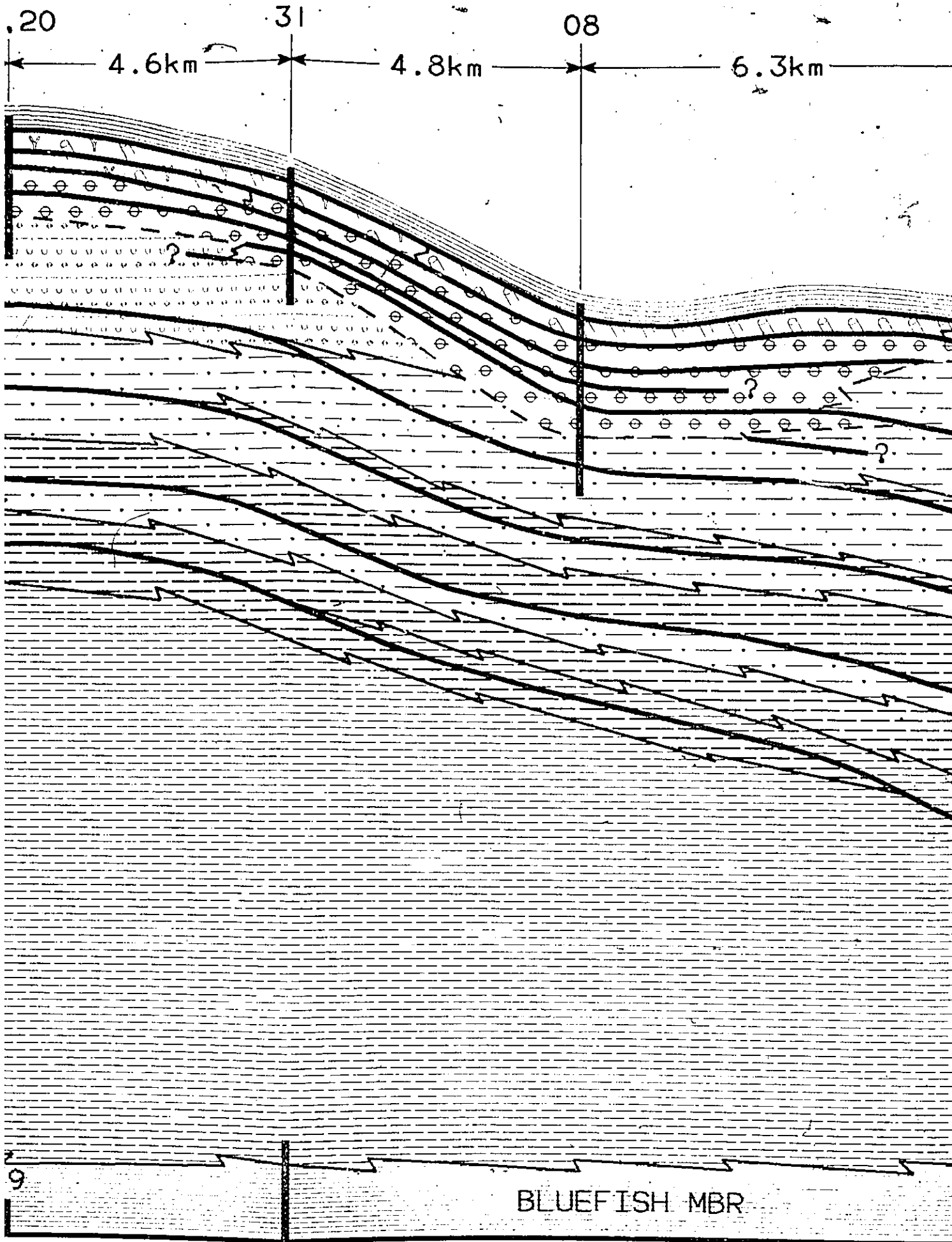
- Mainly light colored, coarse-grained limestones which tend to be thickly bedded (30-50 cm) with only minor shale interbeds.
- Evidence for storm deposition, poorly preserved due to intense bioturbation (Muir and Dixon, 1984).
- High benthic faunal diversity and abundance, particularly for the stromatoporoid-coral fauna.

FIG. 3-1 Facies distribution in the Hare Indian-lower Ramparts basin-fill succession. Subfacies in the lower and upper ramp facies have been grouped together for purposes of simplicity. Lower portion of basin-fill succession shows tentative cycle correlations and facies distributions due to lack of exposure. See FIGS. 3-2, 4-4, for continuation of Ramparts facies distribution.





DATUM - TOP OF HUME FM



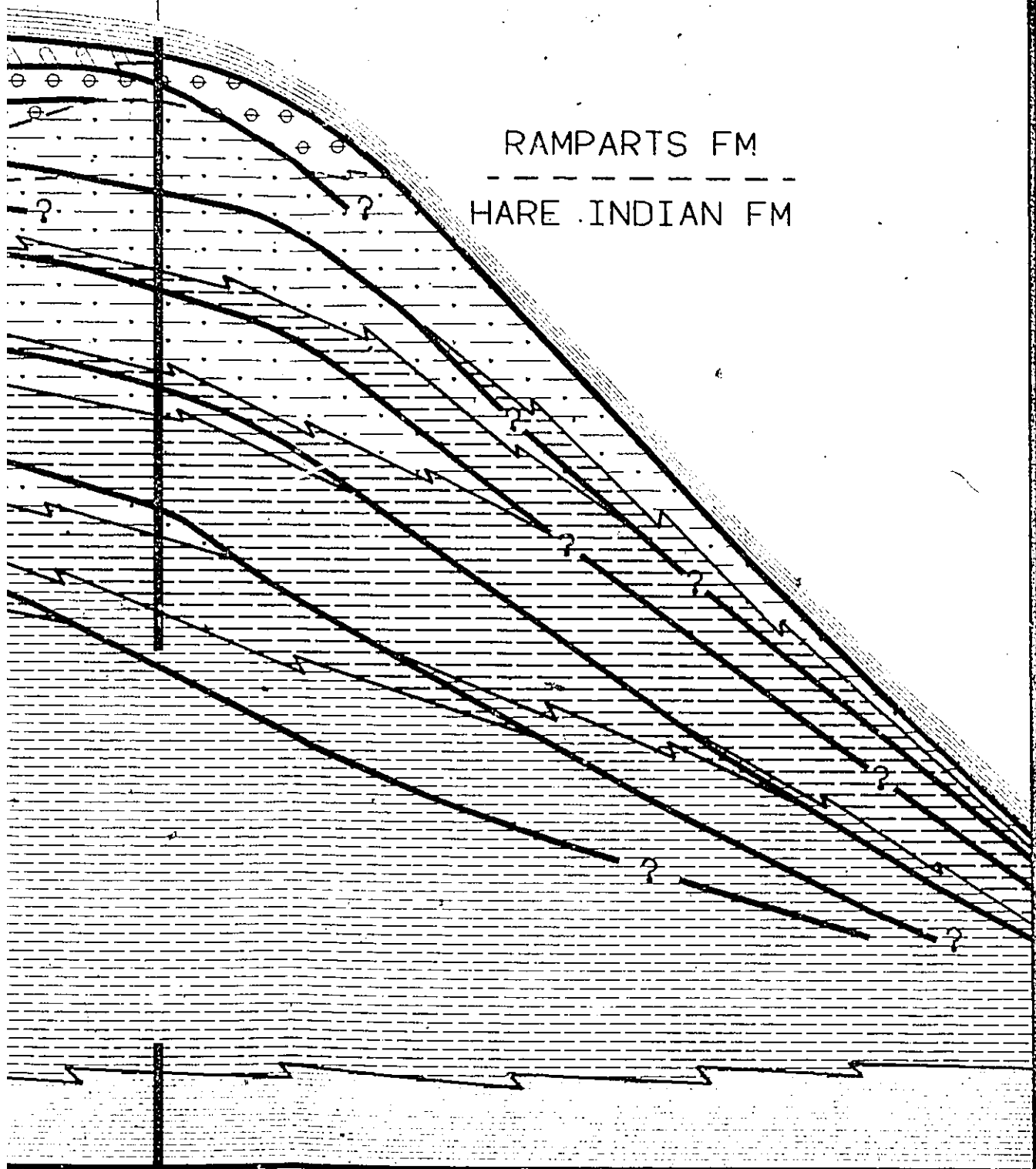
DATUM - TOP OF HUME FM

07

25

11.4km

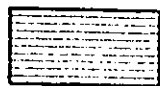
E



FACIES KE

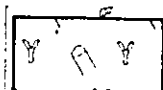
PLATFORM FACIES ASSOCIATION

**CARCAJOU
SUBFACIES**



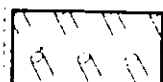
ARGILLACEOUS, PYRITIFEROUS MUDSTONE; STORM-DERIV
MINOR RAMOSE CORAL FLOATSTONE

**UPPER
RAMP
FACIES**



SUBFACIES 1

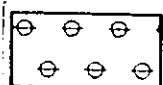
CYLINDRICAL STROMATOPOROID-RAMOSE CORAL RUDSTONE



SUBFACIES 2, 3, 4

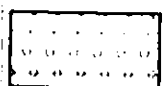
WAVE-TABULAR STROMATOPOROID - RAMOSE CORAL RUDS
RAMOSE CORAL RUDSTONE, FLOATSTONE (SUBFACIES 3);

**LOWER
RAMP
FACIES**



SUBFACIES 1, 2, 4

RAMOSE CORAL RUDSTONE, FLOATSTONE (SUBFACIES 1);
WACKESTONE (SUBFACIES 4)

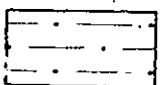


SUBFACIES 3

SLIGHTLY NODULAR PELOIDAL CALCISILTITE WITH COMM
SILTY SHALE

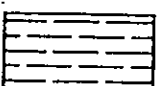
CLINOTHEM FACIES ASSOCIATION

**UPPER
CLINOTHEM
FACIES**



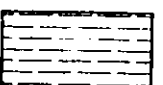
>40% PELOIDAL CALCISILTITE; GREY-OLIVE CALCAREOU
WACKESTONE, PACKSTONE

**LOWER
CLINOTHEM
FACIES**



SUBFACIES 1

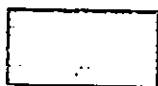
GREY CALCAREOUS SHALE; 15-40% PELOIDAL CALCISILT



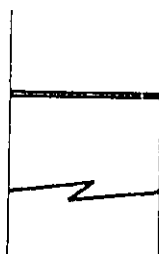
SUBFACIES 2

DARK GREY CALCAREOUS SHALE; RARE PELOIDAL CALCIS

**BASIN
FACIES
ASSOCIATION**



DARK BROWN-BLACK LAMINATED SHALE; VARIABLE CARBO



MAJOR CYCLE BOUNDARY

FACIES OR SUBFACIES BOUNDARY

VERTICAL EXAGGERATION 83X

FACIES KEY

SSOCIATION

S MUDSTONE; STORM-DERIVED CALCISILTITE; DARK NODULAR LIME MUDSTONE, WACKESTONE, TONE

CIATION

D-RAMOSE CORAL RUDESTONE, FLOATSTONE

DID - RAMOSE CORAL RUDESTONE, FLOATSTONE, BOUNDSTONE (SUBFACIES 2),
DATSTONE (SUBFACIES 3); SKELETAL LIME WACKESTONE-PELOIDAL CALCISILTITE (SUBFACIES 4)

DATSTONE (SUBFACIES 1); LIME PACKSTONE (SUBFACIES 2); NODULAR LIME MUDSTONE,

CALCISILTITE WITH COMMON CRINOID-BRACHIOPOD COQUINITES; GREY-OLIVE CALCAREOUS,

ASSOCIATION

; GREY-OLIVE CALCAREOUS SILTY SHALE, SUBORDINATE NODULAR LIME MUDSTONE,

40% PELOIDAL CALCISILTITE

; RARE PELOIDAL CALCISILTITE

SHALE; VARIABLE CARBONATE CONTENT; RARE PELOIDAL CALCISILTITE

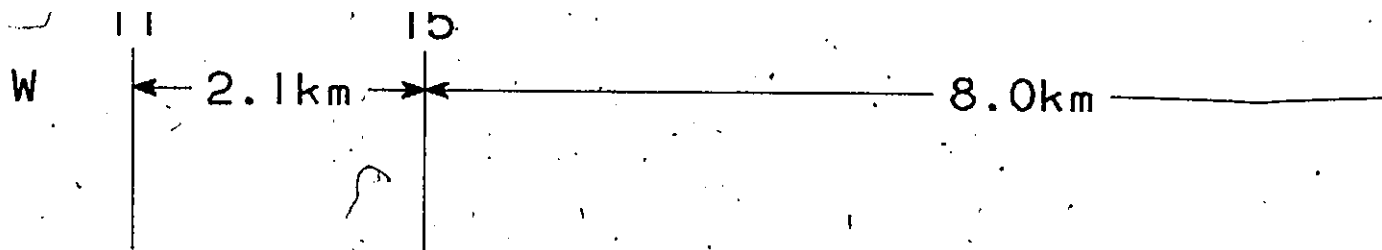
IUNDARY

FIG. 3-1

FACIES DISTRIBUTION IN THE
HARE INDIAN - LOWER RAMPARTS
BASIN-FILL SUCCESSION

STRATIGRAPHIC CROSS SECTION.

FIG. 3-2 Facies distribution in the uppermost Hare Indian to mid-Ramparts succession. Subfacies (numbered) are listed under their facies groupings. See FIG. 3-1 for continuation of Hare Indian facies distribution, and FIG. 4-4 for continuation of Ramparts facies distribution.



IMPERIAL FM

240—

220—

CANOL FM

200—

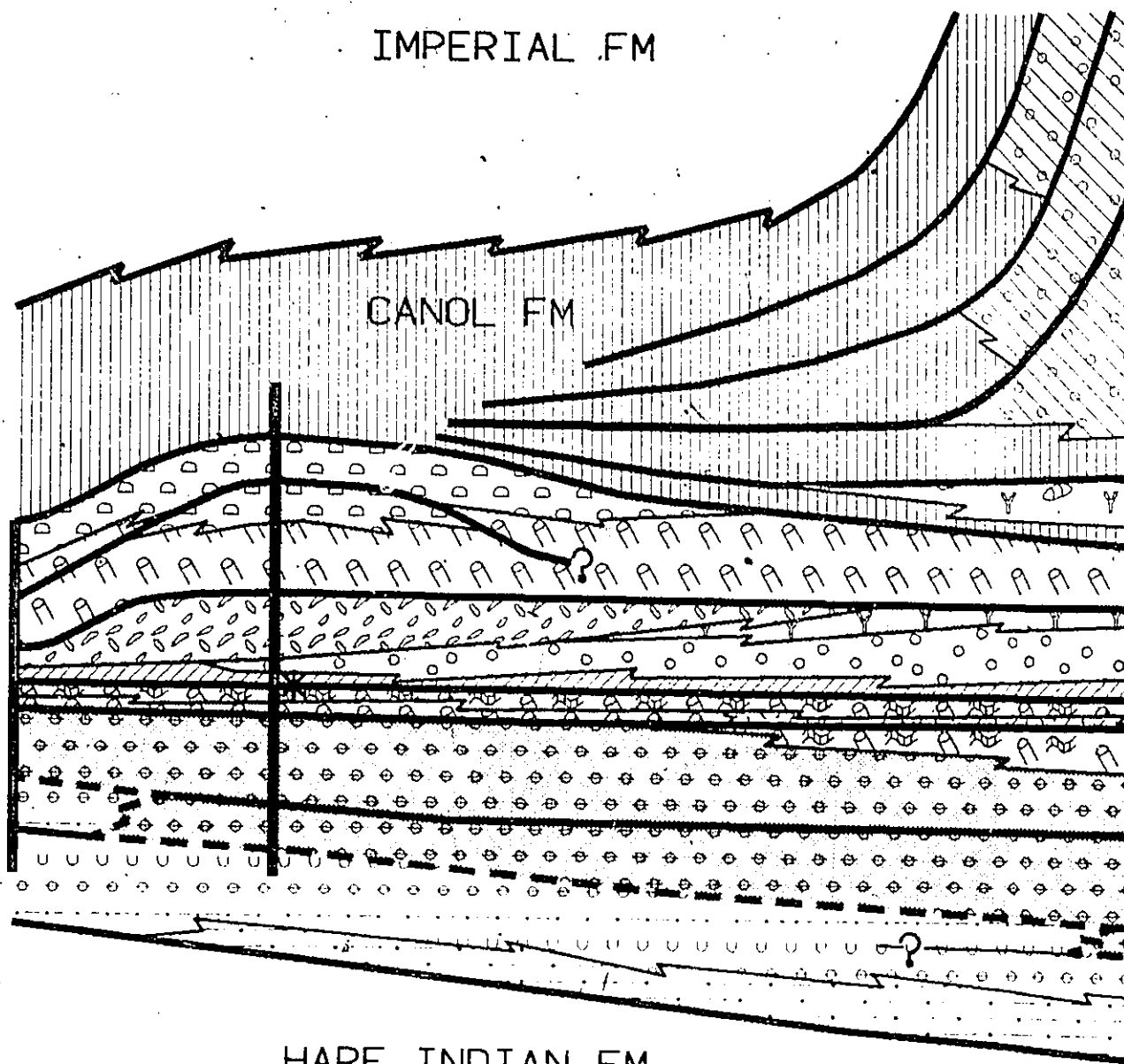
Metres

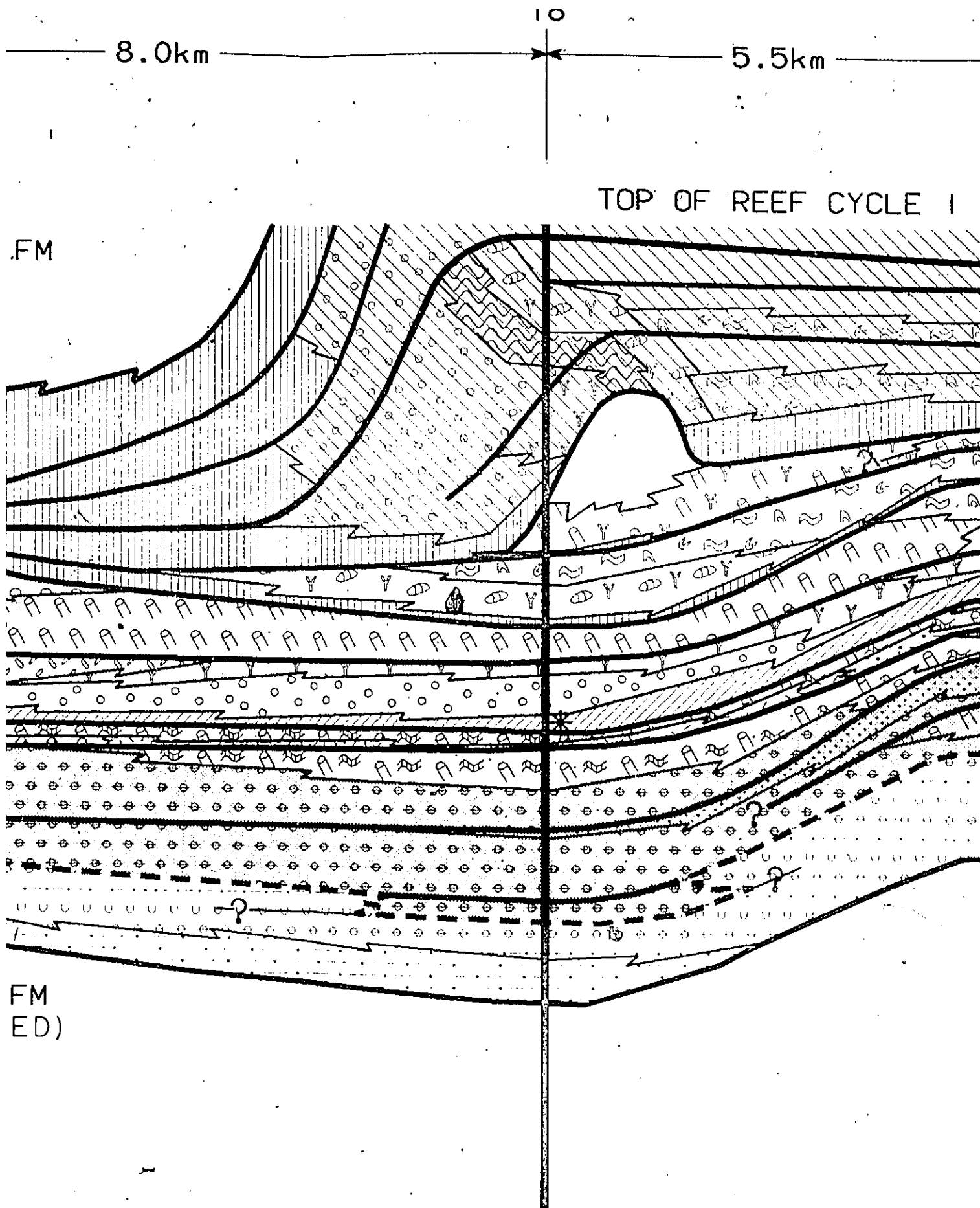
180—

160—

HARE INDIAN FM
(UNDIFFERENTIATED)

140—



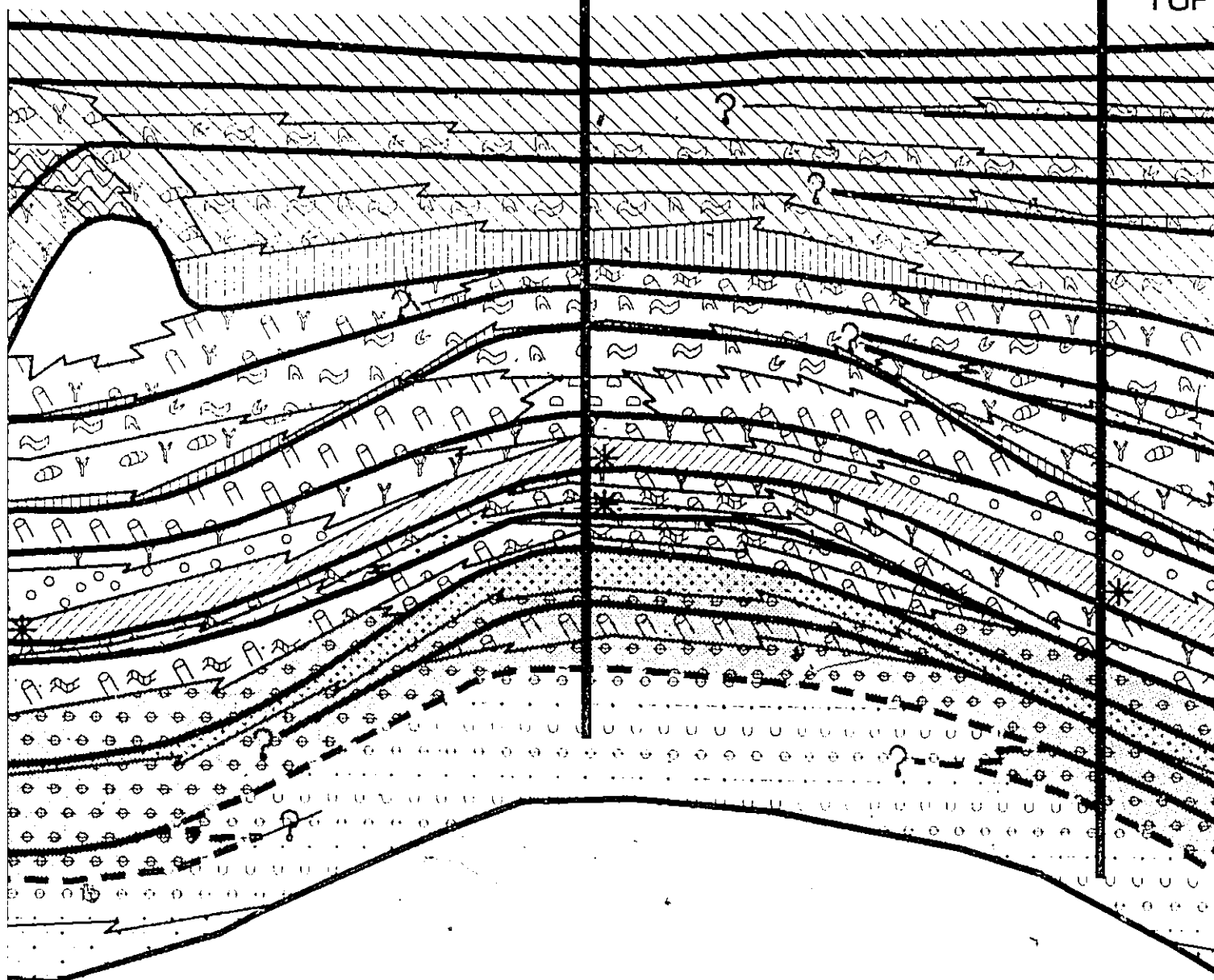


DATUM - TOP OF HUME FORMATION

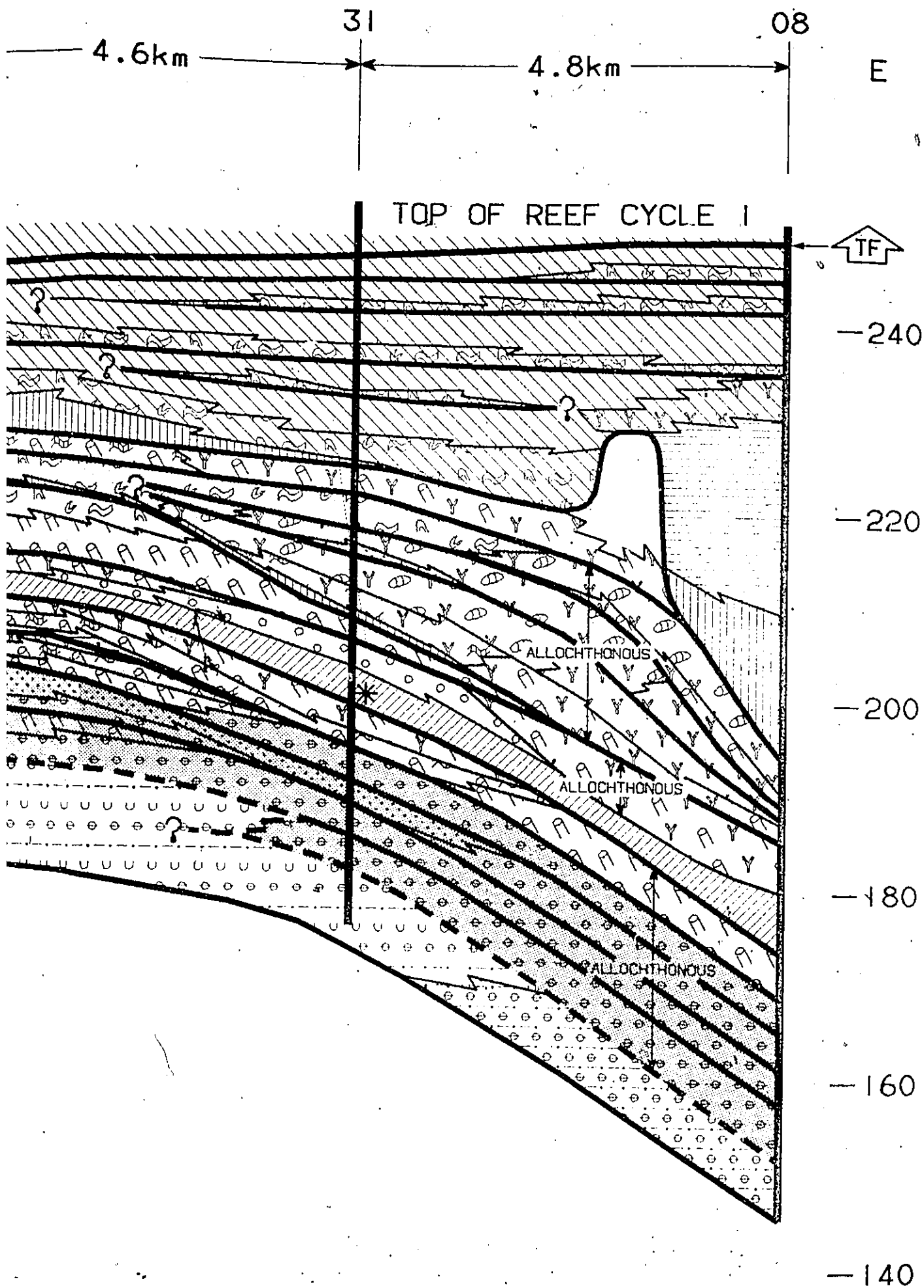
31

4.6km

TOP



- TOP OF HUME FORMATION



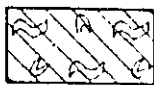
REEF FACIES ASSOCIATION

REEF INTERIOR FACIES



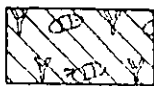
SUBFACIES 1

AMPHIPORA RUDSTONE, FLOATSTONE; LIME MUDSTONE, WACKESTONE



SUBFACIES 2

BULBOUS-ENCrustING-CYLINDRICAL STROMATOPOROID RUDSTONE, FLOATSTONE



SUBFACIES 3

ABRADED STROMATOPOROID RUDSTONE; ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE

REEF MARGIN/ SHOAL FACIES



SUBFACIES 1

THICK TABULAR STROMATOPOROID RUDSTONE, BOUNDSTONE; MINOR ABRADED STROMATOPOROID RUDSTONE



SUBFACIES 2

ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE; MINOR ABRADED STROMATOPOROID RUDSTONE

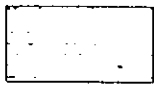
REEF FORESLOPE FACIES



SUBFACIES 3

LIME GRAINSTONE

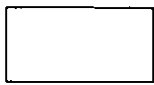
EMBAYMENT FACIES



SUBFACIES 1, 2

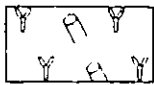
ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE; WAFER-CYLINDRICAL STROMATOPOROID FLOATSTONE, RUDSTONE, BOUNDSTONE; WAFER STROMATOPOROID-RAMOSE CORAL FLOATSTONE, RUDSTONE

UPPER PLATFORM FACIES



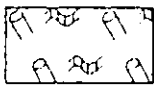
SUBFACIES 1, 2

ABRADED STROMATOPOROID RUDSTONE; THICK TABULAR STROMATOPOROID-ALGAL BOUNDSTONE



SUBFACIES 2

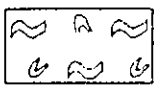
ROBUST CYLINDRICAL STROMATOPOROID-RAMOSE CORAL RUDSTONE, FLOATSTONE; MINOR LIME WACKESTONE



SUBFACIES 3

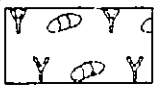
WAFER STROMATOPOROID-RAMOSE CORAL FLOATSTONE, RUDSTONE, BOUNDSTONE

MIDDLE PLATFORM FACIES



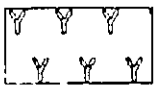
SUBFACIES 1

BULBOUS-ENCrustING-CYLINDRICAL STROMATOPOROID FLOATSTONE, RUDSTONE, BOUNDSTONE



SUBFACIES 2

a) ABRADED STROMATOPOROID RUDSTONE



b) ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE, FLOATSTONE



c) ROBUST CYLINDRICAL STROMATOPOROID-RAMOSE CORAL RUDSTONE, FLOATSTONE

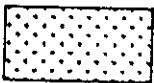
FACIES KEY

MIDDLE PLATFORM FACIES (CONT'D)



SUBFACIES 3

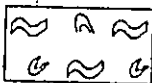
WAFER-CYLINDRICAL STROMATOPOROID FLOATSTONE, RUDESTONE, BOUNDSTONE



SUBFACIES 4

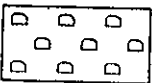
LIME PACKSTONE

LOWER PLATFORM FACIES



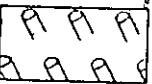
SUBFACIES 1

BULBOUS-ENCRUSTING-CYLINDRICAL STROMATOPOROID RUDESTONE, FLOATSTONE



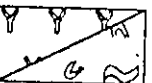
SUBFACIES 2

MASSIVE (HEMISPHERICAL, BULBOUS) CORAL FLOATSTONE; MINOR RAMOSE CORAL RUDESTONE



SUBFACIES 3

RAMOSE CORAL RUDESTONE, FLOATSTONE; MINOR WAFER-RAMOSE CORAL FLOATSTONE; MINOR LIME WACKESTONE, PACKSTONE



SUBFACIES 4

a) ROBUST CYLINDRICAL STROMATOPOROID RUDESTONE; BULBOUS-ENCRUSTING-CYLINDRICAL STROMATOPOROID RUDESTONE, FLOATSTONE



b) SMALL CYLINDRICAL STROMATOPOROID RUDESTONE



c) LIME GRAINSTONE, MINOR LIME PACKSTONE



d) CYLINDRICAL STROMATOPOROID-RAMOSE CORAL RUDESTONE, FLOATSTONE



CARCAJOU SUBFACIES

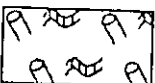
NODULAR LIME MUDSTONE; DARK GREY CALCAREOUS SHALE; LIME WACKESTONE; RAMOSE CORAL FLOATSTONE

UPPER RAMP FACIES



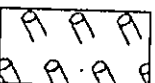
SUBFACIES 1

CYLINDRICAL STROMATOPOROID-RAMOSE CORAL FLOATSTONE, RUDESTONE



SUBFACIES 2

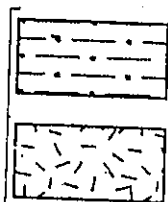
WAFER STROMATOPOROID-RAMOSE CORAL FLOATSTONE, RUDESTONE, BOUNDSTONE



SUBFACIES 3

RAMOSE CORAL RUDESTONE, FLOATSTONE

UPPER RAMP FACIES (CONT'D)

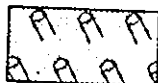


SUBFACIES 4

a) PELOIDAL CALCISILTITE

b) SKELETAL LIME WACKESTONE

LOWER RAMP FACIES



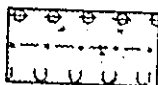
SUBFACIES 1

RAMOSE CORAL FLOATSTONE, RUDSTONE; NODULAR LIME WACKESTONE



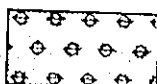
SUBFACIES 2

PELOIDAL LIME PACKSTONE



SUBFACIES 3

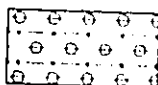
SLIGHTLY NODULAR, QUARTZOSE PELOIDAL CALCISILTITE WITH COMMON CRINOID-BRACHIOPOD COQUINITE; GREY-OLIVE CALCAREOUS SHALE



SUBFACIES 4

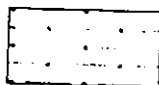
NODULAR LIME MUDSTONE, WACKESTONE, PACKSTONE; MINOR CALCAREOUS SHALE AND SKELETAL WACKESTONE

UPPER CLINOTHEM FACIES



>40% SLIGHTLY NODULAR PELOIDAL CALCISILTITE; GREY-OLIVE CALCAREOUS SILTY SHALE

LOWER CLINOTHEM FACIES



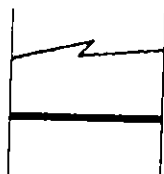
SUBFACIES 1

15-40% PELOIDAL CALCISILTITE; GREY CALCAREOUS SHALE

BASIN FACIES ASSOCIATION



DARK BROWN LAMINATED SHALE; VARIABLE CARBONATE CONTENT; RARE PELOIDAL CALCISILTITE



FACIES OR SUBFACIES BOUNDARY

MAJOR CYCLE BOUNDARY



TIDAL FLAT LITHOFACIES



TEMPESTITE LITHOFACIES

RAMPARTS FM

HARE INDIAN FM

VERTICAL EXAGERRATION 145X

FIG. 3-2

FACIES DISTRIBUTION IN THE
UPPERMOST HARE INDIAN TO
MID-RAMPARTS SUCCESSION

STRATIGRAPHIC CROSS SECTION

semi-quantitative measures of the various shape classes utilized in this study are summarized in TABLE 3-2.

3.2.2 Upper Ramp Facies

3.2.2.1 Upper ramp subfacies 1

Subfacies 1 consists typically of planar-bedded (15-45 cm thick) cylindrical stromatoporoid-ramose coral rudstone and floatstone. It is restricted to paleotopographic highs on the ramp (see FIG. 3-2) where it occupies the upper portions of third-order shallowing-upward cycles in sections 20 and 31. It represents the uppermost ramp facies in section 20 (unit 009) and section 31 (unit 007B) where it is 1.0 and 2.6 m thick, respectively. It is interbedded at the base with upper ramp subfacies 2 and sharply overlain by the Carcajou subfacies. A 20 cm thick bed of crinoid-atrypid brachiopod grainstone forms the topmost part of units 20-009 and 31-007B in both sections. This bed shows upward-fining of allochems, high quartz content (10-20% silt-sized quartz grains) and a scoured basal contact, evidently representing prior deep scouring of the underlying rudstone-floatstone. A brachiopod coquina occurs at the base of the bed and thickens into erosional scours. Most valves are disarticulated, but unbroken, and have no preferred orientation. The fining-upward nature likely represents

TABLE 3-2

STROMATOPOROID AND CORAL GROWTH FORMS AND DEFINITIONS

Wafer	- flat, plate-like; width:height ratio >10:1, height (thickness) generally <1 cm
Tabular	- flat, plate-like; width:height ratio >10:1, height (thickness) generally >1 cm
Hemispherical	- broad, flat base; convex upper surface
Bulbous	- convex upper surface tapers down to small base; vertical and horizontal growth axes approximately equal
Encrusting	- epibionts take the form of the object they encrust
Cylindrical, Robust	- elongate, cylindrical forms having subcircular cross-sections >4 mm in diameter
Cylindrical, Delicate	- elongate, cylindrical forms having subcircular cross-sections <4 mm in diameter

deposition during a waning storm event (cf. Kreisa, 1981; Branchley and Newall, 1982). Because this bed occurs immediately beneath a prominent cycle break (Carcajou Marker), its correlation over the 4.6 km separating sections 20 and 31 supports the hypothesis that cycle boundaries can be used as synchronous time planes in lithostratigraphic correlations.

The cylindrical stromatoporoid-ramose coral rudstone and floatstone making up most of subfacies 1 typically have a matrix of peloidal packstone to wackestone that is coarser than in subfacies 2. A diverse and open-marine assemblage of fossils is present in subfacies 1 (TABLE 3-3, PL. 3-1b).

A variety of evidence collectively suggests that these sediments were deposited in slightly agitated, well-circulated waters with periods of high sediment influx. Robust cylindrical stromatoporoids are common and sometimes form aggregate grains bound by calcareous algae. Micritic envelopes occur on many of the allochems. Current-oriented thamnoporoid corals occur in section 20, unit 009. Thick, tabular stromatoporoids are commonly overturned. Sediment-shedding digitate and high extended hemispherical and bulbous growth forms predominate in the stromatoporoid-coral assemblage. The thick, tabular, and hemispherical forms commonly show ragged edges where sediment periodically encroached on the growing surface. This suggests fluctuating sedimentation rates possibly

TABLE 3-3

MACROFOSSILS OF UPPER RAMP SUBFACIES 1

Common Constituents

robust cylindrical stromatoporoid: Stachyodes
thamnoporoid tabulate coral: Thamnopora
crinoid columnals: robust, 5-10 mm diameter

Rare Constituents

delicate cylindrical stromatoporoid: Amphipora
tabular stromatoporoid
encrusting stromatoporoid
hemispherical stromatoporoid: actinostromatid?
bulbous stromatoporoid: clathrodictyid
hemispherical Alveolites: max. diameter 40 cm; height
bulbous Alveolites 25 cm, max. height 25 cm
solitary rugose coral: thick-walled; deep calice
brachiopods: atrypid; Stringocephalus
encrusting bryozoa
encrusting algae
sponge spicules
fish fragments

associated with varying current strength. The absence of wafer forms, which are more readily smothered by sediment (Kershaw, 1984) further substantiates variable sedimentation rates. However, turbulence was probably not high. Bulbous and hemispherical forms are generally less tolerant of high turbulence and the argillaceous matrix precludes constant winnowing.

3.2.2.2 Upper ramp subfacies 2

Subfacies 2 consists mainly of wafer and tabular stromatoporoid-ramose coral floatstone, rudstone, and boundstone. It is generally resistant, thickly-bedded (30-50 cm), and weathered medium-grey. Stratiform units 0.7-4.1 m thick form the topmost parts of ramp third-order cycles (FIG. 3-2) except where overlain by subfacies 1. Subfacies 2 is much more extensive laterally (10-15 km) and occurs at paleotopographic positions lower on the ramp than subfacies 1. Interestingly, at section 15, subfacies 2 is abruptly capped by a storm deposit, similar to that overlying subfacies 1 in sections 20 and 31, but topographically lower on the ramp (see FIG. 3-2). Units of subfacies 2 thin westward toward the isopach maximum of the Hare Indian lobe (FIGS. 3-1, 3-2) and eastward toward the basin (sections 08-01) as upper ramp facies pass laterally into lower ramp facies.

The subfacies is gradationally interbedded below with upper ramp subfacies 3 and less commonly with lower ramp subfacies 3. The upper contact is either a sharp cycle boundary or gradational with overlying upper ramp subfacies 1. The matrix in subfacies 2 ranges from a fragmented skeletal lime wackestone to peloidal packstone, but tends to be darker, muddier, and more pyritiferous than in subfacies 1.

Bedding contacts are generally stylonodular, and thin (3-5 cm), dark calcareous shale interbeds containing a low diversity thamnoporoid coral fauna locally characterize the basal portion of subfacies 2.

The fossil assemblage is as diverse and abundant as in subfacies 1 (TABLE 3-4) although cylindrical stromatoporoids are much less common and wafer to tabular stromatoporoid and coral growth forms predominate.

Subfacies 2 was apparently deposited in slightly agitated, open-marine water. A small proportion of wafer and tabular stromatoporoids have been disoriented and periodic movement of allochems is suggested by the occurrence of skeletal fragments completely encrusted by corals or stromatoporoids. Tabular stromatoporoids rarely show ragged peripheral margins, possibly indicating periodic changes in sedimentation rate.

However, conditions were probably less turbulent than for subfacies 1. Allochems are commonly pyritized and supported

TABLE 3-4

MACROFOSSILS OF UPPER RAMP SUBFACIES 2

Common Constituents

thamnoporoid tabulate coral: Thamnopora
tabular stromatoporoid: max. diameter 40 cm
wafer stromatoporoid
tabular alveolitid coral: Alveolites
crinoid columnals: robust, 10-20 mm diameter

Rare Constituents

Coenites

bulbous alveolitic coral
encrusting stromatoporoid
robust cylindrical stromatoporoid: more abundant toward
top of cycles
brachiopods: Stringocephalus
ostracod
encrusting calcareous algae
solitary rugose coral: short septa; both thick- and
sponge spicules thin-walled varieties
auloporid coral
fish fragments
encrusting bryozoan
delicate cylindrical stromatoporoid: Amphipora

in a darker, muddier matrix in subfacies 2. A high ratio of fragmented to whole fossils, and predominance of wafer to tabular stromatoporoid and coral growth forms are suggestive of low sedimentation rates. Branching and curved growth forms were not required as an adaption for efficient sediment removal. Despite the fragmented nature of most allochems, there is little evidence for abrasion (see PL. 3-1c). Furthermore, allochems show no evidence for current orientation and tend to be less intensely micritized than in subfacies 1. Epibionts commonly encrusted allochems rather than the surrounding, probably unstable, muddy substrates (PL. 3-2a). Presumably low sedimentation rates permitted successions of epibionts to colonize suitable hard surfaces (PL. 3-2b) such as skeletal fragments.

However, autochthonous wafer stromatoporoids also occur in muddy sediments where appropriate hard surfaces were lacking. Apparently the wafer stromatoporoids could colonize soft, muddy sediments during times of little sediment influx (Kershaw, 1984). The organisms spread laterally with very little upward growth, achieving maximum sediment support with minimal skeletal weight and thus stabilizing the substrate. Bassett and Lawson (1984) noted that most stromatoporoids, with their high initial porosity, would have been less dense than other skeletal materials. In addition, the stromatoporoids were probably sedentary rather than sessile in this depositional environment since

there is no evidence of attachment to the substrate. Therefore, even slight perturbations in current energy could have disoriented the wafer stromatoporoids. Kershaw (1984) reported that in flume studies, wafer-shaped forms tend to be flipped over by currents, whereas heavier equidimensional domal forms are more stable. Periodic storm activity may have been sufficient to disorient some wafer stromatoporoids in subfacies 2 (PL. 3-2c). Woodley (1981) observed that Hurricane Allen (1980) was capable of physical disturbance to depths greater than 50 m off Jamaica where plate-like colonies of Agaricia were damaged.

3.2.2.3 Upper ramp subfacies 3

Subfacies 3 is typified by medium-dark grey, planar to slightly nodular-bedded (average 20 cm thick), ramose coral rudstone, floatstone, and interbedded dark grey calcareous shale. Lensoid (average 50 cm long, 8 cm thick) rudstone beds of crinoid-thamnoporoid coral-brachipod coquinite occur rarely in subfacies 3 along a paleotopographically high portion of the ramp (section 20; FIG. 3-2). Several thamnoporoid corals are preserved in upright positions. These beds were likely deposited rapidly by storms. The first stratigraphic appearance of this upper ramp subfacies is at the same paleotopographic high near section 20 (FIG. 3-2). These are time-equivalent to lower ramp subfacies 4 (mainly dark, nodular, lime mudstone and shale).

Subfacies 3 is the most extensive upper ramp subfacies (10-25 km) and commonly is interbedded above with subfacies 2. In the study area, subfacies 3 typically occupies the basal portion of upper ramp third-order cycles (FIG. 3-2). Units of subfacies 3 are 1.3-2.8 m thick (average 1.6 m), and thin towards the basin (section 11, FIG. 3-1).

Lithologies are predominantly mud-supported, with a dark brown, microstylolitized carbonaceous skeletal wackestone matrix. Fossils are commonly pyritized peripherally and show little evidence of abrasion. Rounded, dark brown lime mudstone intraclasts (average 1 cm diameter) occur rarely in section 08 (unit 008).

A diverse, open-marine fossil assemblage characterizes subfacies 3 (TABLE 3-5), but is distinguished from subfacies 2 by the following:

- (1) A more diverse and abundant assemblage of corals; stromatoporoids occur rarely.
- (2) More abundant ramose corals.
- (3) Lower overall faunal diversity.

At section 08 (FIG. 3-2), much of subfacies 3 appears to be allochthonous based on the following evidence:

- (1) Cycle correlations in FIGS. 3-1, 3-2, show that ramp facies in section 08 were deposited in a paleotopographic low. Interbedded shale is thicker there than in other sections.

TABLE 3-5

MACROFOSSILS OF UPPER RAMP SUBFACIES 3

Common Constituents

thamnoporoid tabulate coral: Thamnopora
 crinoid columnals

Rare Constituents

wafer stromatoporoid: actinostromatid, commonly bored
 encrusting stromatoporoids
 brachiopods
 tabular alveolitid coral
 encrusting alveolitid coral
 auloporid coral

CoenitesHexagonariaBillingsastria?

solitary rugose coral: thick-walled, commonly encrusted
 sponge spicules by stromatoporoids and corals
 bryozoan more abundant at section 08
 high-spired gastropod
 fish fragments
 ostracod

- (2) Wafer stromatoporoids and alveolitid corals are commonly overturned and oriented parallel to bedding. Lime mudstone intraclasts are present rarely.
- (3) Epibionts (alveolitids, stromatoporoids) show evidence for rapid sedimentation (invaginated margins) and redirection of growth. This is suggestive of variable sedimentation rates and episodic toppling and movement.

The mode of emplacement of this allochthonous material is unclear. There are no indications of massive sediment gravity flows. Possibly many of the allochems were periodically moved by storms and rolled downslope. Perkins and Enos (1968) observed that thickets of the ramose coral Acropora cervicornis suffered extensive fragmentation and redistribution in the Florida-Bahamas area after the passage of Hurricane Betsy in 1965. Apparently many of the living fragments survived and, because of their larger size, would have had a greater chance of survival than small, newly settled planulae (Randall and Eldredge, 1977; Neigel and Avise, 1984). The distribution of thamnoporoid corals into deeper waters may have been analogous.

The dark brown, muddy sediments of subfacies 3 accumulated mainly in calm, open-marine waters. The predominance of corals possibly reflects conditions adverse to stromatoporoids. Isaacson and Curran (1981) suggested

that low water turbulence and high turbidity levels could have limited stromatoporoid growth in calm, deep water settings. Storms can resuspend fine sediments in such environments and, together with mud introduced by current action from shallower ramp settings, could have created more persistently turbid conditions for subfacies 3 than for subfacies 1 or subfacies 2. Smosna and Warshauer (1979) suggested that thamnoporoids were suited to turbid waters and they postulated that the open-branching structure could have facilitated removal of mud by currents.

3.2.2.4 Upper ramp subfacies 4

Subfacies 4 is restricted to the basal portion of an upper ramp third-order cycle in sections 18 and 20 (FIG. 3-2). Units of this subfacies are 1-2 m thick at both localities and include a basal, dark brown, calcareous shale (20-40 cm thick). The cycle containing this subfacies is topographically higher at section 20. Subfacies 4 is typically coarser and siltier (admixed quartz and carbonate grains) in section 20 than in section 18.

At section 20 (unit 008), the subfacies consists of slightly nodular, interbedded peloidal calcisiltite, crinoidal lime grainstone, and calcareous shale. The grainstone beds have erosional basal contacts, and fine upward. The peloidal calcisiltite beds commonly contain discontinuous, lensoid, packstone coquinites representing

lag deposits of fragmented crinoids and brachiopods. The calcisiltite beds are intensely bioturbated except near their bases, where they show graded horizontal laminae (2-10 mm). The sequence mainly represents storm deposits that were laid down in relatively deeper water than subfacies 1 to 3. The sparse epifaunal assemblage (TABLE 3-6), common interbedded shale, and stratigraphic position within the ramp cycle support this paleobathymetric interpretation.

Evidence for storm reworking and deposition in the topographically lower facies equivalent at section 18 (unit 021) is less readily detected. Interbedded shale and nodular skeletal lime wackestone become siltier towards the top of the unit. Common epibionts, completely encrusting allochems, suggest periodic movement. Wafer stromatoporoids are commonly disoriented. Allochems are commonly pyritized. Subfacies 4 at this locality was deposited in calmer, deeper waters than at section 20 and, therefore, sediments were less frequently stirred by storm waves.

3.2.3 Lower Ramp Facies

3.2.3.1 Lower ramp subfacies 1

Ramose coral rudstone, floatstone, and interbedded nodular lime mudstone and wackestone characterize this lower ramp subfacies. Subfacies 1 occurs only at the top of a

TABLE 3-6

MACROFOSSILS OF UPPER RAMP SUBFACIES 4

Common Constituents

crinoid columnals

Rare Constituents

atrypa brachiopod: disarticulated, fragmented
thamnoporoid tabulate coral
encrusting bryozoan
solitary rugose coral: thin-walled
encrusting stromatoporoid
wafer stromatoporoid

lower ramp cycle in the vicinity of a paleotopographic high (section 20, upper unit 004). Bedding thickens (10-20 cm) and nodular mudstone and wackestone diminish upsection. Allochems are typically fragmented fossils and many are pyritized. The contained fossils are similar to those in upper ramp subfacies 3 (TABLE 3-7) except that stromatoporoids are nearly absent in the lower ramp facies. The nature of the interbedded nodular lime mudstone and wackestone is discussed in section 3.2.3.3 - lower ramp subfacies 3.

Subfacies 1 likely represents local ramose coral thickets established on a topographic high (e.g. vicinity of section 20). Elsewhere in the study area, the ramp was too deep to support an in situ coral-stromatoporoid fauna, as subfacies 1 passes laterally into lower ramp subfacies 4 (FIG. 3-2).

3.2.3.2 Lower ramp subfacies 2

Similar to subfacies 1, subfacies 2 was apparently controlled by paleotopographic relief near section 20 (unit 005) and the unit is restricted to the upper portion of a ~~ramp~~ third-order cycle. The subfacies thins eastward (section 31) and westward (section 18) as it passes into subfacies 4 on lower portions of the ramp.

Subfacies 2 is composed mainly of peloidal lime packstone with minor interbedded nodular lime mudstone and wackestone. Lenticular bedding (10-20 cm thick) characterizes the lime

TABLE 3-7

MACROFOSSILS OF LOWER RAMP SUBFACIES 1

Common Constituents

thamnoporoid tabulate coral: max. diameter 10 mm,
rarely encrusted by
stromatoporoid

crinoid columnals

Rare Constituents

encrusting stromatoporoid: stromatoporoid
robust cylindrical stromatoporoid
atrypid brachiopod
hemispherical Hexagonaria
tabular alveolitid coral
solitary rugose coral
ostracod
high-spined gastropod

packstone. Contained fossils are broken and abraded with smaller allochems commonly micritized. Erosional scours are filled rarely by discontinuous brachiopod-crinoid-coral coquinite. The peloidal packstone (rounded peloids, average 0.2 mm diameter) shows common disseminated pyrite. The macrofossil assemblage in subfacies 2 (TABLE 3-8) tends to be more diverse in section 20 than in the topographically lower neighboring sections.

The depositional model for these sediments is probably much akin to that of upper ramp subfacies 4 at section 20. The effect of storm events in the vicinity of this shoal diminished with increasing depth, hence the thickest preserved record of storm deposits was at section 20. Because the intensity of storm activity and the potential for storm deposits to be preserved in the stratigraphic record increases with shallowing, the evidence for storm deposition is more areally extensive towards the top of the ramp cycle between sections 18 and 31.

3.2.3.3 Lower ramp subfacies 3

Subfacies 3 consists of slightly nodular-bedded peloidal calcisiltite with common lenses of crinoid-brachiopod coquinite and interbedded grey-olive, calcareous, silty-shale. This subfacies is restricted to sections west of section 08 and thickens over local topographic highs on

TABLE 3-8

MACROFOSSILS OF LOWER RAMP SUBFACIES 2

Common Constituents

brachiopods: Stringocephalus, atrypid
crinoid columnals

Rare Constituents

tabular alveolitid coral: disoriented
bulbous alveolitid coral: very rare
thamnoporoid coral
hemispherical Hexagonaria
solitary rugose coral
fish fragments
sponge spicules
trilobite fragments
gastropod

Fauna observed in section 20

wafer stromatoporoids: disoriented; max. diameter 10 cm,
height 1 cm; actinostromatid and
clathrodictyid
bulbous stromatoporoid: very rare
encrusting stromatoporoid: very rare

the underlying clastic wedge (e.g. section 20, FIG. 3-1), and towards the isopach maximum of the Hare Indian lobe.

Subfacies 3 is interbedded with upper clinothem subfacies 1 and lower clinothem subfacies 1. The uppermost portion of subfacies 3 passes downslope into lower ramp subfacies 4 at sections 18 and 31. A prominent cycle break separates subfacies 3 from overlying darker, more calcareous sediments of lower ramp subfacies 4. Exposures of subfacies 3 range in thickness from 4 m (section 18) to 11 m (sections 11 and 20).

Lower ramp subfacies 3 shows textures and composition grossly similar to the more carbonate-rich lower ramp subfacies 4. However, in subfacies 3, peloidal calcisiltite tends to be more quartzose (20-40%) and shows lenticular-planar bedding rather than nodular bedding. Tucker (1973) observed that lower carbonate content appears to inhibit nodule formation with the result that nodules appear to be more layered and widely spaced.

The macrofossils of lower ramp subfacies 3 are predominantly a low diversity brachiopod-crinoid assemblage (TABLE 3-9).

Because lower ramp subfacies 3 and 4 are similar, their paleoenvironmental settings will be discussed separately following section 3.2.3.4.

TABLE 3-9

MACROFOSSILS OF LOWER RAMP SUBFACIES 3

Common Constituents

brachiopods: Stringocephalus, Rensselandia, Spinatrypa,
Atrypa, productid brachiopod and spines;
fragmented and disarticulated valves
commonly in current unstable positions;
common geopetal structures

crinoid columnals

Rare Constituents

nautiloid
fish fragments
trilobite fragments
dacriconarids: Stylolites, Tentaculites

Coquinite macrofossils:
solitary rugose coral
tabular alveolitid coral
encrusting alveolitid coral
thamnoporoid coral
encrusting bryozoan
gastropod
Hexagonaria?

3.2.3.4 Lower ramp subfacies 4

Subfacies 4 is composed of nodular lime mudstone, wackestone, and packstone, with minor planar-bedded skeletal wackestone and calcareous shale. The interbedded shale becomes subordinate to limestone upsection. Subfacies 4 is the most extensive subfacies in the ramp facies association within the study area (FIGS. 3-1, 3-2).

Subfacies 4 thins westward towards the Hare Indian isopach maximum (FIG. 3-1). Sediments there show much higher quartz content (10-20%) and grade into lower ramp subfacies 3 of the Hare Indian Formation. Typically, limestones in subfacies 4 show less than 5% quartz content in sections east of section 15. Subfacies 4 also thins basinward (eastward) towards section 01, where it passes laterally into upper clinothem subfacies 1 (FIG. 3-1). Subfacies 4 is thickest (18 m) in a paleodepression (FIGS. 3-1, 3-2) near section 08. At this locality, upper ramp facies constitute only 18% of the ramp facies association, compared to 30% in the adjacent section 31. Coeval sediments near section 31 were deposited on a topographically higher (20-25 m) portion of the ramp (FIG. 3-2).

Subfacies 4 is most characterized by nodular bedding (average 10-20 cm thick) which tends to be continuous in the basal portion (PL. 3-3a). Nodules are more discrete in the upper part (PLS. 3-3b, 3-4a) giving the sequence a mottled

appearance in outcrop. These upper sediments typically show few primary sedimentary structures due to intense bioturbation, although discrete traces are well-preserved and abundant. The nodules are generally "sausage"-shaped to ellipsoidal, and are commonly interconnected (PL. 3-4b). They are composed mainly of peloidal mudstone to packstone, and are more carbonate-rich than the surrounding dark grey, calcareous shale matrix. Nodule boundaries vary from sharp to gradational as the clay-rich matrix pinches and swells around the nodules.

The nodular limestones likely formed through differential early cementation and later pressure solution (TABLE 3-10). Attached organisms, including Hexagonaria, Thamnopora, and crinoids, only rarely utilized the nodular topography as a suitable substrate (PL. 3-5a). The nodules do not show borings or staining, and this demonstrates that they were never exposed for extended periods at the sediment-water interface (Baird, 1981).

Macrofossils are generally sparse in subfacies 4. The lower portion of subfacies 4 contains a low diversity crinoid-brachiopod assemblage that also characterizes subfacies 3. However, a ramose and encrusting coral fauna occurs towards the top of subfacies 4 (TABLE 3-11). The common encrusting habits, low faunal diversity and abundance, and abundant evidence of current agitation are

TABLE 3-10

NODULE FORMATION IN LOWER RAMP SUBFACIES 4
- EVIDENCE FOR EARLY LITHIFICATION
FOLLOWED BY DIFFERENTIAL COMPACTION

- (1) Abundant preservation of burrows and unpatterned bioturbation structures in nodules. Burrows appear to be more flattened in surrounding argillaceous matrix.
- (2) Rarely occurring shale-, and spar-infilled, "v"-shaped intrastratal fractures within nodules (e.g. PL. 3-4a).
- (3) Orientation of some horizontal burrows in the surrounding matrix is controlled by the nodular pattern of the limestone (PL. 3-4b).
- (4) Skeletal material in the nodules generally exhibits less compaction. Nodule-matrix contacts commonly abrupt (solution seams) and the matrix exhibits a lower carbonate content.

TABLE 3-11

MACROFOSSILS OF LOWER RAMP SUBFACIES 4

Common Constituents

crinoid columnals: robust
 productid brachiopod and spines
 atrypid brachiopod

Rare Constituents

rhynchonellid brachiopod
Stringocephalus
 thamnoporoid coral: rarely show micritized rims
Coenites
 wafer alveolitid coral
 encrusting alveolitid coral
 auloporid coral
 indeterminate disphyllid rugose coral
 solitary rugose coral: thin-walled; long septa
Rensselandia
 nautiloid
 trilobite
 sponge spicules: ubiquitous in interbedded shale
 gastropod: high spired; thin-shelled
 tentaculitid
 encrusting bryozoan
 ostracod
Hexagonaria
Billingsastrea

suggestive of environmental conditions stressful for benthic organisms.

3.2.3.5 Depositional setting for lower ramp subfacies 3 and 4

The depositional setting for these subfacies is best exemplified by subfacies 3 and the lower portion of subfacies 4, which show less pronounced nodularity. Major characteristics of these subfacies are summarized in TABLE 3-12. Paleobathymetric estimates (see Section 3.3.2) indicate that subfacies 3 and 4 were both deposited in similar depths of water. These show similar macrofossils, trace fossils, and composite lithology, although subfacies 3 is more quartzose and typically contains less limestone.

Interbedding of medium to dark olive-grey shale with lenticular peloidal calcisiltite and calcirudite suggests fluctuating depositional conditions. Hummocky cross-stratification was recognized in lower ramp subfacies 3 but not in subfacies 4, although the prevalent nodular character of subfacies 4 probably precludes recognition of these large scale bedforms. Hummocky cross-strata (HCS) have been reported in many ancient storm-influenced shelf sequences (e.g. Hamblin and Walker, 1979; Leckie and Walker, 1982) but have not been recorded on modern shelves. HCS in subfacies 3 are typically calcisiltite bed sets (10-30 cm thick) showing antiformal hummocks and synformal

TABLE 3-12

DIAGNOSTIC CHARACTERISTICS OF LOWER RAMP SUBFACIES 3 & 4		
	Lower Ramp Subfacies 4	Lower Ramp Subfacies 3
Facies Geometry	- stratiform	- stratiform- lensoid
Thickness Variations	- thickens towards paleodepressions on ramp (e.g. section 08)	- thickens over local paleotopo- graphic highs (e.g. sections 11, 20)
Bedding Style	- slightly nodular to mottled	- slightly nodular to lenticular
Limestone/ Shale	>1	<1
Estimated Paleobathyme- tric Range	~25-50 m	~25-40 m
Trace Fossils	- moderate to high bioturbation - <u>Cruziana</u> <u>Chondrites</u> <u>Teichichnus</u> <u>Planolites</u> <u>Paleophycus</u> <u>Rhizocorallium</u> <u>Diplocraterion</u>	- low to moderate bioturbation; - <u>Chondrites</u> <u>Teichichnus</u> <u>Planolites</u> <u>Paleophycus</u> <u>Rhizocorallium</u> <u>Diplocraterion</u>
Quartz Content	- average <5%	- average 20-40%
Common Macrofossils	- crinoid columnals brachiopods	- crinoid columnals brachiopods
Common Lithologies	- nodular lime mud- stone to packstone (peloidal calci- siltite); minor skeletal wackestone and calcareous shale	- quartzose peloi- dal calcisiltite; interbedded grey- olive calcareous shale

swales spaced 1-3 m apart. Internal stratification is defined by horizontal to broadly convex lamination with dip angles and truncation angles less than 15°. HCS occur mainly above crinoid-brachiopod coquinite beds and pass upwards into horizontally laminated peloidal calcisiltite. Hamblin and Walker (1979) postulated that HCS may represent sediments rapidly deposited from waning storm-generated currents.

The peloidal calcisiltite is more commonly arranged in graded 2-5 cm thick beds (PLS. 3-5b, 3-6a) which generally show horizontal laminae to low angle cross-laminae that thin upwards (1.0 mm to 0.2 mm). The beds show sharp planar to broadly concave basal contacts, and are increasingly bioturbated toward the tops. These features, and the common occurrence of water escape structures (PL. 3-6b) and escape burrows, indicate events of rapid deposition. Rarely occurring lenses of the gregarious brachiopod Rensselandia (PL. 3-7a) and current-aligned crinoid pluricolumnals (PL. 3-7b) were probably preserved in situ by pulses of high sediment influx.

Lenticular calcirudite beds in subfacies 3 (FIG. 3-3) are composed of muddy, poorly sorted, brachiopod-crinoid-gastropod coquinite which thickens into erosional scours (PLS. 3-8a, 3-8b). Some are graded and a few show basal gutter casts and aligned crinoid pluricolumnals that indicate a NW-SE transport direction. Brachiopods are

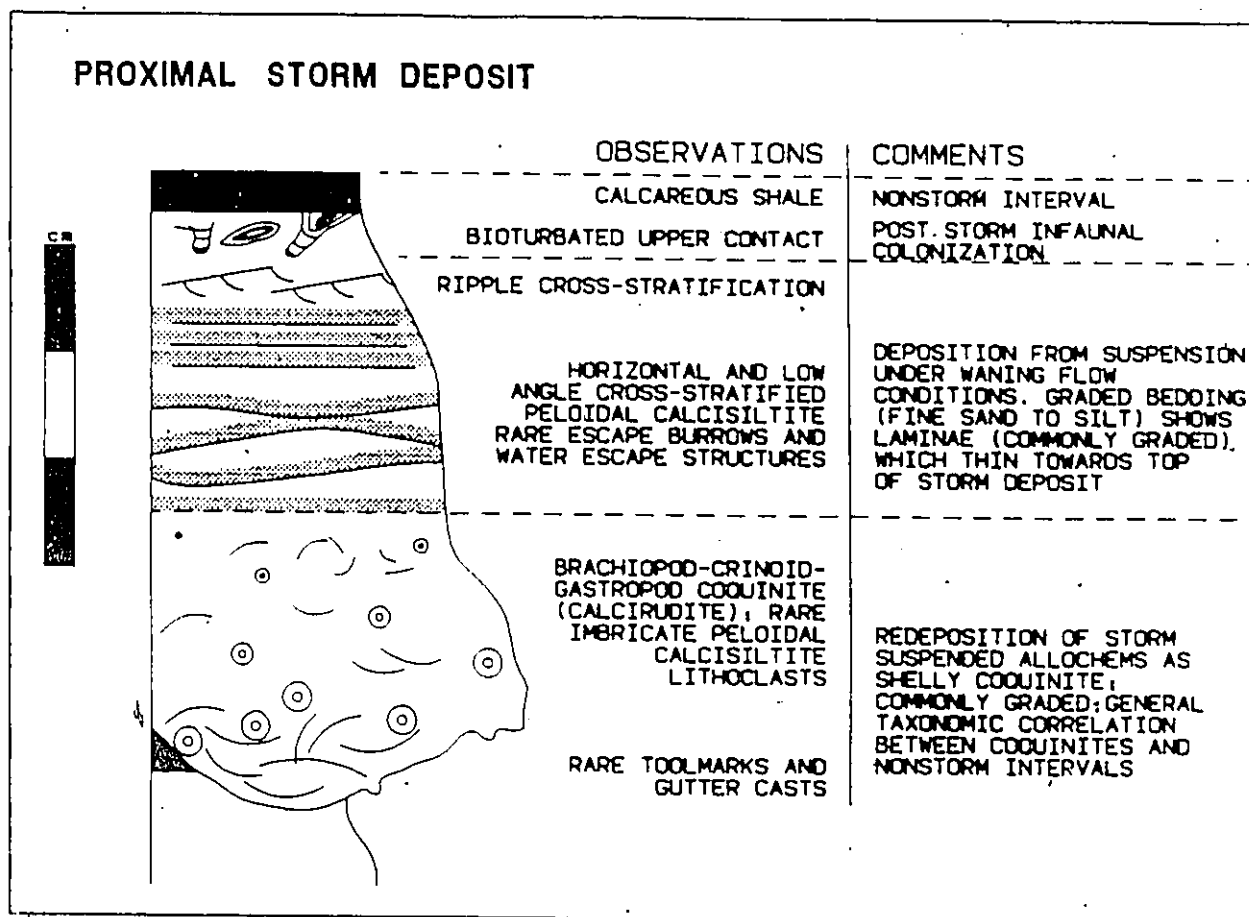


FIG. 3-3 Idealized proximal tempestite in the lower ramp facies and upper clinotherm facies. Distal tempestites are thinner bedded, lack graded shelly coquinite, and are usually more bioturbated throughout.

commonly disarticulated with valves occurring in both current-stable and unstable positions (PL. 3-9a). These units of coquinite typically pass upwards into graded, laminated, peloidal calcisiltite (PL. 3-9b), suggesting that the latter was deposited under lower energy conditions. A complete sequence is shown in FIG. 3-3.

Subfacies 3 and 4 were deposited in a calm, distal ramp setting at depths of 20-50 m, where the background shale deposition was periodically interrupted by storm deposition. Evidence for storm deposition is summarized in TABLE 3-13, and these features compare closely to characteristics of modern storm deposits (TABLE 3-14). Proximal tempestites (FIG. 3-3) can be distinguished from distal tempestites in this study. The latter are thinner-bedded (average 3-5 cm thick), finer-grained, and lack a basal shelly coquinite. They commonly are more bioturbated than proximal tempestites. The proportion of proximal to distal tempestites decreases from lower ramp subfacies 3 (sections 11, 15, 20) downslope into lower ramp subfacies 4 (sections 20, 31, 08).

The use of storm deposits as paleobathymetric indicators assumes that storm-induced turbulence and oscillatory current motion decreases as depth increases (Kreisa, 1981; Aigner, 1982, 1984, 1985; Seilacher, 1982). The presence of common erosional scours and coquinites is evidence that strong bottom currents deposited proximal tempestites in the

TABLE 3-13

CRITERIA INDICATIVE OF STORM DEPOSITS IN LOWER RAMP
SUBFACIES 3 AND 4

- (1) Lenticular bedding - planar to undulatory, erosional bases and non-erosional tops. Some bed tops reworked by wave action.
- (2) Calcirudite coquinites - represent winnowed shell lags as storm-generated currents stirred bottom sediments. General taxonomic comparison with non-storm intervals indicates nearly in situ reworking of coarse-grained sediments.
- (3) Evidence for high energy conditions and rapid sedimentation - upward fining in skeletal coquinite and peloidal calcisiltite (PLS. 3-10a, 3-10b).
 - rarely occurring tool marks and gutter casts.
 - escape burrows.
 - water escape structures.
 - horizontal stratification and low angle cross-stratification in peloidal calcisiltite.
 - amalgamated sequences with common erosional surfaces indicate episodic high energy depositional events.

TABLE 3-14

COMMON CHARACTERISTICS OF HOLOCENE STORM DEPOSITS
(AFTER KREISA, 1981)

- Sharp bases; burrowed or diffuse upper contacts.
- Common occurrence as couplets of shell or gravel lag and laminated sand/silt.
- Most sands and silts are weakly graded and typically laminated ("graded rhythmites" in Reineck and Singh, 1975).
- Common occurrence of escape trace fossils.
- Sand and silt layers typically decrease in thickness and abundance away from shoreline.
- Horizontal stratification and low angle cross-stratification (gentle discordances less than 10°) are common.

ramp depositional setting. Modern proximal tempestites at German Bay in the North Sea (Aigner, 1985) are typically nearshore, although some occur in deeper water (to 30 m depth) due to exceptionally strong or long-lasting storms. The tempestites show sharp, erosional bases, common horizontal stratification, low angle cross-stratification, and rare wave ripple cross-stratification in coarse sand-size sediment (Aigner, 1985).

Distal tempestites and interbedded muds have been reported in water depths as much as 40 m in the Busum area of the North Sea (Reineck and Singh, 1975). These storm deposits are graded rhythmites (Reineck and Singh, 1972) and show many features in common with the distal tempestites of the ramp facies association (PL. 3-10a). Graded rhythmites 1-5 cm thick at German Bay (Aigner, 1985) display coarser-grained and thicker laminae of fine-grained sand that grade upwards to thinner laminae of silt. Distal tempestites show water escape structures (Reineck and Singh, 1975) and wave ripple cross-stratification occurs rarely.

Reineck and Singh (1972) suggested that graded rhythmites were likely deposited from storm-generated density currents. During the waning of each storm, suspended fine sand and silt rapidly drop from suspension. Evidence for wave reworking decreases with depth and waning storm conditions (decreased orbital velocities).

Low angle cross-stratification at the bases of some distal tempestite sequences could have resulted from the irregular pattern of residual storm wave-generated currents. These currents can create "hummocky" bedforms at various scales, depending on grain size and the orbital diameter of wave motion (Kreisa, 1981). Storm turbulence eventually decreases to the point where wave-generated currents no longer "touch" sea floor. Horizontally stratified sediment deposited from waning currents shows thinning- and fining-upwards of laminae (graded rhythmites of Reineck and Singh, 1972) as the storm abates. Reineck and Singh (1972, 1975) suggested that silt layers in Holocene shelf sediment cores, recovered from water depths down to 300 m, could have been deposited by storm-generated, low density, turbidity currents. The implications of this observation will be examined later in this chapter.

3.2.3.6 Nodule formation in lower ramp subfacies 3 and 4

The nodular limestones were apparently formed between storm and fairweather wavebases. Early selective cementation and differential compaction acted upon storm-emplaced calcisiltite and calcirudite beds. These relatively permeable sediments were introduced into an otherwise low energy muddy environment below fairweather wavebase. Post-storm reworking by burrowing organisms could have further enhanced water flow through the coarser

sediments. Progressive stages of cementation can be inferred from characteristics of the contained biogenic structures. Escape burrows show diffuse boundaries and compacted structure indicating the initial softness of the substrate. Other trace fossils, including Rhizocorallium, Planolites, Diplocraterion, and Teichichnus, display more distinct outlines suggestive of a firmer substrate. These burrows predate a final phase of burrowing that resulted in composite burrows. Small (average 1 mm diameter) circular Chondrites commonly show peloidal calcisiltite infill and disseminated pyrite. These were probably formed as the "nodules" were being buried to a depth near the infaunal threshold. Savrda et al. (1985) suggested that infaunal activity is limited mainly by oxygen content in interstitial waters.

Selective cementation and pressure solution processes continued to act upon the nodular limestones as they were buried. Cementation was likely terminated as interstitial water flow decreased. Thereafter, compactional processes could have continued to act upon the sequence (e.g. PL. 3-10c).

Mullins et al. (1980) attributed the distribution of nodular sediments presently forming on the Bahamian platform foreslope to depth-controlled processes. Similar processes could explain apparent bathymetric constraints on the

occurrence of widespread nodular limestones in the lower ramp depositional setting, as follows:

- (1) Bioturbation and lack of persistent bottom currents could have inhibited widespread hardground formation below fairweather wavebase. However, storm-generated currents and active bioturbation were evidently sufficient to initiate early cementation and nodule formation before it was terminated by post-storm mud deposition and reduced permeability associated with burial.
- (2) Currents below storm wavebase apparently were not competent to erode the muddy sediments covering the permeable layers. Furthermore, turbidites in these environments tend to be finer-grained and presumably were less permeable for interstitial water.

3.2.4 Synthesis of the Ramp Depositional Environment

3.2.4.1 Cyclicality in the ramp facies association

The ramp facies association was cyclic in development (see FIGS. 3-1, 3-2). Abrupt deepening initiated each cycle and was followed by shale deposition. The return of carbonate sedimentation was gradual, as evidenced by the increasing carbonate:shale ratio towards the top of each

cycle (FIGS. 3-4, 3-5). These cycles are 2-7 m thick, and are similar to thicknesses of third-order reef interior cycles in the Ramparts upper "platform-reef" member. The third-order ramp cycles could not be correlated into the clinothem facies association. However, second-order upper clinothem cycles that could be correlated into the ramp facies association appear to be time-equivalent to groups of two or three third-order ramp cycles. In contrast, second-order Ramparts reef cycles (see Chapter 5) contain six to eight third-order reef interior cycles. Because conodonts are sparse in the Hare Indian Formation, it is unknown if clinothem second-order cycles had the same periodicity as Ramparts reef second-order cycles.

Ahr (1973) noted that wedge-shaped, thickening-seaward deposits characterize ramps except where modified by local topography. This characteristic has probably been obscured in the study area by sediment compaction, particularly in muddy, mixed siliciclastic-carbonate facies of the lower ramp-upper clinothem transition. Third-order ramp cycles do thicken slightly into the paleodepression at section 08 (FIG. 3-1) from neighboring paleotopographic highs (e.g. sections 31, 20). This demonstrates the progradational aspect of the ramp succession. Ramp sediments accumulated in paleodepressions at higher rates than on topographic highs where sediments were more actively winnowed by storms.

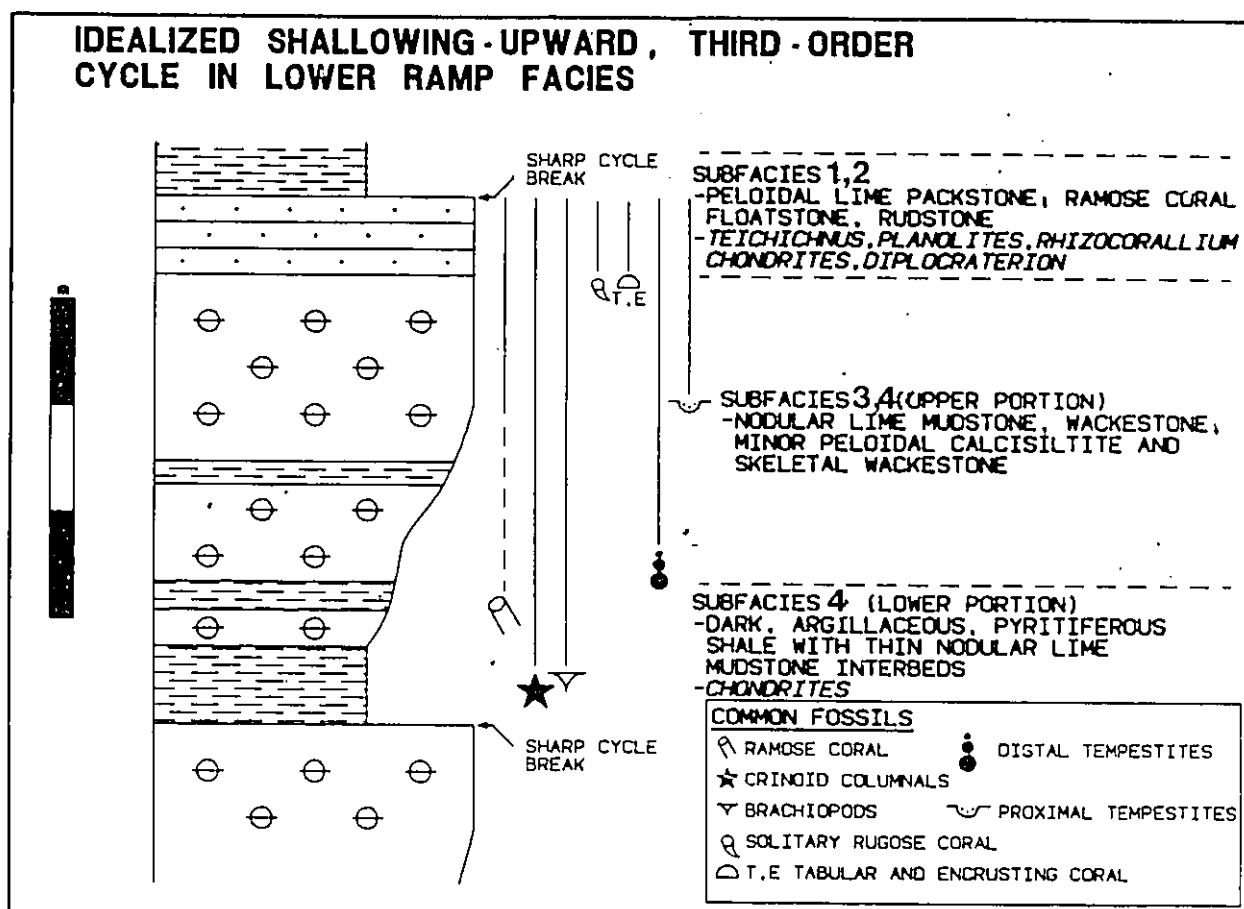


FIG. 3-4 Lower ramp third-order cycle. Shallowing-upward trends indicated by limestone beds becoming thicker and coarser-grained up section. Bioclast diversity and abundance, and trace fossil diversity, increase towards top of shallowing-upward cycle. Apparent amalgamation of storm layers up section with more abundant erosional contacts. Key for lithology symbols in FIG. 3-2.

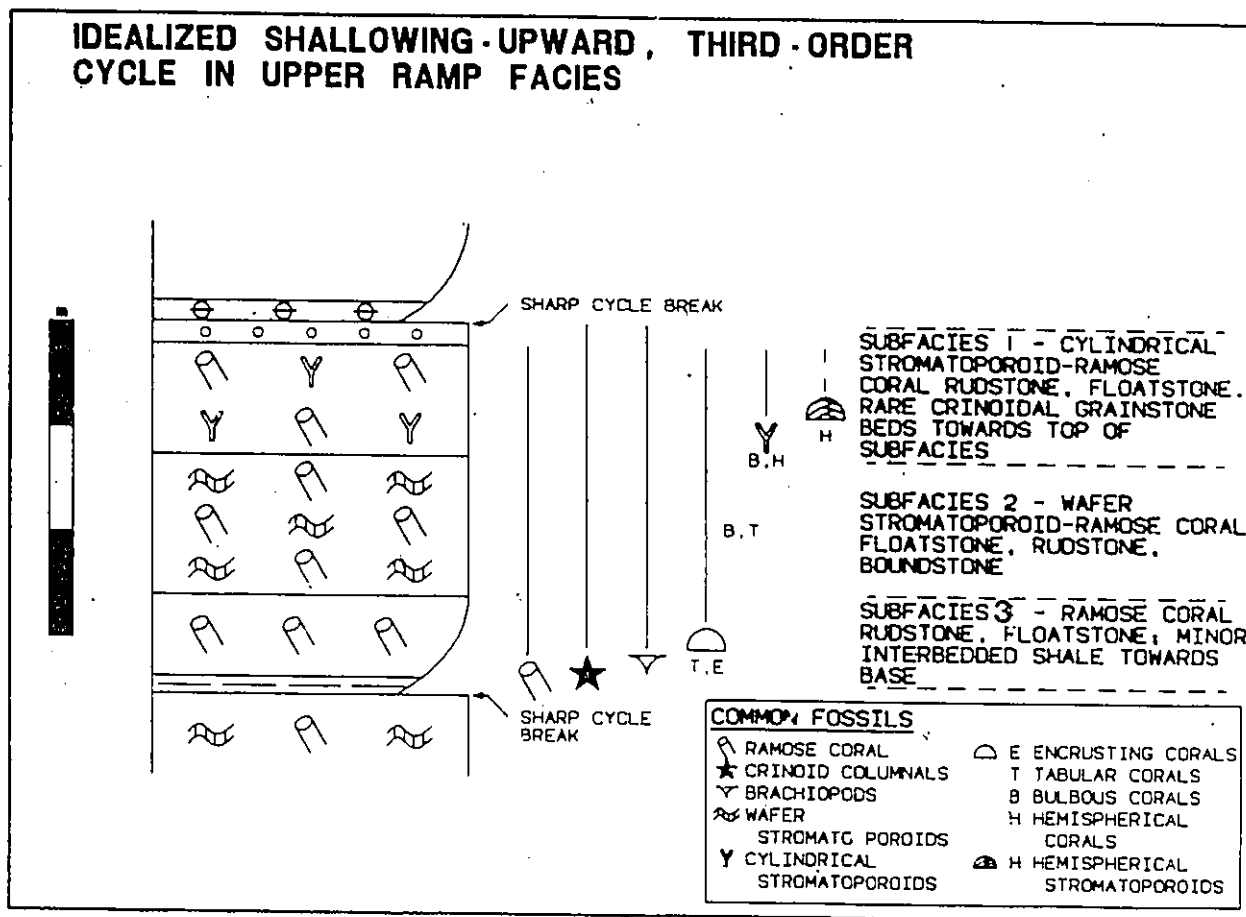


FIG. 3-5 Upper ramp third-order cycle. Bedding thickens up section. Stromatoporoids more diverse and abundant towards cycle top. Limestones lighten and coarsen-upwards with interbedded calcareous shale restricted to basal portion of cycle. Key for lithology symbols in FIG. 3-2.

3.2.4.2 Paleobathymetric constraints

The correlation of third-order cycle boundaries in the ramp facies association provides some constraints for paleodepth estimates for each subfacies. Unfortunately, none of the cycles shoaled to sea level, so that water depth for upper ramp subfacies 1 must be estimated differently. The abundance of lime mudstone and interbedded shale indicates a depth below fairweather wavebase. However, the occurrence of algae-encrusted allochems suggests photic conditions, and upper ramp subfacies 1, therefore, was deposited probably in water depths of 10-20 m. Paleobathymetric estimates for the remaining subfacies making up the ramp facies association are shown in TABLES 3-15, 3-16.

These values are uncorrected for subsequent differential compaction. According to Stoakes (1980); application of a single compaction curve to a heterogeneous assemblage of lithofacies likely results in dubious estimates of paleobathymetry.

Upper ramp facies were deposited apparently in water depths of 10-30 m. The significant overlaps of paleodepth ranges for the upper ramp subfacies probably reflect only slight changes in environments as the sediments shoaled upwards.

The lower ramp facies are dominated by nodular limestones of subfacies 4. These evidently were deposited mainly in

TABLE 3-15

Paleobathymetry and major characteristics of the lower ramp facies.

LOWER RAMP FACIES				
SUBFACIES	LITHOLOGIES	COMMON FOSSILS	EXTENT AND DEPOSITIONAL SETTING	PALEODEPTH ESTIMATE
1	RAMOSE CORAL RUDESTONE, FLATSTONE, INTERBEDDED MODULAR LIME MUDSTONE AND WACKESTONE	THAMNIPORID CORALS CRINOIDS	- RESTRICTED TO PALEOTOPOGRAPHIC HIGHS ON THE RAMP - CALM, TURBID WATERS	20 - 25 m
2	PELOIDAL PACKSTONE WITH MINOR INTERBEDDED MODULAR LIME MUDSTONE AND WACKESTONE	BRACHIOPODS CRINOIDS	- RESTRICTED TO PALEOTOPOGRAPHIC HIGHS ON THE RAMP - COMMON STORM DEPOSITS INTERBEDDED WITH SEDIMENTS DEPOSITED BY CALM, TURBID WATERS	20 - 25 m
3	SLIGHTLY MODULAR QUARTZOSE PELOIDAL CALCISILTITE WITH COMMON LENSOID CALCIRUDITE INTERBEDS, GREY-OLIVE CALCAREOUS SILTY SHALE	BRACHIOPODS CRINOIDS TRACE FOSSILS INCLUDE: DIPLOCRATERION, RHIZOCORALLUM, PLANOLITES, CHONORITES, TEICHIONUS	- PLANAR-LENSOID UNITS THICKEN OVER RAMP PALEOTOPOGRAPHIC HIGHS - COMMON STORM DEPOSITS INTERBEDDED WITH SEDIMENTS DEPOSITED BY CALM, TURBID WATERS	25 - 40 m
4	MODULAR LIME MUDSTONE, WACKESTONE AND PACKSTONE (PELOIDAL CALCISILTITE), MINOR INTERBEDDED SKELETAL WACKESTONE AND SHALE	BRACHIOPODS CRINOIDS TRACE FOSSILS INCLUDE: RHIZOCORALLUM, PLANOLITES, CHONORITES, TEICHIONUS	- EXTENSIVE, STRATIFORM UNITS ON THE RAMP - COMMON STORM DEPOSITS INTERBEDDED WITH SEDIMENTS DEPOSITED BY CALM, TURBID WATERS	25 - 55 m (avg. 25 - 40 m)

TABLE 3-16

Paleobathymetry and major characteristics of the upper ramp facies.

UPPER RAMP FACIES				
SUBFACIES	LITHOLOGIES	COMMON FOSSILS	EXTENT AND DEPOSITIONAL SETTING	PALEODEPTH ESTIMATE
1	CYLINDRICAL STROMATOPOROID -RAMOSE CORAL RUDESTONE FLOATSTONE WITH A PELOIDAL WACKSTONE TO PACKSTONE MATRIX, RARE CRINOIDAL GRAINSTONE	ROBUST CYLINDRICAL STROMATOPORIDS THAMNOPORID CORALS CRINOIDS	-RESTRICTED TO PALEOTOPO- GRAPHIC HIGHS ON THE RAMP -RARE INTERBEDDED STORM DEPOSITS -AGITATED, WELL-CIRCULATED WATERS, PERIODS OF HIGH SEDIMENT INFLUX	10 - 20 m
2	WAFFER STROMATOPOROID -RAMOSE CORAL FLOATSTONE, RUDESTONE, BOUNDSTONE WITH A SKELETAL WACKSTONE TO PELOIDAL PACKSTONE MATRIX, SHALES	WAFFER STROMATOPORIDS TABULAR STROMATOPORIDS TABULAR ALVEOLITIDS THAMNOPORID CORALS CRINOIDS	-EXTENSIVE, STRATIFORM DISTRIBUTION ON RAMP -SLIGHTLY AGITATED, WELL CIRCULATED WATERS, PERIODS OF HIGH AGITATION AND SEDIMENT INFLUX	15 - 25 m
3	PLANAR TO SLIGHTLY NODULAR BEDDED RAMOSE CORAL RUDESTONE, FLOATSTONE, SHALES -MAINLY MUD-SUPPORTED FABRICS	THAMNOPORID CORALS CRINOIDS STROMATOPORIDS ARE RARE	-EXTENSIVE, STRATIFORM DISTRIBUTION ON RAMP -RARE INTERBEDDED STORM DEPOSITS -PREDOMINANTLY CALM - TURBID WATERS	15 - 25 m
4	SHALES, SKELETAL WACKSTONE, PELOIDAL CALCISILTITE, CRINOID GRAINSTONE	CRINOIDS	-PELOIDAL CALCISILTITE STORM DEPOSITS RESTRICTED TO TOPOGRAPHIC HIGHS ON RAMP -CALM WATERS, PERIODIC STORM ACTIVITY	15 - 30 m

water depths of 25-40 m, but could have extended to depths of 55 m within ramp paleodepressions (e.g. section 08). Lower ramp subfacies 1, 2, and 3 are local shoal facies deposited in slightly shallower waters (20-40 m) over topographic highs.

Stoakes (1980) estimated paleodepths of 35-55 m for upper foreslope nodular limestone facies within the Upper Devonian Ireton Formation in Alberta. They include calcareous green shale and lenses of brachiopods and other skeletal allochems typical of a platform environment. The latter are likely tempestites interbedded with calm water argillaceous sediments. The nodular limestone lithofacies is juxtaposed with muddy platform skeletal rudstones, packstones, and bioturbated mudstones. The relative positioning, composition, and estimated paleobathymetry of facies are remarkably similar to those of lower ramp subfacies 4 in this study. No modern analogue of nodular limestone formation in a ramp depositional setting is known. However, texturally similar sediments (skeletal muds) are presently accumulating in the Persian Gulf at 20-50 m water depths (Read, 1985).

3.2.5 Ramp Depositional Model

3.2.5.1 General statement

The ramp facies association was deposited on a gentle slope (0.08-0.18°). The presence of intraramp depressions (e.g. section 08) and shoals (e.g. section 20) directly reflects constructional relief of the underlying Hare Indian clastic wedge. The apparent lack of continuous reef or grainy shoal trends demarcating a slight break in slope, and the absence of channel-fill and gravity flow fan facies, argues against a distally steepened ramp. The ramp facies association is more similar to Read's (1982) homoclinal ramp model in which deeper ramp facies typically display an open marine fauna, nodular bedding, and may contain storm-generated deposits. Deeper ramp facies pass into shallow ramp biostromes and mudstones, then finally into coastal siliciclastics. These characteristics typify the Ramparts ramp facies association (TABLE 3-17).

3.2.5.2 Sediment distribution patterns

The distribution of ramp facies both within the study area and regionally (FIG. 2-6) suggests that carbonate ramp facies developed away from input sites of Hare Indian siliciclastic sediments. An analogous modern depositional setting is in the Arabo-Persian Gulf where Purser (1982) noted that deltaic input of terrigenous detritus down the

TABLE 3-17

COMMON CHARACTERISTICS OF THE RAMP FACIES ASSOCIATION

(1) Geometry

- gently sloping ramp profile (1.3-3.0 m/km or 0.08-0.18°)
- intraramp depressions and shoals mainly reflect prior constructional relief of Hare Indian clastic wedge
- carbonate ramp facies thin basinward and towards the isopach maximum of the Hare Indian lobe.

(2) Facies Distributions

- vaguely concentric facies belts follow bathymetric contours of the Hare Indian lobes
- significant siliciclastic components in interpreted nearshore environments (e.g. west of section 11)
- absence of continuous reef trends
- absence of apron and fan facies containing major channel-fill and gravity flow deposits.

structural axis of the basin excludes carbonate-producing organisms. However, carbonates are presently being deposited distal to the source of siliciclastic sediments.

Ginsburg et al. (1983) observed that mixed siliciclastic-carbonate assemblages are rare because episodic sedimentation, high turbidity, reduced salinity, and shifting substrates generally make siliciclastic depositional environments unsuitable for carbonate-producing benthos.

Although the occurrence of fine-grained terrigenous facies and carbonate facies are generally mutually exclusive in the ramp facies association, there is some evidence for mixing in the study area.

Facies mixing has resulted in a diffuse transition between siliciclastic-dominated ramp facies (mainly in Hare Indian isopach maxima) and peripheral carbonate-dominated ramp facies (see FIG. 2-6). Approximately 100 km north of the study area (Lac Charrue area in FIG. 2-6), the ramp facies association is a carbonate succession that shoals upwards into a quartz arenite unit in an intertonguing manner (MacKenzie et al., 1975). This repeated intertonguing probably reflects episodic nearshore siliciclastic sedimentation that accompanied the repeated outbuilding of the carbonate ramp facies in response to fluctuations in rates of sea-level rise. Downs (1983) observed a similar relationship in the Mississippian Pitkin

Formation in northern Arkansas, where each shallowing-upward platform cycle shows carbonate facies dominating the lower portion and quartz sand culminating the upper portion.

In the study area, siliciclastic and carbonate ramp facies are mixed in lower ramp subfacies 3, which thickens towards the Hare Indian isopach maximum near sections 11 and 15. At these localities, the carbonate ramp facies tend to be more quartzose (10-40%), thin (10 m thick), and display an impoverished coral-stromatoporoid assemblage compared to the carbonate ramp facies to the east (basinward of Hare Indian isopach maximum). Stromatoporoids are particularly rare and apparently were much less tolerant to siliciclastic influx than corals (Bassett and Lawson, 1984). In situ upper ramp facies are only 2 m thick at section 15 (compared to 6 m at section 18, 8 km east of section 15). These facies are characterized by a ramose thamnoporoid coral-crinoid-brachiopod assemblage. Siliciclastic input also influenced the nature of the overlying lower platform sediments, as discussed in Chapter 4.

Punctuational mixing played an important role in transferring siliciclastic sediments into the carbonate ramp setting. Because they lack protective reef belts, ramps are particularly affected by storms (Aigner, 1984, 1985). Storm deposits in the carbonate ramp facies contain various proportions of siliciclastic components (<5%-40%) which could reflect different proximities of storm-generated

currents to a siliciclastic source. These storm deposits are particularly common towards the top of ramp third-order cycles. Jones and Dixon (1976) postulated that if storms occur randomly over long periods of time, then the frequency of storm deposits should increase upwards in a shallowing-upward succession. With progressively lowered effective wavebase, even minor storms could leave an imprint in the stratigraphic record. Topographic relief on the ramp and upper platform (e.g. in section 20) could also have served to localize the effects of storm events (e.g. lower ramp subfacies 2).

Although there is evidence for storm reworking and deposition in the upper ramp facies, it is much more commonly preserved in the lower ramp facies. Tempestites are less common in the upper ramp setting, possibly due to the following factors:

- (1) Dilution resulting from rapid recolonization and proliferation of carbonate-producing benthos.
- (2) Admixing of tempestites by intensive infaunal activity and consequently reduced preservation potential.
- (3) Increased recycling of storm deposits by later storm events in depths closer to fairweather wavebase.
- (4) Localization of storm surge ebb deposits seaward of rip channels (e.g. Fenton and Wilson, 1985) and,

hence, greater difficulty of recognition in the upper ramp facies. Tzui (1985) observed that storm surge generated by Hurricane Eva (1982) off Oahu, Hawaii, was dispersed radially, particularly between patch reefs.

Conversely, several factors could have contributed to increased tempestite occurrence in the lower ramp depositional setting:

- (1) Lower oxygen content at the water-sediment interface could have had the dual effects of:
 - a) restricting colonization by epifauna, thereby reducing "background" carbonate sedimentation and serving to emphasize the importance of tempestites, and
 - b) reducing infaunal activity, thereby decreasing bioturbation and enhancing the preservation potential of tempestites.
- (2) Preservation potential could have increased downslope, with cohesive mud deposited during fairweather conditions (Kreisa, 1981), protecting tempestites from erosion by subsequent storms. Increasing water depths with less recycling of storm deposits also favors a more complete record of storm deposition (Aigner, 1985). However, with increasing water depth, fewer storms are capable of

affecting the sea floor and producing storm deposits.

3.2.5.3 Ramp processes

Ramp facies distribution was controlled significantly by several factors, including antecedent topography, rates of relative sea-level rise, and current dispersal patterns.

Antecedent topography aided in localizing upper ramp facies development during the initial rapid sea-level rise (e.g. on a local high in the vicinity of section 20; FIGS. 3-1, 3-2). Paleotopography was probably a combination of constructional relief (e.g. lower ramp subfacies 3) and differential compaction on top of the Hare Indian lobes. Examples of the effect of local relief in determining the occurrence of carbonate facies can be seen in mixed carbonate-siliciclastic settings in lagoonal areas of both Belize and Great Barrier Reef tracts. Ginsburg et al. (1983) noted that the positions of reefs in these areas were probably determined by local relief (e.g. channel banks, bars, deltaic lobes) of underlying siliciclastic deposits.

Variable rates of relative sea-level fluctuation evidently also partly determined ramp facies distribution. During pronounced rises in relative sea level, siliciclastic input was reduced from Hare Indian source areas, as terrigenous detritus was trapped along shorelines and in coastal plain complexes. Shallowing-upward cycles show

evidence for expansion of the carbonate-siliciclastic mixing zone as siliciclastics spread out onto the carbonate ramp.

The inner 15 km of the West Florida shelf is fringed by a quartz sand that grades seaward into carbonate sand. Doyle (1981) suggested that during Pleistocene low stands of sea level, this quartz sand belt expanded seaward. He postulated that this was accomplished largely by increasingly effective transfer of storm wave energy to the shelf with lowered relative sea level.

Finally, current dispersal patterns influenced ramp facies distribution. Siliciclastic sediments partly make up the Hare Indian clastic wedge and are mainly restricted to axial areas of the lobes (FIG. 2-6). The adverse effect of siliciclastic sediment on carbonate production resulted in development of carbonate ramp facies peripheral to these input sites.

The siliciclastic facies in the ramp facies association are poorly understood (see MacKenzie et al., 1975) and have been studied only on a reconnaissance basis. Processes that possibly were responsible for movement of siliciclastic sediments from the Hare Indian paleoshoreline through the "littoral energy fence" to the ramp depositional setting, include the following:

- (1) Offshore currents generated by prevailing northeasterly winds (see Chapter 5).

- (2) River mouth bypassing during progradation, in which sediment was transferred to the ramp either by ebb-tidal jets or flood-stage jets (Rice, 1984; Turner and Conger, 1984). The lobate nature of the Hare Indian clastic wedge (FIG. 2-6) suggests that the former process in combination with (1) was more significant.
- (3) Bypass resulting from storm surge ebb flow. Along-shore and obliquely onshore winds from the northwest, generated during storms, may have caused wind-drift currents and wave set-up along the coast. This, in turn, could have generated powerful gradient and geostrophic currents obliquely offshore. Coast-to-ramp sediment dispersal could have resulted from offshore currents returning storm-piled water downslope in coastal areas (Aligner, 1985) or downslope from the axes of the Hare Indian progradational lobes. However, once the sediments were moved into deeper waters on the ramp, both waves and geostrophic currents could have redistributed the siliciclastic sediment parallel to the paleobathymetric contours. This possibly explains the shore-parallel distribution of the quartz arenite unit near its western limit (FIGS. 2-6, 3-6).

RAMP FACIES ASSOCIATION

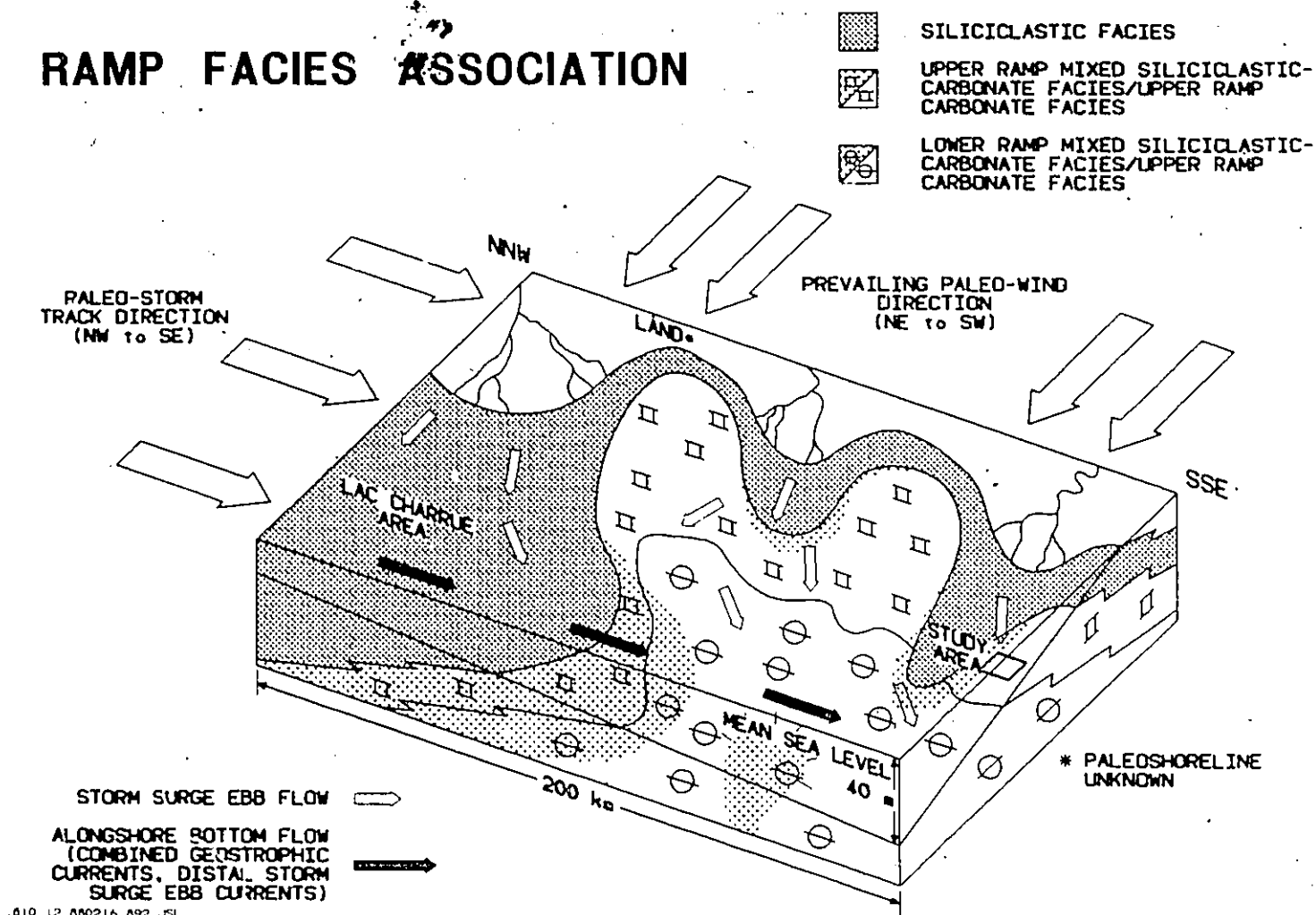


FIG. 3-6 Schematic paleoenvironmental reconstruction of the ramp facies association based on data from study area and regional studies of Mackenzie et al. (1975) and Pugh (1983). FIG. 2-6 shows the regional distribution of ramp facies.

The ramp facies association in the study area was deposited mainly in a low energy environment below fairweather wavebase. However, the common occurrence of tempestites suggests that episodic storm-induced erosion and downslope resedimentation were significant processes in deposition of much of the lower ramp facies and some of the upper ramp facies. Episodic storm winnowing would have effected hydraulic bypassing of both carbonate and siliciclastic sediments into adjacent lower-lying depositional settings such as the lower ramp and upper clinothem. Sparse paleocurrent data (gutter casts; gully-fill structures; aligned allochems) in the ramp facies association tentatively indicate southward to southeastward offshore transport perpendicular to the axis of the Hare Indian lobe maximum (FIG. 3-6). Storm-generated, shallow water buildup probably resulted in offshore-directed, bottom return flows. Sediment could have been transported downslope by mechanisms such as storm surge ebb currents and combined storm-wave density currents. Aigner (1985) documented offshore paleocurrent indicators in proximal tempestites of the Upper Muschelkalk, southwest Germany. Stirring of the seafloor by both violent oscillatory wave motion and unidirectional storm surge ebb currents likely suspended fine sediments (fine sand, silt; McCave, 1971) which were then carried offshore as low density turbidity currents.

Hurricane Carla (1961) piled 6.5 m of water landward of the Texas Gulf shoreline (Hayes, 1967). Morton (1981) suggested that the resultant seaward ebb current was a diffuse gravity flow which deposited a graded bed of fine sand to silt (1-9 cm thick) over an area of at least 1000 km² and extending at least 23 km offshore into waters at least 36 m deep.

Hamblin and Walker (1979) presented evidence that storms triggered turbidity currents in the Jurassic Fernie-Kootenay transition in British Columbia. These turbidite facies are commonly interbedded with sandstone facies showing hummocky cross-stratification, indicating deposition above storm wavebase.

Aigner (1985) noted that the percentage of sand decreases offshore (producing a "graded shelf") in German Bay in the North Sea due to the diminished capacity of storm-induced flows to transport sands towards deeper offshore waters. Proximal tempestites become subordinate to distal tempestites in an offshore direction. Nelson (1982) documented similar proximality trends for storm deposits on the Bering Shelf. Swift and Rice (1984) proposed that geostrophic storm flow in the direction of the wind can transport sediment efficiently in distal muddy shelf settings. Aigner (1985) postulated that most distal tempestites in the Upper Muschelkalk of southwest Germany formed in this way.

Sparse paleocurrent data and the west-to-east "grading" or proximality trends of tempestites in lower ramp subfacies 3 and 4 indicate that offshore sediment transport, perpendicular to the axis of the Hare Indian isopach maximum, predominated in the study area (FIG. 3-6). Although no large scale (several meters thick) channel-fills are evident in the ramp facies association, small gully-fill structures are present rarely in the lower ramp facies and uppermost clinotherm facies (PL. 3-11). These gully-fill structures are 1-2 m thick and 20-40 m wide in cross-section. They are oriented perpendicular to the axis of the isopach maximum of the Hare Indian lobe. The gully-fill sequences show no evidence of lateral migration and are composed of distal and proximal tempestites. This indicates that small scale, storm-generated gullies served to direct subsequent ebb flow from episodic storm surges.

In summary, the ramp depositional sequence is a storm wave-dominated succession that shows evidence for active sediment bypassing down the ramp. Sediment transport was mainly non-channelized except for small gullies oriented perpendicular to the axis of the Hare Indian lobe. Accumulation rates increased downslope, resulting in thickening of second-order cycles as the frequency and velocity of storm-generated currents (and related storm winnowing) decreased towards storm wavebase. Sediments were introduced into this setting by traction currents and low

density turbidity currents. The shallow sloping ramp probably facilitated the downslope movement of storm-generated turbidites.

3.3 FACIES ANALYSIS OF THE CLINOTHEM FACIES ASSOCIATION

3.3.1 General Statement

Fine-grained rocks of the clinothem facies association comprise mainly peloidal calcisiltite and dark grey calcareous shale. The latter becomes subordinate towards the top of the Hare Indian Formation (PL. 3-12a). Most limestone beds are thin-bedded (average 2-15 cm thick), show great lateral continuity (>100's of m, beyond outcrop scale), have sole marks rarely on sharp basal contacts, and show upward fining similar to Bouma DE sequences (predominantly silt-size fraction). Muir et al. (1985) suggested that most limestones in the clinothem succession were emplaced as fine-grained turbidities on a gently sloping (average 0.2-0.6°) clinoform.

The recognition of cyclicity and the observation that calcisiltite turbidites predominate towards the top of each cycle (see Chapter 2) resulted in an initial two-part division of the clinothem facies association: Upper clinothem facies (>40% limestones) are distinguished in this facies analysis from lower clinothem facies (<40%

limestones) in an attempt to document downslope (basinward) sedimentological and paleoecological changes. The detailed facies analysis distinguished three subfacies in the clinothem facies association (FIG. 3-1), and these are described below.

3.3.2 Upper Clinothem Facies

The upper clinothem facies is distinguished from the lower clinothem subfacies in having a higher proportion (>40%) of quartzose peloidal calcisiltite interbedded with grey to olive calcareous shale. The lithofacies also includes minor interbedded nodular skeletal lime wackestone and packstone.

The facies is restricted to the upper third of the clinothem facies association where it forms the upper portions of clinothem second-order cycles (see FIG. 3-1). Units of this facies tend to be thicker higher in the Hare Indian Formation and to thin downslope. Thicker accumulations appear to have been deposited immediately downslope of the ramp facies association, associated with marked steepening of the clinoform (see sections 20, 31, 08, 07 in FIG. 3-1). The facies ranges in thickness from 2-15 m in individual second-order shallowing-upward cycles and shows lateral continuity for tens of km (FIG. 3-1). The facies is typically gradationally interbedded (upward

decreasing shale content) with underlying lower clinotherm subfacies 1 and less commonly clinotherm subfacies 2.

Thin bedding (2-5 cm) is typical and beds are commonly amalgamated into laterally extensive (PL. 3-12a), planar to slightly nodular units (20-30 cm thick), interbedded with grey to olive calcareous shale. Basal contacts of beds are commonly planar-sharp, but locally show load (PL. 3-12b) and scour structures. Rarely occurring tool marks (mainly prod marks and groove casts) indicate southwestward transport (PL. 3-13; Appendix B). Bioturbation is sporadic in occurrence, but commonly more pervasive near tops of beds (PL. 3-14a).

Beds typically fine-upwards (fine calcarenite to calcisiltite) and show lenticular laminae rarely near the base and graded, slightly convolute to planar laminae which thin and fine upwards towards the top (PL. 3-14b). Laminae commonly have sharp basal contacts, and sharp or gradational upper contacts. Microfaults, microscours, and microloading structures are common (PL. 3-14c).

Crinoid-brachiopod coquinite occupies local scours near the clinotherm-lower ramp transition in section 18. This indicates that storms only rarely reworked the upper clinotherm seafloor. The scarcity of wave-formed structures suggests that much of this upper clinotherm facies was deposited below storm wavebase.

Many allochems are pyritized, and pyrite is ubiquitous within the lithofacies, mostly disseminated as framboidal grains and, less frequently, as nodules and filaments. The dark grey calcareous shale shows high C_{org} values ranging from 0.59 to 2.15 wt.% (Monnier, writ. comm., 1986).

Infaunal diversity and burrow size in the facies increases towards the top of the Hare Indian Formation. Chondrites burrows (average 1-2 mm diameter) occur throughout the facies, but Planolites, Rhizocorallium, Diplocraterion, and Teichichnus were observed only in the uppermost Hare Indian sediments. In sections more proximal to the Hare Indian maximum (sections 15, 16), substrates were evidently able to support a sparse epifauna, as indicated by meandering feeding trails, possibly Cruziana (PL. 3-15a). Macrofossils occur rarely and are predominantly a low diversity brachiopod-crinoid assemblage in both shale and limestone (TABLE 3-18). However, at section 25 (FIG. 3-1), interbedded shales are barren of macrofossils. Severe ecologic stresses are interpreted for this depositional environment. Dysaerobic conditions are indicated by:

- (1) scarcity of macrofossils
- (2) dominance of trace fossils by small horizontal burrows
- (3) low level of bioturbation and partial preservation of laminae

TABLE 3-18

MACROFOSSILS OF UPPER CLINOTHEM FACIES

Common Constituents

none

Rare Constituents

brachiopods: atrypid, lingulid, and orbiculoid
 brachiopods; productid brachiopod and
 spines (Spinulicosta?); Schuchertella?
 (broad, flat valves with long hinge up to
 5 cm); Pugnax; rhynchonellid brachiopod
 (heavily ribbed, prominent sulcus and fold,
Cassidirostrum?)

crinoid columnals: 3-15 mm diameter

Components Subordinate to Crinoids and Brachiopods

dacryconarids: probably styliolinids
 plant fragments: broken, elongate
 fish fragments
 sponge spicules
 gastropod
 bivalve: elongate burrower?, 4.5 cm long
 branching and encrusting bryozoa
 solitary rugose coral

- (4) ubiquitous occurrence of pyrite (mainly disseminated); common pyritization of allochems; abundance of organic carbon

Low oxygen content in the bottom waters would probably have prevented colonization by taxa with calcitic shells and high metabolic requirements (Byers, 1979; Cluff et al., 1981).

The substrate also could have been too unstable for most epifauna, although the presence of distinct burrow outlines in calcisiltite beds indicates that the muds were not thixotropic. The more commonly observed epifaunal types are known to have been better adapted for such muddy environments. Rhizoid crinoidal holdfasts would have provided stability for the organisms. Productid brachiopod spines are thought to have served in distributing weight over a larger surface area. Other brachiopods occupy coquinities and represent an allochthonous assemblage.

Another stress factor that probably limited macrobiota in this facies was high turbidity resulting from episodic influx of suspended sediments. The paleoecologic distribution of stromatoporoids appears to have been not only depth-controlled (generally in waters shallower than 25 m; see Chapter 4 in this study), but also adversely affected by turbidity and rapid sedimentation (e.g. see Isaacson and Curran, 1981; Kershaw, 1984; Bjerstedt and Feldman, 1985).

3.3.3 Lower Clinotherm Facies

3.3.3.1 Lower clinotherm subfacies 1

Lower clinotherm subfacies 1 includes those parts of the clinotherm facies containing 15-40% peloidal calcisiltite. Interbedded, medium-grey, calcareous shale makes up the remainder of the subfacies.

Units of subfacies 1 are restricted to the upper portion of the Hare Indian Formation and are interbedded at the base with lower clinotherm subfacies 2 (FIG. 3-1). Units of subfacies 1 in shallowing-upward cycles range in thickness from 2-17 m. They resemble the upper clinotherm facies in thickness variation (see previous section) and this suggests common processes of sediment distribution for both.

Beds are generally planar (2-5 cm thick) and arranged in amalgamated, laterally extensive units (average 10-20 cm thick) interbedded with shale. Basal contacts are predominantly planar-sharp to slightly undulating. Beds commonly fine upwards, and internal lamination is generally horizontal and accentuated by alternating silty/shaly laminae. These laminae also commonly fine upwards and have sharp, locally micro-loaded, lower contacts. Their upper contacts are gradational or sharp. Silty laminae are typically progressively thinner higher in each bed (12-2 mm thick) and remarkably continuous laterally (at least several meters).

Most interbeds of gray calcareous shale are devoid of fossils and show wispy to even lamination (2-3 mm) which is also reflected by varying carbonate content. These shale beds typically show gradational lower contacts and abrupt, planar upper contacts with peloidal calcisiltite beds.

Bioturbation is more pervasive towards the tops of the calcisiltite beds. Burrow outlines are diffuse and preliminary examination indicates a characteristic low diversity trace fossil assemblage. Small (1-3 mm diameter) Chondrites burrows are ubiquitous in lower clinotherm subfacies 1. The average diameter of the Chondrites burrows, trace fossil diversity (with the addition of Planolites burrows and rare Teichichnus), and intensity of bioturbation, all increase toward the tops of second-order shallowing-upward cycles in the vicinity of the Hare Indian isopach maximum (sections 15, 18 in FIG. 3-1). However, trace fossil and macrofossil diversity is substantially lower than in the upper clinotherm facies. Framboidal disseminated pyrite is common, particularly in shalier lithofacies, and pyrite nodules are common in the shale. Two shale samples from section 07 yielded total organic carbon values of 3.2 and 3.8 wt.% (Monnier, writ. comm., 1986).

Apparently dysaerobic, turbid waters characterized the depositional setting for lower clinotherm subfacies 1 for reasons similar to those previously outlined for the upper

clinothem facies. The macrofossils (TABLE 3-19) are much less diverse than in the upper clinothem facies, and are mainly an allochthonous assemblage restricted to the peloidal calcisiltite beds.

3.3.3.2 Lower clinothem subfacies 2

Subfacies 2 consists of dark grey, calcareous shale, with less than 15% peloidal calcisiltite. Field units tend to be poorly exposed due to the recessive weathering nature of the shales. Subfacies 2 makes up the lower portion of the Hare Indian "upper member", and the lower contact is gradational with horizontally laminated black shale of the Bluefish Member (PL. 1-3a). Second-order shallowing-upward cycles thicken upsection (3 m to 25 m) towards the middle of the Hare Indian Formation and then thin slightly (25 m to 10 m in FIG. 3-1) towards the top of the basin-fill succession. Most of lower clinothem subfacies 2 is restricted to the lower portion of the Hare Indian Formation, characterized by the thickening-upward cycles. If these second-order cycles represent approximately similar time periods, subfacies 2 shows increasing rates of net accumulation upsection, with maximum rates of accumulation near mid-clinoform position on the ramp to basin profile. At mid-clinoform position, subfacies 2 usually grades upwards (with decreasing shale content) to lower clinothem subfacies 1. Subfacies 2 is conspicuously absent in upper cycles in sections 20, 31, 08,

TABLE 3-19

MACROFOSSILS IN LOWER CLINOTHEM SUBFACIES 1

Common Constituents

none

Rare Constituents

brachiopods: productid brachiopods and spines, lingulid
brachiopod; Emanuella?, Schuchertella?;
most are disarticulated and commonly in
current unstable positions

crinoid columnals: 1-3 mm diameter
fish fragments
plant fragments
ostracod
ammonoid

styliolinids: more common towards the depositional basin
tentaculitids in the vicinity of section 25;
sponge spicules dacryconarids rarely current-
oriented

07. In this area, correlated cycle boundaries indicate progressively steeper clinoform profiles. The significance of clinoform geometry and subfacies distribution will be discussed in section 3.3.4, below.

Thin, peloidal calcisiltite beds (2-5 cm thick) are arranged in amalgamated, laterally extensive units (>1 km; average 10 cm thick) that typically occur towards the tops of second-order shallowing-upward cycles. Basal bed contacts are typically planar-sharp (PL. 3-15b) and upper bed contacts are sharp to gradational.

Peloidal calcisiltite beds show fining-upward trends and internal lamination defined by alternating silty and shaly laminae. However, these beds overall display greater argillaceous contents than in the other clinotherm facies. Regular, parallel silty laminae (average 1-5 mm thick) are progressively thinner, less distinct, and less continuous towards the top of each bed (PL. 3-16a). Basal contacts of laminae are typically sharp and show micro-load structures rarely. The silty laminae grade upward into shaly laminae.

The dark grey to grey-olive calcareous shale manifests wispy to even lamination defined by variable carbonate content as in lower clinotherm subfacies 1. These shale beds are barren of fossils and contain ubiquitous disseminated framboidal pyrite and pyrite nodules. Two samples 1-2 meters above the Bluefish Member in sections 15 and 25

yielded 1.7 and 2.9 wt.% total organic carbon, respectively (Monnier, writ. comm., 1986).

Bioturbation in peloidal calcisiltite beds is moderate to intense, and mainly restricted to bed tops. Trace fossil diversity in subfacies 2 is the lowest in the clinotherm facies association. Small (average 1 mm diameter), discrete Chondrites burrows were the only common trace fossil observed in the subfacies. Macrofossils, represented by pyritized fossil fragments (TABLE 3-20), are very rare in subfacies 2 and confined to the peloidal calcisiltite beds.

The fine-grained lithology in subfacies 2, high organic content of interbedded grey shale, pyrite, absence of an in situ epifauna, and presence of a low diversity trace fossil assemblage suggest poorly oxygenated waters at the sediment-water interface.

3.3.4 Synthesis of the Clinotherm Depositional Environment

3.3.4.1 Introduction

A discussion of the clinotherm depositional environment must attempt to resolve two major problems to help establish a cogent ramp-clinotherm-basin model for the Ramparts (lower "ramp" member) - Hare Indian succession.

- (1) Sedimentation on the clinoform in general terms comprised calcisiltite and shale deposition. How

TABLE 3-20

MACROFOSSILS IN LOWER CLINOTHEM SUBFACIES 2

Common Constituents

none

Rare Constituents

productid brachiopod spines: small (average 1-3 mm
diameter), observed only in
upper cycles at section 18

crinoid columnals

fish fragments

plant fragments

dacryconarids: pyritized

did these sediments accumulate and how are their facies related in a depositional model?

- (2) The characters of infauna, epifauna, and enclosing sediments indicate poorly oxygenated waters at the depositional interface. How did water stratification influence faunal and sediment distribution in the Hare Indian depositional basin?

3.3.4.2 Evidence for a stratified water column in the Hare Indian depositional basin

Isolation of bottom waters from oxygenated surface waters, and resultant basin stagnation, can be produced by water density stratification (Rhoads and Morse, 1971; Byers, 1977; Ettensohn and Elam, 1985). Warm, tropical epicontinental seas are thought to have characterized much of the Laurasia landmass during the Middle to Late Devonian (Ettensohn and Elam, 1985). As a consequence, well developed thermoclines could have been the principal controls on contemporary water density stratification (Hallam, 1981). Inability of warm surface waters to sink and displace colder bottom waters could have led to reduced vertical mixing and replenishment of bottom waters and, thus, to establishment of a thermocline and stratified water column (Cluff, 1980).

Bottom waters in stratified basins become oxygen-depleted as oxygen is consumed during organic decay (Rhoads and

Morse, 1971; Curtis, 1980). Ettensohn and Elam (1985) noted that water stratification may be enhanced by a salinity gradient in nearly-enclosed seas with large fresh-water influx. Lighter, fresh-to-brackish surface waters above denser, more saline bottom waters can further hinder vertical circulation (e.g. in the Black Sea).

There is evidence that water density stratification in the Hare Indian depositional basin caused oxygen depletion with depth. These oxygen levels can be interpreted from color, sedimentary structures, and fossil content of sediments (Byers, 1977; Ettensohn and Elam, 1985).

Rhoads and Morse (1971) defined three depth-related zones in oxygen-depleted basins. They noted that metazoan populations are extremely sensitive to oxygen levels in sea water and categorized facies in the different zones, as follows:

- (1) Aerobic Zone - well-bioturbated, fossiliferous sediments poor in organic carbon; oxygen contents in sediments are typically greater than 1.0 ml/l.
- (2) Dysaerobic Zone - moderately bioturbated sediments lacking calcareous fossils and characterized by intermediate organic carbon contents; oxygen contents in sediments 0.1 to 1.0 ml/l.
- (3) Anaerobic Zone - nonbioturbated sediments lacking calcareous fossils and characterized by high

organic carbon contents; oxygen contents in sediments typically less than 0.1 ml/l.

Three analogous broad facies can be recognized in the Hare Indian-Ramparts basin-fill succession. The significance of organic carbon content is discussed briefly in section 3.4 (basin facies association).

The aerobic zone is generally well-oxygenated by wind- and wave-generated currents. Typical sediments formed are fossiliferous, light-colored in situ carbonates, and intensely burrowed muds. A diverse, normal marine benthic fossil assemblage and an abundant and diverse trace fossil assemblage in the ramp facies association suggests that it formed in the aerobic zone. Low total organic carbon content (generally <0.5 wt.% in ramp shales; Monnier, writ. comm., 1986) and low pyrite content (allochems rarely pyritized), in addition to abundant evidence of storm current reworking, indicate that much of the ramp depositional setting was well oxygenated. However, the presence of dark grey, faunally impoverished, pyritiferous shale at bases of lower ramp cycles (PL. 2-4) is evidence of slightly lower levels of oxygen in waters over the lower ramp during pulses of accelerated sea-level rise.

The dysaerobic zone, or pycnocline, is a broad oxygen-depleted layer between the aerobic zone and an anaerobic zone. The dysaerobic zone shows a marked density gradient between warm surface waters and cool, more dense

bottom waters (Ettensohn and Elam, 1985). This density stratification prevents vertical turnover, and oxygen content in the pycnocline consequently rapidly declines.

While there is evidence to suggest that the aerobic-dysaerobic boundary extended up into the lower ramp during periods of accelerated sea-level rise, the boundary appears to have been more typically near the ramp-clinothem transition in 40-50 m of water (lower ramp subfacies 4-upper clinothem subfacies 1; see FIG. 3-7 for method of paleodepth estimate). Low oxygen levels apparently excluded most in situ epifauna from the clinothem facies association. Ettensohn and Elam (1986) point out that the top of the paleopycnocline can be difficult to delineate precisely due to other factors that adversely affect macrobiota (e.g. high sedimentation rates, unstable substrates, high levels of turbidity). Stoakes (1979, 1980) recognized the following down-slope trends in Ireton basin-fill sediments, presumed to have been deposited in the dysaerobic zone:

- (1.) decrease in shelly benthic fossils
- (2.) decrease in trace fossil diversity and bioturbation intensity
- (3.) increase in proportion of pelagic fossils.

Facies deposited in the dysaerobic zone can also be subdivided according to the ichnofossil characteristics at different oxygen levels (Rhoads and Morse, 1971; Savrda et al., 1985; Savrda and Bottjer, 1986) as follows:

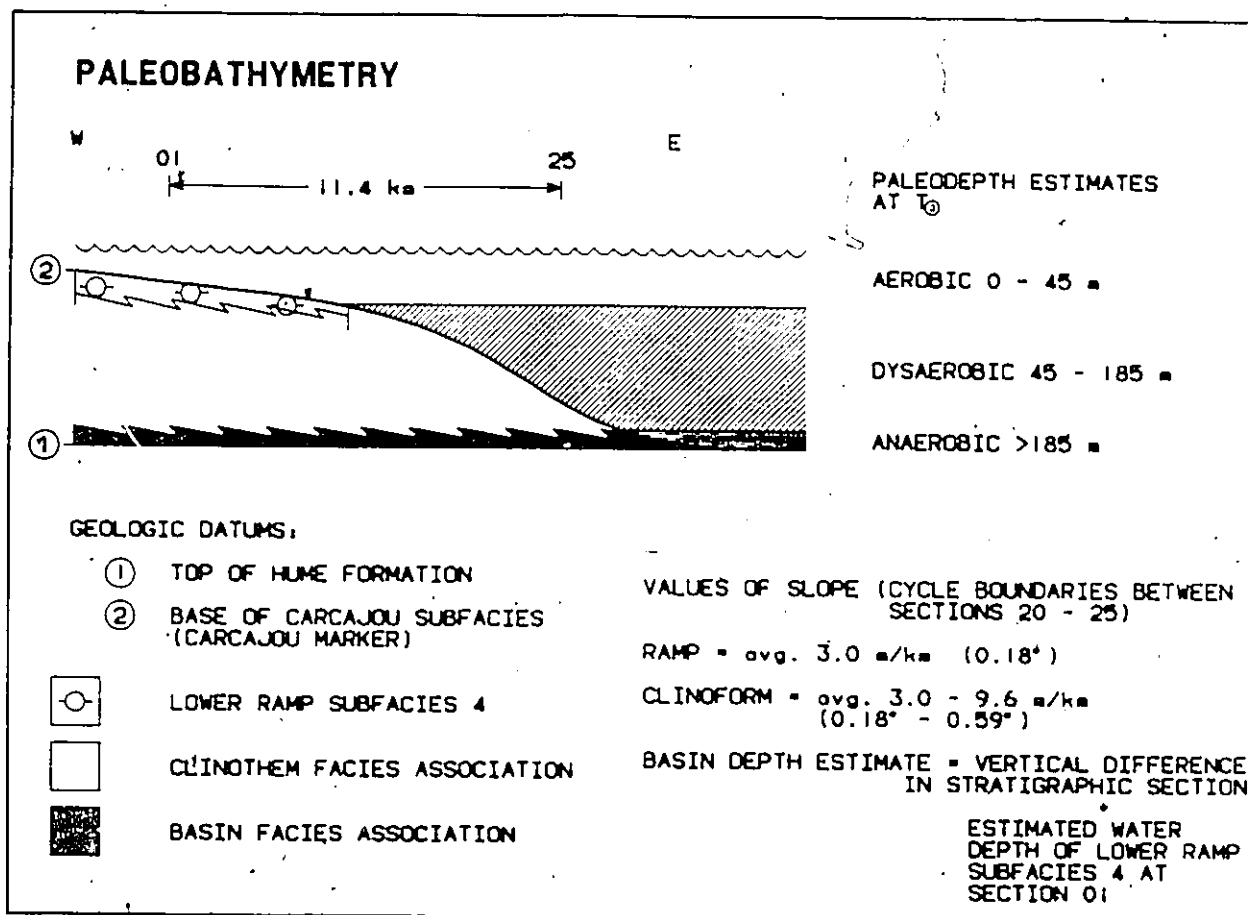


FIG. 3-7 Paleobathymetric reconstruction of the Hare Indian-Ramparts lower "ramp" member basin-fill succession at the time of the Carcajou drowning event.

- (1) Burrow Size - The average diameter and range in diameter decreases with depth and decreasing oxygen levels in oxygen-deficient California borderland basins (Savrda et al., 1985). Rhoads and Morse (1971) suggested that larger organisms with higher oxygen requirements are excluded from oxygen-depleted environments.
- (2) Trace Fossil Diversity - Savrda and Bottjer (1986) noted that certain producers of trace fossils are less tolerant of low oxygen levels.

Higher organic carbon and pyrite contents in most clinotherm facies, compared to the ramp facies, presumably reflect more reducing conditions in the dysaerobic zone (e.g. Curtis, 1980; Thickpenny, 1984). The entire dysaerobic zone probably ranged from ~45 m to 185 m water depth (FIG. 3-7). Two groups of subfacies that formed in this zone show evidence (FIG. 3-8) that oxygen levels were slightly higher in the upper portion of the clinotherm succession (dysaerobic zone A) than in the lower clinotherm facies association, or lower Hare Indian Formation (dysaerobic zone B). Poor exposure of the recessive lower portion of the Hare Indian Formation makes delineation of the A-B zone boundary impossible. Lower clinotherm subfacies 2 grades downward into laminites of the basin facies association throughout the study area. The evidence of

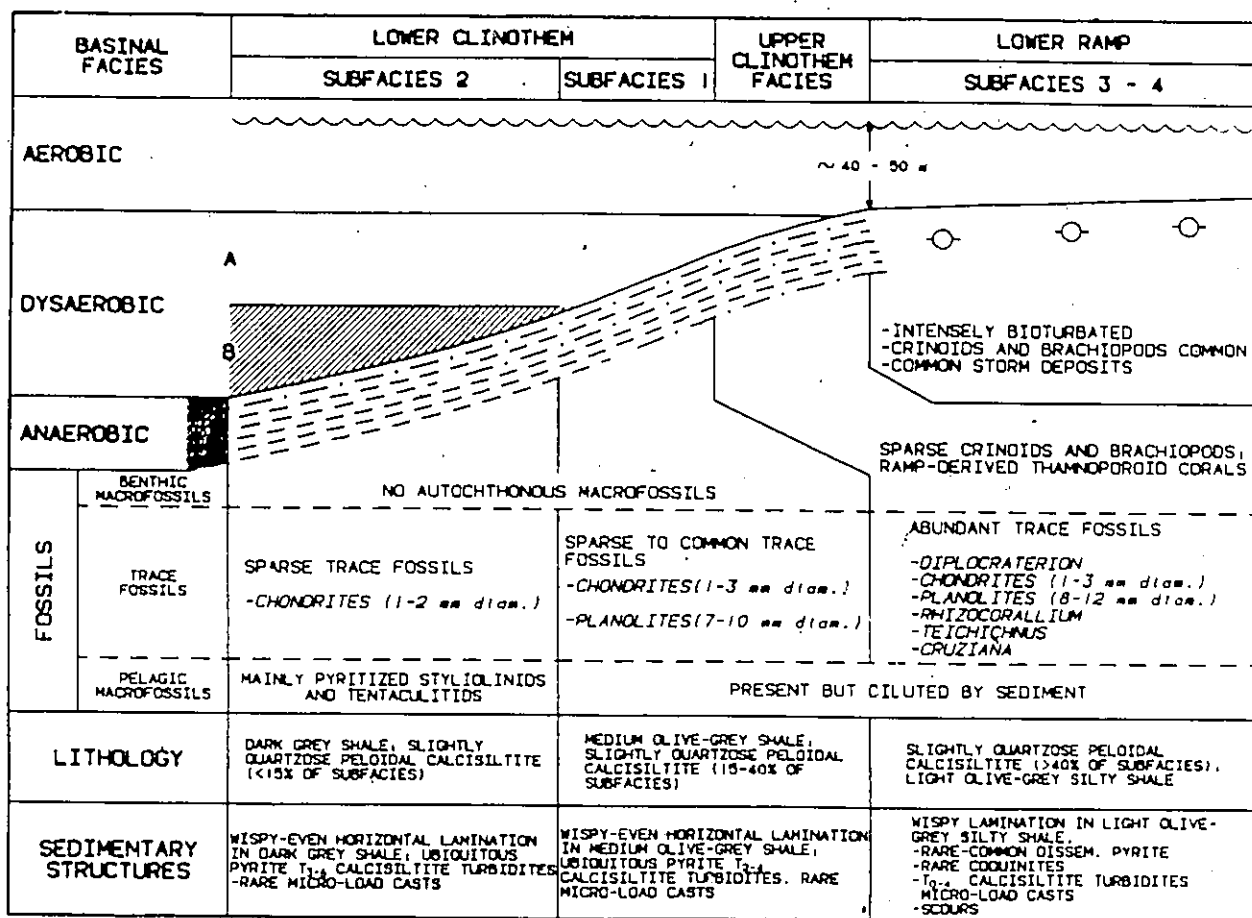


FIG. 3-8 Distribution of fossils, lithologies, and sedimentary structures in the clinotthem facies association. Turbidite subdivisions (T₀₋₆) illustrated in FIGS. 3-10 and 3-11.

slightly greater oxygenation in the upper portion of the clinothem succession includes the following:

- (1) Coarser-grained sediments predominate in this portion of the succession and crinoids and brachiopods rarely occur.
- (2) Burrows are typically smaller, trace fossil diversity lower, and total organic carbon and pyrite contents higher in lower clinothem subfacies 2 than in sediments deposited under dysaerobic zone A conditions. Sediments less intensely bioturbated in dysaerobic zone B.

The anaerobic zone in a density-stratified water column contains little or no oxygen. Sediments deposited there are predominantly evenly laminated, pyritiferous, organic-rich (>5 wt.% total organic carbon; Curtis, 1980) black shale with common pelagic faunal elements (no benthic epifauna or infauna). Jones (1983) noted that bioturbation by deposit feeders is largely restricted to bottom waters with oxygen contents above 0.5 ml/l.

The basin facies association (Bluefish Member) represents anaerobic depositional conditions (Muir et al., 1984, 1985). The depositional environment for the basin facies association is discussed in more detail in section 3.4 below.

3.3.4.3 Clinothem depositional model

A model for the sediment transport and deposition of the clinothem facies association must take into account several observations:

- (1) Cycle correlation (FIGS. 3-1, 3-2) shows no evidence for a sharp break in slope in the ramp-clinotherm transition. However, in eastern exposures of the Hare Indian Formation (section 20 to section 25), upper Hare Indian second-order cycle boundaries show the most change in slope (0.2° to 0.6° over several kilometers) and muddy sediments of lower clinotherm subfacies 1 are thin or absent. This suggests that the eastern area was a site for active bypassing of fine-grained sediments.
- (2) Upper sequences of upper clinotherm facies contain evidence of storm activity. The close association of scours filled by crinoid-brachiopod coquinite with calcisiltite turbidite beds indicates a common genetic relationship. The thickest accumulation of calcisiltite (upper clinotherm facies) is on the proximal slope close to the storm-winnowed lower ramp subfacies 3 and subfacies 4.
- (3) Slump and channel features are absent and gully-fill structures rare towards the top of the basin-fill succession (PL. 3-11). Laterally

extensive (10's of km) second-order shallowing-upward cycles generally display upward thickening and coarsening trends. There is, therefore, little evidence for channelized flow on the clinoform.

- (4) Peloidal calcisiltite beds are remarkably similar in each clinotherm subfacies. Bedding is typically 2-5 cm thick, although beds are slightly muddier and thinner in lower clinotherm subfacies 2. The fine-grained nature of the calcisiltite turbidites along the entire clinoform (10's of km) argues for extensive, non-channelized flow from a fine-grained source along the storm-winnowed ramp. The lack of coarse, sand-size components suggests that these were low density turbidity currents. This could explain the near-absence of sole markings if the muddy sediments were too firm to be sculptured by low density turbidity currents.
- (5) The peloidal calcisiltite beds are generally amalgamated into units 10-30 cm thick. Intervening shales are typically unfossiliferous except in the upper clinotherm facies. Evidently the basin-fill succession was deposited in a density-stratified basin, and most of the clinotherm facies association was deposited under dysaerobic conditions.

The above observations suggest that calcisiltite beds were periodically emplaced below storm wavebase onto a

surface that normally received hemipelagic calcareous mud. Turbid clouds of silt- and clay-sized grains, stirred by storm activity on the ramp would have been dispersed into the basin mainly by gravity flow. This mechanism more aptly explains the non-channelized flow and linear source for the turbidites. Because the incidence of storm influence increased during deposition of ramp shallowing-upward cycles, there was a corresponding increase in turbidite generation (coarsening-upward trends). Silt and clay introduced to the ramp-clinothem transition could also have been subjected to resedimentation (FIG. 3-9) not related to storms. Remobilization of fine sediments could have been aided by increased bioturbation accompanying shoaling-upwards into more oxygenated waters. Biogenic reworking of sediment would increase water volume and make the sediments more prone to resuspension (Baird, 1981). Higher rates of sedimentation associated with shoaling would also promote slope instability, although slump features were not observed in the clinothem facies association. Sediments could have been remobilized by turbidity currents generated by internal waves propagated along the top of the dysaerobic zone (FIG. 3-9). Instabilities along this density boundary could have been caused by tilting of the pycnocline from horizontal (Brenner, 1980). For example, oxygenation events associated with turbidite emplacement along the upper clinoform could depress the pycnocline (Ettensohn and Elam,

CLINOTHEM PROCESSES

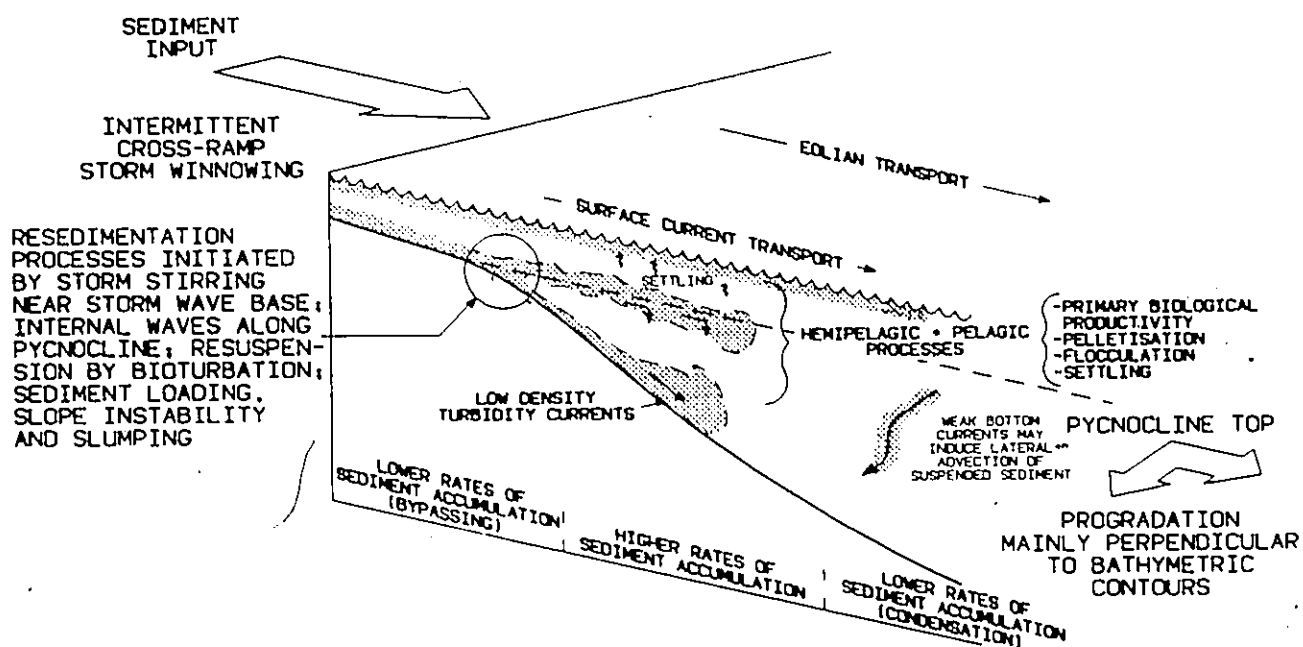


FIG. 3-9

FIG. 3-9

Transport and depositional processes in the clinothem facies association. Model based on field observations and the works of Stanley (1982), Woodrow (1983), and Stow (1985).

1985) and generate internal waves along it that would influence the ramp-clinothem transition. Woodrow and Isley (1983) suggested that this process could have been significant in resuspending sediment in epicontinental seas. They noted that these sediments would likely move downslope across the clinoform as dilute, low velocity flows capable of eroding only surficial, incohesive sediments.

However, density stratification within the water column could also impede or deflect downslope flow. A portion of the low-concentration suspension cloud can be separated from the clinoform and transported in stratified layers within the dysaerobic zone (Stanley, 1982, 1985).

Large plumes of muddy sediment have been observed moving off the Bahama Banks after winter storms (Heath and Mullins, 1985). These plumes can be transported in surface layers or sink and spread out in denser, mid-water layers. Heath and Mullins (1985) noted that some material also continues downslope as low density turbidity currents.

Second-order cycle thicknesses in the Hare Indian Formation indicate that the highest rates of sediment accumulation were approximately mid-clinoform in position. Similar observations were made by Stoakes (1979, 1980) for the Upper Devonian Ireton Formation in Alberta. The upper clinoform was a site of more temporary sediment accumulation; some of these sediments were remobilized and transported further downslope. Stanley (1982) noted that

the Mediterranean basin-margin is characterized by turbid-layer bypassing. He viewed these slopes as active surfaces typified by high sedimentation rates, but low accumulation rates. Progressive redeposition downslope was probably due to a number of factors, including high sedimentation rates, earthquake tremors, and increased offshelf spillover during periods of falling sea level. His gravity transport model predicts fining grain size downslope towards the Mediterranean basin.

Fine-grained sediments of lower clinothem subfacies 2 are characterized by rare occurrence of predominantly pelagic fossils near the base of the clinothem succession. Second-order cycles in this portion of the basin-fill sequence are quite thin (3-5 m) and are probably condensed sequences (see PL. 1-3a).

Evidence for episodic current activity was observed in both the basin facies association (aligned allochems, see section 3.4) and lower clinothem facies (PL. 3-13a). Paleocurrent data (Appendix B) revealed westward current flow mainly perpendicular (east to west) to the bathymetric contours of the Hare Indian lobes. Evidence for contourites (see Stow, 1985) and persistent current activity are absent from the basin facies association (see section 3.4) and progradation was mainly perpendicular to the inferred paleocoastline.

3.3.4.4 Nature of calciturbidite emplacement

In an excellent review of processes affecting deep sea transport and deposition of fine-grained sediments, Stow (1985) outlined common characteristics of low density turbidity currents. He noted that turbulent autosuspension is maintained while there is excess density of suspended sediment to propel the flow. Flow generates both friction and flow turbulence, and it is the latter that maintains sediment in suspension (Allen, 1970). The loss of energy by friction for the storm-generated turbidites on the ramp-clinoform profile could have been compensated somewhat by gravitational energy as flows travelled great distances downslope.

Limited research has been conducted on recent fine-grained calciturbidites. The peloidal calcisiltite beds in the study area resemble Late Quaternary fine-grained (silty muds) carbonate turbidites reported in the Gulf of Aden (Faugères et al., 1984). These recent turbidites show sharp, erosional basal contacts and typically consist of horizontal, sometimes graded, laminae. The plane lamination results mainly from the alternation of silt- and clay-rich laminae.

Stow (1985) outlined a structure sequence model for fine-grained turbidites. An average unit was observed to be 7 cm thick and composed of nine subdivisions (T_{0-8}). He suggested that the grading and sequence may be explained by

waning current velocities during passage of a single flow. Proximal fine-grained turbidites were distinguished from those more distal on the basis of a higher silt/clay ratio. Furthermore, partial sequences typify downslope turbidity current evolution in an analogous manner to the model invoked for partial Bouma sequences (Stow et al., 1984). Top-cut-out sequences are generally more proximal, while base-omitted sequences tend to be more distal (Stow et al., 1984).

Calcisiltite beds in the clinotherm facies association show proximality trends. Proximal fine-grained turbidites (FIG. 3-10) are abundant in the upper clinotherm facies. These are top-cut-out sequences (T_{0-4}) according to the fine-grained turbidite model of Stow and Shanmugan (1980). Proximal calciturbidites in the clinotherm facies association more typically display T_{2-4} sequences. In the alternating graded silty and shaly laminae, the calcisiltite shows thinning-upward trends from irregular, thick laminae (T_2) to thin, discontinuous laminae (T_4).

The cause of this arrangement of laminae is unclear. Because of the overall graded nature of the calcisiltite laminae, the lamination is unlikely to be due to a series of thin, turbid flows. Stow and Bowen (1978) postulated that alternation of silt and clay laminae can result from depositional sorting of silt grains from clay flocs due to increasing shear in the bottom boundary layer of a turbidity

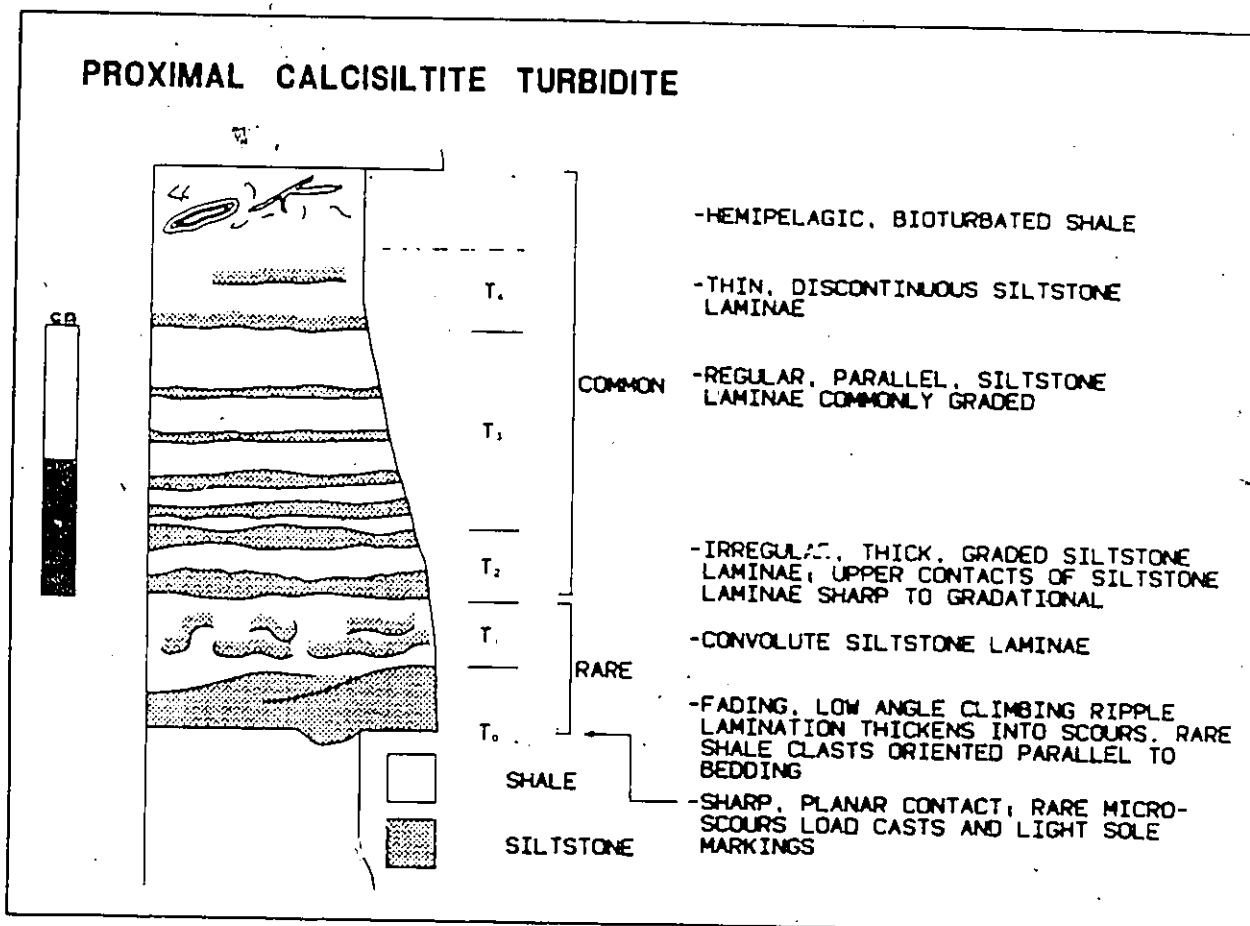


FIG. 3-10 Idealized proximal fine-grained carbonate turbidite. Data obtained from upper clinotherm facies. Subdivisions (T_{0-4}) taken from Stow and Shanmugam (1980). Note that subdivisions T_0 , T_1 are not common. Most turbidites in this facies are top-cut-out sequences.

current. They (ibid., p. 326) suggested that as the clay-silt slurry settled, the clay flocs were broken up while the larger silt grains continued to settle to form a silt lamina. As more sediment was supplied to the top of the boundary layer, the clay concentration would increase until reflocculation occurred. These clay flocs could have been large enough to resist shear break-up and be deposited rapidly as a "blanket" over the coarser silt lamina. The process could then repeat with formation of successively finer silt layers. Variations from this thinning-upward, graded aspect to the calcisiltite beds may reflect temporary disturbance of the boundary layer (e.g. due to velocity fluctuations).

Peloidal calcisiltite beds comprise less than 15% of lower clinotherm subfacies 2, and show features that distinguish them as mainly distal calciturbidites (FIG. 3-11). These beds are thinner and display higher clay/silt ratios than the proximal calcisiltite turbidites. Basal contacts are sharp and rarely show evidence for scouring. The beds are typically base-omitted sequences (T_{3-7}) which fine upwards. Alternating silty-shaly laminae define internal stratification. The calcisiltite laminae thin upwards (T_{3-5}) much as in the proximal turbidites. A weakly laminated, nonbioturbated shale ($T_{6, 7}$) caps the sequence.

Much of the sequence was deposited probably from turbid flows in well-defined, density-stratified layers in the

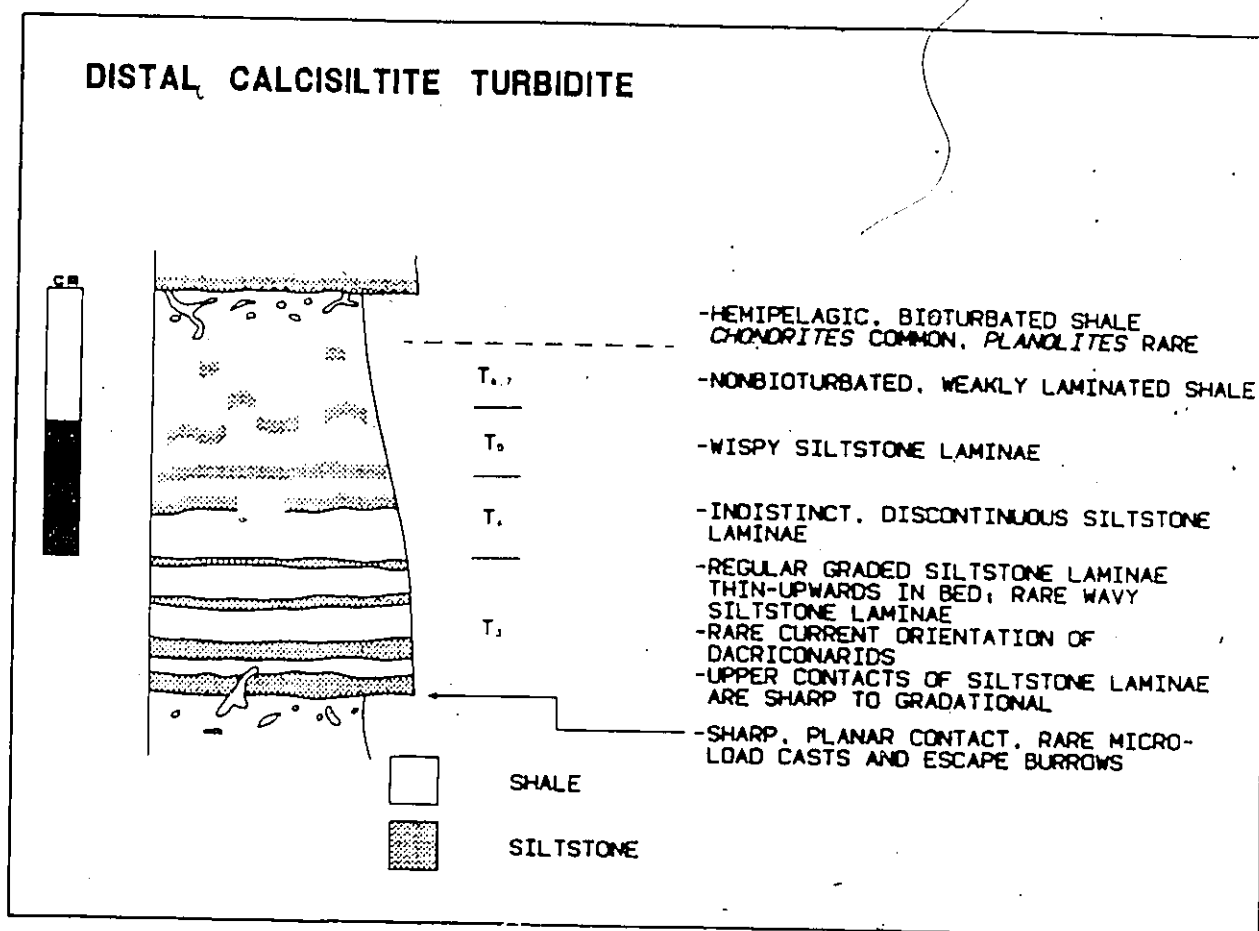


FIG. 3-11 Idealized distal fine-grained carbonate turbidite. Data obtained from lower clinotherm subfacies 2. Turbidite subdivisions (T_3-7) taken from Stow and Shanmugam (1980). Most turbidites in this subfacies are base-omitted sequences ($T_0, 1, 2$ generally absent) capped by bioturbated hemipelagic shale.

pycnocline (Stanley, 1982) and from distal, clay-laden turbidity currents which had lost most of their silt fraction on the upper portion of the clinoform (base-omitted sequences).

3.4 FACIES ANALYSIS OF THE BASIN FACIES ASSOCIATION

3.4.1 General Statement

The basin facies association is represented by the Bluefish Member of the Hare Indian Formation. The distribution and contact relationships of this sequence were briefly discussed in Chapter 1. The main Bluefish lithology is black to dark brown, organic-rich, laminated shale, with rare limestone concretions. Minor intercalated beds of medium brown calcisiltite and fibrous calcite (see section 3.4.3.3) are present in the Bluefish Member.

The shale in the basin facies association is calcareous immediately above the Hume-Hare Indian formational contact, but is increasingly argillaceous and less calcareous towards the gradational upper contact with lower clinothem subfacies 2 (Hare Indian "upper member"). The weathering profile of the Bluefish Member reflects this compositional trend by becoming more recessive upwards. Detailed examination of hand specimens and thin sections shows several lithofacies. These will be elaborated upon following a detailed

discussion of the nature of the upper Hume succession in the study area.

3.4.2 Nature of the uppermost Hume strata

The upper Hume Formation is a transgressive cyclic limestone sequence in which each successive shallowing-upward cycle terminated in relatively deeper water (see Chapter 1). Preliminary work in the vicinity suggests that the carbonate platform built to sea level (PL. 3-16b) during middle Hume time. Unfortunately, the uppermost 40-50 m of the Hume strata are poorly exposed in this area.

The topmost 5 m of the Hume are typically nodular lime mudstone and wackestone, with intervening medium grey calcareous shale beds (PL. 3-16c). The shale pinches and swells about the nodular bedding. Pyrite is ubiquitous as spheroidal aggregates of microcrystallites (framboids) and as mineralized replacement of allochems (PL. 3-17a). The limestones are bioturbated and show small, discrete Chondrites (1-2 mm diameter) burrows. These sediments generally contain a sparse, low diversity macrofossil assemblage (TABLE 3-21). However, the brachiopod Leiorhynchus castanea is locally abundant in the uppermost 2 m in some sections.

The Bluefish-Hume contact is sharp and pyritized, although evidence for hardground development was not

TABLE 3-21

MACROFOSSILS IN THE UPPERMOST HUME FORMATION

Common Constituents

Leiorhynchus castanea: mainly disarticulated and valves commonly in current-unstable positions

dacryconarids: styliolinids, tentaculitids
crinoid columnals

Rare Constituents

other brachiopods: Orbiculoidea; lingulid, productid and strophomenid brachiopods

ostracod

nautiloid

sponge spicules

fish fragments

ramose bryozoan

low-spired gastropod

long, tapered bivalve: low convexity, gape

observed. This pyritized surface is overlain by a 15-30 cm thick skeletal grainstone in all sections in the study area except section 03. The skeletal grainstone contains abundant styliolinids and rare tentaculitids, fish fragments, and small crinoid columnals. Pyrite is common both as disseminated grains and replacement of allochems. Indeterminate black to brown (phosphatic?) spheroidal grains (0.1-0.2 mm) are ubiquitous in the skeletal grainstone.

3.4.2.1 Depositional environment

The fine grain size of the interbedded nodular limestone and shale, and lack of current-induced sedimentary structures, suggest calm water below wavebase. The formation of pyrite commonly as finely disseminated framboids and as selective replacements of allochems possibly indicates slow deposition in oxygen-depleted waters (Carstens, 1985). Most sedimentary pyrite results from the slow decomposition of organic matter (bacterial decay) in environments with poorly circulated, oxygen-depleted seawater (Hallam, 1981; Blome and Albert, 1985). Relatively slow sedimentation permits wholesale bacterial sulphate reduction where sulphate ions in pore water are replenished by diffusion from seawater (Curtis, 1980).

Fossils are the best indicators of oxygen deficiency. Low infaunal and epifaunal diversity in the uppermost Hume Formation suggest that dysaerobic conditions prevailed. The

brachiopod Leiorhynchus, according to other workers (e.g. Stoakes, 1979; Boucot and Perry, 1981), persistently occupied soft substrates in low-energy, moderately deep-water environments. Concentrations of their shells possibly represent condensed sedimentary sequences (e.g. see Kidwell and Jablonski, 1983). Remains of pelagic organisms (fish fragments, acriconarids, nautiloids) are a significant portion of the uppermost Hume macrofossil assemblage, and a coral-stromatoporoid assemblage is lacking.

In the study area, the uppermost 5 m of Hume strata were deposited probably in several tens of meters of water. Accelerated sea-level rise terminated the Hume platform. The 15-30 cm thick, skeletal grainstone sharply overlying the Hume Formation probably represents prolonged decreased sedimentation with little or no clastic input. The rain of planktic styliolinids and other pelagic shelled forms produced a condensed sequence of relatively pure carbonate preceding the black laminated shale typical of the remainder of the Bluefish Member. Brett and Baird (1985) documented similar condensed carbonate units in the Frasnian Genundewa Limestone in New York.

3.4.3 Basinal Facies

3.4.3.1 Black laminated shale

This lithofacies consists of dark brown to black laminated shale, with a high total organic content ranging from 1.7 to 7.1 wt%. The shale is black and calcareous at the base of the Bluefish Member, and increasingly argillaceous and lighter-colored (olive-brown) towards the top. Horizontal laminae (average 1-2 mm thick) are typically undisturbed, continuous (PL. 3-17b), and defined mainly by slight changes in content of fine-grained organic matter. Papery fissility on weathered surfaces appears to arise from lamination.

Pyrite contents in the shale vary from 2-15% (visual estimates). Pyrite is most common as finely disseminated framboids (average <0.1 mm diameter), and as mineral replacements of dacriconarids and crinoid columnals. The fine-grained pyrite is ubiquitous in the shale, although some also occurs as scattered blebs and laminae.

A well-preserved, low-diversity macrofossil assemblage (TABLE 3-22) is restricted mainly to the more calcareous basal portion of the Bluefish Member. The assemblage is more impoverished (rare dacriconarids, plant fragments) in the more argillaceous higher portions of the basin facies association. Burrows were not observed in the basinal lithofacies.

TABLE 3-22

MACROFOSSILS IN THE BASIN FACIES ASSOCIATION

Common Constituent:

styliolinids: including Styliolina fissurella; may be weakly aligned in some beds

tentaculitids: including Nowakia; may be weakly aligned in some beds

Rare Constituents

lingulid brachiopod

plant fragments: elongate; average 4x20 mm; finely striated parallel to long dimension (Psilophyton?)

fish fragments

crinoid columnals: average 1.5 mm diameter, stems rarely up to 10 cm long display current orientation

ammonoid

thin-shelled bivalves: including Leptodesma, Buchiola and indeterminate tapering bivalve

Leiorhynchus castanea: present in basal 2-3 cm of Bluefish Member

3.4.3.2 Dacriconarid grainstone

Thin-bedded (1-2 cm), sharp-based packstone to grainstone units (PL. 3-18a) occur rarely in the basal 3.0 m of the basin facies association. The soles of these beds commonly display aligned allochems which provide paleocurrent data (FIG. 3-12). These indicate westward paleocurrent flow.

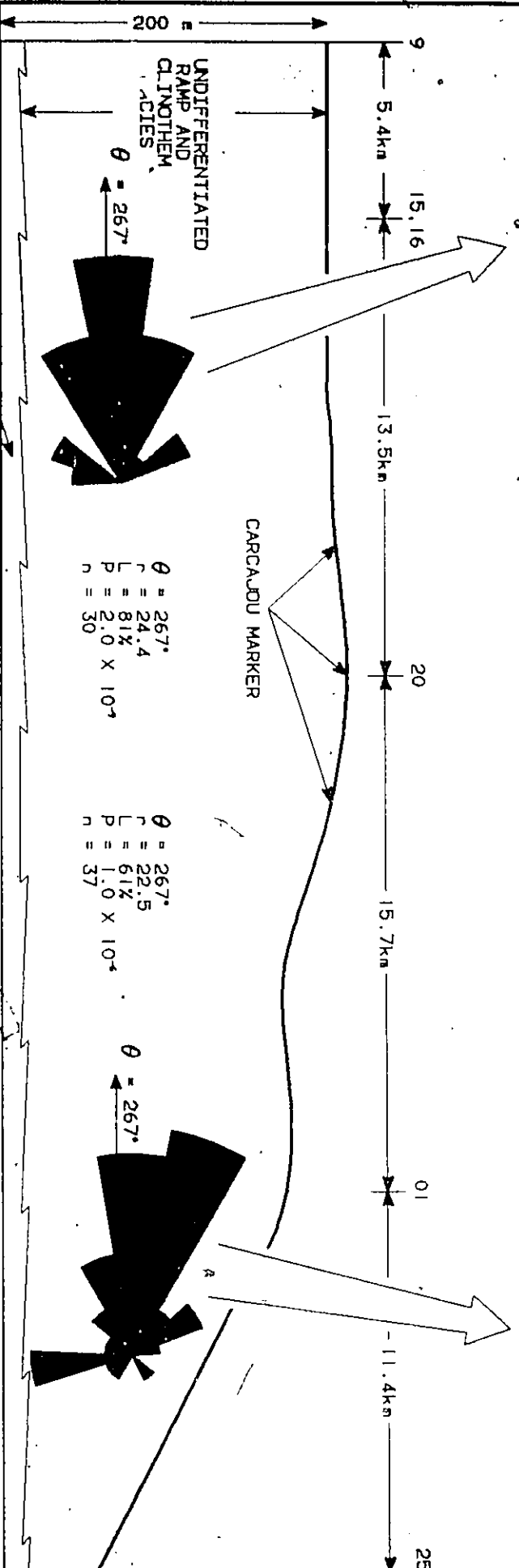
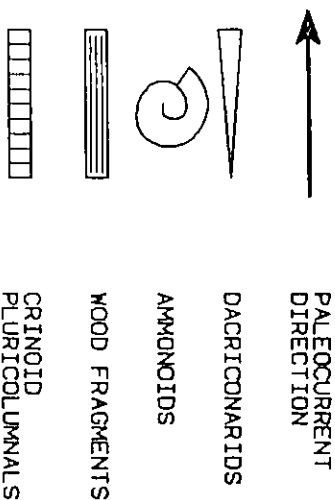
The dacriconarid grainstone beds commonly display an upward transition from grain-supported to mud-supported fabric, and less commonly show poorly developed fining-upward (PL. 3-18b). Thicker units (3-4 cm thick) exhibit two distinct subdivisions (e.g. PL. 3-18a): a lower dacriconarid grainstone or packstone bed (1-2.5 cm thick) is abruptly, but not erosionally, overlain by an apparently unfossiliferous, structureless, lime mudstone (1-2.5 cm thick).

Some dacriconarid grainstone/packstone beds display gradational lower and upper contacts with black laminated shale, and show no evidence of current-aligned allochems. Their fossils are predominantly styliolinids with subordinate crinoid columnals, tentaculitids, fish fragments, and bivalves.

3.4.3.3 Peloidal calcisiltite

Slightly quartzose (<1%) calcisiltite beds (average 2.5 cm thick) occur rarely throughout the basin facies association. These beds typically exhibit even, horizontal,

PALEOCURRENT DATA -BASIN FACIES ASSOCIATION



BASIN FACIES ASSOCIATION
(BLUEFISH MEMBER)

FIG. 3-12

PALEOCURRENT DATA IN THE BASIN FACIES ASSOCIATION
IN SECTIONS 15 AND 25. CURRENT ALIGNED PLANT FRAGMENTS,
AND CRINOID PLURICOLUMNALS. SCALE IS IN CENTIMETRES.

TOP OF HUME FORMATION

continuous lamination (1-2 mm thick) defined by variations in pyrite and organic content. Low angle cross-stratification and possible convolute lamination occur rarely near the bases of the calcisiltite units. Beds generally display gradational to planar-sharp basal contacts and more gradational upper contacts (PL. 3-18c).

The peloidal calcisiltite shows weak fining-upward and a macrofossil assemblage that is similar to, but less abundant than, that in the dacriconarid grainstone beds (styliolinids-plant fragments-ammonoids-crinoid columnals-fish fragments). Several calcisiltite beds contain concretions at various developmental stages (e.g. PL. 3-19a). However, other carbonate concretions are completely enclosed in black laminated shale, and may not have originated from calcisiltite beds.

The concretionary zone typically occurs 3-6 m above the top of the Hume Formation in the lower, more organic-rich calcareous sediments of the Bluefish Member. The concretions are regular ellipsoids (long axis parallel to bedding), and probably developed proximal to a carbonate and/or organic source during compaction. Bacterial decay of organic material under anaerobic conditions could have provided the alkaline environment and carbon dioxide necessary for carbonate concretion development (Blome and Albert, 1985). The fact that concretions initially grew preferentially along bedding planes indicates that ions were

transported primarily along layers permeable to pore water (Carstens, 1985). Concretions continued to develop during compaction of the sediment. Uncrushed macrofossils within these concretions indicate that early cementation and carbonate content were significantly greater in the cores than along concretion peripheries. Blome and Albert (1985) suggested that this variability of carbonate content supports the idea of continued concretion growth during compaction. The carbonate content would be directly related to the porosity of the surrounding sediments at the time of concretion formation. Decreasing values towards the concretion margins would reflect growth as sediments were progressively compacted (Marshall, 1982). Laminae in the more argillaceous concretion peripheries are slightly draped about the carbonate-rich concretion nucleus. The black shale laminae are further compacted, wrapping around the carbonate concretions (PL. 3-19b), and displaying crushed macrofossils.

3.4.3.4 Fibrous calcite veins

Fibrous calcite veins (average 2-6 cm thick) are confined mainly to the basal, more calcareous, and organic-rich sediments of the basin facies association. They are usually distinct layers parallel to bedding (PLS. 3-18c, 3-19b) and extend for several meters to beyond outcrop scale. Their fibrous structure is manifested by the internal organization

of cone-in-cone structures (PL. 3-20a). Conical apices are commonly demarcated by black shale inclusions. Apical angles usually range from 30-60°, and the sides of the cones are ribbed or grooved due to differential height terminations of fibrous crystals. Many of the veins show a crude two-part subdivision (PL. 3-20a). The lower portion is thicker (60-70% of vein) and characterized by narrow, cone-in-cone structures. Crystal fibres do not cross the near planar growth discontinuity separating the lower and upper portions. This juncture is marked by a concentration of shale inclusions. The upper portion is darker and characterized by smaller, broader cone-in-cone structures, and more abundant shale inclusions than in the lower portion. The darker color probably reflects a higher percentage of microscopic opaque inclusions.

Cone structure is shown both by crystallographic boundaries and shale inclusions so that fibrous calcite veins must have been primary growth features and not recrystallization features induced by tectonic strain (Marshall, 1982). Evidence that partially consolidated sediment was displaced by the growing calcite crystals is as follows:

- (1) Rupturing of shale laminae into folded plastic shale "hats" or conical forms indicates the displacive pressures exerted by the growing calcite

crystals (Franks, 1969; MacKenzie, 1972; Stoneley, 1983).

- (2) The outermost surfaces of fibrous calcite veins show raised circular areas which likely reflect growth continuation of some of the cones (Marshall, 1982).

The interpenetrative cone-in-cone structures and the common two-part division of the veins demonstrate episodic growth, possibly during periods of maximum pore water flow and supply of bicarbonate. Determination of the chemical environment in which these veins were precipitated is beyond the scope of this study, and is the subject of ongoing research by Dr. Ihsan Al-Aasm at the University of Ottawa.

The timing of fibrous calcite growth is also unclear. Marshall (1982) conducted carbon (C) and oxygen (O) isotope work on fibrous calcite veins and determined a relatively late diagenetic origin after a few tens to hundreds of meters burial. The shale was still relatively plastic when the fibrous calcite veins displaced bedding in the Bluefish Member, and possibly preceded concretionary growth (see PL. 3-19b). The extensive lateral continuity of the veins (MacKenzie, 1972; this study) along bedding planes indicates that pore water flow was primarily parallel to stratification, and permeability was much greater horizontally than vertically. Displacive fibrous calcite also occurs rarely immediately above the basal contact in:

presumably slightly more permeable, upward-fining calcisiltite beds (PL. 3-20b).

The formation of fibrous calcite veins is problematic. Somehow, bedding planes were forced apart against lithostatic pressure to allow episodic fluid migration and calcite precipitation. Stoneley (1983) suggested that if hydrostatic pressure approached lithostatic overburden pressure (overpressuring), then this could have caused increased plasticity in the sediments. Pore waters would have been capable of holding apart the two surfaces of the bedding plane to permit displacive crystal growth. Periodic overpressure of shales in the Bluefish Member could have resulted from periods of rapid sedimentation associated with progradation of the Hare Indian clastic wedge. Marshall (1982) suggested that effects of overpressure are common in shales undergoing rapid burial where the hydraulic conductivity of the sediment cannot cope with the expulsion of the pore waters.

Furthermore, multiple episodes of fibrous calcite growth could be generated as impermeable fibrous calcite veins are incorporated in shales (Stoneley, 1983). Temporary overpressuring could have occurred until these limestone units were fractured.

The apparent restriction of thick fibrous calcite veins (2-6 cm thick) to the basal 6 m of the Bluefish Member probably reflects proximity to an available source of

suitable ions (Ca^{2+} from calcareous shale, HCO_3^{2-} from connate waters) and poor vertical permeability (basal beds are more organic-rich and less silty than upper sediments of the Bluefish Member).

3.4.4 Synthesis of the Basinal Depositional Environment

3.4.4.1 Facies interpretation

The basin facies association was deposited in water depths in excess of 185 m (FIG. 3-7). Bottom-water oxygen concentrations were sufficiently low to prevent infaunal activity (FIG. 3-13) and preserve lamination. Other indicators of oxygen-depleted depositional conditions include:

- (1) Rarely occurring fossils representing planktic, epiplanktic, and nektic organisms only.
- (2) High levels of pyrite (up to 15%) and organic matter (section 3.4.4.3) compared to normal marine shales (see Curtis, 1980). This suggests deposition in a reducing O_2 -starved environment.
- (3) Good preservation of plant fragments as carbon impressions.

These observations are similar to those outlined by Authur et al. (1985) as diagnostic of facies deposited under anaerobic conditions (FIG. 3-13).

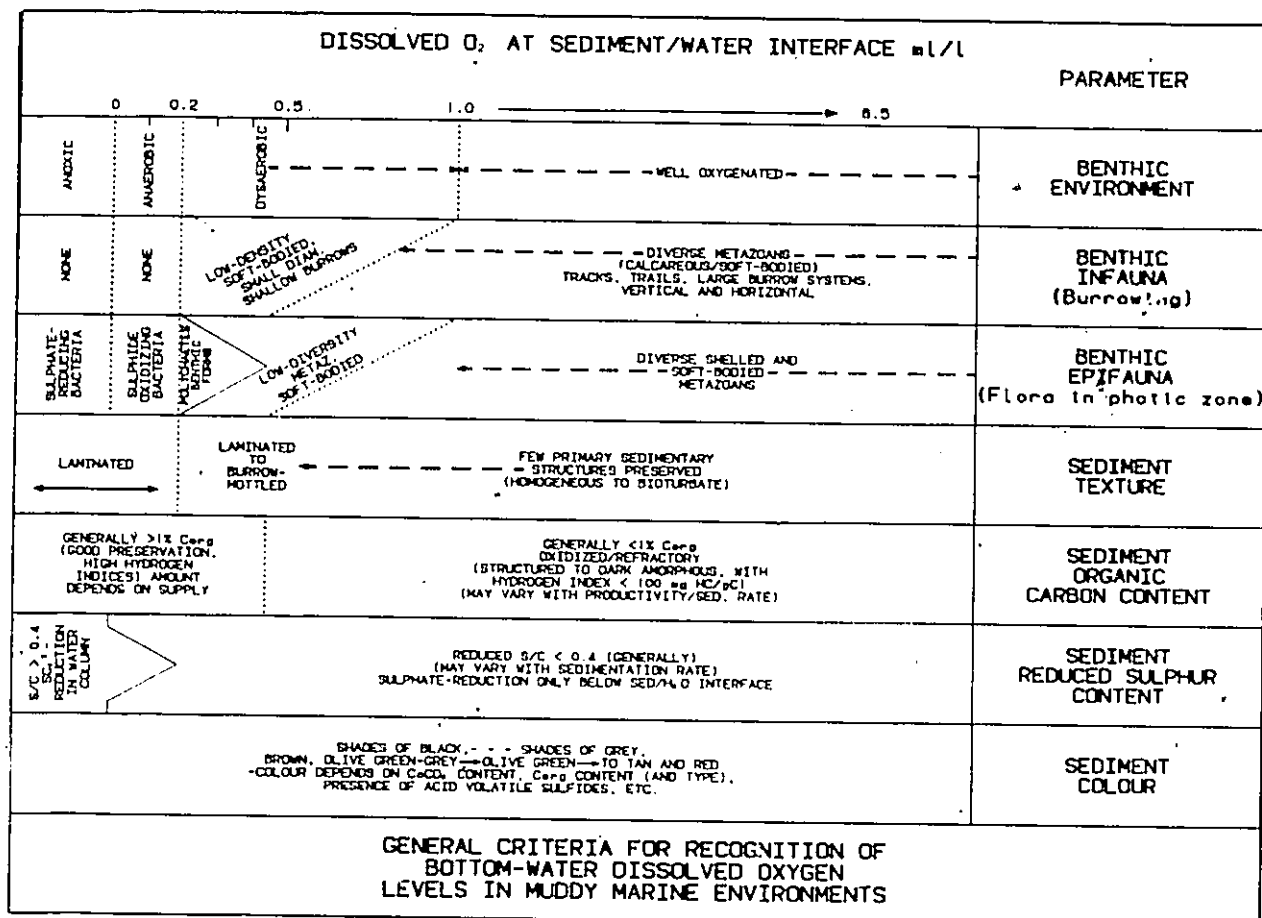


FIG. 3-13 Oxygen content at the sediment/water interface and generalized expected relationships between types of benthic organisms, primary sedimentary structures, sediment chemistry and mineralogy, and organic content and type (after Authur et al., 1985, Fig. 5).

The lamination in the basinal shale could have several possible origins, but typically reflects variations in contents of organic carbon and clastic sediment. Organic-rich layers normally accumulate by settling of hemipelagic materials^s from suspension. This organic accumulation can be diluted periodically in a number of ways, as follows:

- (1) Pelagic "mass kills" (Brower et al., 1978; Wetzel, 1981). Short-term toxicity in normally productive surface waters could have resulted in catastrophic mortality and deposition of the thin dacryconarid grainstone beds in the study area. Vai (1980) documented thin beds rich in styliolinids in Devonian pelagic limestones in the Southern Alps. He suggested that turbid surface waters (storm-generated?) caused local mass mortality.
- (2) Variations in organic productivity (Hallam and Bradshaw, 1979; Hallam, 1980; Wetzel, 1981). These authors suggested that laminae of organic matter can be produced seasonally and arranged in rhythmic couplets with slightly thicker clay interlayers.
- (3) Deposition from unidirectional flows (Carey and Roy, 1985; Stanley, 1982, 1985, 1986; Melvin, 1986). Carey and Roy (1985) showed in flume studies that intermittently laminated mud can be deposited from steady unidirectional flows carrying

suspended clay and silt. Analogous deposition in the study area could have occurred both from turbid layer flow within the stratified water column or directly from low density turbidity currents.

In addition to intermittent lamination developed in shale (e.g. PL. 3-17b), there is evidence of lamination produced by pulsatory sedimentation in the basin facies association. Several thin dacriconarid grainstone beds show sharp basal contacts, weak fining-upward trends, and current-aligned allochems. These beds are abruptly overlain by structureless lime mudstone lacking fossils (e.g. PL. 3-18a) and either grade upwards, or are abruptly overlain by black laminated shale. Stanley (1985, p. 398) noted that sediment dispersal downslope through a stratified water column in the Hellenic Arc region of the Mediterranean, resulted in compositional segregation of terrigenous silt and clay facies from planktic tests. This combined gravity flow and hemipelagic settling appears to have been operant during most of the basinal sedimentation in the study area. Stanley (1986) postulated that laminar variations in organic content can also reflect episodic release of sediments from turbid layer flows and low concentration turbidity currents in the basinal setting. Dilution effects on total organic carbon contents in the basin-fill succession will be discussed briefly in section 3.4.4.3.

It is difficult to distinguish units deposited from detached turbid layer flows at interfaces in the water column from those deposited by low concentration turbidity currents flowing directly downslope. Peloidal calcisiltite beds observed rarely in the basin facies association could have been deposited by low density sediment gravity flows on the basis of the following evidence:

- (1) Sharp basal contacts, gradational upper contacts.
- (2) Current-aligned allochems rarely on bedding soles.
- (3) Fining-upward occurring rarely.
- (4) Slight thinning-upward of indistinct laminae (T_{5-6} in Stow, 1985).

Bergman (1983) reported oriented crinoid pluricolumnals and tentaculitids in the Silurian Slite Marl of Sweden. He (ibid.) suggested that orientation and preservation of crinoid pluricolumnals indicate rapid emplacement and burial by low density turbidity currents. Preliminary observations mainly from aligned fossils (Appendix C; FIG. 3-12) indicate that paleocurrent directions in the basin facies association were nearly perpendicular to the depositional strike of the Hare Indian clastic wedge. Although data is sparse, this is consistent with the few paleocurrent data from the clinotherm facies association (Appendix C). These transverse turbidity currents were not deflected longitudinally possibly because of gentle slopes, as postulated elsewhere by Lundegard et al. (1985). They noted that homogeneous transverse

paleocurrent patterns are rare and typically delta-associated, and cited examples in the turbidite succession of the Upper Devonian Catskill clastic wedge.

In summary, the basin facies association accumulated in oxygen-depleted waters about 185 m (± 10 's of m) deep. Prevailing tranquil conditions of hemipelagic sedimentation were periodically interrupted by low concentration turbid water flow and turbidity currents. These environmental constraints permit a brief comment on the paleoecology of the basin facies association.

3.4.4.2 Paleoecology

The basinal facies association is characterized by a low diversity, high dominance fossil assemblage typical of stressful environmental conditions during deposition. Depressed oxygen levels precluded bioturbation. Lingulid brachiopods occur in the basinal facies, but do not appear to occupy burrows. Their persistent association with plant remains suggests that they were possibly epiplanktic. Bassett and Lawson (1984) made a similar suggestion for lingulids in Ludlovian basinal sediments in Wales. They postulated that lingulids and other invertebrates lived on Sargassum-like rafts because of their close association with graptolites. The thin-shelled bivalves (including Leptodesma and Buchiola) similarly could have been epiplanktic. An allochthonous origin is suggested as none

are in infaunal positions, and most are disarticulated despite the general absence of current features and bioturbation.

Opportunistic fauna, as well, could have settled on the basin-floor during turbidity current events. These infrequent, sediment-laden, oxygenated currents could have temporarily ameliorated bottom conditions sufficient for colonization of the substrate by organisms tolerant of reduced oxygen levels. Crinoid pluricolumnals oriented on the soles of these turbidities could have been preserved due to high sedimentation rates. In the Devonian, some crinoids are reported to have attached to floating plant debris (Brett and Baird, 1985). Rarely occurring, diminutive (average 2 mm stem diameter) crinoids in the Bluefish Member could have been dispersed in this manner.

A large percentage of fossils identified in the Bluefish Member (TABLE 3-22) clearly represent planktic organisms (styliolinids, thin-walled tentaculitids) or nektic organisms (ammonoids, fish). The remaining fossils evidently represent either allochthonous epipelagic organisms or epifaunal opportunists exploiting short-term amelioration of bottom conditions.

3.4.4.3 Preservation of organic matter

Organic matter in the Bluefish Member consists of mixed kerogen types (Monnier, written comm., 1986). Recycled,

refractory, terrestrial, organic matter (yielding Type III/IV kerogen) was likely transported by deltaic-fluvial systems into the Hare Indian depositional basin. Marine organic matter was supplied by primary biological productivity in surface waters (yielding Type II kerogen). Normally terrestrial organic matter would be highest at a point of fluvial discharge and steadily diluted by aquatic material with increasing distance from shore. Furthermore, the growth of marine aquatic organisms would be stimulated locally by nutrients brought in by fluvial discharge.

Basinal shale in the Bluefish Member is unusually enriched in organic matter compared to shale near the top of the basin-fill succession (Appendix C, FIG. 3-14). The black laminated basinal shale also shows much higher organic contents (1.7-7.1 wt%) than is typical of an "average" shale. The modal content of total organic carbon (TOC) in Devonian sedimentary rocks in the North American and Russian Platforms ranges from 0.3-0.6 wt% (Barker, pers. comm., 1983). Curtis (1980) determined the average TOC for 800 shale samples from North America to be 0.33 wt%.

The following factors could have influenced the TOC abundance in the basin facies association:

- (1) Source of organic matter. The influx of terrestrial materials replenishes nutrients in the ocean and enhances planktic productivity.

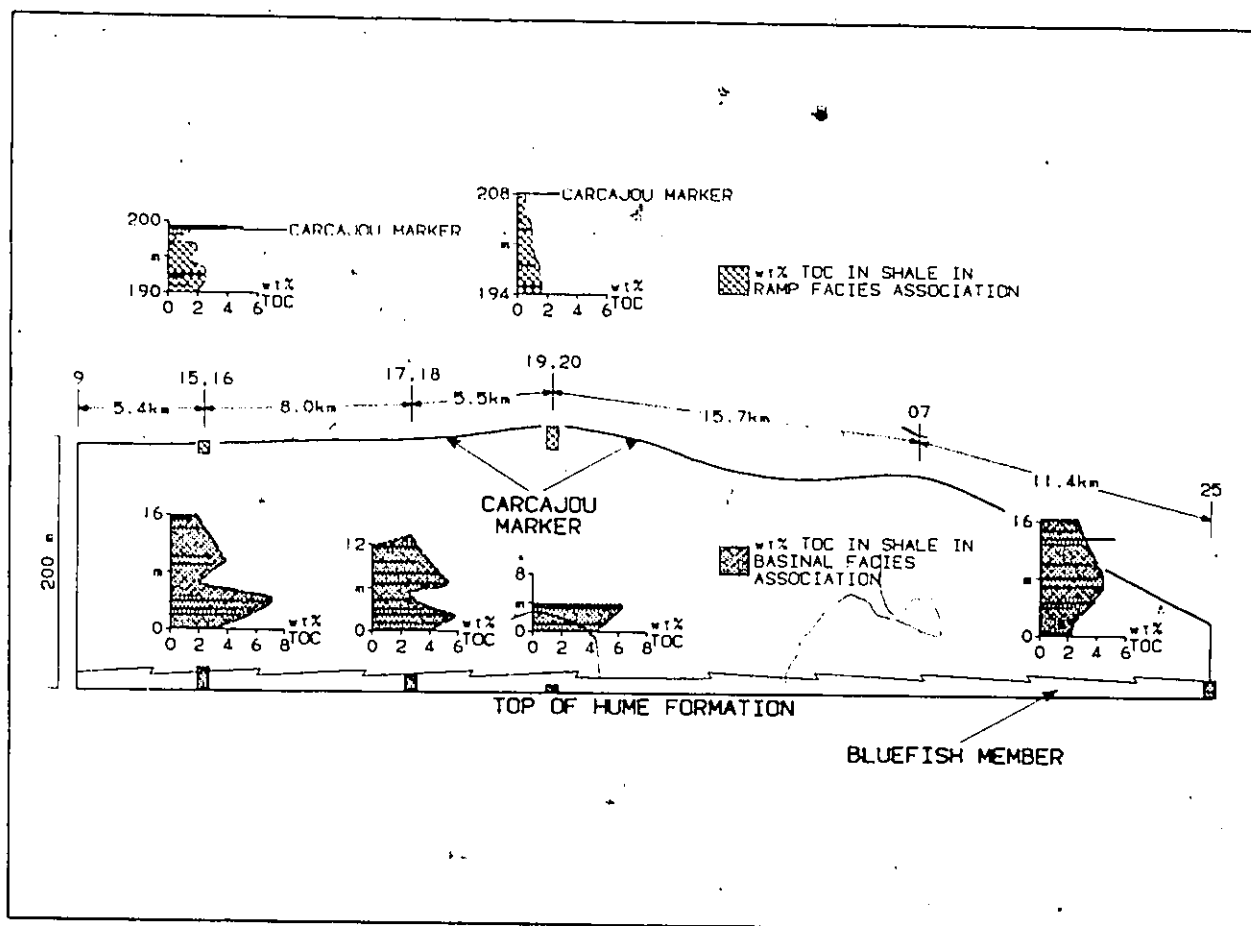


FIG. 3-14 Distribution of total organic carbon (wt %) in the Hare Indian-Ramparts (lower "ramp" member) basin-fill succession.

(2) Protection of organic matter from physical oxidation and biological consumption.

Rapid sedimentation effectively incorporates organic matter into the sedimentary record, removing it from zones of bioturbation, oxic decomposition, and sulphate reduction (Authur et al., 1985). However, increased sedimentation rates would also result in excessive clastic dilution, and it is unlikely that much of the organic matter in the Bluefish Member was deposited rapidly.

Water density stratification and the development of anaerobic conditions in the Hare Indian basin were apparently the prime reasons for preservation of organic matter in the basin facies association. Oxygen concentrations of less than 0.2-0.5 ml/l inhibit the activity of epifaunal and infaunal organisms (Rhoades and Morse, 1971) and organic matter has better preservation potential with reduced physical oxidation.

In the basin facies association, the presence of an anoxic sediment/water interface, slow sedimentation rates, and high organic productivity resulted in the accumulation of organic-rich sediments of the Bluefish Member.

The depositional model for the basin-fill succession has several ramifications. Shallowing-upward cycles could not be ascertained in the basinal facies (see Chapter 2). However, the model predicts that clastic input associated

with shallowing should dilute TOC values. In FIG. 3-14, the following trends were observed:

- (1) TOC values are highest near the base of the basin facies association and decrease towards the transition into the lower clinothem facies. The amount of organic matter, therefore, varies inversely with clastic supply during basin-fill conditions. Low values of organic content in the ramp facies association probably reflect a combination of increased clastic dilution, physical oxidation, and biological degradation.
- (2) TOC values within the Bluefish Member appear to be cyclic and most simply explained by variations in sedimentation rates. Episodic progradation of the Hare Indian clastic wedge (shown by stacked shallowing-upward sequences in the clinothem and ramp facies associations) would have increased sedimentation rates and, hence, diluted TOC values in the basin. The basinal cycles are not as obviously asymmetric as the ramp and clinothem shallowing-upward cycles, and this could reflect the more subtle response of basinal anaerobic environments to fluctuations in sedimentation rates. Variations in TOC values in the off-lobe section (25) show only slight change, reflecting a

basinal setting more distal from Hare Indian clastic input than sections 15 and 17.

Cycle thicknesses of 5-7 m in the basin facies association, based on TOC cyclicity, are comparable to thicknesses of second-order cycles near the base of the lower clinotherm facies.

3.5 SUMMARY

The Hare Indian Formation and the overlying lower "ramp" member of the Ramparts Formation are the result of episodic progradational basin-fill. General stratigraphic considerations suggest that the clastic wedges represent relatively high stands of sea level. Composite facies associations (ramp, clinotherm, basin) can be distinguished, can indicate different degrees of oxygenation, and can point to density stratification in the overlying water column.

The ramp facies association is a cyclic assemblage of storm-influenced strata which accumulated under aerobic to slightly dysaerobic conditions (paleobathymetric range ~15-45 m). Carbonates were deposited on a low angle slope (0.1-0.2°) peripheral to main sites of siliciclastic input along the axis of the Hare Indian lobe maximum. The ramp succession shows evidence for active sediment bypassing down the ramp mainly by storm winnowing and by generation of low density turbidity currents.

The clinotherm facies association accumulated under dysaerobic conditions (paleobathymetric range ~45-185 m). Peloidal calcisiltite beds were emplaced by non-channelized, low density turbidity currents and are particularly abundant towards the top of second-order, shallowing-upward cycles. Background hemipelagic sedimentation resulted in the deposition of typically unfossiliferous, olive-grey calcareous shale. Cycle thickness trends indicate maximum accumulation rates along the mid-clinoform position, with more condensed sequences characterizing the lower clinoform to basin profile.

The basin facies association is represented by sediments of the Hare Indian Bluefish Member. Black, organic-rich, laminated shale and minor peloidal calcisiltite and dacryconarid grainstone accumulated under anaerobic conditions (paleobathymetric range ~185 ± 10's of m) on top of the drowned Hume carbonate platform. The basin facies association represents slow hemipelagic sedimentation that was infrequently interrupted by fine-grained gravity flows. Cyclic variation of total oxygen content in the Bluefish Member is apparently a product of repeated dilution by clastic sediments during prograding of shallowing-upward ramp-clinothem cycles. These basinal cycles are similar in thickness to cycles in the lowermost clinothem succession.

PLATE 3-1

Ramp facies association
and typical macrofossils.

- a Thin-bedded nodular lime mudstone and interbedded shale of lower ramp facies pass upward into thicker bedded limestone of upper ramp facies (section 31). Ramp facies association 18 m thick.
- b Positive print of acetate peel of typical macrofossils in upper ramp subfacies 1 (section 31, unit 007). Robust cylindrical stromatoporoids (A) are commonly encrusted by stromatoporoids and algae. Thamnoporoid corals (B) are fragmented, but show little evidence for abrasion.
- c Encrusting stromatoporoid (A)-thamnoporoid coral (B)-solitary rugose coral (C)-Stringocephalus (D) assemblage in upper ramp subfacies 2 (section 31). Note the dark, micritic nature of the enclosing matrix. Positive print of acetate peel.



PLATE 3-1

PLATE 3-2

Macrofossils in upper ramp subfacies 2.

- a Encrusting stromatoporoid (A) and alveolitid coral (B) upon thamnoporoid coral fragments (C) (section 20). Positive print of acetate peel.
- b Encrusting stromatoporoid (A)-alveolitid coral (B) composite allochem (section 18). Note evidence for episodic movement and colonization. Positive print of acetate peel.
- c Disoriented tabular and wafer stromatoporoids in floatstone (FL), underlain by graded crinoidal grainstone (GR) (section 18, unit 023). Scale is 15 cm.



PLATE 3-2

PLATE 3-3

Lower ramp subfacies 4.

- a Continuous, nodular, lime mudstone interbedded with calcareous shale in lower portion of subfacies (section 01, unit 016). Scale is 15 cm.
- b "Mottled" nodular lime wackestone in upper portion of subfacies (section 07, unit 017). Hammer is 20 cm long.



PLATE 3-3

PLATE 3-4

Lower ramp subfacies 4.

- a Shale- and calcite spar-infilled "v"-shaped fractures within lime mudstone nodule (section 03, unit 015).
- b Bedding plane of "mottled" nodular limestone illustrating interconnected nodules (section 15, unit 014). Note that horizontal burrows in shale infill meander around nodule topography. Scale in cm.

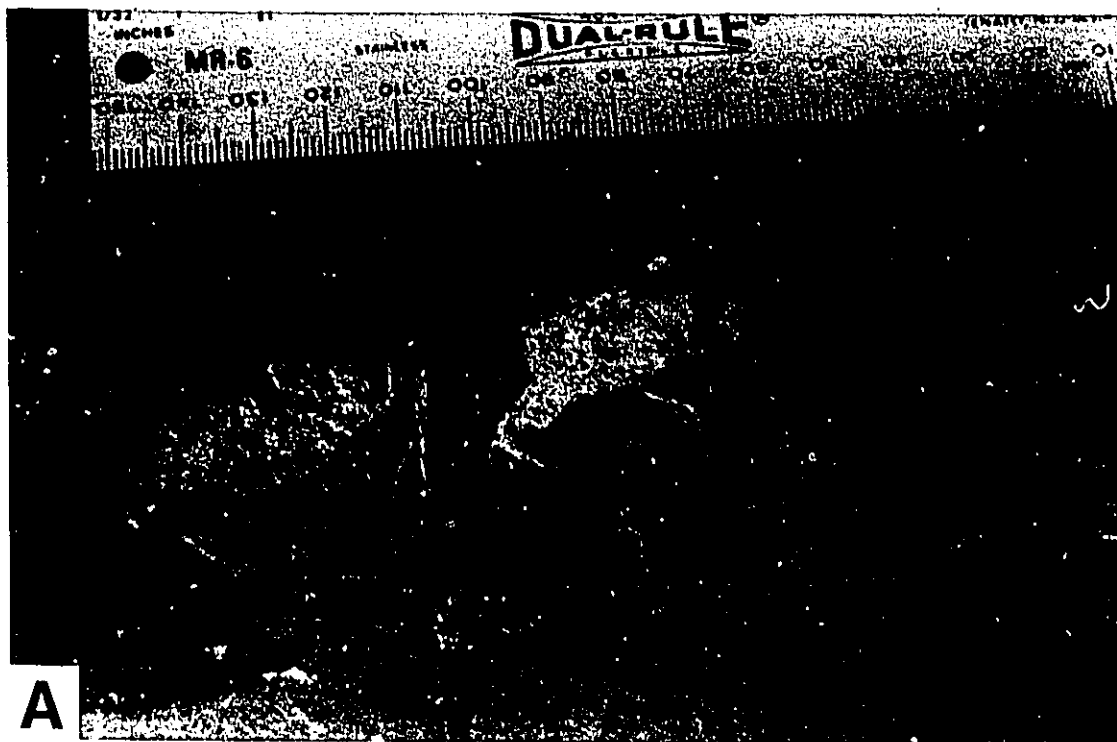


PLATE 3-4

PLATE 3-5

Macrofossils and distal storm
deposits in the lower ramp facies.

- a Nodular limestone bedding plane in lower ramp subfacies 4 (section 31, unit 006). Fossils include Hexagonaria (A), Thamnopora (B), and crinoid columnals (C). Scale is 30 cm.
- b Fining-upward peloidal calcisiltite beds show broadly concave, sharp basal contacts and bioturbated tops. Lower ramp subfacies 3 (section 18, unit 015). Scale is 15 cm.



PLATE 3-5

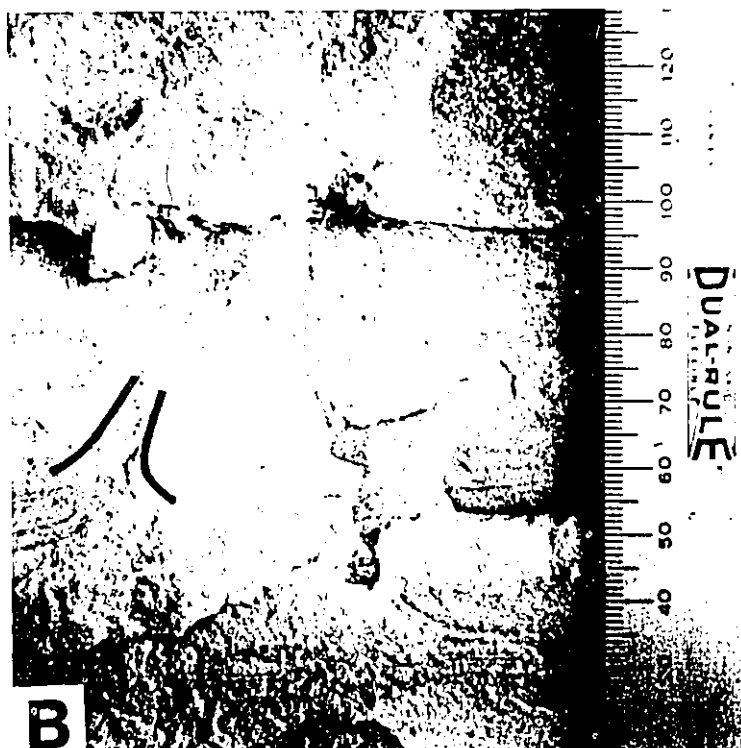
PLATE 3-6

Storm deposits in lower ramp subfacies 3.

- a Graded quartzose peloidal calcisiltite bed (3 cm thick) (section 11, unit 001). Silty laminae thin upwards in bed. Positive print of acetate peel.
- b Closeup of PL. 3-5b. Note water escape structure and upturned, deflected laminae along the margins of the structure.



A



B

PLATE 3-6

PLATE 3-7

Macrofossils in lower ramp subfacies 3.

- a In situ cluster of the brachiopod Rensselandia (section 15, unit 013). Scale is 15 cm.
- b Current-aligned crinoid pluricolumnals (section 15). Slab is 20 cm long.



PLATE 3-7

PLATE 3-8

Proximal storm deposits in lower ramp facies.

- a Lenticular brachiopod-crinoid-gastropod coquinite occupying erosional scour. Note the fining-upward peloidal calcisiltite beds adjacent to scale. Lower ramp subfacies 3 (section 15, top of unit 013). Scale is 15 cm.
- b Crinoid coquinite occupying erosional scour in bioturbated calcisiltite. Lower ramp subfacies 4 (section 18). Positive print of acetate peel.

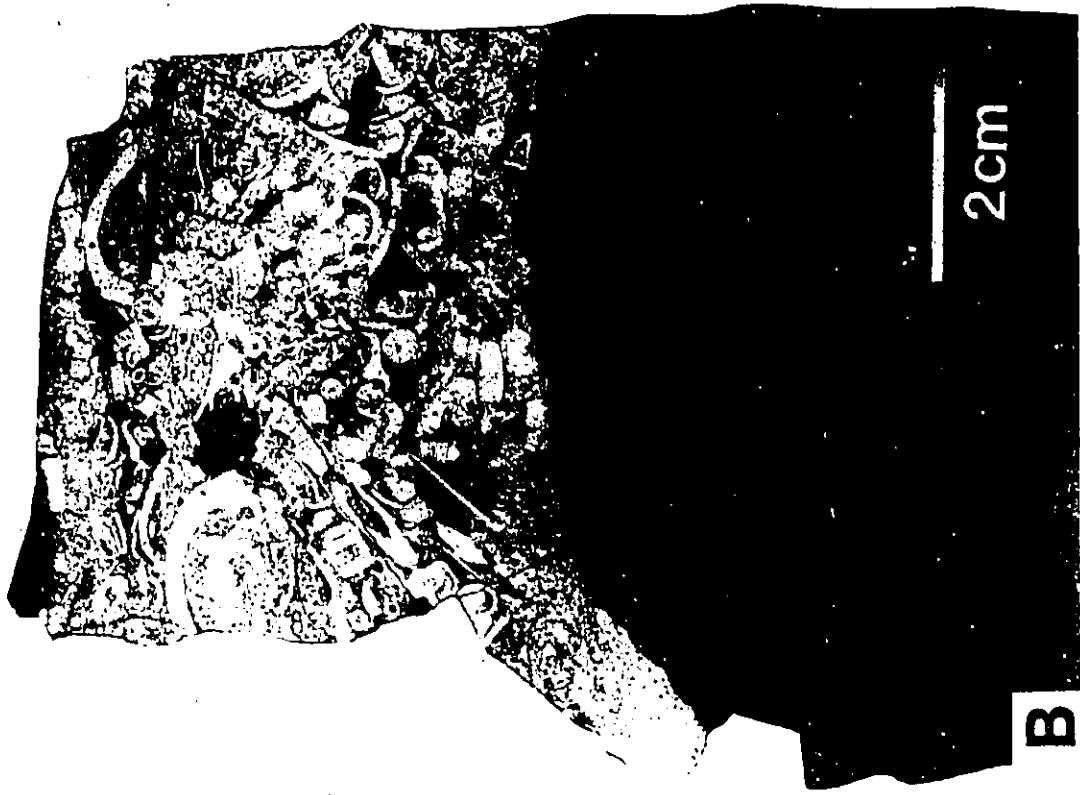


PLATE 3-8

PLATE 3-9

Proximal storm deposits in lower ramp subfacies 3.

- a Current unstable brachiopod valves in coquinite. Note geopetal structure and incomplete mud-infill (arrows) (section 15, unit 012). Scale in cm.
- b Crinoid coquinite (A) and graded laminated peloidal calcisiltite (B) (section 15, unit 012). Scale is 15 cm.

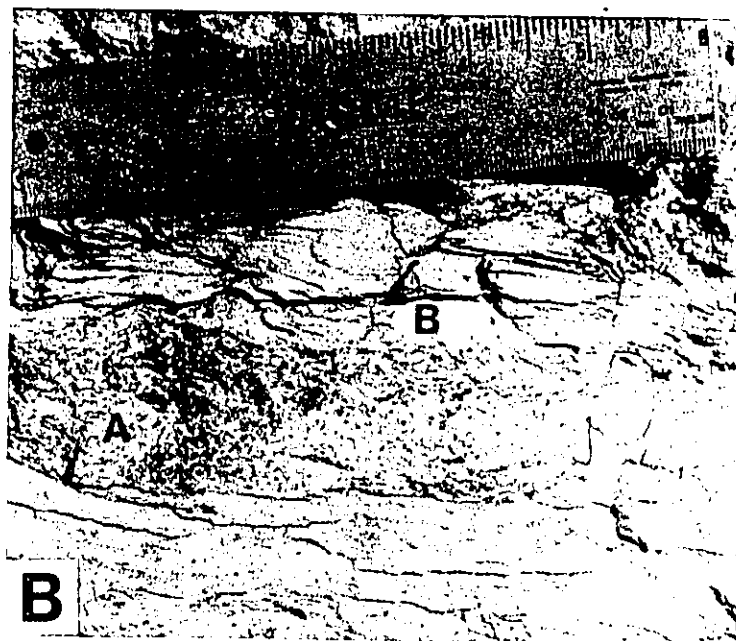


PLATE 3-9

PLATE 3-10

Nodule formation in lower ramp facies.

- a Interbedded distal tempestites (graded, horizontally laminated, peloidal calcisiltite) and grey-olive, silty calcareous shale. Note sharp basal contacts. Lower ramp subfacies 3 (section 18, unit 008). Scale is 15 cm.
- b Nodular limestone from lower ramp subfacies 4 (section 18, unit 013). Early cementation localized along more permeable calcirudite. Nodule wrapped by silty shale. Positive print of acetate peel.
- c Continuous nodules formed about a proximal tempestite. Note that sediment laminae can be traced from adjacent nodular protuberances through intervening marl. This is indicative of pressure solution phenomena. Lower ramp subfacies 3 (section 15). Scale in cm.

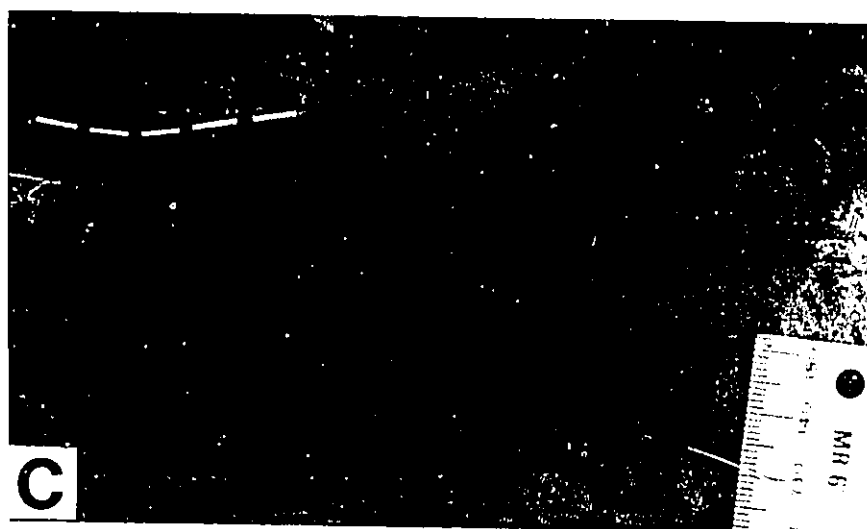
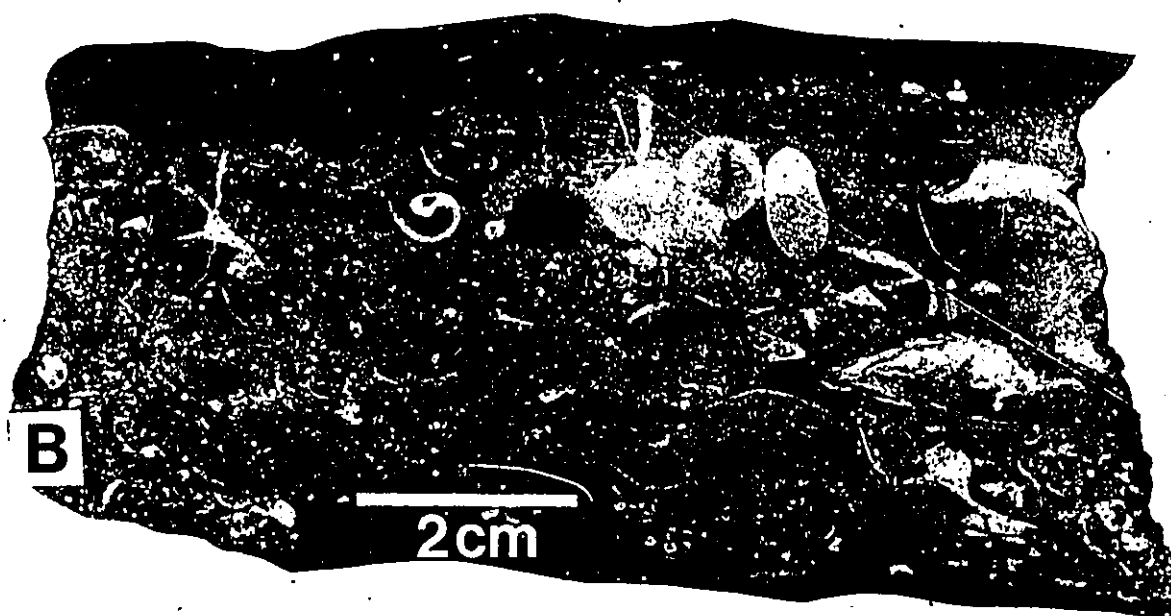
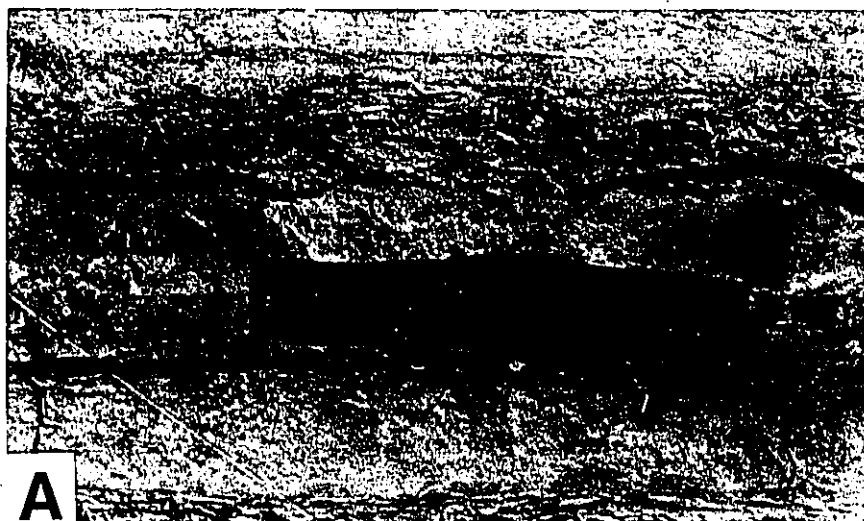


PLATE 3-10

PLATE 3-11

Oblique view of section 01, Powell Creek
(units 013-039).

Gully-fill sequences (arrows) in the lower ramp facies, Ramparts Formation and uppermost clinotherm facies, Hare Indian Formation. Unit 025 is 3.5 m thick. A, B, and C are localities for other plates cited in this study.

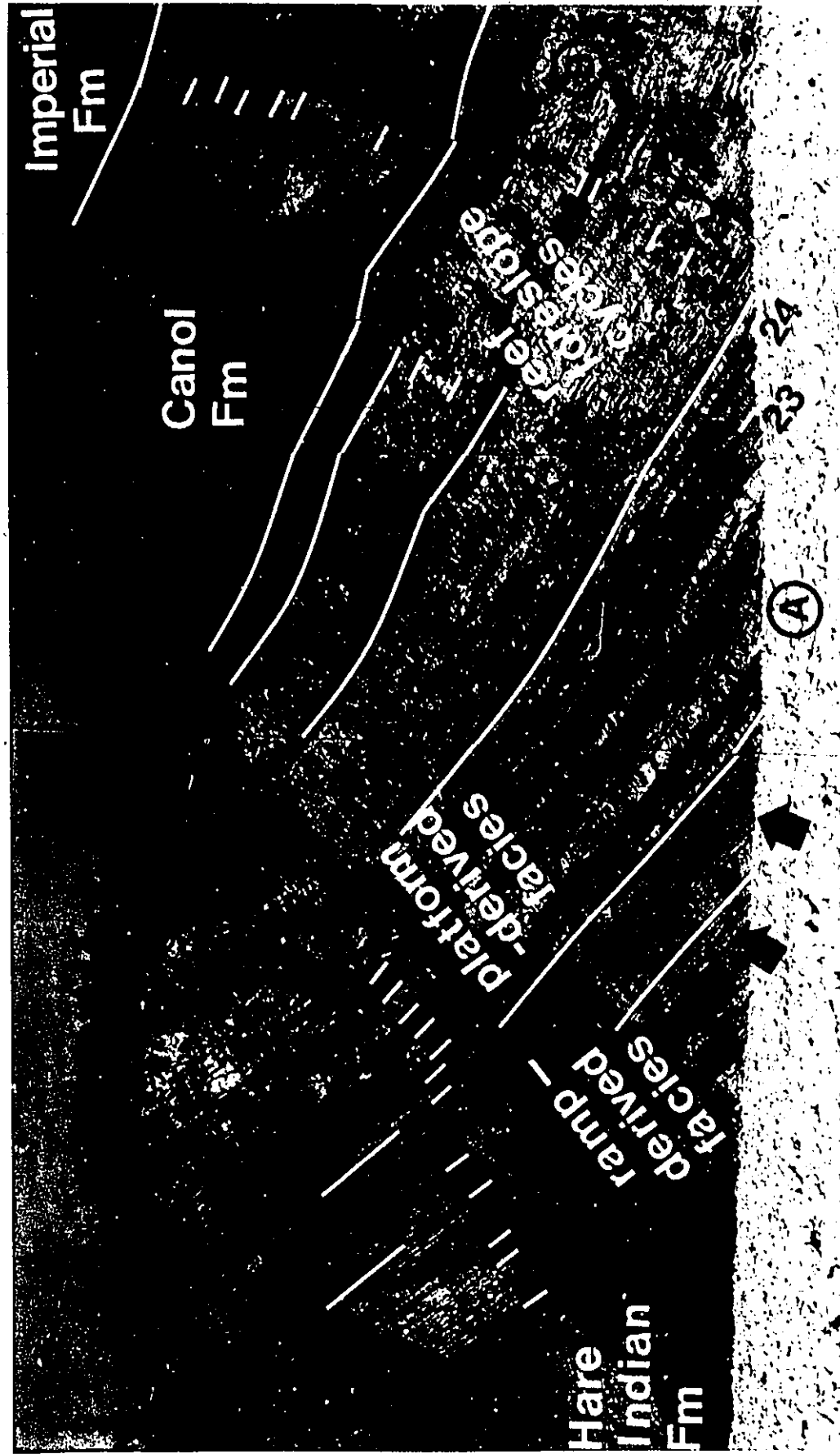


PLATE 3-11

PLATE 3-12

Upper clinothem facies at section 01.

- a Upper clinothem facies association (field units 008-015) at section 01 (locality C in PL. 3-11). Dark grey shale is subordinate to limestone towards the top of the association. Vertical bars indicate second-order, shallowing-upward cycles. Cycle comprising units 012-014 is 15 m thick. Note lateral continuity of thin (average 5-10 cm thick) limestone beds.
- b Interbedded peloidal calcisiltite and dark grey calcareous shale in upper clinothem subfacies 1 (section 01). Note sharp, planar, basal contact for lower bed and loaded, basal contact in upper bed. Scale is 20 cm.

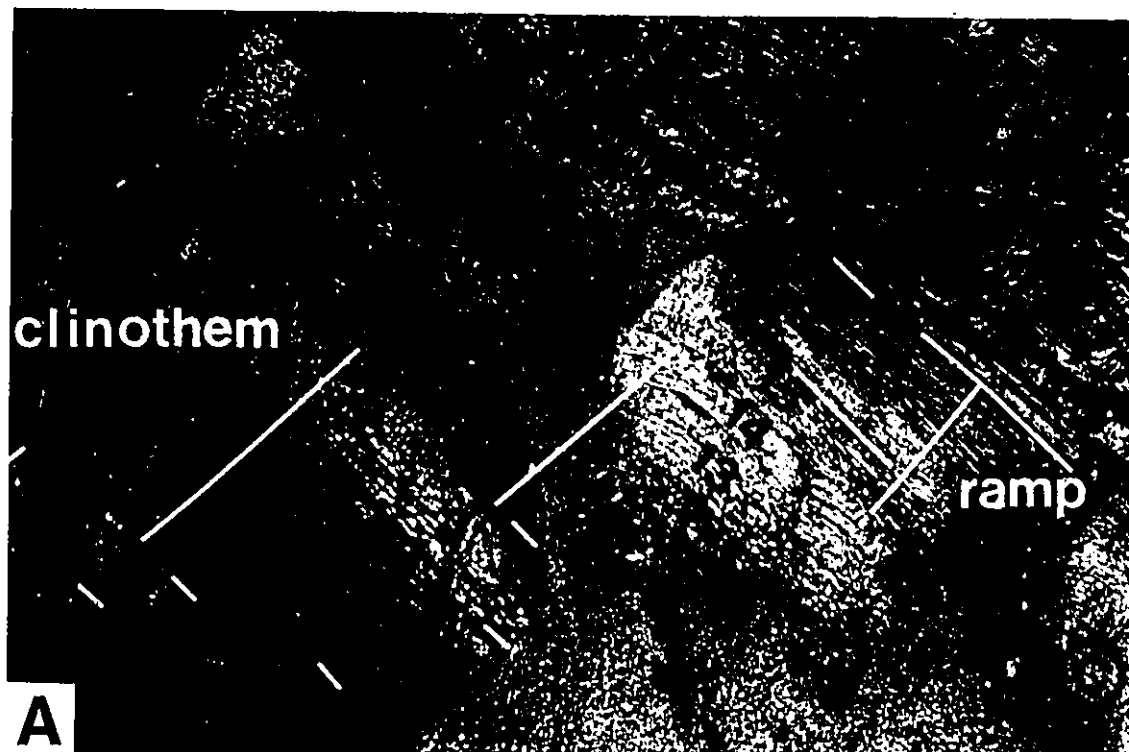


PLATE 3-12

PLATE 3-13

Sole markings in upper clinotherm subfacies 1 (section 15).
Scale is 15 cm in both photographs.

a Up-paleocurrent directions indicated by abrupt terminations of groove casts.

b Light sole markings (arrows) and bulbous load casts.



B

PALEOCURRENT DATA IN
UPPER CLINOTHEM FACIES,
SUBFACIES 1



A

SECTION 25, UNIT 012

$n = 20$

$r = 19.28$

$P = 9.0 \times 10^{-9}$



PLATE 3-13

PLATE 3-14

Calciturbidites in upper clinoform subfacies 1.

- a Amalgamated, graded, laminated beds (3-5 cm thick) show bioturbation concentrated near muddier top (light color, arrows) of each bed (section 07, unit 012). Scale in cm.
- b Thick, basal, lenticular siltstone laminae pass upwards into thinner, slightly convolute, siltstone laminae (section 16). Note sharp basal contact with fining-upward trend.
- c Regular, graded, parallel laminae of siltstone (resistant) and mudstone (recessive) (section 15). Siltstone laminae display microload and microscour structures rarely (arrows). Scale is 15 cm.

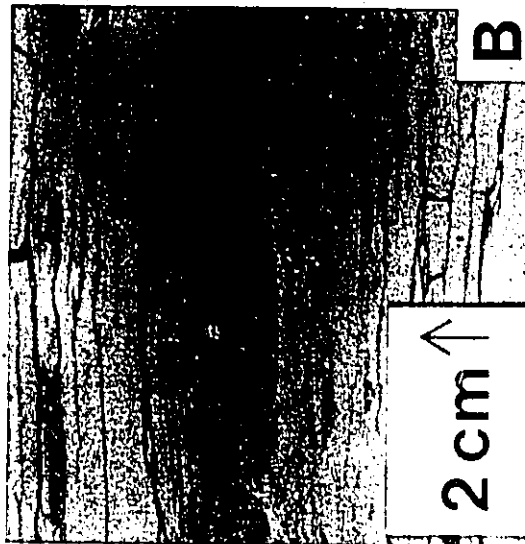
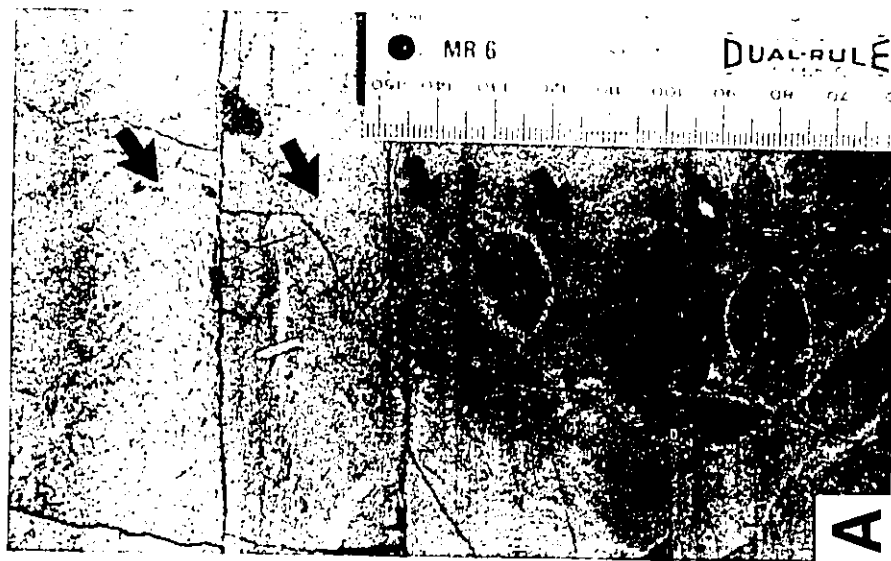


PLATE 3-14

PLATE 3-15

Trace fossils and calciturbidites
in clinotherm facies association.

- a Meandering feeding trails (possibly Cruziana) and indeterminate u-shaped burrows on top of bedding plane in upper clinotherm subfacies 1 (section 15). Scale is 15 cm.
- b Peloidal calcisiltite beds (amalgamated unit) arranged in "doubly" graded fashion with siltier (lighter-colored, 2-3 cm thick) beds occurring in mid-unit. Note sharp, basal and upper contacts, and horizontally laminated nature of enclosing shale. Lower clinotherm subfacies 2 (section 25). Scale is 15 cm.



PLATE 3-15

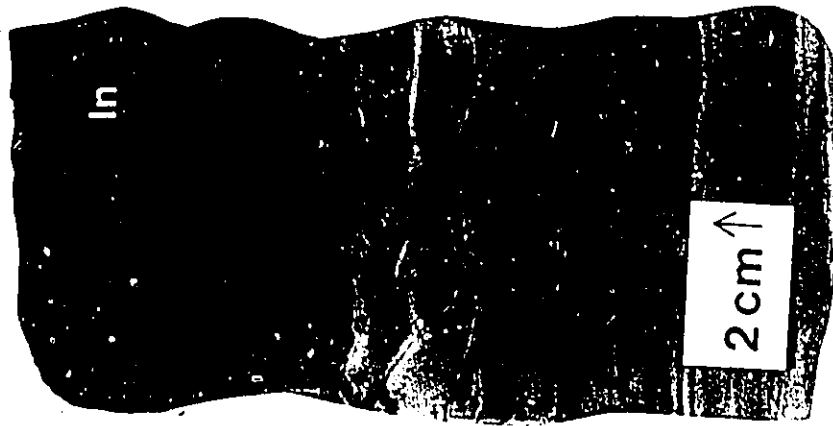
PLATE 3-16

Sedimentary structures in lower clinotherm subfacies 2.
Cycle contacts in Hume Formation.

- a Horizontal, discontinuous lamination in graded peloidal calcisiltite beds (section 18). Laminae are weakly graded and mudstone laminae (dark) thicken towards top of each bed. Note small, discrete Chondrites burrows (Ch). Positive print of acetate peel.
- b Cycle break (arrows) in Hume Formation ~40-50 m below Hume top (vicinity of section 09). Tidal flat sediments abruptly overlain by subtidal peloidal packstone. Note tidal flat intraclast (In) above discontinuity.
- c Uppermost 2 m of Hume Formation showing nodular lime mudstone, wackestone beds and interbedded shale (section 15, unit 002). Top of 15 cm scale marks the Hume-Bluefish contact.



A



B



C

PLATE 3-16

PLATE 3-17

Nodular lime wackestone, Hume Formation.
Horizontal lamination in basin facies
association (Bluefish Member).

- a Nodular crinoid-brachiopod lime wackestone 2 m below Hume-Bluefish contact (section 15, unit 002). Note pyritized allochems (crinoid columnals, brachiopod fragments - arrows).
- b Undisturbed horizontal lamination in shale from the basin facies association (section 15). Dark laminae are organic-rich compared to light laminae.



A

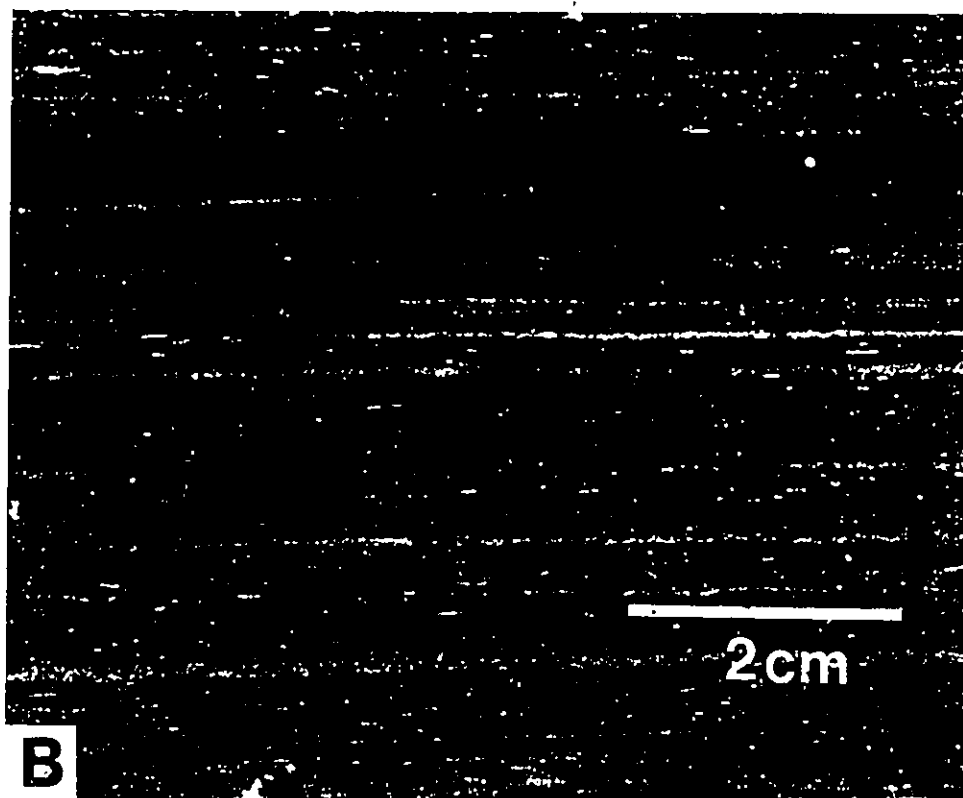


PLATE 3-17

PLATE 3-18

Major lithofacies in basin facies association.

- a Sharp-based, dactyonarid grainstone (section 17, unit 004). Note that upper portion of bed is more matrix-supported. Other fossils include crinoid columnals and fragmented bivalves. Positive print of acetate peel.
- b Sharp-based, graded dactyonarid grainstone to wackestone (section 15). Positive print of acetate peel.
- c Black, horizontally-laminated, calcareous shale; fibrous calcite vein; and peloidal calcisiltite bed (section 15, unit 005). Note gradational contacts of horizontally laminated calcisiltite bed. Scale is 15 cm.

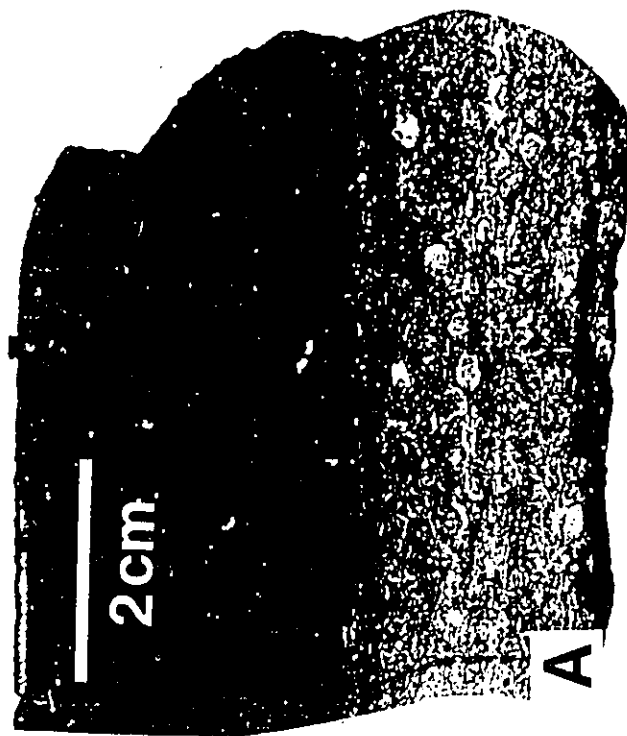


PLATE 3-18

PLATE 3-19

Concretion development in basin facies association.

- a Early stage of concretion development in peloidal calcisiltite bed (section 15). Maximum thickness of concretion is 8 cm. Note compacted shale between concretion and underlying calcisiltite bed.
- b Carbonate concretion (section 03). The underlying shale and fibrous calcite vein have been displaced by concretion growth during compaction of the enclosing sediments. Scale is 15 cm.

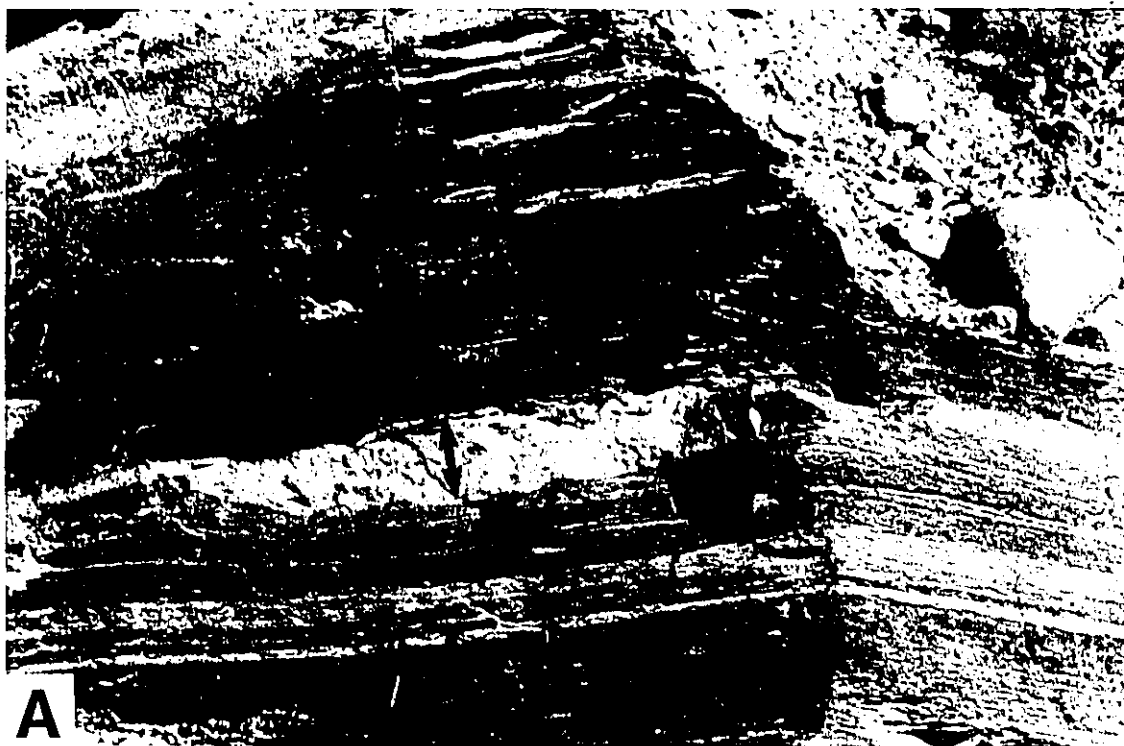


PLATE 3-19

PLATE 3-20

Fibrous calcite veins in basin facies association.

- a Fibrous calcite vein with crude two-part subdivision (section 15). Lower portion shows fewer shale inclusions and narrow, longer cone-in-cone structures. The upper part is more inclusion-rich with smaller, broader cone-in-cone structures. Positive print of acetate peel.
- b Displacive fibrous calcite developed along base of fining-upward calcisiltite bed (section 15, unit 005). Scale in cm.

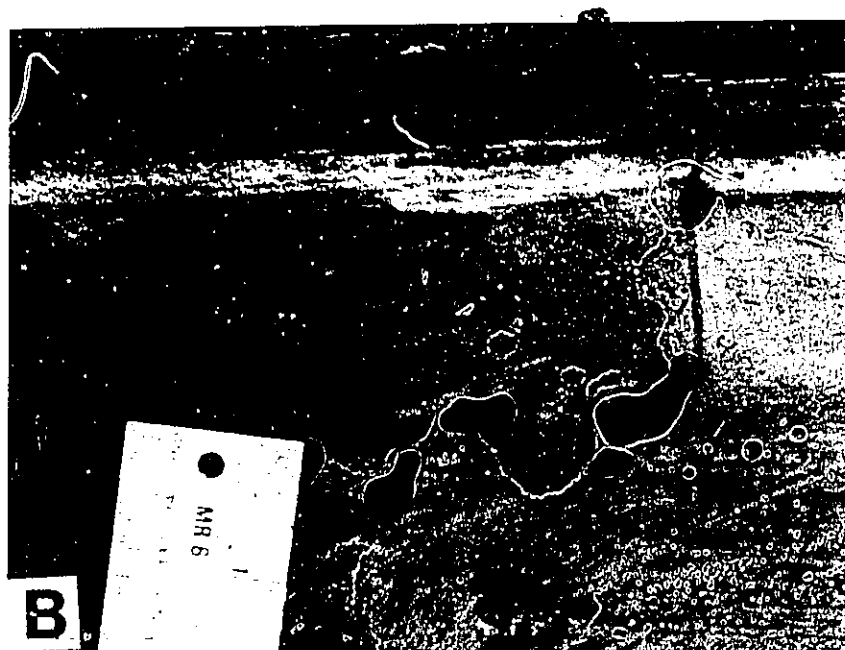
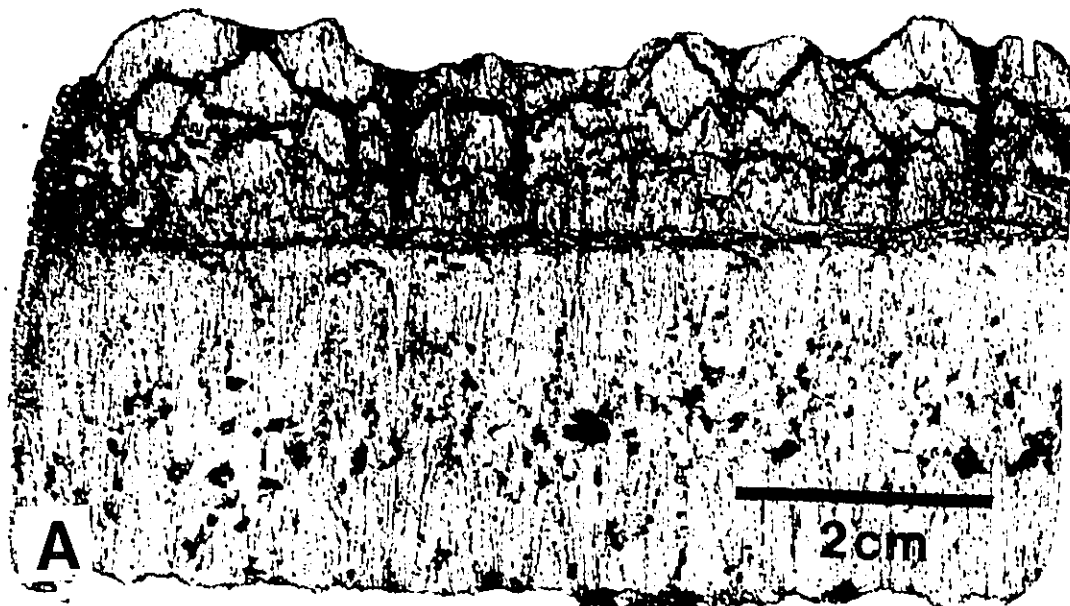


PLATE 3-20

IV

PLATFORM EVOLUTION IN
THE RAMPARTS FORMATION
(UPPER "PLATFORM-REEF" MEMBER)

4.1 INTRODUCTION

The upper member of the Ramparts Formation can be divided broadly into a platform facies association and a reef facies association (Muir et al., 1984, 1985). The platform association is a laterally extensive cyclic assemblage (FIGS. 2-3, 3-2) of shallow water limestones and minor shale. It can be divided into three second-order, upward-shoaling cycles. The lower platform cycle, up to 45 m thick, is the thickest and most extensive, and typically contains a coral-dominated faunal assemblage (Muir et al., 1984; Muir and Dixon, 1985). The middle and upper platform cycles are more areally restricted (see FIG. 3-2) and contain stromatoporoid-dominated faunas but no evidence of shallow, restricted marine deposition (Muir et al., 1984, 1985).

The platform cycles had topographic relief and more or less abrupt margins marked by increased slopes (see later sections) and by typical occurrence of platform buildups (Muir and Dixon, 1987). Sequential platform backstepping resulted in bathymetric variations across the platform that became more pronounced through time. The platform was not flat-topped like many others (e.g. in Wilson, 1975; Flugel, 1982; Hine, 1983), but was an undulating surface with up to 15-35 m paleotopographic relief in the platform interior (FIG. 3-2).

Few workers have documented time-synchronous growth stages in platform evolution (e.g. Wendte and Stoakes, 1982; Muir and Dixon, 1987). Correlation of cycle contacts permits construction of a more accurate time-stratigraphic framework and furthers understanding of the evolution of platform deposition.

Chapter 4 follows, in format, evolution of the platform facies association. Each platform cycle consists of several subfacies which are described individually below. Platform margins are marked by local thickening of buildup subfacies 1 and 2 in each platform cycle. The eastern platform margins are exposed in the vicinity of section 23 (FIG. 1-1) and the western platform margins between sections 11 and 18 (FIGS. 1-1, 3-2).

4.2 FACIES ANALYSIS OF THE LOWER PLATFORM CYCLE

4.2.1 General Statement

The lower platform cycle was initiated by accelerated rise in sea level which terminated basin-fill sedimentation. This upward-shoaling, second-order cycle consists of a number of subsidiary third-order cycles averaging 3-5 m thick. However, these were difficult to correlate between outcrop sections mainly due to the subtlety of facies change across each cycle boundary.

The lower platform cycle is the most laterally extensive second-order cycle in the platform succession. In the vicinity of the underlying ramp-clinothem transition (sections 23, 03), the lower platform cycle thickens to 45 m (FIG. 4-1) compared to 10-15 m thicknesses in the platform interior (sections 18, 20, 31 in FIG. 3-2). The cycle also thickens to 24 m towards section 15 before thinning westward to 10 m in section 09.

Five main subfacies are distinguished in the lower platform cycle, and are described and interpreted below. A concluding depositional synthesis documents their spatial and temporal interrelationships within the stratigraphic framework defined by second-order cycle boundaries, namely the Carcajou Marker and the lower-middle platform boundary.

4.2.2 Carcajou Subfacies and Termination of the Hare Indian-lower Ramparts Basin-Fill Succession

4.2.2.1 Description of the Carcajou subfacies

The Carcajou subfacies is 1.0-7.6 m thick and composed mainly of dark grey, pyritiferous, calcareous shale, ramose coral floatstone and nodular lime mudstone and wackestone. Peloidal calcisiltite and calcarenite beds are also present, primarily near ramp topographic highs (e.g. section 20,

FIG. 4-1 Platform-lower reef facies distribution in the Ramparts Formation, eastern portion of the study area.

28

21

22

23

0.75 km

0.2 km

0.3 km

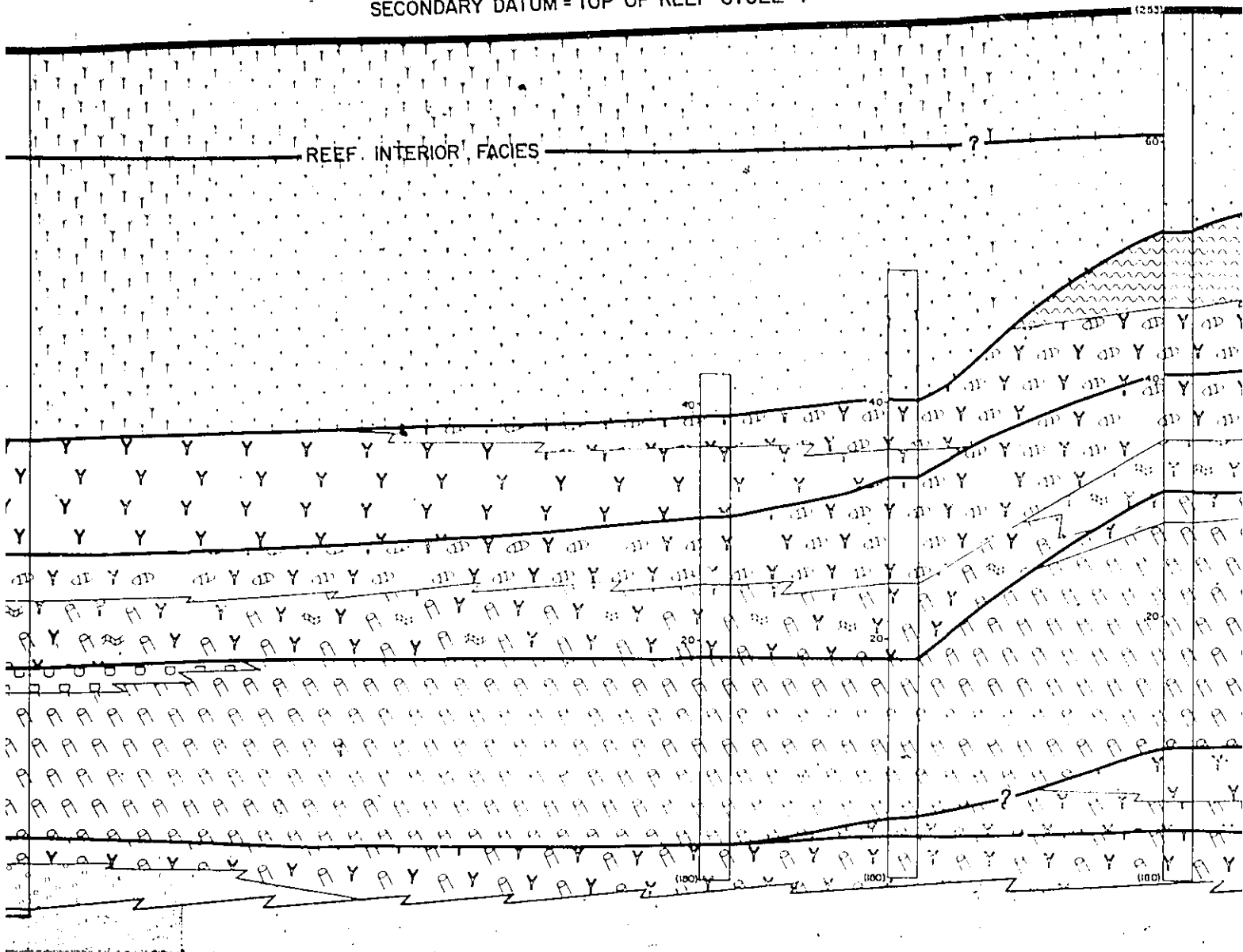
SECONDARY DATUM = TOP OF REEF CYCLE 1

(1253)

REEF INTERIOR FACIES

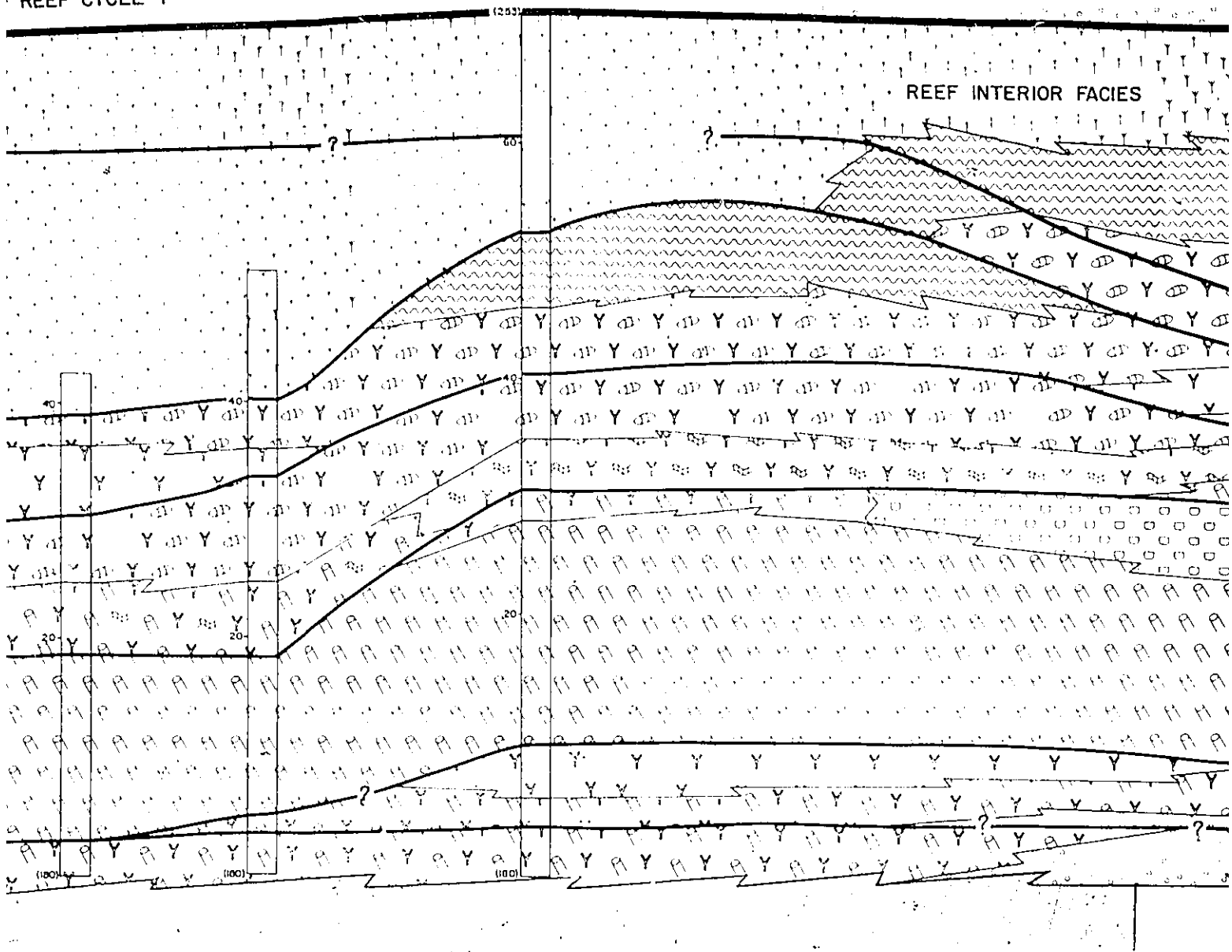
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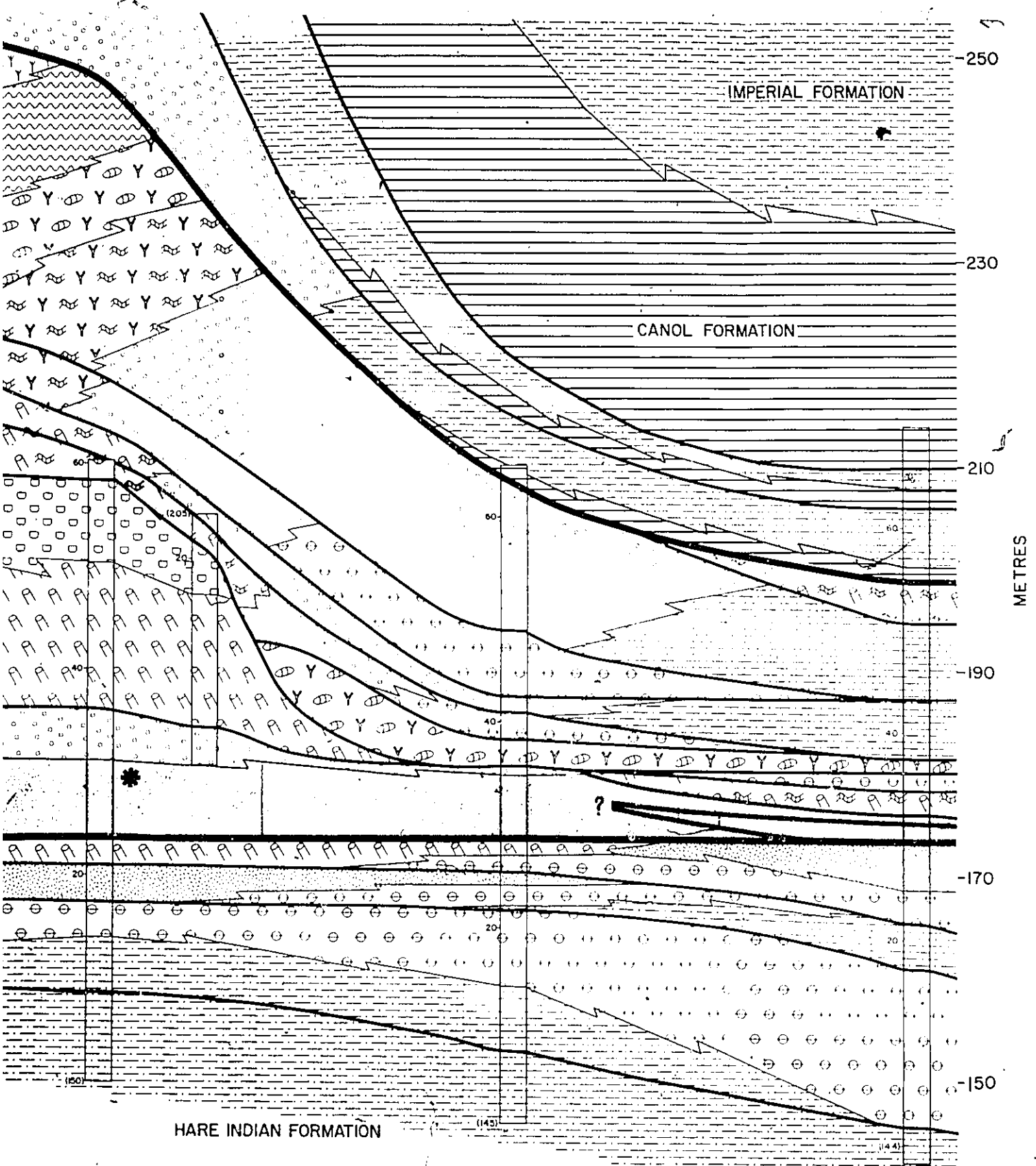
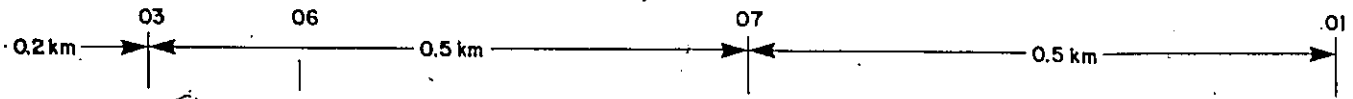
60°





REEF CYCLE 1





REEF FACIES ASSOCIATION

SUBFACIES 1-3

AMPHIPORA RUDSTONE, FLOATSTONE; LIME MUDSTONE;
BULBOUS-ENCrustING-CYLINDRICAL STROMATOPOROID
RUDSTONE, FLOATSTONE; ABRADED STROMATOPOROID
RUDSTONE

SUBFACIES 1

THICK, TABULAR STROMATOPOROID RUDSTONE,
BOUNDSTONE; MINOR ABRADED STROMATOPOROID
RUDSTONE

SUBFACIES 1

ABRADED STROMATOPOROID RUDSTONE; MINOR ROBUST
CYLINDRICAL STROMATOPOROID RUDSTONE

SUBFACIES 2

- a) WAFER-CYLINDRICAL STROMATOPOROID FLOATSTONE,
RUDSTONE, BOUNDSTONE
- b) WAFER STROMATOPOROID-RAMOSE CORAL
FLOATSTONE, RUDSTONE

SUBFACIES 3

- a) LIME GRAINSTONE
- b) PELOIDAL CALCISILTITE

SUBFACIES 4

NODULAR LIME MUDSTONE, WACKESTONE, PACKSTONE

UPPER PLATFORM FACIES

SUBFACIES 1

THICK TABULAR STROMATOPOROID-ALGAL BOUNDSTONE;
MINOR ABRADED STROMATOPOROID RUDSTONE

SUBFACIES 2

- a) ABRADED STROMATOPOROID RUDSTONE; MINOR THICK
TABULAR STROMATOPOROID-ALGAL BOUNDSTONE
- b) ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE,
FLOATSTONE

SUBFACIES 3

WAFER STROMATOPOROID-RAMOSE CORAL FLOATSTONE,
RUDSTONE; BOUNDSTONE

SUBFACIES 4

- a) LIME GRAINSTONE
- b) PELOIDAL CALCISILTITE

MIDDLE PLATFORM FACIES

SUBFACIES 2

- a) ABRADED STROMATOPOROID RUDSTONE

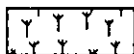
SUBFACIES 3

- a) WAFER-CYLINDRICAL STROMATOPOROID, RAMOSE CORAL
RUDSTONE; FLOATSTONE
- b) ROBUST CYLINDRICAL-WAFER STROMATOPOROID
FLOATSTONE, RUDSTONE, BOUNDSTONE
- c) WAFER STROMATOPOROID-RAMOSE CORAL
FLOATSTONE, RUDSTONE, BOUNDSTONE; MINOR SHALE

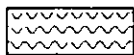
SUBFACIES 4

- a) LIME GRAINSTONE, PACKSTONE
- b) NODULAR LIME MUDSTONE, WACKESTONE, PACKSTONE

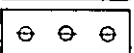
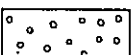
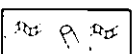
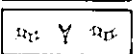
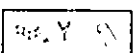
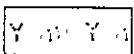
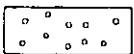
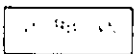
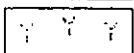
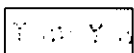
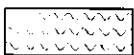
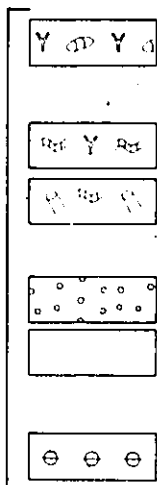
REEF INTERIOR
FACIES



REEF MARGIN/
SHOAL FACIES



REEF FORESLOPE
FACIES



SOCIATION

STONE; LIME MUDSTONE;
ORICAL STROMATOPOROID
ADED STROMATOPOROID

OROID RUDSTONE,
D STROMATOPOROID

RUDSTONE; MINOR ROBUST
ID RUDSTONE

ATOPOROID FLOATSTONE,

RAMOSE CORAL

CKESTONE, PACKSTONE

M FACIES

ROID-ALGAL BOUNDSTONE;
ROID RUDSTONE

D RUDSTONE; MINOR THICK
-ALGAL BOUNDSTONE
MATOPOROID RUDSTONE,

IOSE CORAL FLOATSTONE,

M FACIES

RUDSTONE

TOPOROID, RAMOSE CORAL

R STROMATOPOROID
UNDSTONE
AMOSE CORAL
UNDSTONE; MINOR SHALE

NE

WACKESTONE, PACKSTONE

LOWER PLATFORM FACIES

SUBFACIES 1

CYLINDRICAL STROMATOPOROID-RAMOSE CORAL
RUDSTONE, FLOATSTONE

SUBFACIES 2

'MASSIVE' (HEMISPHERICAL, BULBOUS, TABULAR) CORAL
RUDSTONE, FLOATSTONE; MINOR RAMOSE CORAL
RUDSTONE

SUBFACIES 3

RAMOSE CORAL RUDSTONE, FLOATSTONE; MINOR LIME
PACKSTONE

SUBFACIES 4

a) ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE,
FLOATSTONE
b) LIME GRAINSTONE

'CARCAJOU' SUBFACIES

NODULAR LIME MUDSTONE, SHALE; LIME WACKESTONE,
RAMOSE CORAL FLOATSTONE

UPPER RAMP FACIES

SUBFACIES 3

RAMOSE CORAL FLOATSTONE, RUDSTONE

LOWER RAMP FACIES

SUBFACIES 4

a) NODULAR LIME MUDSTONE, WACKESTONE; MINOR
PELOIDAL CALCISILTITE
b) SKELETAL LIME WACKESTONE

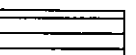
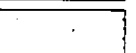
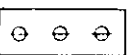
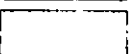
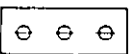
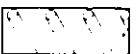
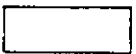
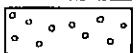
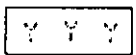
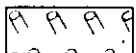
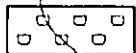
UPPER CLINOTHEM FACIES

SUBFACIES 1

a) NODULAR LIME MUDSTONE, WACKESTONE; DARK GREY
CALCAREOUS SHALE
b) PELOIDAL CALCISILTITE, SUBORDINATE GREY-OLIVE
CALCAREOUS SILTY SHALE

BASIN FACIES ASSOCIATION

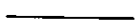
DARK BROWN, NONCALCAREOUS, LAMINATED SHALE WITH
MINOR CALCAREOUS SHALE, AND CRINOID GRAINSTONE



TEMPESTITE LITHOFACIES



SECONDARY DATUM



CYCLE BOUNDARY

DATUM-TOP OF HUME FORMATION

VERTICAL EXAGGERATION 13X

FIGURE 4 - I

STRATIGRAPHIC CROSS SECTION

IAIN MUIR
87-01-20

T30.496

FIG. 4-2) and downslope from the ramp-clinothem transition (section 25, FIG. 4-2).

The Carcajou subfacies is a distinctive, regionally correlatable unit in the study area. Preliminary conodont studies (Uyeno, writ. comm., 1986) suggest that the subfacies was deposited in the time interval between the middle varcus subzone and the lower part of the disparilis zone (see Appendix B). Pedder (1975) stated that any hiatus between platform (ramp in this study) and reefs (platform-reef in this study) was of minor significance since both were in the hermani-cristatus conodont zone.

The Carcajou subfacies onlaps topographically higher portions of the basin-fill succession. It is as thin as 1.0 m in section 15, 3.2 m thick in section 20, and thickens into paleodepressions on the ramp, for example, reaching 6.2 m in section 08. It also thickens downslope from the position of the underlying ramp-clinothem transition, reaching 5.6 m in section 03 and 7.6 m in section 25 (FIG. 4-2; PLS. 4-1, 4-2).

The Carcajou subfacies abruptly overlies the ramp facies association. Hardground development at the contact appears to be restricted to topographic highs on the ramp (PL. 4-3a). The subfacies grades sharply into more massive limestones of the lower platform cycle and the boundary is probably diachronous (PL. 4-3b).

58-301

CARCAJOU SUBFACIES

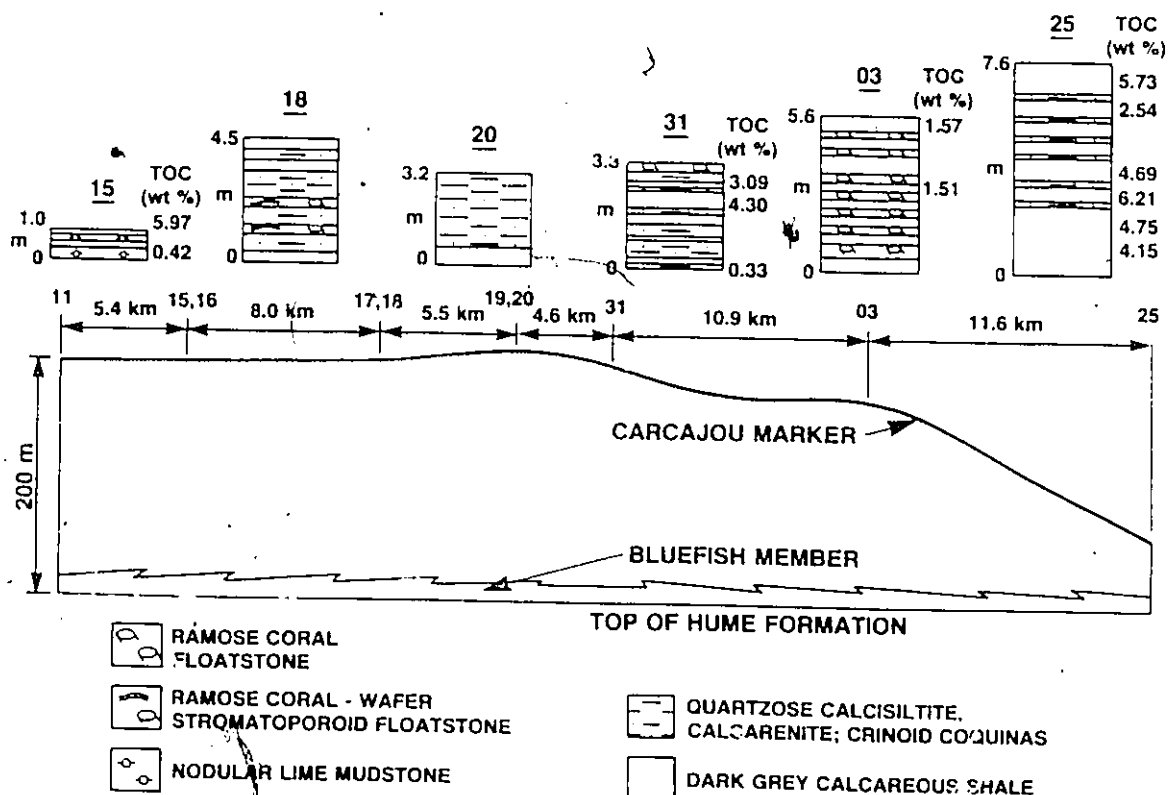


FIG. 4-2 Thickness variations in the Carcajou subfacies. Total organic carbon content (wt %) from selected shale samples at locations shown adjacent to stratigraphic sections.

The average total organic carbon content of 17 shale samples from the Carcajou subfacies was 2.88 wt% (range 1.12-8.27 wt%). Preliminary chromatograph analyses (Monnier, writ. comm., 1986) suggested that much of the organic matter was derived from a marine source. Pyrite content is also high in the Carcajou subfacies (1-2% visual estimate) mainly as framboid aggregates (PL. 4-4a) and replacement mineralization of allochems. Pyrite occurs rarely as filaments in nodular limestones or is disseminated (<0.5 mm) particularly within shale laminae.

Fossils in the Carcajou subfacies are listed in TABLE 4-1. They appear to be more diverse and abundant in the vicinity of the underlying ramp-clinothem transition (FIGS. 4-2, 4-3). Most allochems in the subfacies are highly fragmented, but show little evidence of abrasion. Furthermore, many skeletal allochems are intensely bored and are commonly mud-supported in current-unstable positions. Graded, crinoid-brachiopod, coquinoid grainstone interbeds are restricted mainly to paleotopographic highs, such as the area near section 20 (FIG. 4-2).

4.2.2.2 Interpretation

Marked deepening terminated ramp development in the study area. The following sedimentological and paleoecological evidence, in the immediately overlying Carcajou subfacies, substantiates this deepening:

TABLE 4-1

MACROFOSSILS OF THE CARCAJOU SUBFACIES

Common Constituents

Thamnopora: robust; up to 1 cm diameter, 15 cm long
crinoid columnals

Spinatrypa

indeterminate atrypids

Rare Constituents

solitary rugose corals: more abundant at section 03
branching and encrusting bryozoa

sponge spicules

fish fragments

dacriconarids

StringocephalusCoenitesAmphipora

wafer stromatoporoid

encrusting stromatoporoid

robust cylindrical stromatoporoid

trilobite

productid brachiopod

Leiorhynchus

ostracodes

gastropods

FAUNAL DISTRIBUTION IN UPPERMOST CARCAJOU SUBFACIES

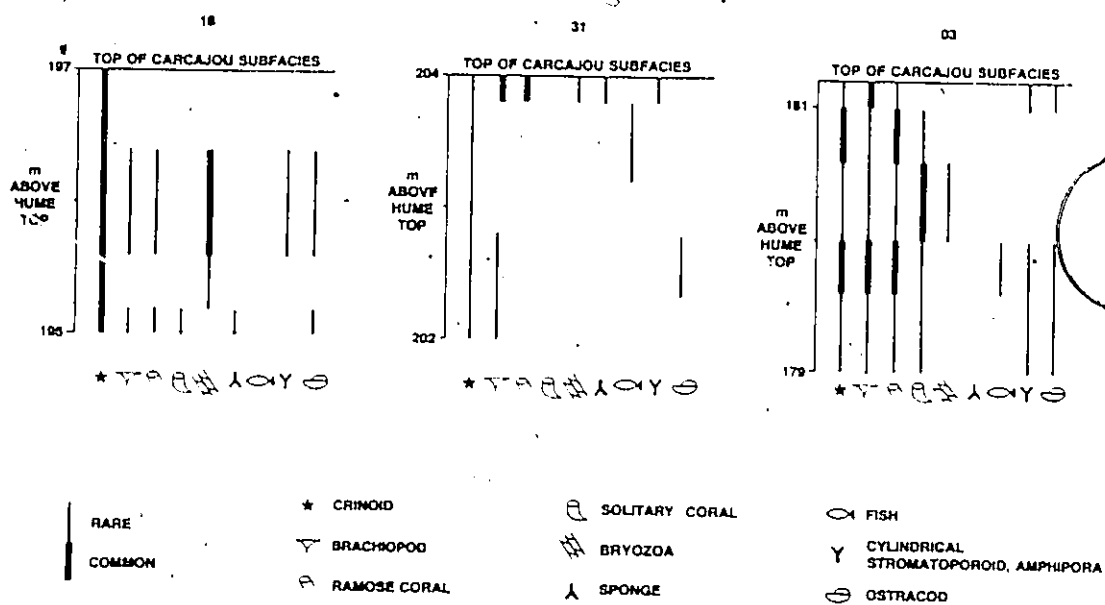


FIG. 4-3 Faunal distribution in the uppermost Carcajou subfacies.

- (1) Hardgrounds and nodular limestones occur rarely above paleotopographically higher portions of the ramp (PL. 4-3a). This restriction of submarine lithification to paleotopographic highs may reflect its development only with particular sediment types. Purser (1969) noted that hardgrounds record incipient deepening and typically occur at the tops of regressive carbonate cycles. Early submarine cements and hardgrounds develop almost exclusively in calcareous substrates. Stoakes (1979) suggested that argillaceous content of perhaps greater than 2% may be sufficient to inhibit early cementation. This might account for the absence of hardground development in the "muddier" paleodepressions on the ramp.
- (2) A sharp transition from grain-supported limestone fabrics to mud-supported limestone fabrics and interbedded shale across the Carcajou Marker indicates an abrupt shift in depositional environment. High values of total organic carbon (FIG. 4-2) and abundant pyrite, particularly as fossil steinkerns, suggest slow sedimentation under poorly oxygenated conditions. Slow accumulation of sediments and long residence times in the sulphate reduction zone would have resulted in precipitation of relatively large quantities of iron sulphides.

Poorly oxygenated waters and diminished clastic influx during the Carcajou drowning event would have contributed to deposition of organic-rich muds in the Carcajou subfacies.

- (3) Preliminary conodont work (see Chapter 1, Appendix A) suggests that the Carcajou subfacies is a condensed sequence that probably spans most of the hermanni-cristatus conodont zone (Uyeno, writ. comm., 1986). Paleoeological studies also point to slow sedimentation associated with the Carcajou drowning event. Fossils are generally disarticulated, fragmented, and compressed (PL. 4-4b). Variable faunal diversity (FIG. 4-3) may reflect discontinuities, and possible presence of thin subcycles in the Carcajou subfacies. Allochems are commonly bored and show little evidence of abrasion, such as the rounding of skeletal parts or loss of fine sculptural detail. These likely reflect long intervals of exposure at the water-sediment interface. Common occurrence of suspension-feeding organisms, such as crinoids, sponges, and bryozoans, that would have been adversely affected by turbid conditions (Dodd and Stanton, 1981) suggests low turbidity during Carcajou deposition. Most fossils show evidence of adaptation that allowed them to colonize soft

substrates: epibionts are common, as are spinose and globose brachiopods (e.g. productids, Spinatrypa, rhynchonellids), and wafer stromatoporoids and corals. The absence of allochems with higher ratios of weight to unit area in contact with the substrate may be due partly to the unstable nature of the muddy sediment.

- (4) Preservation of the record of storm sedimentation in the Carcajou subfacies. The high quartz content of these storm deposits (35-70% visual estimate) suggests diminished carbonate production during early lower platform time.

The tempestites are composed mainly of horizontally-laminated calcisiltite and calcarenite beds, with rare crinoid coquinas, and are areally restricted in the vicinity of paleotopographic highs on the underlying ramp (see FIG. 4-2). Basal contacts with the underlying dark grey shale are typically planar-sharp (PL. 4-5a). Upper contacts are gradational and rarely show trace fossils (mainly Chondrites, Planolites, escape burrows; PL. 4-5b). The scarcity of biogenic reworking was likely due to poorly oxygenated conditions in calm, muddy environments of emplacement. The 5-10 cm thick tempestites are predominantly laminated siltstone and fine sandstone commonly arranged as graded rhythmities (PL. 4-6), with a typical vertical transition from horizontal stratification

and low-angle cross-stratification to ripple cross-stratification. These fine-grained storm deposits are similar to those described by Aigner (1985) at German Bay, North Sea, in 30 m of water. The tempestites in the Carcajou subfacies probably resulted from periodic storm activity, with erosion of mixed carbonate-siliciclastic sediments from basin-fill highs and deposition offshore. The stacking of tempestite facies in the vicinity of a shoaling site on the ramp (sections 18, 20, 31) probably suggests slow background sedimentation between storm events.

As described above, the Carcajou subfacies thickens into ramp paleodepressions and basinward from the ramp-clinothem transition. However, it thins and contains substantially less shale over paleotopographic highs and westward towards the Hare Indian isopach maximum. Presumably towards higher portions of the ramp, the Carcajou subfacies may be absent due to a period of nondeposition followed by accumulation of shallow-water facies equivalents.

Interestingly, a more abundant and diverse fauna characterizes the Carcajou subfacies in the vicinity of the ramp-clinothem transition at section 03, despite initially accumulating in relatively deeper waters than in sections 15, 18, 20, 31. Cylindrical stromatoporoids and Amphipora are rarely, but more frequently, encountered in sections west of section 03, possibly suggesting more restricted circulation on a shallower part of the ramp. The

atrypid brachiopod-coral faunal assemblage likely became well-established, in the vicinity of the ramp-clinothem transition due to improved circulation and nutrient-upwelling from the adjacent depositional basin. Johnson and Flory (1972) described a similar Middle Devonian "Rasenriff" fauna in Nevada, which occupied a shallow, calm water biotope in a platform margin depositional setting.

Thickening of the Carcajou subfacies basinward from the ramp-clinothem transition suggests active bypass of sediments on the upper clinoform (PL. 4-7a) and progressively higher accumulation rates downslope (PL. 4-7b). In the Carcajou subfacies at section 01 (2.6 m thick), four graded sediment gravity flow units occupy a broad gully as much as 1.7 m deep eroded into dark grey, calcareous Carcajou shale. These gravity flow deposits show broken, disoriented, mud-supported fossils similar to the thamnoporoid coral-atrypid brachiopod-wafer stromatoporoid-crinoid fauna in the Carcajou subfacies on shallower portions of the ramp. Sole markings (mainly groove and prod casts) indicate a northerly source (azimuth = 331°) and attest to the erosive capacity of the sediment gravity flows. The unit is abruptly capped by 0.9 m of dark grey, calcareous shale which was also partly removed by overlying gully-occupied gravity flow sediments of the middle platform cycle. Redeposition of Carcajou sediments may have been common in this depositional setting.

Increased slope values at the ramp-clinothem transition likely contributed to generation of gravity flows. Furthermore, sediments with higher percentages (>4 wt%) of organic carbon have a notably higher potential for slope failure (Stanley, 1985).

The downslope thickening of Carcajou subfacies is accompanied by a decreasing percentage of peloidal calcisiltite turbidites, a change similar to that observed in the Hare Indian clinothem facies association, and reflecting higher mud accumulation rates in the vicinity of section 25. FIGURE 4-4 illustrates the broad depositional trends observed for the Carcajou subfacies. Poorly oxygenated waters associated with the Carcajou deepening event could have resulted from increased organic productivity in the shallow water thus generated. Much of the Carcajou subfacies in the study area was deposited probably near storm wavebase in 20-40 m of water on the drowned ramp. Circulation was likely damped by broad, subdued ramp paleotopography under relatively deep, density-stratified waters. Epifauna only thrived in areas of presumed nutrient upwelling at the ramp-clinothem transition and possibly along ramp depositional highs outside of the study area.

DISTRIBUTION OF THE CARCAJOU SUBFACIES

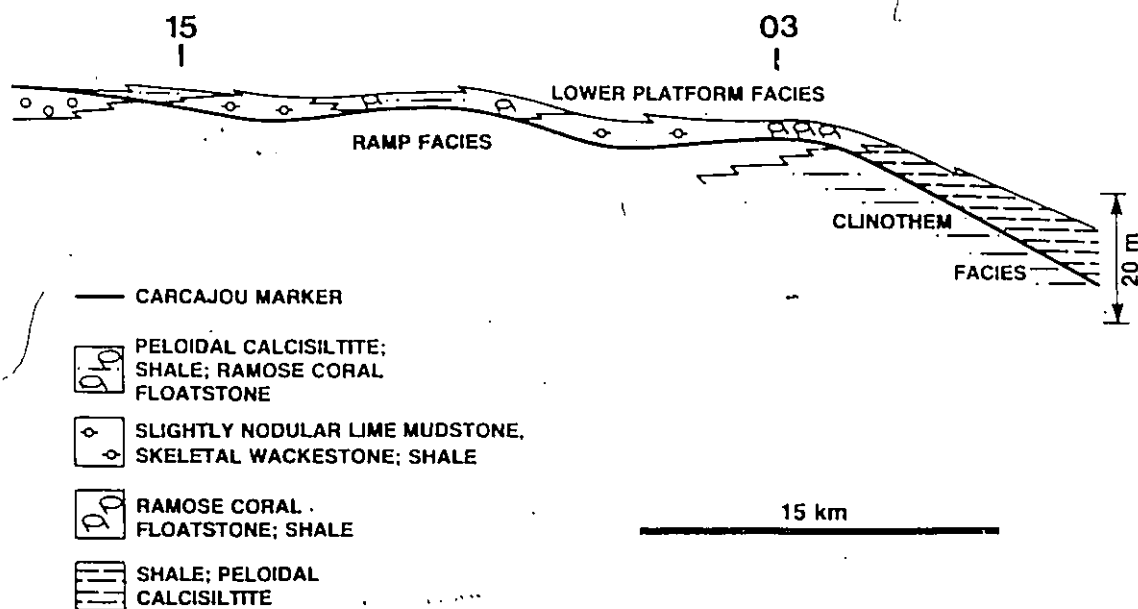


FIG. 4-4 Distribution of the Carcajou subfacies.

4.2.3 Lower Platform Subfacies 1

4.2.3.1 Description

Subfacies 1 consists of planar beds, averaging 30 cm thick, of bulbous-encrusting-cylindrical stromatoporoid rudstone, floatstone, and cylindrical stromatoporoid-ramose coral rudstone. This lithofacies is restricted to the uppermost portions of the lower platform cycle in the vicinity of paleotopographic highs as defined by the lower-middle platform cycle boundary (e.g. at section 20 in FIG. 3-2, and section 23 in FIG. 4-1). In these localities, the upper contact is a major cycle boundary that is sharply overlain either by 15 cm of recessive black shale (section 20) or by crinoid grainstone (section 23). At section 20, the lower contact grades upward from hemispherical-ramose coral floatstone of subfacies 2. The lithofacies becomes lighter and more thickly bedded upward, along with a coarsening of the rudstone matrix of slightly pyritiferous, skeletal packstone to grainstone. At section 23, the cylindrical stromatoporoid-ramose coral rudstone shows an increasing stromatoporoid/coral ratio towards the top of the cycle, with tabular stromatoporoids becoming increasingly common. This unit is gradational eastward into lower platform subfacies 2, and is the culmination of a shallowing-upward succession from the mainly ramose coral-rudstone and floatstone of lower platform subfacies 3.

At sections 20 and 23, lower platform subfacies 1 ranges from 2.4 to 4.8 m thick. Fossils in subfacies 1 are summarized in TABLE 4-2.

4.2.3.2 Interpretation

Several lines of evidence suggest that lower platform subfacies 1 was deposited in well-circulated, agitated, open-marine conditions:

- (1) Poorly sorted, skeletal packstone to grainstone predominates as a matrix in the rudstone. This, and the common occurrence of toppled and fragmented allochems, suggests deposition and reworking in agitated waters.
- (2) The diverse stenohaline fauna, including crinoids, corals, brachiopods, and stromatoporoids, points to normal marine salinity.
- (3) Subfacies 1 is the culminating shoaling phase of the lower platform cycle in areas of antecedent relief. Oxygen availability and turbulence along the topographic highs could have promoted colonization by biostrome-forming stromatoporoids.
- (4) The predominant bulbous and ramose or cylindrical stromatoporoid growth forms are interpreted as ecological adaptations to periodically high sedimentation (Riding, 1977; Bjerstedt and Feldman, 1985). Jamieson (1971) observed that, in Devonian

TABLE 4-2

MACROFOSSILS IN LOWER PLATFORM SUBFACIES 1

Common Constituents

robust cylindrical stromatoporoids
small, bulbous stromatoporoids: average 2-5 cm diameter
indeterminate brachiopods: fragmented, disarticulated
Coenites

Rare Constituents

encrusting stromatoporoids: stromatoporid,
actinostromatid
tabular stromatoporoids: more common at section 23
thamnoporoid corals
auloporid corals: encrusting bulbous stromatoporoids
hemispherical Alveolites
solitary rugose corals
crinoid columnals

reefs in Western Canada, small bulbous stromatoporoids were confined almost exclusively to platform and reef interior facies where periodic strong water currents apparently caused frequent toppling.

4.2.4 Lower Platform Subfacies 2

4.2.4.1 Description

Subfacies 2 is typically thickly-bedded, bulbous-hemispherical-tabular alveolitid rudstone, floatstone, and boundstone. Subfacies 2 in the study area is more extensive geographically than subfacies 1 (see FIGS. 3-2, 4-1), but apparently displays similar relationships to topographic highs. In the eastern portion of the study area (FIG. 4-1), subfacies 2 thickens to 8 m at section 03, as a thick, tabular alveolitid bindstone gradationally interbedded beneath with lower platform subfacies 3. The underlying lower platform succession is 20-27 m thick at this locality and, within 1.5 km westward towards the platform interior, thins to 20 m (section 22 in FIG. 4-1). Associated with thinning, subfacies 2 is either thin (section 28) or absent.

Subfacies 2 also thins downslope or eastward towards the depositional basin, to 4.5 m in section 06. At this locality, it consists of alveolitid floatstone with

characteristically disoriented, fragmented, irregular-encrusting colonies (PL. 4-8). Subfacies 2 is abruptly overlain by deeper water sediments of middle platform subfacies 3 near the eastern limit of the lower platform.

Within the platform interior (FIG. 3-2), subfacies 2 is restricted to antecedent topographic highs (e.g. section 20, PL. 4-9, FIG. 3-2). Aligned thamnoporoid coral fragments near the base of the subfacies indicate a north-south current alignment. Hemispherical and thick tabular alveolitid corals are increasingly abundant towards the sharp upper contact with subfacies 1. Ramose and hemispherical tabulate corals are commonly in contact. Interstitial dark grey calcareous mudstone (PL. 4-9) was possibly baffled or bound within the coral framework.

Subfacies 2 is up to 7.5 m thick where the underlying lower platform facies thickens to 12-16 m in the vicinity of section 15. However, the subfacies thins westward to 0-3 m in section 9 and 11, as the underlying lower platform facies thins towards the axis of the Hare Indian lobe. At section 15, the following up-section trends were observed:

- (1) Coarsening of supporting matrix from Coenites floatstone to rudstone; grainstone-occupied, scour-fills occur rarely.
- (2) Progression of dominant alveolitids from wafer to bulbous (PL. 4-10a) to hemispherical and irregular encrusting growth forms (PL. 4-10b); robust

cylindrical stromatoporoids occur rarely at the top of the subfacies.

(3) Increased frequency of overturned colonies.

In section 15, subfacies 2 is abruptly overlain by basal laminites of the Canol Formation. However, there is no evidence for hardground development as Canol shale appears to drape over original microtopography of alveolitid colonies (PL. 4-11a).

In the western portion of the study area (sections 09-15), lower platform facies contain more subangular quartz grains, averaging 0.03-0.10 mm diameter, both towards the top of the lower platform cycle, and westward towards the axis of the Hare Indian lobe. Thirty cm of calcareous quartz siltstone (~60% quartz), containing the brachiopod Leiorhynchus hippocastanea abundantly, abruptly cap subfacies 2 in sections 09 and 10. Fossils in subfacies 2 are listed in TABLE 4-3.

4.2.4.2 Interpretation

Antecedent topography and proximity to siliciclastic input were apparently the major controls on distribution of lower platform subfacies 2.

High turbidity in areas proximal to siliciclastic input, possibly related to reworking along Hare Indian highs, prevented stromatoporoid-rich subfacies 1 from forming in the western portion of the study area. Stromatoporoids

TABLE 4-3

MACROFOSSILS OF LOWER PLATFORM SUBFACIES 2

Common Constituents

thick tabular alveolitid: maximum dimensions 50 cm long,
20 cm high; common in
subfacies 2 along eastern
lower platform margin

hemispherical alveolitid: average 9 cm diameter, 6 cm
high

bulbous alveolitid: common in subfacies 2 along western
lower platform margin

encrusting alveolitid

CoenitesRare Constituents

thamnoporoid coral

crinoid columnals

ostracod

echinoid spines

robust cylindrical stromatoporoid: near top of subfacies
on coral fragments

encrusting stromatoporoid

rhynchonellid brachiopod

Cyrtina

*solitary rugose coral

hemispherical syringoporoid coral

nautiloid

bryozoan

trilobite

appear to have been more adversely affected by sediment influx than corals. Tsien (1971) noted that, in Devonian buildups in Belgium, large, thick, hemispherical to irregular alveolitids tend to occur in shallower water facies representing more turbulent conditions. He suggested that stromatoporoids were more sensitive to turbidity and were commonly excluded from more turbid depositional environments. This may explain the localization of subfacies 1 on topographic highs within the platform interior (section 20) and behind the high energy platform margin at section 23 (FIG. 4-1). The predominant alveolitids in subfacies 2 in the western portion of the study area change westward from broad, hemispherical growth forms at section 15 to small, bulbous to irregular growth forms at sections 09-11. Philcox (1971) suggested, that bulbous and cylindrical growth forms are favored in environments with high sedimentation rates. Lateral growth, as in tabular and hemispherical forms, is prevented, and upward growth may be barely sufficient to avoid burial. The irregular alveolitid growth form, common in section 09-11, reflects environmental changes probably associated with periodic storm influx of mixed carbonate and siliciclastic sediments, derived from the Hare Indian lobe.

The thick accumulation of subfacies 2 along the eastern platform margin reflects optimal growth, probably due to well-circulated, nutrient-bearing waters from the adjacent

depositional basin. The local accumulation of subfacies 2 around section 15 (FIG. 3-2) lacks the thick tabular alveolitids that are so common along the eastern margin. Local buildups in this area likely formed in lower energy settings where conditions were still favorable due to antecedent topography, and sufficient distance from harmful siliciclastic input. Subfacies 1 and 2 are absent from the platform interior except on depositional highs (e.g. at section 20, FIG. 3-2). Circulation of oxygenated, nutrient-bearing waters was generally insufficient in the platform interior to allow the characteristic coral and stromatoporoid faunas of subfacies 1 and 2 to develop.

Reconnaissance suggests that subfacies 2 represents isolated alveolitid patch reefs that coalesced as relative sea-level rise diminished (PL. 4-11b). The sequence shoaled into shallow, agitated waters, possibly in depths of 5-10 m.

4.2.5 Lower Platform Subfacies 3

4.2.5.1 Description

Subfacies 3 is the most common in the lower platform cycle. The facies typically consists of ramose coral floatstone and rudstone, with minor interbedded calcareous shale, skeletal lime wackestone, and wafer alveolitid bindstone. Subfacies 3 is laterally extensive, thickens

near the platform margins (14-19 m thick at the eastern margin in section 03, 23; 5-7 m thick at the western margin in section 11, 15) and thins towards the platform interior (2-4 m thick at section 18, 20, 31). The subfacies grades into subfacies 2 (FIG. 4-5; PL. 4-12) and bedding plane relationships indicate deposition on shallow-dipping buildup flanks and inter-buildup regions of the platform (FIG. 3-2). A minor cycle boundary separates subfacies 3 from the underlying subfacies 4 (FIGS. 3-2, 4-1, 4-5). The basal 5-10 cm of subfacies 3 are either dark brown, pyritiferous shale or, less commonly, a dark brown, slightly nodular-bedded, thamnoporoid coral floatstone containing pyritized allochems. The basal portion of the succession is characterized by "muddier" sediments comprising dark brown, ramose coral floatstone (PL. 4-13a) and interbedded shale. Beds show upward increase in bed thickness, and coarsening to ramose coral rudstone supported by peloidal packstone matrix (PL. 4-13b).

Faunal diversity (TABLE 4-4) increases towards the top of the subfacies and is much higher near the eastern platform margin (FIG. 4-6). The proportion of whole fossils to fragments decreases upward. Ramose Coenites and Thamnopora are better preserved in lower subfacies 3 (PL. 4-14a), and more robust, fragmented forms are typical of grainier, upper sediments (PL. 4-14b). Bulbous alveolitids are larger (3-7 cm diameter) and more prevalent toward the gradational upper

DISTRIBUTION OF THE PLATFORM FACIES

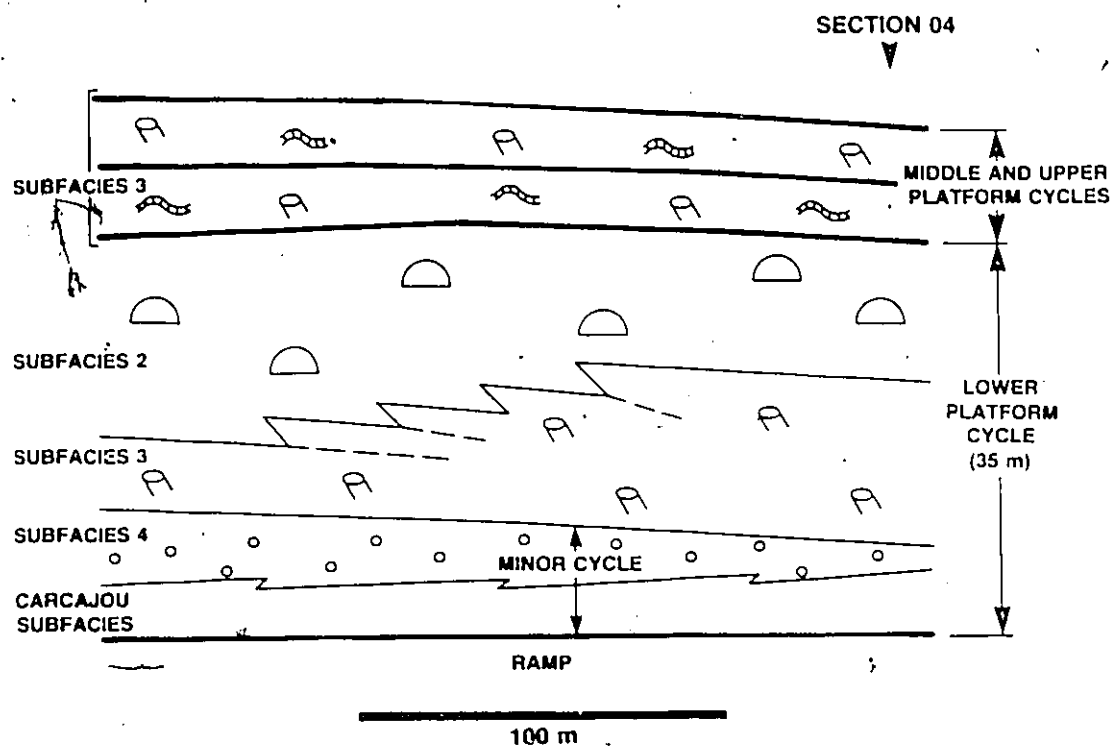


FIG. 4-5 Distribution of platform facies at section 04
(see PLS. 4-12, 4-18).

TABLE 4-4

MACROFOSSILS OF LOWER PLATFORM SUBFACIES 3	
<u>Common Constituents</u>	
<u>Coenites</u>	
crinoid columnals	
atrypid brachiopods	
<u>Rare Constituents</u>	
wafer alveolitid	mainly in upper portion of subfacies 3
hemispherical alveolitid	
bulbous alveolitid	
encrusting stromatoporoid	
robust cylindrical stromatoporoid	
wafer stromatoporoid	
gastropod	
encrusting bryozoa	
ostracod	
dacriconarids	
thamnoporoid coral	
solitary rugose coral	
fish fragments	
<u>Cyrtina</u>	

contact (FIG. 4-6) of subfacies 3 with subfacies 1 and 2. Robust cylindrical and encrusting stromatoporoids occur rarely, mostly in upper subfacies 3.

4.2.5.2 Interpretation

The widespread distribution of the ramose coral rudstone and floatstone facies is suggestive of faunal tolerance to considerable variation in turbulence, turbidity, substrate type, and possibly other depth-related environmental factors. The distribution of subfacies 3, particularly near platform margins, was important as the subfacies served as a foundation for initiation of small buildups (subfacies 2) in the lower platform (FIGS. 4-1, 3-2). Subfacies 3 was deposited in waters probably 10-25 m deep based on 5-10 m paleodepth estimates for subfacies 1 and 2. The upward changes summarized previously, including decreased shale content, coarsening, increase in faunal diversity, collectively are evidence of an overall shallowing during deposition of subfacies 3.

Evidence of high sedimentation rates includes the following:

- (1) Prevailing ramose and rare bulbous growth forms among the corals are adaptations for efficient sediment-shedding.

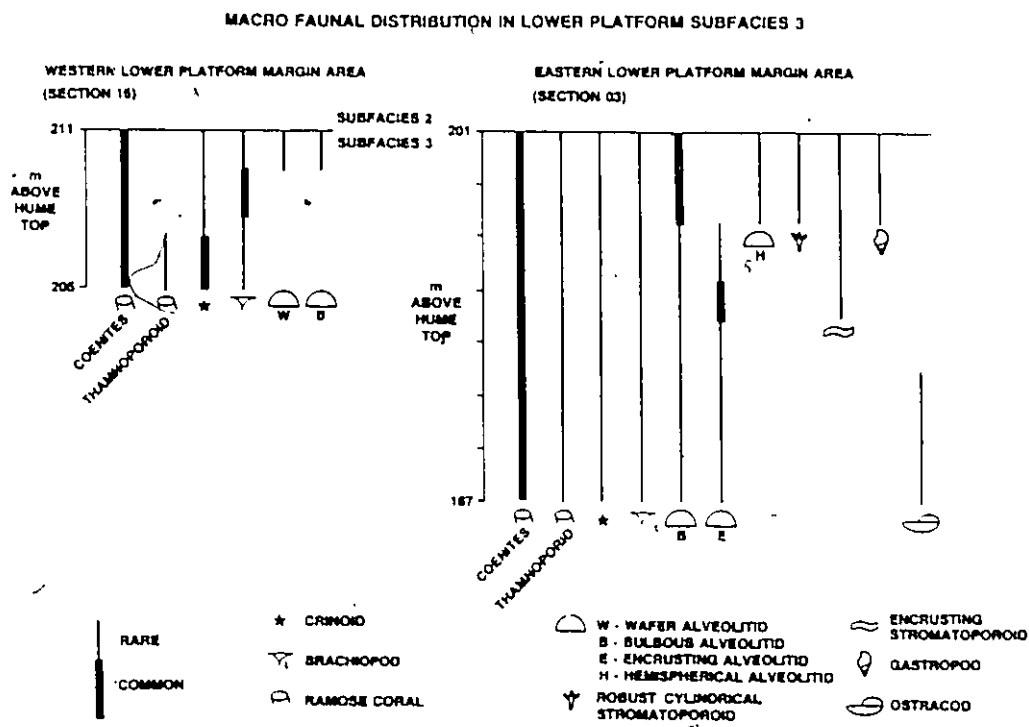


FIG. 4-6 Macrofaunal distribution in lower platform subfacies 3.

- (2) Stromatoporoids are rare to absent, and were probably excluded by turbidity (Tsien, 1972; Boucot, 1981).
- (3) Alveolitid corals commonly show evidence of termination of growth by layers of sediment.
- (4) Borings or encrustation of growth surfaces are generally absent. Allochems show evidence of abrasion and fragmentation, particularly towards the top of the subfacies.

Thickness variations of subfacies 3 are possibly due partly to the baffling effect of the abundant ramose corals, especially in areas of good circulation such as the platform margins (FIGS. 3-2, 4-1). However, the ramose corals are rarely upright and are typically fragmented. Thus, their more important sedimentological role was likely in contributing to sediment volume. Consequently, subfacies 3 thickness variations can reflect the combined effect of the following factors:

- (1) Stimulated growth in areas of good circulation of nutrient-bearing waters and areas where antecedent topographic highs improved circulation (e.g. vicinity of lower platform margins in FIGS. 3-2, 4-1). In the evolving depositional topography, shallower waters would have favored higher growth potential (Schlager, 1981).

(2) Mechanical redistribution by wave energy dependent upon water depth, prevailing wind direction, and distribution according to predominant storm tracks. There was probably little redistribution in the platform interior compared to platform margin areas.

(3) Differential compaction (minor).

The ramose coral distribution is analogous to the distribution of Acropora cervicornis in modern Caribbean reefs. Typically, this modern coral is concentrated in zones behind and downslope from the A. palmata-dominated breaker zone in deeper (4-20 m), less agitated waters (Scatterday, 1974; Geister, 1977; James and Macintyre, 1985). Randall and Eldridge (1977) noted that the branching A. cervicornis is less resistant to wave action than A. palmata. Consequently, storm damage and fragmentation of the branching form tend to be more intense and widespread in the zones of A. cervicornis growth.

4.2.6 Lower Platform Subfacies 4

4.2.6.1 Description

Subfacies 4 consists mainly of grain-supported lithofacies including brachiopod-crinoid-Amphipora grainstone and Amphipora-robust cylindrical stromatoporoid

ramosa coral rudstone. The upper contact of subfacies 4 is a minor cycle boundary that is abruptly overlain by dark brown, pyritiferous shale or dark brown, slightly nodular, thamnoporoid coral floatstone. At section 09, the upper contact is a pyritized surface encrusted by wafer alveolitids. Subfacies 4 generally displays a sharply gradational lower contact with the Carcajou subfacies. However, basal beds in subfacies 4 rarely show black shale intraclasts and thamnoporoid corals with black shale-infilled, intra-allochem porosity (PL. 4-15), suggesting local marine erosion of the underlying Carcajou sediments. In section 07, meandering tool marks at the base of 0.6 m thick subfacies 4 likely represent gutter casts.

The subfacies can be traced throughout the study area and exhibits the following thickness trends:

- (1) Thinning to 2.1 m (section 20) over paleotopographic highs within the platform interior, and thickening to 3.3 m (section 18) and 3.4 m (section 31) in adjacent paleodepressions.
- (2) Thickening to a maximum 12 m (section 23) in the vicinity of the ramp-clinoform break in slope where the eastern margin of the lower platform developed (FIG. 4-1), and thickening to 6.6 m at the western margin in section 15.

Detailed mapping near the eastern margin (sections 21-23, 28, 03, 07) revealed a predictable lithofacies sequence for

the subfacies (FIG. 4-7). A medium brown brachiopod-crinoid-Amphipora packstone to grainstone unit (PL. 4-16a) typically fringes and is gradational upwards into a ramose coral-cylindrical stromatoporoid rudstone showing a substantially higher ratio of sparite cement to lime mud matrix. This unit, in turn, passes into local accumulations of cylindrical stromatoporoid rudstone (PL. 4-16b) which contributed 5-15 m of topographic relief in the eastern platform margin area. The abrupt upper cycle boundary of subfacies 4 provides the evidence of paleotopographic relief represented in FIG. 4-7. Fossil content of subfacies 4 is listed in FIG. 4-8 and plotted against the vertical succession of major lithofacies.

Horizontal strata 3-10 cm thick are defined by variable allochem and matrix content (PL. 4-16b), and there is a general thickening- and lightening-upward trend in beds of subfacies 4. Allochems are typically fragmented, and disoriented stromatoporoids are common towards the top of the sequence. An abundant, thick-shelled, brachiopod fauna (including Stringocephalus) characterizes the basal portion of subfacies 4. Valves are typically disarticulated and in current-unstable positions (PL. 4-16a). Primary intra-allochem porosity (calcite cement-occluded) increases towards the top of the sequence and there is a concomitant decrease in faunal diversity with larger, more robust stromatoporoid allochems (FIG. 4-8) becoming predominant.

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LOWER PLATFORM: STAGE 1 - SHOAL INITIATION

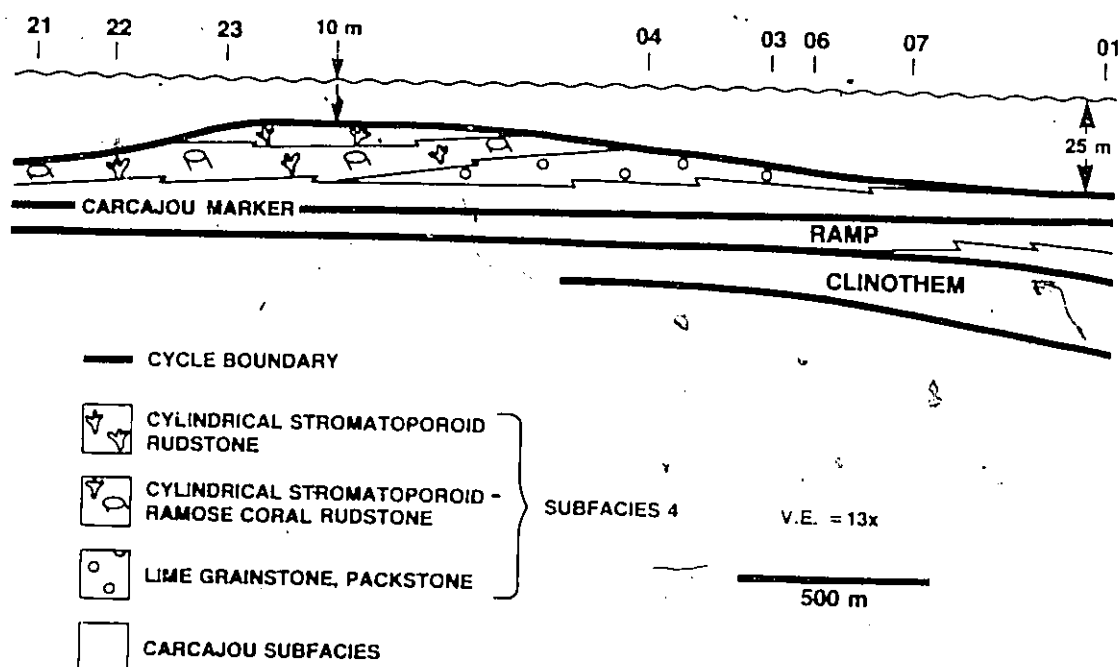


FIG. 4-7 Paleoenvironmental reconstruction of the lower platform facies (stage 1) in the eastern portion of the study area (sections 21 to 01).

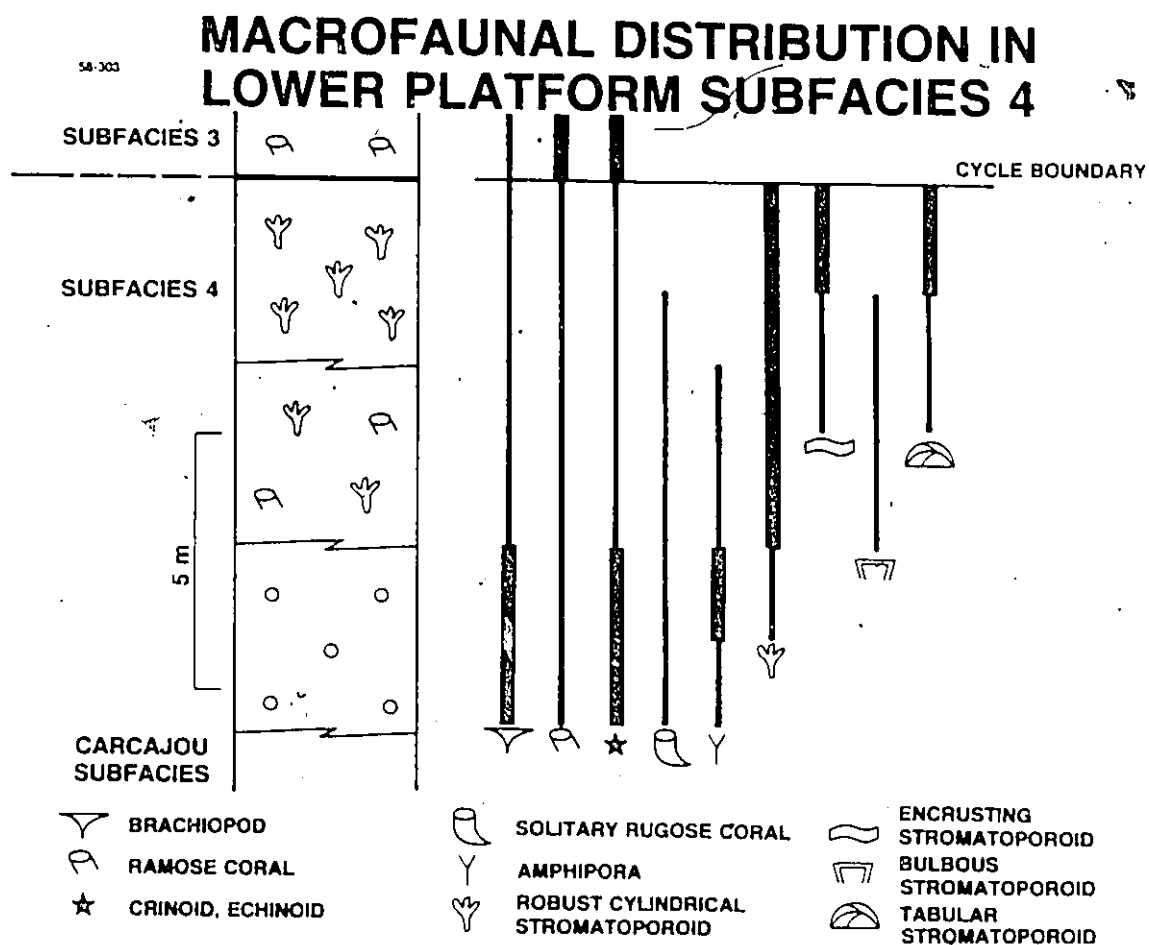


FIG. 4-8 Macrofaunal distribution in lower platform subfacies 4 at sections 04, 23.

4.2.6.2 Interpretation

There is abundant evidence to suggest that most of subfacies 4 accumulated as shoal sediments on the drowned ramp. Subfacies 4 thins over platform interior depositional highs and thickens into adjacent topographic lows and into marginal areas of the lower platform (FIGS. 3-2, 4-1). Circulation was sufficient in the area of the underlying ramp-clinothem transition, presumably with upwelling of nutrient-bearing waters from the adjacent basin, to promote vigorous growth of the shoal-forming organisms. In the Gayna River area (section 15), local shoals developed on a topographically higher portion of the ramp in presumably more agitated waters, distant from possibly storm reworked mixed siliciclastic-carbonate sediments.

The shoal sediments were commonly redistributed by storm wave activity, as shown by hydrodynamic sorting of abraded bioclasts. The muddy crinoid-brachiopod grainstone and packstone appear to have developed around shoal accumulations, particularly along depositional margins facing away from the platform interior (FIG. 4-7). Rare gutter casts and common fragmented allochems in current-unstable positions suggest periodic storm reworking. More robust, fragmented, cylindrical and tabular stromatoporoids are localized on shoal highs and are supported by a skeletal grainstone matrix showing sparite-occluded interparticle porosity. These sediments

were likely more winnowed at shallower depth, estimated to have been about 10 m (FIG. 4-7), and probably represent near in situ accumulations. Smaller cylindrical stromatoporoids were easily transported because of their high initial porosity and possible sedentary rather than sessile life habit (Kobluk, 1975; Bassett and Lawson, 1984; Kershaw, 1984). An Amphipora-robust cylindrical stromatoporoid-crinoid-brachiopod-ramose coral faunal assemblage suggests a unique depositional environment.

As discussed earlier in this chapter, the Carcajou drowning event terminated ramp deposition. It probably resulted in organic enrichment of sediments due to increased productivity in areally-expanded shallow waters. Sluggish circulation and reduced oxygenation in these shallow waters could have restricted colonization by opportunistic faunas to particular parts of the drowned ramp. More favorable sites would have been:

- (1) On topographic highs in better circulated, more oxygenated waters, well removed from areas of high siliciclastic sedimentation and associated high turbidity (e.g. sections 15, 20; FIG. 3-2).
- (2) Along the ramp-clinothem transition where nutrient-bearing waters could have upwelled from the adjacent basin, and circulation would have been slightly improved due to storm and wave action.

Small cylindrical stromatoporoids, such as Amphipora, were probably initially favored due to their tolerance to extremes in oxygen levels and water energy fluctuations (Jamieson, 1971). Low turbidity probably characterized deposition of the Carcajou subfacies and the lower platform subfacies 4, as indicated by the common stromatoporoid-crinoid fauna. However, a cylindrical stromatoporoid fauna was not re-established following the relative rise in sea level that terminated subfacies 4. A combination of slowing sea-level rise and developing platform topographic relief likely resulted in increased turbidity and restriction of the stromatoporoid fauna to local highs during the close of the lower platform cycle.

4.2.7 Synthesis of Lower Platform Evolution

The lower platform depositional cycle is the thickest and most extensive in the platform facies association. At section 15, the lower platform is abruptly overlain by Canol basinal laminites (PL. 4-17). In the eastern portion of the study area (sections 03, 04; FIG. 4-1), lower platform margin facies (subfacies 1, 2) culminate in a 45 m upward-shoaling sequence and are abruptly overlain by thin (8 m) foreslope facies of the middle and upper platform cycles (PL. 4-18; see Sections 4.3 and 4.4). The foreslope of the lower platform steepened from 8.6 m/km at stage 1 (sections 03 to 01, FIG. 4-7) to 42 m/km at stage 2

(sections 03 to 01, FIG. 4-9). Interbedded foreslope peloidal calcisiltite and shale constitute a unit that thickens from 7 m in section 01, downslope to 13 m in section 25, and rarely includes coarse-grained, gully-fill gravity flow sediments (section 01, unit 018).

Overall ramp-lower platform development shows a complex and persistent relationship to antecedent topography. Following a relative rise in sea level during Carcajou Marker time, an impoverished ramose coral fauna became established on portions of the drowned ramp where circulation was slightly improved and siliciclastic input was minor (FIG. 4-4). Preferred sites were:

- (1) The ramp-clinothem transition area (section 03).
- (2) Antecedent topographic highs on the ramp (sections 20, 15).

Local shoals eventually developed at these sites for similar reasons. The unusual Amphipora-robust cylindrical stromatoporoid-crinoid-brachiopod faunal association was probably opportunistic and occupied clear, normal marine but slightly oxygen-depleted environments. Shoal development enhanced topographic relief on the lower platform (FIGS. 3-2, 4-1, 4-7, 4-9) and was terminated by accelerated rise in relative sea level. Changing circulation patterns associated with this drowning and the evolved shoal topography probably resulted in more turbidity, particularly in platform paleodepressions. Consequently, the greatest

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LOWER PLATFORM: STAGE 2 - MARGIN DEVELOPMENT

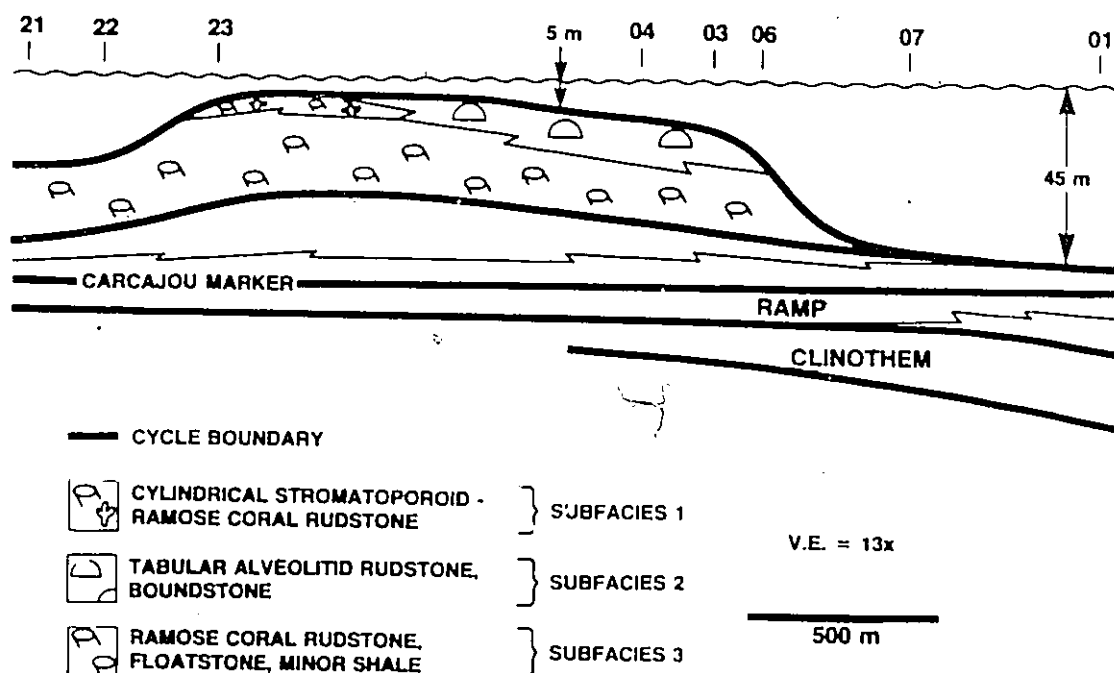


FIG. 4-9 Paleoenvironmental reconstruction of the lower platform facies (stage 2) in the eastern portion of the study area (sections 21 to 01).

growth potential for lower platform subfacies 1-3 was in the vicinity of antecedent topographic highs, including the western platform margin (section 15), a platform interior high (section 20), and the eastern platform margin (sections 23, 03).

Hydrographic features and aspects of sediment distribution on the Bahama Banks are known to be influenced, in part, by pre-existing Pleistocene bedrock topography. Dravis (1977) noted that the Bahama Bank margins coincide with topographically higher areas of Pleistocene bedrock. Most of the platform interior is floored by a Pleistocene limestone paleotopographic low at depths of 6-7 m.

In the eastern portion of the study area, the lower platform displays a depositional margin of high relief. Compared to the thick accumulation of platform margin facies as section 03, very little sediment escaped basinward (FIGS. 4-1, 4-9). Faunal evidence indicates that open marine conditions prevailed for platform interior deposition. This suggests that platform margins were discontinuous and characterized by small, coalescing Coenites-Thamnopora-alveolitid coral buildups. However, platform interior circulation was sufficiently restricted that carbonate production was reduced there relative to platform margin areas, and platform topography, therefore, was progressively accentuated (FIGS. 3-2, 4-1).

4.3 FACIES ANALYSIS OF THE MIDDLE PLATFORM CYCLE

4.3.1 General Statement

A pronounced and rapid sea-level rise terminated the lower platform cycle. The overlying middle platform cycle is a less extensive stromatoporoid-dominated, upward-shoaling, second-order cycle (FIGS. 3-2, 4-1). It thins to 4 m (section 20) and 9 m (section 23) over pre-existing platform highs, and thickens to 13 m (section 31) and 15 m (section 22) in adjacent depressions. Correlation of the middle/upper cycle boundary indicates a "smoothing" of depositional topography compared to the beginning of the middle platform cycle. No discrete, isolated buildups, such as those in the lower platform cycle, are present in the middle platform cycle. As a consequence, the margins of the middle platform are less clearly defined. In the eastern portion of the study area, the middle platform margin is near section 23 (FIG. 4-1). The middle platform margin facies pass downslope into foreslope facies eastward, and into platform interior facies westward (see details below). Exposure is less extensive in the western portion of the study area. Platform margin facies probably extended to near section 18 (FIG. 3-2), with basinal facies equivalents present beyond in the lower Canol Formation at section 15.

The middle platform cycle contains four main subfacies, as described and interpreted below. A concluding depositional synthesis outlines their spatial and temporal interrelationships.

4.3.2 Middle Platform Subfacies 1

4.3.2.1 Description

Subfacies 1 consists of planar-bedded, bulbous-encrusting-cylindrical stromatoporoid rudstone and floatstone. Units are typically 3-4 m thick, and are restricted to platform topographic highs (e.g. sections 18, 20, 31 in FIG. 3-2) where they are sharply overlain by dark calcareous shale of the upper platform cycle. The subfacies either rests abruptly on the lower platform cycle (in section 20) or passes gradationally into abraded stromatoporoid rudstone of middle platform subfacies 2 in adjacent platform paleodepressions (in sections 18, 31, 08). Units commonly coarsen-upward from argillaceous floatstone, with a high coral-to-stromatoporoid ratio, to light-colored, bulbous-hemispherical-cylindrical stromatoporoid rudstone and boundstone with a fragmented skeletal grainstone matrix (PL. 4-19a). Fossils in subfacies 1 are listed in TABLE 4-5.

TABLE 4-5

MACROFOSSILS OF MIDDLE PLATFORM SUBFACIES 1

Common Constituents

bulbous stromatoporoids: common stromatoporids, many
overturned; average height 10-
18 cm; average diameter 5-9 cm
robust cylindrical stromatoporoids
hemispherical stromatoporoids
encrusting stromatoporoids: common stromatoporids

Rare Constituents: more common at base of subfacies

Coenites

solitary rugose coral
thamnoporoid coral
tabular alveolitid coral
wafer stromatoporoid
tabular stromatoporoid
ostracod
crinoid columnals

4.3.2.2 Interpretation

Subfacies 1 was deposited in slightly agitated open marine waters on platform paleotopographic highs. The association of a higher coral content with more argillaceous floatstone near the base of the units implies more turbid conditions initially. The abundance of bulbous and hemispherical stromatoporoids towards the top of the subfacies probably reflects shallower, slightly more turbulent conditions and episodic sedimentation (Kobluk, 1975; James, 1979). These predominant morphotypes would be less suited to turbulent depositional settings (Bjerstedt and Feldman, 1985).

Subfacies 1 represents autochthonous sediments preserved on platform interior highs and fringed by allochthonous sediments of subfacies 2. This relationship will be discussed below.

4.3.3 Middle Platform Subfacies 2

4.3.3.1 Description

Subfacies 2 comprises mainly abraded stromatoporoid rudstone with minor robust cylindrical stromatoporoid rudstone and floatstone, robust cylindrical stromatoporoid-ramose coral rudstone and floatstone, and skeletal lime wackestone interbeds.

It is the most common subfacies in the middle platform cycle, particularly adjacent to platform highs, for example, west of section 08 (FIG. 3-2) where some units are as much as 16 m thick. In the eastern portion of the study area, bedding planes within the subfacies show clinoform geometry as they downlap onto the underlying lower platform cycle (PL. 4-19b, FIG. 4-10).

Allochems are typically fragmented, disoriented, and grain-supported. The matrix varies up sequence from muddy peloidal packstone to skeletal grainstone, with calcite-occluded primary interparticle porosity. Beds become lighter-colored and thicken-upward. Skeletal fragments are commonly bored and encrusted by epibionts, particularly stromatoporoids. This upward-shoaling sequence shows progressive decrease in the ratio of corals to stromatoporoids, and increase in proportions of tabular stromatoporoids and algae upward. Large (40 cm diameter, 15 cm high) stromatoporoids commonly appear to be autochthonous. TABLE 4-6 provides a complete list of fossils in subfacies 2.

4.3.3.2 Interpretation

Middle platform subfacies 2 is predominantly allochthonous sediment derived from adjacent platform highs. In section 01, on the platform foreslope (FIG. 4-1), it consists of abraded stromatoporoid floatstone (unit 022),

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MIDDLE PLATFORM

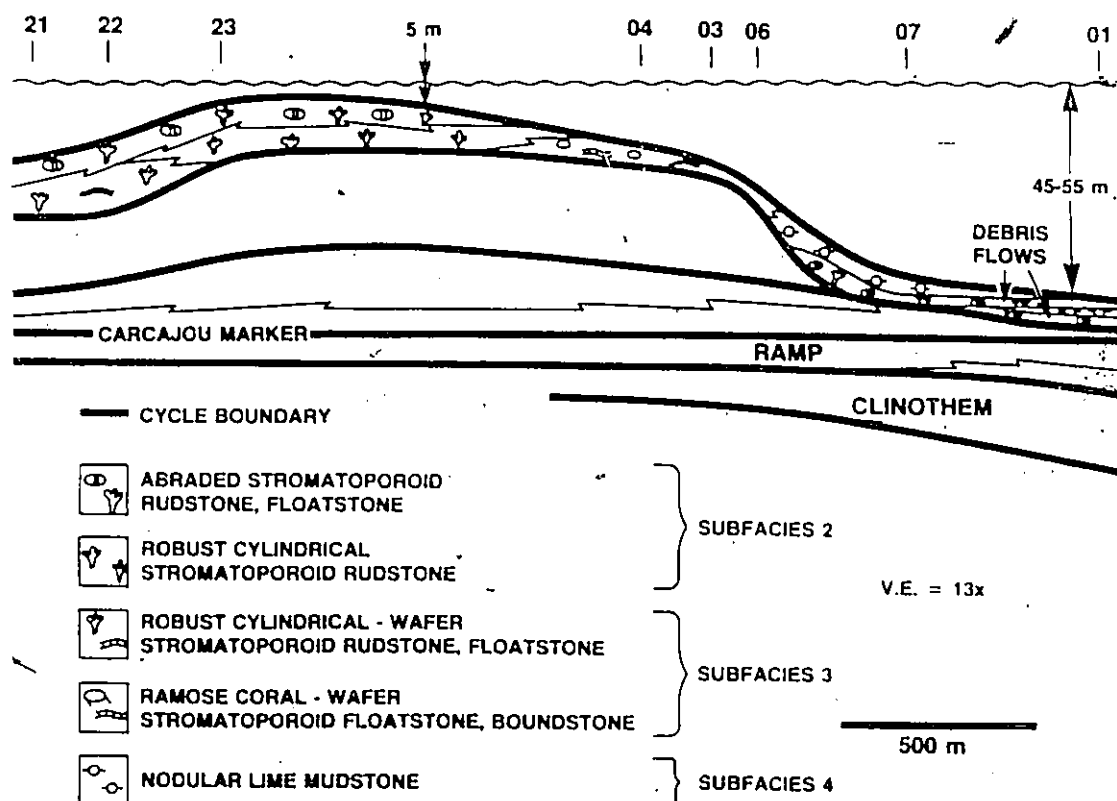


FIG. 4-10 Paleoenvironmental reconstruction of the middle platform facies in the eastern portion of the study area (sections 21 to 01).

TABLE 4-6

MACROFOSSILS OF MIDDLE PLATFORM SUBFACIES 2

Common Constituents

robust cylindrical stromatoporoid	-	Common only in upper portion of subfacies. Tabular stromatoporoids commonly abraded, overturned, and bored. Upper surface commonly digitate.
binding algae	-	
thick, tabular stromatoporoid	-	

Rare Constituents

encrusting stromatoporoid:	stromatoporoid	
low extended hemispherical stromatoporoid		
bulbous stromatoporoid:	actinostromatid	
thamnoporoid coral		more common in basal portion
<u>Coenites</u>		of subfacies
crinoid columnals		
solitary rugose corals		
atrypid brachiopod		
<u>Stringocephalus</u>		
gastropod		
ostracod		

probably emplaced as a slightly lobate debris flow deposit (FIG. 4-10, PL. 4-20). Its base is nearly planar and shows groove and prod markings. The upper contact is a hardground with predominantly convex-upward surface overlain by slightly nodular lime mudstone of the upper platform cycle. Contained allochems are extensively fragmented and arranged chaotically in a lime mudstone matrix. However, much of middle platform subfacies 2 is fragmented skeletal rudstone and grainstone derived by wave action from nearby margins and platform interior highs.

Kershaw (1984) suggested that common, broken margins on stromatoporoids, and evidence for disorientation in all size ranges, points to storm transport. The common occurrence of thick, tabular stromatoporoids and robust cylindrical stromatoporoids indicates that these sediments were probably derived from shallow (<5 m) waters. Storms would probably have affected such shallow depths frequently, and resulted in the episodic accumulation of allochthonous sediment. Perkins and Enos (1968) noted an analogous Recent example in the Florida-Bahamas area where Hurricane Betsy (1965) caused extensive fragmentation and redistribution of Acropora cervicornis. Portions of the platform interior may have been sufficiently protected by the damping of storm wave energy across shallow surrounding areas of the platform, to permit the accumulation of middle platform subfacies 1 (FIG. 3-2).

4.3.4 Middle Platform Subfacies 3

4.3.4.1 Description

Middle platform subfacies 3 consists of wafer stromatoporoid-robust cylindrical stromatoporoid-ramose coral floatstone, rudstone, boundstone, and minor interbedded shale. The subfacies is typically thinly-bedded (5-10 cm) and commonly contains fine disseminated pyrite and pyritized allochems. Middle platform subfacies 3 (average 5 m thick) at the base of the middle platform cycle in sections 28 to 23, and grades up into lighter colored limestones of subfacies 2. Along the platform foreslope in sections 04 to 06 (FIG. 4-1), subfacies 3 is abruptly overlain by dark grey calcareous shale and argillaceous limestone of the upper platform cycle. The subfacies was not observed in the western portion of the study area.

Floatstone predominates, with allochems supported by a dark brown, microstylolitized skeletal wackestone matrix. Wafer stromatoporoids are generally oriented parallel to bedding. In section 28 (FIG. 4-1), subfacies 3 shows the following changes up-section:

- (1) Beds become lighter colored as mud matrix decreases and allochem content increases.
- (2) The ratio of stromatoporoids to corals increases, along with an increased proportion of disoriented or imbricated and overturned stromatoporoids..

- (3) Skeletal fragments in the matrix appear to be more micritized towards the top, possibly due to increased algal infestation associated with shallowing.
- (4) Wafer growth forms are succeeded by "ragged" tabular and hemispherical forms. The latter possibly reflect phenotypic responses to increased turbidity.

A comprehensive list of macrofossils in subfacies 3 is provided in TABLE 4-7.

4.3.4.2 Interpretation

Paleobathymetric estimates (FIG. 4-10) place middle platform subfacies 3 in the 11-27 m depth range. The typical, dark, carbonaceous micritic bindstone and floatstone with in situ and reworked wafer stromatoporoids resemble lower foreslope limestone facies in the Middle Devonian Judy Creek reef complex (Swan Hills Formation). Their interpreted bathymetric constraints are also similar (Wendte and Stoakes, 1982). The previously noted upward changes in subfacies 3 in section 28 suggest shoaling into more agitated waters.

The wafer stromatoporoid growth form is possibly analogous to sheet-like colonies of Diploria, Agaricia, and Montastrea, which are adapted to reduced light conditions in Recent deep forereefs. The wafer growth form could also

TABLE 4-7

MACROFOSSILS OF MIDDLE PLATFORM SUBFACIES 3

Common Constituents

wafer stromatoporoid: max. dimensions: 40 cm diameter,
1 cm height; rarely mammellate
upper surfaces; common mud-filled
borings

Coenites

robust cylindrical stromatoporoid

Rare ConstituentsThamnopora

solitary rugose coral
encrusting stromatoporoid: actinostromatid
crinoid columnals
fish fragments
sponge spicules
ostracod
atrypid brachiopod
gastropod

have enabled the stromatoporoid organism both to maximize surface feeding area and to rest on soft, muddy substrates without foundering. Wafer growth forms are inherently advantageous in environments of low wave energy and slow sedimentation (James, 1979). The following taphonomic evidence confirms low sedimentation rates:

- (1) Wafer stromatoporoids are abundant, possibly evidence of slow sedimentation rates and low turbidity. Such laminar growth forms might be expected to be less common in areas of rapid sedimentation because they would be more readily smothered. Also, if stromatoporoids are sponge-related, suspended fines may have been as harmful to the stromatoporoid organism as they are to modern sponges (Kobluk, 1975).
- (2) Allochems are commonly bored and show common epibiont encrustation, both indications of lengthy exposure on the sea floor.
- (3) Much of the skeletal debris is fragmented and the matrix is considerably bioturbated, evidence of prolonged mechanical and biological reworking.
- (4) Allochems are commonly pyritized, which generally requires slow sedimentation with sulphate ions provided by sea water.

The disorientation of some wafer stromatoporoids could have been due to one or more of the following factors:

- (1) Episodic increase in current energy; for example, during storms, particularly at shallower depths (e.g. in section 23, FIG. 4-10).
- (2) Disruption of the substrate by burrowers.
- (3) Foundering into soft sediment due to increased weight during growth (Kobluk et al., 1977).
- (4) Predation (Pandolfi, 1984).

4.3.5 Middle Platform Subfacies 4

4.3.5.1 Description

Middle platform subfacies 4 is restricted to the eastern portion of the study area (sections 07, 01, 25; FIG. 4-1). Thin-medium beds, 5-20 cm thick, of dark brown, planar to nodular lime mudstone, wackestone, and packstone, interbedded with dark brown calcareous shale, are typical. Allochthonous faunal elements tend to be fragmented, intensely micritized, and concentrated in laminae and very thin beds. The lime mudstone beds grade weakly upward from thin (2-5 mm), regular calcisiltite laminae into wispy (1-3 mm) calcilutite laminae. Fine disseminated pyrite and pyritized allochems are ubiquitous. The interbedded calcareous shale is faunally impoverished compared to the limestone beds, and contains mainly styliolinids. The shale

commonly displays fissile, even papery, lamination and contains pyrite nodules.

Fossils in middle platform subfacies 4 are listed in TABLE 4-8.

4.3.5.2 Interpretation

Subfacies 4 is restricted to a lower foreslope depositional setting (FIG. 4-1) and incorporates strata representing hemipelagic mud deposition and episodic emplacement of fine-grained calciturbidites. The turbidites probably originated along a line-source on the slope and were deposited from low concentration turbidity currents, as indicated by the following:

- (1) Fossils are mixed and fragmented, but characteristic of a foreslope setting, such as in subfacies 3. They include wafer stromatoporoids, robust cylindrical stromatoporoids, and ramose corals.
- (2) Turbidites extend laterally more than 400 m at section 01, and are sharp-based. However, sole markings are generally absent.
- (3) Imbricated bioclasts occur rarely at tops of beds. Bioturbation is most common along upper contacts of turbidites.

TABLE 4-8

MACROFOSSILS OF MIDDLE PLATFORM SUBFACIES 4

Rare Constituents

styliolinids	}	limestone macrofossils
crinoid columnals		
<u>Leiorhynchus hippocastanea</u>		
<u>Coenites</u>		
cylindrical stromatoporoid		
wafer stromatoporoid		
thin-shelled ostracod		
fish fragments	}	shale macrofossils
sponge spicules		
styliolinids	}	shale macrofossils
fish fragments		

- (4) Calcisiltites show slight fining-upward and are similar to base-omitted distal turbidite sequences (T_{3-6}) described by Stow (1985).
- (5) Channel-fill sequences are absent from the foreslope setting both in the study area and in the time-equivalent subsurface buildup at Norman Wells (Muir et al., 1985).

The calciturbidites likely formed coalescing apron deposits derived from the evolving middle platform sequence. Embayments such as the Tongue of the Ocean, in the Bahamas platform, display coalescing carbonate sand and gravel deposits derived by sediment gravity flow (Schlager and Chermak, 1979). These sequences form an apron 15-25 km wide along the basin margin, with muddier sediments predominating toward the embayment.

Gravity flows during middle platform time could have been generated as a result of oversteepening and instability of sediments accumulating on the shallow dipping ($1-3^\circ$) foreslope, storm activity and current undercutting, and possibly liquefaction of carbonate muds by compaction and dewatering.

4.3.6 Synthesis of Middle Platform Evolution

The middle platform cycle differs from the underlying second-order cycles in several ways (TABLES 4-9, 4-10). It is thinner, less extensive, and shows evidence for

TABLE 4-9

LOWER PLATFORM CYCLE - OVERALL CHARACTERS

1. Distribution and Geometry

- maximum thickness = 45 m
- extent >31 km (east-west direction)
- maximum relief of lower cycle boundary (platform interior) = 25 m
- maximum relief of upper cycle boundary (platform interior) = 45 m
- thickness ratio of margin/foreslope thickness ratio (sections 23, 01) = 9:1
- average inclination of foreslope (sections 03-01) = 42 m/km
- style of deposition: aggradation > progradation

2. Internal Characteristics (excluding foreslope facies)

- lime mud-supported lithofacies > grain-supported lithofacies
- coral fauna > stromatoporoid fauna
- minor third-order cycles arranged in an overall shallowing-upward sequence

TABLE 4-10

MIDDLE PLATFORM CYCLE - OVERALL CHARACTERS

1. Distribution and Geometry

- maximum thickness = 16 m
- extent = 20 km (east-west direction)
- maximum relief of upper cycle boundary (platform interior) = 35 m
- thickness ratio of margin/foreslope facies (sections 23, 01) = 2:1
- average inclination of foreslope (sections 03-01) = 35 m/km
- style of deposition: progradation > aggradation

2. Internal Characteristics (excluding foreslope facies)

- grain-supported lithofacies > lime mud-supported lithofacies
- stromatoporoid fauna > coral fauna; mainly allochthonous faunal assemblages
- minor third-order cycles rarely observed

progressively reduced platform relief, as it thickens into depositional lows (see FIG. 3-2) and thins over paleotopographic highs. The abundance of grain-supported, abraded stromatoporoid rudstone suggests that this phenomenon was accomplished mainly by intensive current activity (e.g. related to storms) at relatively shallow depths. Near the eastern margin, the cycle displays less aggradational and more progradational style than the lower platform sequence (FIG. 4-10). Instead, the upper cycle boundary of the middle platform sequence is more ramp-like, with a gradient of 10 m/km (sections 23 to 03), before steepening into the basin at 35 m/km (sections 03 to 01). Marginal facies of the middle platform, mainly abraded tabular stromatoporoid rudstone, backstepped ~800 m towards the platform interior from the eastern limit of the lower platform margin (FIG. 4-1).

The middle platform cycle contains a much higher proportion of coarse foreslope debris to margin facies than the lower platform cycle (TABLES 4-9, 4-10). The ramp-like middle platform margin in the eastern portion of the study area, and the associated reworked sediments of subfacies 2, show evidence of frequent storm modification. Woodley (1981) documented Hurricane Allen's (1980) effect on Jamaican coral reefs. Wind-generated waves over 12 m high carried dislodged material across the shallow reef in Discovery Bay. Dense, 1-3 m high stands of Acropora

palmata, which dominated the reef crest, were leveled. The breaker zone and reef flat were transformed from constructional reefs into a gently sloping rubble rampart.

In situ bulbous-encrusting²-cylindrical stromatoporoid floatstone, rudstone, and boundstone of subfacies 1 are located in the platform interior and towards the leeward western margin (FIG. 3-2), presumably due to the damping of wave energy on the windward eastern margin.

The bypass nature of the middle platform margin, "smoothing" of depositional topography, and abundance of grain-supported stromatoporoid rudstone suggest that the middle platform cycle represents more prolonged relative sea level still-stand than during deposition of the underlying cycle. This would have provided more time for storm reworking and subsequent decrease in depositional relief between platform margin and interior.

4.4 FACIES ANALYSIS OF THE UPPER PLATFORM CYCLE

4.4.1 General Statement

A pronounced sea-level rise terminated the middle platform cycle and led to backstepping of the upper platform margin. Thus, the upper platform cycle is the most areally restricted second-order cycle in the platform facies association (FIGS. 3-2, 4-1).

The upper platform cycle consists of buildup facies (subfacies 1 and 2), platform interior facies (subfacies 2 and 3), and platform foreslope facies (subfacies 3 and 4). A discrete, 15 m thick, upper platform buildup occurs ~400 m west of the underlying middle platform margin in the eastern portion of the study area (FIG. 4-11). An 18 m thick buildup was mapped along the margin of a platform embayment in the vicinity of section 08 (FIG. 3-2). Another buildup of unknown thickness marks the western margin of the platform at section 18 (FIG. 3-2). Platform interior facies are thin (average 4-6 m thick), dark-colored units containing a mixed coral-stromatoporoid fauna. Platform evolution during upper platform time apparently reverted to a more aggradational style, similar to that of the lower platform cycle, with the accentuation of depositional relief compared to the underlying middle platform. The subfacies of this upper platform depositional sequence are described and interpreted below.

4.4.2 Upper Platform Subfacies 1

4.4.2.1 Description

Upper platform subfacies 1 comprises massive to thickly bedded, tabular stromatoporoid-algal boundstone and subsidiary, abraded tabular stromatoporoid rudstone. The

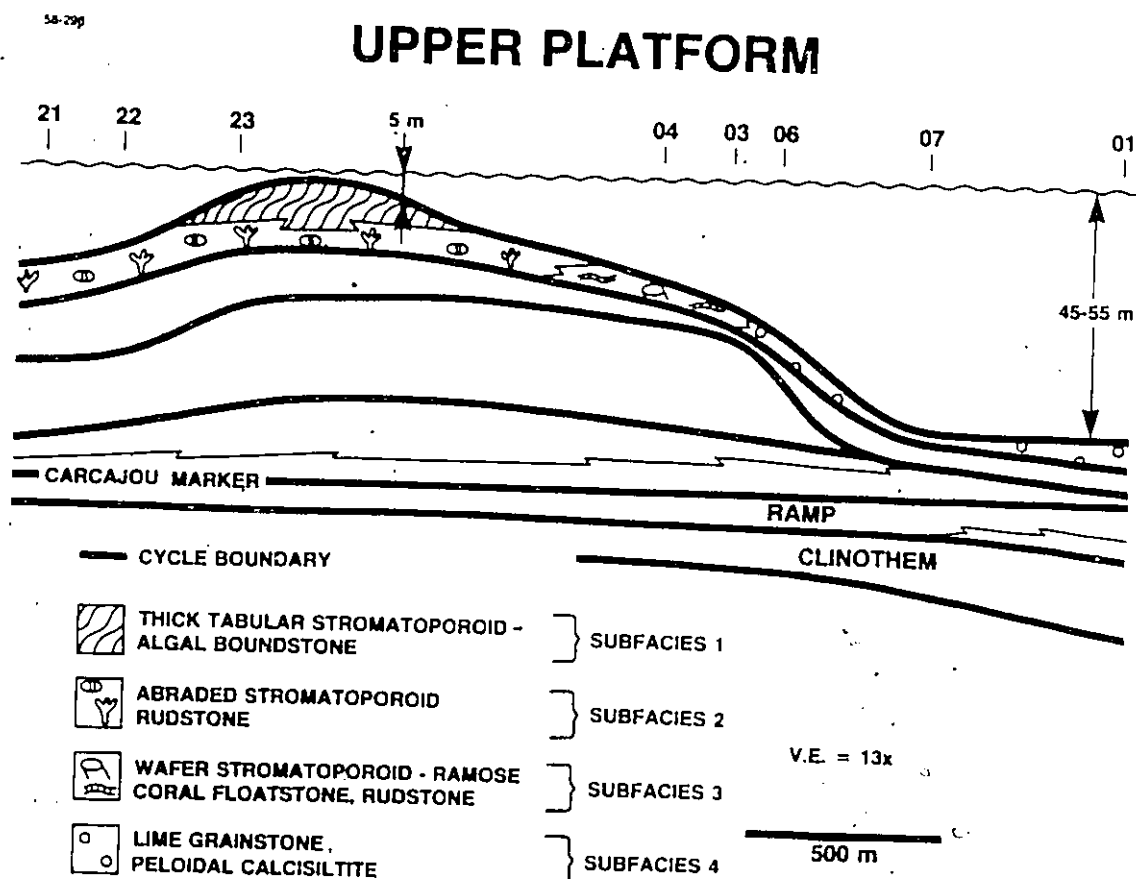


FIG. 4-11 Paleoenvironmental reconstruction of the upper platform facies in the eastern portion of the study area (sections 21 to 01).

facies is restricted to buildups along platform margins and in the vicinity of a platform interior embayment at section 08 (see FIG. 3-2). At section 23, the subfacies is 8 m thick, and gradationally interbedded at the base with abraded stromatoporoid rudstone of upper platform subfacies 2. The upper contact of subfacies 1 is a hardground which marks the top of the platform facies association beneath the overlying reef. The hardground is a mineralized, undulating surface which truncates allochems and shows small borings rarely. The latter are less than 1 mm in diameter, and possibly represent echinoid pitting. Sharply overlying the hardground is a 5 cm thick crinoid-robust cylindrical stromatoporoid-ramose coral grainstone (PL. 4-21a). This unit represents transgressive lag sediments of the first reef cycle, which probably served to abrade the tops of the drowned platform buildups during prolonged current reworking.

Bedding thickens upwards in upper platform subfacies 1 and in situ, thick tabular stromatoporoids (PL. 4-21b) and low-extended hemispherical stromatoporoids become increasingly abundant (fossil listing in TABLE 4-11). Robust cylindrical stromatoporoids are commonly algae-encrusted and constitute the grain-supported matrix. Some tabular stromatoporoids changed with growth into fasciculate forms, and ragged flanks with interlayered sediment are common.

TABLE 4-11

MACROFOSSILS OF UPPER PLATFORM SUBFACIES 1

Common Constituents

hemispherical stromatoporoid: average diameter 40 cm,
average height 20 cm

thick, tabular stromatoporoid: some show ragged flanks;
actinostromatid; average
diameter 35 cm

binding algae: encrusting cylindrical stromatoporoids

robust cylindrical stromatoporoids: 5-10 mm diameter

Rare Constituents

gastropod

crinoid columnals

Coenites

ostracod

4.4.2.2 Interpretation

Upper platform subfacies 1 is restricted to buildups at sites inferred to have had good water circulation and nutrient upwelling, such as in the vicinity of antecedent middle platform margins and along embayments. The presence of robust cylindrical stromatoporoids and thick, low-profile stromatoporoid growth forms is suggestive of well-agitated waters at depths estimated to have been 0-5 m. However, the common occurrence of forms transitional from tabular to fasciculate indicates that forms better suited for sediment-shedding developed periodically due to fluctuations in sedimentation rate. Beds flanking the buildups show slopes of 2-5° at sections 08 and 23, and consist of upper platform subfacies 2 (FIG. 4-11).

4.4.3 Upper Platform Subfacies 2

4.4.3.1 Description

Abraded stromatoporoid rudstone and minor thick, tabular stromatoporoid-algal boundstone comprise upper platform subfacies 2 and form proximal "haloes" enclosing discrete upper platform buildups. However, these lithofacies pass distally from the buildups into robust cylindrical stromatoporoid rudstone and floatstone, and finally to more argillaceous ramose coral-robust cylindrical stromatoporoid

floatstone in the upper platform interior (FIG. 4-1). Subfacies 2 thins from 9 m to 4 m over a distance of 4 km, approaching the embayment buildup at section 08 (FIG. 3-2). The subfacies overlies the middle-upper platform cycle boundary and is laterally transitional into dark, wafer stromatoporoid-ramose coral floatstone of subfacies 3 within the platform interior. The basal unit of subfacies 2 in the eastern portion of the study area (sections 28, 22-23) is 15 cm of cross-stratified, crinoid-peloidal grainstone which is sharply overlain by robust cylindrical stromatoporoid rudstone. The peloids average 0.1-0.3 mm in diameter and are subangular, suggestive of micritized skeletal debris. Towards the top of the subfacies, fragmented allochems are larger and crinoid-brachiopod content decreases sharply. Bedding thickens and coarsens-upwards, and there is a corresponding increase in autochthonous fossils, particularly thick tabular and hemispherical stromatoporoids. The fossil content of subfacies 2 is listed in TABLE 4-12. In section 18, subfacies 2 is 6.7 m thick and shows the following upward changes:

- (1) Supporting matrix coarsens from dark brown, pyritiferous, microstylolitized lime mudstone to peloidal-fragmented skeletal packstone.
- (2) Beds thicken and become lighter-colored upwards.
- (3) Faunal diversity decreases as robust cylindrical stromatoporoids become increasingly dominant.

TABLE 4-12

MACROFOSSILS OF UPPER PLATFORM SUBFACIES 2

Common Constituents

Coenites: common only in basal portion

robust cylindrical stromatoporoid

thick, tabular stromatoporoid: abraded and autochthonous
forms; upper surface
rarely fasciculate

Rare Constituents

crinoid columnals

indeterminate brachiopod | less common towards top of
subfacies

binding algae

ostracod

gastropod

wafer stromatoporoid

solitary rugose coral

hemispherical stromatoporoid: max. dimensions: height 20
cm, diameter 100 cm;
mainly autochthonous

encrusting stromatoporoids: stromatoporid,
stromatoporellid

4.4.3.2 Interpretation

Upper platform subfacies 2 is mainly an allochthonous assemblage derived from nearby isolated buildups. Fragmentation and abrasion of allochems are interpreted as resulting from periodic storm activity in relatively shallow water. The intensity of winnowing was progressively less with increased depth distally in the platform interior. The crinoid-peloid grainstone at the base of subfacies 2 in sections 28 and 21-23 represents a transgressive lag overlying the drowned middle platform surface, although no underlying hardground was observed. Skeletal fragments were intensely micritized, possibly because of prolonged exposure at the sediment-water interface (Dravis, 1977).

Cylindrical stromatoporoids and ramose corals on the buildup flanks were well adapted to shed sediment, but were easily fragmented and redistributed downslope by storm activity. This hydrodynamic sorting is reflected in the crude concentric pattern of sediments surrounding discrete upper platform buildups. Upward changes in texture, color, bedding thickness, and faunal diversity of subfacies 2, noted in the previous section, are evidence of upward-shallowing.

4.4.4 Upper Platform Subfacies 3

4.4.4.1 Description

Upper platform subfacies 3 is characterized by medium brown, thin-bedded wafer and robust cylindrical stromatoporoid-ramose coral floatstone, rudstone, and bindstone, with minor interbedded shale. The subfacies is 5 m thick at section 04, and 3 m thick at section 20. Both shale content and the ratio of corals to stromatoporoids increase toward the top of the subfacies. Limestone beds generally thin and become more argillaceous upward with mud-supported fabrics predominating towards the top. Faunal diversity and abundance decrease upsection and allochems are commonly pyritized and silicified. Fossils in subfacies 3 are listed in TABLE 4-13.

4.4.4.2 Interpretation

Upper platform subfacies 3 was deposited in a calm, open marine depositional setting. A paleodepth range of 15-28 m was estimated for the subfacies (FIG. 4-11). The predominance of wafer growth forms attests to slow sedimentation. Because current energy was low, and muddy substrates were typical for subfacies 3, larger surface areas may have been required for respiration, feeding, and stability (Kershaw, 1984). Corals are common only in the more argillaceous lithofacies, reflecting their greater

TABLE 4-13

MACROFOSSILS OF UPPER PLATFORM SUBFACIES 3

Common Constituents

wafer stromatoporoid: max. dimensions: 35 cm diameter
0.8 cm height; rarely disoriented;
stromatoporid

encrusting alveolitid coral
thamnoporoid coral

Coenites

robust cylindrical stromatoporoid

Rare Constituents

crinoid columnals
styliolinid
ostracod
atrypid brachiopod
lingulid brachiopod
encrusting bryozoan
trilobite
encrusting stromatoporoid

tolerance than stromatoporoids to turbid conditions. The increasing shale content, thinning-upward of argillaceous limestone beds, and increasing ratio of corals to stromatoporoids towards the top of subfacies 3, points to a deepening-upward style of sedimentation. This probably indicates minor backstepping third-order cycles of shallow upper platform facies towards the platform interior in response to accelerated pulses of sea-level rise. The relationship of upper platform subfacies 3 to the other subfacies will be examined in section 4.4.6.

4.4.5 Upper Platform Subfacies 4

4.4.5.1 Description

Upper platform subfacies 4 consists mainly of interbedded calcareous shale and slightly nodular peloidal calcisiltite (PL. 4-22), with minor grainstone and packstone. The subfacies was observed only in a foreslope setting at sections 07, 01, and 25. It becomes finer and contains more shale interbeds downslope (towards section 25). At each locality, the limestone beds become thicker and coarser upwards. The calcisiltite beds average 5-10 cm in thickness, fine slightly upward, and commonly have planar, sharp lower, and gradational upper contacts with shale. Discrete burrows (Chondrites) occur rarely in the topmost

parts of calcisiltite beds. The calcisiltite beds grade upward into shale containing styliolinids that rarely display current-orientation. Other fossils typically occur rarely (TABLE 4-14) and comprise a low diversity fragmented assemblage. Allochems tend to be intensely micritized and concentrated along laminae. Fine disseminated pyrite is ubiquitous in both shale and limestone.

4.4.5.2 Interpretation

The depositional setting for subfacies 4 was a lower foreslope environment (FIG. 4-11) similar to that of middle platform subfacies 4. Periodic input of fine-grained calciturbidite in areas where deposition of hemipelagic calcareous mud prevailed, resulted in the interbedding of shale and limestone in the subfacies. The thickening and coarsening upward of these turbidites may reflect increased frequency and intensity of sediment gravity flows as the upper platform cycle shoaled upwards. Sedimentological attributes of these calciturbidites are similar to those observed in middle platform subfacies 4 (section 4.3.5) and will not be reiterated here.

4.4.6 Synthesis of Upper Platform Evolution

The upper platform cycle was initiated by another sea-level rise. Successive minor cycles in the platform interior terminated with progressively deeper water

TABLE 4-14

MACROFOSSILS OF UPPER PLATFORM SUBFACIES 4

Rare Constituents

styliolinid

crinoid columnals

cylindrical stromatoporoid: fragmented

brachiopods: fragmented, silicified; include lingulids,
atrypids and Stringocephalus

sponge spicules

fish fragments

lithofacies, reflecting—deepening-upward overall. The embayment relief at section 08 increased to 35-43 m after middle platform time (TABLES 4-10, 4-15) and dark, argillaceous, lime mud-supported lithofacies predominated over grain-supported lithofacies. Buildup subfacies 1 and fringing subfacies 2 developed locally in areas of presumed good circulation and nutrient upwelling near platform margins and embayment margins. Consequently, a "finger-like" distribution of these subfacies is envisaged for the study area (FIG. 4-12). Circulation in the remainder of the platform interior was not sufficient to stimulate profuse benthic organism growth and, in these areas, more micritic limestones were deposited. Because these sparsely fossiliferous lithofacies had less growth potential and built upward more slowly, the buildups and flank beds became discrete accretionary highs by the end of upper platform time.

Both the middle and upper platform cycles contributed much more coarse foreslope debris relative to platform margin thickness than the lower platform cycle (TABLES 4-9, 4-10, 4-15). In the eastern part of the study area, the upper platform margin backstepped only slightly from the position of the middle platform margin. Interpreted increase of relief probably enhanced basinward bypass of debris and the wedge of debris thickens towards section 01. Interestingly, the buildup along the embayment margin at

TABLE 4-15

UPPER PLATFORM CYCLE - OVERALL CHARACTERS

1. Distribution and Geometry

- maximum thickness = 18 m
- extent = 18 km (east-west direction)
- maximum relief of upper cycle boundary (platform interior) = 43 m
- thickness ratio of margin/foreslope facies (sections 23, 01) = 2:1
- average inclination of foreslope (sections 03-01) = 35 m/km
- style of deposition: aggradation > progradation

2. Internal Characteristics (excluding foreslope facies)

- grain-supported lithofacies < lime mud-supported lithofacies
- mixed coral-stromatoporoid faunal assemblage
- successive third-order cycles in platform interior terminate with progressively deeper water lithofacies

58-294

UPPER PLATFORM

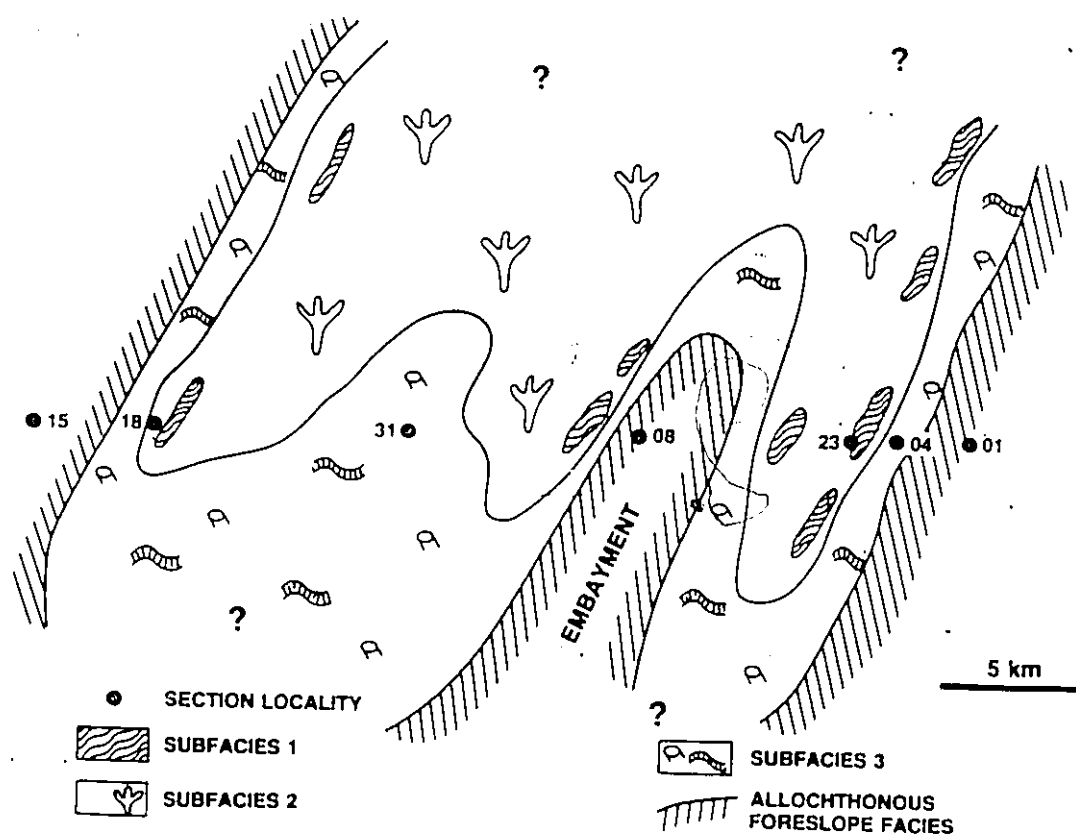


FIG. 4-12 Paleogeographic reconstruction of the upper platform facies within the study area.

section 08 provided very little allochthonous debris for the embayment (FIG. 3-2). This may reflect lower energy conditions although circulation was sufficient to stimulate reef growth.

It is doubtful that much material was being transported far into the basin. In section 25 (PL. 4-2) facies correlative with the upper platform are quite thin compared to underlying facies correlative with the lower and middle platform. Shallow water buildup facies (subfacies 1) were possibly more isolated along the upper platform margins in response to rapid rise in sea level. Consequently, less of these facies were exposed to current and wave reworking, and less debris was distributed downslope, than during deposition of the underlying middle platform cycle.

The upper platform cycle shows properties that suggest it was an incipient drowned platform (cf. Kendall and Schlager, 1981; Hine and Steinmetz, 1983; James and Mountjoy, 1983; Read, 1985). James and Mountjoy (1983) related this style of platform development to rapid sea-level rise. They noted that considerable relief may develop between platform margin buildups and the platform interior, although the rim does not appear to be continuous or to restrict fauna in the shelf lagoon. A modern example of a partially drowned carbonate platform is the Cal Sal Bank in the Bahamas. This isolated platform characteristically has very limited reef development on antecedent, nearly barren, Pleistocene

terraces (Hine and Steinmetz, 1983). The margins are at depths of 20-30 m, and the platform possesses a 10-20 m deep shelf lagoon. These authors also noted that there is only limited off-bank transport of carbonate sands. On portions of the Yucatan Shelf, only rim and patch reefs in sites of good water circulation kept pace with Holocene sea-level rise, while the rest of the platform shows evidence for incipient drowning (Kendall and Schlager, 1981).

4.5 PLATFORM EVOLUTION: CONTROLS ON SEDIMENTATION

General characteristics of the cyclic platform facies association are summarized in TABLE 4-16. A pronounced sea-level rise, represented by the Carcajou Marker, terminated ramp progradation in the study area. The lower platform cycle is characterized by depositional margins of high relief (FIG. 4-9) and overall aggradational sedimentation. Consequently, the top of the cycle shows marked depositional relief, particularly near platform margins above the antecedent ramp-clinothem transition, and over topographic highs on the ramp.

Another accelerated rise in sea level initiated the middle platform cycle, and platform margins developed on previous lower platform depositional highs (FIG. 4-10) in areas of good water circulation. The middle platform sequence typically contains grainy, abraded stromatoporoid

TABLE 4-16

PLATFORM CHARACTERISTICS

General

1. Cyclic backstepping mode of evolution.
2. Maximum depositional relief develops during upper platform stage.
3. Position of platform margin buildups mainly controlled by antecedent topographic highs near the shelf-slope break.

Lower Cycle

- Predominantly aggradational style of sedimentation.

Middle Cycle

- Predominantly progradational style of sedimentation.

Upper Cycle

- Predominantly aggradational style of sedimentation.

lithofacies, and thickens into adjacent depositional lows in the platform interior. Following the initial deepening, this sequence shows evidence that suggests deposition under relative stillstand conditions that were more prolonged than during deposition of the underlying and overlying platform cycles. This is reflected by the predominantly progradational nature of the middle platform and progressive subduing of depositional topography.

A pronounced sea-level rise terminated the middle platform sedimentation. Upper platform sedimentation was predominantly aggradational with localized upbuilding in areas of good water circulation, such as the shelf-slope break and antecedent middle platform topographic highs (FIG. 4-11). Sediment accumulation in the platform interior did not keep pace with relative sea-level rise, a characteristic of incipient drowning, and this led to development of maximum depositional relief for the entire platform facies association by the end of upper platform time.

PLATE 4-1

Platform facies distribution near section 03.

Dark, argillaceous limestone and interbedded shale of the Carcajou subfacies (5.6 m thick) abruptly overlie the ramp facies association in the vicinity of sections 03, 04 and 05. The base of a conspicuous shale bed near the middle of the subfacies marks the base of a sequence in which limestone interbeds thin slightly upward. Dotted and black lines mark indistinct and distinct bedding planes in the platform facies association and illustrate progressive steepening of depositional slope. A = lower platform cycle. B = middle and upper platform cycles. RFS = reef foreslope facies of reef cycle 1.

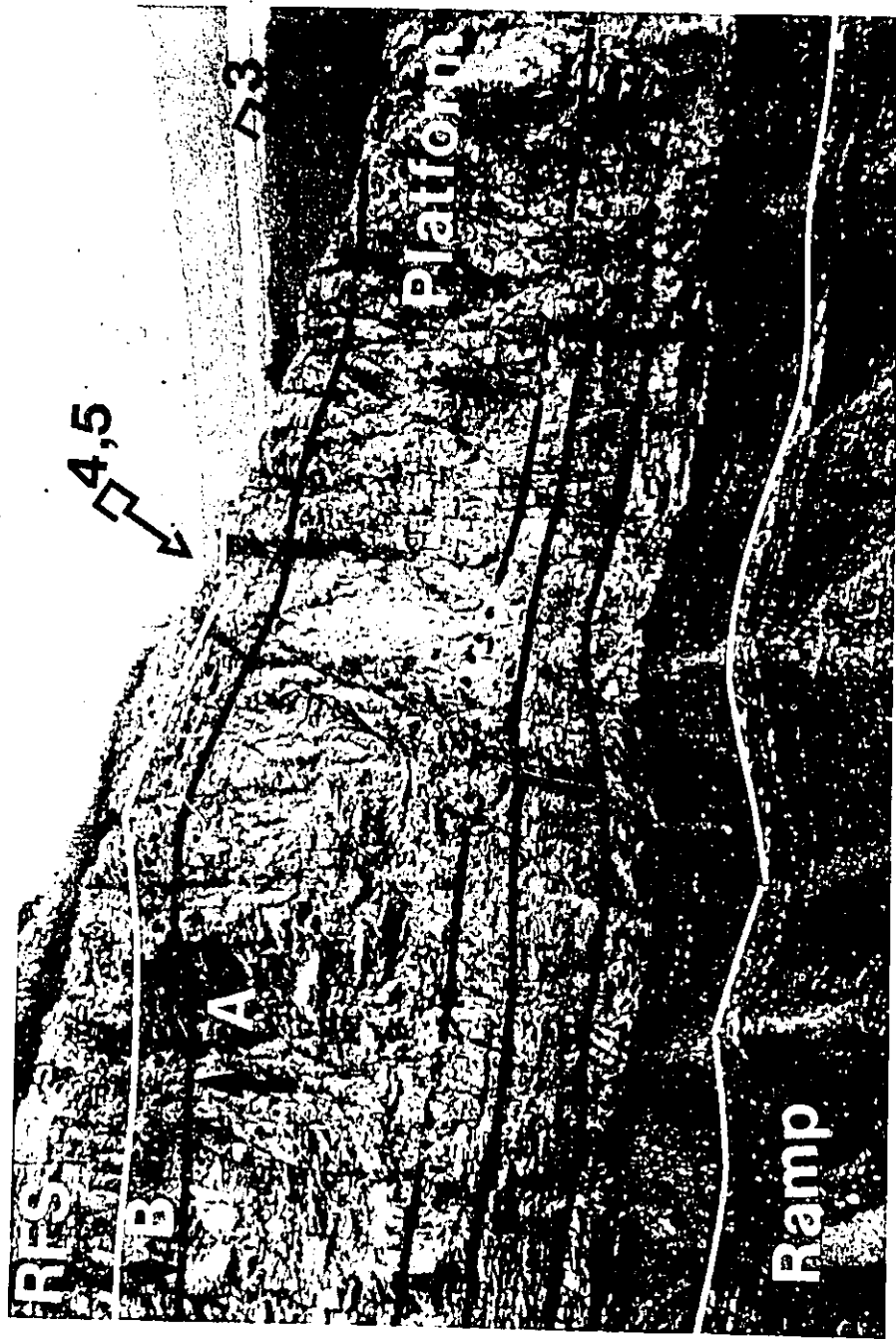


PLATE 4-1

PLATE 4-2

Basin-fill facies at section 25.

Dark grey, slightly calcareous shale and minor interbedded peloidal calcisiltite of the Carcajou subfacies (A1 = 7.6 m thick) abruptly overlie the Hare Indian clinothem facies association at section 25. Although Ramparts sediments are not mapped at this basinward locality, units A1-2 are considered to be time-equivalent to the lower platform cycle. Unit A3 may be time-equivalent to the middle and upper platform cycles. Large arrows indicate interpreted cycle breaks. Unit B is predominantly peloidal calcisiltite, possibly derived from reef cycle 1. Small arrows in the Hare Indian Formation indicate shallowing-upward sequences.

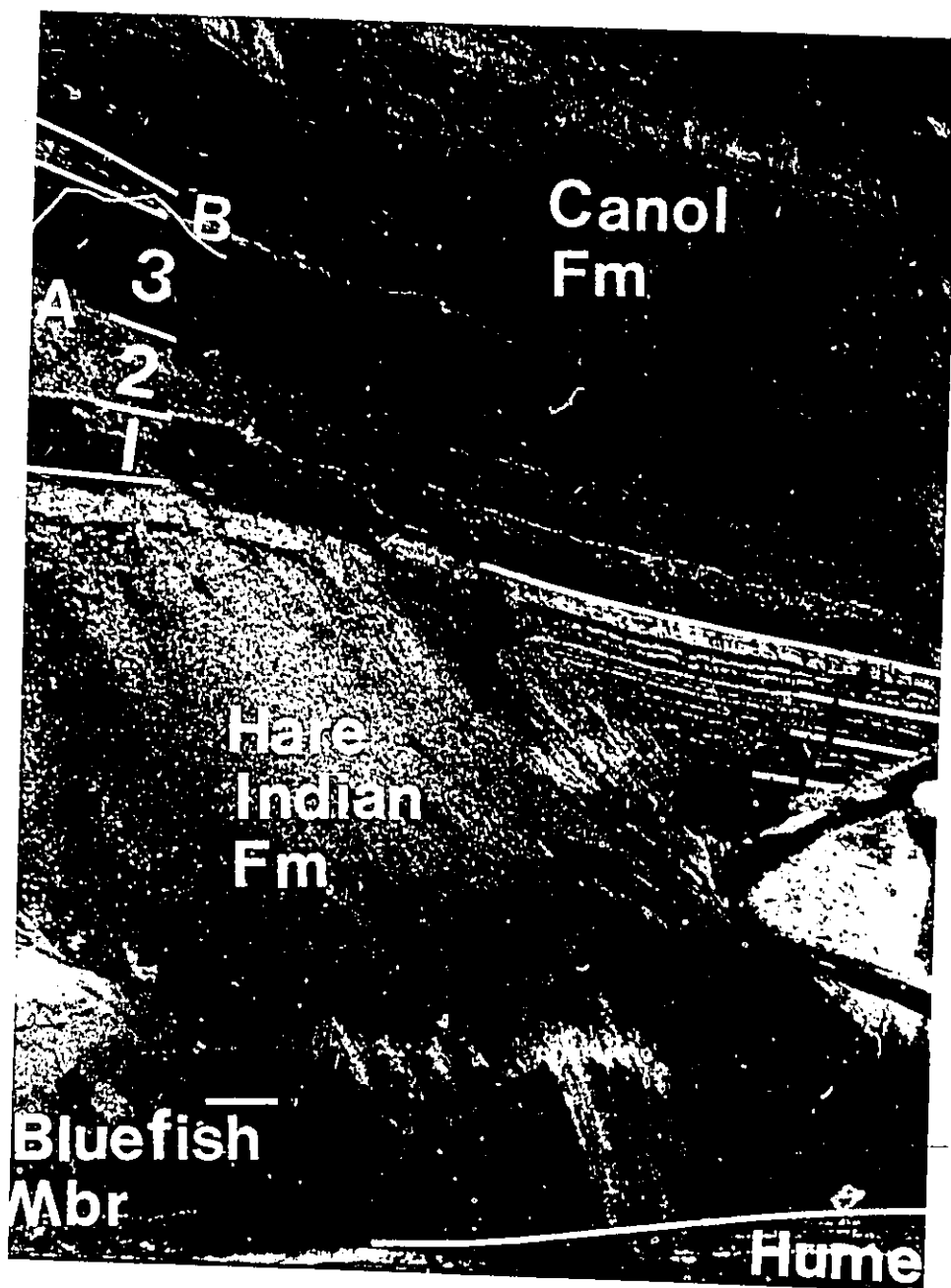


PLATE 4-2

PLATE 4-3

Carcajou subfacies contact relationships.

- a Pyritized hardground on top of the ramp facies association in section 20, unit 011. Note reentrants along the hardground surface. Overlying thamnoporoid coral floatstone is the basal portion of the Carcajou subfacies. Scale is in cm.
- b Carcajou subfacies rich with thamnoporoid corals near the Ramparts-type section (see FIG. 2-6). The basal portion is hematitic (after pyrite?) and faunally impoverished. The upper contact is gradational with more massive limestone of the lower platform. Scale is 75 cm long.

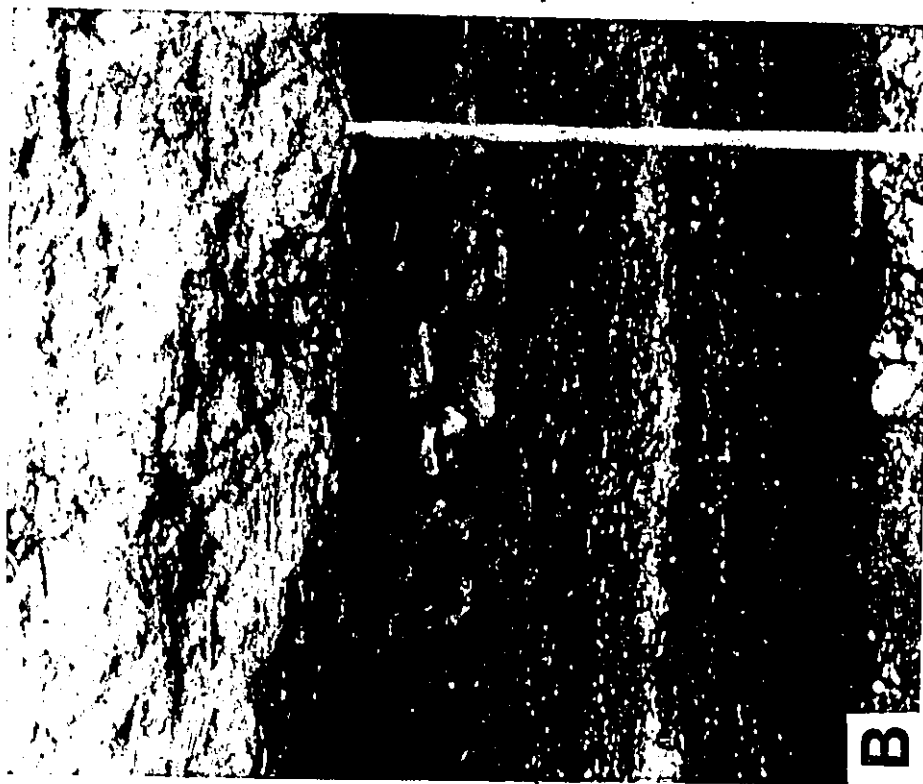
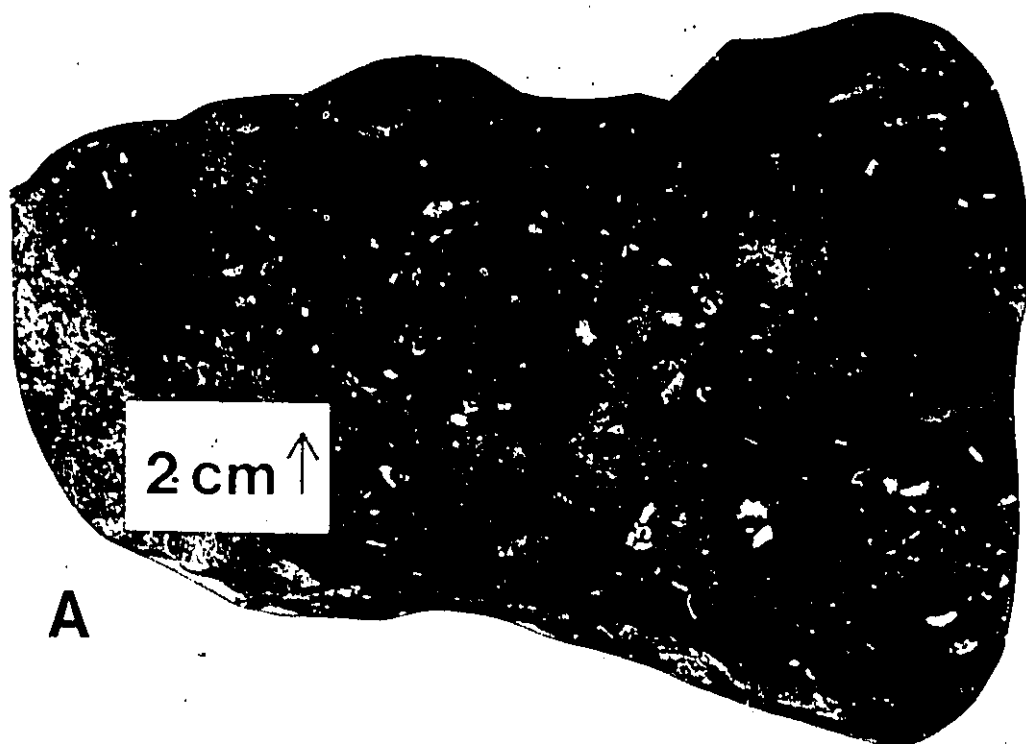


PLATE 4-3

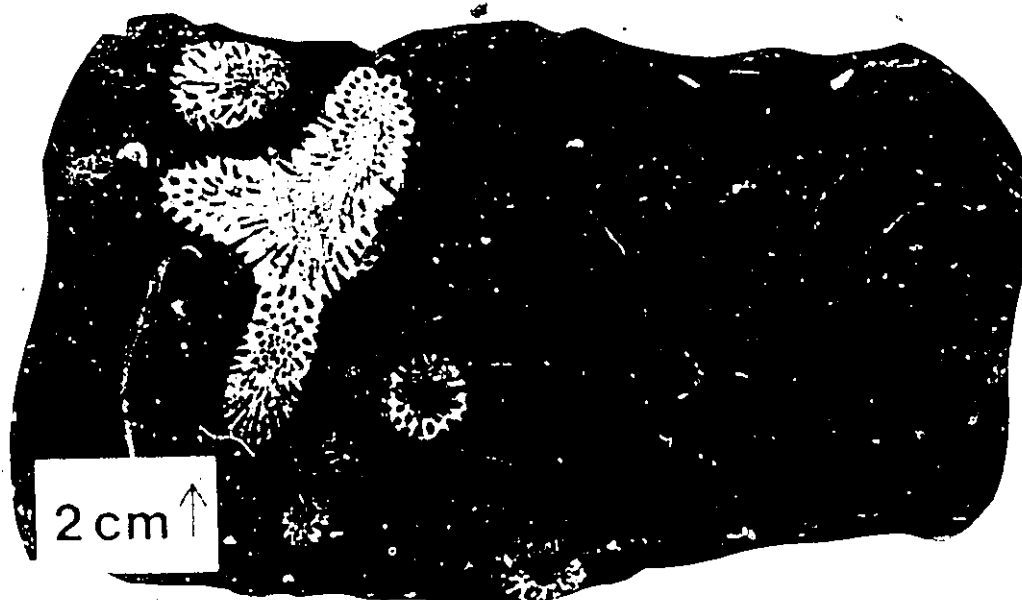
PLATE 4-4

Typical macrofauna within Carcajou subfacies.

- a Dark brown-black; argillaceous, thamnoporoid coral-crinoid-solitary rugose coral floatstone (section 03, unit 018). Note high pyrite content (arrows). Bar scale is 2 cm long.
- b Thamnoporoid coral-atrypid-bryozoan floatstone (section 18, unit 023). Many atrypid brachiopods are in current-unstable positions and disarticulated. Well-preserved skeletal fragments and the fine-grain size of the supporting matrix suggest calm water deposition. Bar scale is 2 cm long.



A



B

PLATE 4-4

PLATE 4-5 ~

Tempestites in Carcajou subfacies.

- a Distal tempestite at section 18, unit 023. Sharp basal contact with shale shows gutter cast. Horizontally-laminated calcisiltite passes upwards into ripple cross-stratified calcisiltite. Bar scale is 2 cm long.
- b Distal tempestite at section 20, unit 011. Note escape burrow (arrow), bioturbated gradational upper contact, and minor scour along basal contact. Bar scale is 2 cm long.

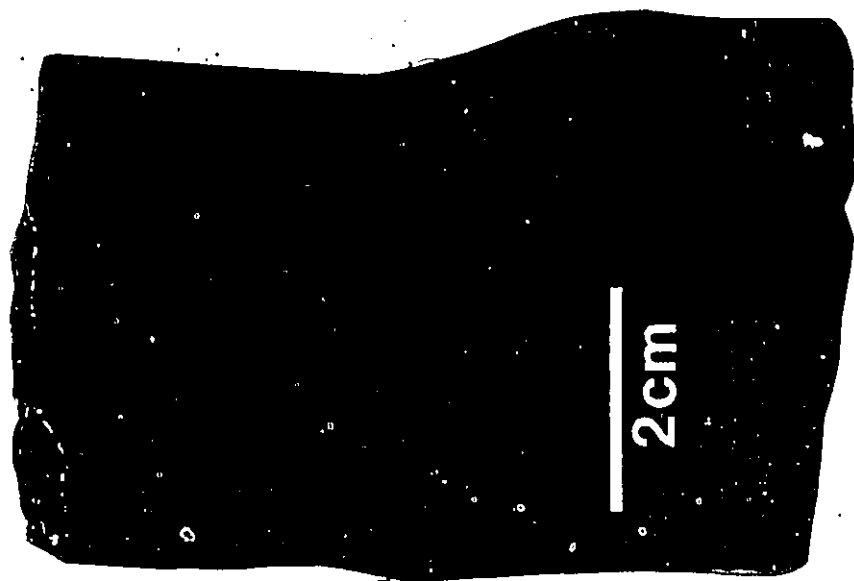
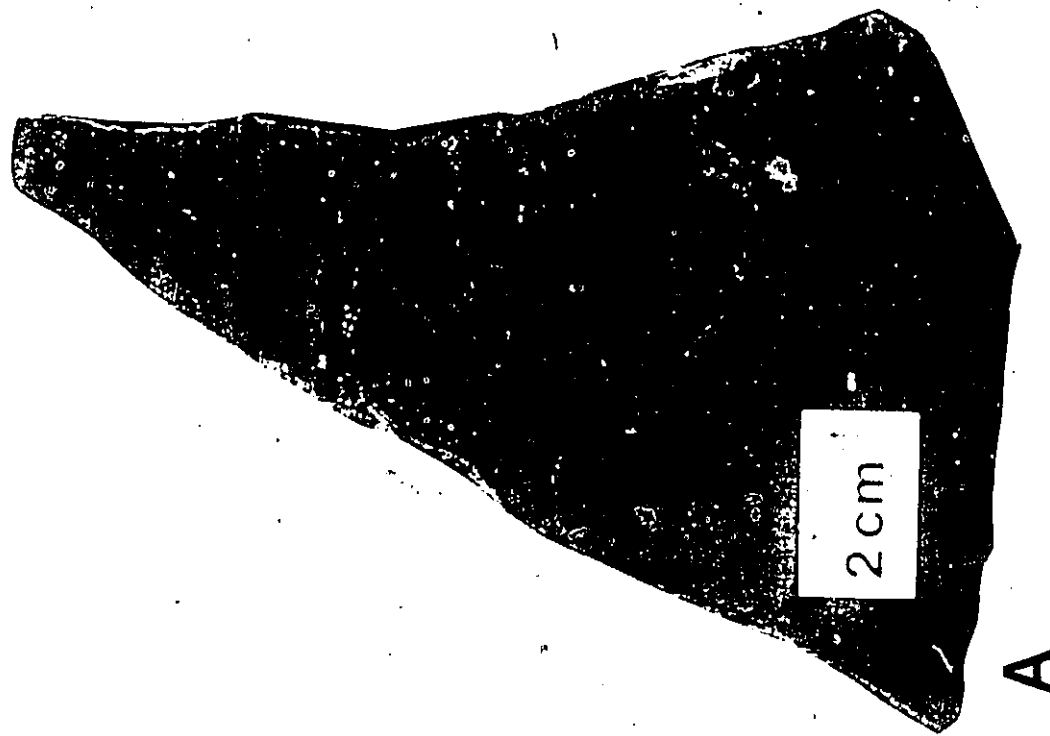


PLATE 4-5

or

PLATE 4-6

Distal tempestites in Carcajou subfacies.

Lower portion of a graded distal tempestite from the Carcajou subfacies at section 31. Chondrites burrows (lighter grey) more common towards top of bed. x1 scale.

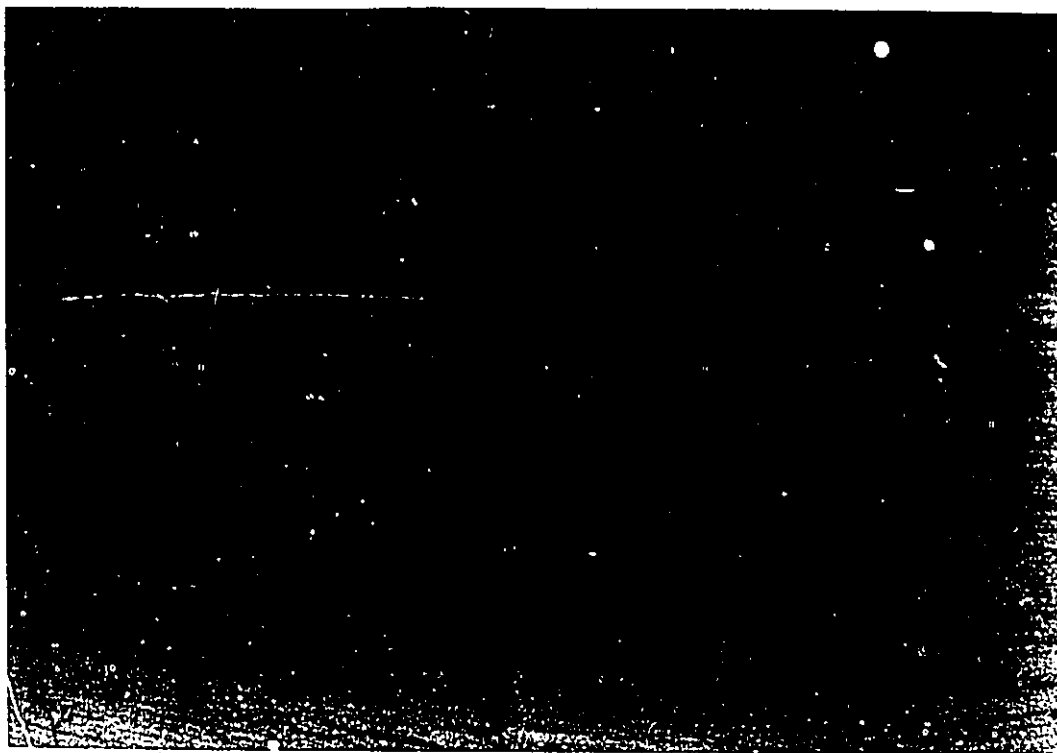


PLATE 4-6

PLATE 4-7

Sediment gravity flow deposits .
in the Carcajou subfacies.

- a Carcajou subfacies at section 01, units 018, 019 (2.6 m thick). Thick, resistant sediment gravity flow deposits (unit 018) are overlain by recessive, dark brown, slightly calcareous shale and lime mudstone. Figure (1.8 m high) on outcrop has his right foot on the Carcajou Marker at the base of the Carcajou subfacies.
- b Carcajou subfacies at section 25 (7.6 m thick). Note increasing percentage of peloidal calcisiltite towards the top of the unit, representing increased input from shallow platform (lower cycle).

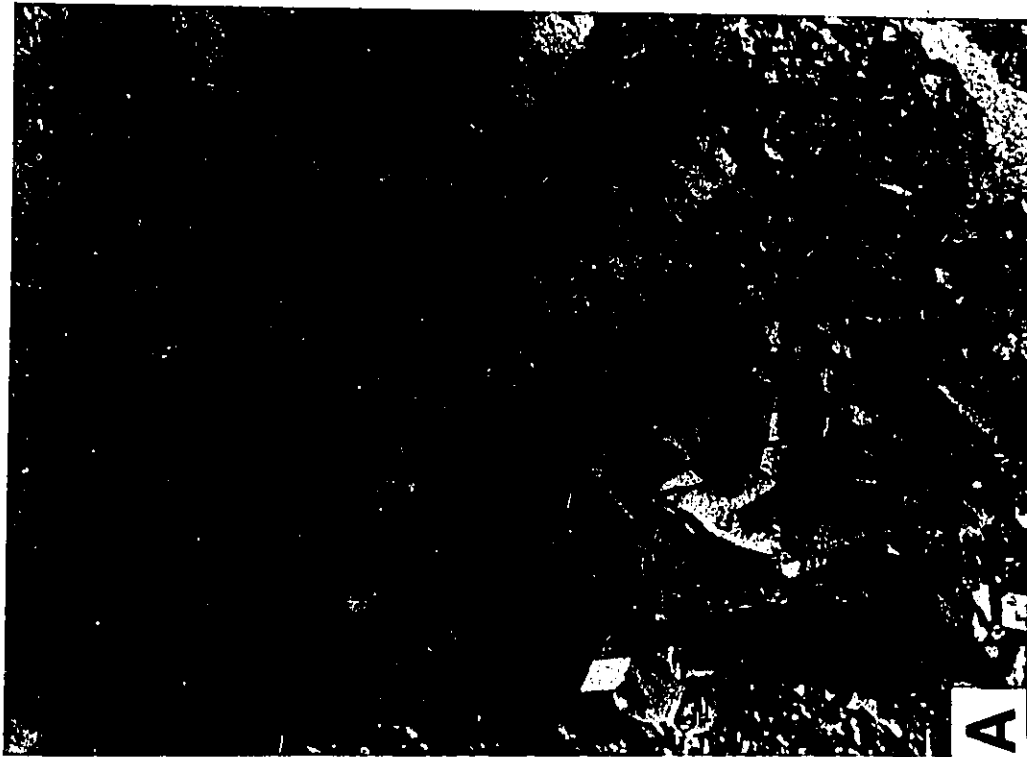


PLATE 4-7

PLATE 4-8

Lower platform subfacies 2.

Lower platform subfacies 2 at section 06. Broken, irregular-encrusting alveolitid corals are supported by a slightly argillaceous, lime mudstone matrix. Scale is 1 cm long.



PLATE 4-8

PLATE 4-9

Lower platform subfacies 1 and 2
at section 20, unit 013.

Lower platform subfacies 1 and 2 in section 20, unit 013.
Symbols in subfacies 1 as in FIG. 4-8.

- a Current-aligned thamnoporoid corals in subfacies 2.
- b Hemispherical-encrusting alveolitid corals in subfacies 2 showing ragged, peripheral margins with the enclosing mud. Hammer is 30 cm long.

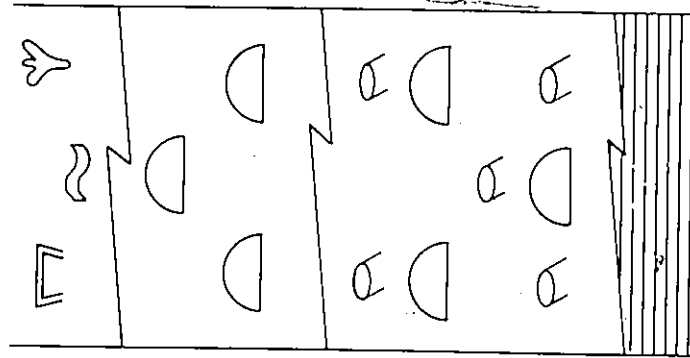
LOWER PLATFORM SUBFACIES 1, 2

1 METRE

SECTION 20
UNIT 013

SUBFACIES 1

SUBFACIES 2



CURRENT-ALIGNED
THAMNOPOROIDS

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



- HEMISPHERICAL - THICK
TABULAR ALVEOLITID
BOUNDSTONE
- HEMISPHERICAL - THICK
TABULAR ALVEOLITID FLOATSTONE;
THAMNOPOROID FLOATSTONE
- BLACK CALCAREOUS
SHALES

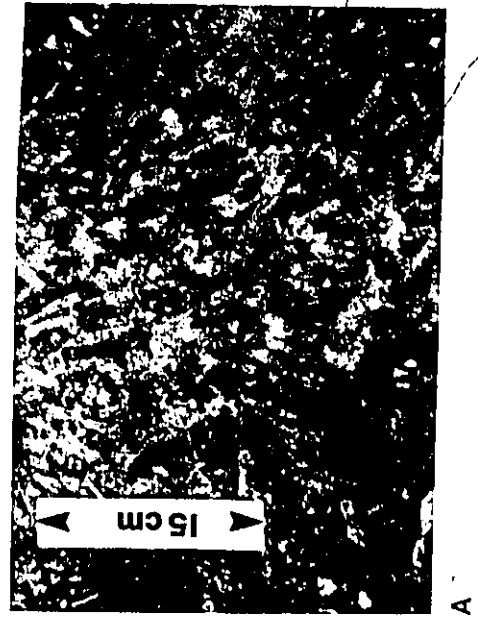


PLATE 4-10

Macrofauna in lower platform subfacies 2.

- a Bulbous alveolitid corals in lower platform subfacies 2 at section 10. Scale is 15 cm long.
- b Slightly irregular to hemispherical alveolitid corals supported by a Coenites-Thamnopora rudstone matrix in section 15, unit 022. Bar scale is 1 cm long.

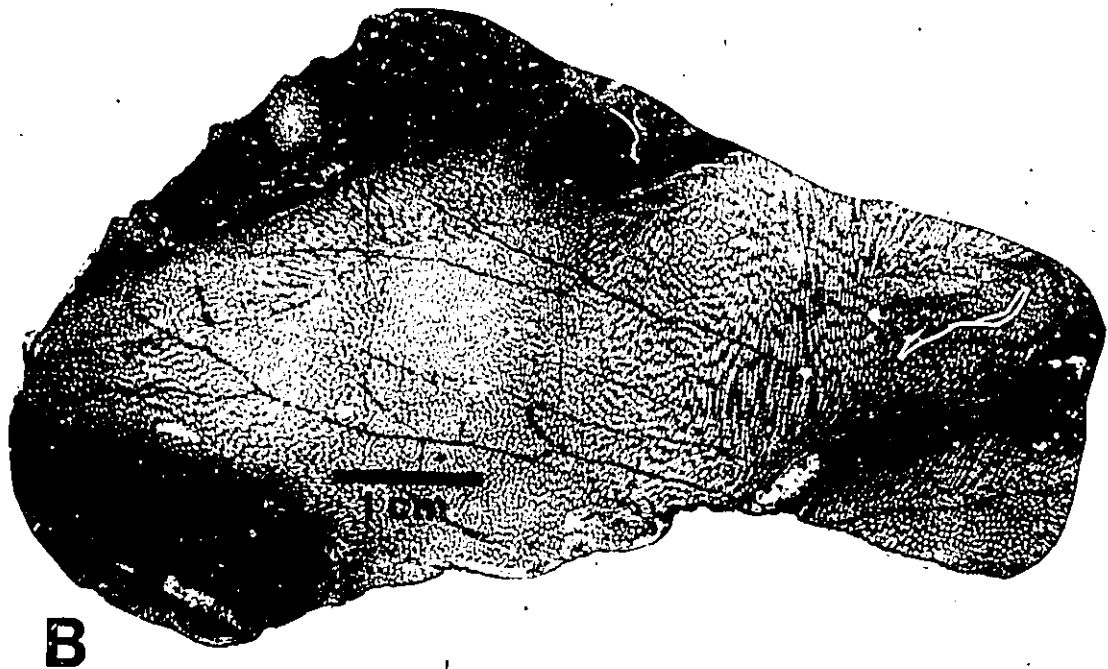


PLATE 4-10

PLATE 4-11

Lower platform subfacies 2
- contact relationships.

- a Bedding plane view of the top of the lower platform cycle (subfacies 2), with Canol shale "draping" alveolitid coral colonies. Section 15.
- b Lower platform subfacies 2 overlying planar-bedded subfacies 3 at section 15. Subfacies 2 is 7.5 m thick.

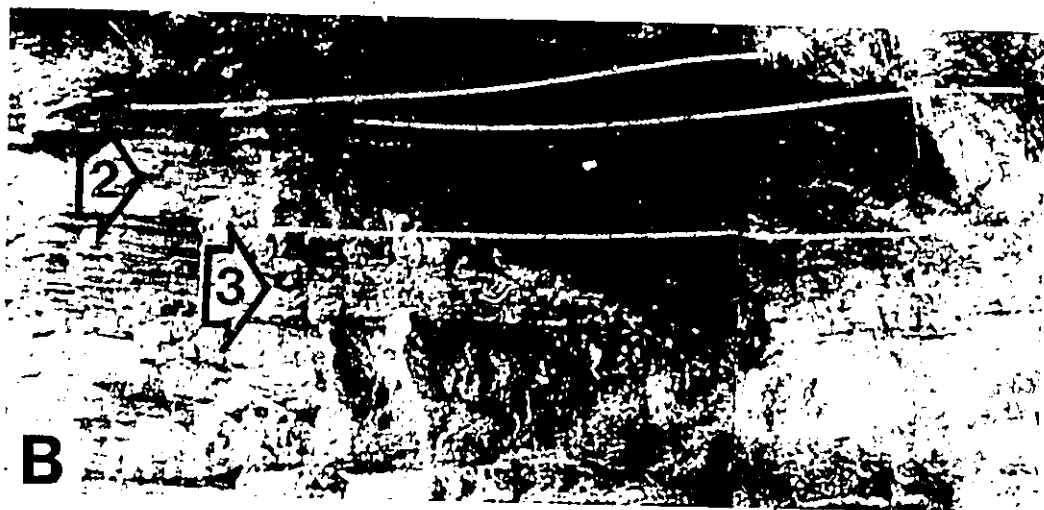
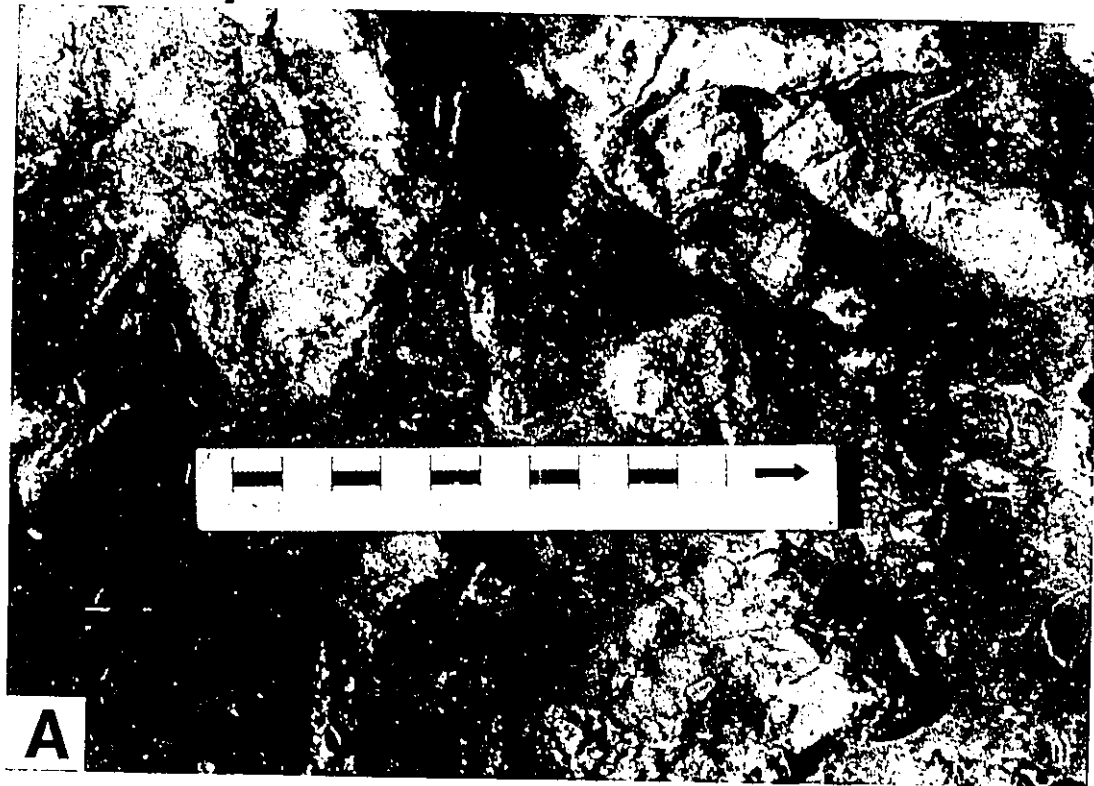


PLATE 4-11

PLATE 4-12

Distribution of platform facies near section 04.

Distribution of platform facies ~150 m west of section 04 (see FIG. 4-5 for schematic illustration, and PL. 4-18 for broader setting). A = lower platform cycle (~35 m thick). Note clinoform nature of bedding planes mainly in subfacies 3. B = middle and upper platform cycles. Rm = reef margin facies of reef cycle 1.

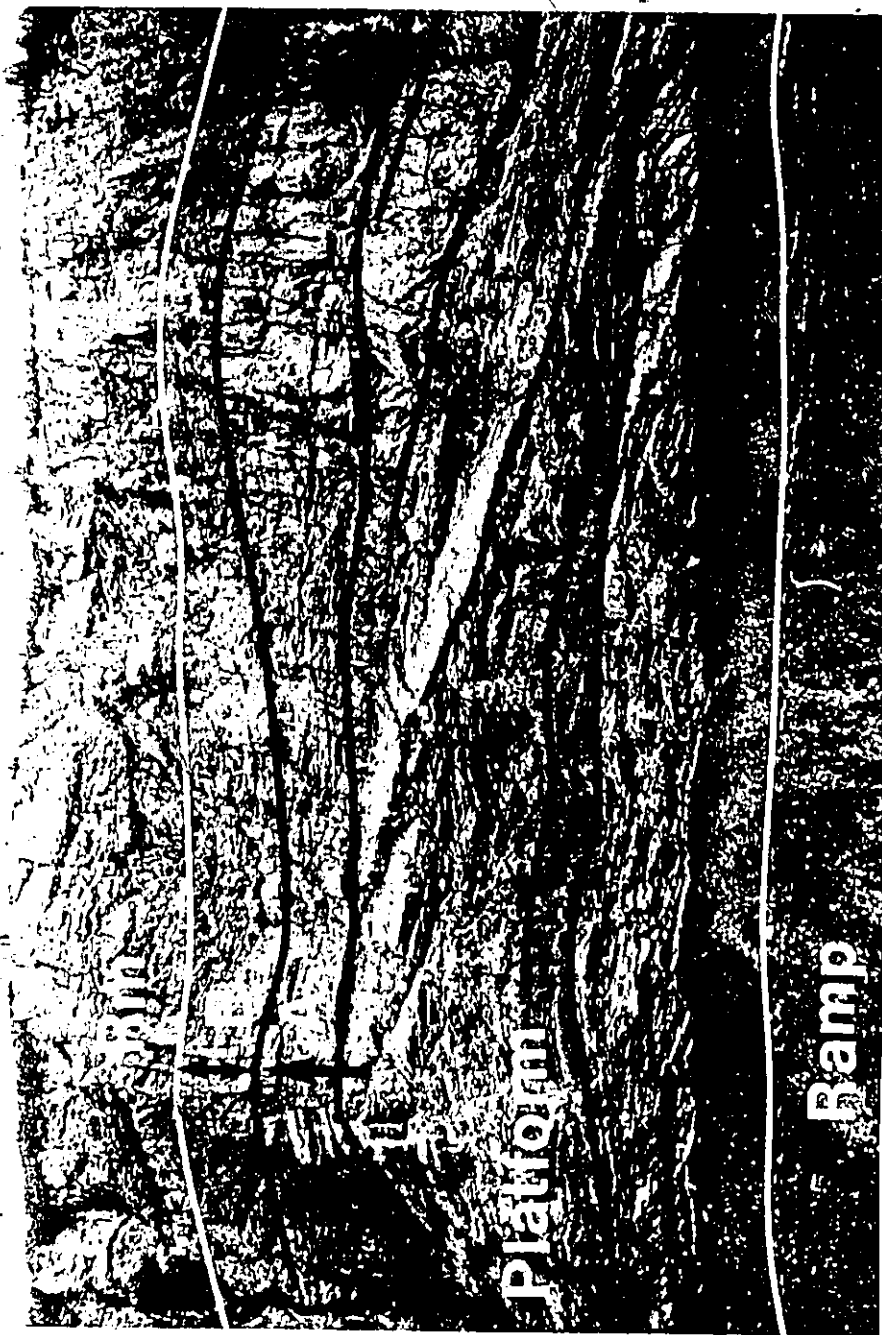


PLATE 4-12

PLATE 4-13

Macrofauna in lower platform subfacies 3.

- a Thamnopora-Coenites-wafer stromatoporoid floatstone with a dark brown skeletal wackestone matrix. Lower portion of subfacies at section 06. Bar scale is 2 cm long.
- b Coenites rudstone supported by a peloidal packstone matrix. Upper portion of subfacies at section 06. Bar scale is 2 cm long.



PLATE 4-13

PLATE 4-14

Ramose tabulate corals, lower platform subfacies 3.

- a Well-preserved, delicate ramose Thamnopora on bedding plane in lower portion of subfacies at section 15.
- b Robust Coenites fragments on a bedding plane near the top of subfacies at section 10.



PLATE 4-14

PLATE 4-15

Lower platform subfacies 4 at section 03.

Lower platform subfacies 4 at section 03 containing transported thamnoporoid corals with Carcajou mud-occluded intra-allochem porosity. Bar scale is 2 cm long.

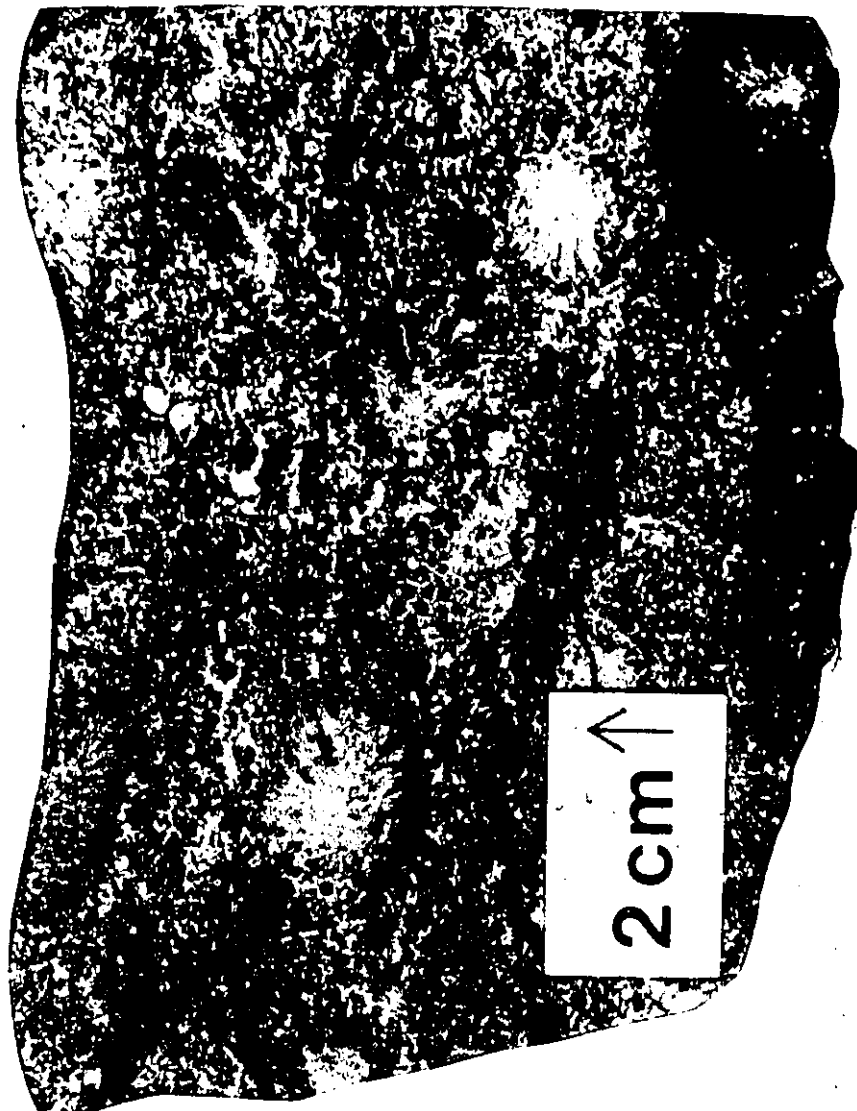


PLATE 4-15

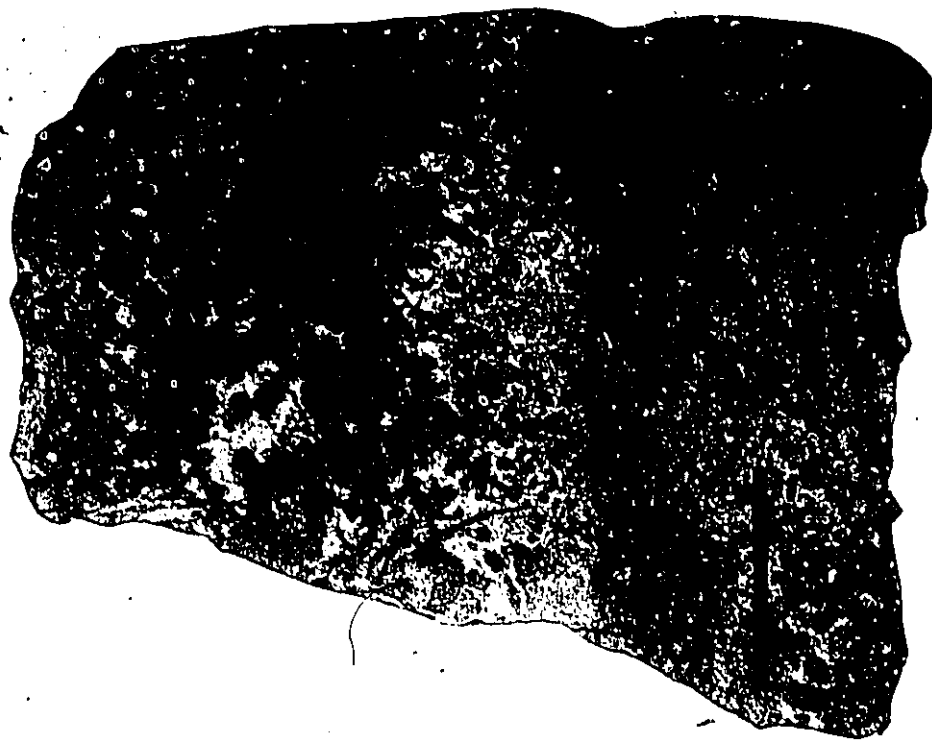
PLATE 4-16

Macrofauna in lower platform subfacies 4.

- a Lower portion of subfacies at section 07. Abundant brachiopod fragments and few crinoid and Amphipora allochems supported by a medium brown, muddy packstone matrix. Bar scale is 2 cm long.
- b Cylindrical stromatoporoid rudstone at section 15, unit 019. Note abundant calcite-occluded interparticle porosity. Bar scale is 2 cm long.



A



B

PLATE 4-16

PLATE 4-17

Lower platform cycle abruptly overlain
by Canol basinal shale.

Lower platform cycle abruptly overlain by Canol basinal
shale at section 15. Platform is 21 m thick.

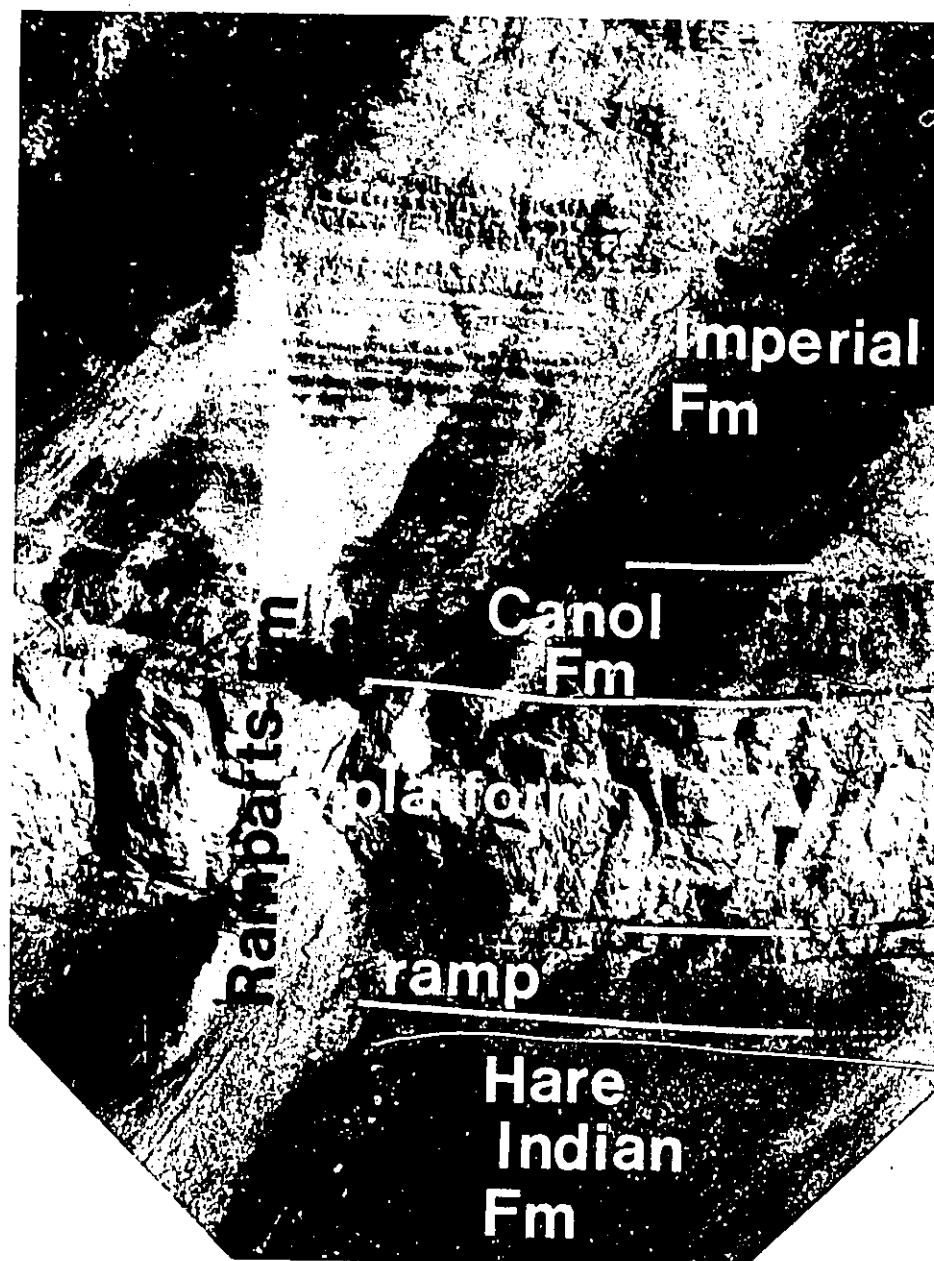


PLATE 4-17

PLATE 4-18

Platform-reef facies distribution
near section 04.

Platform facies association (~35 m thick) near section 04 in the eastern portion of the study area (see FIGS. 4-7, 4-9). A = lower platform cycle. B = middle and upper platform cycles. Thin black lines delineate bedding planes. Note the progradation (downlapping) of the lower platform cycle. Black dot marks location of PL. 4-12. Ri = reef interior facies. Rm = reef margin facies. Rfs = reef foreslope facies.

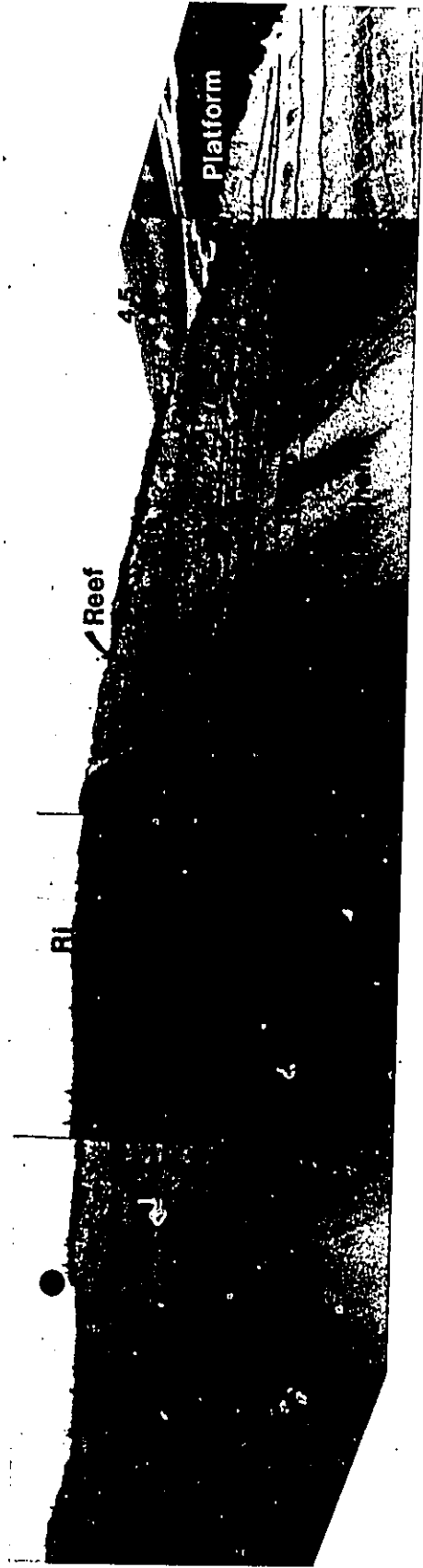


PLATE 4-18

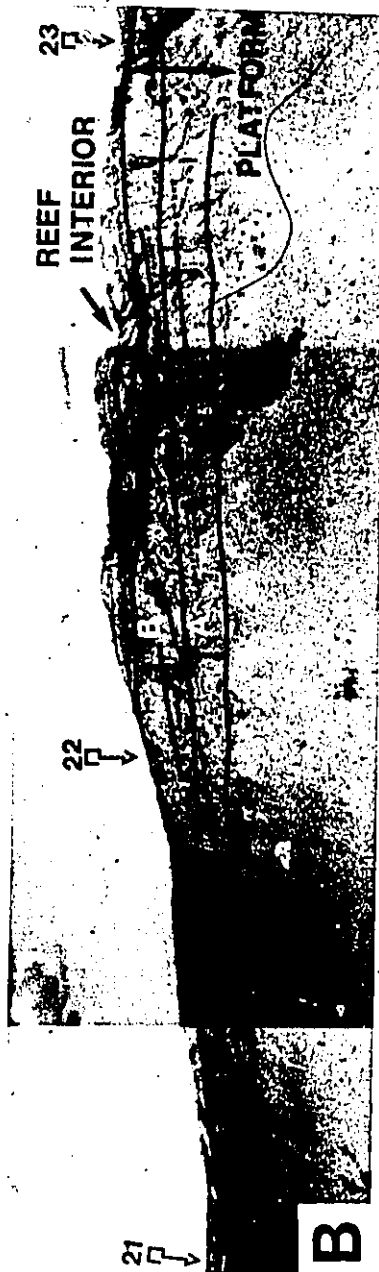
PLATE 4-19

Upper platform buildup at section 23.

- a Middle platform subfacies 1 at section 18 with large, in situ, hemispherical stromatoporoid adjacent to figure.
- b Lower platform cycle (A) and middle and upper platform cycles (B) in the area of sections 21 to 23. Heavy black lines tracing bedding planes, and dotted lines tentatively marking other bedding planes, clearly define clinoform bed geometry. Middle platform subfacies 2 in the lower part of the B succession is mainly abraded stromatoporoid rudstone. Platform attains a maximum thickness for the study area (57 m) at section 23.



A



B

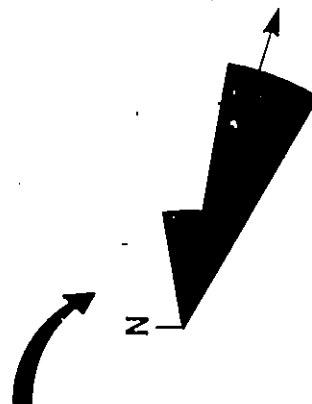
PLATE 4-19

PLATE 4-20

Platform-derived sediment gravity
flow deposits at section 01.

Platform-derived sediment gravity flow deposits (middle platform subfacies 2) in section 01. Arrows in A designate sole markings from which paleocurrent measurements were made. Note nearly flat base and slightly convex-upward top to the debris flow unit. Abraded stromatoporoid-coral floatstone (B) makes up most of this unit. Underlying the debris flow unit in A are thin-bedded, slightly nodular lime mudstone and interbedded shale of middle platform subfacies 4. Similar lithofacies overlying the debris flow unit constitute upper platform subfacies 4. Note thickening-upward trend for limestone beds.

MIDDLE PLATFORM SUBFACIES 2 - DEBRIS FLOW UNIT, SECTION 01



SECTION 01 - GROOVES, PROD AND SKIP MARKS

$n = 7$
 $() = 105^\circ$
 $r = 6.68$
 $L = 95\%$
 $e = 1.8 \times 10^{-3}$

PLATE 4-21

Macrofauna in upper platform facies.

- a Top of the platform facies association at section 22 is a hardground separating light-colored, abraded stromatoporoid rudstone from overlying dark-colored crinoidal transgressive lag of reef cycle 1. Note truncated allochems (stromatoporoids) along hardground surface. Bar scale is 2 cm long.
- b Thick, tabular stromatoporoids supported by a robust cylindrical stromatoporoid rudstone in upper platform subfacies 1 at section 23.

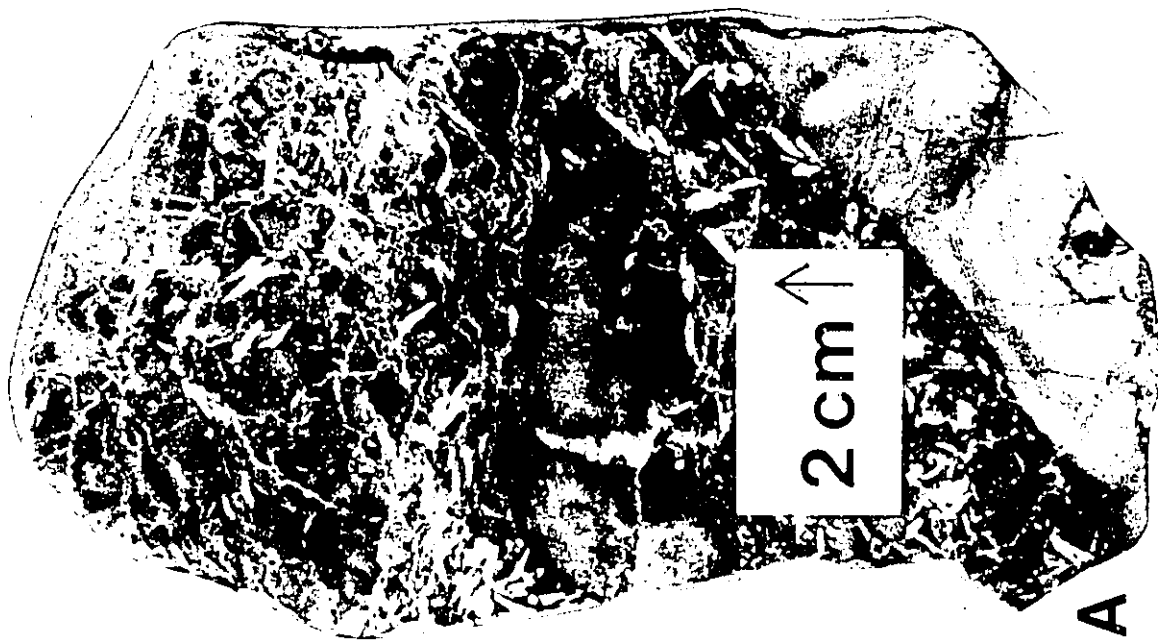


PLATE 4-21

PLATE 4-22

Upper platform subfacies 4 at section 01.

Interbedded calcareous shale and peloidal calcisiltite in upper platform subfacies 4, section 01. Pen is 15 cm long.



PLATE 4-22

V

INCEPTION, DEVELOPMENT, AND TERMINATION OF THE
REEF FACIES ASSOCIATION IN THE RAMPARTS
FORMATION (UPPER "PLATFORM-REEF" MEMBER)

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 competently 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-impoverished 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).

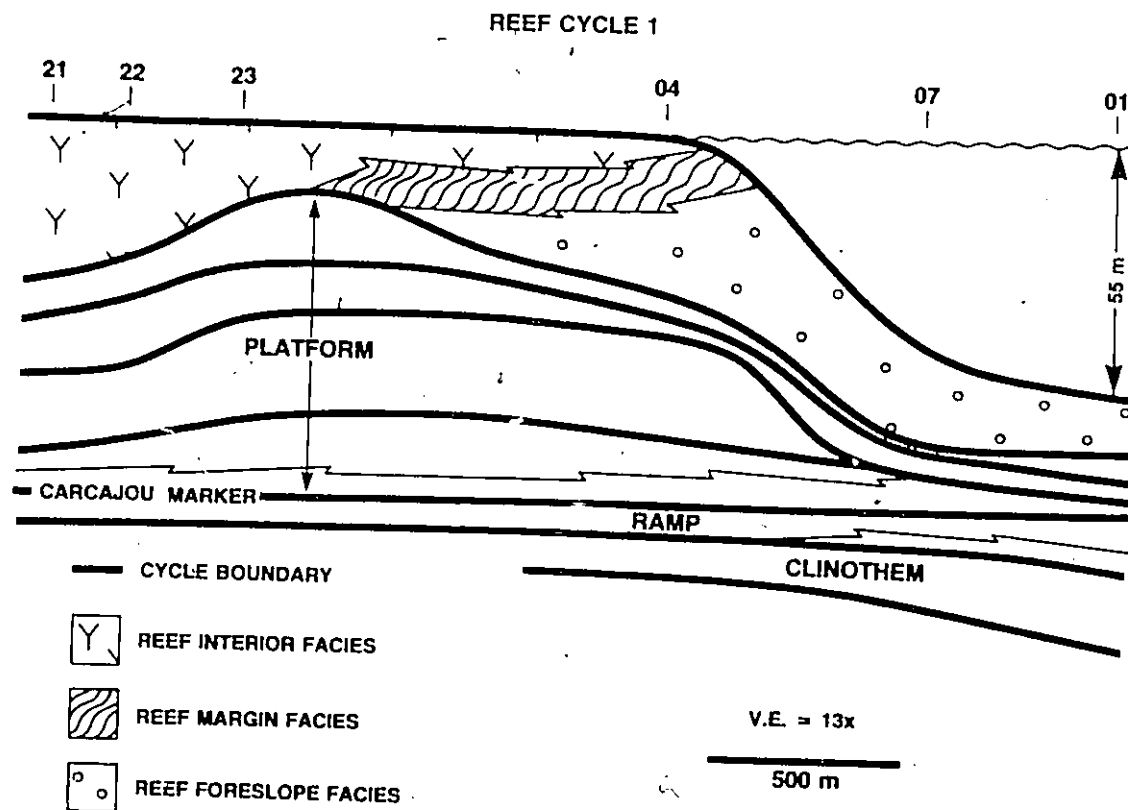


FIG. 5-1 Distribution of reef facies in reef cycle 1, eastern portion of study area.

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 clinothem 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

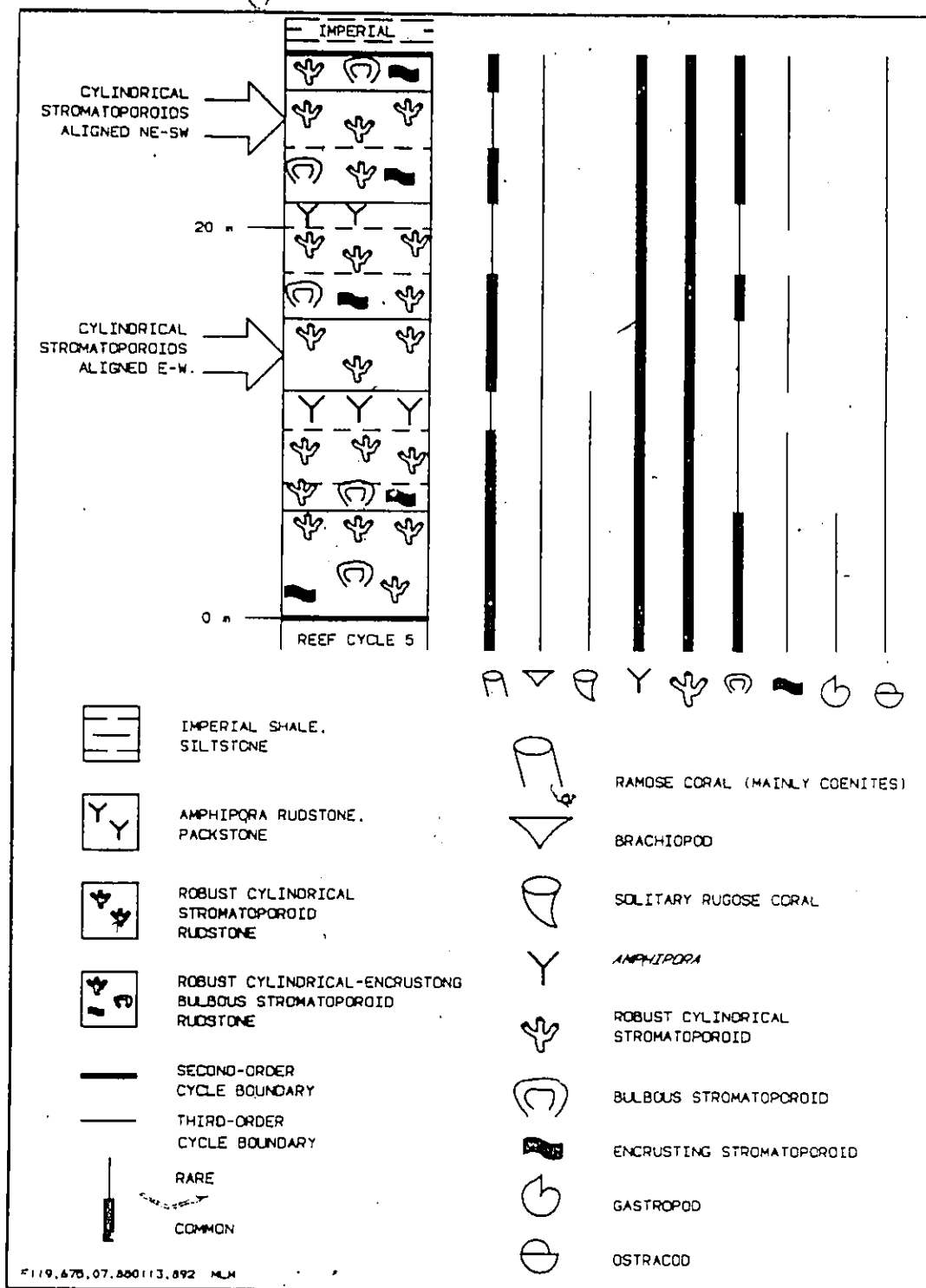


FIG. 5-2 Macrofossil distribution in shoal subfacies of reef cycle 6, Ramparts Formation (section 20).

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

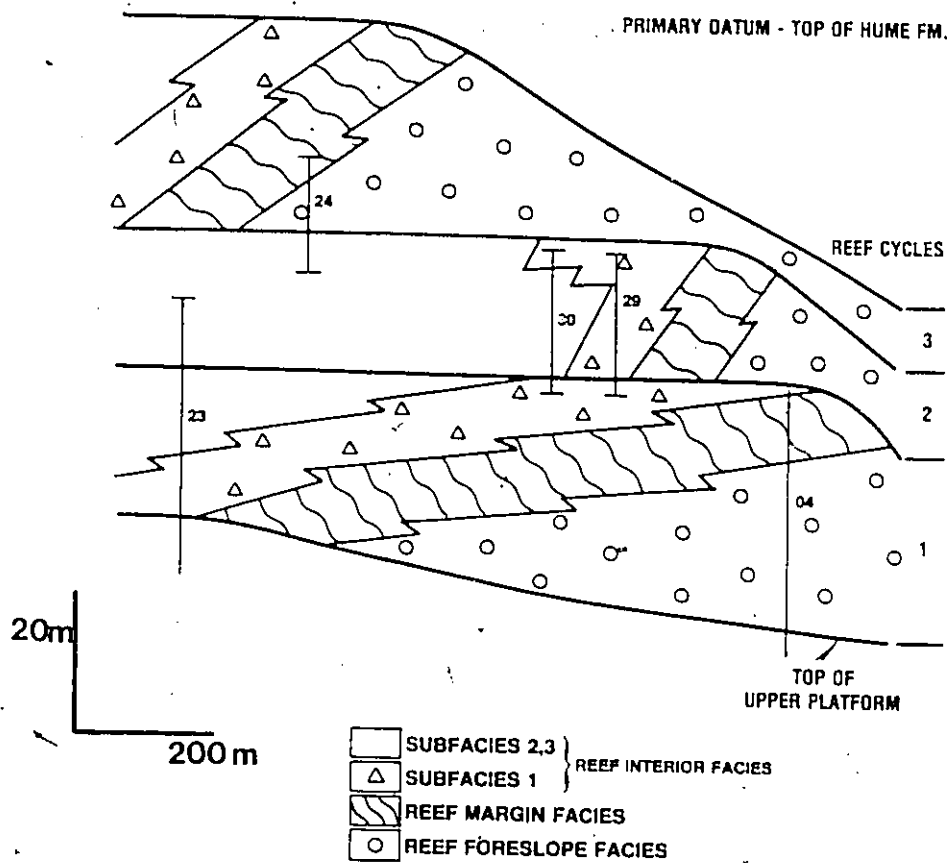


FIG. 5-3 Distribution of reef interior subfacies 1 and associated rocks in reef cycles 1-3 at sections 04, 23, 24, 29, and 30.

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

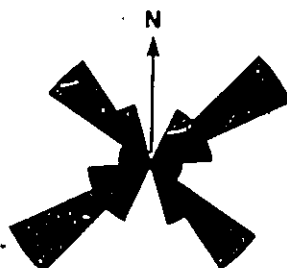
Amphipora

encrusting algae
crinoid columnals

Rare ConstituentsThamnopora

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

GROUPED PALÉOCURRENT DATA - REEF INTERIOR SUBFACIES 1



ALIGNED ROBUST CYLINDRICAL
STROMATOPOROIDS

SECTION 18 UNIT 034

SED 1	SED 2
056/236°	144/324°
050/230°	130/310°
038/218°	138/318°
048/228°	058/238°
058/238°	128/308°
090/270°	117/287°
078/258°	157/337°
130/318°	046/226°
	064/244°
	121/301°
	171/351°

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 3

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

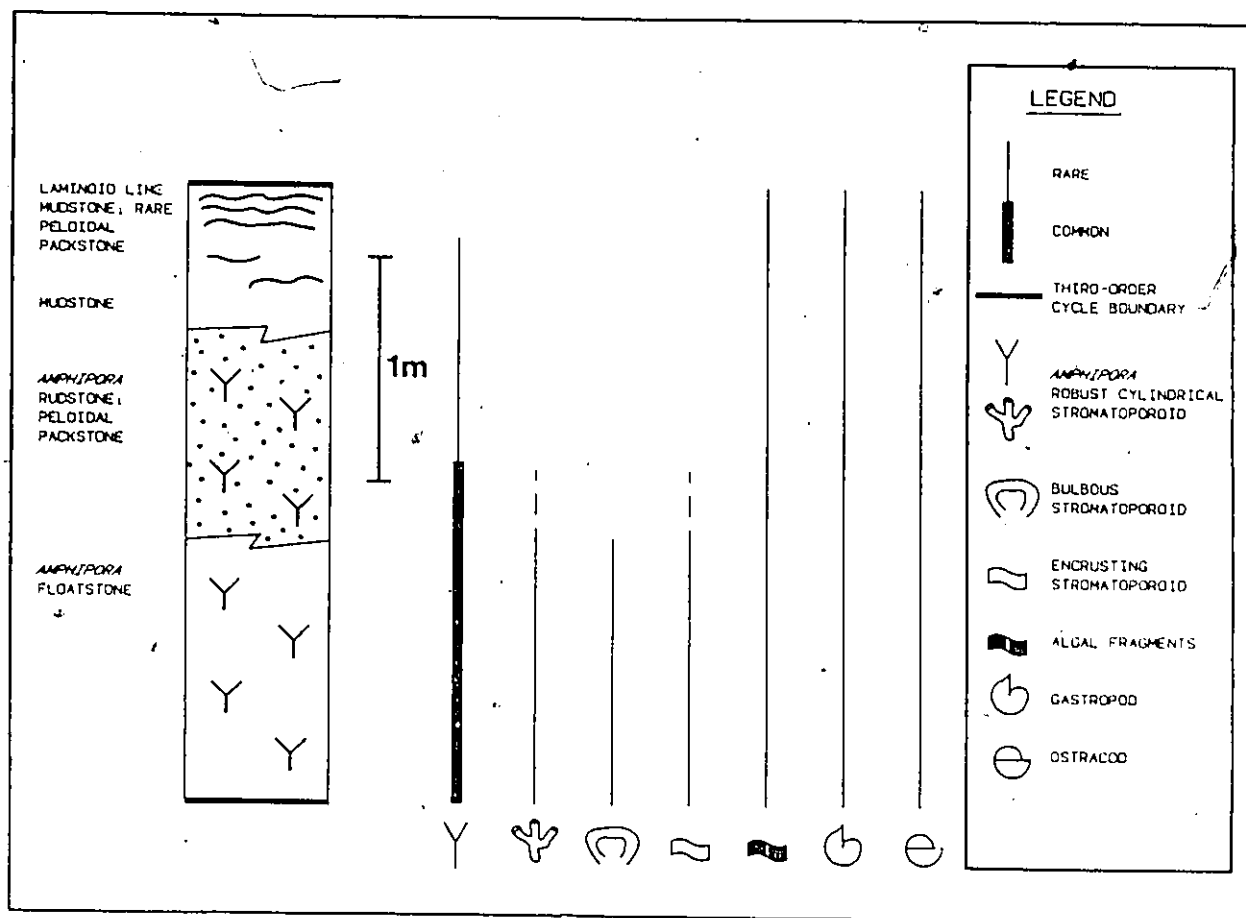


FIG. 5-5 Typical macrofossil distribution in reef interior subfacies 3, section 20.

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).

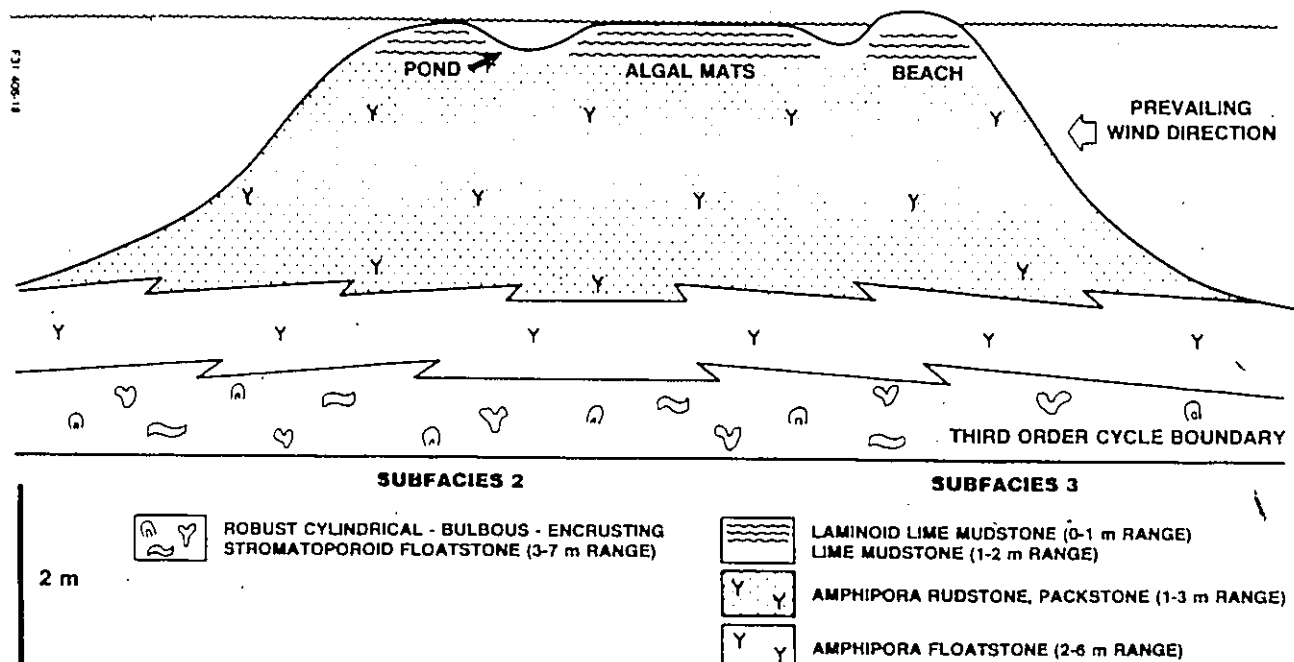


FIG. 5-6 Interpreted paleobathymetry of reef interior subfacies 2 and 3.

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, allochthonous, thick tabular-hemispherical stromatoporoid 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 nektonic-planktonic 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), megaclasts 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 clinothem 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

TOTAL ORGANIC CARBON CONTENT (WT %) - BASIN FACIES

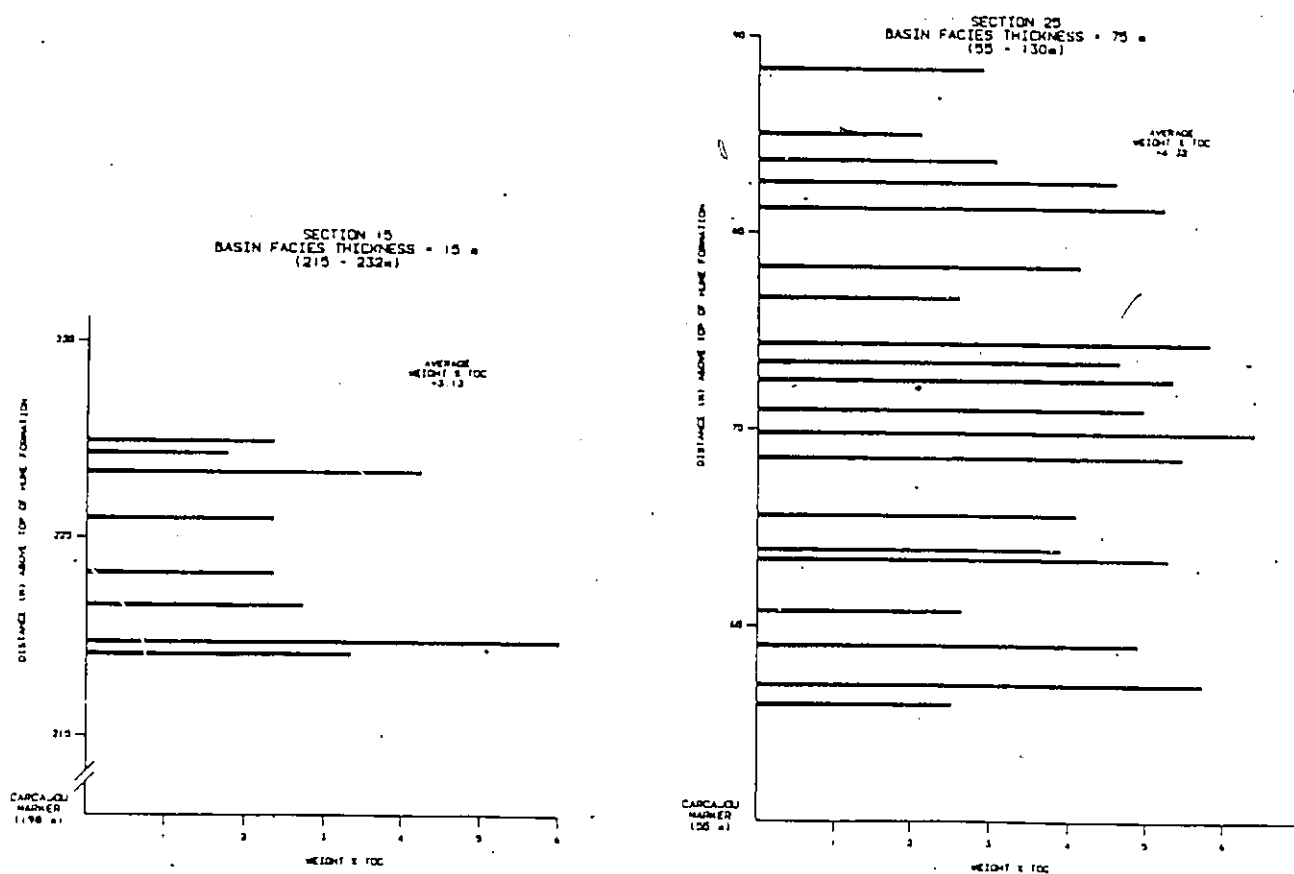


FIG. 5-7 Total organic carbon content (wt %) of selected samples from the basinal facies (sections 15 and 25).

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 overlies 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. 5-3).

- (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)

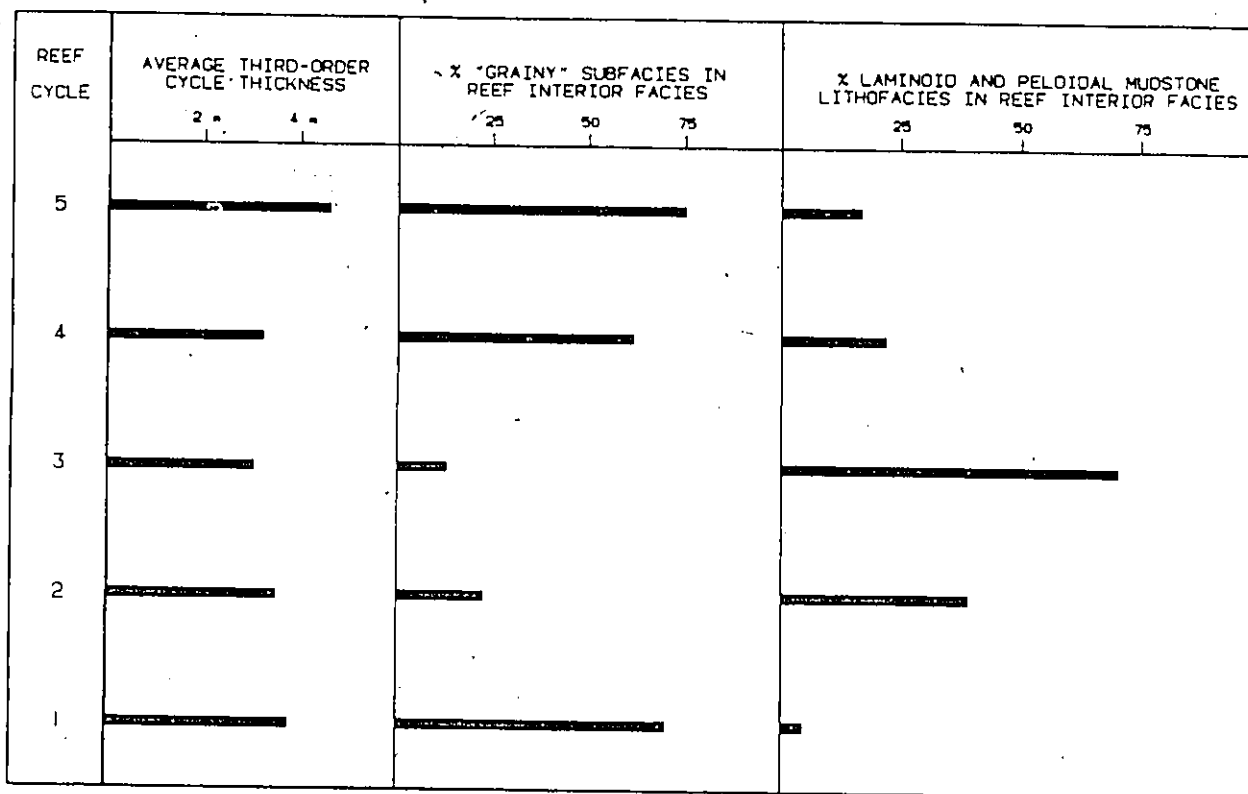


FIG. 5-8 Reef cycle facies variation in a reef interior depositional setting (section 20).

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
COENITES						
CRINOID						
BRACHIOPOD						
SOLITARY RUGOSE CORAL						
BRYOZOA						

SECTION 31

FAUNA	1	2	3	4	5	6
COENITES						
CRINOID						
BRACHIOPOD						
SOLITARY RUGOSE CORAL						
BRYOZOA						

RARE - <1% OF TOTAL ALLOCHEMS
- OBSERVED IN < 50% OF UNITS

RARE TO COMMON - 1-5% OF TOTAL ALLOCHEMS
- OBSERVED IN >50% OF UNITS

COMMON - > 5% OF TOTAL ALLOCHEMS
- 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).

NW

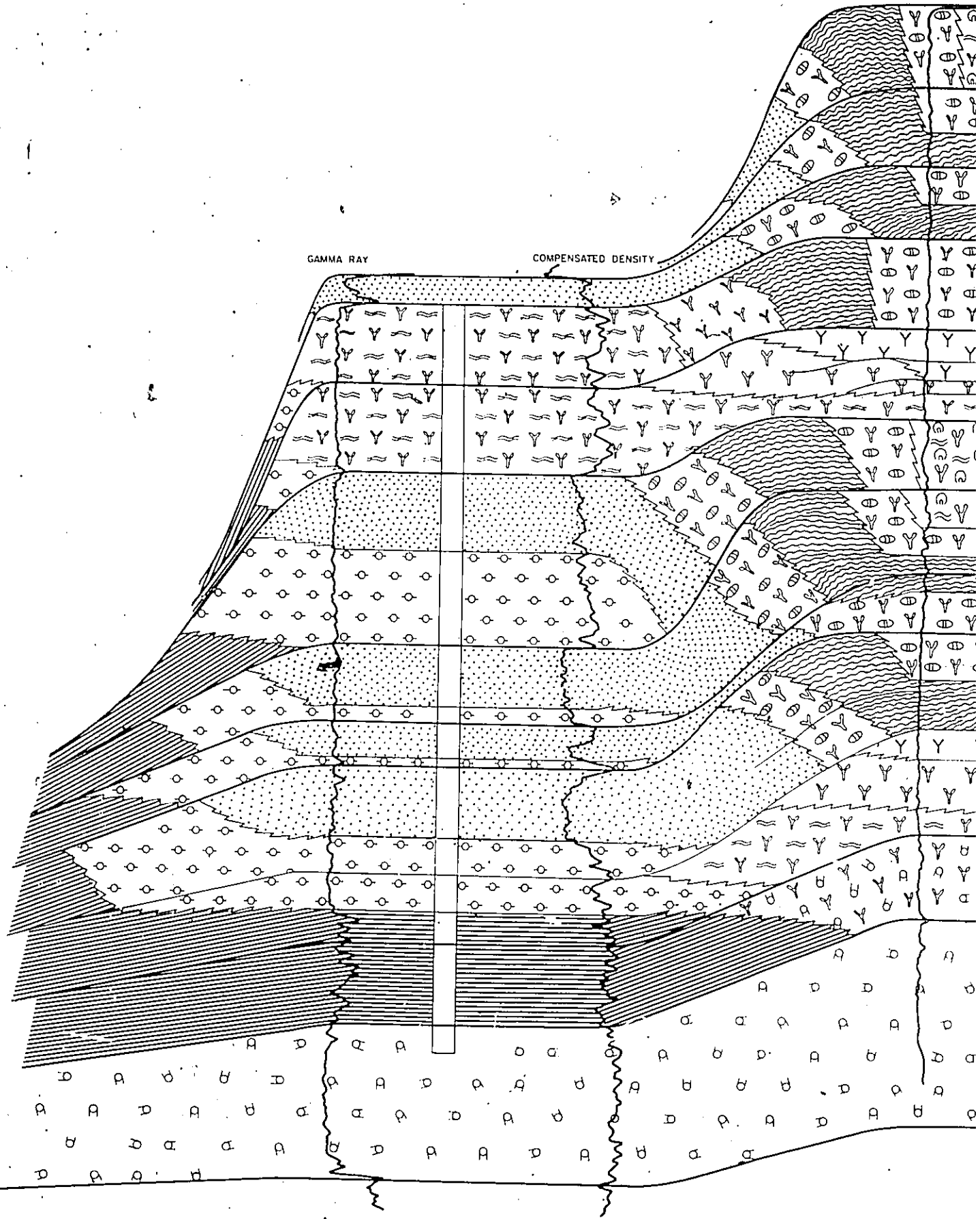
P-9x

0.80 km

GAMMA RAY

GAMMA RAY

COMPENSATED DENSITY



P-15x

0.80 km

0.68 km

GAMMA RAY

COMPENSATED DENSITY

GAMMA RAY

COMPENSATED DENSITY



STRATIGRAPHIC CROSS SECTION

P-15x

P-21x

0.68 km

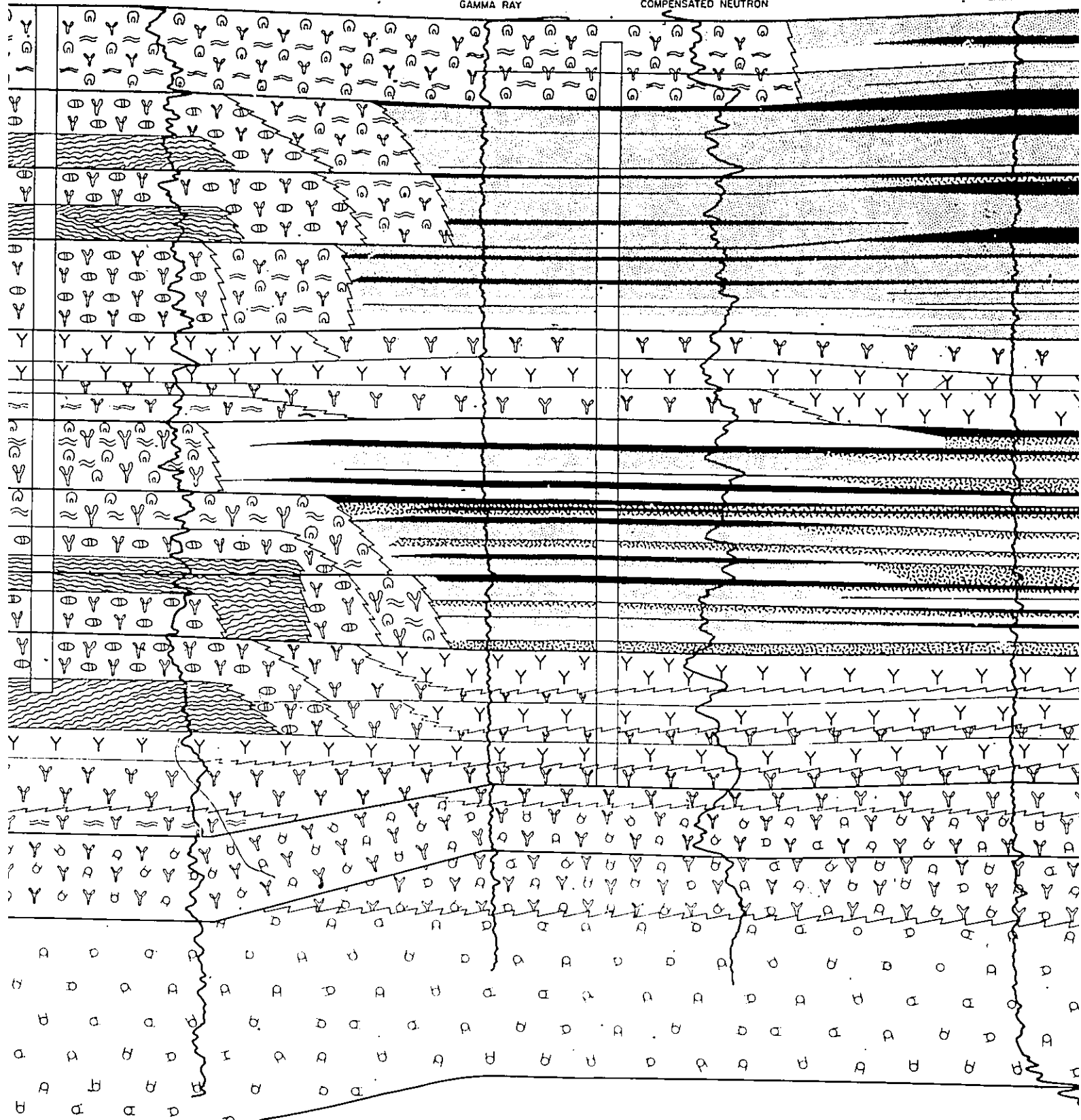
0.64 km

COMPENSATED DENSITY

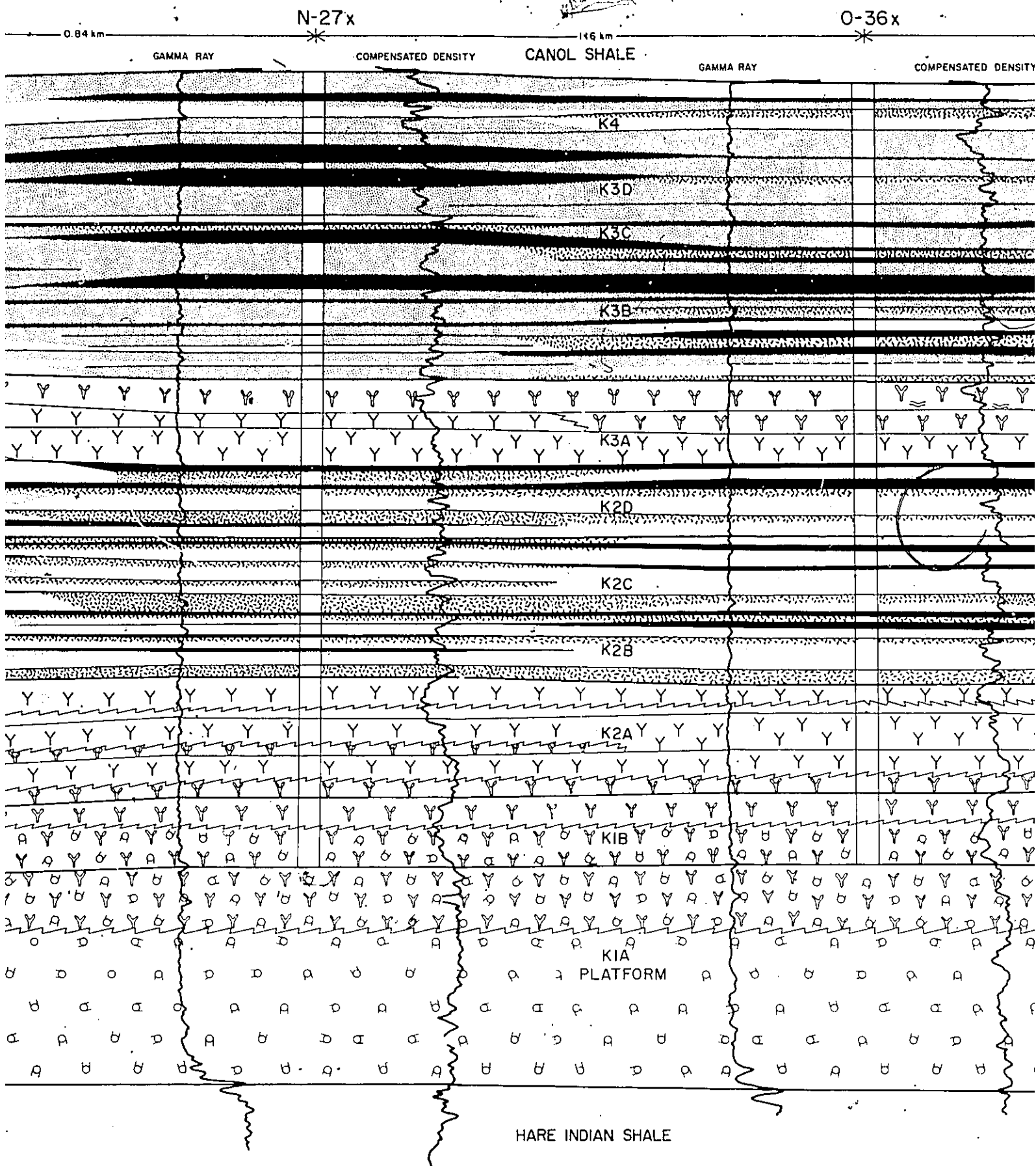
GAMMA RAY

COMPENSATED NEUTRON

GAMMA RAY



CROSS SECTION-UPPER DEVONIAN KEE SCARP REEF AT NORMA



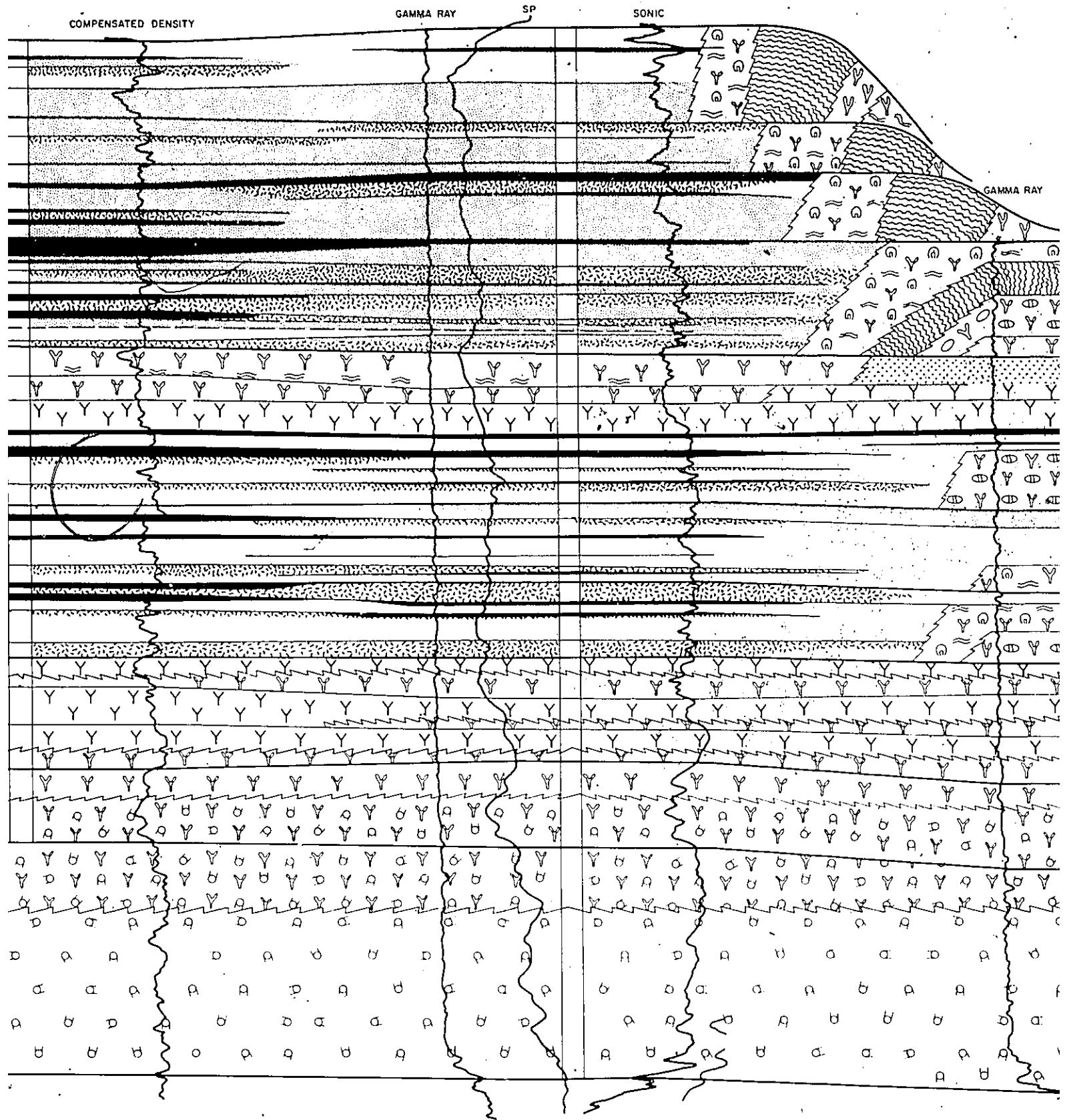
AT NORMAN WELLS

-36x

R-34 x

0.70 km

1.48 km



R-34 x

0-45x

1.48 km

SONIC

GAMMA RAY

COMPENSATED DENSITY

65°20'

65°10'

127°15'

STRATIGRAPHIC CROSS SECTION UPPER DEVONIAN KEE SCARP REEF AT NORMAN WELLS

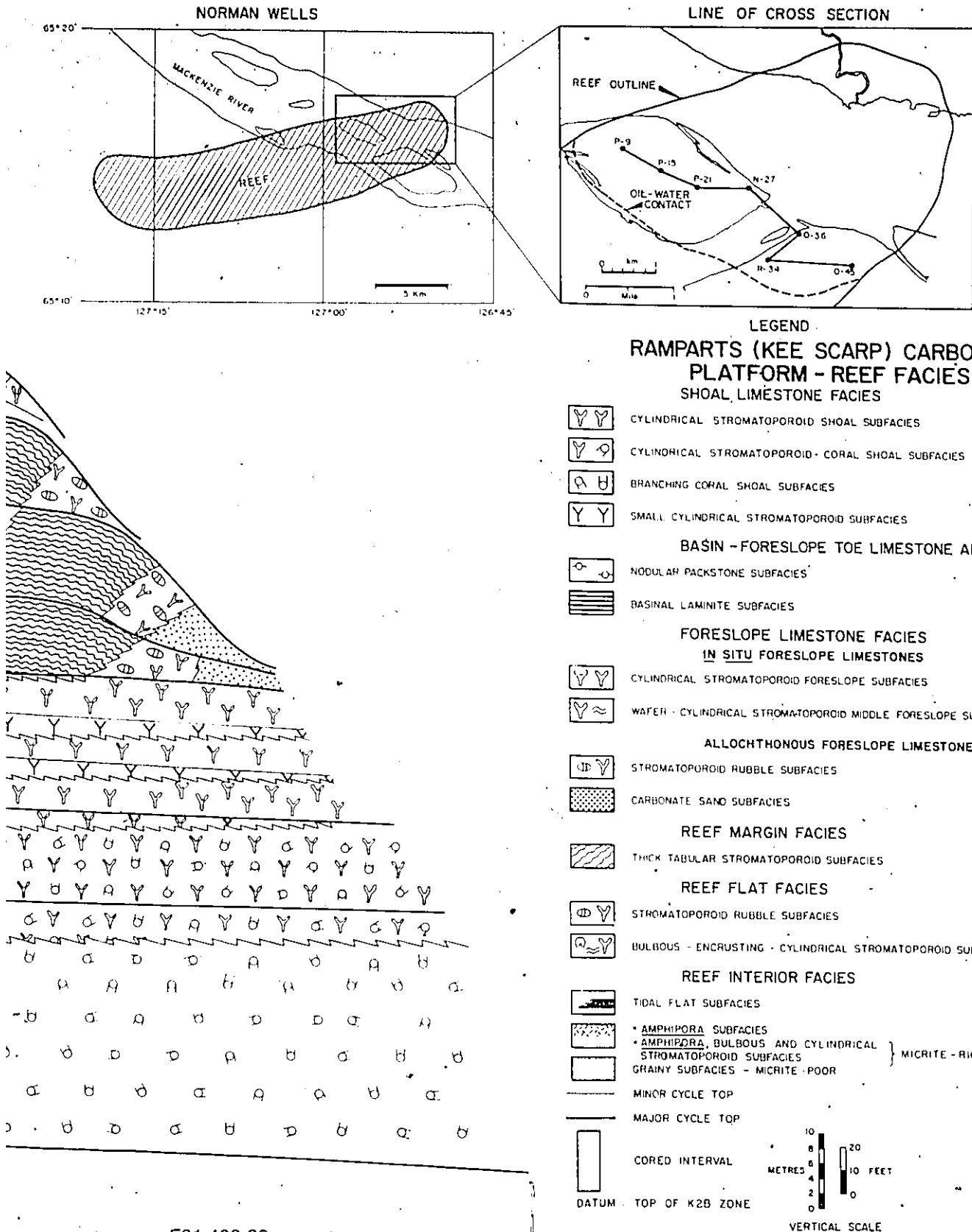


FIG. 5-11 Correlation of platform and initial reef cycles
in the Mackenzie Mountains and Norman Wells
buildups (left and right, respectively).

A number line diagram with three points marked: 28, 22, and 20. The distance between 28 and 22 is labeled as 75 km. The distance between 22 and 20 is labeled as .3 km.

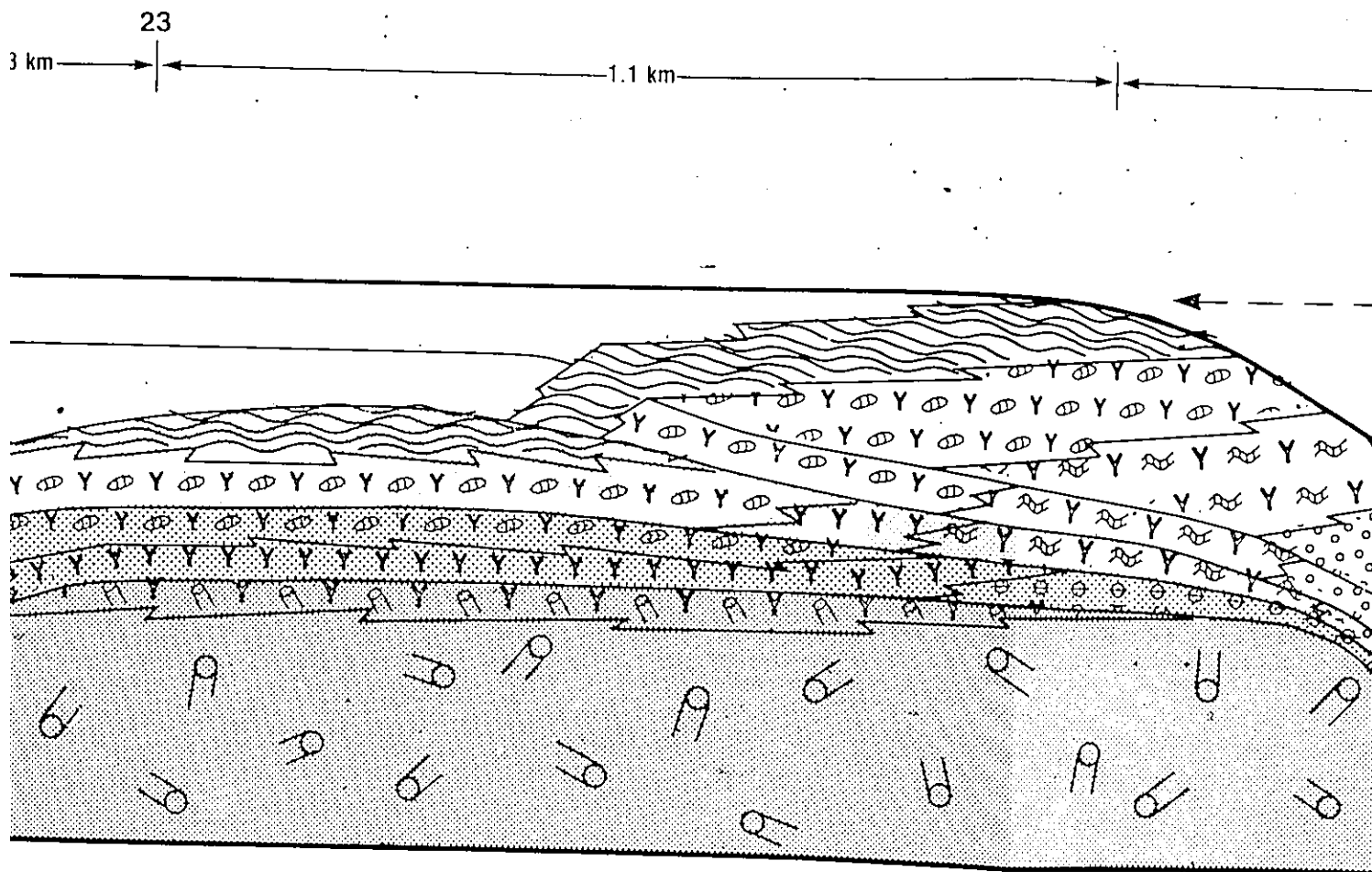
UPPER

MIDDLE

LOWER

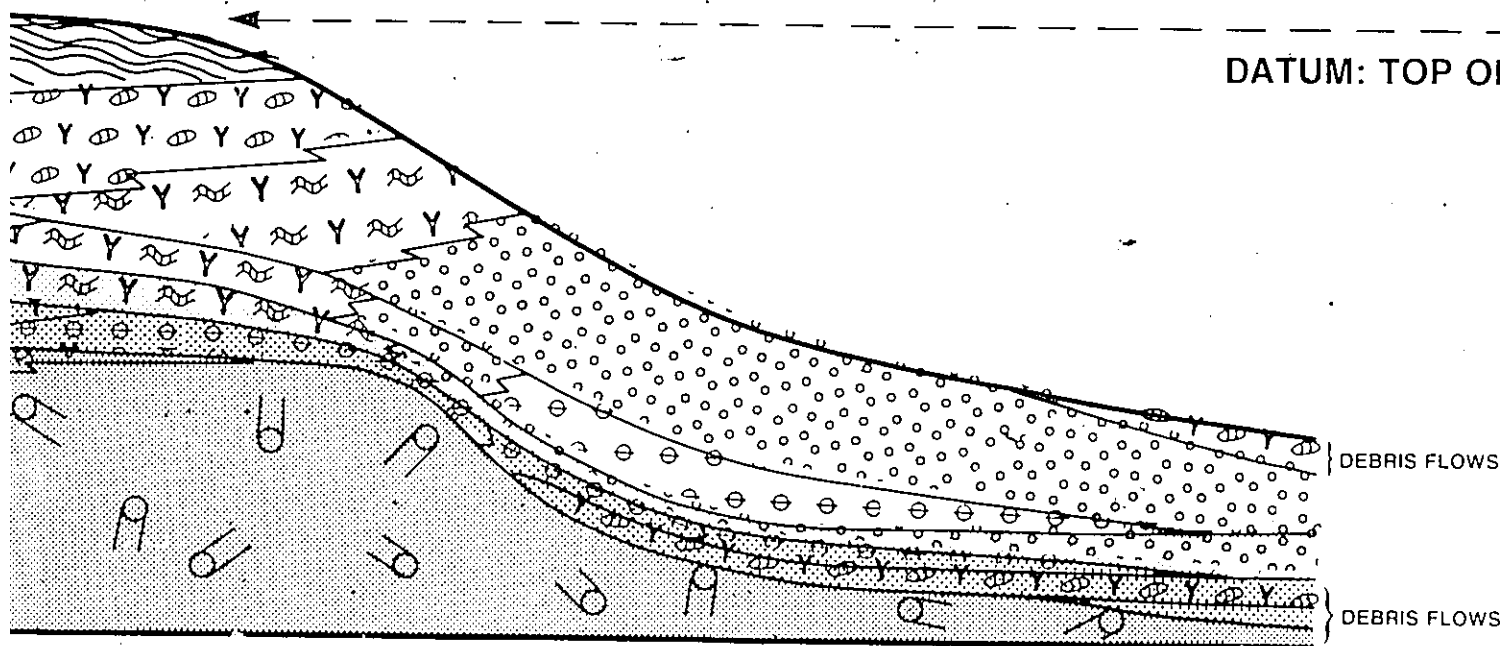
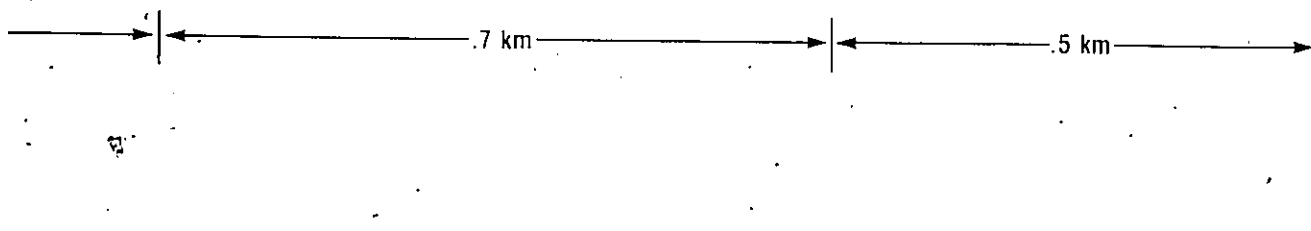
PLATFORM

BASE OF CARCAJOU SUBFACIES
(CARCAJOU MARKER)



IBFACIES
(ER)

E



NW

P-21x

P-15x

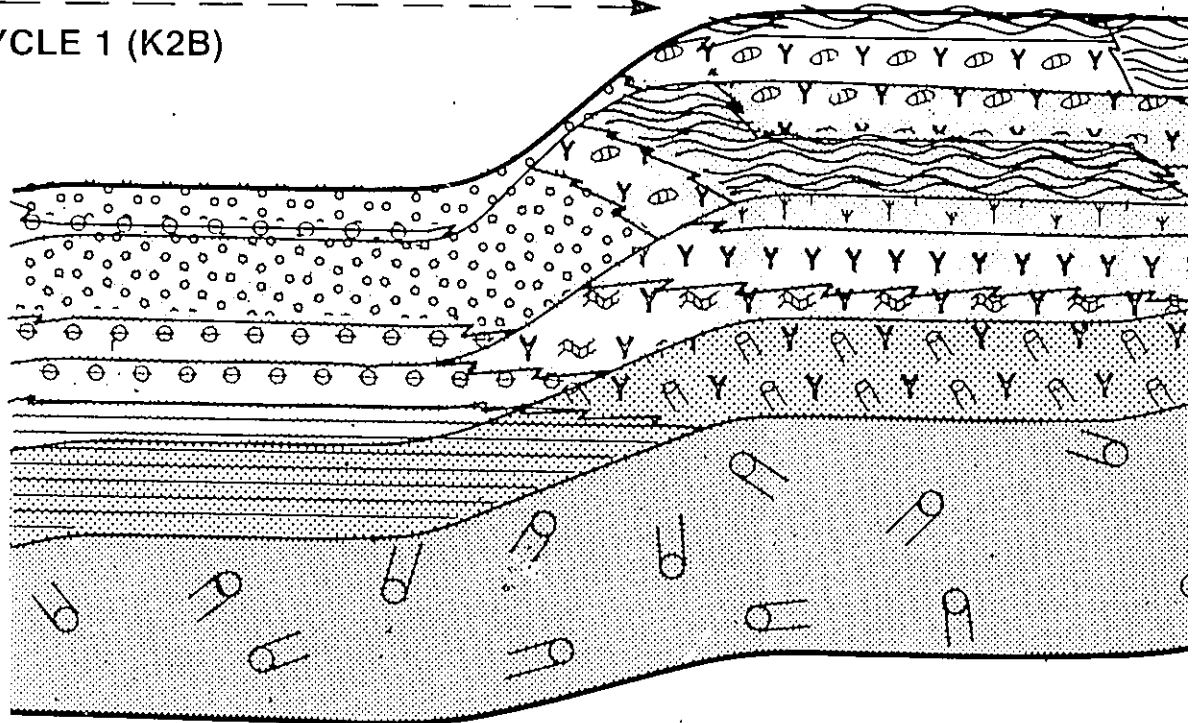
8 km

TOP OF REEF CYCLE 1 (K2B)

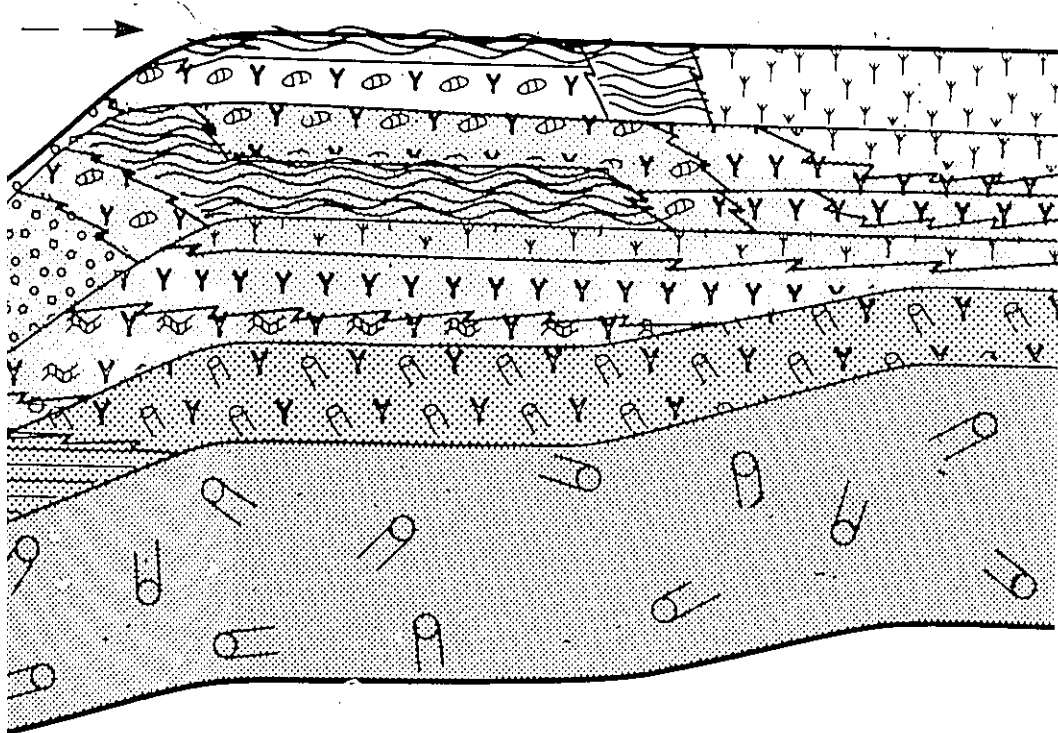
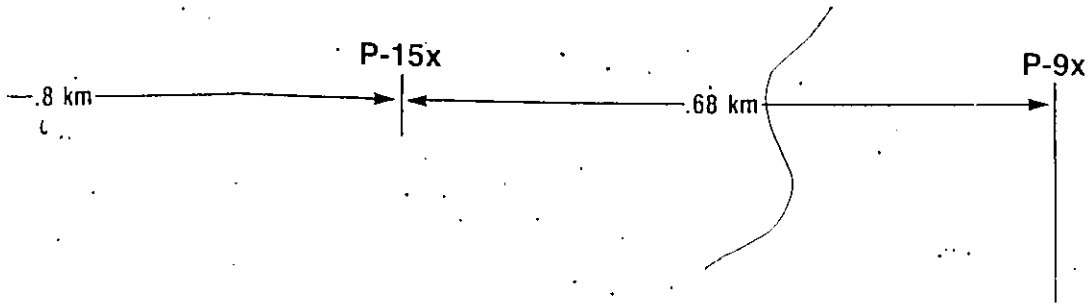
EBRIS FLOWS

EBRIS FLOWS

BASE OF CARCAJOU SUBFACIES
(CARCAJOU MARKER)



SE



K2B

K2A

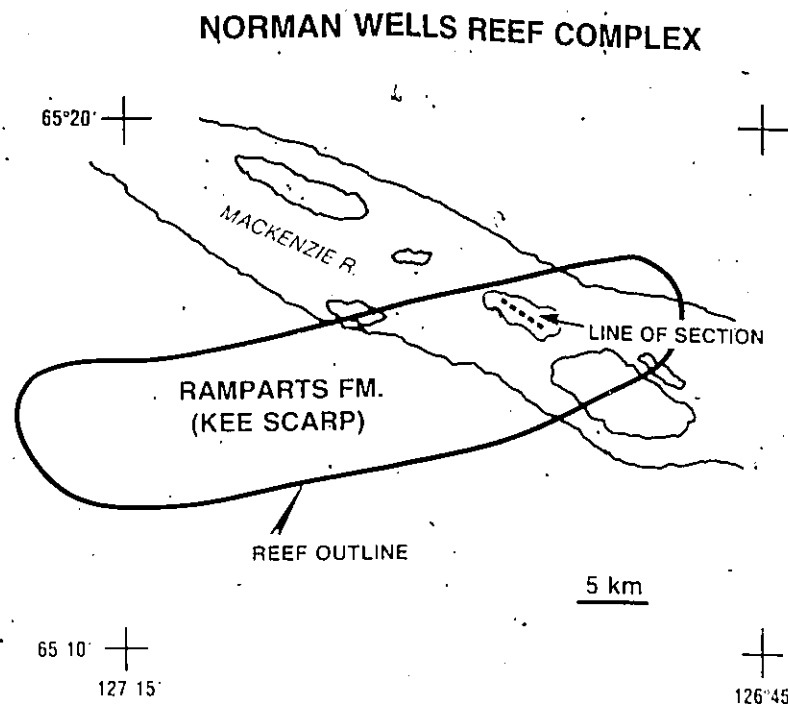
K1B

K1A

PLATFORM

CARCAJOU SUBFACIES
(ARCAJOU MARKER)

20 m



- | | |
|--|---|
| | UNDIFFERENTIATED REEF INTERIOR FACIES |
| | SMALL CYLINDRICAL STROMATOPOROID RUDSTONE, FLOATSTONE |
| | THICK TABULAR STROMATOPOROID RUDSTONE, BOUNDSTONE |
| | ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE, FLOATSTONE |
| | ABRADED STROMATOPOROID RUDSTONE, FLOATSTONE |
| | LIME GRAINSTONE |
| | CYLINDRICAL STROMATOPOROID - RAMOSE CORAL RUDSTONE, FLOATSTONE |
| | RAMOSE CORAL RUDSTONE, FLOATSTONE, 'MASSIVE' CORAL BOUNDSTONE |
| | WAFFER STROMATOPOROID - ROBUST CYLINDRICAL STROMATOPOROID
FLOATSTONE, RUDSTONE, BOUNDSTONE |
| | NODULAR LIME MUDSTONE, WACKESTONE PACKSTONE |
| | LAMINATED SHALE, LIME MUDSTONE |
| | MAJOR CYCLE BOUNDARY |

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

IMPE

W

REEF CYCLES

6 29 m

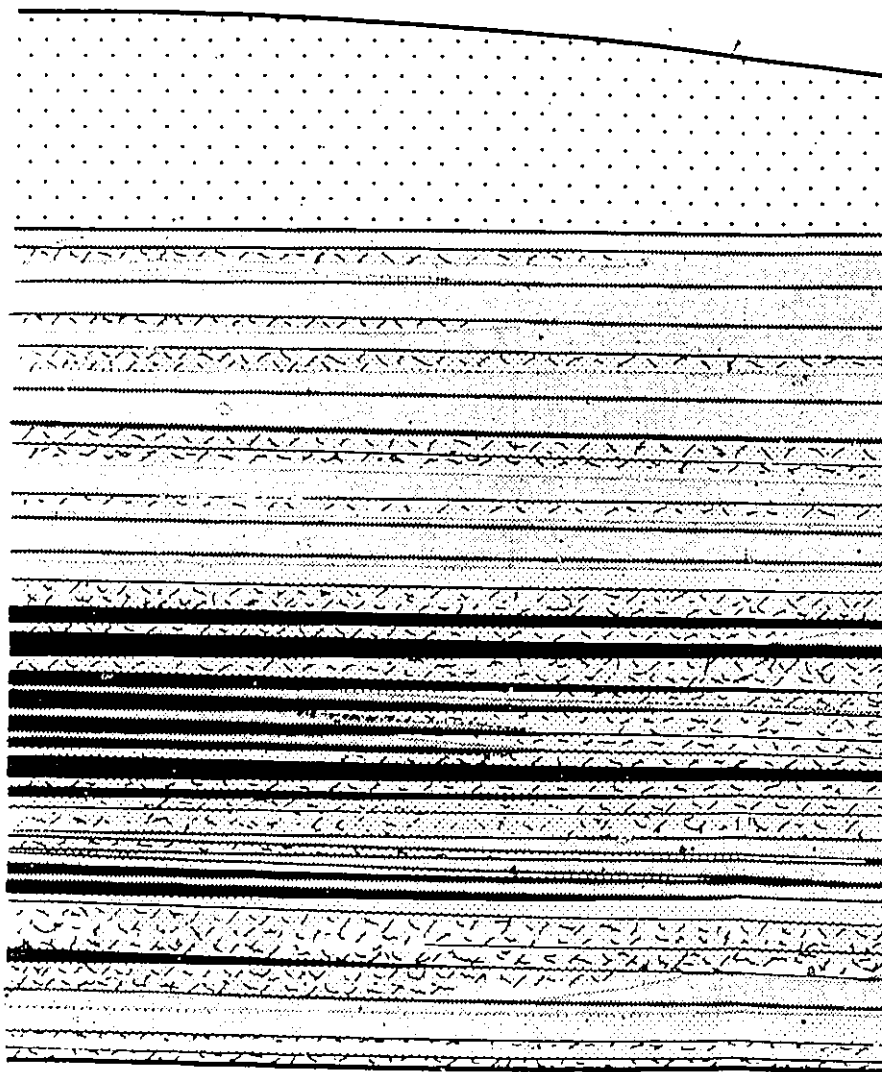
5 26 m

4 26 m

3A 34 m

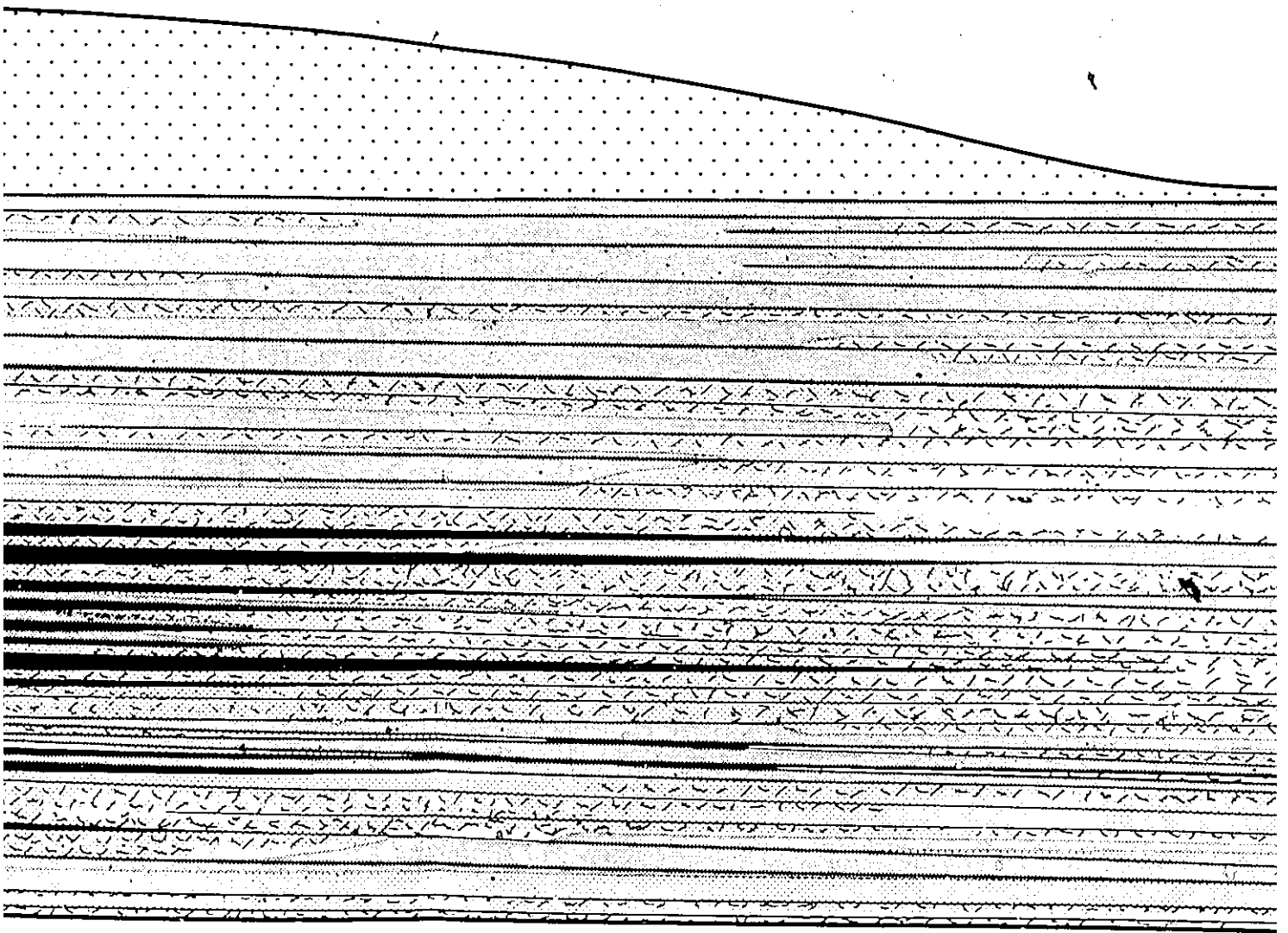
3B

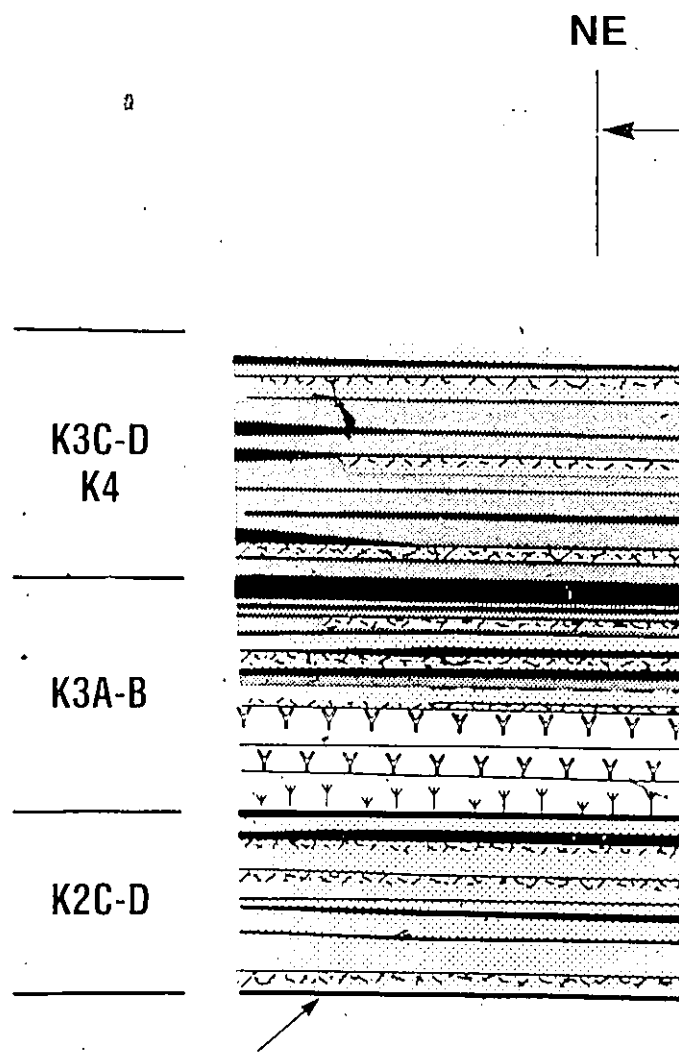
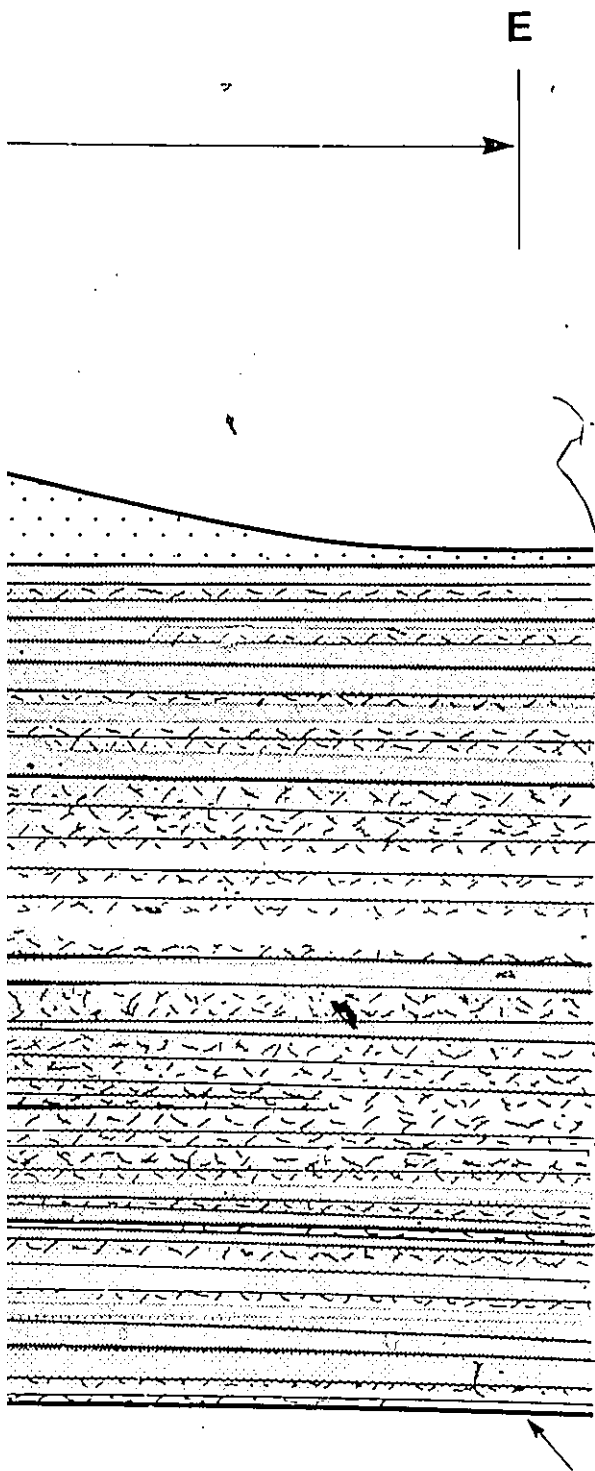
2 26 m



IMPERIAL FM.

4.6 km





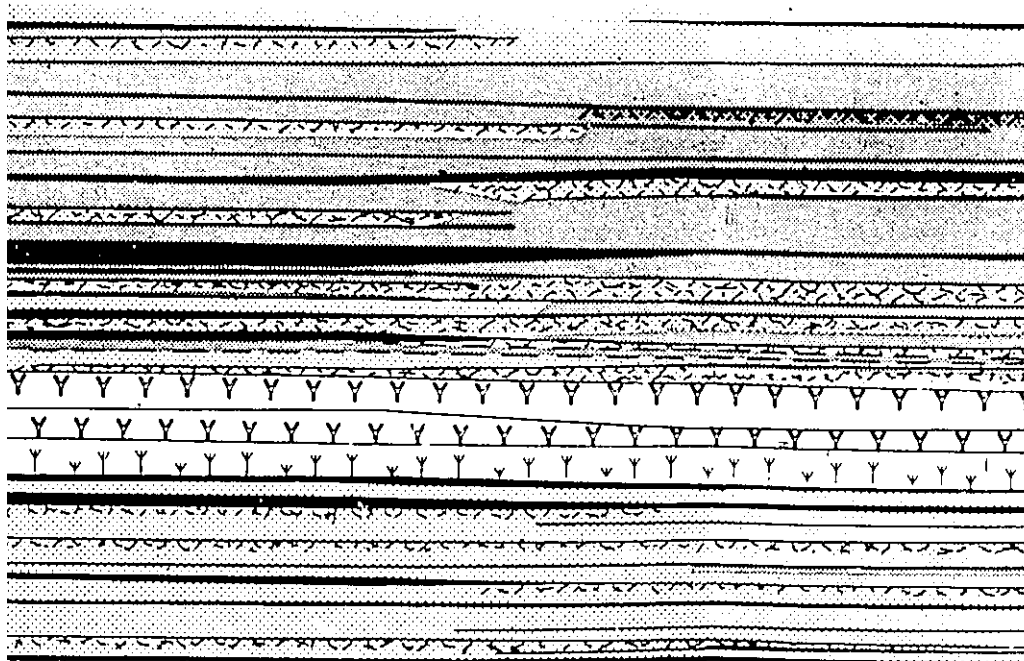
DATUM: TOP OF REEF CYCLE 1 (K2B)

CANOL FM.

NE

SW

.7 km



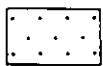
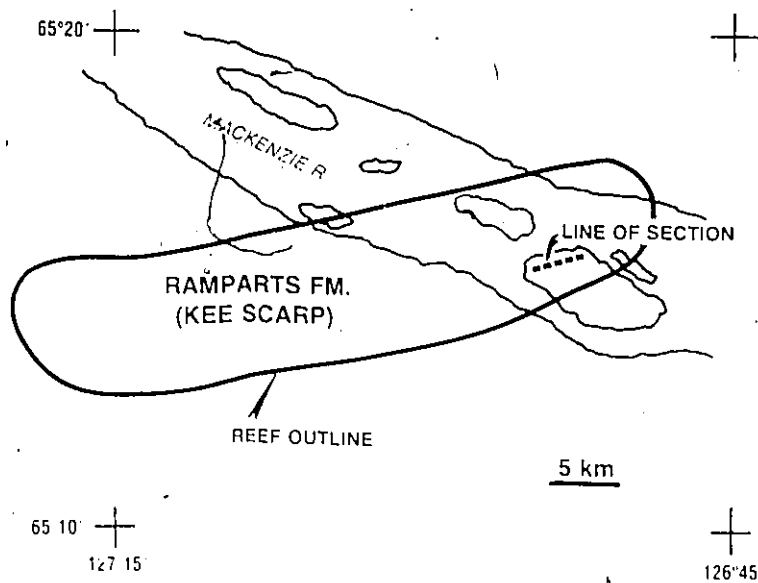
32 m

29 m

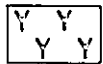
22 m



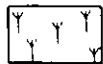
NORMAN WELLS REEF COMPLEX



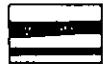
UNDIFFERENTIATED SHOAL SUBFACIES; ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE; LIME PACKSTONE; BULBOUS, ENCRUSTING AND CYLINDRICAL STROMATOPOROID RUDSTONE.



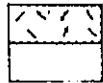
SHOAL SUBFACIES; ROBUST CYLINDRICAL STROMATOPOROID RUDSTONE



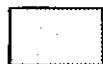
SHOAL SUBFACIES; SMALL CYLINDRICAL STROMATOPOROID RUDSTONE



TIDAL FLAT SUBFACIES, FENESTRAL LIME MUDSTONES



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



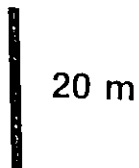
GRAINY SUBFACIES; AMPHIPORA-BEARING PACKSTONE, RUDSTONE;
AMPHIPORA BULBOUS-CYLINDRICAL STROMATOPOROID RUDSTONE



MINOR CYCLE BOUNDARY



MAJOR CYCLE BOUNDARY



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.

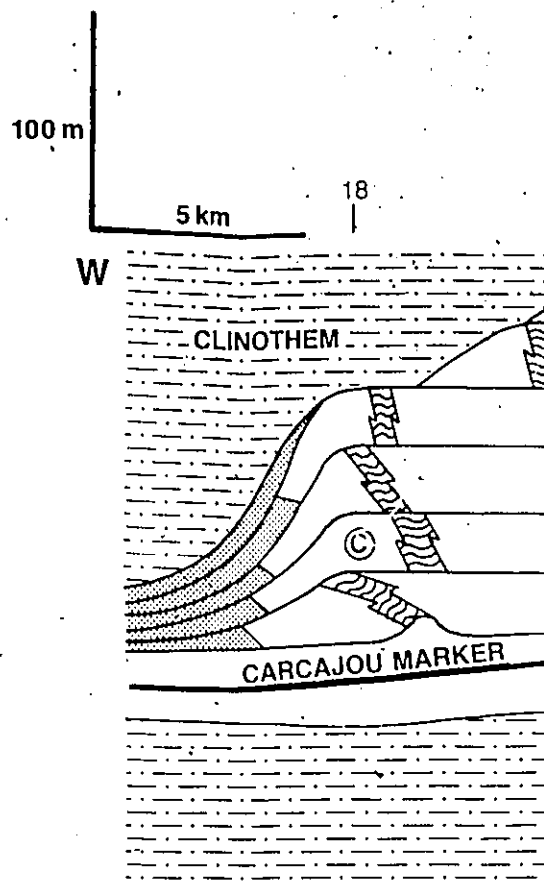
PLATE 5-1

Second-order cycle boundaries
in the reef facies association.

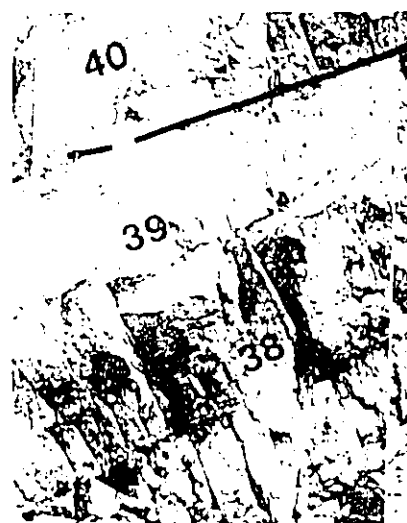
Second-order cycle boundaries in the reef facies association. Aerial view of lowermost three reef cycles in 5-1a. Reef cycle 1 is ~30 m thick. In 5-1b, a dark brown, laminated shale unit (arrows) occupies the basal portion of reef cycle 2 in a foreslope depositional setting. Shallowing-upward trends 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.



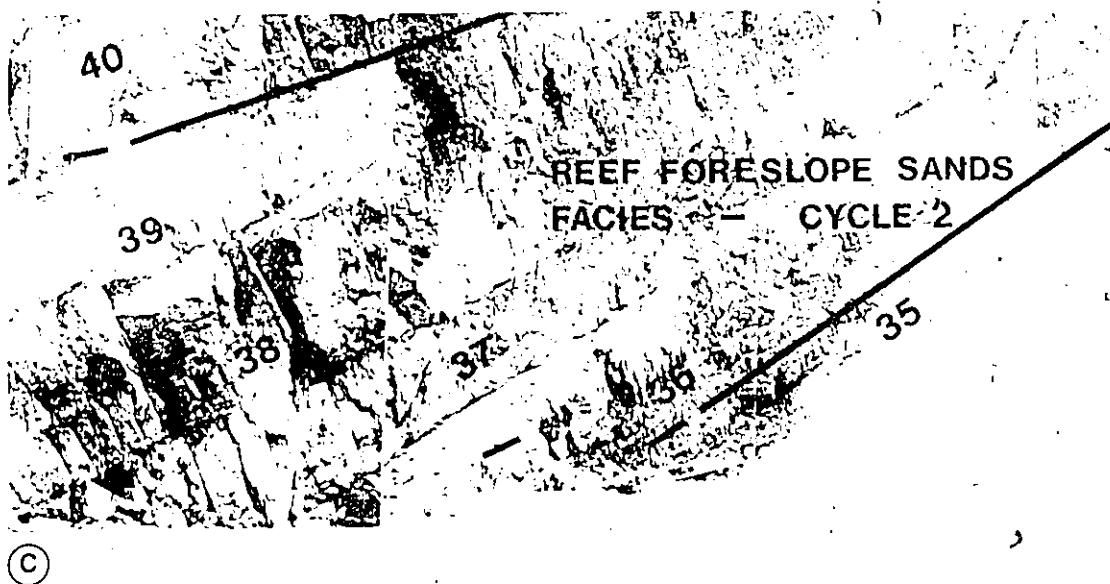
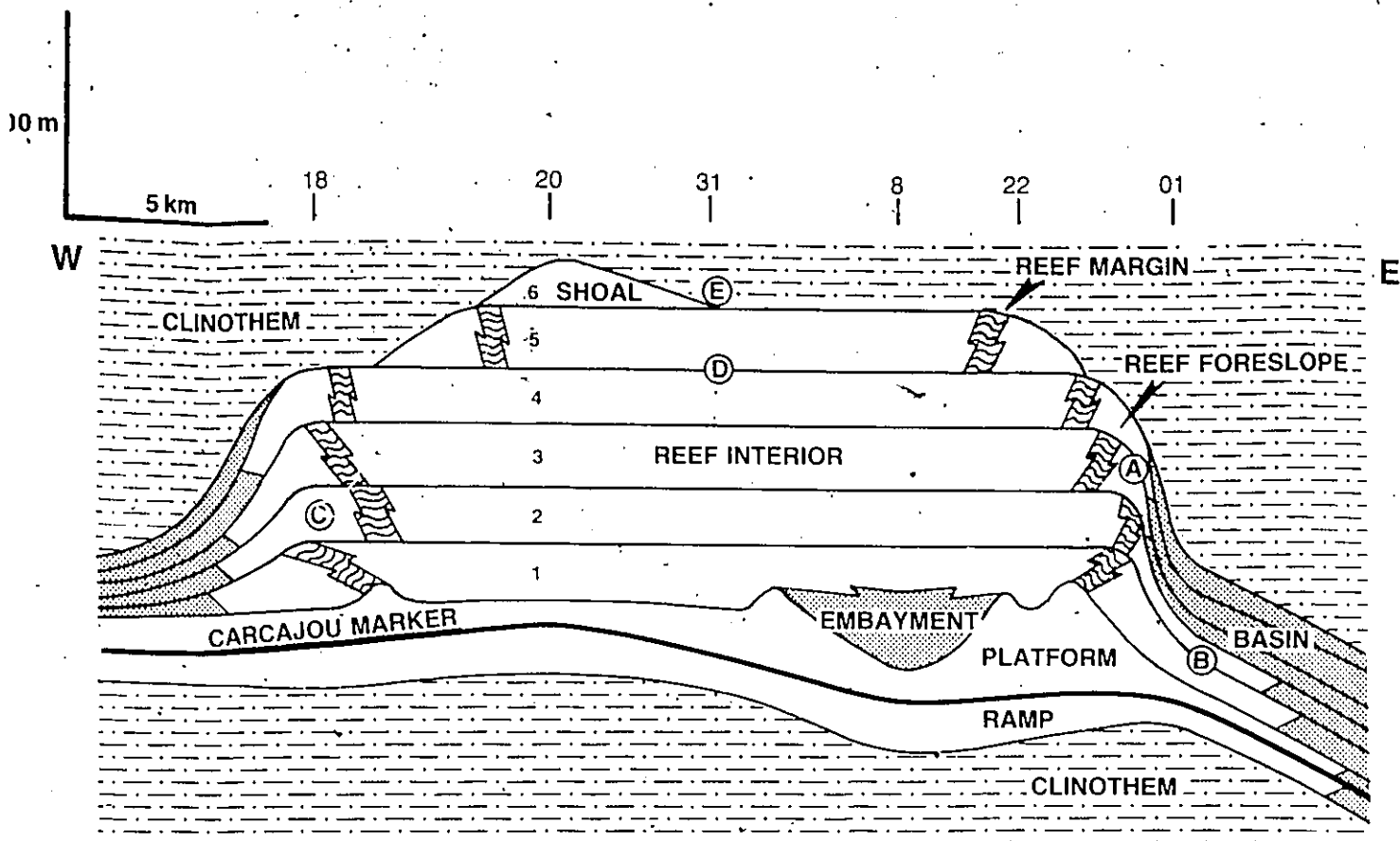
(E)

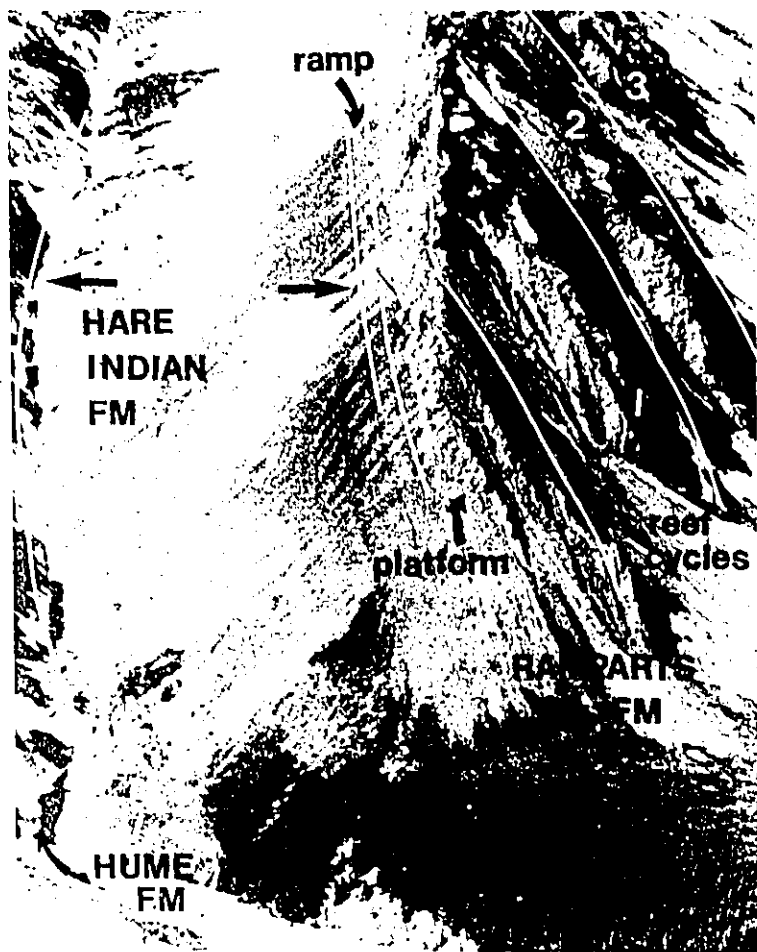
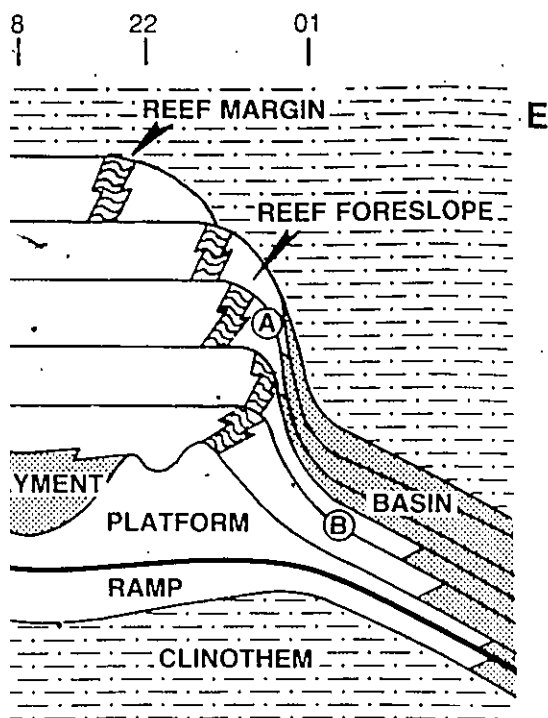


(D)

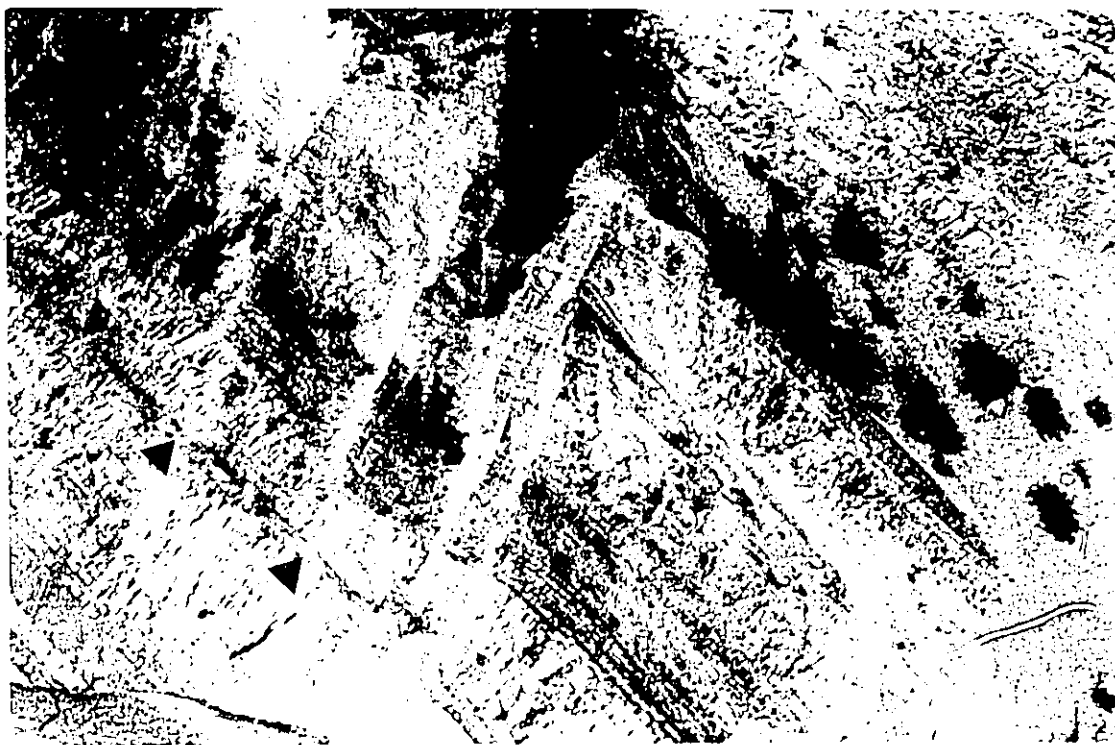
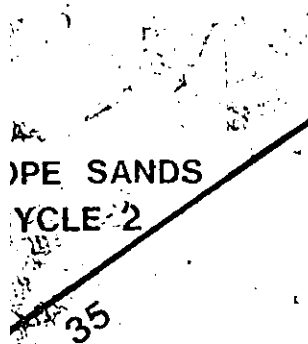


(C)





(A)



(B)

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.

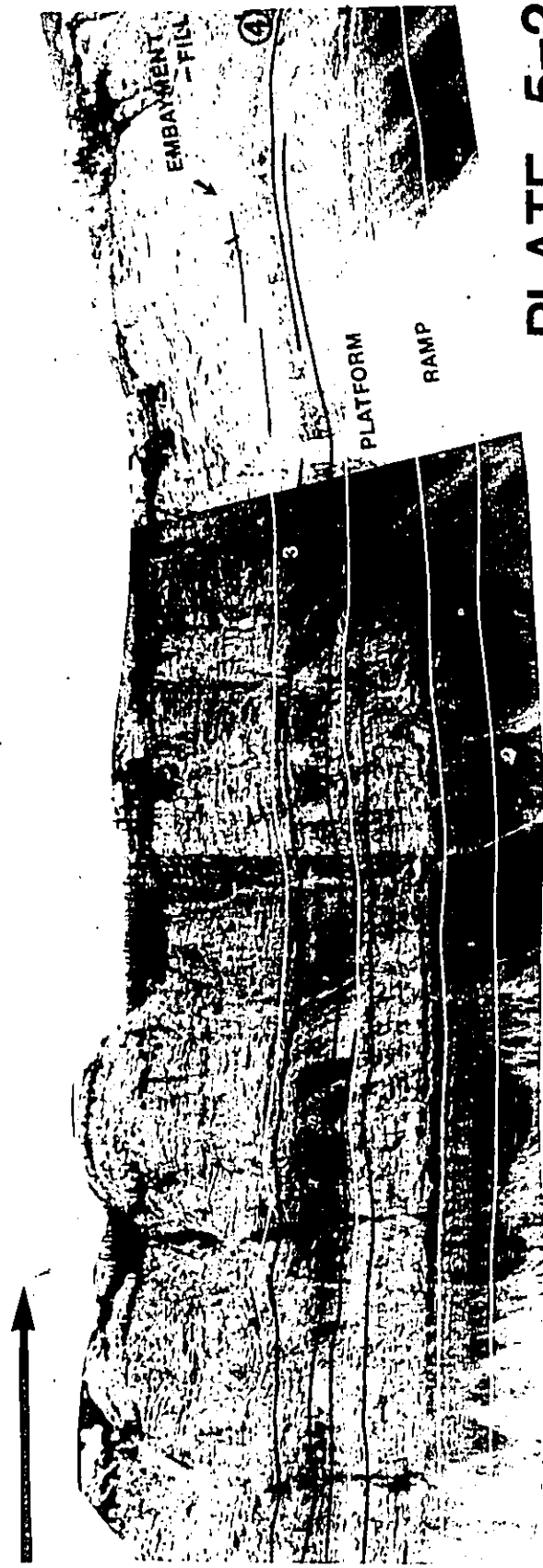
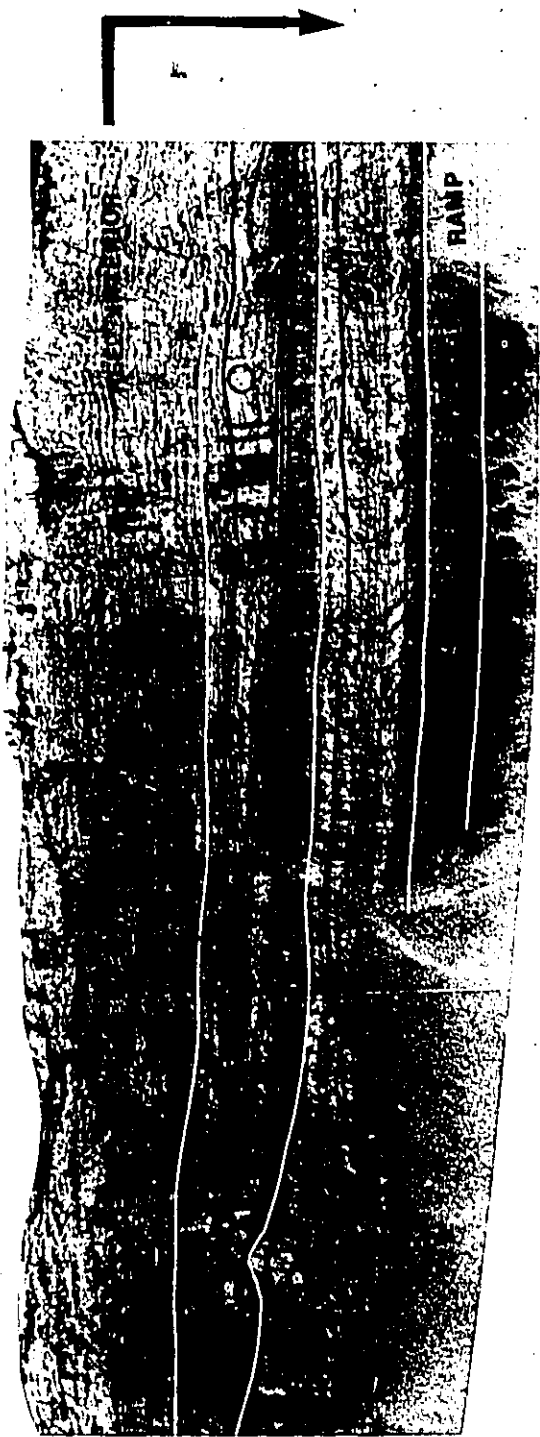


PLATE 5-2

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.

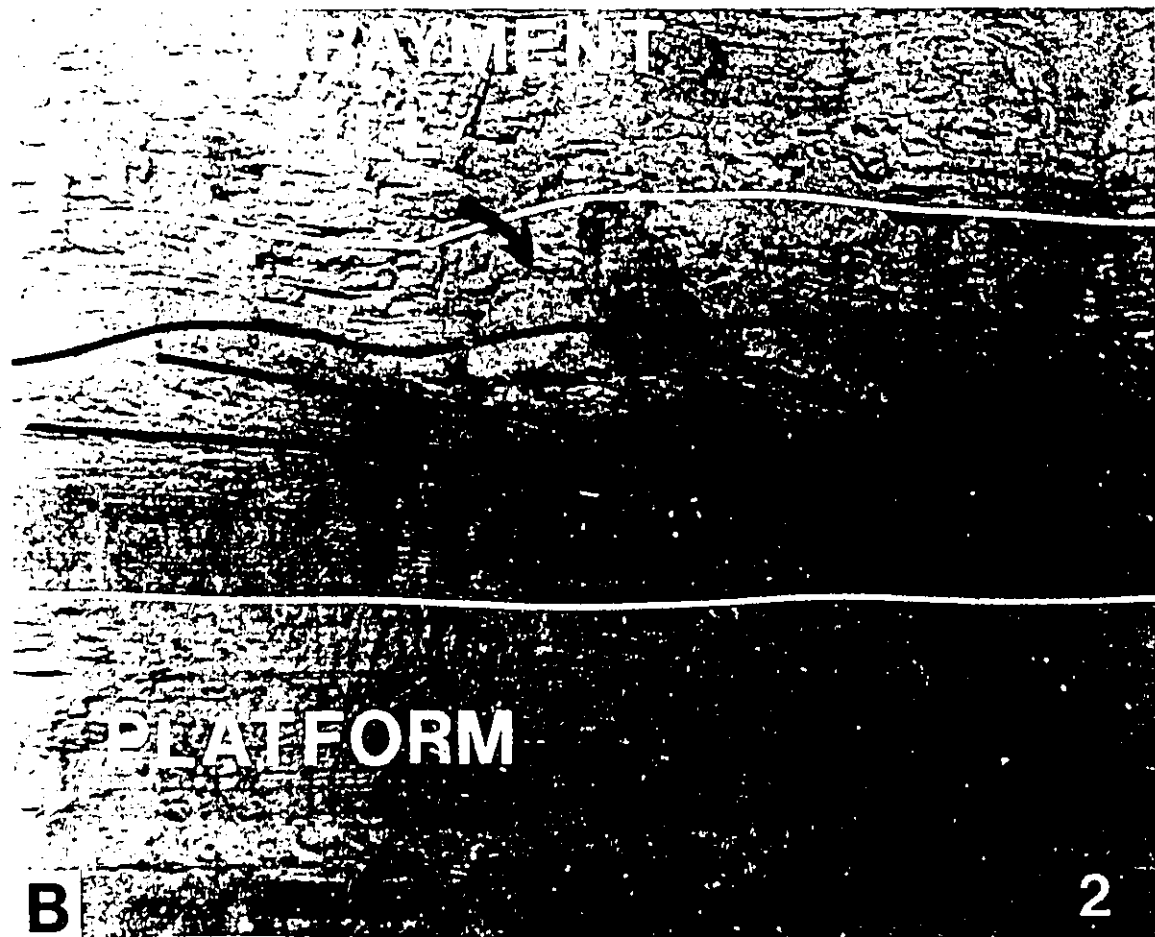
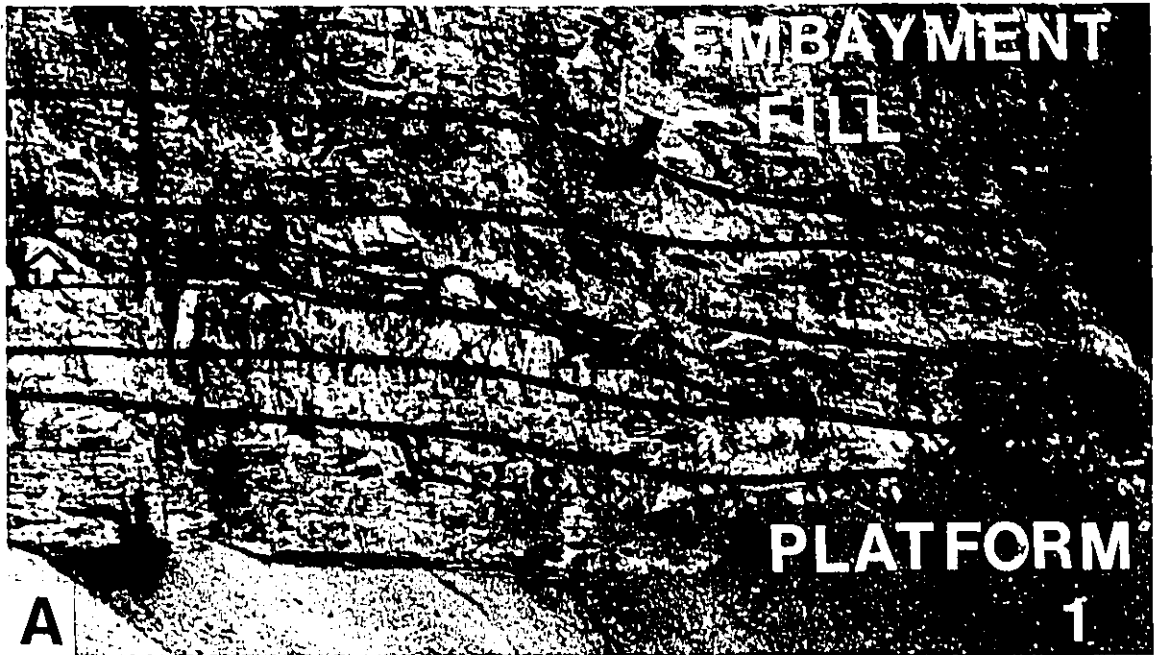


PLATE 5-3

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.

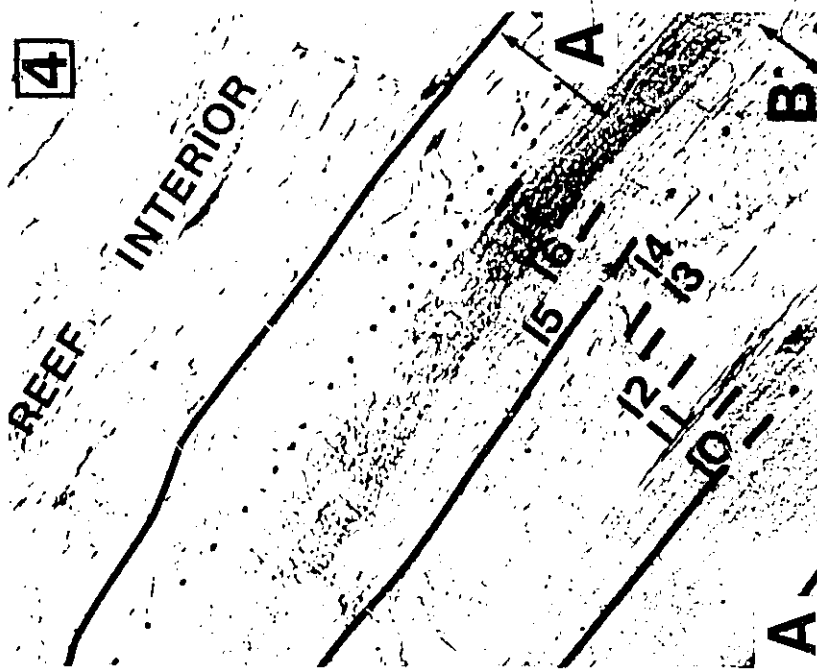


PLATE 5-4

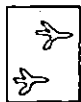
PLATE 5-5

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.

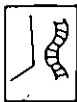
EMBAYMENT - FILL FACIES (REEF CYCLE 1)



SHOAL



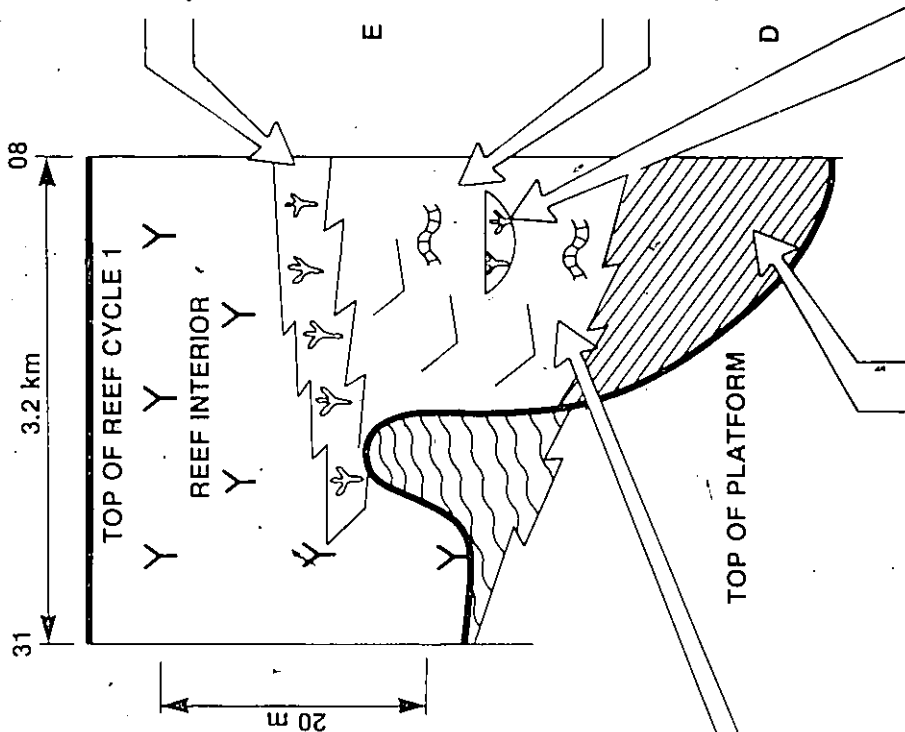
CHANNEL-FILL



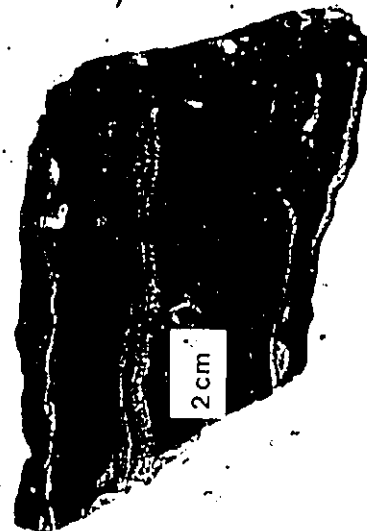
LOWER-MIDDLE FORESLOPE



BASINAL LAMINITES



A



B



C



D



E

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.

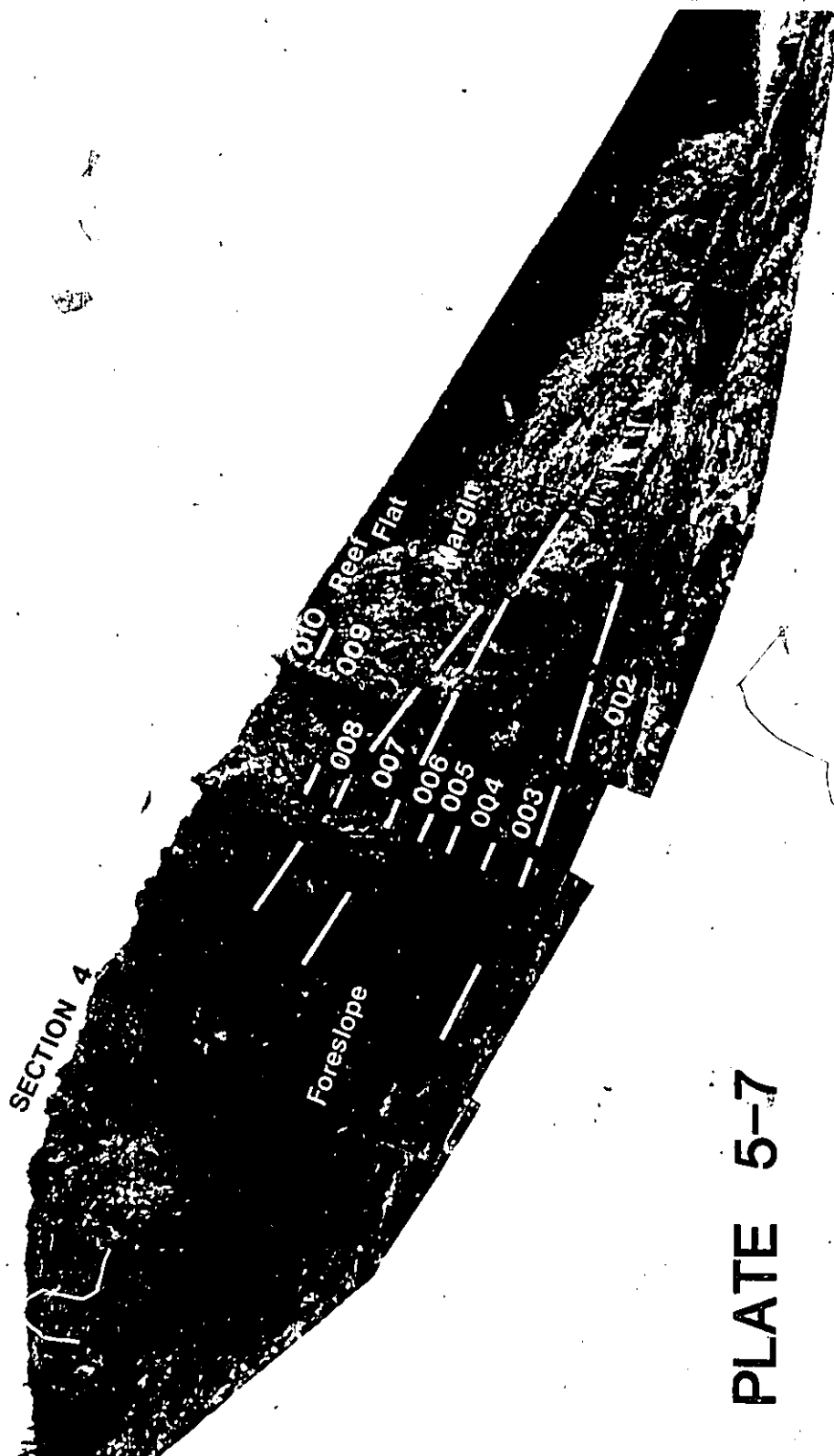


PLATE 5-7

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.

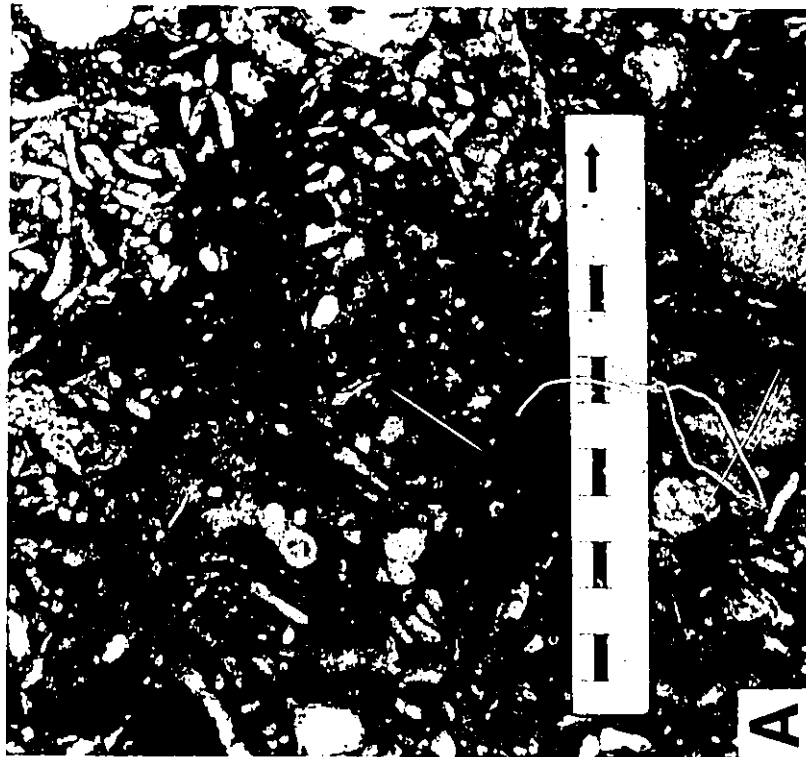
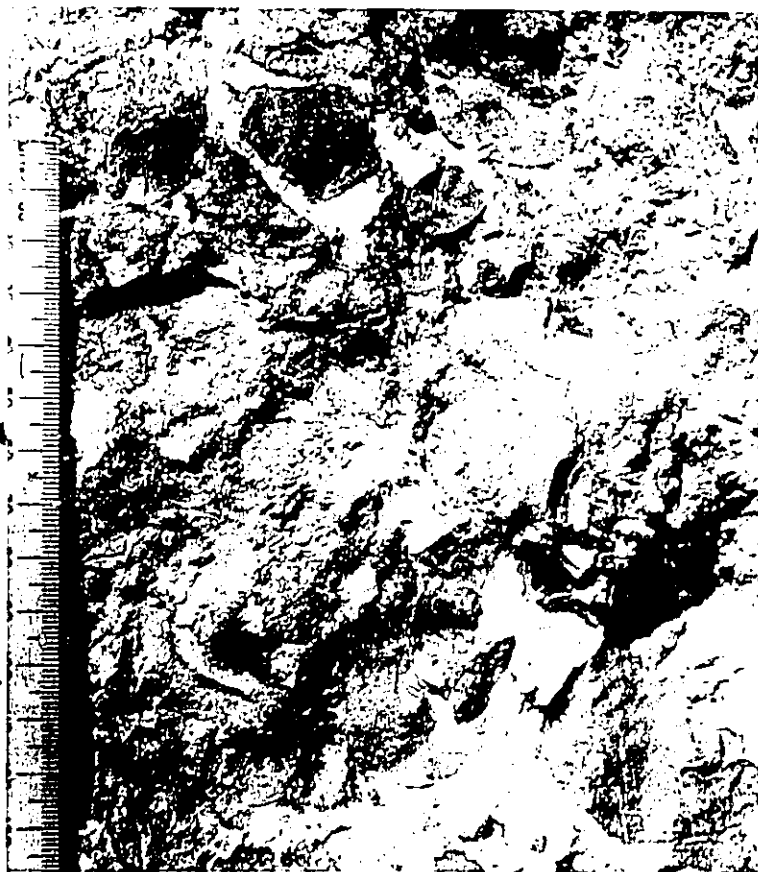


PLATE 5-9

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



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.

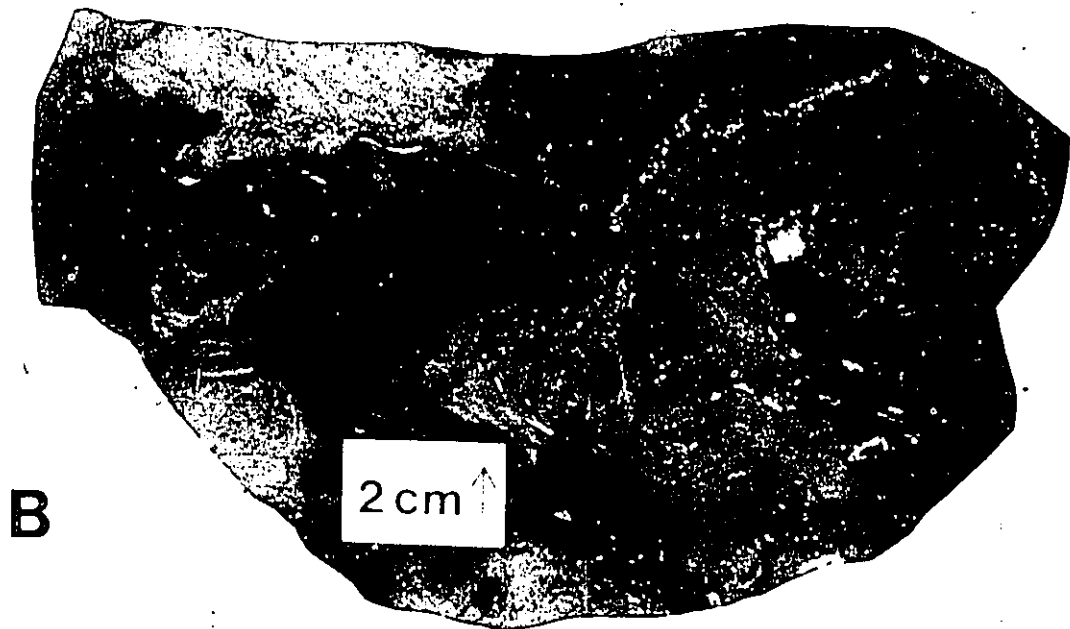
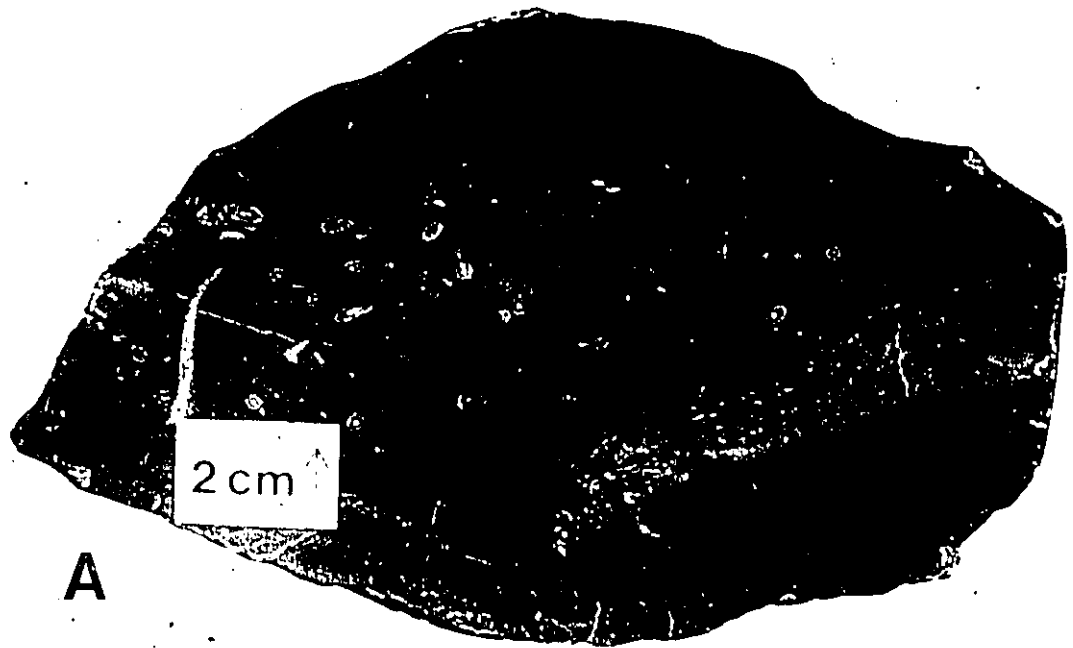


PLATE 5-11

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



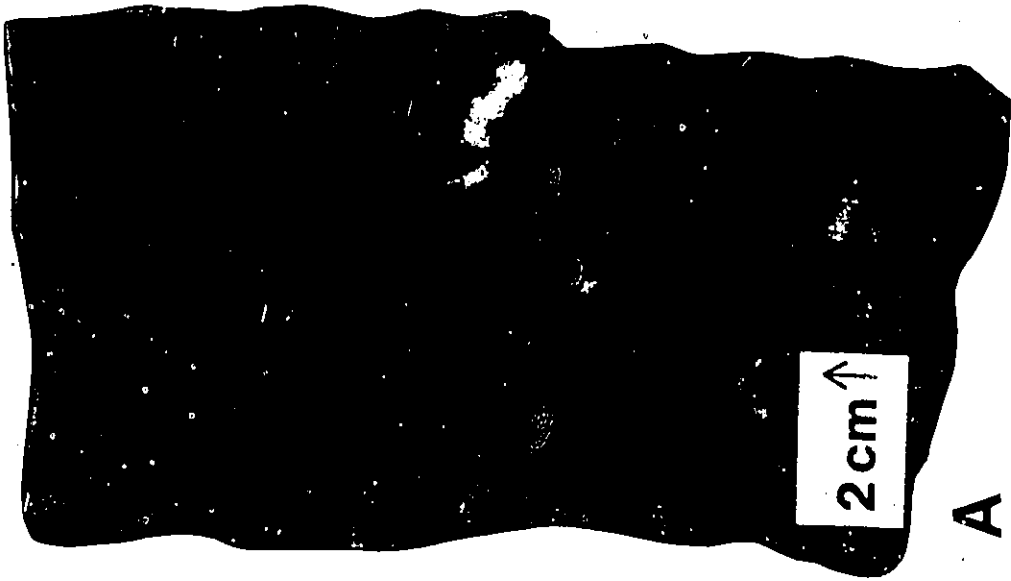
B

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

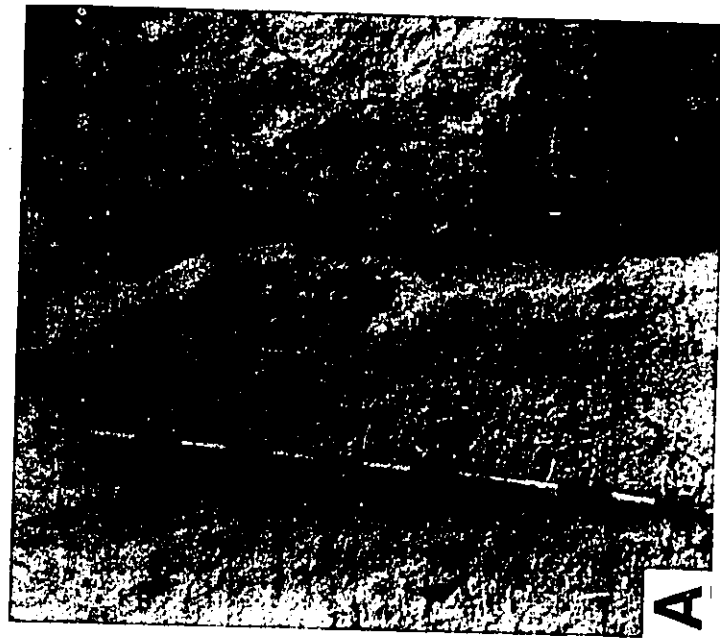


C

PLATE 3-14

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 5-15

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.

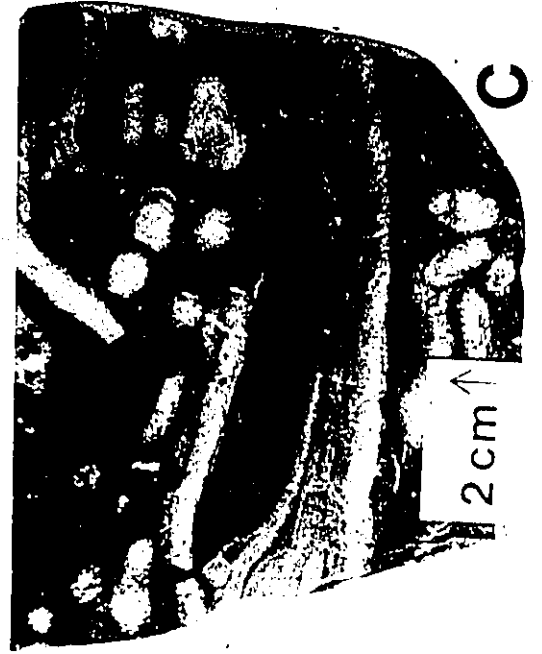
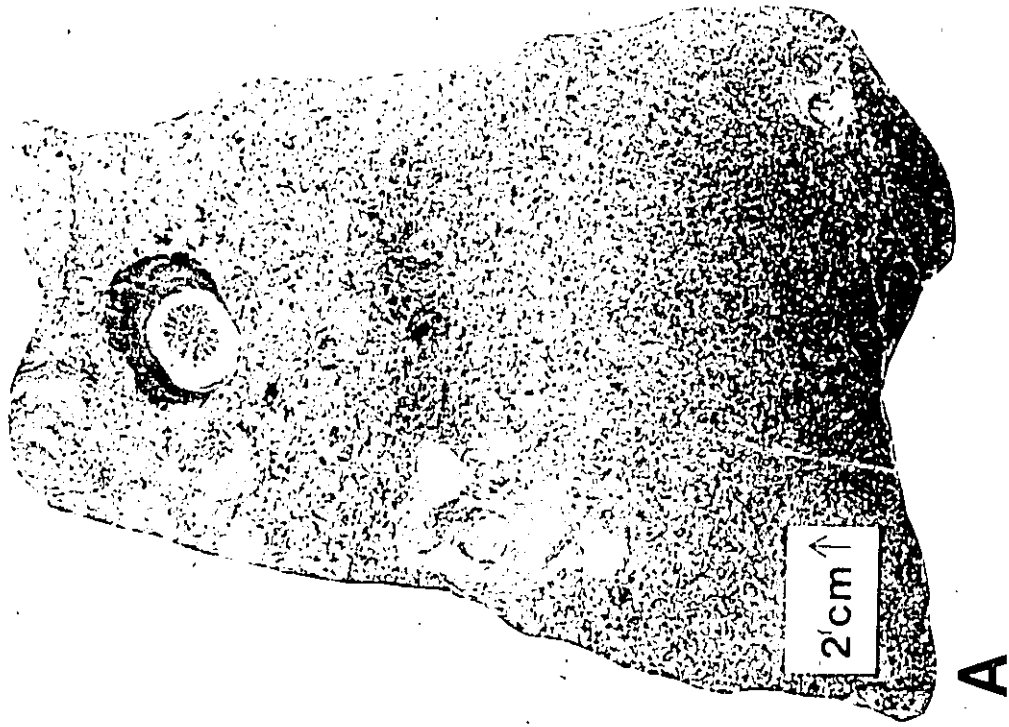


PLATE 5-15

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.

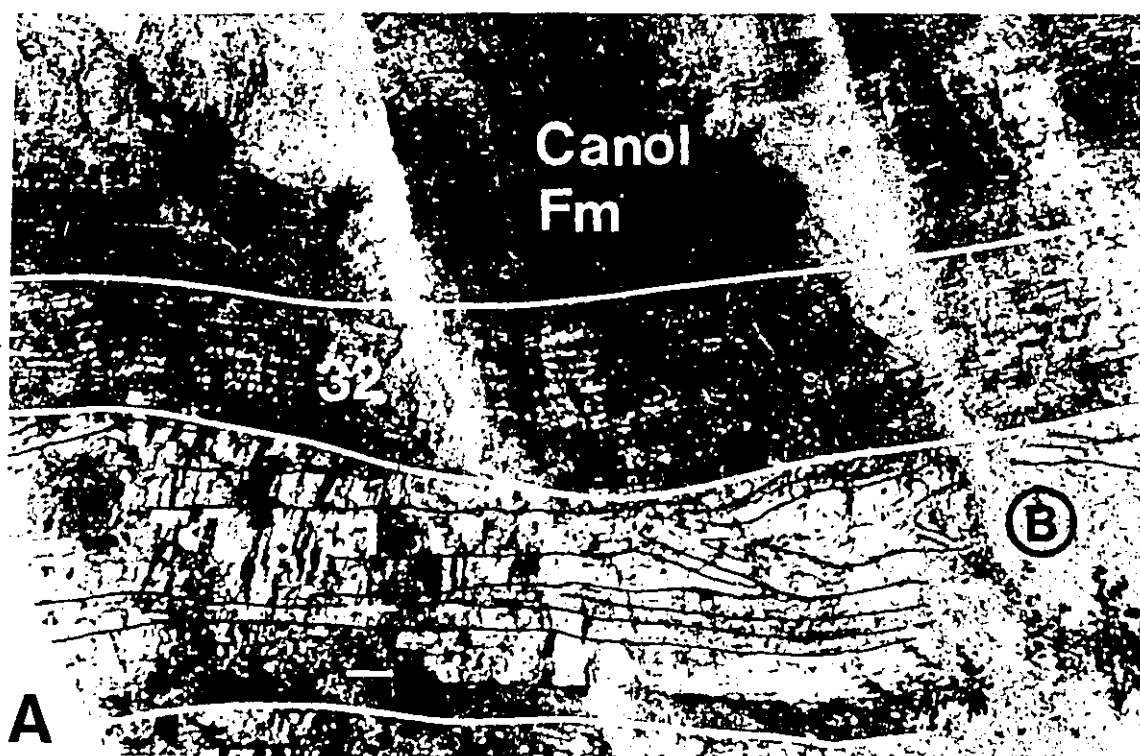


PLATE 5-16

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.

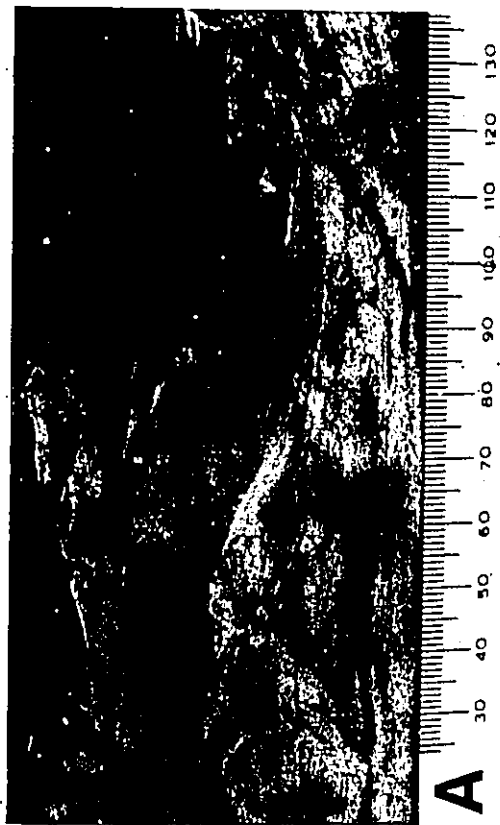


PLATE 5-17

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.

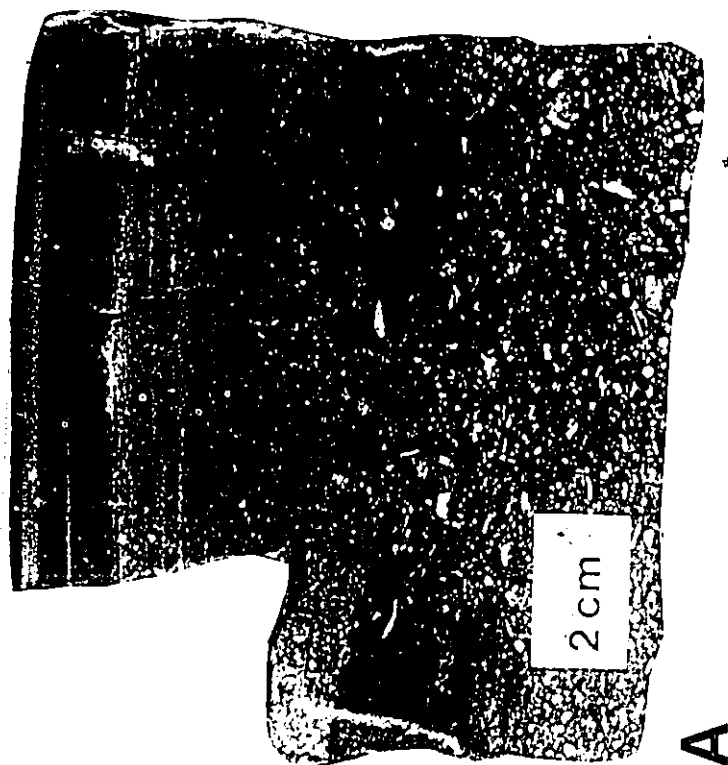
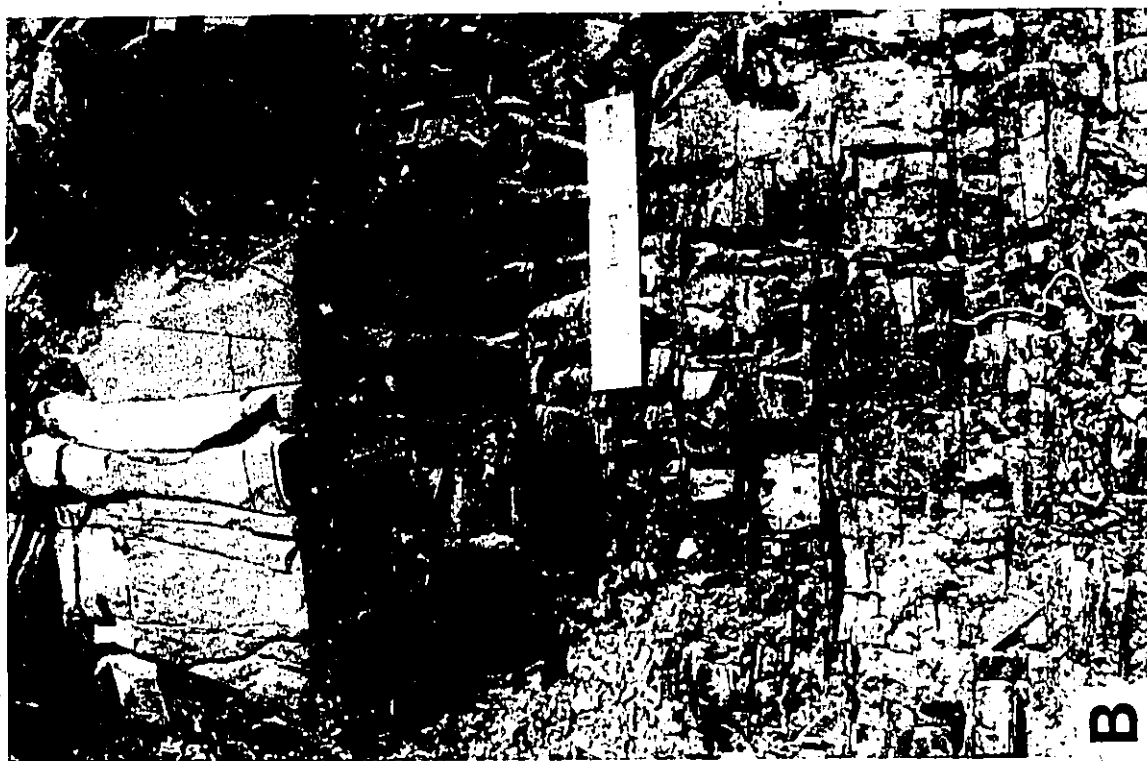


PLATE 5-19

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)



(C)

F31.406-20



(A)

SECTION 02 UNIT 008

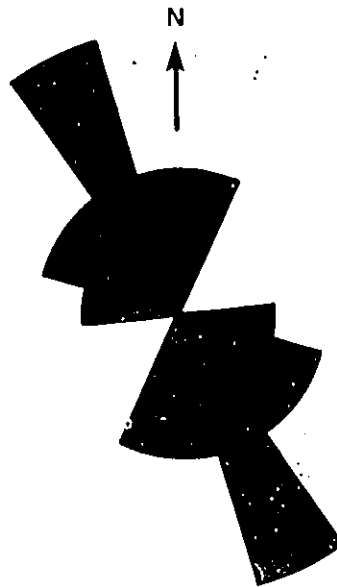
- GROOVE CASTS

- SKIP MARKS

$n = 20$

$O = 139^\circ/319^\circ$

$P = 1.3 \times 10^{-5}$



(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

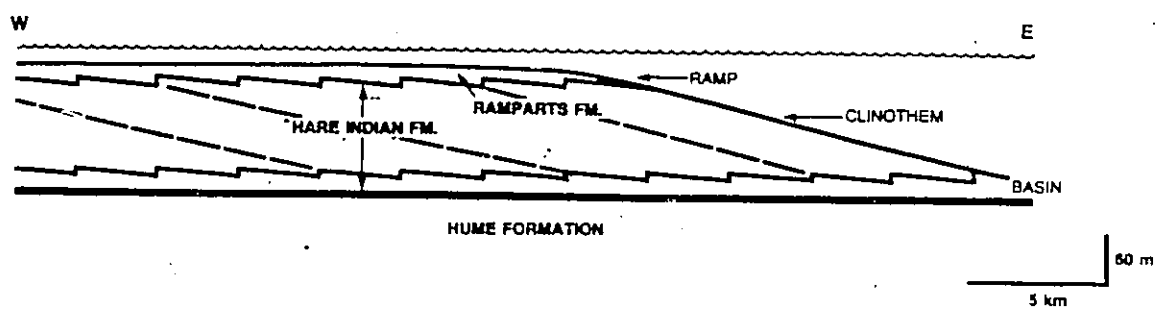
(1) Drowning of the Hume Platform (FIG. 6-1)

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.

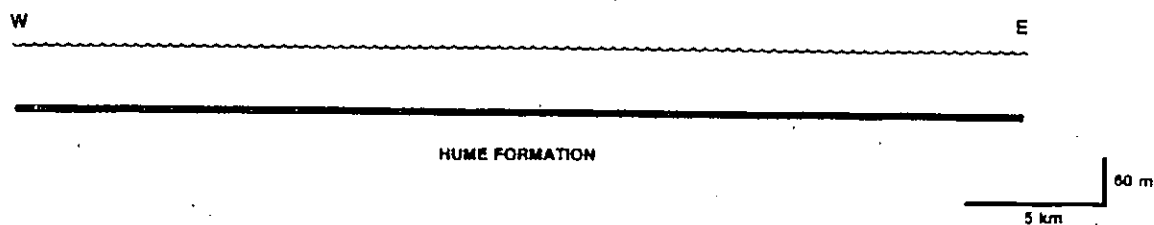


FIG. 6-1 (1) Drowning of the Hume platform.
 (2) Progradation of the Hare Indian clastic wedge and Ramparts ramp facies.

6.2.2 Stages 3 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).

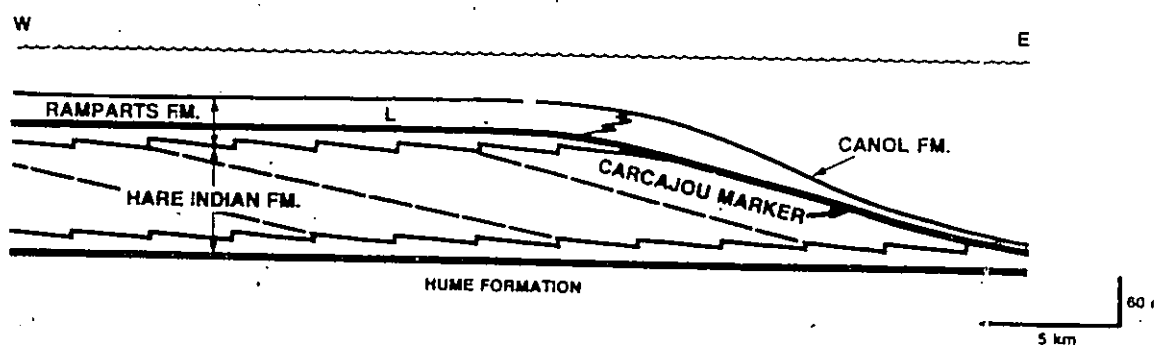
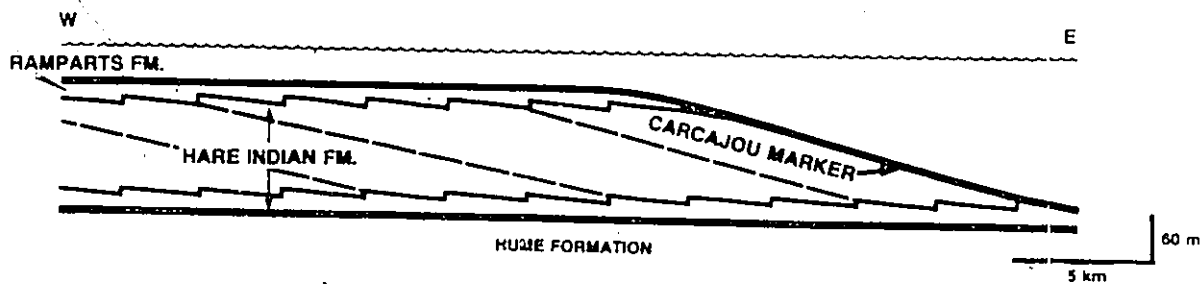
3. TERMINATION OF CLASTIC WEDGE PROGRADATION
— THE CARCAJOU MARKER

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).

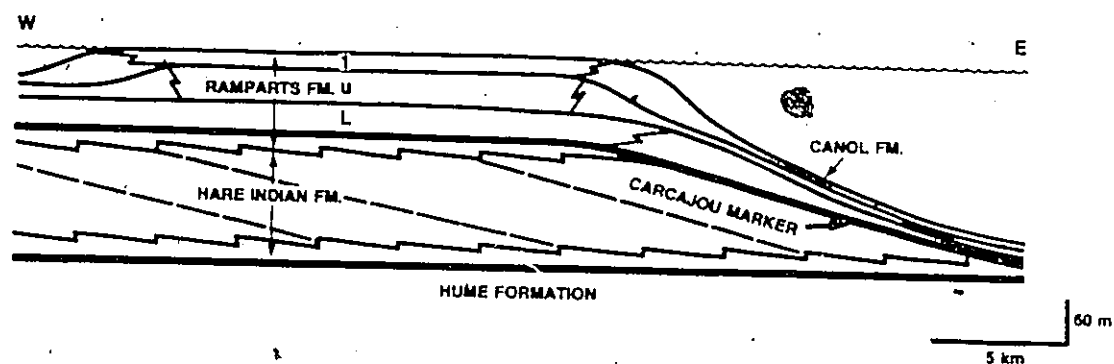


FIG. 6-3 (5) Localized upbuilding of the carbonate platform.
 (6) Reef inception and progradation.

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.

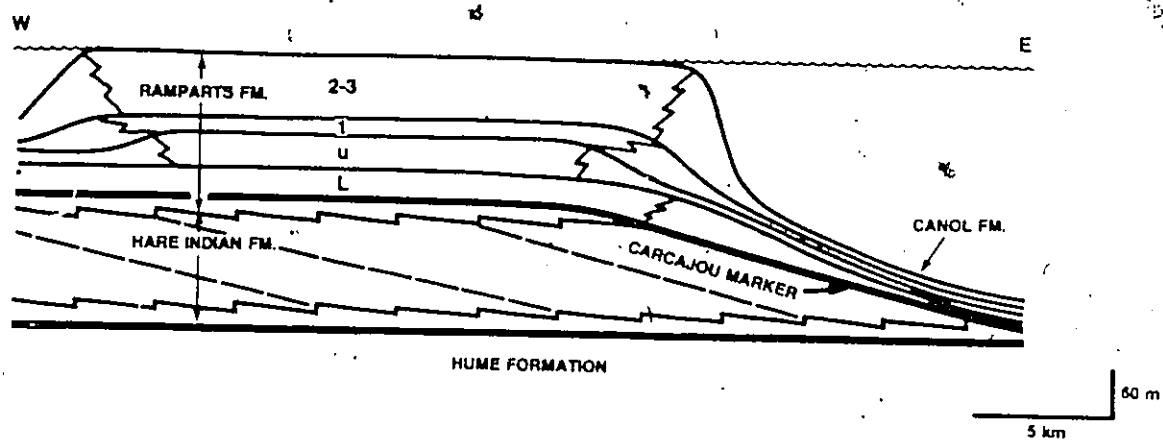


FIG. 6-4 (7) Aggradation of second- and third-order reef cycles.

8. BACKSTEPPING AND SUBSEQUENT AGGRADATION OF FOURTH REEF CYCLE.

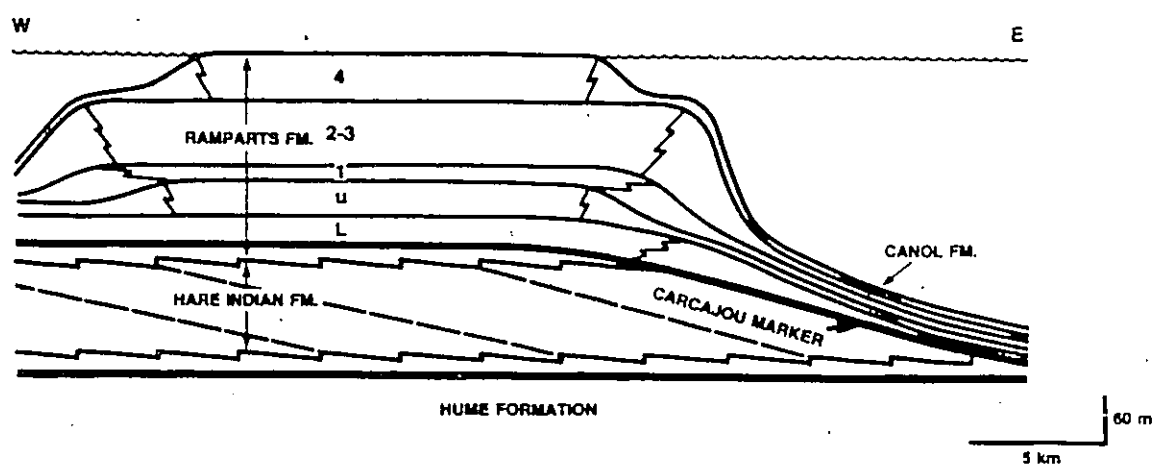


FIG. 6-5 (8) Backstepping and subsequent aggradation of fourth reef cycle.

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.

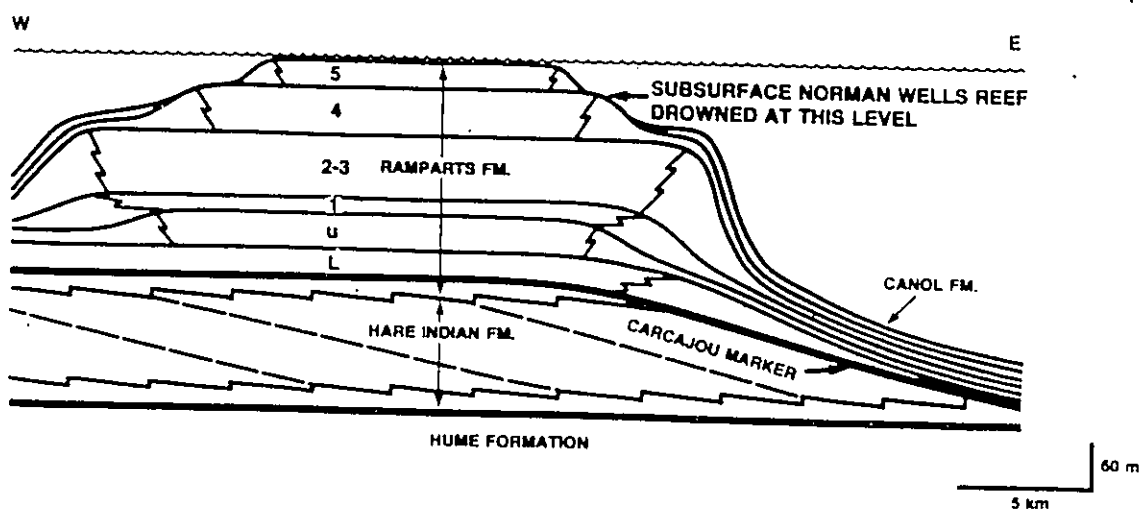


FIG. 6-6 (9) Drowning of the Norman Wells reef complex; backstepping and aggradation of the fifth reef cycle in the Mackenzie Mountains reef complex.

10. AGGRADATION OF SHOAL CYCLE.

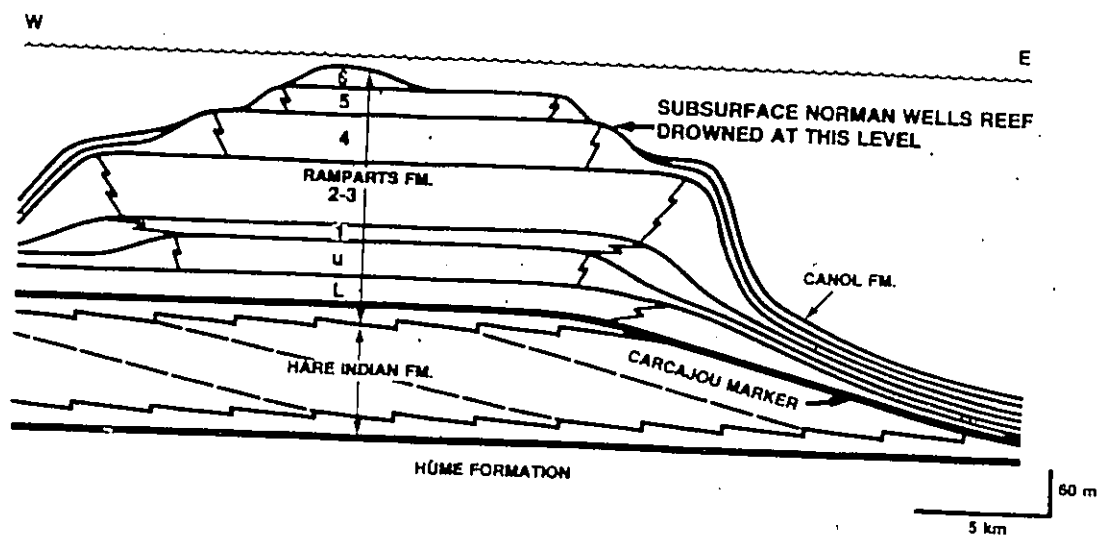


FIG. 6-7 (10) Aggradation of shoal cycle.

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.

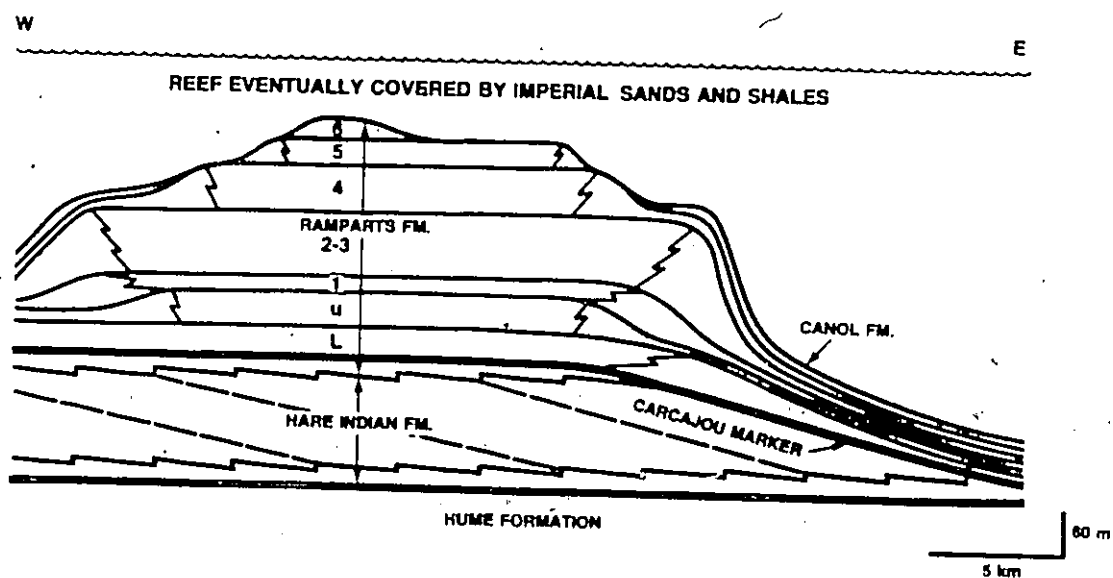


FIG. 6-8 (11) Drowning of the Mackenzie Mountains reef complex.

3

2

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1

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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	0.5 below Hume top	Hume	c-108351	01-003	735-01	<u>Polygnathus parawebbi</u> <u>P. pseudofoliatus</u>	<u>australis zone to lower</u> <u>varcus subzone</u>
	128.5	Hare Indian (upper member)	c-108352	01-006	735-02	<u>Polygnathus linguiformis linguiformis</u> <u>P. varcus</u> <u>P. timorensis?</u>	<u>lower varcus to hermanni-</u> <u>crisatus subzones</u>
	133.0	Hare Indian (upper member)	c-108353	01-008	735-03	<u>Polygnathus linguiformis linguiformis</u> <u>P. timorensis</u>	<u>lower varcus to hermanni-</u> <u>crisatus subzones</u>
	141.5	Hare Indian (upper member)	c-108354	01-010	735-04	<u>Icriodus brevis</u>	<u>lower varcus to lower</u> <u>hermanni-crisatus</u> <u>subzones</u>
	160.0	Hare Indian (upper member)	c-108356	01-013	735-06	<u>Icriodus brevis</u> <u>Polygnathus linguiformis linguiformis</u> <u>P. ansatus</u>	<u>middle varcus subzone</u>
	164.5	Hare Indian (upper member)	c-108357	01-015	735-07	<u>Icriodus brevis</u> <u>Polygnathus linguiformis linguiformis</u> <u>P. varcus</u>	<u>probably lower varcus to</u> <u>lower hermanni-crisatus</u> <u>subzones</u>
Base of Ramparts at 165.5 m	168.0	Ramparts (ramp)	c-108358	01-016	735-08	<u>Icriodus brevis</u> <u>Polygnathus linguiformis linguiformis</u> <u>P. ansatus</u>	<u>middle varcus subzone</u>
	175.0	Ramparts (lower platform - "Carcajou Marker")	c-108359	01-018	735-09	<u>Icriodus brevis</u> <u>I. cf. I. difficilis</u> <u>Polygnathus linguiformis linguiformis</u> <u>P. timorensis</u>	<u>lower varcus to lower</u> <u>hermanni-crisatus</u> <u>subzones</u>

SECTION 01 (cont'd) HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONCOMITS	AGE
177.5	Ramparts (middle platform)	c-108360	01-020	735-10	<u>Icriodus difficilis</u> <u>Ozarkodina brevis</u> <u>Polygnathus dubius</u> <u>P. xylus xylus</u> <u>Schmidtognathus peracutus</u>	<u>disparilis zone, lower</u> part
181.5	Ramparts (middle platform)	c-108361	01-022	735-11	<u>Elsonella rhenana</u> <u>Palmatolepis disparata</u> <u>P. disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u> <u>S. ? sp.</u>	<u>disparilis zone, lower</u> part
184.5	Ramparts (upper platform)	c-108362	01-023	735-12	<u>Elsonella rhenana</u> <u>Ozarkodina semialternans</u> <u>Palmatolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u>	<u>disparilis zone, lower</u> part
190.5	Ramparts (reef cycle 1)	c-108363	01-025	735-13	<u>Polygnathus cristatus</u> <u>P. dengleri</u> <u>P. xylus xylus</u>	<u>disparilis zone, upper</u> part
193.5	Ramparts (reef cycle 1)	c-108364	01-026	735-14	<u>Elsonella rhenana</u> <u>Ozarkodina semialternans</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>P. dengleri</u>	<u>disparilis zone, upper</u> 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>Palmatolepis disparalvea</u> <u>Polygnathus cristatus</u> <u>P. dengleri</u> <u>P. dubius</u> <u>P. norrisi</u> <u>P. sp.</u>	lowermost <u>asymmetricus</u> zone
199.5	Ramparts (reef cycle 2)	c-108366	01-028	735-16	<u>Ozarkodina brevis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>P. norrisi</u> <u>P. sp.</u>	lower most <u>asymmetricus</u> zone
202.5	Ramparts (reef cycle 2)	c-108367	01-030	735-17	<u>Ozarkodina brevis</u> <u>Polygnathus dubius</u> <u>P. xylus xylus</u> <u>P. sp.</u>	lower <u>hermanni-cristatus</u> subzone to lower <u>asymmetricus</u> zone
207.5	Ramparts (reef cycle 3)	c-108369	01-032	735-19	<u>Polygnathus dubius</u> <u>P. xylus xylus</u> <u>P. sp.</u>	probably lower <u>hermanni-</u> <u>cristatus</u> subzone to lower <u>asymmetricus</u> zone
219.8	Canol	c-108372	01-035	735-22	<u>Icriodus</u> sp. <u>Palmatolepis</u> cf. <u>P. transitans</u> <u>Polygnathus varcus</u> <u>P. xylus xylus</u>	probably lower <u>asymmetricus</u> zone
231.5	Canol	c-108375	01-039	735-25	<u>Ancyrodella</u> (possibly <u>A. nodosa</u>) <u>Ancyrognathus</u> ? sp. (possibly <u>A. ancyrognathoides</u>) <u>Palmatolepis subrecta</u> <u>Polygnathus</u> sp.	possibly middle <u>asymmetricus</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>Polygnathus 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>Polygnathus linguiformis linguiformis</u> <u>P. varcus</u> <u>P. timorensis ?</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones
	171.6	Ramparts (ramp)	c-76900	03-016	840-08	<u>Icriodus sp.</u> <u>Polygnathus linguiformis linguiformis</u> <u>P. varcus</u>	<u>ensensis</u> to lower <u>asymetricus</u> zones
	181.1	Ramparts ("Carcajou Marker")	c-76899	03-018	840-09	<u>Icriodus sp.</u> <u>Ozarkodina brevis</u> <u>Polygnathus cf. P. varcus</u>	<u>ensensis</u> to middle <u>asymetricus</u> zones, possibly middle to upper <u>varcus</u> subzone
Base of Ramparts at 143.3 m	191.3	Ramparts (lower platform)	c-76897	03-021	840-11	<u>Icriodus sp.</u> <u>Polygnathus timorensis</u> <u>P. xylus xylus</u>	lower <u>varcus</u> subzone to probably lowermost <u>asymetricus</u> zone
	203.9	Ramparts (lower platform)	c-76896	03-024	840-12	<u>Icriodus sp.</u> <u>Ozarkodina brevis</u> <u>Polygnathus dubius</u> <u>P. varcus</u>	lower <u>hermanni-cristatus</u> subzone to lower <u>asymetricus</u> zone
	210.1	Ramparts (middle platform)	c-76895	03-025	840-13	<u>Ozarkodina brevis</u>	<u>ensensis</u> to middle <u>asymetricus</u> zones

SECTION 04	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. 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>Polygnathus xylus xylus</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>Polygnathus 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>Polygnathus 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.	CONCONENTS	AGE
Ridge Section 65° 16' 30" W 128° 47' 30" W. 40 m distance from Section 04 at bearing 290°	213.4	Ramparts (middle platform)	c-60197	05-001	841-04	Icriodus sp. Ozarkodina brevis Polygnathus varcus P. xylus xylus	lower varcus subzone to lower <u>asymetricus</u> zone
	217.3	Ramparts (upper platform)	c-60198	05-002	841-05	Ozarkodina brevis Polygnathus timorensis P. xylus xylus Schmidtognathus peracutus ?	probably hermanni- cratatus subzone to <u>asymetricus</u> zone
	221.1	Ramparts (reef cycle 1)	c-60199	05-003	841-06	Elsonella rhenana Ozarkodina brevis Polygnathus cf. P. collieri P. dubius P. xylus xylus	probably upper <u>disparilis</u> zone to lower <u>asymetricus</u> zone
	226.3	Ramparts (reef cycle 1)	c-60200	05-004	841-07	Icriodus sp. Ozarkodina brevis Polygnathus dubius P. varcus	probably lower hermanni- cratatus subzone to lower <u>asymetricus</u> zone

SECTION 06	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONTENTS	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	Icriodus sp. Polygnathus xylus xylus P. ovatinodosus	middle varcus subzone to lower asymetricus zone
	205.5	Ramparts (middle platform)	c-108-410	06-008	841-10	Icriodus difficilis Ozarkodina brevis O. semialternans Polygnathus obolus	lower hermanni-cristatus subzone to lowermost asymetricus 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' N. Approximately 500 m distance at bearing 290° from Section 01.	0.3 m below Hume top	Hume	c-60179	07-001	736-01	<u>Polygnathus angustipennatus</u> <u>P. linguiformis linguiformis</u> <u>P. parawebbi</u>	<u>australis to ensensis</u> zones
	85.6	Hare Indian (upper member)	c-60180	07-002	736-02	<u>Icriodus brevis</u> <u>Polygnathus 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 cf. I. brevis</u> <u>Polygnathus 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>Polygnathus 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>Polygnathus 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>Polygnathus 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 sp.</u> <u>Polygnathus 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>Polygnathus timorensis</u> <u>P. xylus xylus</u>	lower <u>varcus</u> to lower <u>hermanni-cristatus</u> subzones

SECTION 07 (cont'd) HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	COM. NO.	CONCOMITANTS	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 zone, lower</u> part
186.4	Ramparts (upper platform)	c-60190	07-024	736-12	<u>Palmatolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>Schmidtognathus peracutus</u>	<u>disparilis zone, lower</u> part
192.3	Ramparts (reef cycle 1)	c-60191	07-025	736-13	<u>Ozarkodina brevis</u> <u>Palmatolepis disparalvea</u> <u>Polygnathus cristatus</u> <u>P. timorensis</u> <u>P. xylus xylus</u>	<u>disparilis zone, lower</u> part
206.6	Ramparts (reef cycle 1)	c-60192	07-026	736-14	<u>Ozarkodina brevis</u> <u>O. semialternans</u> <u>Palmatolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dengleri</u> <u>P. timorensis</u> <u>P. xylus xylus</u> <u>Schmidtognathus peracutus</u>	<u>disparilis zone, upper</u> part
209.6	Ramparts (reef cycle 1)	c-60193	07-027	736-15	<u>Ozarkodina brevis</u> <u>Palmatolepis disparilis</u> <u>Polygnathus cristatus</u> <u>P. dubius</u> <u>P. ovatinodosus</u>	<u>disparilis zone, upper</u> part

SECTION 08	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONCONENTS	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>Polygnathus 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>Polygnathus varcus</u>	<u>ensensis</u> to lower <u>asymetricus</u> zones
Base of Ramparts at 152 m	171.0	Ramparts (ramp)	c-108414	08-008	842-04	<u>Icriodus brevis</u> <u>Polygnathus linguiformis</u> <u>linguiformis</u> <u>P. ansatus</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>Polygnathus varcus</u>	<u>ensensis</u> to lower <u>asymetricus</u> zones
	199.2	Ramparts (reef cycle 1)	c-108418	08-016	842-08	<u>Icriodus</u> cf. <u>I. difficilis</u> <u>Polygnathus</u> cf. <u>P. ovatinodosus</u>	probably middle <u>varcus</u> subzone to lower <u>asymetricus</u> zones

SECTION 15	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CONCOMITS	AGE
Gayna River (eastern bank) 65° 18' W 129° 21' W	198.0	Ramparts (ramp)	c-76892	15-017	Icriodus cf. <i>I. difficilis</i> <i>Ozarkodina brevis</i> <i>Polygnathus xylus xylus</i>	lower varcus subzone to lower <u>asymmetricus</u>
Base of Ramparts at 185 m	198.9	Ramparts ("Carcajou Marker")	c-76883	15-081	Icriodus sp. <i>Polygnathus linguiformis linguiformis</i> <i>P. varcus</i>	ensensis to lower <u>asymmetricus</u> zones
	199.1	Ramparts (lower platform)	c-76884	15-019	Icriodus sp. <i>Polygnathus linguiformis linguiformis</i> <i>P. varcus</i>	probably ensensis to lower <u>asymmetricus</u> zones
	205.7	Ramparts (lower platform)	c-76885	15-020	<i>Polygnathus xylus xylus</i> ?	probably ensensis to lower <u>asymmetricus</u> zones
	215.1	Ramparts (lower platform)	c-76886	15-023-4b	<i>Polygnathus xylus xylus</i> ?	probably ensensis to lower <u>asymmetricus</u> zones
Base of Canal at 218.0 m	218.4	Canal	c-76888	15-024	Icriodus <i>difficilis</i> <i>Palmatolepis disparilis</i> <i>Polygnathus cristatus</i> <i>P. cristatus</i> transitional to <i>Palmatolepis disparilis</i> <i>P. dengleri</i> <i>P. dubius</i> <i>P. norrisi</i>	lowermost <u>asymmetricus</u> zone

SECTION 18	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	COL. NO.	CONODONTS	AGE
Creek Section 65°17'W 129°11'W	170.8	Hare 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>Polygnathus varcus</u>	probably middle to upper <u>varcus</u> subzones
	186.8	Ramparts (ramp)	c-76868	GG-01-09-4a	830-17	<u>Polygnathus ansatus</u>	middle <u>varcus</u> subzone
	333.4	Ramparts (reef cycle 4)	c-198381	18-047-c	812-01	<u>Ozarkodina brevis</u>	<u>ensis</u> to middle <u>asymmetricus</u> zones

SECTION 20	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONCOMITS	AGE
Creek Section 65° 17' W 129° 04' W	189.3	Hare Indian (upper member)	c-99820	GG-02-01-4a	829-01	<u>Icriodus brevis</u> <u>I. difficilis</u> <u>Polygnathus linguiformis linguiformis</u>	lower varcus 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>Polygnathus linguiformis linguiformis</u> <u>P. xylus xylus</u> <u>P. sp.</u>	lower varcus to lower <u>hermanni-cristatus</u> subzones
	199.3	Ramparts (ramp)	c-99830	GG-02-06-4b	829-11	<u>Ozarkodina cf. O. semialternans</u> <u>Polygnathus varcus</u>	possibly middle varcus subzone to lowermost <u>asymmetricus</u> zone
	201.3	Ramparts (ramp)	c-99832	GG-02-07-4a	829-13	<u>Icriodus brevis</u> <u>Polygnathus timorensis</u>	lower varcus 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>Polygnathus lingoiformis lingoiformis ?</u> <u>P. varcus ?</u>	possibly middle and upper varcus subzones
Top of Hare Indian at 55 m	91.3	Canol	c-126428	25-021-5c	895-05	<u>Elsonella chenana</u> <u>Icriodus sp.</u> <u>Ozarkodina semialternans</u> <u>Palaeolepis disparilis</u> <u>Polygnathus dengleri</u> <u>P. dubius</u> <u>P. xylus xylus ?</u>	<u>disparilis zone, upper</u> part

SECTION 31	HEIGHT (m)	FORMATION	G.S.C. LOCATION	FIELD UNIT	CON. NO.	CONCOMITS	AGE
Stream Cut 65° 16' 30" N 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>Polygnathus xylus xylus</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	3.18	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