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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
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V O L U M E I

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

by:

IAIN D. MUIR

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FRONTISPIECE

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

Supervisor

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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 clinothem 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 clinothem 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.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

CHAPTER I: General Introduction

CHAPTER I: Figures

CHAPTER I: Tables

CHAPTER I: Plates

CHAPTER II: Shallowing-Upward Cycles in the Hare Indian-Ramparts Succession: A Method of Correlating Depositional Facies

CHAPTER II: Figures

CHAPTER II: Tables

CHAPTER II: Plates

CHAPTER III: Sedimentology and Paleoenvironmental Reconstruction of a Basin-Fill Succession: Hare Indian Formation and Ramparts Formation (Lower "Ramp" Member)

CHAPTER III: Figures

CHAPTER III: Tables

CHAPTER III: Plates

CHAPTER IV: Platform Evolution in the Ramparts Formation (Upper "Platform-Reef" Member)

CHAPTER IV: Figures

CHAPTER IV: Tables

CHAPTER IV: Plates

CHAPTER V: Inception, Development, and Termination of the Reef Facies Association in the Ramparts Formation (Upper "Platform-Reef" Member)

CHAPTER V: Figures

CHAPTER V: Tables

CHAPTER V: Plates

CHAPTER VI: Summary

CHAPTER VI: Figures

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

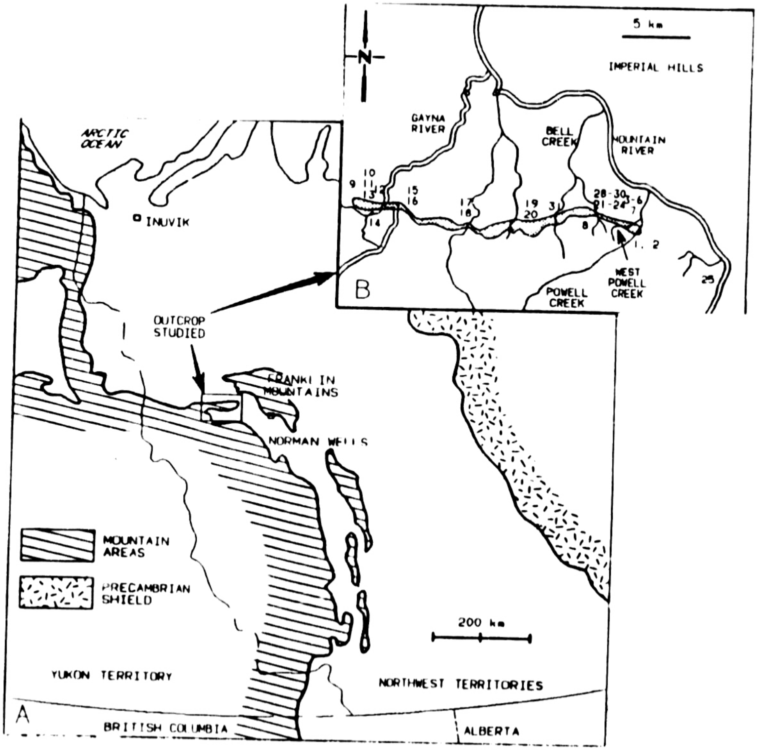


FIG. 1-1 Location of study area (A). Index map (B) showing measured sections (1-25, 28-31). Stippled area marks escarpment where Middle-Upper Davonian strata are exposed.

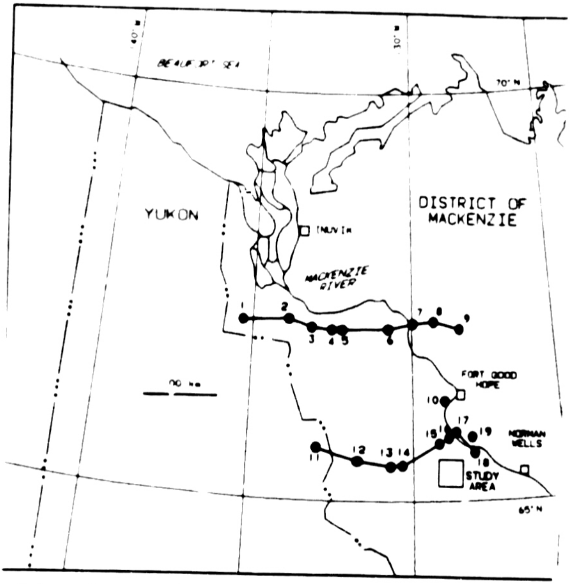


FIG. 1-2 Subsurface and outcrop location sites outside study area, used for supplementary data.

1. Union McPherson B-25
2. I.O.E. Nevejo K-05
3. I.O.C. Clare 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

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

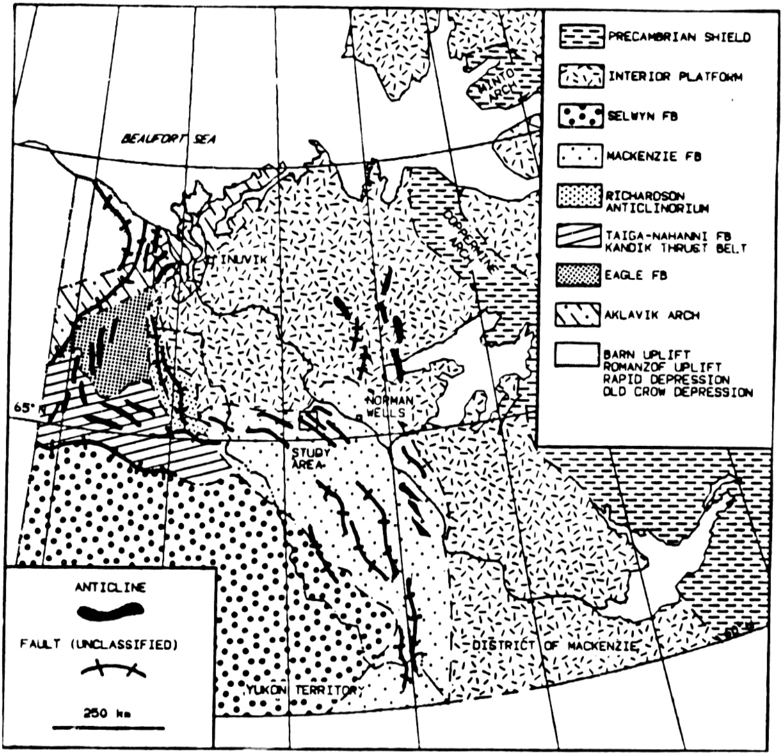


FIG. 1-3 Tectonic elements of the eastern Cordilleran Orogen of northern Canada (modified from Norris, 1985). FB = Foldbelt.

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 onlapped by Canol basinal shales or downlapped by Imperial clinothem 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).

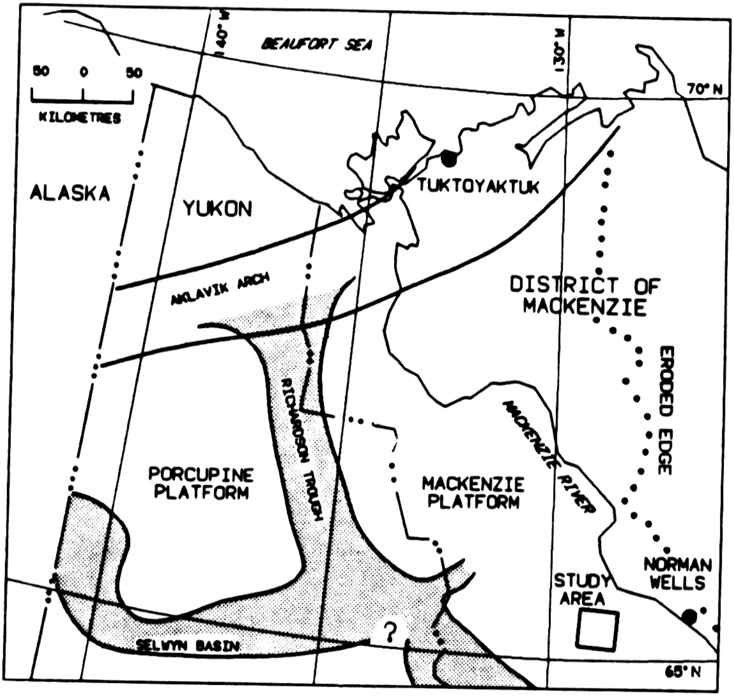


FIG. 1-4 Map showing regional Middle Devonian paleogeography (modified from Pugh, 1983; Williams, 1983; Norris, 1985). Delineation of platform margins is uncertain in the Aklavik Arch area. The Aklavik Arch complex embraces a number of smaller uplifts and structural depressions intermittently active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

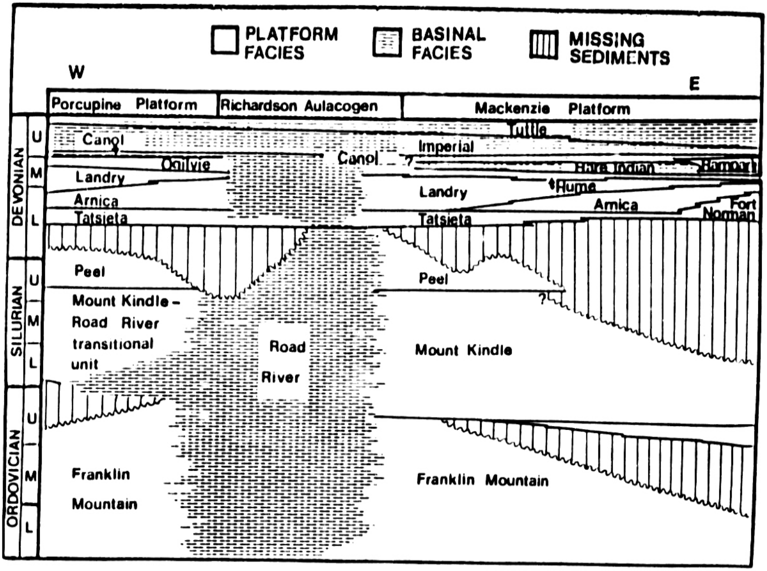


FIG. 1-5 Ordovician-Devonian platform and basin facies distribution in the Mackenzie Mountains-Richardson Mountains (modified from Pugh, 1983).

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. 43B-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 "reefoid" 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

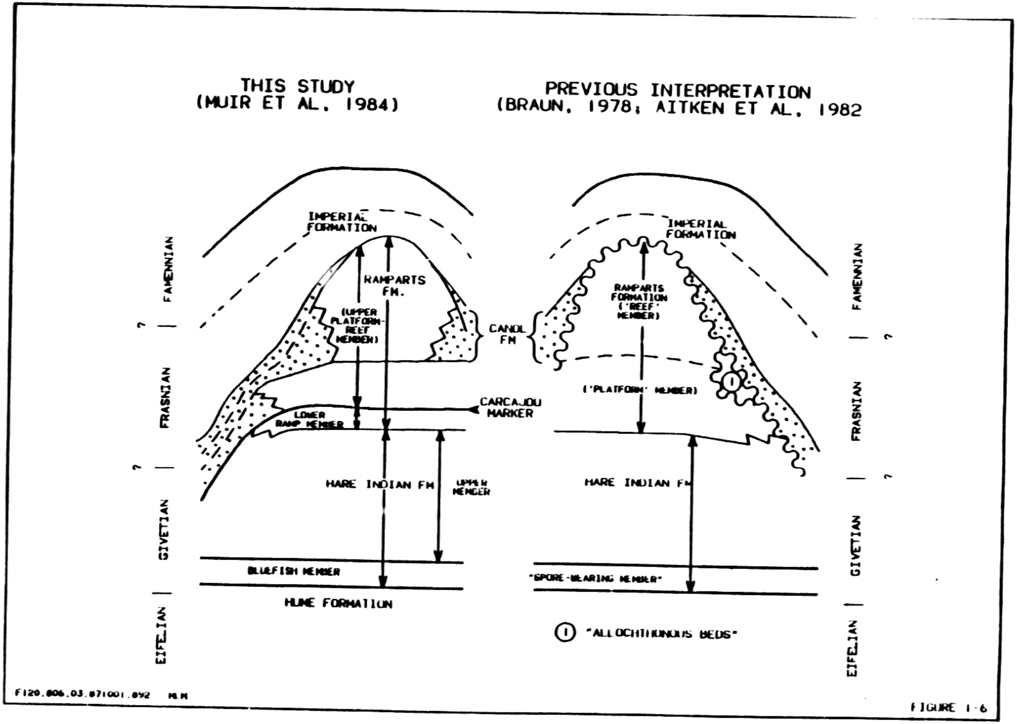


FIG. 1-6 **Middle and Upper Devonian stratigraphy in the study area.**

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

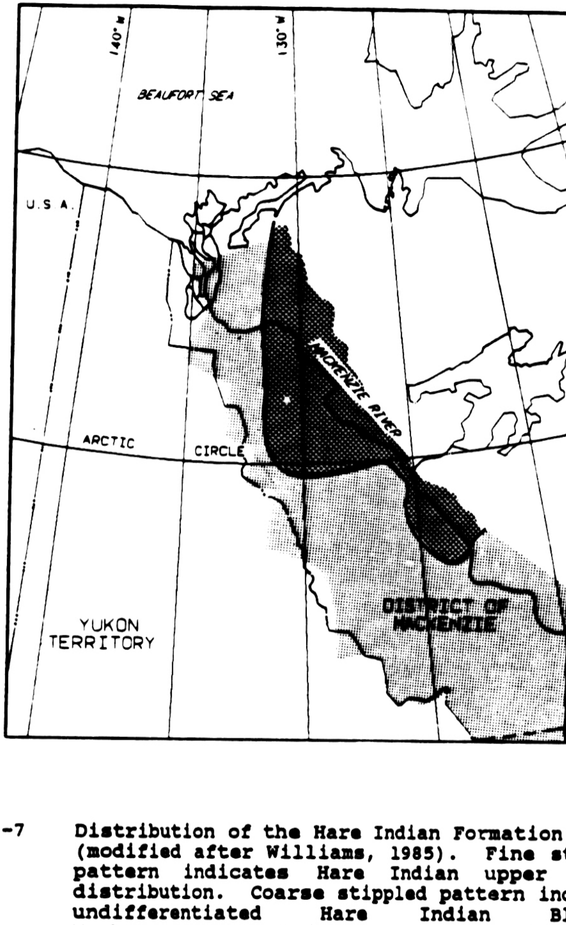


FIG. 1-7 Distribution of the Hare Indian Formation (modified after Williams, 1985). Fine stippled pattern indicates Hare Indian upper member distribution. Coarse stippled pattern indicates undifferentiated Hare Indian Bluefish Member-Canol Formation distribution where Hare Indian upper member-Ramparts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

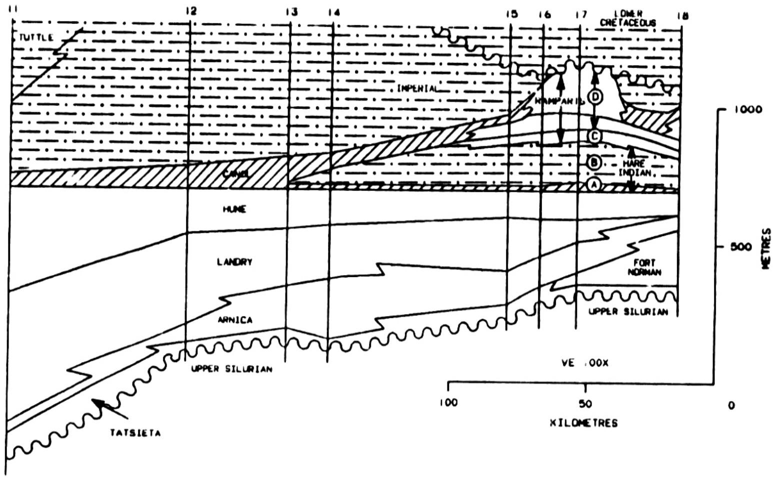


FIG. 1-8 Stratigraphic correlation based on wells (11-18) along an east-west transect approximately 20 km north of study area (see FIG. 1-2).

(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.

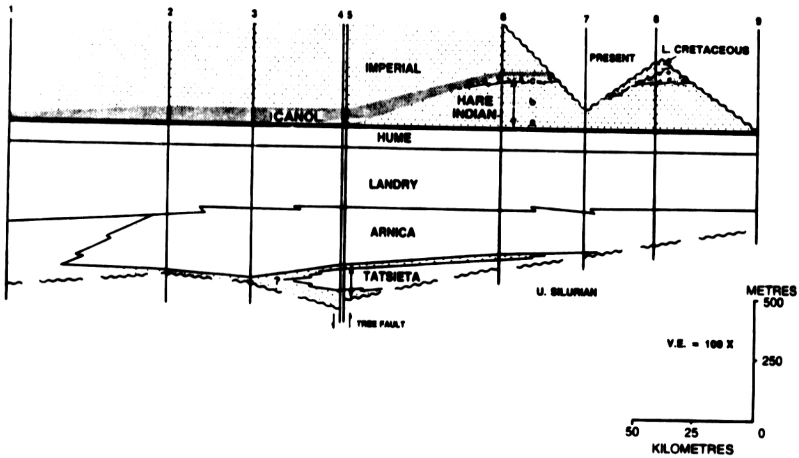


FIG. 1-9 Stratigraphic correlation based on wells (1-9) along an east-west transect approximately 200 km north of study area (see FIG. 1-2).
(a) Hare Indian Formation, Bluefish Member; thins westward to 2 m at 1 (Union McPherson B-25).
(b) Hare Indian Formation, upper member; note westward thinning.
(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

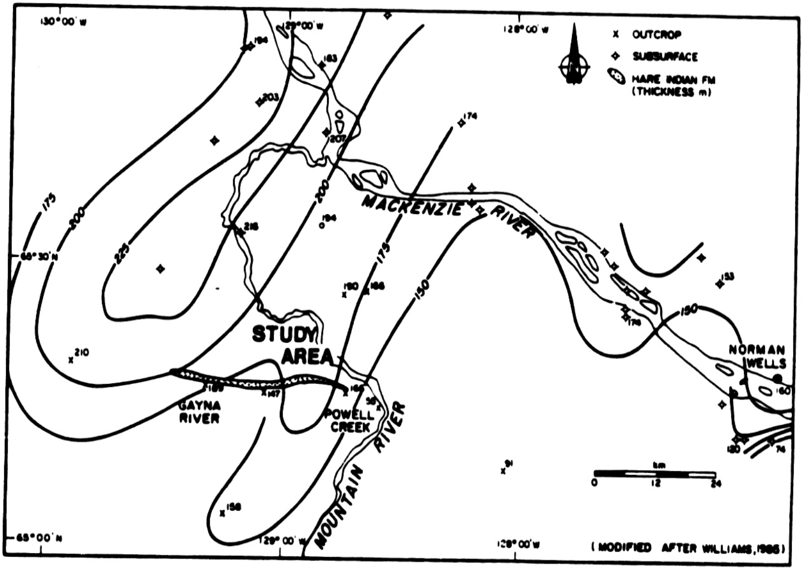


FIG. 1-10 Distribution and thickness of the Hare Indian Formation in the study area.

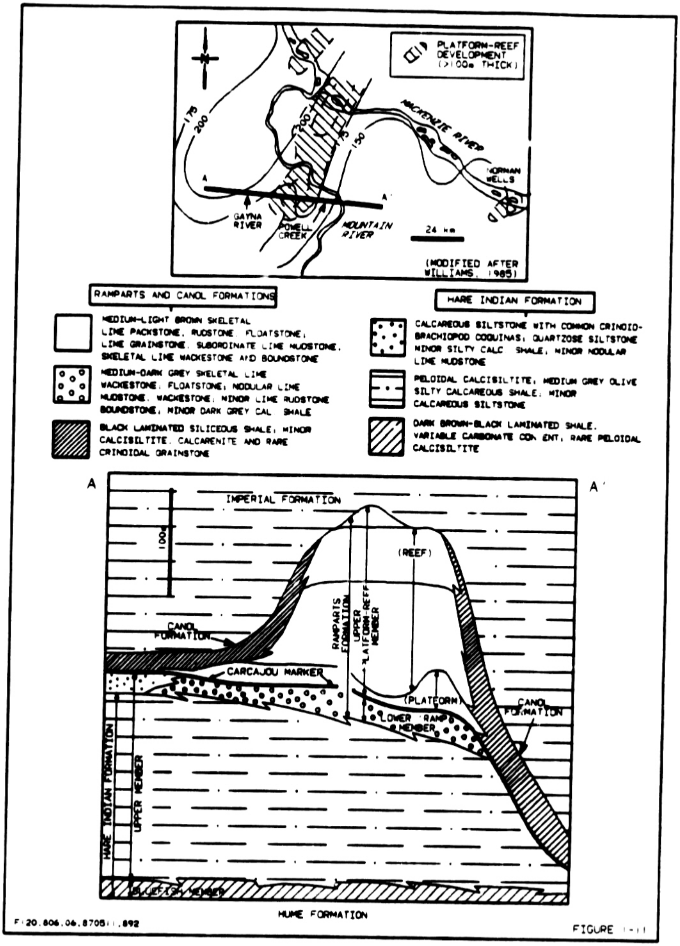


FIG. 1-11 Lithostratigraphic chart showing distribution of major lithologies in study area. Detailed facies distributions are illustrated in relevant portions of this thesis. Hare Indian isopach thick indicated in meters.

calcisiltite 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 calcisiltite 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 calcisiltite, 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

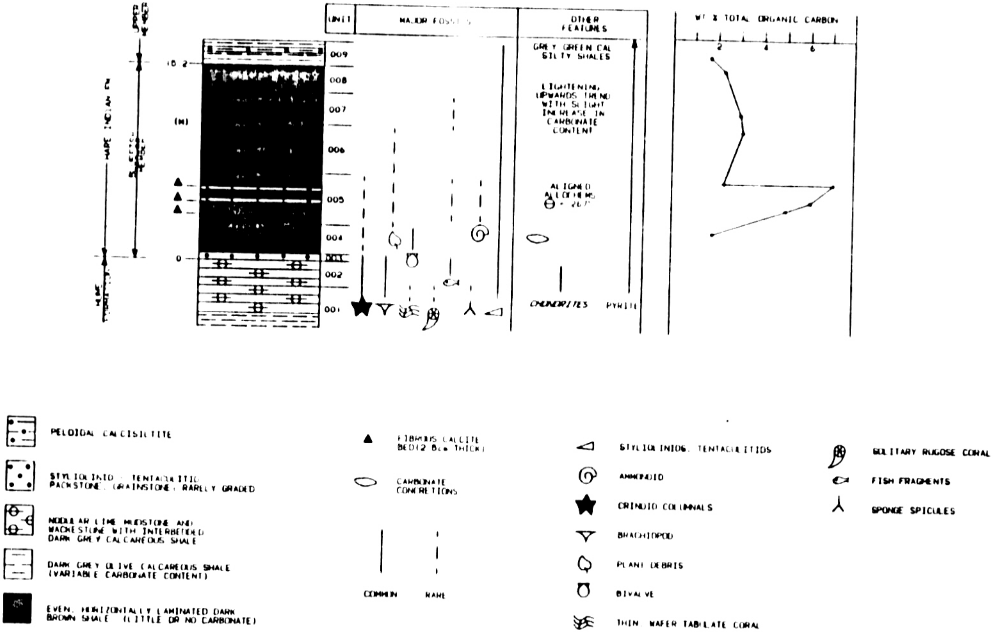


FIG. 1-12 **Reference section for the Bluefish Member at Gayna River (section 15).**

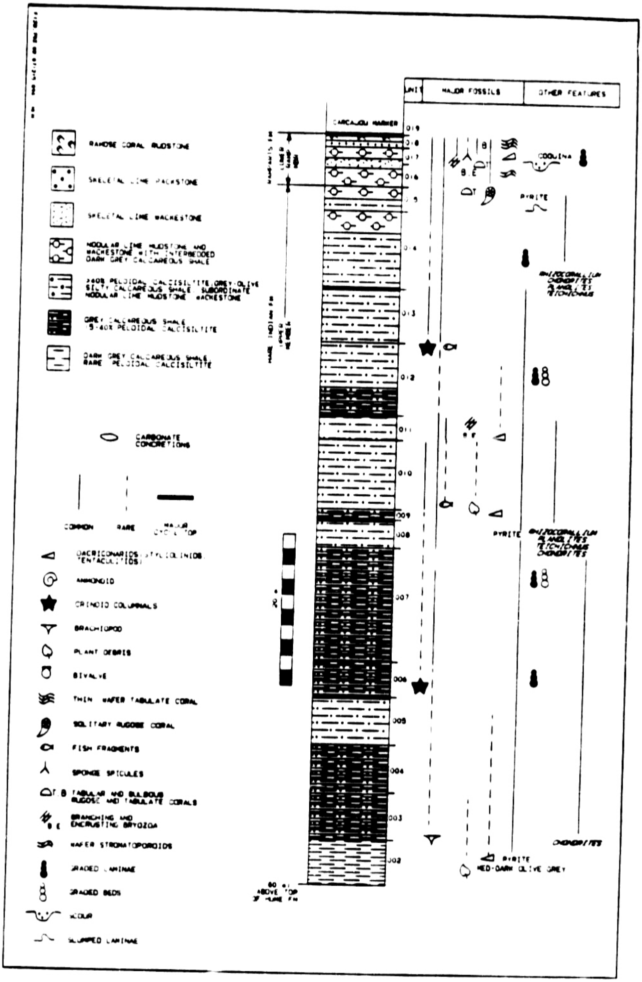


FIG. 1-13 **Reference section for the Hare Indian upper member at West Powell Creek (section 07). Conodont listing in Appendix A.**

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

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.

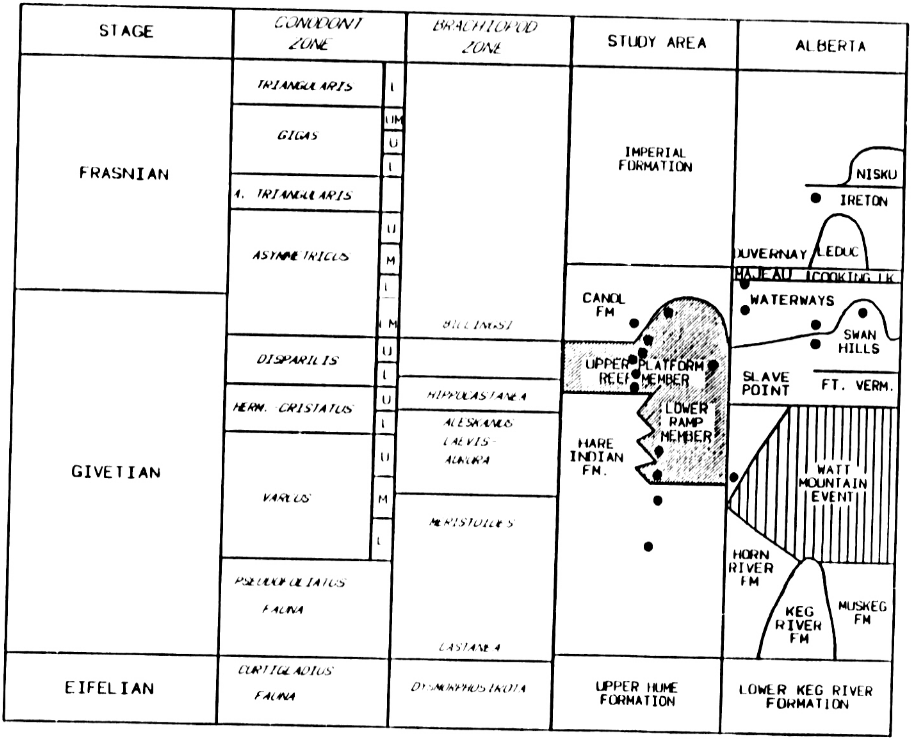


FIG. 1-14 Time-rock transect of some Devonian rocks in northern Alberta and study area. Black dots indicate conodont control (Uyeno, 1985, pers. comm.; Johnson et al., 1985). Modified after Johnson et al. (1985). Erosional Watt Mountain event more fully documented in Williams (1984).

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.

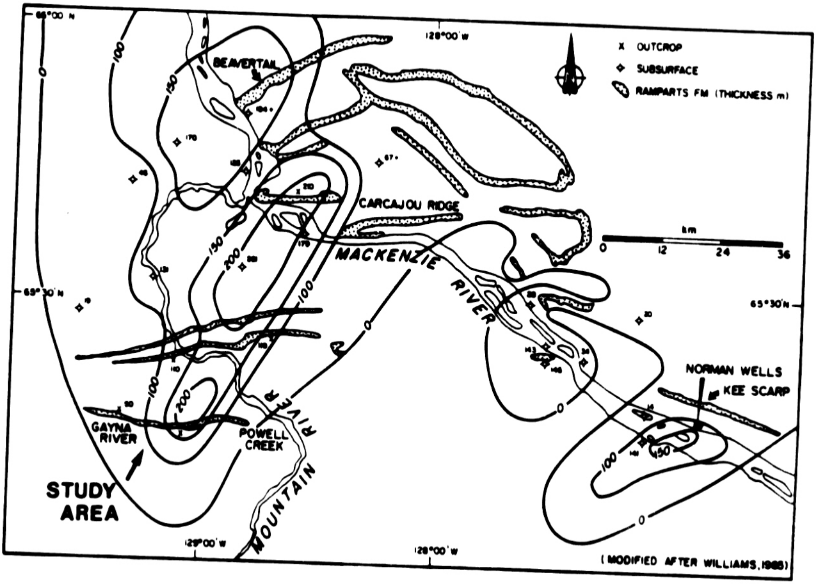


FIG. 1-15 Distribution and thickness of the Ramparts Formation in study area.

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 (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.

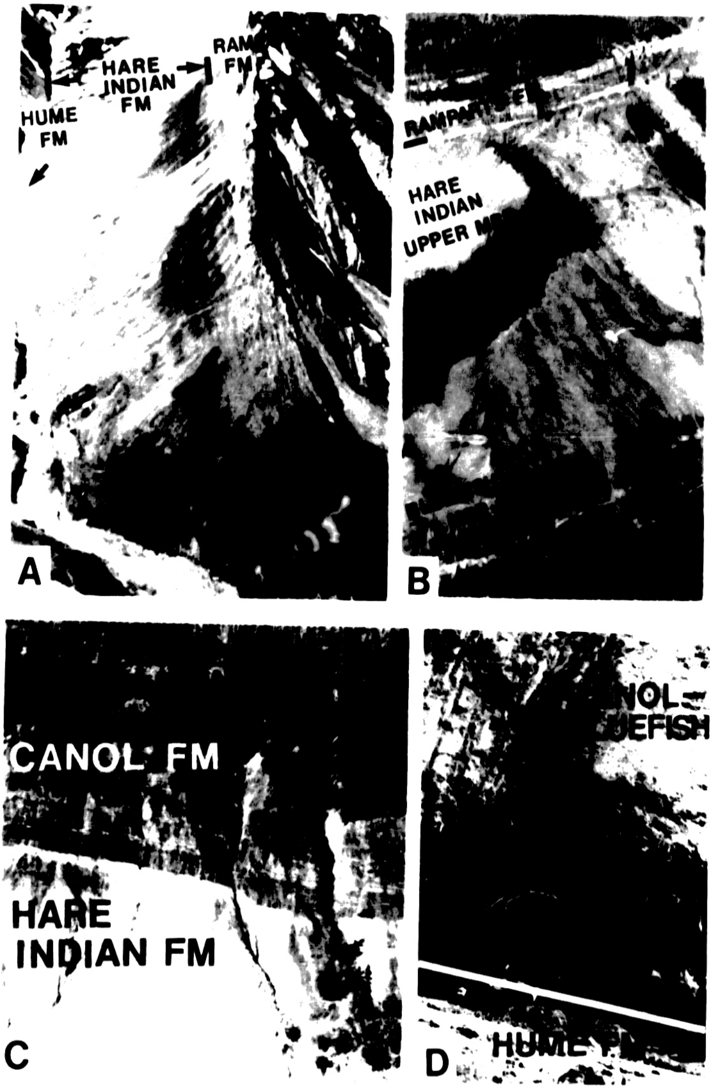

HARE INDIAN FM
HUME FM
A
HARE INDIAN
B
CANOL FM
HARE INDIAN FM
C
D

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).

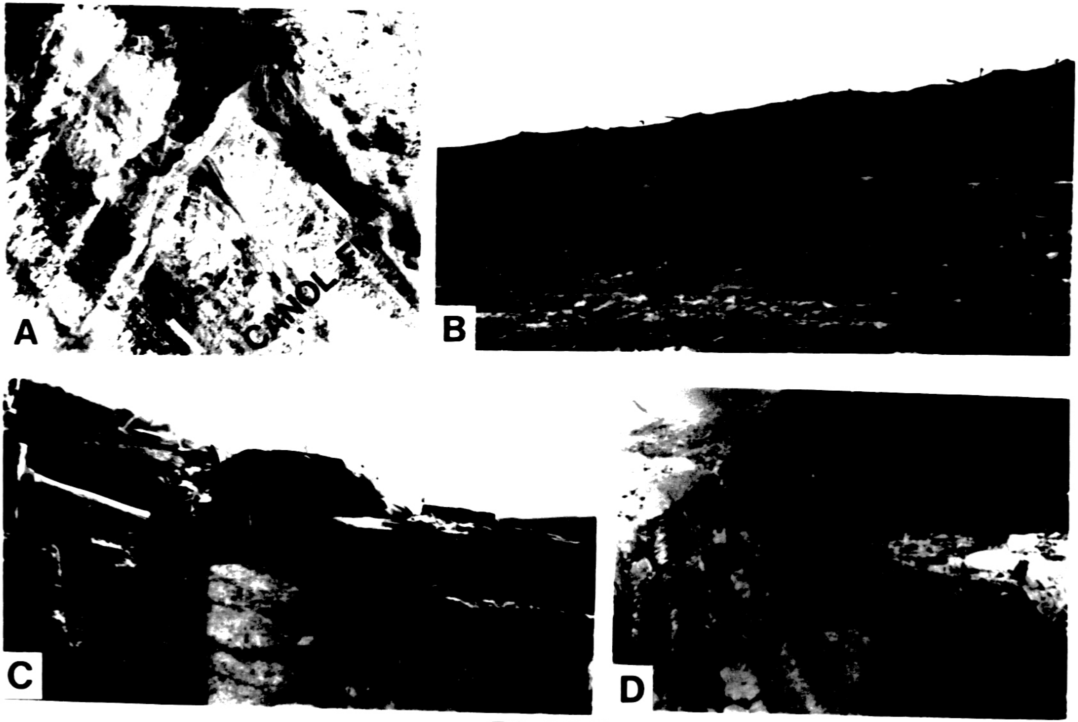


PLATE I-2

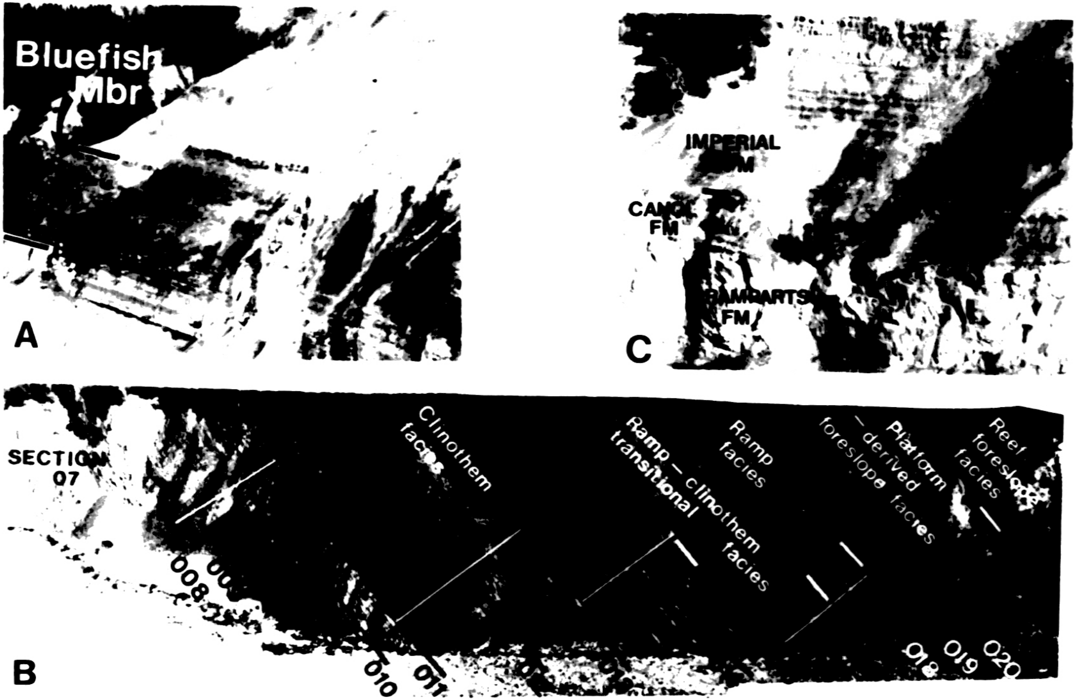
PLATE 1-3

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.



Bluefish Mbr
A
IMPERIAL FM
CANOL FM
RAMPARTS FM
C
SECTION 07
Clinothem facies
Ramp – clinothem transitional facies
Ramp facies
Platform – derived foreslope facies
Reef foreslope facies
008
010
011
018
019
020
B

PLATE I–3

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.

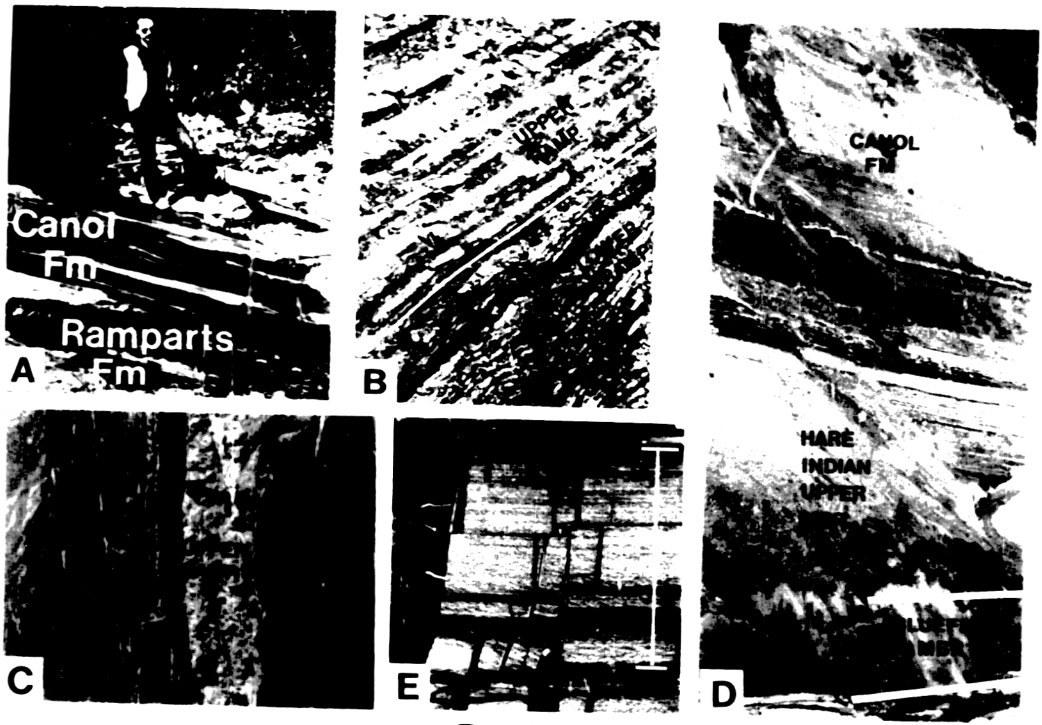


PLATE I–4

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.

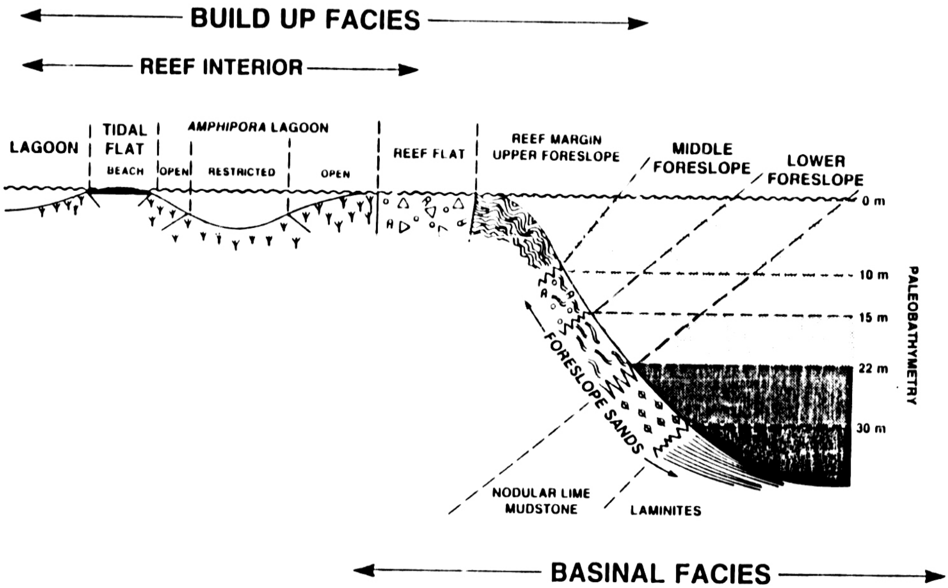


FIG. 2-1 Paleobathymetric profile across the Judy Creek Reef Complex - Swan Hills Formation (after Wendte and Stoakes, 1982).

(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.

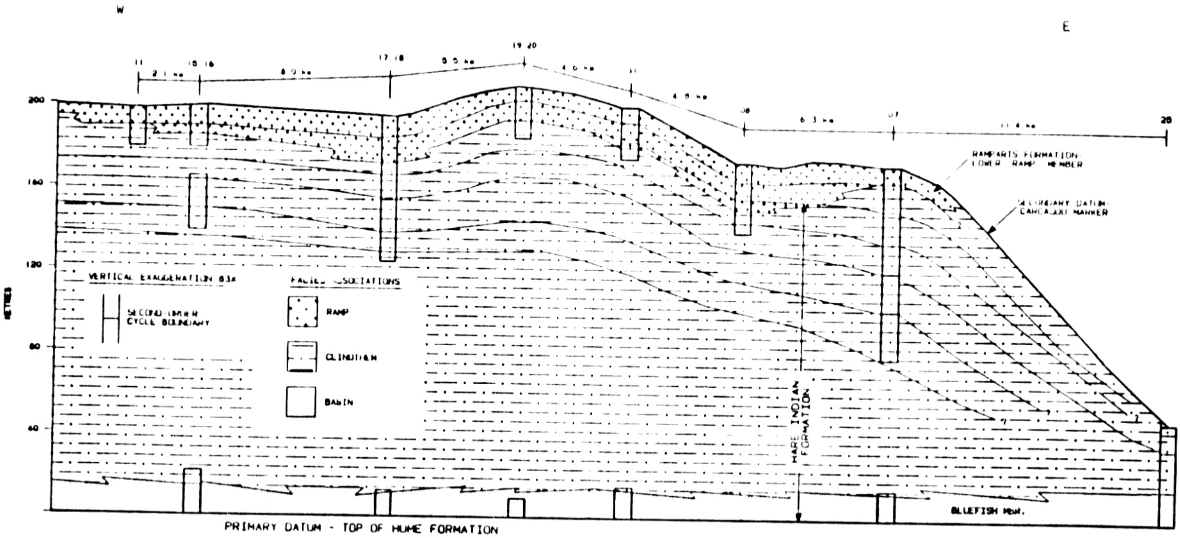
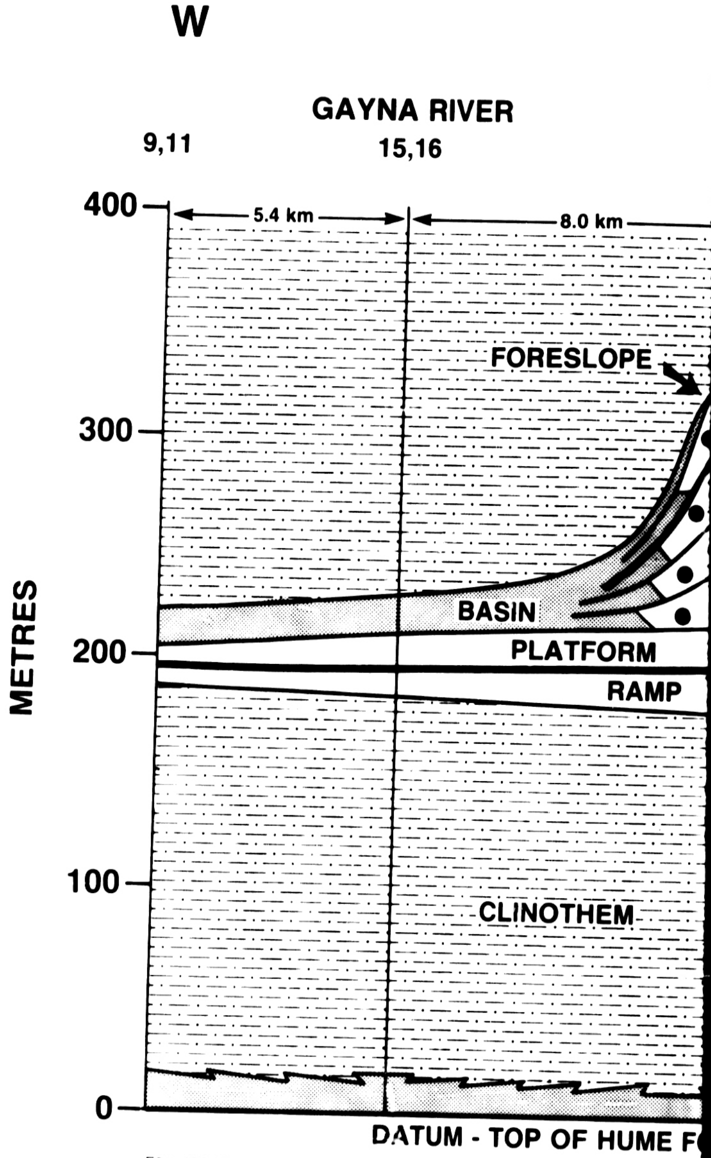


FIG. 2-2 Correlation of second-order shallowing-upward cycles in the Hare Indian Formation and Ramparts lower "ramp" member. The lower portion of the Hare Indian Formation is quite recessive and commonly covered in the study area.

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.



W
GAYNA RIVER
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15,16
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100
0
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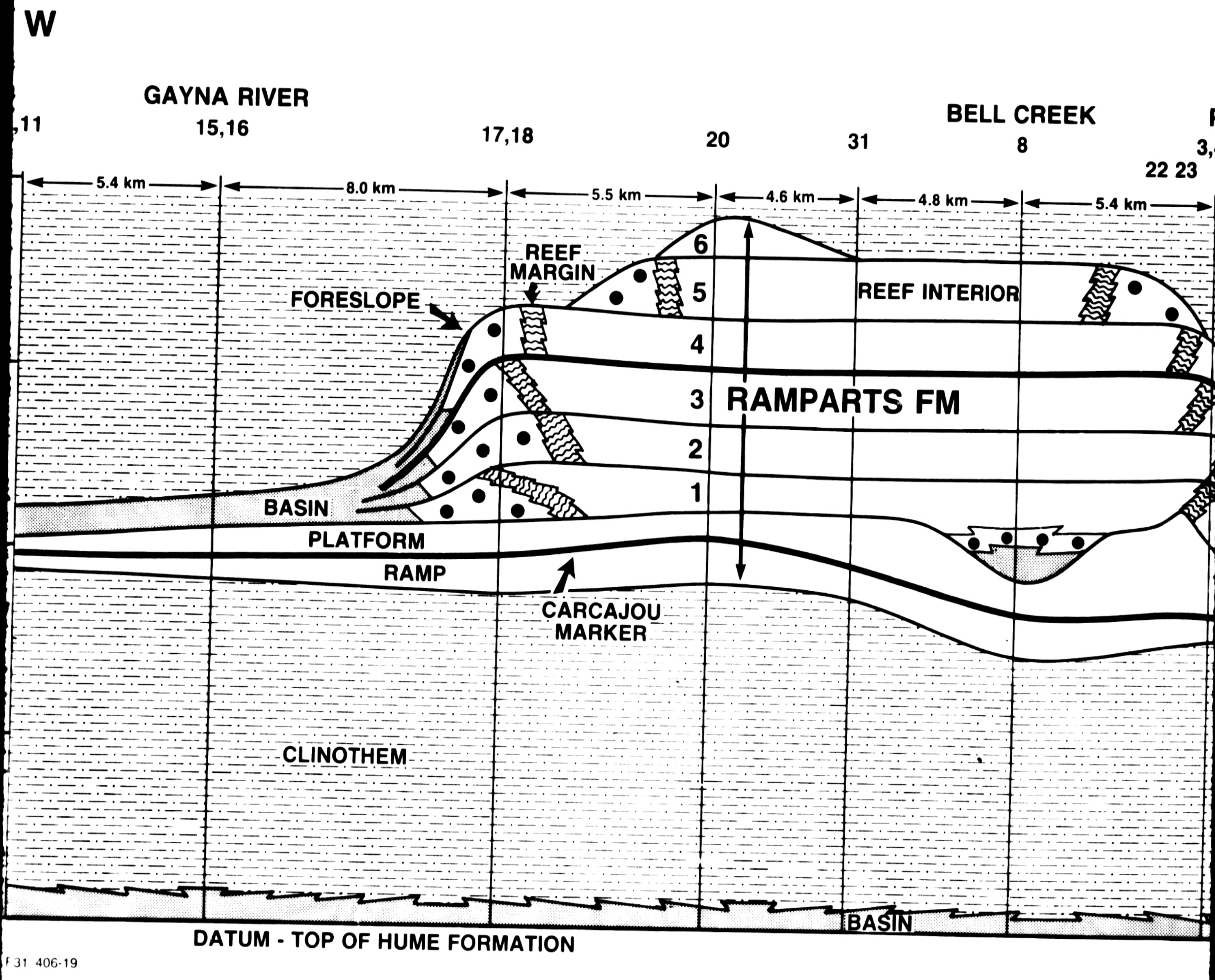
F31 406-19


W
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8
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5.4 km
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REEF
MARGIN
FORESLOPE
6
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3
2
1
REEF INTERIOR
RAMPARTS FM
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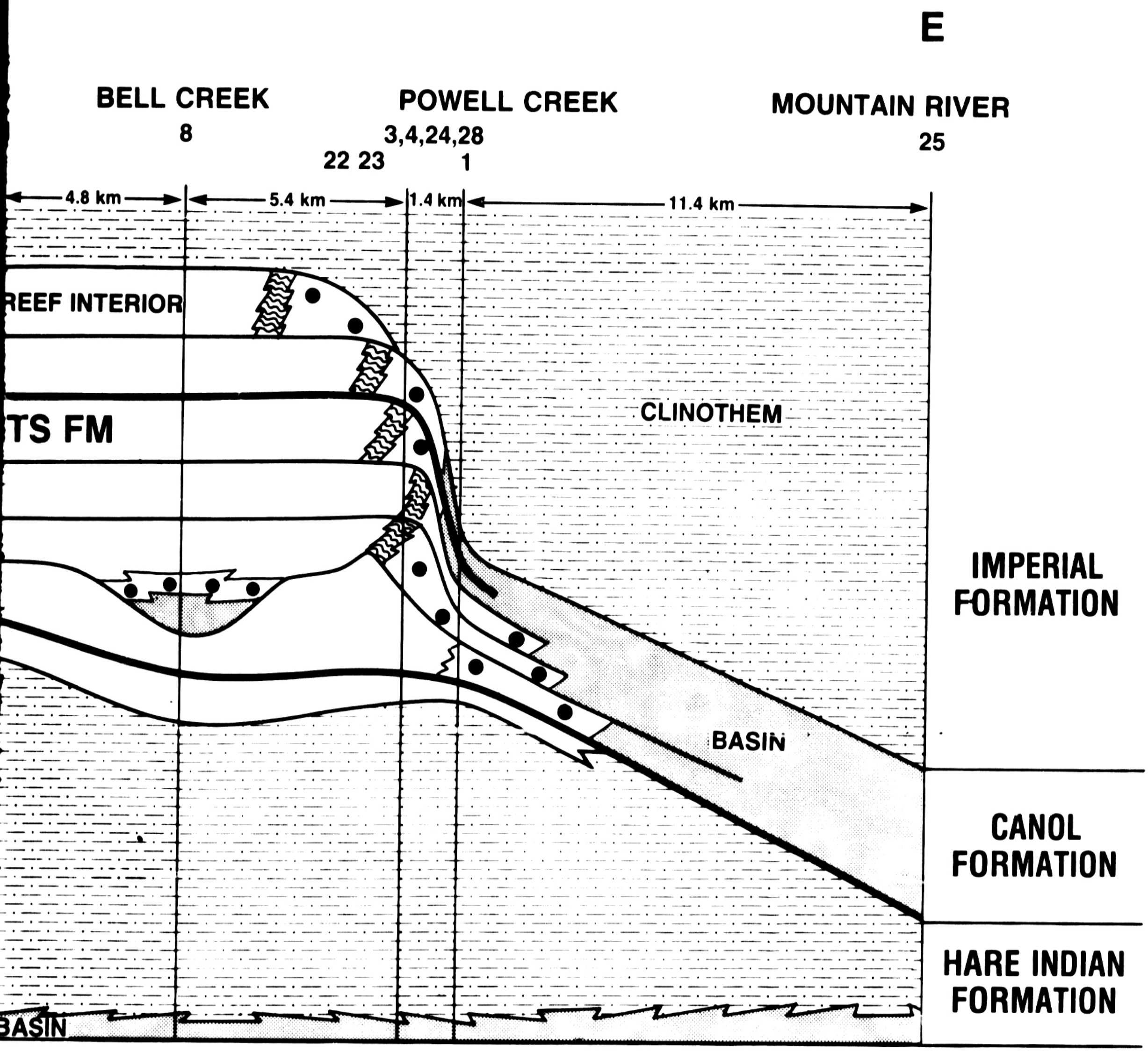
MARKER
CLINOTHEM
BASIN
DATUM - TOP OF HUME FORMATION
F 31 406-19


E
BELL CREEK
8
POWELL CREEK
3,4,24,28
22 23
1
MOUNTAIN RIVER
25
4.8 km
5.4 km
1.4 km
11.4 km
REEF INTERIOR
TS FM
CLINOTHEM
BASIN
BASIN
IMPERIAL FORMATION
CANOL FORMATION
HARE INDIAN FORMATION

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

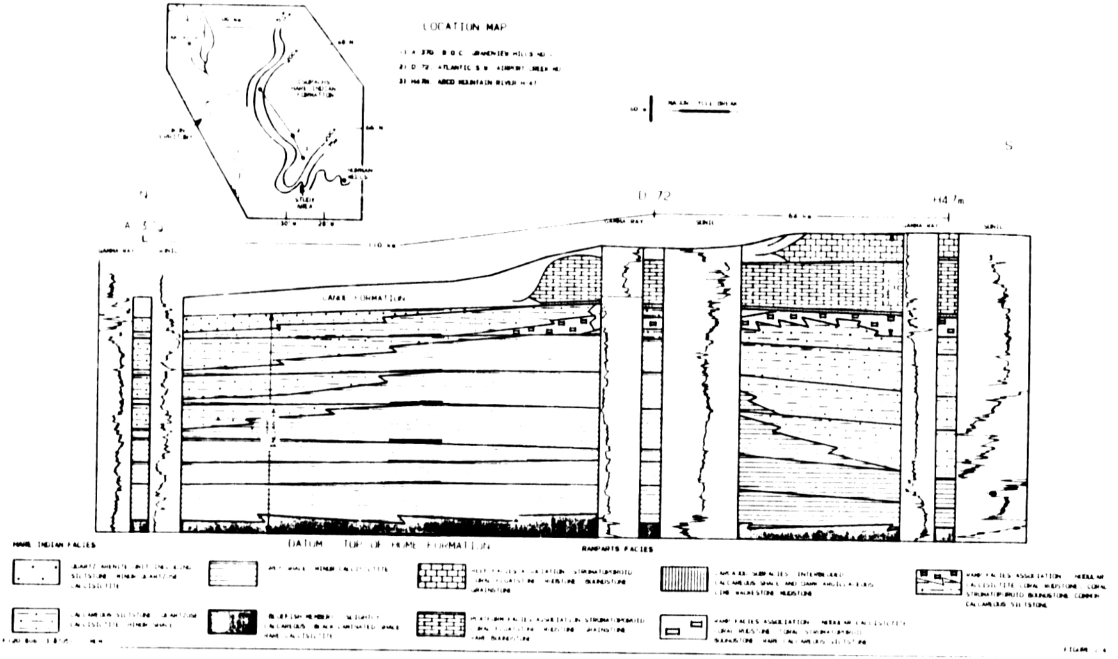


FIG. 2-4 Regional correlation of shallowing-upward cycles in the Hare Indian Formation. Some cycles may be composite second-order cycle sets.

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

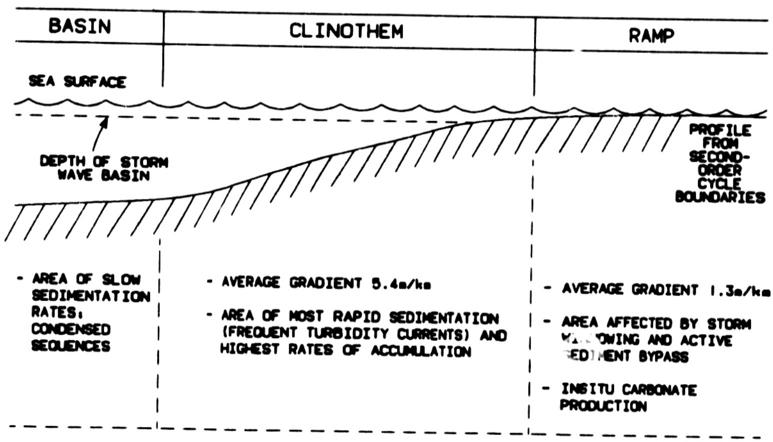


FIG. 2-5 Depositional facies associations in the Hare Indian Formation - Ramparts lower "ramp" member basin-fill succession.

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

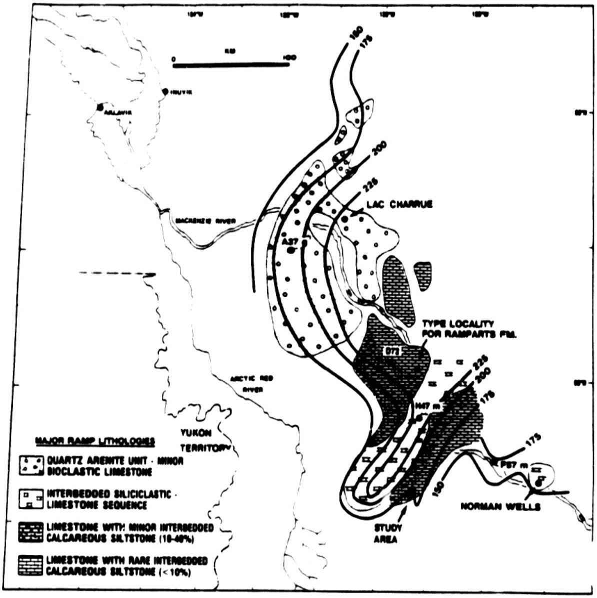


FIG. 2-6 Distribution of major ramp lithologies superimposed on an isopach map (m) for the basin-fill succession between the top of the Hume Formation and the Carcajou subfacies. Stratigraphic cross-section through wells A37g, D72 and H47m, shown in FIG. 2-4. Ramp facies are dominated by siliciclastic 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 westard-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

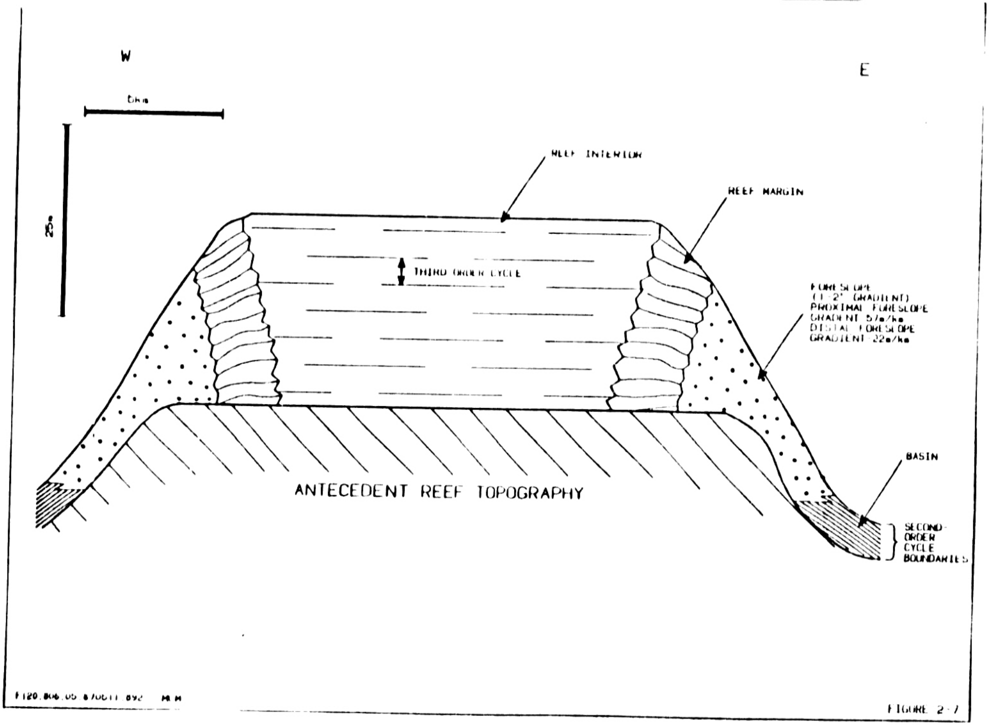


FIG. 2-7 Major facies distribution within a second-order reef cycle.

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 values in the Hume shale.

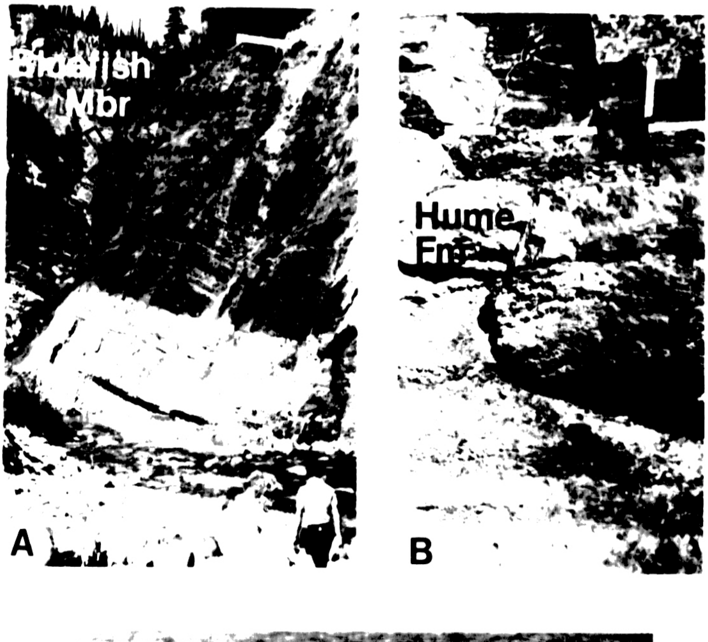


PLATE 2-1

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.

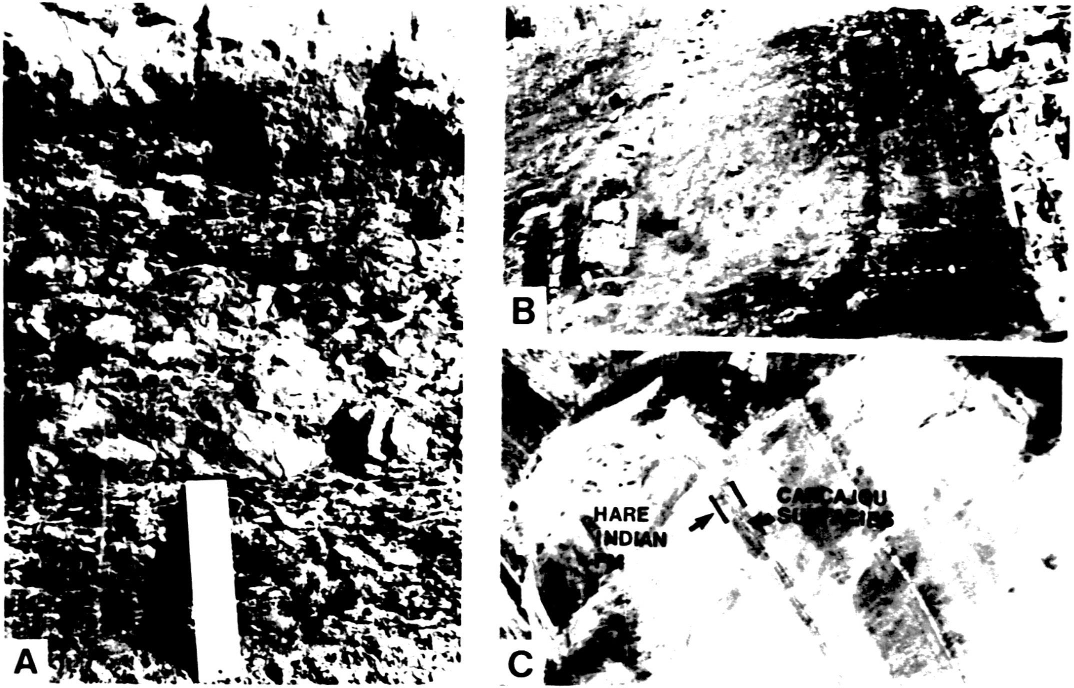


PLATE 2-2

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.

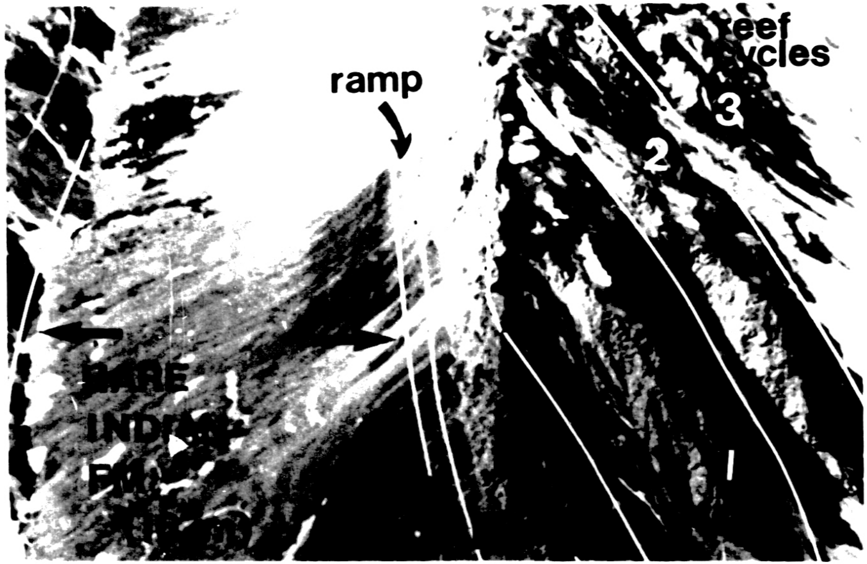


PLATE 2–3

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.

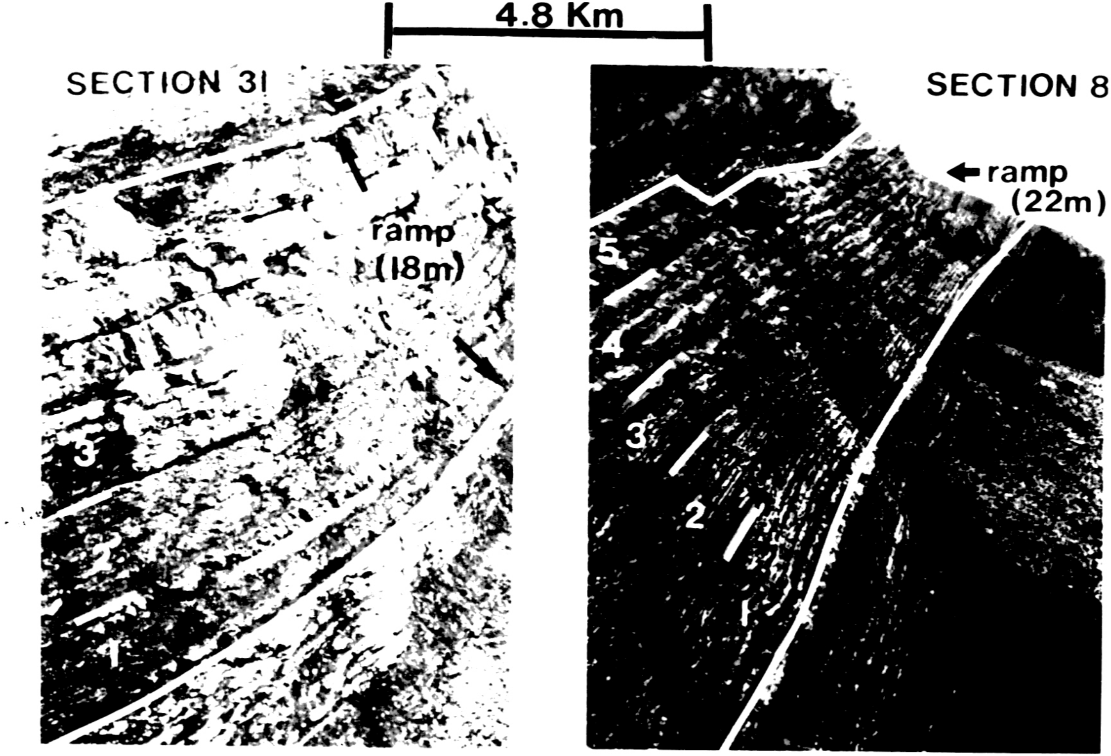


PLATE 2-4