GEOLOGICAL SURVEY
OF
WESTERN AUSTRALIA

REPORT 1

DEVONIAN CARBONATE COMPLEXES OF ALBERTA AND WESTERN AUSTRALIA : A COMPARATIVE STUDY

by Phillip E. Playford
in collaboration with
Marathon Oil Company

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Issued under the authority of
the Hon. A. F. Griffith, M.L.C.,
Minister for Mines
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DEVONIAN CARBONATE COMPLEXES OF ALBERTA AND WESTERN AUSTRALIA : A COMPARATIVE STUDY

SUMMARY AND CONCLUSIONS

THE Devonian reef complexes of the Canning Basin in Western Australia are believed to be among the world's best-preserved Palaeozoic reef complexes. They therefore have an important role in the understanding of others that are not as well preserved or exposed. This applies especially to the Devonian complexes of western Canada, which are of the same age but are known only from well sections and from largely dolomitized exposures in the structurally complex Rocky Mountains area. The principal objective of the present study was to make a detailed comparison between the Canning Basin reef complexes and those of Alberta, and thereby to increase the understanding of both.

Devonian reef complexes are also known in Western Australia from the Bonaparte Gulf Basin, but these are not as well preserved and have not yet been studied in as much detail as the Canning Basin examples.

COMPARISON OF THE CANNING BASIN AND ALBERTA COMPLEXES

1. The carbonate complexes in the Canning Basin are regarded as true reef complexes, whereas both reef and bank complexes occur in Alberta. Reef, back-reef, fore-reef, and inter-reef facies are recognized in the Canning Basin; the equivalent deposits in Alberta are named the reef, shelf-lagoon, marginal-slope, and basin facies.

2. The reef and back-reef (or shelf-lagoon) facies constitute carbonate platforms, which accumulated in both areas with topographic relief above the surrounding basins. A reef rim was normally present around most or all of the margin of each platform in the Canning Basin, whereas in western Canada the reef rim in some complexes is either absent or only weakly developed.

The absence of a reef rim may, in certain areas, be linked to lack of strong wave action, shallowness of the water in the adjacent basin, substantial depth of water over the platform margin, rapid subsidence, or the collapse of large sections of the platform margin.

3. Carbonate complexes are areally far more widespread in Alberta than the known occurrences in Western Australia.

4. The total maximum thickness of individual complexes in the Canning Basin may be more than 3,000 feet, which is much thicker than any known in western Canada, where they seldom exceed 1,000 feet. However, individual complexes grew for a much longer period of time in the Canning Basin than in Alberta, and it is possible that the rate of deposition was actually higher in Alberta.

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5. Most of the Canning Basin reef complexes began growth on Precambrian rocks along the mainland shore of the Kimberley Block, and around islands. The isolated complexes in Alberta were normally established on widespread foundation platforms, which are composed of similar facies but are thinner and have a much greater areal extent. The isolated platforms may have been localized by broad warping of the foundation platforms, associated with rapid subsidence. One Alberta complex fringes the Peace River Precambrian high, which formed a Devonian landmass, and is thus analogous to the situation found in the Canning Basin.

6. The reef complexes of the northern Canning Basin range from late Givetian to late Famennian in age, and reef growth is thought to have been essentially continuous during this period. Reef and bank growth in Alberta were restricted to the Givetian and Frasnian, and in any one area the complexes developed intermittently during this time. There were three main periods when the complexes which now contain oil developed in Alberta; during the Givetian (Keg River Formation, Rainbow Member), early Frasnian (Swan Hills Formation), and later Frasnian (Leduc Formation). In the Bonaparte Gulf Basin of Western Australia there is minor reef development in the Frasnian, but the main reef complexes are Famennian, possibly ranging into the Tournaisian.

7. Growth of the Canning Basin complexes was normally upwards and outwards, though there are a few examples of retreating complexes. In Canada, both retreating and advancing types occur, but retreating complexes are far more common than in the Canning Basin, and they retreated at much lower angles.

8. Extinction of the Canning Basin reef complexes is thought to have resulted from the filling of the basins by terrigenous sediments, thereby destroying the reef-to-basin relief necessary for reef growth. Most of the Canadian complexes are thought to have been drowned by rapid subsidence, though some may have been killed in the same way as in the Canning Basin, while others may have died through uplift and erosion. One group of reef complexes in northern Alberta (the Rainbow complexes) were apparently killed by hypersaline conditions consequent on the closing of the Presqu'ile barrier.

9. Dolomitization is far more extensive in Alberta than in the Canning Basin. Most Canadian complexes are completely dolomitized, whereas in the Canning Basin dolomitization is rarely widespread. In both areas the reef and back-reef (or shelf-lagoon) deposits are the most dolomitized.

10. Evaporites are not known to occur in association with the Western Australian reef complexes, whereas they are extensive in Canada.

11. Calcareous algae, especially *Renalcis* and *Sphaerocodium,* are the principal framebuilders in the Canning Basin reefs, but are less conspicuous in most of the Alberta reefs, with the notable exception of the 'Middle Leduc' reef facies at Redwater. It is possible that these algae were important in the reef facies of all the Leduc complexes, but are no longer recognizable in most because of extensive dolomitization.

12. Stromatoporoids (mainly encrusting and tabular forms) are the principal reef framebuilders in many of the Alberta complexes. In the Canning Basin they are second only to the algae in this role. Similar types of stromatoporoids are found in both areas.

13. Corals probably rank third in importance as reef framebuilders in both areas.

14. The back-reef and shelf-lagoon facies in the Canning Basin and Alberta are very similar. Closely comparable stromatoporoid, coral, birdseye, and oncolite limestones occur in each. However, oolite is conspicuously absent in the Alberta shelf-lagoon deposits, whereas it is an important constituent of the back-reef in several Canning Basin complexes.

15. A striking difference between the two areas is the much greater development of fore-reef talus in the Canning Basin. Moreover, depositional dips as high as 30 to 35 degrees are common in the Canning Basin fore-reef facies, but depositional dips of this magnitude have rarely been demonstrated in the Canadian marginal-slope deposits. These differences are probably linked to the greater development of reef facies, and greater platform-to-basin relief, in the Canning Basin. In addition, wave action may have been stronger in the Canning Basin than in Alberta, resulting in the generation of more talus.

16. The basin sediments in Alberta are better known than the inter-reef deposits in the Canning Basin, which are relatively poorly exposed in the valleys between the limestone ranges, and have not been penetrated in many wells. The basic lithologies and faunas in these deposits are similar in both areas, consisting of calcareous shale, siltstone, and silty or clayey limestone, with characteristic pelagic faunas.

17. Devonian carbonate complexes contain the bulk of Alberta's oil reserves, whereas no economic discoveries have yet been made in the Canning Basin complexes. The striking similarities between these rocks suggest, however, that commercial fields are likely to occur in buried reef complexes in the Canning Basin, or offshore around the Kimberley Block.

RECOMMENDED FUTURE RESEARCH IN WESTERN AUSTRALIAN REEF COMPLEXES

1. Detailed palaeoecological studies need to be made of the principal organisms in the reef complexes, with special emphasis on the algae, stromatoporoids, corals, and brachiopods.

2. An attempt should be made to carry the precise conodont zonation that has been established in the inter-reef facies through into the limestone platforms. Detailed stratigraphic sections should be measured in association with the conodont sampling.

3. Areas where the reef rim is absent need to be studied to determine whether the lack of reef is related to depth of water in the adjacent basin, degree of wave

action, or the nature of the shelf-lagoon deposits; also to determine whether in any of these areas there is evidence of large-scale collapse of the platform margins.

4. Attention should be focussed on the back-reef facies immediately behind the reef rim to determine whether the common dip away from the reef is depositional or is due to compaction. The factors controlling the amount of dip in the fore-reef facies also need to be determined.

5. The origin of fibrous calcite and the possibility that inorganic precipitation of calicum carbonate took place directly on the sea floor need to be studied, as well as the origin and history of porosity in the limestones.

6. Detailed studies need to be made of the distribution and origin of dolomite in the complexes.

7. The reasons for the abrupt 'stepping-back' of reef fronts in some areas require special study.

8. Further studies of the subsurface occurrences of reef complexes on the Lennard Shelf need to be made, to incorporate the detailed surface data and to integrate recent drilling and seismic results.

9. Detailed investigations of the reef complexes in the Bonaparte Gulf Basin should be undertaken after completion of the Canning Basin projects.

INTRODUCTION

As a result of my experience in studying the Devonian reef complexes of the northern Canning Basin in Western Australia, I was invited to spend three months with Marathon Oil Company's Denver Research Center to compare these complexes with those studied by Marathon in Alberta. It was felt that the detailed information obtained from the well-preserved Canning Basin complexes could be of value in interpreting the Devonian complexes of Alberta. The project was also designed to benefit research in the Canning Basin by the Geological Survey of Western Australia.

Marathon has been conducting research on Devonian carbonate complexes in Alberta intermittently since 1958, with the major effort concentrated during 1965, 1966, and 1967. The main emphasis has been on field work, particularly in the Miette complex. Other areas include the Ancient Wall, Southesk, and Fairholme complexes. This field work has been complemented with considerable laboratory work. Marathon's research objectives have focussed on the morphologic evolution of these complexes with particular emphasis on the buildup mechanism, general facies types and their distributions, the role of stromatoporoids and algae in carbonate complex evolution, and the nature and origin of the transition zone between the basin and bank or reef. As a result of this work, Marathon had gained valuable perspective concerning the genesis of Devonian complexes in Alberta.

Marathon's data and perspectives on Albertan carbonate complexes and mine on the Australian complexes were fully shared in discussions during the period August 1 through October 31, 1967, at Marathon's Denver Research Center, and during several days of joint field work on the Miette complex. During the collaboration I had the opportunity of studying and discussing unpublished Marathon reports and subsurface rock samples. Although many of the ideas, concepts, and interpretations contained in this report were developed and sharpened through frequent, at times spirited, discussion with the Marathon group, final responsibility for them rests with me.

Special thanks are due to J. L. Wray, whose keen interest in the Canning Basin algae initiated the project, and to D. B. MacKenzie, who arranged for my visit. Marathon geologists from the Denver Research Center who participated in this study include P. W. Choquette, H. E. Cook, P. N. McDaniel, L. C. Pray and J. L. Wray. Discussions were also held with Marathon exploration geologists, including W. P. Gruman, C. E. Kallsen, W. J. Meyers, and R. P. Steinen. I would also like to thank E. W. Mountjoy of McGill University for his advice and able leadership on the Miette field excursion of the International Symposium on the Devonian System. Finally I wish to thank Marathon Oil Company and the Mines Department of Western Australia for affording me the opportunity to make this study.

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CARBONATE COMPLEXES

THE known extent of Devonian carbonate complexes in Alberta and Western Australia are shown (at the same scale) on Figure 1. In Alberta my field studies were restricted to the Miette complex (Mountjoy, 1965), but I also studied some samples from Ancient Wall, and subsurface material from Redwater (Klovan, 1964) and Judy Creek (Murray, 1966). In Western Australia my detailed studies have been confined to the reef complexes in the northern Canning Basin (Playford and Lowry, 1966; Playford, 1967), but I have also briefly examined the principal exposures of reef complexes in the Bonaparte Gulf Basin (Playford, Veevers, and Roberts, 1966).

NOMENCLATURE

The terminology applied by Playford and Lowry (1966) to the Canning Basin complexes, and that recommended for the Alberta complexes, are shown on Figure 2.

Reef, back-reef, fore-reef and inter-reef facies are recognized in the Canning Basin reef complexes. The reef and back-reef facies together form limestone platforms which commonly accumulated some hundreds of feet above the surrounding inter-reef basins. The reef rim around each platform enclosed a broad, shallow, shelf lagoon in which the back-reef deposits were laid down. The fore-reef facies accumulated as talus on the fore-reef slope fronting each platform.

There is no standard terminology now in use in the Canadian complexes, but my recommended terms are shown on Figure 2.

Most exploration geologists refer to the Canadian carbonate buildups as 'reefs', using the term to embrace the whole of each buildup. Others have applied the terms reef, back-reef, fore-reef, and inter-reef in much the same way as they are used in the Canning Basin. On the other hand, some geologists have tended to reject the term reef altogether in describing the Canadian complexes, and instead refer to them as banks. In my opinion the Canadian complexes include true reef complexes as well as banks, and both bank and reef development are commonly developed within a single complex.

The following is a discussion of the more important terms applied to carbonate complexes.

Reef. There is agreement among many carbonate workers that the term reef should be restricted to rigid, potentially wave-resistant structures that had topographic relief above the adjacent sea floor and were built up of a framework of colonial organisms. I accept this usage and reject the loose application of the term reef to any discrete carbonate body.

Reef complex. According to Nelson and others (1962) the term reef complex embraces the aggregate of reef, fore-reef, back-reef, and inter-reef facies. This is also the usage of Playford and Lowry (1966). However, where the term is used in Canada it does not normally include the inter-reef or basin facies, and I now support this usage.

The term reef complex should only be used where the presence of reef facies has been interpreted and is regarded as important to the complex as a whole. The general term carbonate complex can be used where the presence of reef is uncertain, or where the body is in part a reef complex, and in part a bank complex.

Bank. There is no generally accepted definition of the term bank. Nelson and others (1962) regard a bank as a 'skeletal limestone deposit formed by organisms which do not have the ecological potential to erect a rigid, wave-resistant structure'. A skeletal deposit, according to their usage, is one that consists of, or owes its characteristics to, the virtually in-place accumulation of calcareous skeletal matter. Dooge (1967) on the other hand defines banks as 'structures that are only partly biogenic in origin, usually formed of lime mud and skeletal debris, that has been transported to the bank location by currents or wave action. . . . Banks are essentially concentrations of outside material'. None of the Canadian carbonate bodies would be banks according to this definition. Yet another usage of the term bank is that of Lees (1964). He applied the term in a very broad sense to embrace 'all structures which formed conspicuous mounds on the sea floor'. He states that 'Such banks may have been built by local sedimentation or carved by erosion of once-continuous sediments. Those formed by local accumulation include structures as diverse as current-drifted piles of sand and *in situ* coral and algal reefs. There seems to be no reason why an organic reef should not be regarded as a special kind of bank. . . '

I am unable to agree with any of the three definitions of the term bank quoted above. Nelson and others (1962) do not require that a bank have topographic relief, and they would not regard oolite or lime-sand deposits as banks. Dooge requires that banks be accumulations of transported material, and this certainly does not apply to many banks that have been recognized either in the Recent or in the geological record. Few carbonate workers would agree with Lees that reefs are to be regarded as special types of banks.

I feel that the essential characteristics of banks are topographic relief, lack of rigidity or wave resistance, and the accumulation of either skeletal or non-skeletal material. A definition of a carbonate bank drawn up jointly by L. C. Pray and myself is: 'A deposit composed of skeletal or non-skeletal carbonate material that accumulated topographically higher than the adjacent sea floor, and in which reef growth was essentially absent.'

Bank complex. A bank complex consists of a bank and the adjacent marginal-slope deposits.

Carbonate platform. Playford and Lowry (1966) apply the term limestone platform to the reef and back-reef facies of the Canning Basin reef complexes. This is in accordance with the usage of the term for the Bahama Banks (or Bahamian platforms) by Newell (1955). However, the general term carbonate platform is preferable in Canada, where the complexes are largely dolomitized. Carbonate platforms are flat-topped carbonate bodies that accumulated topographically higher than the adjacent sea floor. Such platforms may be banks, table reefs, or they may

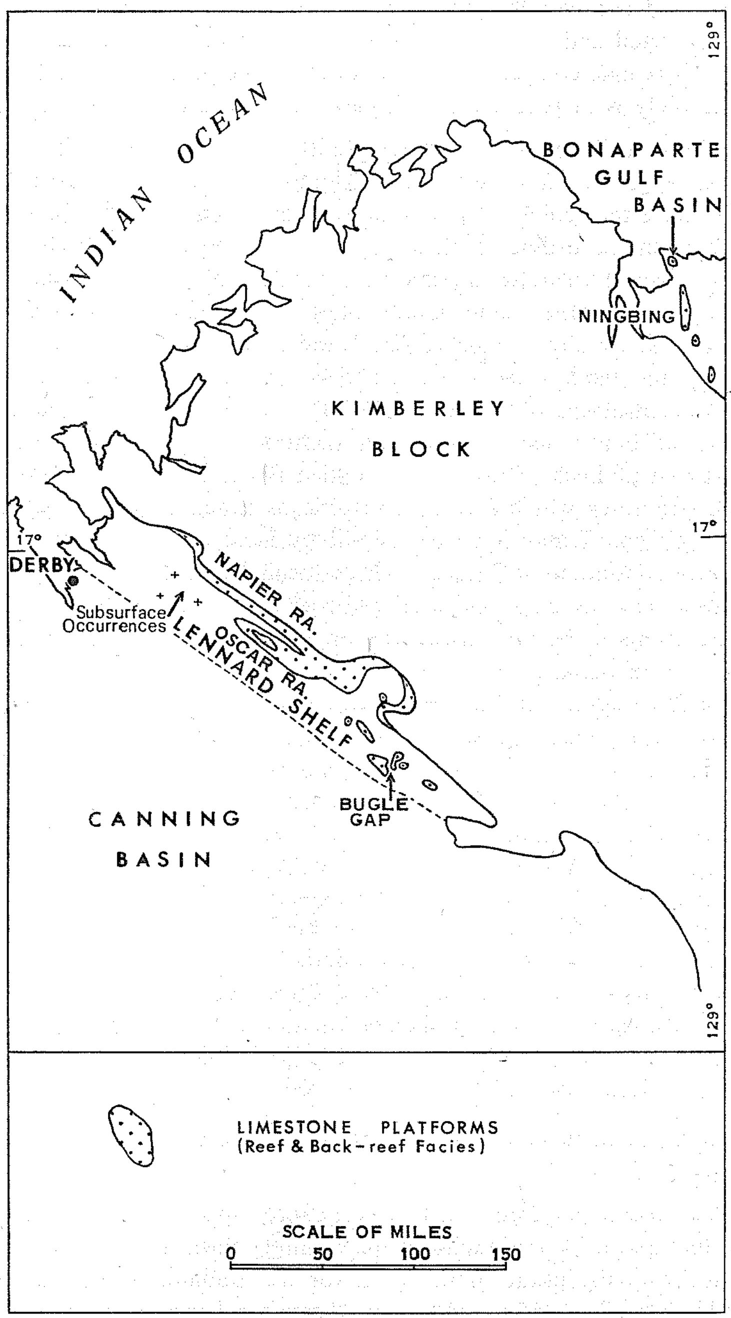
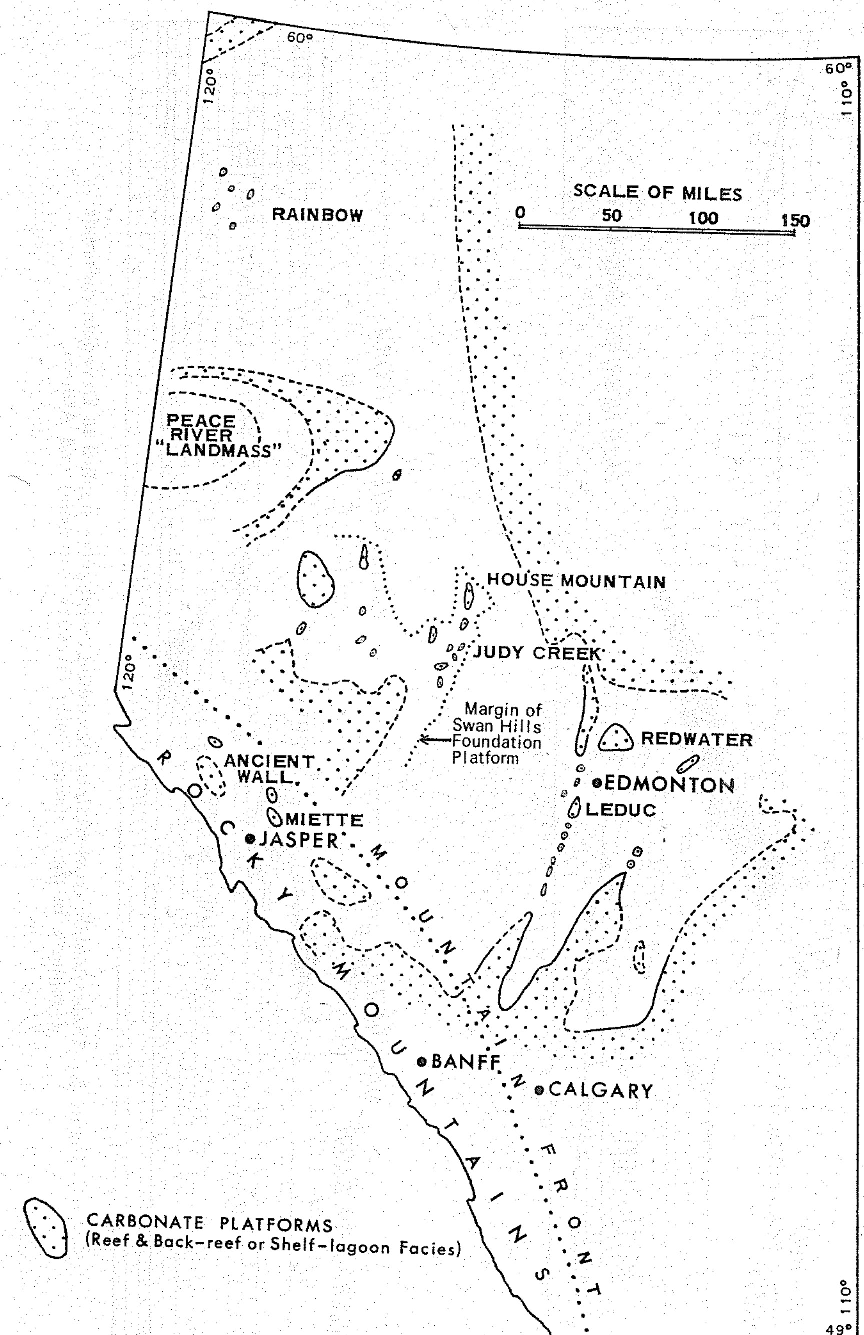


Figure 1. Maps of Kimberley district (Western Australia) an



Alberta showing distribution of Devonian carbonate platforms.

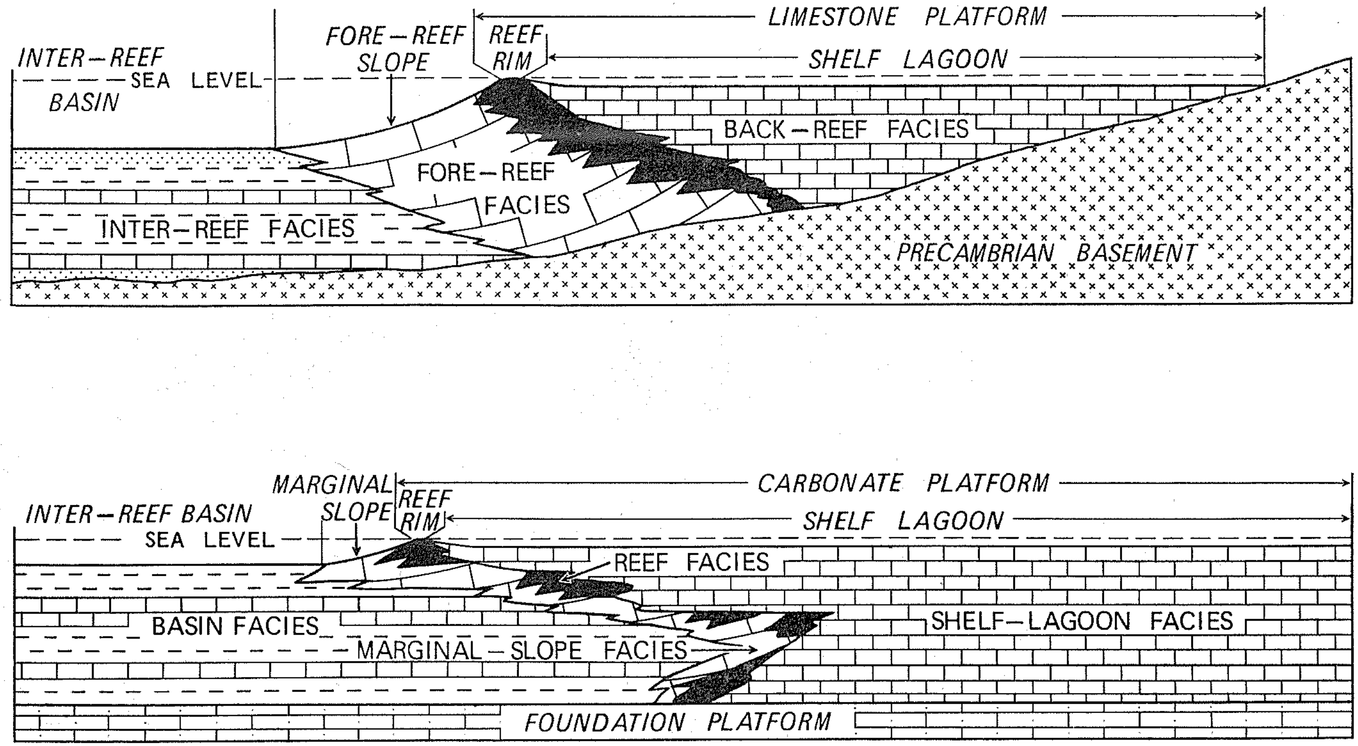


Figure 2. Diagrammatic cross-sections illustrating terminology applied to Devonian carbonate complexes in the Canning Basin (Western Australia) and Alberta.

consist of a reef surrounding a shallow shelf lagoon. Carbonate platform is thus a useful general term.

In Canada the term platform has hitherto been restricted to the widespread tabular carbonate bodies which formed the foundations for isolated, areally more restricted, carbonate buildups. These isolated buildups have not hitherto been called platforms, even though the main difference between them and the foundation platforms relate to thickness and extent. The isolated platforms are composed of very similar facies to those found in the foundation platforms, but the isolated bodies are generally thicker and cover smaller areas. Both stood with topographic relief above adjacent shale basins.

It is recommended that the term carbonate platform be applied to both the areally restricted buildups and the underlying more extensive bodies. The latter can be referred to as foundation platforms where the distinction is necessary.

Marginal slope. The term marginal slope has been applied by Marathon geologists to the outer slope of a carbonate complex which is mantled by platform-derived detritus, with or without contributions from indigenous organisms. The deposits on this slope are referred to as the marginal-slope facies, and they are essentially equivalent to the fore-reef facies of Playford and Lowry (1966).

Shelf lagoon. Marathon geologists apply the term shelf lagoon to the shoal-water area which was present on top of each platform, and which may or may not have been rimmed by reef. The term is also used in this manner in the Canning Basin. It is recommended that the deposits laid down in this environment be called the shelf-lagoon facies in Alberta, although in the Canning Basin (where reef development is stronger) they are referred to as the back-reef facies.

Basin. This term as generally applied in Canada refers to the open ocean area surrounding carbonate platforms, where the water was deeper. No distinction is normally made in the Canadian nomenclature between the basin facies that are equivalent to adjacent platforms and the later basin deposits which commonly envelop the platforms. This is partly due to the difficulty in distinguishing between these two types of basinal deposits.

In the Canning Basin the term inter-reef basin is applied to the open ocean between platforms, and the deposits are called the inter-reef facies. The unqualified terms basin and basin facies are applied in the Canning Basin to the open ocean and its deposits that are far-removed from platforms.

WESTERN AUSTRALIA

The distribution of Devonian reef complexes in the Kimberley District of Western Australia is shown on Figure 1. They occur along the northern margin of the Canning Basin and in the western part of the Bonaparte Gulf Basin. The Canning Basin complexes are much better exposed and have been studied in more detail than those of the Bonaparte Gulf Basin.

CANNING BASIN

Few Devonian reef complexes in the world are as well preserved as those of the northern Canning Basin. Exposures are excellent over a wide area, the rocks are only mildly deformed, and most of the section is undolomitized. From 1962 to 1965 these complexes were the subject of a detailed stratigraphic study by the Geological Survey of Western Australia (Playford and Lowry, 1966; Playford, 1967). The project was undertaken primarily to assist oil exploration in the Canning Basin, though it was realized that detailed information on these well-preserved complexes could have application to prospecting elsewhere in the world, and especially in Canada. For detailed information the reader is referred to the bulletin by Playford and Lowry (1966); the geology of these rocks will only be summarized here.

The reef complexes are exposed as a series of rugged limestone ranges in a belt 180 miles long and from less than a mile to 30 miles wide. The best exposures occur in a series of classic canyon sections through the ranges, especially at Windjana and Geikie Gorges. The upper surface of the ranges is an old planation surface, thought to be essentially the exhumed Permian unconformity.

The Devonian rocks occur in the northernmost structural subdivision of the Canning Basin, known as the Lennard Shelf (Figure 1). This is bounded on the north by the Precambrian Kimberley Block, which formed the main landmass in Devonian times, and on the south by a deep graben of Permian and Carboniferous sediments named the Fitzroy Trough. The complexes are known to occur in the subsurface in four wells, Meda Nos. 1 and 2, Hawkstone Peak No. 1, and the 67-mile water bore, where they are covered by Carboniferous, Permian and Mesozoic sediments.

The reef complexes developed as fringing reefs, barrier reefs, and atolls around islands of Precambrian rocks and along the mainland shore of the Kimberley Block. One reef complex commenced growth on Ordovician dolomite. The basement surface on which the reefs developed had considerable relief, amounting to at least 3,000 feet. It seems probable that an important period of block faulting immediately preceded reef development, giving rise to the topography which localized the complexes.

Masses of terrigenous conglomerate, containing clasts up to boulder size, interfinger with the reef complexes in some areas. Similar conglomerates of probable Permian age overlie the reefs and the younger conglomerates with angular unconformity. The conglomerates are believed to be torrential deposits shed from active fault scarps.

Structurally the reef complexes are relatively little deformed. There are a few normal faults having throws of as much as 2,000 feet, with associated tilted blocks, and some minor folding, but for large areas the reef complexes are almost undisturbed. The main fault in the area is the Pinnacle Fault, which probably first developed during the Late Carboniferous and which is believed to have a maximum throw of more than 10,000 feet. It marks the boundary between the Lennard Shelf and the Fitzroy Trough.

Four basic facies are recognized in the complexes: the reef, back-reef, fore-reef, and inter-reef facies (Figure 2). The reef and back-reef deposits make up a series of limestone platforms that accumulated some tens to hundreds of feet above the surrounding inter-reef basins. They are flanked by extensive fore-reef talus deposits having steep depositional dips, and these pass into the low-dipping, predominantly terrigenous, sediments of the inter-reef basins.

The limestone platforms range from tiny patch reefs and atolls to extensive bodies covering hundreds of square miles. Each platform is normally rimmed by a massive algal or stromatoporoid reef from a few feet to a mile or more in width, but in some areas the reef rim is absent for considerable distances around the platform margin. The average width of the reef facies at the time of development is thought to have been about 300 feet. The reefs normally grew upward and outward, advancing over their own talus deposits. However, in some areas the reefs grew nearly vertically or horizontally, while in others they retreated over the back-reef deposits.

The main framebuilders in the reefs were calcareous algae, especially minute blue-green forms referred to the genus *Renalcis* (Wray, 1967a; Wray, 1967b). The blue-green or green alga *Sphaerocodium* is also important, and much of the massive limestone without recognizable cellular structure is thought to have been precipitated or bound by blue-green algae. Massive domal and tabular stromatoporoids are the main framebuilders in some reefs, and corals are locally important. The reef facies is extensively recrystallized to sparry calcite in some areas.

The reef facies formed a rigid mass which was eroded by wave action. The fore-reef facies consists largely of talus derived from the growing reef, with contributions from the shelf lagoon, terrigenous sources, and organisms that grew on the fore-reef slope. The depositional dip of the fore-reef talus is commonly 30 to 35 degrees near the reef, flattening gradually down the fore-reef slope. The talus includes some enormous megabreccias containing reef blocks up to 300 feet across.

The back-reef sediments of the shallow shelf lagoon behind the reef form the main part of each limestone platform. They consist of well-bedded stromatoporoid, coral, and oncolite limestones, birdseye limestone, oolite, calcarenite and calcilutite. Five sub-facies are recognized in the back-reef: the stromatoporoid, birdseye limestone, coral, oncolite, and oolite sub-facies. These deposits are believed to have accumulated in very shallow water, generally less than about 10 feet deep. The birdseye limestones are interpreted as algal-mat deposits, and at least part of these were laid down in the intertidal zone.

The inter-reef facies consists of shale, siltstone, and sandstone, interbedded with fine-grained limestone. These deposits are essentially devoid of talus from the platforms and were laid down nearly horizontally or with very low depositional dips. The depth of water in the basins may have ranged from perhaps 30 feet in very shallow areas to 600 feet or more in others.

Both the reef and the back-reef facies are dolomitized fairly extensively in some areas. The fore-reef deposits are less dolomitized, while dolomite is absent or rare in the inter-reef facies.

The total maximum thickness of individual reef complexes is not known, but it is conservatively estimated to have been at least 3,000 feet in some cases.

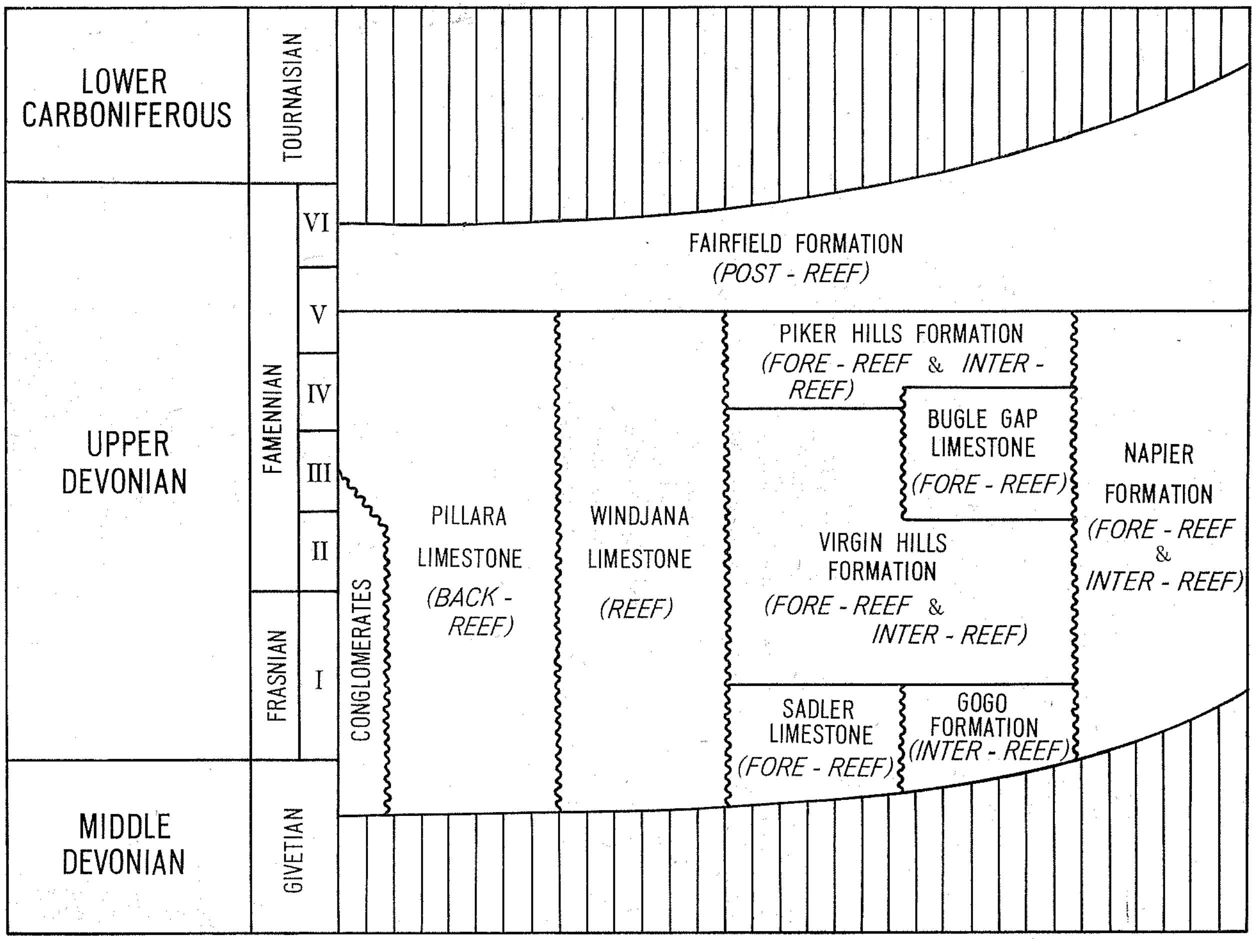


Figure 3. Correlation chart, Devonian and Lower Carboniferous sequence of the northern Canning Basin.

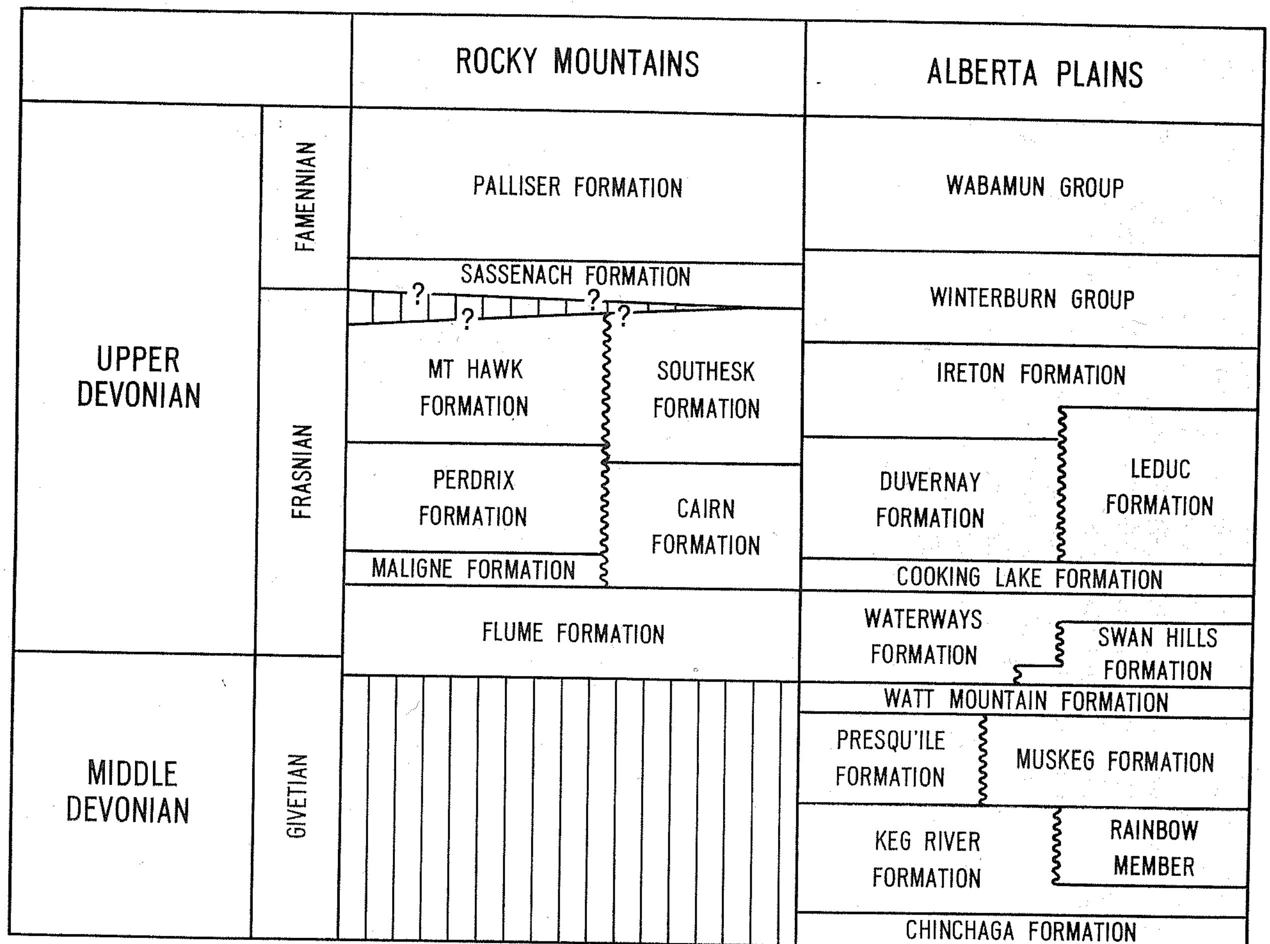


Figure 4. Correlation chart, part of Devonian sequence of Alberta.

The stratigraphic nomenclature that has been applied to the reef complexes is shown in Figure 3. The reef facies in each complex is known as the Windjana Limestone, while the back-reef facies is the Pillara Limestone. The whole of the fore-reef and inter-reef facies in the Napier Range—Oscar Range area is placed in the Napier Formation. However, in the reef complexes exposed in the south-eastern part of the Lennard Shelf it has been possible to subdivide the fore-reef and inter-reef facies into five formations, as shown on Figure 3.

The complexes range in age from Middle to Late Devonian, from late Givetian to late Famennian. Correlation with the standard European succession is based mainly on conodonts and ammonoids. Middle Devonian is known only from the base of the section in the Pillara, Home and Emanuel Ranges. Most of the exposed section in the limestone platforms is Frasnian.

Extinction of the reef complexes during the late Famennian allowed the shallow-water Fairfield Formation to spread over the whole area of the shelf. Extinction is believed to have resulted from the filling of the inter-reef basins by terrigenous sediments, thereby destroying the conditions of water circulation and bottom topography necessary for reef growth.

BONAPARTE GULF BASIN

Reef complexes ranging from Frasnian to possibly Tournaisian in age are known from the Bonaparte Gulf Basin (Playford, Veevers, and Roberts, 1966; Veevers and Roberts, 1967). They appear closely similar to their counterparts in the Canning Basin, but are not so well exposed.

The best exposures are in the Ningbing (also spelled Ninbing) Range described briefly by Playford and others (1966). Most of the range consists of Famennian back-reef deposits, which are largely birdseye limestone, but which also include some stromatoporoid limestone. The reef facies is largely recrystallized to sparry calcite, but it includes some well-developed *Renalcis* limestone. It seems that in this area reef growth continued into the Tournaisian, whereas in the Canning Basin it ceased during the late Famennian.

A good deal more detailed work remains to be done on the complexes exposed in the Bonaparte Gulf Basin. Especially rewarding would be the Frasnian 'incipient reefs' of the Westwood Creek area on the north coast (Veevers and Roberts, 1967).

ALBERTA

There have been three main periods of development of carbonate complexes that contain oil in Alberta. These are represented by the Givetian Rainbow complexes of northern Alberta, and the early Frasnian Swan Hills and later Frasnian Leduc complexes of central Alberta. Each period has yielded prolific oil and gas fields. The stratigraphic nomenclature for the most important part of the Devonian section in Alberta (surface and subsurface) is illustrated in Figure 4. The Devonian stratigraphy of western Canada is summarized by Grayston, Sherwin and Allan (1964), Committee on Slave Point and Beaverhill Lake Formations (1964) and Belyea (1964).

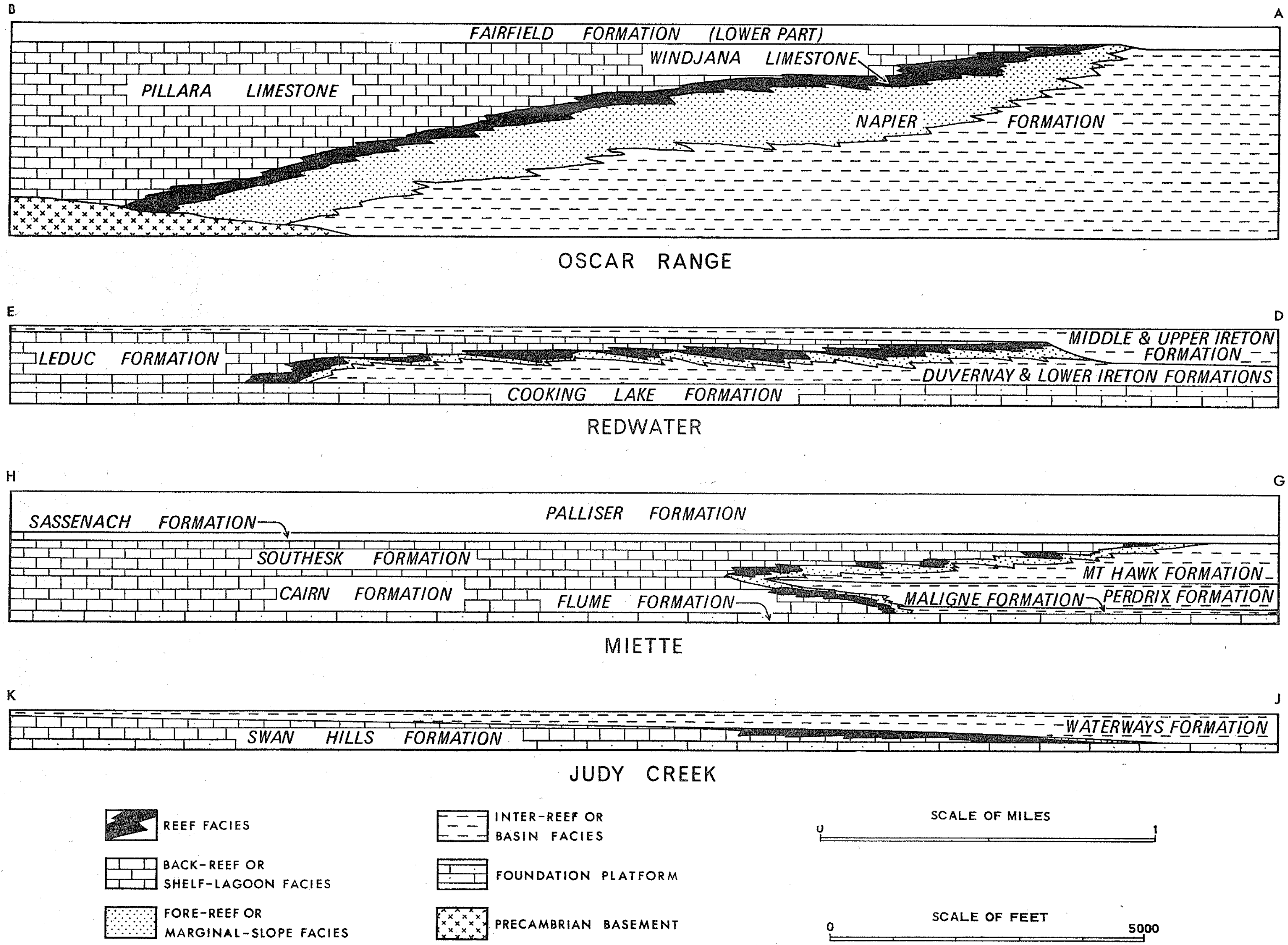


Figure 5. Diagrammatic cross-sections through the margins of the Judy Creek, Miette, and Redwater complexes (Alberta) and the Oscar Range reef complex (Western Australia).

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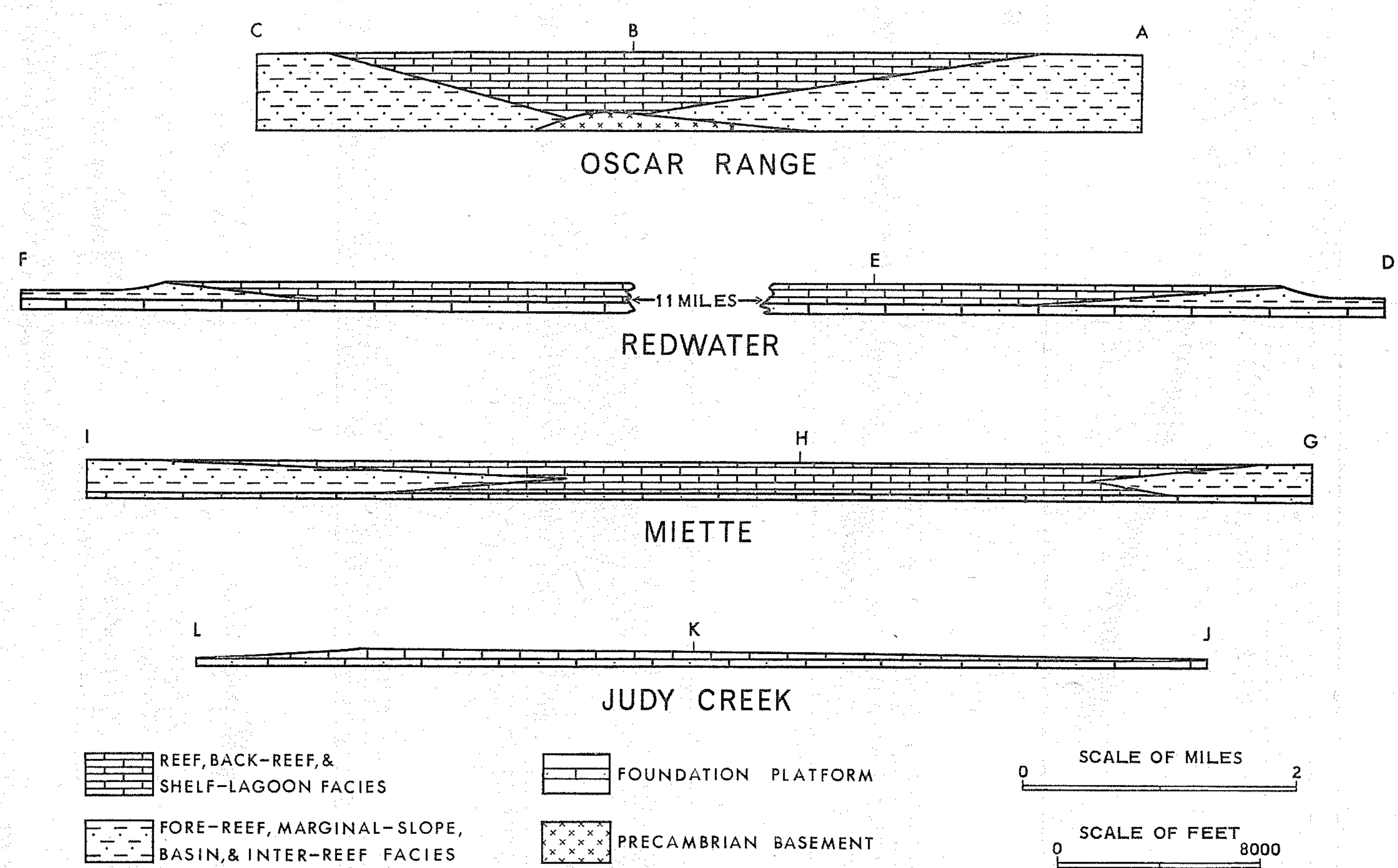

Figure 6. Diagrammatic cross-sections through the Judy Creek and Redwater complexes (Alberta) and the Oscar Range reef complex (Western Australia).

My study has been principally concerned with the Upper Devonian complexes. Their distribution in Alberta is shown on Figure 1. In the field I was shown part of the Miette complex near Jasper, and I have examined samples, publications, and unpublished Marathon reports dealing with a number of subsurface occurrences, principally Redwater and Judy Creek.

MIETTE COMPLEX

The Miette carbonate complex has been described by Mountjoy (1965) and Noble (1965). Mountjoy concentrated on the overall stratigraphy and structure of the complex, whereas Noble's work was concerned principally with the palaeoecology of the Cairn Formation and the adjacent basinal deposits. Marathon Oil Company has also carried out detailed field studies at Miette.

I accompanied P. N. McDaniel, W. J. Meyers and R. P. Steinen in the field at Miette from August 17 to August 24, 1967. Sections were examined and measured at a number of localities between Bryant Creek and Utopia Creek. The work was concerned principally with the Flume foundation platform which underlies the Miette complex.

From August 31 to September 5, 1967, I joined a field trip to Miette sponsored by the International Symposium on the Devonian System. It was led by E. W. Mountjoy and was attended by a total of 30 geologists from many parts of the world. During this trip important sections were examined at Marmot Cirque, Section Creek, and Slide Creek.

Stratigraphy

The stratigraphy and general facies relationships of the Miette complex are shown on Figure 4 (the section headed 'Rocky Mountains') and on Figure 5, 6 and 7. The complex is exposed in three thrust sheets in Jasper National Park.

The Flume Formation is the foundation platform, 100 to 150 feet thick, on which the Miette platform grew. The Flume is a biostromal deposit, the main lithologies represented being stromatoporoid limestones (in which *Amphipora* and massive stromatoporoids are abundant), birdseye limestone, calcarenite, calcilutite, and some shaly beds. Dolomitization is extensive in certain areas. The dark colour (dark grey to nearly black) of many of the Flume limestones is very noticeable, and these have a strong fetid odour when freshly broken. The main exception is the Utopia Member (near the base) which is medium to light grey.

The Flume Formation overlies Cambrian dolomites of the Waterfowl Formation in the Miette area. It is possible that broad warping occurred in this area during the final stages of Flume deposition, so that the platform was able to continue growing at Miette, but was drowned elsewhere. If this is so, the top of the Flume is not a time plane, but is oldest in those areas where the formation is thinnest.

The Flume platform is similar to the foundation platforms of some other reef complexes in the Alberta Devonian, such as the Keg River platform on which the Rainbow complexes grew, and the Cooking Lake platform of the Leduc

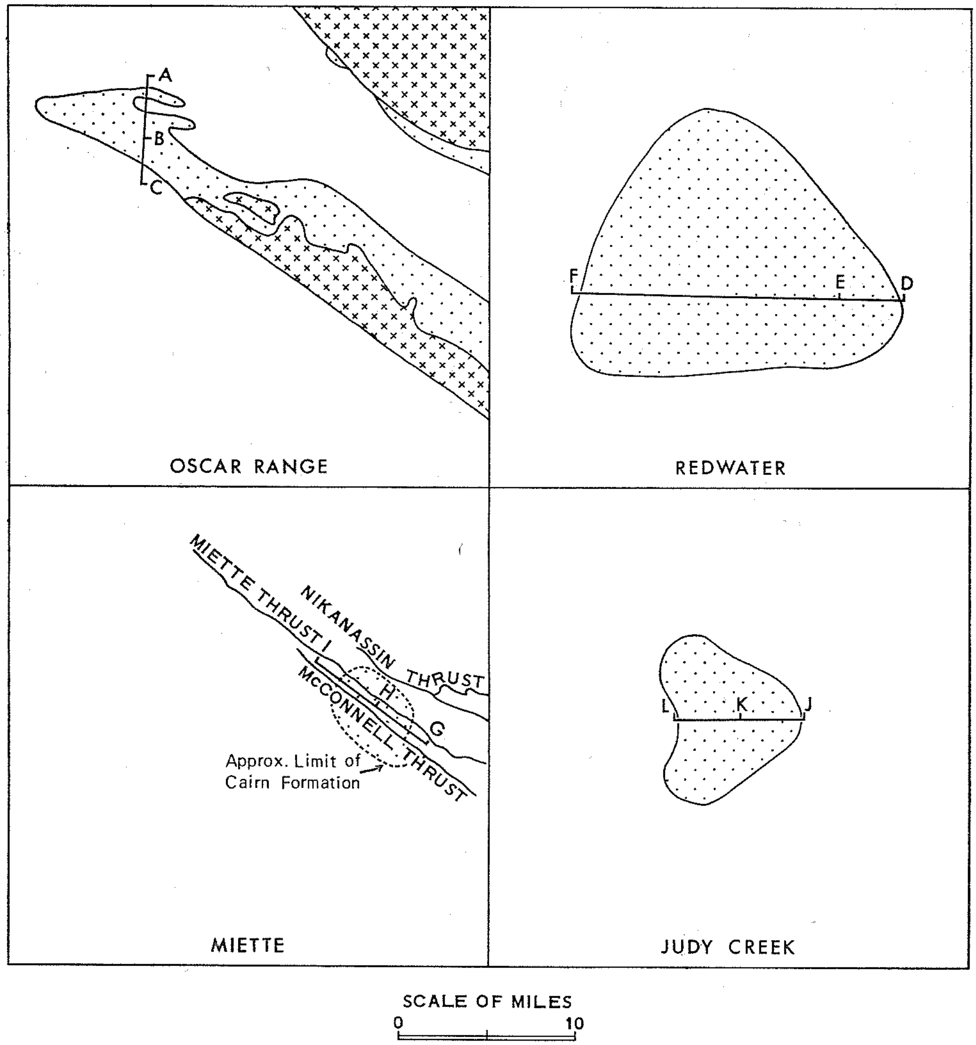

Figure 7. Maps showing the location of each section shown in figures 5 and 6.

complexes. Each of these foundation platforms has a basinal equivalent, and the platform margin almost certainly includes true reefs in some areas. The margin of the Flume platform does not crop out in the Rockies, and it is believed to occur in the subsurface beneath the Alberta Plains.

The Cairn Formation, which overlies the Flume with a gradational contact, consists of well-bedded dolomitic limestone, with a narrow marginal zone of massive dolomite in some areas. Mountjoy (1965) and Noble (1965) regard the Cairn as a stromatoporoid reef complex. Most of the formation consists of stromatoporoid (*Amphipora* and bulbous stromatoporoid) biostromal limestones, which are commonly partly dolomitized and grade into dolomites. The rocks are not as dark as those in the underlying Flume platform, but are commonly medium to dark grey. Massive light-grey dolomites occur discontinuously at the margin of the Cairn in contact with the marginal-slope strata of the Maligne and Perdrix Formations. These dolomites were interpreted by Mountjoy (1965) and Noble (1965) as representing reef facies.

The margin of the Cairn Formation slopes away from the interior of the platform (Figures 5 and 6). The angle of retreat is between 7 and 10 degrees in the plane of the present erosion surface at Marmot Cirque. It is clearly an erosional surface, as can be seen in a number of exposures on the cirque wall. The margin of the lower part of the Cairn consists of massive dolomite, but in the upper part (high in the cirque) bedded dolomites extend to the margin, and the bedding is clearly truncated at the contact with the marginal-slope beds. In my opinion it is probable that the erosion surface at the Cairn platform margin is the result of contemporaneous erosion during Cairn deposition, and that the platform had significant relief above the basin floor during this period. The amount of relief cannot be demonstrated with any degree of certainty at present, but at times it may have been 100 to 200 feet. Such an erosion surface is to be expected at the edge of any limestone platform that was subject to wave action, had significant relief above the surrounding basin, and is known to have supplied debris to the surrounding basin sediments.

An alternative hypothesis is that the erosion surface is an unconformity developed after deposition of the Cairn Formation, rather than being due to contemporaneous erosion during Cairn and Perdrix deposition. However, the presence of debris flows in the marginal-slope deposits has been demonstrated at Miette and other exposed carbonate complexes in Alberta (Pray and others, 1967), and contemporaneous erosion of the platform margin therefore seems to have been established. Furthermore, if the platform had been uplifted sufficiently for more than 100 feet of dissection to have occurred at the margin, there should be clear evidence of erosion within the shelf-lagoon deposits, but this has not been found. Perhaps the most likely place for such an erosion surface (if it were present) would be at the contact between the Cairn and Southesk Formations, yet this contact is transitional over an interval of about 40 to 100 feet, with no sign of an erosional break.

There seems to be no conclusive evidence for the presence of a reef margin on the Cairn platform. However, in my opinion it is probable that the massive dolomite that rims the Cairn in its lower part does represent reef facies. Unfortunately, dolomitization has destroyed the organic features of the rock, so that the presence of reef frame-builders cannot be proved. However, this massive dolomite rim is very similar in appearance to the dolomitized reef rim of some Canning Basin complexes.

The Southesk Formation consists of well-bedded medium to light-grey limestone, which is much less dolomitized than the underlying Cairn Formation. Birdseye limestone seems to be the most common lithology, but there are also stromatoporoid and coral biostromes. Some beds contain abundant megalodont pelecypods which closely resemble the *Eumegalodon* of the back-reef oncolite sub-facies in the Canning Basin complexes. Mountjoy (1965) recognizes four members within the Southesk: the Peechee, Grotto, Arcs, and Ronde Members (from the base up). The boundary between the Peechee and Grotto Members is particularly hard to identify in the Miette complex.

The full lateral extent of the Southesk part of the Miette complex is indefinite, and the upper limit as shown on the cross-sections (Figures 5 and 6) is essentially the limit of the Arcs Member. There is some uncertainty as to whether or not the Ronde Member should be considered as being part of the complex (H. E. Cook, personal communication, 1967).

In contrast to the retreating Cairn complex, the Southesk advanced at a low angle over the basin (Figures 5 and 6). At a number of localities long tongues (presumably of talus) can be seen extending down from the Southesk limestones into the basinal shales and limestones of the Mount Hawk Formation. The relief indicated at the edge of the Southesk platform in such areas appears to be at least 50 feet.

During the field season we examined the basal Southesk at Bryant Cirque and in Utopia Creek (see maps *in* Mountjoy, 1965). At Bryant Cirque the basal bed is commonly about 15 to 20 feet thick and is composed of stromatoporoid limestone with abundant laminar stromatoporoids, some of which are up to a foot long and are only .05 to .1 inches thick. They are clearly in growth position and are set in a matrix of medium to light-grey micrite with 'micro-birdseye' texture. I believe that this matrix is either algal-bound or algal-precipitated.

There is evidence that limestone of this type contributed debris to the marginal-slope Mount Hawk sediments which underlie the Southesk at this locality. Many blocks of laminar stromatoporoid limestone containing up to 50% of stromatoporoids by volume were noted in the debris beds, the largest being a slab 16 feet long and 1 foot thick. Therefore it appears that rigid stromatoporoid limestone, which could possibly be classed as reef facies, did occur around the margins of the Southesk platform in the Bryant Cirque area.

However, the most likely occurrence of true reef I have seen at the margin of the Southesk occurs in the central branch of Utopia Creek. At this locality the basal unit is about 50 to 70 feet thick and is quite massive. In the creek bed there are a few feet of Mount Hawk Formation between the Southesk and Cairn Formations, and the Mount Hawk appears to pinch out before reaching the cliff exposures to the east. There was insufficient time during our visit to prove that this unit is in fact reef, but it seems very probable. Samples collected from the unit were polished and thin-sectioned, and they indicate that it is largely composed of a framework of tabular to domal stromatoporoids, with a matrix ranging from grainstone to micrite, some of which may be algal-bound or precipitated. Coral heads and *Thamnopora* are also present, apparently in their growth positions, Well-bedded limestones of the Southesk may grade into this massive unit in the creek bed, suggesting a transition from reef to back-reef. The underlying Mt. Hawk limestones contain many heads of coral, *Thamnopora*, and some broken stromatoporoids, none of which seem to be in growth position. I believe that these organisms were probably derived from the reef, but detailed study would be necessary to test this hypothesis. This area is certainly one that warrants a more detailed investigation.

The basin and marginal-slope facies of the Miette complex are divided into the Maligne, Perdrix and Mount Hawk Formations (from the base up). These deposits consist largely of dark-grey to black limestone, grading basinward to black calcareous shale. Prominent breccia beds occur in all the marginal-slope deposits near the platform margin, and these possibly extend for more than a mile into the basin. The breccias are composed of platform-derived debris (blocks of limestone and fragmentary stromatoporoids and corals) together with fragments of basin limestone. The fragments of basin limestone are commonly sub-rounded, indicating that they were only partly lithified when eroded. The plaftorm-derived blocks I saw in the Miette complex are either laminar or tabular stromatoporoid limestones, or (less commonly) coral limestone. At least some of these blocks were probably derived from a reef rim. Thin-section studies of material collected by previous Marathon parties showed only two samples (in the Maligne Formation at Marmot Cirque) containing fragments of *Renalcis* limestone.

Development of the complex

The development of the Miette complex is illustrated in Figures 5 and 6, which are interpretive cross sections through the complex in the Miette thrust sheet. The most important feature of the complex is that it retreated at a low angle during Cairn deposition, but advanced at an even lower angle during Southesk deposition.

The Miette buildup is interpreted as being partly a reef complex, and partly a bank complex. The existence of a reef rim has certainly not been proved conclusively, but for the reasons given above, it seems likely that a discontinuous reef rim was present from time to time around the margins of both the Cairn and the Southesk platforms.

The Miette platform may have been localized by a broad upwarping in the Flume foundation platform. In other words, the site of the Miette platform may have been slightly positive during the closing phase of Flume deposition.

The reason for cessation of platform growth at the end of Southesk times is not clear. The complex is overlain by the Sassenach Formation without noticeable discordance in the Miette area, though regionally this contact may be disconformable (H. E. Cook, personal communication, 1967). Emergence of the complex during the late Frasnian could have been the cause of extinction, or alternatively the basin may have filled with sediments, thus removing the elevation difference between platform and basin that had been necessary for platform growth.

REDWATER COMPLEX

The Redwater reef complex is the largest undolomitized isolated complex in the subsurface of Alberta. It is located north of Edmonton (Figure 1) and covers about 200 square miles. The average thickness of the complex (excluding the foundation platform) is about 700 feet, and in the producing part of the field the top occurs at a depth of about 3,100 feet. Production is obtained from the up-dip northeastern part of the complex, in the upper 150 feet of section.

The Redwater complex has been described by Andrichuk (1958) and Klovan (1964). Andrichuk's paper also includes descriptions of related reef complexes in the Leduc and Stettler areas. Klovan's detailed study concentrates on the 'Upper Leduc' section at Redwater, which is the upper 150 feet of the complex from which production is obtained. He has less information on the lower part of the complex (the 'Middle Leduc'), or the Cooking Lake foundation platform (the 'Lower Leduc').

Klovan regards Redwater as a true reef complex, and recognizes organic-reef, back-reef and fore-reef facies in the 'Upper Leduc'. He uses the unqualified term 'reef' in a general sense to embrace both the organic-reef and the back-reef facies. Klovan's usage of reef is thus equivalent to the term carbonate platform of this paper. His organic reef is what I understand by the term reef.

The principle framebuilders in the organic reef facies of the 'Upper Leduc' are massive stromatoporoids. The back-reef deposits consist of birdseye limestone, *Amphipora* limestone, calcarenite, calcirudite, and minor green shale. The marginal-slope deposits are composed mainly of talus from the organic reef, and Klovan records depositional dips of up to 20 degrees. He reports the presence of abundant megalodont pelecypods and tabular stromatoporoids in the marginal-slope facies, but regards them as being indigenous rather than derived from the reef or shelf lagoon. It seems more probable to me that the megalodonts were derived from the shelf lagoon, as they also occur in this environment in the 'Upper Leduc' and in the Southesk Formation at Miette. Moreover, a closely similar form, identified as *Eumegalodon,* occurs abundantly *in situ* in some parts of the back-reef facies of the Canning Basin reef complexes, and it also contributes to the talus of the fore-reef facies in these complexes.

The tabular stromatoporoids in the marginal-slope deposits at Redwater are most likely derived from the organic reef, based again on the occurrences at Miette and in the Canning Basin.

In the 'Middle' and 'Lower Leduc' sections control is much less, as complete cores are only available in four widely spaced wells. The 'Lower Leduc', which is the foundation platform for the complex, consists of calcarenite, calcirudite, and calcilutite, with abundant stromatoporoids and corals in some beds. This platform is equivalent to the Cooking Lake Formation, and it extends well beyond the limits of the Redwater complex.

The 'Middle Leduc' includes the lower 550 feet of the Redwater complex. It is continuous with the 'Upper Leduc', and the boundary is based solely on the fact that abundant well control is available in the upper 150 feet of the complex referred to as 'Upper Leduc'. The most significant facies in the 'Middle Leduc' is an organically bound limestone, which Klovan interprets as organic reef facies. It consists of a solid framework of tabular stromatoporoids with abundant to rare *Renalcis* (which Klovan referred to the genus *Chabakovia* and regarded as an encrusting foraminifer).

I examined cores of this facies from Salt-Water-Disposal Wells Nos. 1 and 5. They are white to light-grey *Renalcis* and tabular stromatoporoid limestones which appear identical to parts of the reef facies in the Canning Basin. Klovan (1964) believes that the lime-mud matrix (now largely recrystallized to fine spar) in this facies indicates a lack of turbulence in relatively deep water. However, in the Canning Basin it seems that the micritic matrix of these limestones must have been precipitated as limestone and was never a soft mud. The *Renalcis* limestone there occurs in the high-energy reef environment and contributes fragments, ranging from sand grade to huge boulders, to the fore-reef talus. I am confident that the thick *Renalcis* and tabular stromatoporoid limestones in the 'Middle Leduc' show that a true reef wall was developed in the complex at this time.

Above and interfingering with the organic reef facies in the 'Middle Leduc' there are typical shelf-lagoon *Amphipora* and birdseye limestones, while beneath the reef in Salt-Water-Disposal Well No. 5 there is a very thin section of marginal-slope limestone with possible depositional dips of up to 20 degrees, and this passes into dark basinal argillaceous limestone which is apparently equivalent to the Duvernay Formation. The marginal-slope deposits and the upper part of the basinal deposits contain reef-derived organic detritus. Basinal limestone also occurs beneath the reef in Imperial Eastgate No. 1.

Reference to Klovan's Figure 17 shows that the organic reef facies in the 'Middle Leduc' occurs in Salt-Water-Disposal Wells 1, 4 and 5, at depths of 300 to 700 feet below the top of the complex. These three wells are each situated some 1½ to 2 miles from the margin of the complex where the organic reef comes to the surface. Therefore it seems that the reef front must have grown progressively upward and outward with time, advancing over the marginal-slope and basin facies (Figures 5 and 6). The depth of water in front of the Redwater platform in the 'Middle Leduc' section was apparently rather shallow, so that the marginal-slope facies is at most only weakly developed. It also seems probable that the reef facies was not continuous around the platform margin.

Renalcis, the key fossil in the 'Middle Leduc' organic reef, does not seem to be present in the 'Upper Leduc'. However, I have no doubt that the tabular and massive (domal to irregular) stromatoporoids that occur in the 'Upper Leduc' organic reef do have the ecologic potential to form true reef frameworks.

The Redwater complex is surrounded and enveloped by basinal argillaceous sediments. The Duvernay Formation and the lower part of the Ireton Formation are interpreted by McCrossan (1959) as containing some reef-derived debris, while the rest of the Ireton 'shales' filled the basin and covered the complex after its extinction. According to this interpretation the relief of the complex at the time of its extinction would have been a maximum of about 300 feet.

Much has been made of the fact that the crest of the Redwater complex is not at the margin, but is displaced some 1¾ miles inwards. Klovan (1966) states that in general the organic reef is 25 to 50 feet lower than the crest of the complex, and that therefore the organic reef grew in water 20 to 40 feet deep. This assumes that the organic reef penetrated in the marginal wells is the time equivalent of the shelf-lagoon deposits at the crest, whereas certainly this has not been demonstrated. Reef growth may have ceased at the margin owing to rapid subsidence, while deposition of *Amphipora* limestone, birdseye limestone, and calcarenite continued in the central part of the complex. Furthermore, there is evidence that the organic reef front was retreating and discontinuous during the closing phase of the complex.

Another alternative is that the basinward slope of the outer part of the platform is causd by compaction of the basinal argillaceous sediments over which the complex advanced. If this is so, the compaction would need to have occurred during deposition of the upper part of the Ireton. Yet another possibility is that the top of the complex is an erosion surface, but I do not think this is likely on the evidence available. In any case I can see no reason why the organic reef facies represented in the 'Upper Leduc' should not have grown very close to sea level, as has been interpreted for similar facies in the Canning Basin.

JUDY CREEK COMPLEX

The Judy Creek complex is one of a series of carbonate platforms developed in the upper part of the Swan Hills Formation about 100 miles northwest of Edmonton. These platforms are not dolomitized and are therefore amenable to detailed facies studies where there is sufficient well control. The stratigraphic nomenclature is illustrated on Figure 4, the location of the complex is given on Figure 1, and its general structure is shown on Figures 5, 6 and 7.

The Judy Creek complex is described in an excellent paper by Murray (1966). He regards it as a 'reef-fringed bank', one of several which developed on the broad foundation platform that forms the lower part of the Swan Hills Formation. The foundation platform consists of biostromal stromatoporoid and coral limestone, birdseye limestone, and micritic limestone. It ranges in thickness from about 75 feet to 210 feet, the thickest sections underlying the isolated platforms. Gentle warping associated with rapid subsidence during the later phases of foundation-platform deposition may have resulted in the drowning of the platform over the downwarped areas while it continued to grow over the 'highs'. If this interpretation is correct then the top of the foundation platform is time transgressive.

The foundation platform itself appears to be at least partly reef fringed (Edie, 1961). A narrow zone rich in tabular stromatoporoids occurs around the margin in some areas, and probably formed a rigid, wave-resistant mass. I examined cores of this facies from the House Mountain field (by courtesy of Mr. P. Reed of Columbia University), and interpret it as true stromatoporoid reef. *Renalcis* is present in association with the tabular stromatoporoids in some of these cores, but it is not a significant framebuilder.

The Judy Creek complex, like others in the Swan Hills Formation, has only gentle relief (Figures 5 and 6). The cross-sections presented by Murray are too exaggerated to give a realistic impression of the geometry of the body. The steepest marginal slope is on the west side, where it slopes down to the narrow channel that separates the Judy Creek and West Judy Creek platforms, but this slope amounts to only about 5 degrees. On the east flank it is less than 2 degrees. The Judy Creek platform covers about 50 square miles, and it is up to 250 feet thick. The average thickness of the underlying foundation platform in this area is about 150 feet.

The main framebuilders in Murray's reef facies are massive and tabular stromatoporoids with some *Stachyodes*. The red alga *Parachaetetes* is locally important, but no *Renalcis* has been found. Some geologists have doubted the ability of massive (domal to hemispherical) stromatoporoids to form true reef frameworks. However, the well-exposed sections in the Canning Basin reef complexes show that stromatoporoids of this type do form rigid reef masses, and the stromatoporoid limestones from the platform margins in Alberta do not appear significantly different from these.

The reef rim around the margin of the Judy Creek platform appears to have been discontinuous, and it did not persist to the top of the complex. Murray, like Klovan at Redwater, is disturbed that *Amphipora* beds apparently persist higher in the section than the reef rim. However, in the Canning Basin it is found that the presence of a reef rim is not necessary for the development of *Amphipora* limestone in the shelf lagoon. In fact it seems that the deposits over the major part of a shelf lagoon are little affected by the presence or absence of a reef rim.

There is relatively little development of fore-reef detritus at Judy Creek. However, Murray (1966) does recognize reef-derived detritus on both the west and east sides of the complex, with depositional dips as high at 30 degrees. The detritus is well graded, and is associated with tabular stromatoporoids which Murray has assumed to be in place. I think it is more likely, however, that the tabular stromatoporoids are also reef-derived and have come to rest parallel to the bedding. I would expect depositional dips as high as 30 degrees to be rare at Judy Creek, as the reef and the platform as a whole appear to have retreated quite uniformly at low angles.

The Waterways Formation, which surrounds and overlies the Judy Creek complex, consists of about 550 feet of dark brown, argillaceous, micritic limestone with some calcareous shale. Clastic limestones, that are in part reef-derived, have been found interbedded with the Waterways Formation up to 60 feet above the top of the foundation platform. Murray believes that no more than 100 feet of section at the base of the Waterways is time equivalent to the

Judy Creek platform, the rest of the formation having been laid down after its extinction. Thus, on his interpretation, the complex had at least 150 feet of relief at the end of Swan Hills time. Murray notes that over the upper part of the platform the contact with the Waterways is very sharp, with truncation of stromatoporoid colonies and other evidence of erosion. However, as with the Miette complex, there is no reason why this erosion should not have occurred contemporaneously with platform growth, contributing material to the marginal-slope deposits.

Murray also has evidence of an erosional break within the platform, marked by green shale and brecciated limestone beds in the upper part of the complex. There does not, however, seem to be any reason to believe that this emergence amounted to more than a few feet, exposing only the crest of the complex.

OTHER COMPLEXES

Ancient Wall Complex

The Ancient Wall complex is situated north of Miette in the Rocky Mountains (Figure 1). It has not been studied in as much detail as the Miette complex, but the two seem to be quite similar. The most marked difference is the greater development of coarse debris beds interfingering with the basinal deposits at Ancient Wall (Pray and others, 1967; Mountjoy, 1967). These debris beds include huge blocks of platform-derived limestone up to 50 metres across. Marathon found that some of the samples from debris beds contain *Renalcis*, though it is abundant in only a few. At least some of these blocks are believed to be derived from reef facies, possibly Mountjoy's (1967) 'wave-resistant structures (bioherms?) locally formed during deposition of the uppermost Cairn and lowermost Southesk on the flanks of the biostromes and banks'. Further work is desirable to clarify the relationships around the platform margin in this complex.

Rainbow complexes

There is little published information on the reef complexes of the Rainbow Lake area in northern Alberta*. These are Middle Devonian (Givetian) in age and were first discovered in 1965.

The Rainbow complexes range from 'pinnacles' less than a mile across to small atolls up to four miles wide. They are composed of stromatoporoid limestone which formed a rigid reef frame around the margins, enclosing a shelf lagoon in the case of the larger atolls. The flank slopes are of the order of 25 degrees and are formed, at least partly, of reef-derived talus. The maximum thickness of an individual complex is 800 feet, and the complexes had up to 650 feet of relief above the surrounding basin floor when reef growth ceased. The reefs began growing on crinoidal banks on top of the extensive Keg River foundation platform. The reef complexes themselves are referred to the Rainbow Member of the Keg River Formation (Figure 4).

* After completion of the manuscript, important papers were published on these complexes by Langton and Chin (1968) and McCamis and Griffith (1967).

It is noticeable that the smaller pinnacle reefs are not dolomitized whereas dolomitization is extensive in the larger atolls (J. R. Langton and G. Chin, personal communication, 1967). This may be linked to the lagoon development in the atolls, which could give rise to dolomitization by the seepage-refluxion process.

The complexes are surrounded and enveloped by evaporites (including salt) of the Muskeg Formation. The evaporites may have been deposited in deep water after reef growth had ceased. There is no evidence that the complexes have been subaerially exposed, and extinction is thought to have resulted from the closing off of this section of the Devonian sea from the open ocean by the Presqu'ile barrier.

COMPARISON OF CARBONATE COMPLEXES IN ALBERTA AND WESTERN AUSTRALIA

INTRODUCTION

Playford and Lowry (1966) after a review of the literature on ancient reef complexes, concluded that 'It is probable that the Devonian reef complexes of western Canada bear most resemblance to those of the Lennard Shelf'. Taking all factors into account, such as biotic constituents, structure of the complexes, water depths, distribution, thickness, and age, this generalization may be true. However, although I know relatively little about the reef complexes of the U.S.S.R., it seems likely that they are even more like the Canning Basin complexes than those of Canada. The Devonian reefs of the Spanish Sahara (Dumestre and Illing, 1967) are very similar to the pinnacle reefs of the Rainbow area, but there seem to be no close analogies in the Spanish Sahara to the more extensive complexes of Western Australia and Alberta.

Although the Canadian complexes are clearly similar to those of Western Australia, there are also some important differences, to be discussed below.

DEVELOPMENT AND DISTRIBUTION

EXTENT

The distribution of the carbonate complexes in Alberta and Western Australia is shown in Figure 1. The Alberta complexes are far more extensive than those known in Western Australia. In Alberta they occur in a belt perhaps 300 miles wide and 600 miles long (Figure 1). They are known in Western Australia from a belt only 30 to 40 miles wide (including the subsurface occurrences) and up to 180 miles long in the northern Canning Basin, and in a belt perhaps 20 miles wide and up to 60 miles long in the Bonaparte Gulf Basin. However, the wide extent of the complexes in Alberta has only been found through extensive drilling. It is possible that exploration will eventually show that the complexes in Western Australia extend right around the offshore northern and western sides of the Kimberley Block and into areas of the Canning Basin beyond the Lennard Shelf.

AGE

The reef complexes of the northern Canning Basin range from Middle Devonian (late Givetian) to Late Devonian (late Famennian, *Stufe* V) in age. Conodonts have shown that a continuous sequence is present from the oldest Frasnian to the late Famennian, without any significant breaks in sedimentation. No conodonts have yet been found in the Givetian sediments, which are dated solely by the brachiopod *Stringocephalus,* but there is no reason to believe that any significant break is present in that part of the section either. Local disconformities have been found in the Upper Devonian platforms, but these are believed to be of only local significance, possibly caused by nearby faulting. Alternatively they could represent very brief periods of regional emergence.

In the Bonaparte Gulf Basin the complexes range from Frasnian to possibly Tournaisian (Early Carboniferous) in age, but reef growth was not continuous between the Frasnian and the Famennian. In this basin the Frasnian is largely represented by sandstone without reef development except in a small local area. No Middle Devonian reefs are known.

The Canadian complexes range from Middle Devonian (Givetian) to Late Devonian (late Frasnian) in age. No definite reef or bank complexes are known from the Famennian, and in this respect the situation differs significantly from that in Western Australia. Also, whereas in the Canning Basin reef growth appears to have proceeded almost continuously from the late Givetian through to the late Famennian, in Alberta there have been three main periods of isolated platform development, of Givetian, early Frasnian, and later Frasnian age. Each began with a widespread foundation platform and culminated with a series of isolated buildups which eventually became extinct. Thus, platform development was essentially intermittent in Alberta but continuous in the Canning Basin. It appears to have been somewhat intermittent in the Bonaparte Gulf Basin, but not as much as in Alberta.

THICKNESS

The total maximum thickness of individual Canning Basin reef complexes is expected to be more than 3,000 feet, though this has not been measured in any one complex at the surface. The thickest section penetrated in the sub-surface is in the Meda No. 1 well, where the complex is 2,883 feet thick. A reconstruction of the Oscar Range reef complex (Figures 5 and 6) shows an estimated total thickness of between 2,500 and 3,000 feet.

In Alberta, individual complexes are much thinner than this, rarely exceeding 1,000 feet (including the foundation platform). One of the thickest is the Miette complex which (including the Flume Formation) is about 1,350 feet thick. I am not able to compare the total thickness of platform sediments for an equivalent period of time in the Canning Basin and Alberta. It is possible, however, that although the individual complexes are thinner in Alberta, some have probably been deposited more rapidly, but over a much shorter period of time, than the Canning Basin complexes. The answer to this question is only likely to come through zonal studies utilizing conodonts, equating sections of the same age in the two countries. Such studies may also give important clues regarding the relationships between platform morphology and rates of subsidence.

GENESIS

The origins of the Canning Basin and the Alberta complexes were generally quite different. Whereas in the Canning Basin the complexes usually began growth on a Precambrian surface having strong relief (caused by block faulting), it seems unlikely that comparable relief was ever present on the foundation of any of the Canadian complexes I have studied. Furthermore, the isolated complexes in Canada developed on widespread foundation platforms, and the controlling factors that localized them are not altogether clear, though broad warping may have been involved. Although block faulting is said to have localized some chains of complexes, this does not seem to have been satisfactorily proved, and in any case, strong relief apparently did not result from such faulting.

Perhaps the closest analogy in Alberta to the type of foundation found in the Canning Basin is the 'Peace River landmass' (Figure 1), a Precambrian high around which a fringing carbonate complex developed.

Most of the large platforms in the Canning Basin clearly developed directly on Precambrian rocks, either along the mainland shore of the Kimberley Block or around islands, but one developed on Ordovician dolomites. However, there are examples of 'stepping back' over older platforms to localize smaller buildups, as in the southeastern Pillara Range and Home Range areas (Playford and Lowry, 1966). This is analogous to the 'stepping back' of the Swan Hills foundation platform to form the isolated Swan Hills buildups. In the Canning Basin this phenomenon has been explained by local tectonism drowning all or part of the marginal area of a platform. The same could be true in the Alberta complexes, with broad (but abrupt) warping being responsible.

GROWTH

Growth of the Canning Basin reef complexes was predominantly upward and outward, with the reef front advancing over its own talus deposits. However, in some areas the reef grew nearly vertically, in others horizontally, while in a few restricted areas the reef retreated steeply over the back-reef deposits. In Canada both advancing and retreating complexes are found, and there are also some cases of near-vertical growth (for example the Rainbow complexes). However, retreating complexes are far more common in Alberta than in Western Australia, and they retreated at much lower angles (Figures 5 and 6). Whereas retreating margins sloping at 3 degrees or less are not uncommon in Alberta (as for example with the Swan Hills complexes), the lowest angle of retreat known in Western Australia is about 30 to 35 degrees (at Menyous Gap).

The reasons for an advancing versus a retreating platform margin are probably to be found in rates of subsidence. A retreating reef probably develops in response to rapid subsidence, when the reef is only able to avoid being drowned by retreating over the shallow areas of the shelf lagoon. An advancing reef is known as a regressive reef according to the classification of Link (1950). However, I feel that this is a poor term, as this type of reef development need not indicate a regression, and in fact it probably occurs most commonly during a slow transgression, when the rate of subsidence is such that the reef front is able to generate enough talus to advance basinward. Similarly I prefer the term retreating reef to transgressive reef.

EXTINCTION

Extinction of the Canning Basin reef complexes is believed to have resulted from a gradual shallowing of the inter-reef basins by terrigenous sedimentation. This destroyed the conditions of water circulation and wave action necessary for platform growth, and allowed the shallow-water sediments of the Fairfield Formation to spread over the extinct complexes. In Alberta there were several periods of platform development, and for many of them rapid subsidence, resulting in the drowning of the platforms, may have been the cause of extinction, as for example with the Swan Hills complexes. Some, such as the Miette complex, could have died because of the filling of the adjacent basin, though emergence is another alternative in this case.

The Rainbow complexes are exceptional in that they are enveloped by evaporites. It seems that extinction resulted from the restriction of the area by the Presqu'ile barrier, causing hypersaline conditions in the surrounding basin.

DOLOMITIZATION

Dolomitization is far more widespread in the carbonate complexes of Alberta than it is in Western Australia. Whereas in Canada the majority of the complexes are almost completely altered to dolomite, most complexes in the Canning Basin show comparatively little dolomitization. The reef and shelf-lagoon deposits in both areas are more thoroughly dolomitized than the adjacent deposits of the fore-reef (or marginal-slope) and basin facies.

EVAPORITES

The Devonian carbonate complexes of western Canada are associated with extensive evaporite deposits. Such evaporites are known from both the Middle and the Upper Devonian. On the other hand no evaporites have been found in association with the Western Australian complexes. They may have developed from time to time when small embayments were closed off by reef growth, but this has not been confirmed. Evaporites of possible Middle to Early Devonian age are known in the Southern Canning Basin (Johnstone and others, 1967), but there is no evidence that they are associated with reef complexes.

FACIES

REEF FACIES

Biotic constituents

The principal biotic constituents in the reef facies of the Canning Basin are calcareous algae, of which the most important with recognizable cellular structure are the blue-green form *Renalcis* and the blue-green or green form *Sphaerocodium.* Other important algae in this facies are the blue-green or green genus *Parapiphyton,* and the red genera *Keega, Tharama, Solenopora,* and *Parachaetetes* (Wray, 1967a; Wray, 1967b). In addition, much of the massive limestone in the reef facies without recognizable cellular structure, but with birdseye or micro-birdseye texture, is thought to have been precipitated or bound by blue-green algae.

In the complexes of western Canada algae are generally not so conspicuous as reef framebuilders. The only complex I have studied which has abundant *Renalcis* is Redwater, where it seems that this alga is one of the principal frame-builders in the 'Middle Leduc' reef facies. J. L. Wray (personal communication, 1967) has found both Canning Basin species, *Renalcis devonicus* (the most common) and *R. turbitus,* in the samples he has examined from the 'Middle Leduc' reef. He has also found *Sphaerocodium* and *Keega* in these samples. This occurrence of *Renalcis* reef in the Redwater complex is very important, for Red-water is one of the few Leduc complexes that is undolomitized. Algae were probably similarly important in the other Leduc complexes, but they are no longer recognizable because of dolomitization. *Renalcis* has not been reported in the reef facies of the 'Upper Leduc' at Redwater, but this unit represents the dying phase of the complex shortly before extinction, and its reef facies a (stromatoporoid limestone) is apparently weakly developed and discontinuous.

Renalcis also appears as a minor framebuilder in the reef margin of the Swan Hills foundation platform, but there it is overshadowed by the tabular stromatoporoids.

No *Renalcis* reef facies has yet been identified in the exposed carbonate complexes of the Rocky Mountains. However, large blocks of *Renalcis*-bearing limestones are present in the debris flows at Mt. Haultain in the Ancient Wall complex and these are clearly derived from a platform margin (H. E. Cook, personal communication, 1967). Could Mountjoy's 'wave-resistant' structures be *Renalcis* reefs?

Only two definite samples of *Renalcis*-bearing limestone have been found at Miette, as already mentioned. The *Renalcis* is detrital and occurs in marginal-slope deposits of the Maligne Formation. It therefore seems that *Renalcis* is not a significant framebuilder in any part of the Miette complex, or at least not in the places that have been sampled.

The only other reef-building algae that have been found to occur in significant abundance in Canada are *Parachaetetes* and other solenoporid algae, which make up as much as 15% of the reef facies in some parts of the Judy Creek Complex (Murray, 1966). *Renalcis* and *Keega* may also be abundant in parts of the Alexandra reef complex of the Hay River area (J. L. Wray, personal communication, 1967). Jamieson (1967) states that coralline algae (cf. *Keega australe* according to J. L. Wray) were the most conspicuous organisms in the reef facies of this complex.

It should be noted that *Renalcis* limestone is most important in the later Frasnian and Famennian reefs in the Canning Basin; it is less common in the Givetian and earliest Frasnian reefs (Playford and Lowry, 1966). This may have time significance, or it may be related to the manner of reef growth. The later Frasnian and Famennian reefs in the Canning Basin appear to have advanced at lower angles than the earlier reefs. The Leduc complexes are the youngest of the major carbonate buildups in western Canada; is the occurrence of abundant *Renalcis* in these complexes of time significant, or could it be linked to a strong horizontal component of growth in the Leduc reef fronts?

Whereas algae are the most important reef-builders in the Canning Basin, it seems that stromatoporoids may be more important in many of the Alberta complexes. The stromatoporoids in both areas are very similar, but detailed comparison of genera and species will have to await completion of J. St. Jean's study of the Canning Basin material.

The corals are the third most important group of framebuilders in the Canning Basin reefs, following the algae and the stromatoporoids. They are probably also third in Canada, and, as in the Canning Basin, the most important are tabulate and massive colonial rugose forms. In both areas much more work needs to be done on the palaeoecology of the corals before the relationships of species and growth forms to specific environments are understood.

In addition to the obvious framebuilding constituents in the Canning Basin complexes, there were probably algae which did not leave any recognizable cellular structure, but which are thought to have been responsible for deposition of much micritic limestone in the reef facies. There were also various reef-dwellers such as brachiopods, sponges, and crinoids, which often make up a large volume of the reef rock. The same is probably true in the Canadian complexes, but I have not examined enough material to make detailed comparisons.

Distribution

It seems clear that the reef facies is not as well developed in most Canadian carbonate platforms as it is in the Canning Basin. The reef facies in the Canning Basin had an average width of about 300 feet, and it was present around most or all of the platform margin in each complex. It is true that the reef rim is missing in some areas, but in most complexes this is for only a small part of the total platform margin. In many of the Canadian complexes the reverse seems to be true; a reef rim may be present around the platform margin, but in many cases it is discontinuous or absent. This is clearly the case with the Miette complex and others exposed in the Rockies, where reef development at the margins of both the Cairn and Southesk Formations is discontinuous and narrow.

Analogies with this situation can be found in parts of the Canning Basin complexes: for example, along the northern margin of the Pillara Range, Emanuel Range, and Laidlaw Range platforms, and the western margin of the Horseshoe Range platform (for these see Playford and Lowry, 1966, Plate 4); also the Leopold Downs embayment (between Brooking Gorge and the Oscar Plateau), and for a short distance on the southern side of the Oscar Range west of Brooking Gorge (Playford and Lowry, 1966, Plate 2). In all of these localities, except the Oscar Range, the lack of a reef rim is probably attributable to the shallowness of the inter-reef basin immediately in front of the platform. This was probably associated with a low level of wave action. The reason for the reef rim being absent or extremely narrow for a short distance along the southern side of the Oscar Range (and a few similar localities) is not known conclusively. It could have resulted from large-scale collapse and sliding of the platform margin in these areas to form megabreccias in the fore-reef facies. Alternatively, it is entirely possible that there never was any reef, and another explanation for its absence is necessary. Perhaps the platform margin in such areas was too deep for strong wave action, possibly because of rapid subsidence. It is clear that more study is necessary to solve this problem.

BACK-REEF OR SHELF-LAGOON FACIES

Much of the back-reef facies in the Canning Basin is very similar to the shelf-lagoon facies in Alberta. In particular, the stromatoporoid, birdseye-limestone, coral, and oncolite sub-facies of the Canning Basin are closely comparable to parts of the Alberta shelf-lagoon deposits. On the other hand, the oolite sub-facies, which is conspicuous in the Canning Basin back-reef, seems to be quite absent in Alberta. One noticeable difference is that the shelf-lagoon carbonates of Alberta are commonly much darker than equivalent rocks in the Canning Basin. Whereas the Canning Basin back-reef limestones are typically white, light yellow-grey, or pale red, many of the Alberta rocks are dark grey or almost black. The dark colour seems to be associated with the deposits of retreating platforms, such as the Cairn Formation. On the other hand, limestones of the advancing complexes, such as the Southesk Formation and the 'Middle Leduc' of the Redwater complex, are generally much lighter and are similar to the colour of the Canning Basin back-reef deposits (which are also normally part of advancing complexes). Could this be the result of rapid subsidence and deposition in the case of retreating platforms, causing more unoxidized organic matter to be incorporated in the limestones? It is important to note that Murray (1966) found that the characteristic dark colour of the foundation platform limestones at Judy Creek is due to the presence of a complex mixture of hydrocarbons, and that this material is most abundant in rocks with a high content of organisms.

The biotic constituents of the back-reef or shelf-lagoon deposits in the two areas are strikingly similar. Virtually the same stromatoporoids (at least at the generic level) occur, and there are also similar corals and algae. It also seems that similar calcareous Foraminifera are present (J. L. Wray and H. E. Cook, personal communication, 1967).

FORE-REEF OR MARGINAL-SLOPE FACIES

Perhaps the most striking difference between the Canning Basin and Canadian complexes is the much greater development of fore-reef talus in the Canning Basin. Whereas the fore-reef facies makes up a large part of the complexes in the Canning Basin, talus deposits are relatively minor in those of Alberta. It is true that debris flows as coarse as megabreccias, containing huge blocks of platform-margin limestone, do occur in the exposed complexes of the Rocky Mountains (Pray and others, 1967), but they are not nearly as extensive or as thick as in the Canning Basin. In addition, high depositional dips have rarely been demonstrated in the Canadian marginal-slope deposits, whereas dips of 30 to 35 degrees are common in the Canning Basin fore-reef facies.

The lack of extensive talus deposits in the exposed complexes of the Rocky Mountains can probably be attributed to the absence of well-developed reef rims throughout much of the history of the complexes. Similarly in the Canning Basin in areas where a reef rim is absent and the inter-reef basin is relatively shallow, the fore-reef facies is not strongly developed. The depth of water in front of many of the platforms in the Canning Basin was probably significantly greater than in Alberta. In addition wave action may have been stronger in the Canning Basin, causing more talus to be derived from the reef and shelf-lagoon deposits.

As has been previously mentioned, high depositional dips are not to be expected in marginal-slope debris where the platform margin is retreating at a low angle. The depositional dips in such cases will not normally exceed the angle at which the platform is retreating. The best development of depositional dips is to be expected where the reef front is advancing over its own talus. Thus, at Miette the most conspicuous depositional dips (amounting to a maximum of perhaps 15 degrees) are seen in tongues (presumably talus) extending down from the Southesk platform margin into the Mt. Hawk basinal deposits. The Canning Basin complexes have normally advanced strongly throughout most of their history, with strong reef developments, and for these reasons steeply dipping talus deposits are to be expected.

INTER-REEF OR BASIN FACIES

The sediments of the inter-reef basins in Western Australia are not as well known as the basin facies in Alberta. This is because exposures are generally poor in this part of the Canning Basin section, and there has not been much drilling. However, the basic lithology in both areas seems similar: calcareous shale and siltstone grading to clayey and silty limestone, with thin nodular limestone beds. It is possible that the basin facies in Alberta is generally more calcareous than in the Canning Basin.

A conspicuous difference between the two areas, however, is that the Virgin Hills inter-reef facies in the Canning Basin is characteristically bright red in colour, whereas the basin sediments in Alberta are dark grey or black. The Gogo Formation (inter-reef) of the Canning Basin is dark grey, but it contains calcareous concretions of a type unknown in Alberta.

The fauna of the inter-reef or basin facies in the two areas contains conspicuous pelagic elements, especially in the Canning Basin, where goniatites, conodonts, fish, crustaceans, and *Tentaculites* are abundant in some horizons. *Tentaculites* is particularly abundant in Alberta, and conodonts also seem to be common, but the general scarcity of goniatites is surprising. Some fish plates and bones also occur in the Alberta basin facies.

OIL EXPLORATION

The Devonian reef complexes of western Canada contain the major part of the country's oil reserves, whereas no economic discoveries have yet been made in the Canning Basin. However, the striking similarities between these complexes suggest that economic oil and gas accumulations are likely to occur in the subsurface Canning Basin reef complexes. Many dry holes were drilled through Devonian rocks in Alberta prior to the initial Leduc discovery in 1947, and the few holes that have been drilled to date on the Lennard Shelf are clearly inadequate to evaluate the area.

In both Alberta and the Canning Basin the main approach to exploration for buried reef complexes has been by seismic surveys followed by test drilling. Most of the Alberta discoveries have resulted from seismic surveys. The presence of elevated platforms can be indicated by draping of the overlying sediments, caused primarily by compaction of the adjacent basin deposits. A 'high' is also commonly present in reflecting horizons beneath an isolated platform, caused by the shorter transit times for seismic waves travelling through the carbonates of the platform compared with the adjacent basin facies. Complexes have also been located by refraction surveys and by the fact that reflections commonly cut out when passing from the basin sediments to the carbonates of the platforms.

Other methods used to locate buried complexes in Alberta include detailed gravity surveys (based on the higher density of the carbonates compared with the basin sediments) and photogeological studies (which detect draping in the overlying deposits).

In the case of the Swan Hills isolated platforms (where the marginal slopes are very gentle, the total relief is small, and there is little difference in velocity between the platforms and the basin deposits) geophysical methods have not been very successful. The main approach to exploration in this area has been stratigraphic.

In Western Australia exploration for buried reef complexes has to date been confined to the Lennard Shelf, and the main exploration tool has been the seismograph, followed by the drill. However, the seismic results have been generally disappointing. Reliable reflections are rarely obtained below the Fairfield Formation (the first post-reef unit), and the draping of this unit over the edge of the limestone platforms has been the main criterion for locating buried complexes.

The isolated reef complexes on the Lennard Shelf are normally thought to be associated with basement ridges, and these can be broadly located by gravity surveys. They are not generally expressed as aeromagnetic anomalies. The velocities encountered in the basement rocks in this part of the Lennard Shelf are commonly similar to those of the limestone. This has prevented the effective mapping of basement highs by refraction methods. Nevertheless, it would seem that the refraction method could be useful in locating the carbonate bodies themselves, as a significant velocity contrast may be expected between the carbonates and the adjacent inter-reef sediments. Moreover, with further seismic exploration in the area and continuing improvements in seismic techniques, it is likely that reliable methods for mapping the buried complexes will be developed before long.

Six test wells have now been drilled on the Lennard Shelf specifically to find buried reef complexes. Three of these (Meda Nos. 1 and 2, and Hawkstone Peak No. 1) were geologically successful in locating reef complexes, and the Meda wells had significant oil and gas showings. However, all were abandoned as dry holes.

Exploration for buried reef complexes in Western Australia has so far been restricted to the Lennard Shelf itself, adjacent to the Devonian exposures. However, in my opinion it is likely that the complexes will occur in other parts of the Canning Basin such as the Jurgurra Terrace, and that they will girdle the offshore margin of the Kimberley Block. They are also potential targets in the Bonaparte Gulf Basin, although the area in which they are likely to be found onshore in this basin is rather restricted.

RECOMMENDATIONS FOR FUTURE RESEARCH IN WESTERN AUSTRALIAN

THE Devonian reef complexes of the northern Canning Basin offer unequalled opportunities for basic research into the detailed stratigraphy, palaeoecology, and diagenesis of ancient reef complexes. The regional study recently completed has focused attention on key areas where additional work will be most rewarding. The first of these is Bugle Gap, where the Geological Survey and the Bureau of Mineral Resources will conduct a detailed stratigraphic, palaeoecological, and zonal mapping study during 1968.

This work is intended primarily to assist oil exploration in Western Australia, but it is also likely to have application in other parts of the world, and especially in Canada. Detailed information obtained in the Canning Basin on the palaeoecology of Devonian reef and bank-building organisms, facies relationships, rates of deposition, and limestone diagenesis, will certainly be valuable in the interpretation of the Canadian complexes.

It is intended that attention be focused on some of the following matters during the forthcoming research programme.

Palaeoecology

The descriptive palaeontology of most of the major groups represented in the complexes should be completed during 1969. These will consist of the algae, stromatoporoids, corals, brachiopods, ammonoids, conodonts, and bryozoans. Palaeontologically the Canning Basin Devonian will then probably be the best known Upper Devonian area in the world, excluding perhaps the type Devonian of the Rhenish Schiefergebirge. The way is now open for detailed palaeoecological studies to relate the various species and growth forms to their environments in the reef complexes. Special emphasis will be placed, during the forthcoming studies, on the algae, stromatoporoids, corals, and brachiopods, as they are the principal rock-building organisms in the complexes. Of particular importance from the Canadian viewpoint will be the study of stromatoporoid growth forms. In addition, more emphasis needs to be placed on micro-organisms such as calcispheres and foraminifers, which are abundant in thin-section. The Foraminifera are one of the most important groups in the complexes that have still to be described systematically, and this should be undertaken as soon as possible.

Of special interest will be the study to be made of algal stromatolites. The stromatolite beds in the inter-reef facies of the Virgin Hills Formation in Bugle Gap will be examined and mapped in detail, and other stromatolite occurrences in the reef, back-reef, and fore-reef facies will also be studied. This work could be of world-wide significance in the interpretation of algal stromatolites in the geological record.

Another matter to be investigated will be the differences (width, structure, porosity and evidence of wave-resistance) of reefs composed of different organisms. Most of the reefs were built by algae, but stromatoporoids and corals predominate in some areas. It will be interesting to compare and contrast the reefs constructed by these different organisms.

Zonation

Conodonts and ammonoids are the most important groups for correlation. To date they have only been found in abundance in the inter-reef deposits. However, it is hoped to carry the conodont zones through into the limestone platforms and thus prepare zonal maps independent of facies. This will be useful in determining the reef-to-basin relief at various times during reef development, in determining whether specific events in the development of the complexes are of regional significance, and in providing time lines for the palaeoecological studies. Detailed stratigraphic sections need to be measured and sampled for lithology and fossils in association with the conodont sampling.

Facies relationships

More work needs to be done in examining platform margins to determine whether the absence of reef in certain areas is related to the depth of water in adjacent basins, degree of wave action, or the nature of the shelf-lagoon deposits. The absence of a reef rim in other areas could be explained by the collapse of the platform margin to form megabreccias in the fore-reef, but this also needs checking in the field.

A potentially very rewarding study will be the detailed mapping of the various back-reef sub-facies. We still do not have the full answer as to why the stromatoporoid facies occur in some areas whereas the birdseye limestone, oolite, or coral sub-facies occur in others. In some cases the principal control is certainly environmental, in others it may be the age of the deposit. The conodont zonal studies will be especially valuable in this regard, by providing time lines through the various sub-facies.

Depositional dips

The dip of the fore-reef talus ranges from about 50 degrees in 'reefoid' sections to less than 3 degrees in others. The factors controlling these dips are not fully understood at present and should be the subject of special study. It seems, however, that dips steeper than about 40 degrees may be associated with sediment-binding algae, and that very low dips occur only where a reef rim is absent around the adjacent platform.

The back-reef deposits commonly dip away from the reef facies at low angles. This dip has hitherto been interpreted as depositional, but I have increasing doubts as to whether this really is correct. It may be more likely that the dips are due to differential compaction (by stylolitization) of the back-reef deposits relative to the reef facies. This requires careful checking in the field, involving the examination of stylolites and the degree of dolomitization in the various facies.

Dolomitization

The work carried out to date has not included detailed study of dolomite distribution. Such a study could be very revealing and could throw significant light on the origin of dolomite in the complexes and on the localization of porosity and permeability.

Diagenesis

Studies of the diagenesis of these limestones are important in understanding the development of the complexes and the origin and time of development or loss of porosity. There is good evidence that lithification of the limestones occurred at an early stage. L. C. Pray has also suggested that there may be evidence in some of my thin-sections of early precipitation of carbonate (?aragonite) crusts on the sea floor. This is an important possibility which will require careful checking.

Another matter of related significance is the origin of the fibrous calcite which is so extensive in some facies, especially the reef. I believe that much of this is due to the replacement of limestone very early in the diagenetic history of the complexes. Careful sampling and analysis of the evidence will be necessary to prove whether this is so. It will be interesting to relate the time of dolomitization to the time of development of fibrous calcite.

'Stepping-back' of reef fronts

The reasons for the abrupt 'stepping-back' of reef fronts, as has occurred in the Pillara Range—Home Range area, and also possibly around Bugle Gap, need to be thoroughly investigated. Playford and Lowry (1966) interpret this phenomenon as being caused by local tectonism resulting in the drowning of part of a complex. Whether or not these movements are purely local may be demonstrated through the conodont zonation, which will indicate whether these events can be correlated throughout the Lennard Shelf.

Subsurface

It is desirable that the Geological Survey undertake a detailed study of the section encountered in all wells drilled to date on the Lennard Shelf. Some studies have already been made, but more could be done as a result of additional information obtained from recent wells, and our increased knowledge of the surface exposures. This study should be integrated with all existing seismic information to give a more realistic interpretation of the distribution of the reef complexes in the subsurface.

Bonaparte Gulf Basin

Detailed study of the facies relationships and development of the Bonaparte Gulf Basin reef complexes will be desirable in the future so that adequate comparisons can be made with the Canning Basin complexes. One type of reef development is present in the Westwood Creek area of the Bonaparte Gulf Basin that may not be present in the Canning Basin (J. J. Veevers, personal communication, 1966). This is a so-called 'incipient reef' development, consisting of small patch reefs composed of *Renalcis* limestone.

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