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THE STRATIGRAPHY OF AN UPPER DEVONIAN CARBONATE-SHALE TRANSITION BETWEEN THE NORTH AND SOUTH RAM RIVERS OF THE CANADIAN ROCKY MOUNTAINS

BY

JASPER DOOGE[1]

ABSTRACT

The Upper Devonian Fairholme Group in the Canadian Foothills and Rocky Mountains is correlated to the reef-bearing subsurface Woodbend-Beaverhill Lake Formations of the Alberta Plains. The group is divisible into the upper Southesk and the basal Cairn Formation, each of which occurs in a carbonate and a clastic facies, commonly referred to as the reef and shale provinces.

This thesis reports the results of a detailed study of the transition between the carbonate and shale provinces, which is well exposed in the Cripple Creek area of the Front Range of the southern Rocky Mountains. This transition only occurs in the Southesk Formation at this locality and takes place gradually over a distance of eight miles, reflecting depositional patterns in successive positions on a shallowing shelf.

Biostratigraphic zonation allows the delineation of areally segregated carbonate facies, characterized by distinctive lithological and faunal criteria.

A concentration of coral biostromes occurs at the transition between the shallow shelf and deeper water marginal seas. This zone of biostromal dolomite grades seaward through fossiliferous, nodular and argillaceous limestones to calcareous, open marine shales. The transition from shelf to sea areas coincides with transition from complete to incomplete dolomitization. Complete dolomitization is indicated to occur when no argillaceous admixture is present. The zone of biostromes grades shoreward into intertidal and algal deposits towards the central platform area. A progressive increase in water salinity is indicated by a marked decrease in faunal content accompanied by a differentiation in the faunal composition from predominantly coralline to an algal-ostracod-calcisphere assemblage. The dolomite sequences are assigned to the semi-restricted and restricted dolomite facies.

Regional studies indicate the presence of other types of carbonate-shale transitions in the Fairholme of the Rockies. The abrupt juxtaposition of dolomites and shales at Wapiabi Creek is in sharp contrast to the gradational nature of the Cripple Creek transition. The occurrence of detrital carbonates, swept off the platform, indicates the presence of relief between the carbonate and shale provinces. At Cripple Creek, a buffer zone of intervening carbonate types indicates the absence of any appreciable amount of relief. The Cripple and Wapiabi types constitute the end members of a range of carbonate-shale transitions. The areal distribution of these transition types are explained by variation in terms of paleogeographic setting during Southesk time. The gradational Cripple Creek type transition is postulated to occur in areas on the leeward side of the Fairholme shelves, protected from the influences of direct wind and current action. The Wapiabi type occurs in windward areas. This postulation infers the predominance of northeasterly winds during Southesk time.

The study of the spatial arrangement of the Upper Devonian carbonate facies in the Cripple Creek area has resulted in the definition of a depositional carbonate pattern, designated as the "carbonate model". This model constitutes a synthesis of all pertinent data, necessary to represent the areal configuration, composition and environmental milieu of the major facies, into a simple and orderly form.

The model can be applied profitably on a world-wide basis to illustrate the facies distribution of carbonate-shale transitions in other geologic systems with only minor changes in the composition of the faunal assemblages.

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[1] Shell Canada Limited, Edmonton (Alberta, Canada).

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CHAPTER I

INTRODUCTION

1. SCOPE OF THE PRESENT STUDY

Approximately three-quarters of the proven oil reserves in the Western Canada Sedimentary Basin occur in carbonate reservoirs. The discovery of Devonian "reef dolomite" production at Leduc, Alberta, in 1947, sparked the study of Canadian carbonate sequences.

The Upper Devonian (Frasnian) sequence in the subsurface of the Plains of Alberta is characterized by the presence of carbonate complexes encased in calcareous shales. The sedimentary features of most of these Upper Devonian carbonate complexes have been obliterated by complete dolomitization. Detailed information on lithologic and faunal variations are largely based on cores and ditch cuttings of the Redwater complex, which escaped the effects of secondary dolomitization.

The small size of the ditch cuttings and the lack of well and/or core control in strategic places often prevent a full understanding of the stratigraphy and attention was drawn to time-equivalent strata in the Canadian Foothills and Rocky Mountains.

These outcrop studies would lead to a facies zonation which could be applied to recognize facies patterns in the subsurface. Generally speaking, three stages can be recognized in the stratigraphic investigations of the Mountains. The earliest studies were carried out by such famous geologists as McConnell (1887), Walcott (1928) and Warren (1927). The areal extent of these early studies was limited.

This situation changed drastically after the 1947 Leduc discovery, when petroleum geologists and officers of the Geological Survey of Canada turned to the mountain outcrops to look for clues which could aid in the subsurface search for additional Leduc carbonate complexes. Most of this information, accumulated during the second phase, remains confidential. Released data were generally gathered by the Geological Survey and by universities. Excellent studies were carried out by DeWit (1953), McLaren (1953a), Belyea (1954), Crickmay (1950), Warren and Stelck (1950). The results have led to the definition of the areal extent of the carbonate and clastic provinces in the Upper Devonian of the Foothills and the Rocky Mountains. The carbonate provinces have been considered to be reef complexes, divisible into fore-reef detritus, a biohermal rim, and a central portion composed of lagoonal sediments. It must be emphasized that this concept was based on regional field work, primarily directed towards a delineation of the carbonate complexes.

The results of the second phase studies lack detailed information on facies distribution, porosity development and faunal assemblages. It became apparent that a large amount of additional stratigraphic detail was needed and this is presently being accumulated and reported (Price, 1964; MacKenzie, 1965). This thesis describes the results of such a phase III study, carried out to investigate the lithologic and faunal aspects of a carbonate-shale transition in a restricted locale.

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I am much indebted to my field assistants during the 1960 field season, and to my colleagues of the Exploration Department. I would like to express special gratitude to Mr. G. I. Lewis and E. R. Parker of Shell Canada Limited, who supervised the field work. The contribution by Drs. G. O. Raasch and A. Wells, respectively of Shell Canada and Bataafse Internationale Petroleum Maatschappij, is gratefully acknowledged. Dr. Raasch studied our fossil collections and established time correlations. Dr. A. Wells accompanied the

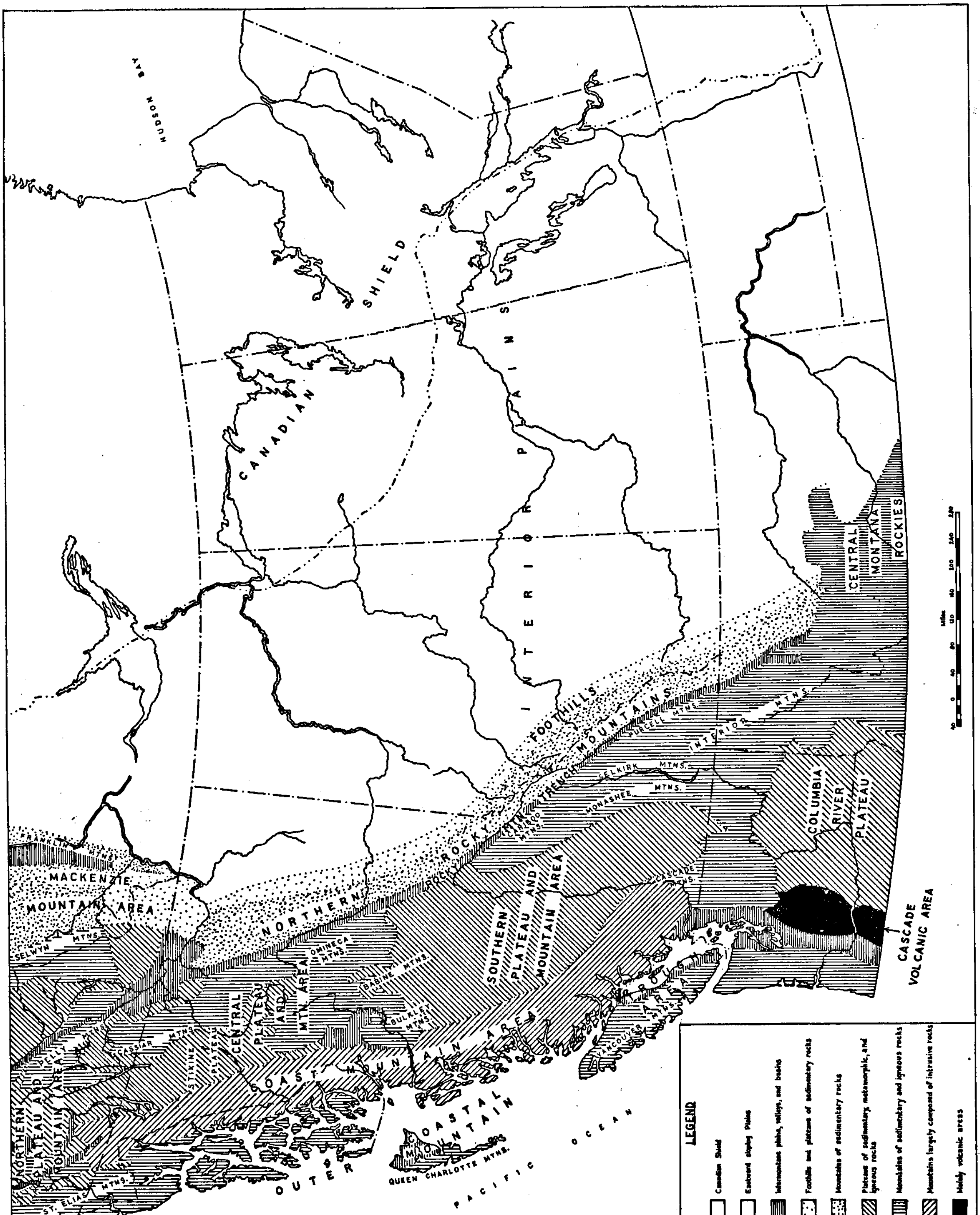


Fig. 1. Physiographic divisions of northwestern North America.

author on reconnaissance trips outside the map area. His carbonate experience in other parts of the world proved to be extremely helpful. Mr. F. A. Kidd and Dr. A. W. Bally, respectively Exploration Manager and Chief Geologist of Shell Canada Limited, encouraged the author to proceed with this publication. Their interest and constructive comments were most welcome and are hereby acknowledged.

2. REGIONAL SETTING OF THE MAP AREA

Western Canada is readily divisible into three major physiographic and geologic provinces, i.e. from east to west, the Canadian Shield, the Interior Plains and the Cordillera. The following comments serve to illustrate the pertinent characteristics of these provinces (figs. 1 and 2).

The Canadian Shield

The vast Shield region occupies nearly half of Canada. The greater portion of the Shield has a relief of less than 200 feet. Glacial deposits and myriads of lakes, characterize the landscape. Rock exposures are estimated to total less than 10 percent.

During Precambrian times great accumulations of sedimentary and volcanic rocks were deposited. Orogenetic processes took place and large bodies of granitic and other igneous rocks were formed in the roots of these mountains. Several cycles of deposition, intrusion and erosion are indicated.

The Canadian Shield consists of Archaean and Proterozoic sediments and volcanic rocks. The Proterozoic eon is divided into the Aphebian, Helikian, and Hadrynian eras (with a progressively younger age connotation) (Stockwell, 1964).

Stockwell (1964, 1965) recognizes four main orogenies, the Kenoran, the Hudsonian, the Elsonian, and the Grenville. As a general rule, each orogenic period was followed by erosion and by unconformable deposition of overlying strata.

Archaean sedimentary and volcanic rocks have been involved in the Kenoran orogeny. Age determinations, by the potassium-argon methods on micas, indicate a mean age of 2490 million years for this orogeny (Wanless et al; 1965). Aphebian rocks have been affected by the Hudsonian orogeny (mean age: 1735 million years). Helikian units have been subjected to the Elsonian and Grenville orogenies (mean age: 1370 and 945 million years, respectively).

The area constitutes Canada's most prolific metal producer. The copper-nickel deposits at Sudbury and the iron ore deposits of Labrador are just a few examples of this mineral wealth.

The Interior Plains

The part of Western Canada between the Precambrian Shield on the east, and the Cordillera on the west, is designated as the Interior Plains. They constitute a continuation of the Interior Plains of the United States, northward from the Gulf of Mexico. Approximately 775,000 square miles of Canadian territory is assigned to the Plains of which 375,000 are located within the Prairie Provinces of Manitoba, Saskatchewan and Alberta.

The Canadian Shield dips westward beneath the Phanerozoic rocks of the Interior Plains. The boundary between these two provinces occurs without any noticeable break or with a sudden drop of a few feet. The Plains merge with the Foothills of the Rocky Mountains.

Elevations range from about 4000 feet on the eastern edge of the Foothills to 500 feet in southeast Manitoba. The Interior Plains is predominantly an area of flat or subdued topography. Many irregularities of topography are present, both as deeply incised river valleys and pronounced flat-topped hills that are erosional remnants of a higher plateau.

The stratigraphic sequence of the Interior Plains consists primarily of sedimentary rocks of Paleozoic or later age, resting unconformably on a "crystalline basement" of Precambrian igneous and metamorphic rocks. These basement rocks constitute an extension of the Canadian Shield and slope gently westward towards the Cordillera. Subsurface information on depth to basement is rather sparse and local variations on basement elevation are expected.

The site of the Interior Plains has been relatively stable for a long time. The surface of the basement was at or near sea level; present control indicates erosion to a level quite similar to that of the present day Canadian Shield. Lower Cambrian sediments are absent and Middle-Upper Cambrian strata overlie the basement complex, indicative of erosion well into Cambrian time. The facies distribution of the younger sequences suggests predominantly continental shelf deposits with few and regional erosional periods.

Some indications of gentle folding occur within the region, partially due to differential compaction of sand-versus shale sequences or drape across carbonate build-ups.

The Interior Plains and the adjacent Foothills are commonly designated as the Western Canada Sedimentary Basin. Metal production to date has been relatively small; the most important mineral products being oil, gas and coal.

The sedimentary sequence of the Interior Plains is thin and extremely widespread. Two broad groups of sediments are readily discerned, i.e. the Paleozoic carbonate- and the Mesozoic plus Tertiary clastics groups. The thinning onto the Canadian Shield is both erosional and depositional, and extremely gradual. The Paleozoic, Triassic and Jurassic strata are dominantly marine. The Cretaceous is mixed continental and marine, and the Cainozoic rocks are continental. Pleistocene deposits of highly variable thickness overlie the bedrock of the Plains area.

The extremely widespread nature and uniform thickness of the larger units indicate that the Interior Plain has been part of the stable craton throughout most of Phanerozoic time. Many marker horizons can be traced for hundreds and even a thousand miles. The wedge-shaped geometry of this body of sediments is

such that the term "basin" can be used only in a general sense.
The Canadian Shield and adjacent Interior Plains are assigned to a cratonic area. A stable to metastable platform is indicated. The stable platform is characterized by a thin veneer of Paleozoic carbonates and Mesozoic clastics. The metastable platform is typified by thicker Paleozoic carbonates as well as Mesozoic and Tertiary clastics deposited in a fore-deep.

The Cordilleran Region

The Cordilleran region in Canada, bordering the Pacific Ocean, is some 500 miles wide. It is part of the great mountain systems in North and South America. This mountainous terrain is in sharp contrast with the nearly flat Interior Plains. Elevations range from 5000 to 11,000 feet.
The Cordillera is divisible into three northwesterly trending physiographic provinces: a western system of mountains, an interior system of plateaus and mountains, and an eastern system of mountains. A long trough known as the Rocky Mountain Trench, and extending for nearly 1000 miles, divides the Eastern and Western Cordillera (fig. 1,3).
The geology of the interior and western systems is not well known. Partial map coverage on a scale of four miles to one inch is presently available, but more detail is required. The available data indicate the extreme complexity of Cordilleran geology. Moreover, the subject area of this thesis is located within the Eastern Cordillera and the following general remarks are therefore considered to suffice.
The interior and western systems make up the eugeosynclinal Western Cordillera, located in a belt of active volcanism and relatively rapid subsidence during Paleozoic time. Deeply subsiding troughs with limited volcanism and narrow uplifts characterize the Mesozoic.
Sedimentary and volcanic strata, ranging from Proterozoic to Recent, record a number of periods of crustal disturbance followed by uplift and erosion. Late Mesozoic to early Tertiary disturbances are most prominent. Invasion of deep-seated granitic bodies (batholiths) and a host of smaller intrusions occurred at that time.
Metallization accompanied, or closely followed, these Mesozoic-Tertiary intrusions, resulting in numerous ore deposits (copper, lead, zinc, gold, silver, etc.). Coal intercalations occur in the Mesozoic and Tertiary sequences.
The Rocky Mountain Trench forms a prominent topographic lineament. Throughout most of its length, it forms the boundary between the intensely deformed, altered and intruded rocks of the Western Cordillera and the moderately deformed sequences of the Eastern Cordillera. Various interpretations have been proposed by many authors for different portions of the Trench. No definite solution is possible at present as the area has not been mapped in sufficient detail. North and Henderson (1954) reviewed the tentative interpretations and favoured thrusting processes being responsible. Bally (oral communication) suggests that the location of the Trench is related to a system of young Tertiary, listric, normal faults.
The geology of the Eastern Cordillera, compared to the Western Cordillera, is fairly well known. Accessibility, magnificent exposure, and a lesser degree of complexity help to unravel the geology. The discovery of large oil and gas fields in the Interior Plains spurred exploration in the adjacent Cordillera and a wealth of geologic information has become available by the activity of the petroleum industry.
The *Eastern Cordillera* occupies the area between the Interior Plains and the Rocky Mountain Trench. Four broad topographic and geological provinces are present (North and Henderson, 1958) (fig. 3). Relatively low and rounded ridges occur along the eastern fringe of the Cordillera, adjacent to the Interior Plains, and are designated as the *Foothills*. The structural skeleton of the Foothills is formed by relatively large and flat thrust sheets, involving Paleozoic carbonates with some frontal imbrications. Intensive imbrications of Mesozoic clastics drape this Paleozoic "skeleton". The whole is underlain by the relatively undisturbed westward continuation of the Canadian Shield.
The *Front Ranges* are formed by thrust sheets mainly involving Paleozoic carbonates and Precambrian (Beltian) carbonates and clastics. Seismic evidence in the Front Ranges (Shaw, 1963) indicates a relatively undisturbed, westerly dipping crystalline basement. Typical elevations range from 7000 to 11000 feet.
The *Main Ranges* show elements composed of Precambrian and lower Paleozoic sediments which often are less disturbed and relatively flat-lying. Shearing and some normal faulting is indicated. Precambrian and lower Paleozoic sediments are dominant.
The *Western Ranges*, the westernmost component of the Eastern Cordillera, are not well known. The stratigraphic sequence ranges from Precambrian to Middle Devonian sediments with an apparent dominance of Ordovician and Silurian. Thrusting and shearing towards the east and west is common. Normal faulting occurs frequently.
The four provinces are not distinct along the entire length of the Eastern Cordillera. The variation in surface expresssion between the Foothills and Front Ranges is quite pronounced. The more recessive nature of the softer Mesozoic clastics of the Foothills leads to a subdued topographic expression in comparison with the extremely rugged physiographic appearance of the Front Ranges with their resistant carbonate sequences. The Foothills and Front Ranges are assigned to a miogeosynclinal belt, characterized by thick Precambrian and Lower Cambrian clastic sequences overlying the crystalline basement. Thick non-volcanic Paleozoic carbonate and Mesozoic clastic sequences are typical.
The Eastern Cordillera is genetically closer related to the Interior Plains than to the Western Cordillera. In spite of the thicker Proterozoic and Lower Paleozoic thicknesses and the more continuous stratigraphic succession of the Eastern Cordillera, a gradual thinning

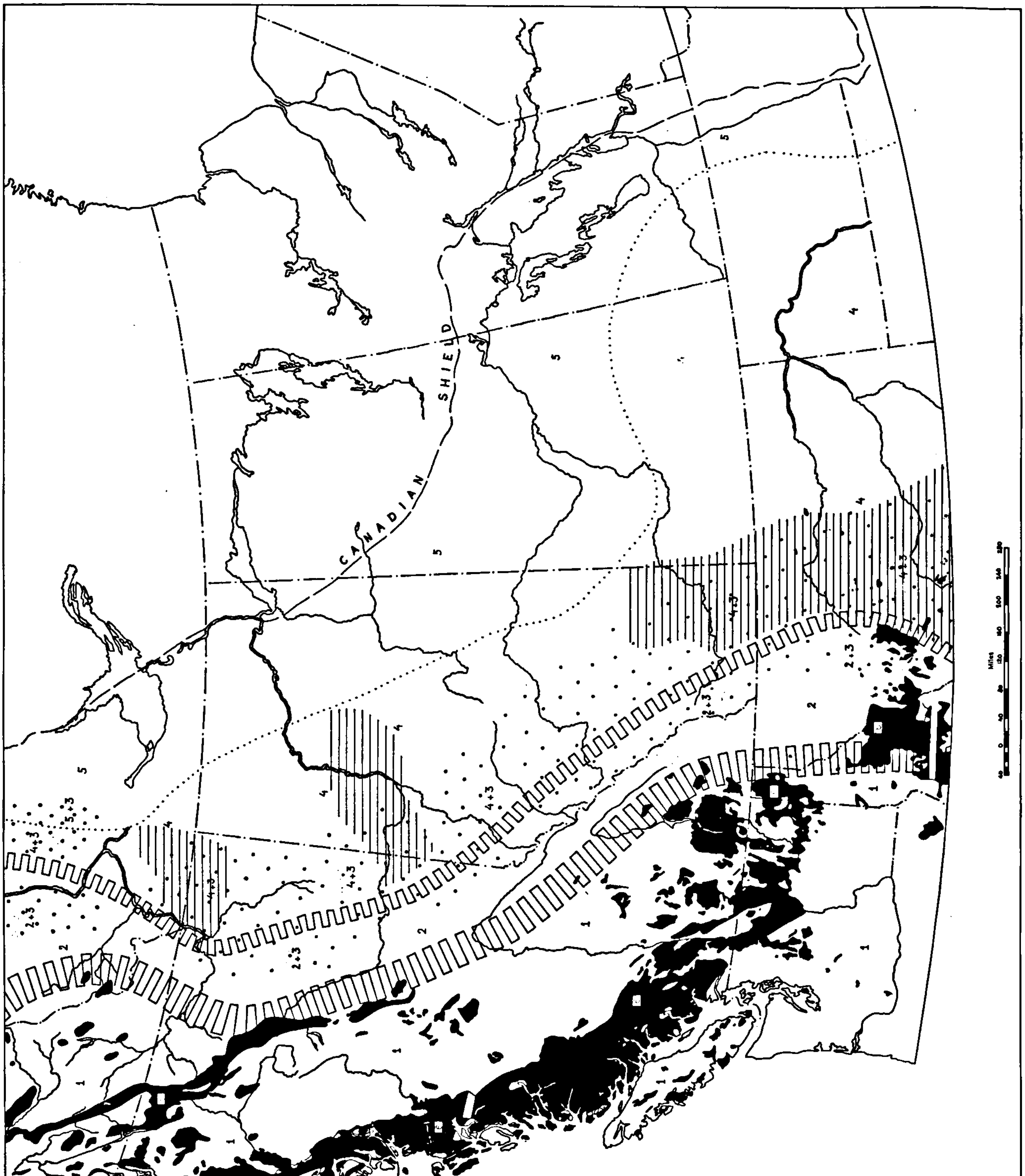


Fig. 2. Regional geologic units of northwestern North America

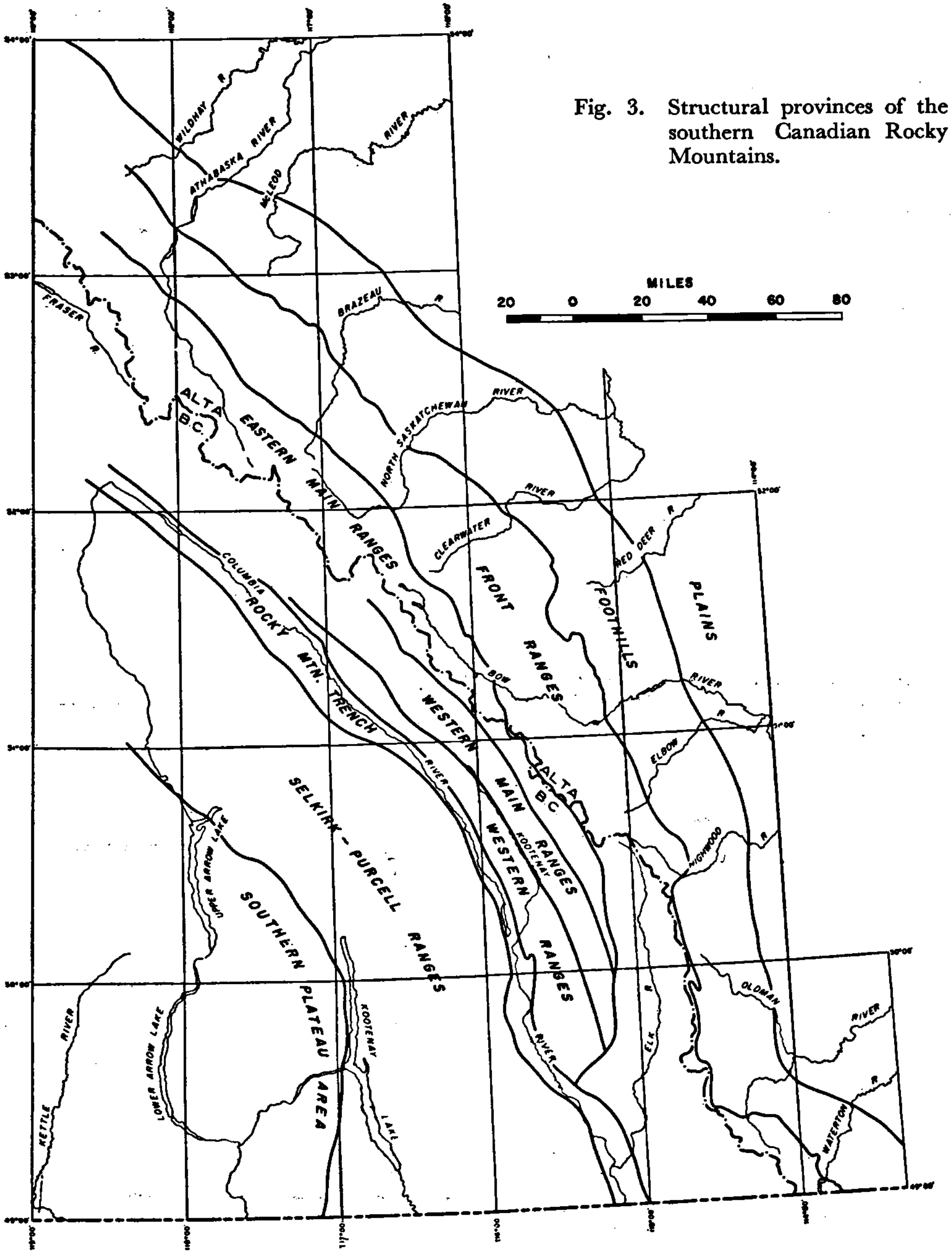


Fig. 3. Structural provinces of the southern Canadian Rocky Mountains.

Fig. 2 (legend)

1 Paleozoic eugeosyncline

Located in belt of active volcanism, with relatively rapid subsidence (M. Kay), foli formation of Mesozoic deeply subsiding troughs with limited volcanism associated narrow uplifts (epi-eugeosyncline M. Kay). Orthotectonic (or alpinotype) deformation including the igneous and metamorphic phase of this category. Inner belt of crustal folding (W. Bucher).

2 Paleozoic miogeosyncline

Located in nonvolcanic belt and within cratonic borders with accelerated subsidence (M. Kay), followed by formation of Mesozoic exogeosyncline (M. Kay). Orthotectonic (or alpinotype) deformation (H. Stille) during Mesozoic and Tertiary, but including only the peel thrust and shallow folding phase of this category (W. Bucher).

3 Mesozoic and early Tertiary exogeosyncline (stippled)

Located within the cratonic borders and getting sediments from the progressively deformed orthogeosynclinal belts (M. Kay). Eastward migrating foredeep with "molasse" type sedimentation (peri-orogenic foreland E. Kuendig). Transition between the miogeosynclinal phase and the exogeosynclinal phase is characterized by centripetal tilt (E. Kuendig) of the under-lying craton. Where this belt overlaps 2 and 3 deformation is alpinotype in the west and germanotype in the east.

4 Paleozoic, Mesozoic and Tertiary metastable platform

Nonvolcanic Paleozoics with normal subsidence, followed by exogeosynclinal Mesozoics and subjected to paratectonic or germanotype (H. Stille) deformation with areas of intensified blockfaulting (shaded area), sedimentary sequence reduced because of frequent and long hiati due to increased effect of centripetal tilting.

5 Stable platform

Same as above, with drastically reduced sedimentary sequence due to centripetal tilting but not deformed to any marked degree (including the outcropping craton — the Canadian Shield).

6 Mesozoic and Tertiary intrusives

Note pyjama patterns mark transition zones.

Fig. 4. Index map of Canadian Rocky Mountains.

of the Devonian — Jurassic is indicated towards the Interior Plains.
The main orogenic phase of the Eastern Cordillera took place during the Eocene and is indicated as the Rocky Mountain or Laramide orogeny.

The area of study is located along the Front Range of the Rocky Mountains between the North and South Ram Rivers (fig. 4). The locale is easily accessible by the Forestry Trunk Road, parallelling the mountains, and the Onion Lake Fire Road, which leads westward from the Forestry Trunk Road and cuts through the Front Range. Thrusting has carried Paleozoic strata over Cretaceous sediments along the McConnell fault. The Paleozoic sequence is composed of rocks of Cambrian, Devonian, Mississippian and Permo-Pennsylvanian age. The Cambrian and basal Devonian sequences are exposed on the steep front face of the fault block, the upper portion of the Devonian and younger Paleozoic beds are exposed on the dip slopes. Exposures are generally good. Detailed stratigraphic studies have been restricted to the Fairholme Group (Frasnian). Overlying and underlying strata are included when their examination is considered pertinent to the problems at hand.

CHAPTER II

CHRONOLOGICAL REVIEW OF DEVONIAN NOMENCLATURE

Following is a chronological review of the development of the Devonian nomenclature in the Rocky Mountains. McConnell (1887) proposed the first formational subdivision of the Devonian sediments in the eastern portion of the Canadian Rocky Mountains (fig. 4; Bow River region). Later workers (Shimer, 1911; Walcott, 1923; Warren, 1927) commented on this nomenclature and revised formation boundaries and age determinations. Their classifications have fallen into disuse and will not be discussed. Beach (1943) studied the Devonian system over an extensive area in the Rocky Mountains and proposed a twofold subdivision: a lower Fairholme and an upper Palliser Formation. The type section of the Fairholme is indicated to be located on "the unnamed mountain immediately north of Bow River between Kananaskis and Exshaw railway stations" (fig. 4; latitude 52° 10-15′ N, longitude 115° 08-12′ W). The formation overlies arenaceous dolomites and underlies the massive dolomites and limestones of the Palliser. No type section is designated for the Palliser other than that the formation occurs "in the Moose Mountain-Morley map area and in the Fairholme Mountains" (approximately 51° N, and 115° W). Beach reports an average thickness of 1420 feet for the Fairholme Formation and 800-950 feet for the Palliser.
DeWit and McLaren (1950) published a regional paleontological and stratigraphic study of the Devonian and proposed to redefine the Fairholme Formation.
Beach had included silty strata at the top of the Fairholme which, on the basis of lithologic and faunal characteristics, could be separated from the Fairholme. These silty beds were therefore raised to formation status, i.e. the Alexo Formation.
The Fairholme was retained for the basal portion of the original formation and the Devonian system is thereby divided into three formations, in ascending order: Fairholme, Alexo and Palliser.
Fox (1951) and McLaren (1953) summarized the present classification. Excluding the Palliser and the Alexo Formation, a twofold formational scheme has been generally adopted: "a series of formation names for sequences of rocks containing a high proportion of terrigenous clastic material, and a single name for sequences of rocks formed chiefly of limestone or dolomite".

"Clastic sequence"	*"Carbonate sequence"*
Mount Hawk Formation	
Perdrix Formation	Fairholme Formation
Flume Formation	

The Mount Hawk Formation, introduced by DeWit and McLaren (1950), attains a maximum thickness of 380 feet at its type locality on Roche Miette (fig. 4; latitude 53°10′ N, longitude 117°55′ W). The formation is correlated with the upper member of the Fairholme and consists of dark grey, silty, and argillaceous limestones with thin shale partings. The contact with the underlying Perdrix Formation is gradational.
The Flume Formation (Raymond, 1930) is composed of hard, grey limestone and dolomite. DeWit and McLaren (1950) divided the Flume into two parts. The lower member consists of light grey to black cherty carbonates, containing stromatoporoid-coral reefs. Scattered detrital beds and silty zones occur at the base. The upper member consists of dark grey, argillaceous limestones, commonly fossiliferous with several bands of black shale. The thickness of the formation varies from 250 to 500 feet.
McLaren (1953) distinguished several distinctive lithology types in the Fairholme Formation. They include:

(1) "black, bedded, biostromal dolomites, fetid and bituminous, composed largely of stromatoporoids, *Amphipora*, and corals in varying proportions". This lithology is indicated to be most common in the lower Fairholme and in the Flume Formation.

(2) "black, massive dolomite, bituminous, vuggy, largely or entirely composed of stromatoporoids with subordinate *Amphipora* and corals". They are referred to as the "black reefs". They are broadly lenticular in development and most common in the lower Fairholme.

(3) pale grey, massive dolomite, porous and vuggy, frequently with a bituminous smell and without obvious structure in the field. The field term "white reefs" is applied to them and, like the "black reefs", they are broadly lenticular in form. They constitute an important building unit in the upper Fairholme.

McLaren (1950) defined the boundary between the lower and upper Fairholme at the base of the "well-marked white reefs".
The Fairholme was subsequently raised to group status and two formations, Cairn and Southesk, in ascending order, were introduced.
The type section of the Cairn and the Southesk Formation is located near the junction of Southesk and Cairn Rivers (latitude 52° 39'N; longitude 116° 58' W). McLaren subsequently extended the Fairholme Group to include the "clastic sequence", i.e. the Mount Hawk, the Perdrix, and the Flume Formation. This nomenclature, generally used in the geological literature, warrants a closer view.

"The carbonate sequence"

The *Cairn Formation* is composed of brown to black, organic dolomites in the lower part of the Fairholme Group. The type section is located on the northern spur of Mount Dalhousie, immediately south of the Southesk and Cairn Rivers junction (latitude 52° 37'N, longitude 116° 56' W). The Cairn is divisible into two members. The upper or organic dolomite member is 457 feet thick and consists of brown dolomites with abundant traces of organic remains. Spheroidal stromatoporoids, *Amphipora*, and corals are common. The lower, or *cherty dolomite*, is 101 feet thick at the type section and consists of dark grey dolomite with chert nodules and an *Amphipora*-stromatoporoid assemblage.

The *Southesk Formation* includes a thick bedded to massive sequence of grey dolomites, limestones, and coral beds in the upper portion of the Fairholme Group. The formation is 528 feet thick at its type locality and divisible into three members.

(a) The upper or granular limestone member is 202 feet thick and composed of thick bedded to massive limestones with scattered *Amphipora* and stromatoporoids. Subsequent field work has indicated that the limestone member is essentially composed of dolomites in the southern portion of the Rocky Mountains and consequently the informal name was changed to "upper grey dolomite member" (Belyea and McLaren, 1956).

(b) The middle or coral bed member (45 feet) is composed of slightly argillaceous dolomites with abundant *Amphipora*, massive stromatoporoids, and corals.

(c) The lower or grey dolomite member (281 feet) is composed of light grey, thick bedded to massive, coarse grained, structureless dolomite. The basal beds of the member grade into the Cairn Formation. The boundary between the Cairn and Southesk Formation is reported as transitional over some 20 to 50 feet.

"The clastic sequence"

McLaren (1955) redefined the *Mount Hawk Formation* at its type section and established a thickness of 549 feet. The basal boundary is lowered to include a sequence of 156 feet formerly placed in the underlying Perdrix Formation. The upper boundary was lowered 82 feet to exclude a sequence now placed in the Alexo Formation.
The Mount Hawk is divided into three members:

(a) a lower or grey mudstone and limestone member (246 feet),
(b) a middle or argillaceous limestone member,
(c) an upper or grey limestone member (105 feet).

The Mount Hawk rests on the Perdrix and is overlain by the Alexo. The formation is richly fossiliferous; corals and diagnostic brachiopods are common.

DeWit and McLaren originally (1950) attributed 536 feet to the *Perdrix Formation*, but later McLaren (1955) restricted the formation to the basal 380 feet. The Perdrix consists of black calcareous shales with banks of calcareous nodules grading downwards into black, non-calcareous friable shale. The section is almost unfossiliferous in certain regions, containing only a few very small species of *Lingula* and *Tentaculites*. Brachiopods are common in Perdrix sections with a high calcareous content.

McLaren (1955) considers the *Flume Formation* as the lowest formation of undoubted Devonian age in the Rocky Mountains of Central Alberta. The formation is divisible into a basal, cherty, and biostromal member and an upper, or argillaceous carbonate member.

Belyea and McLaren (1956) discussed Devonian correlations between the outcrop and the subsurface of the Alberta Plains.
Belyea and McLaren (1957) gave formal names to the members of the Southesk Formation; in descending order, Arcs, Grotto, and Peechee. The type section for these members is chosen on the southeast end of Mount Rundle (fig. 4; latitude 51° 05' N, longitude 115° 25' W). The Arcs corresponds with the "upper grey dolomite", the Grotto Member with the "coral bed member" and the Peechee Member with the "lower grey dolomite" of the 1955 nomenclature.
The Peechee Member (201 feet) consists of light grey, porous, coarse grained dolomites. The sequence is massive and becomes slightly argillaceous and fetid downwards. The Peechee Member is underlain by the

Cairn Formation and overlain by the Grotto Member of the Southesk Formation.

The Grotto Member (160 feet) is composed of dark grey and black, slightly argillaceous dolomites, containing poorly preserved corals and *Amphipora*. The junction with the overlying Arcs Member is sharp and clearly defined.

The Arcs Member (244 feet) consists of light grey, thick bedded, coarse grained dolomites. The member is almost devoid of organic remains but vague traces of *Amphipora* may be discernible towards the base. The Arcs is overlain by the Alexo Formation and underlain by the Grotto Member.

Taylor (1957) proposed a major revision of the Devonian nomenclature in the Rocky Mountains. The Flume Formation was redefined "to contain only the widespread, mappable, cherty biostromal carbonate unit". The formation, so defined, is restricted to the "lower member of the Flume Formation" of DeWit and McLaren (1950). The upper portion of the original Flume Formation is raised to formation status, i.e. Maligne Formation. The Mount Hawk Formation is redefined to exclude the upper carbonate member, which is equated with the Nisku Formation of the subsurface. Taylor introduced subsurface formation names in the outcrop nomenclature. This usage was controversial but emphasized correlations between the Plains and Rocky Mountains. Such correlations have been found to be valuable in the construction of regional maps.

Taylor disagrees with McLaren's proposal to attribute formation status to the Southesk and the Cairn and states that it is "extremely difficult and a matter of personal opinion to establish a consistent boundary between the light and dark carbonates". The Southesk and the Cairn are considered as facies types and not as formations.

Belyea and McLaren (1957) opposed the introduction of subsurface terms (e.g. Nisku, Leduc) into the outcrop nomenclature and disagreed with Taylor's correlations. The formation status, attributed to the Cairn and the Southesk, is defended and McLaren states that this boundary is "of great regional significance". The two formations differ "lithologically because they differ genetically" and should be separated on the basis of lithology and not on color alone. The Cairn is "largely organic", while the Southesk is composed of dolomites which are not recognizably organic. The criterion is "commonly associated with a color change".

McLaren explains Taylor's difficulty in defining the Southesk-Cairn boundary by the statement that Taylor "only studied the color of the rocks and not their composition".

Taylor (1958) detailed his revision of the Devonian nomenclature in the light of Belyea's and McLaren's opposition. He agrees with McLaren's statement that the Southesk and Cairn differ genetically but states that this criterion, if rigorously applied, will lead to a repetition of Southesk and Cairn intervals in the Fairholme, indicating a facies variation.

Belyea (1958) reported on the Devonian formations between the Nordegg area (surface geology) and the Rimbey-Meadowbrook reef chain (subsurface). This publication is of special interest and includes the results of a study of the Cripple Creek area. The proposed correlations between the two areas fall outside the scope of this study and are therefore omitted from discussion.

Mountjoy (1965) described the Devonian stratigraphy of the Miette area (Jasper National Park). The nomenclature is essentially based on Taylor's proposals. The Cairn Formation is subdivided into two members. The Flume Member is composed of grey stromatoporoidal limestones with abundant chert nodules. The upper unit of the Cairn consists of thick to massive, noncherty, stromatoporoid-bearing limestones. The Southesk Formation consists of a basal and upper member, composed of cryptocrystalline limestones and a middle or coral bed member. The clastic sequence of the Fairholme Group is divided into four formations, in ascending order: the Flume (Taylor, 1957), the Maligne, the Perdrix and the Mount Hawk Formation.

Belyea and McLaren (1964) report on correlations between Fairholme carbonates and clastic sequences in the general Sunwapta Pass area of Banff National Park. Unfortunately, the contact between the two facies is not exposed and, therefore, little information is available on the nature of the transition.

An excellent study of a Frasnian carbonate-shale transition in the Flathead-Crowsnest Pass area of Alberta and British Columbia is described by Price (1964) and discussed in this thesis.

MacKenzie (1965) studied the Upper Devonian stratigraphy in the vicinity of Mount MacKenzie (fig. 4; 52° 51′ N, 117° 14′ W), and paid special attention to the variable stratigraphy of the Fairholme Group.

The author's 1960 fieldwork in the Cripple Creek area has resulted in several additions and revisions of the nomenclature in order to better delineate the complex facies variations of the Fairholme Group.

CHAPTER III

BIOSTRATIGRAPHY AND TIME ZONATION OF THE UPPER DEVONIAN IN THE SOUTHERN ROCKY MOUNTAINS

The following account on the faunal zones and time-rock units of the Upper Devonian in the central portion of the Canadian Rocky Mountains is based on the results of studies made by Dr. G. O. Raasch, consultant to Shell Canada Limited.

1. THE FRASNIAN STAGE

The Frasnian in the Rocky Mountains comprises the Fairholme Group and its time-equivalents. The Fairholme sequence is bounded, both above and below, by regional unconformities. The pre-Frasnian erosional surface is indicated by Middle Cambrian to Middle Devonian subcrop belts under the Fairholme Group (Aitken, 1966). McLaren and Mountjoy (1962) supply pertinent information on the hiatus between the Frasnian and Famennian sequences in the Jasper region of Alberta (1962, figure 4). Faunal control indicates that the pre-Famennian unconformity is less important than the pre-Frasnian unconformity.
The Frasnian group, within itself, is a sequence in which the ordinal succession of faunal zones and time-rock units is maintained throughout the central Rockies. Within the group no unconformities or significant hiati are evident.
The following summary denotes the Upper Devonian Frasnian faunal zones (DFR) in Alberta, followed by the designate brachiopod species.

Zone	*Designate species*
DFR 12	Vandergrachtella scopulorum Zone
DFR 11	Cyrtospirifer whitneyi Zone
DFR 10	Cyrtospirifer placitus Zone
DFR 9	Leiorhynchus albertense Zone
DFR 8	Leiorhynchus carya Zone
DFR 7	Receptaculites Zone
DFR 6	Leiorhynchus insculptum Zone
DFR 5	Leiorhynchus athabaskense Zone
DFR 4	Allanaria allani Zone
DFR 3	Lagodioides kakwaensis Zone
DFR 2	Lagodioides pax Zone

Emergence and subsequent erosional peneplanation of the pre-Devonian deposits preceded the Frasnian transgression. The Frasnian seas onlapped onto the pre-Devonian erosional surface. This situation is indicated by the areal extent of the basalmost Frasnian deposits. Time-stratigraphic units corresponding to the DFR 1 and DFR 2 zones have not been encountered along the Front Range of the Central Rocky Mountains. The same holds true for the subsequent DFR 3, representatives of which do occur in the Central Rockies, but west of the Front Range. Elsewhere, and also in the area of study, the Allanaria allani Zone (DFR 4) rests directly on the pre-Frasnian strata (Upper Cambrian within the map area).
Yellow and buff-weathering silt- and sandstone, mudstone and carbonates of the Alexo Formation overlie the Frasnian. Faunal criteria indicate that the Alexo is Famennian in age (DFA).
The Frasnian succession in western Canada comprises eleven faunal zones, each of which is characterized by a specific faunal assemblage. This is particularly so in the case of the brachiopodal component. Few species extend beyond the span of a single zone. The present information suggests that it seems reasonable to prognosticize that most brachiopods will eventually be found to extend throughout the vertical span of their particular zones. In other words, the faunal zones appear to coincide with the biochrons of the majority of their component species. This is the reason why the biostratigraphic zonation of the Frasnian is primarily based on brachiopod distribution. The fact that some Frasnian facies are devoid of brachiopods constitutes a problem.
The coral species appear to have been more deliberate, so that, for example, many of the species are found to range throughout all of the Upper Frasnian (i.e. zones DFR 10 through DFR 12). Stromatoporoids are expected to behave in a similar manner but caution is advised due to lack of study and discrimination. The rest of the macrofauna, which constitutes a minority of the total biota, suffers largely from lack of basic and systematic study. Gastropods hold good possibilities for further discrimination, but the abundant evidence supplied by the brachiopods and corals is adequate. Among the microfauna, the ostracods have shown possibility of range discrimination; relatively little is known on foraminiferal and conodont distribution. Palynological studies of the Frasnian in the Canadian Rocky Mountains have not been published as yet.
Compilation of all available faunal control strongly suggests that in western Canada the Frasnian is virtually complete. Not only are there no hiatal gaps within the sequence, but the basal zone lies at or near the beginning of Frasnian time, and the top at or near its close.
As evidence continues to accumulate, moreover, it begins to appear that a more complete sequence is present in western Canada than is shown from elsewhere in North America. Appendix 1 tabulates the most important ecologic components of the Frasnian zones and the surface and subsurface formations in which their presence has been established.

2. THE FAMENNIAN STAGE

Although this thesis is restricted to the Frasnian portion of the Upper Devonian, a few comments on the Famennian are in order. Unfortunately, the number of detailed Famennian stratigraphic outcrop sections and fossil collections is limited in comparison to those of the Frasnian. This situation is partially caused by the emphasis placed on the Frasnian by the exploration-oriented petroleum geologists. Their efforts were concentrated on the time equivalents of the Leduc and the Nisku Formation of the subsurface in the Alberta portion of the Interior Plains. Another reason is the rather unfossiliferous nature of the Famennian in comparison to that of the Frasnian. Our present information has led to the discrimination of three successive faunal zones in the Famennian (DFA 1A, DFA 1, DFA 2 in ascending stratigraphic order). Following is a short resume of the Famennian faunal zones and the surface and subsurface formations in which their presence has been established (appendix 2):

DFA 2 Leiorhynchus ventricosum Zone,
DFA 1 Leiorhynchus seversoni Zone,
DFA 1A Leiorhynchus basilicum Zone,

It is of interest to note that the DFA 1 (Leiorhynchus basilicum Zone) seems to be readily correlatable into the European standard section of Belgium. Sartenaer (1956 a and b) illustrates both *Cyrtiopsis nahanniensis* (his *Cyrtiopsis senceliae*) and *Leiorhynchus basilicum* (his *Pugnoides basilicum*) from the Belgian Lower Famennian.

3. ISOCHRONOUS PLANES

The following planes of time equivalence are present within the confines of the thesis area.

(a) *The Cambrian erosion surface.* — Peneplanation of the pre-Devonian sequence resulted in a rather smooth plane without appreciable variation in relief within the map area. Transgression during early Frasnian time resulted in deposition of a series of biostromes and associated carbonates over the shoal.

(b) *The boundary between the DFR 4 (Allanaria allani Zone) and DFR 5 (Leiorhynchus athabaskense Zone).* — Regional studies in the area south of the Athabaska River indicate the coincidence of the DFR 4 faunal zone with the cherty dolomite sequences in the basalmost portion of the Fairholme Group. Therefore, the top of the Flume Formation is placed at the DFR 4 — DFR 5 boundary.

(c) *The DFR 12 (Vandergrachtella scopulorum Zone)* is established over the entire map area by study of numerous large fossil collections.

(d) *The Frasnian-Famennian boundary.* — A marked lithologic break denotes this boundary within the map area. The thick-bedded, pure, light grey, resistant dolomites of the Late Frasnian are overlain by platy, argillaceous and silty, yellow and orange, recessive dolomites, shales and sandstones of the Famennian Alexo Formation. The unfossiliferous nature of the formation precludes collecting faunal evidence to substantiate the Frasnian-Famennian boundary within the map area.

Lithological analogies and homotaxial stratigraphic position allow correlation of the Alexo in the map area with adjacent sparsely fossiliferous sections where a Famennian age has been established (e.g. the Flathead-Crowsnest Pass area; Price, 1964; fig. 4).
McLaren (1955) reports *Nudirostra gibbosa* from Head of Cripple Creek (northwest side) and the DFR 6 (Leiorhynchus insculptum Zone) is indicated.
This tabulation indicates that most of the Frasnian faunal zones could not be established within the confines of the map area. The lower Fairholme, consisting of *Amphipora*-stromatoporoid dolomites, contains only an extremely slight brachiopod admixture. Insufficient time was available to permit a thorough search. The upper Fairholme within the map area consists predominantly of light grey dolomites and fossiliferous limestones. Brachiopodal content in the former sequences is unrecognizable due to complete dolomitization, while the coralline faunal component predominates in the latter. The marine shales in the northwesternmost portion of the map area are primarily characterized by a pelagic faunal content. Consequently, a faunal zonation based on brachiopods is not well suited for the thesis area.
The presence of the aforementioned datum planes serves to delineate a true facies distribution pattern within the successive time-stratigraphic divisions of the Fairholme Group of the area.
The accompanying Frasnian and Famennian faunal zonation charts (appendices 1 and 2) illustrate the correlations between the outcrop sections of the Mountains with the subsurface Devonian nomenclature of the Interior Plains. It must be emphasized that these correlations are subject to corrections as additional faunal information becomes available.
The desirability of introducing subsurface Devonian nomenclature to the outcrop sequences is still being debated. Several geologists (Taylor, 1958; Hargreaves, 1959) advocate this practice and stress its importance in the paleogeographic interpretation of the Alberta Basin. Others (Belyea and McLaren, 1958) question the validity of this procedure and emphasize that insufficient faunal control is available at present.

CHAPTER IV

METHODS OF MEASUREMENT OF OUTCROP SECTIONS, STRATIGRAPHIC DEFINITIONS AND CARBONATE TERMINOLOGY

1. METHODS OF MEASUREMENT

The geographic location of the measured outcrop sections within the map area is shown on the index map of the enclosed stratigraphic cross-section (appendix 3).
All outcrop sections were measured on the sides of mountains, with the exception of the South Ram River section (JD14-F60)[2], which is exposed along the Onion Lake Road. It was most convenient to measure up scarp slopes. Where possible, stream beds were followed. Water-worn beds revealed their fossil content much better than craggy intervals.
For the most part a five foot calibrated staff was used for measuring. Measurements were also made using a

[2]) All measured outcrop sections are indicated by the initials of the party chief (JD), an alloted number (e.g. 14), the geographic location (F=Foothills) and year of study (1960).

50 foot tape and a Brunton compass. The latter method was employed to traverse across large covered intervals or to obtain occasional checks on the accuracy of the staff method of measuring.

Representative lithologic samples, measuring approximately 2 1/2" × 2" × 1 1/2" were taken at 10 foot intervals or in every rock unit, whichever was the smaller. Lithologic and characteristic field observations were recorded by the geologist. The samples were packed in 3" × 6" cloth bags, which were labelled with the locality and section letters and the distance above a datum horizon.

The detailed nature of the stratigraphic studies in the Cripple Creek area required additional equipment not normally issued to surface geological parties. These include a diamond saw and a laboratory for the preparation of thin sections and acetate peels. The diamond saw driven by a generator enabled the laboratory assistant to cut and polish all rock specimens. This procedure proved to be necessary for detailed study of the largely dolomitized rocks. It became apparent that the oiled rock slabs showed many depositional features which could not be detected in the outcrop or in unprepared hand specimens. The slabbed and oiled rock surfaces were studied under the binocular microscope. Microscopic, mapping and faunal studies were carried out in an office tent, which was equipped with electric lights. Adverse weather conditions have no influence on this type of surface party due to the large amount of work which must be carried out in base camp.

2. STRATIGRAPHIC DEFINITIONS

Communication among geologists is often hindered by the confusion in the usage of stratigraphic terms. Moreover, stratigraphic thought and methods used in North America differ from those of the Old World. The following comments serve to remove some of these obstacles.

North American usage of such terms as group, formation, zone, etc. is based on the *Code of stratigraphic nomenclature* of the American Commission on Stratigraphic Nomenclature.

Introduction of the American nomenclature into other parts of the world has met with resistance. Schindewolf (1954) assigns the North American practice to the realm of "prostratigraphy", which should only be used for the Cryptozoon. However, this nomenclature is very valuable and constitutes the only practical operational method in poorly fossiliferous or unfossiliferous terrains and in lightly explored or virgin territories. Schindewolf presents a rather one-sided view of time-stratigraphy by insisting on fossils as the sole guide to geologic time correlation. Petroleum geologists correlate „kicks" on mechanical logs as approximate time markers and there is ample evidence to demonstrate the validity of this practice within a particular basin.

The proposals of the International Stratigraphic Commission (Hedberg, 1961) have had a clarifying effect. The essentials of both viewpoints are clearly understood and warrant no further comments.

Our present knowledge of the structure and stratigraphy of the Canadian Rocky Mountains is almost exclusively based on mapping marker horizons with typical lithologic and weathering characteristics, combined with a certain amount of measured stratigraphic outcrop sections. Detailed stratigraphic studies, in a restricted locale, are few and far between. It cannot be denied that mistakes have been made. The contents of this thesis illustrate the extent and relative importance of these mistakes.

The detailed nature of this study permits a direct comparison between rock-stratigraphic and time-stratigraphic practices. The results indicate a certain degree of coincidence between rock-stratigraphic formations and particular fossil assemblages. This observation supports the idea that if conditions remain sufficiently constant to produce a uniform and recognizable rock-unit, they also tend to produce a uniform faunal assemblage.

The term „facies" is also subject to various interpretations. Precision in our usage of this term should contribute to clearness of thinking. Many geologists employ the term to stress areally segregated parts of differing nature belonging to a genetically related body of sedimentary deposits (Longwell, 1949, 1955). A study of recent geologic literature shows that the "body of sedimentary deposits" varies greatly in magnitude and that the term facies is often used without the framework of defined stratigraphic units. The present author uses the term to indicate areally segregated portions of a time-stratigraphic unit as defined by planes of interpreted and extrapolated time equivalence. This usage corresponds to Longwell's proposed definition of a "sedimentary facies".

Regional studies of carbonate sequences of varying age strongly indicate that similar sediments are formed under like environments without regard to age or local geologic settings. These similarities allow an accurate interpretation to reconstruction of conditions, processes, and events during part of the geologic past. This principle is used in this thesis and the environmental connotation of the various carbonate-shale sequences is applied to denote origin and depositional environment of several additional carbonate-shale sequences in America and Europe. The term "facies group" is used to denote these sets of lithologic and organic characters having origin in a particular sedimentary environment.

There is considerable confusion over the use of the word "reef". Two schools of thought are indicated. The first group likes to restrict "reefs" to those carbonate bodies that fulfill the following criteria:

(a) a rigid organic framework must be present, which helps in the building of the structure above the surrounding sea floor,

(b) the mass should be capable of withstanding the destruction of wave action,

(c) all the carbonate forming the reef mass is produced by the organisms living there,

(d) there is usually a significant vertical element to the body and detritus of reef-building organisms should be present,

(e) sedimentary structures, such as massive bedding in the core of these bodies, surrounded by a fringe of outwardly dipping lime sands, suggest a reef.

A second group of geologists uses the term "reef" in a progressively looser sense. Andrichuk (1958) describes a "reef" as to include the portions "formed by active organic growth as well as related detrital carbonate and fossil debris within the same mass". He also states that lime sands and lime muds of precipitated origin are genetically related to the other reef deposits and "are considered important constituents of certain reefs".
Cloud (1952) agrees and states that the term "reef" should be applicable to the entire structure even though the larger portion of this mass may not have been a wave-breaking feature during its deposition.
Henson (1950) proposes a compromise and introduces the term "reef complex" to designate a reef plus its auxilliary deposits. It is quite evident from the geologic literature that the word reef has been used for such masses, wherefore it should be understood that all reefs most likely are reef-complexes. It is obvious that this definition converts the word "reef" into a sack term, in direct contrast with the specific and carefully defined criteria mentioned previously.
The terms "carbonate-complex" and "carbonate buildup" are frequently used to describe the carbonate province of the outcrop sections and the subsurface in a neutral and non-committal manner.
This problem has led to numerous discussions and it is advantageous to define three common carbonate structures more precisely.

Cumings (1932) introduced the term *bioherm* for "mound-like carbonate bodies, constructed by sedentary organisms such as corals, stromatoporoids, coralline algae etc., and enclosed in rocks of different lithological character". Such mounds can form at several depths. Shallow water bioherms could be synonymous with "reefs". In deep water, where the mound was not subject to direct wave action, the term "bioherm" should be used in preference to reef.

Biostrome is a term proposed by Cumings (1932) for purely bedded structures such as shell beds, crinoid beds, coral beds etc., consisting of, and built by, sedentary organisms and not swelling into mound or lens-like forms. Depth of formation is not taken into account so that the term would remain the same whether the biostrome occurs in deep or shallow water. The basic difference between bioherms and biostromes is the geometric shape: i.e. a mound-like versus a flattened or lens-shaped body.

Bank is a term to denote 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. The material might be trapped by organisms or be concentrated by eddy action. The geometric shape of such structures varies greatly. The basic difference between these banks and the formerly described structures is indicated by the composition. The bulk of the sediment, forming the bioherms and biostromes is directly derived from within the confines of the structure. Banks are essentially concentrations of outside material.

The present author is fully aware of the fact that only a slight amount of the Fairholme carbonates is of reefal origin (sensu stricto). However, the fact remains that an accumulation of biostromal and very fossiliferous carbonates occurs around the periphery of the carbonate complex in the area of study. An envelope curve, following the top of the biostromal carbonate, displays a marked domal development at the rim of the carbonate complex. Moreover, this position is generally most favourable for reef development in the restricted sense. It is for these reasons that the term "reef" sensu lato may be applied.

3. CARBONATE TERMINOLOGY

The detailed descriptive petrology of carbonates is still in its initial stages and there is no generally accepted comprehensive terminology at present. There have been several proposals to produce such a scheme in recent years, but the results indicate an array of overlapping terms or terms used in divergent senses. The following comments serve to illustrate the terminology used in this thesis.
Early carbonate classifications were primarily based on variations of grain-size. Grabau introduced three major divisions; i.e. calcilutite, calcarenite and calcirudite. Calcilutites were described as "very fine grained limestones formed of lime-mud". Most of these rocks are aphanitic and no original grain structure can be observed even under the microscope. Calcarenites are described as "limestones composed of small, sand-like calcareous fragments", while calcirudites are reported as "limestone breccia or conglomerate composed of calcareous fragments". This terminology found considerable favour amongst geologists and is still widely used. Kay (1951) supplemented this classification by introducing the term "calcisiltite" to cover limestones of silt-grade, however these sizes are very difficult to resolve with a binocular microscope, and the term calcilutite is used in this report to include all sizes under the sand grade (1/8 mm).
Three newly-proposed systems of carbonate classification have drawn considerable attention and warrant further comments.
Bramkamp and Powers (1958) base their classification on an exhaustive study of the Arabian Jurassic outcrop belt, diamond cores from the Jurassic Arab D carbonate reservoir, and preliminary studies of modern calcareous sediments in the Persian Gulf. The authors stress the relationship between environment and

current regimen. Finegrained limestone (calcilutite) and calcarenitic limestone are deposited in quiet water, while calcarenite and coarse carbonate clastics are considered as current-washed deposits. After classification of the rocks according to particle size, a further subdivision is made according to the degree to which their original texture has been altered by diagenetic and post-lithification processes (primarily due to progressive dolomitization). Four stages of dolomitization are discerned, resulting respectively in non-visible, moderate, strong, and complete alteration of the original texture.

Organic-reef carbonates are not included in this classification, which is primarily oriented towards the study of ditch cuttings. According to the authors, outcrop control is needed to distinguish between organic-reef and current-washed deposits. The authors comment only briefly on the environmental aspects of the various carbonate types. The classification is descriptive rather than genetic and obviously developed to establish a relationship between the carbonate reservoirs and degree of alteration.

The Fairholme carbonates in the thesis area are extensively or exclusively dolomitized and Bramkamp and Powers' classification is readily applied. However, the present author has attempted to stress the environmental aspects of the carbonates despite the far-advanced degree of dolomitization.

The carbonate classification proposed by Folk (1959) is essentially based on three end-members:

(a) terrigenous constituents,
(b) allochemical components,
(c) orthochemical constituents.

Terrigenous constituents include all materials derived from an adjacent land mass and carried into the depositional basin, e.g. quartz and chert grains, felspar and argillaceous material.

Allochemical components, or "allochems", are carbonate bodies which formed by chemical or biologic processes within the depositional basin. There are, according to Folk's terminology, four types of allochems; i.e. intraclasts, oolites, fossils and pellets. Intraclasts are fragments of penecontemporaneous carbonate sediments eroded from the sea floor by various agents. Such fragmental material is weakly consolidated, and this criterion distinguishes intraclasts from lithoclasts. The latter are true rock fragments, torn away from pre-existing and well-indurated carbonate rocks.

Orthochemical constituents, or „orthochems", include all normal precipitates formed within the depositional basin or within the rock itself and show little or no evidence of transport. Microcrystalline calcite ooze matrix, or "micrite", and coarser, clearer sparry calcite are assigned to the orthochems.

Micrite, composed of calcite grains ranging from 1 to 4 microns in diameter, is considered to originate by rapid chemical and biochemical precipitation. Mechanically produced micrite, produced by abrasion of shell debris, is considered to be negligible and is included with the chemically precipitated ooze. Sparry calcite, or "spar", forms clear grains or crystals 10 microns or more in diameter.

A third group of orthochems includes minerals formed by recrystallization and dolomitization processes, such as replacement dolomite and recrystallized calcite. Folk introduces ingenious names. Appropriate abbreviations of allochems serve as prefixes for the components of his classification; i.e. "intra" for intraclasts, "oo" for oolites, "bio" for fossils, and "pel" for pellets. To this is added "mic" or "spar" depending on the presence of micrite or sparry calcite in the groundmass. If the allochems average coarser than 1 mm, the rock is called a calcirudite (or dolorudite); if they lie between 0.0625 and 1 mm, the rock is a calcarenite (or dolorenite); if under 0.0625 mm, calcilutite or dololutite.

Varying proportions of the three end members, as well as the average size of the allochems, determine the

TABLE I

CLASSIFICATION OF CARBONATE ROCKS ACCORDING TO DEPOSITIONAL TEXTURE

<table>
<tr><td colspan="5">Depositional texture recognizable</td><td>Depositional texture not recognizable</td></tr>
<tr><td colspan="4">Original components not bound together during deposition</td><td rowspan="4">Original components were bound together during deposition . . . as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be insterstices.</td><td rowspan="4">Crystalline Carbonate
(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
<tr><td colspan="3">Contains mud (particles of clay and fine silt size)</td><td rowspan="3">Lacks mud and is grain-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10 percent grains</td><td>More than 10 percent grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Boundstone</td><td></td></tr>
</table>

name applicable to a particular carbonate. Folk's classification pays particular attention to the nature of the groundmass. The amount of winnowing, to which the sediment is subjected, depends on the strength of currents acting in the particular locale. Strong currents result in removing the micrite groundmass and porosity development or subsequent spar infill will occur. Carbonates deposited in quiet waters contain a large amount of micrite. These ideas are generally valuable and this classification is extensively used in North American geologic literature. The present author uses the terms "mud-supported" for those carbonates supported by micrite and containing varying amounts of allochems and "grain-supported" for carbonates whose framework is supported by allochems and a varying micrite admixture.

The classification by Dunham (1962) is based primarily on the depositional fabric of the carbonates, with subdivisions divided on the degree and nature of the support of constituent particles. Two end-members are indicated, i.e. grain-supported and mud-supported carbonates. Grain-supported fabrics are those in which the particles are in contact, therefore offering a supporting framework, with the interstitial spaces occupied by carbonate mud or calcite spar. Mud-supported fabrics are characterized by floating particles in the carbonate mud. Presence or absence of carbonate mud permits a differentiation between "muddy carbonates" and "grainstone". A further subdivision, based on the abundance of grains and particles, distinguishes between mudstone, wackestone, and packstone.

The term „boundstone" is used to describe those rocks which owe their origin to some organic binding mechanism. Unfortunately, the entire group of recrystallized and dolomitized carbonates is lumped together and remains undiscussed.

The following table presents an outline of Dunham's classification (table 1). The present author uses this classification in a synthesis of the Fairholme facies groups and their spatial distribution (chapter VII, appendix 6). However, a large portion of these carbonates fall into Dunham's "crystalline carbonate" group.

The results of this thesis indicate that representatives of the „crystalline carbonates" can often be assigned to the mudstone-boundstone groups by means of detailed microscopic study and field relations.

CHAPTER V

STRATIGRAPHY: FIELD OBSERVATIONS

1. THE PRE-FAIRHOLME SEQUENCE

The oldest strata exposed in the area are of basal Upper Cambrian age.

The sequence is divisible into three lithological units. The basal unit, composed of coarsely oolitic limestone or dolomite, contains well preserved trilobite fragments. Thin intercalations (1 to 2 feet) of olive green, flaky shale and scattered limestone-pebble conglomerates occur.

The base of this oolitic carbonate unit is not exposed; a thickness of 107 feet (incomplete) is present at Cripple Creek (JD6B-F60). Faunal collections include abundant, well preserved fragments of *Kormagnostus esterius* Lochman, *Cedarina victoria* Lochman, and *Arapahoia* sp., indicative of the Lower Cedaria Zone of basal Upper Cambrian age (determinations by Dr. G. O. Raasch). Erdman (1946) reports "Upper Cambrian trilobites below the Devonian base" at Cripple Creek.

Aitken (1966) reports a similar *Cedarina-Kormagnostus-Arapahoia* trilobite assemblage (early Upper Cambrian Cedaria Zone) from lithologically identical sequences (lower division of Lynx Formation) at Windy Point, 20 miles northwest of Cripple Creek.

The middle unit is composed of light grey, red-weathering, lithographic to very finely crystalline, silty dolomite. The sequence is thinly bedded and laminated in parts. The sediments show flow textures and occasional mottling, which is attributed to slumping of the soft, unconsolidated material. Mud cracks and "scour and fill" are observed in Boundary Creek (JD2-F60), where a thickness of 170 feet is established.

The upper unit of the Upper Cambrian sequence is composed of thick bedded, light grey sublithographic dolomite with a trace of pure quartzose silt. The sequence weathers with a conspicuous yellowish-grey color and is more resistant to erosion than the underlying unit. Ghost features indicate an original pelletal mud texture. The light weathering color is easily recognized on aerial photographs and serves to establish the Cambrian-Devonian contact (fig. 5).

Fossil content is restricted to an outline showing concentric layers suggesting an algal ball. The uppermost pre-Devonian beds, excellently exposed in Cripple Creek, are primarily composed of leached breccias. The erosion surface is only rarely exposed in the area under discussion and is almost everywhere covered by debris. The exposures of the Cambrian-Devonian contact along Cripple Creek (JD6-F60) and Tina Creek North (JD8-F60) show large boulders of Cambrian dolomite encased in a "matrix" of light green shale.

2. THE FAIRHOLME GROUP

The stratigraphy of the Fairholme Group was studied by examination of a network of closely-spaced outcrop sections, in some instances not more than a few hundred yards apart. Lateral traverses have established the correlation between sections and the areal extent of the various facies (appendix 3).

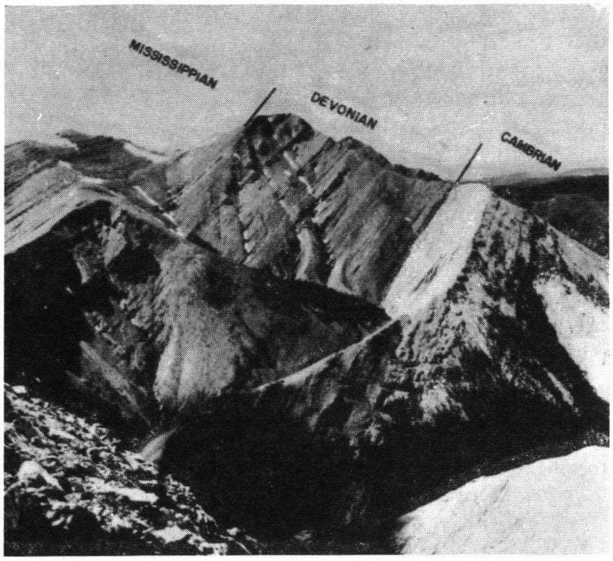


Fig. 5. General view of thrust block showing light colored Cambrian dolomite on right hand side overlain by Upper Devonian and Mississippian sequence.

The Fairholme Group within the area is divisible into three time-stratigraphic units, the upper and basal boundaries of which are established by regionally controlled time lines.

The Cambrian erosion surface and the boundary between the DFR 4 (Allanaria allani Zone) and DFR 5 (Leiorhynchus athabaskense Zone) constitute respectively the basal and upper boundaries of the lower unit. The upper boundary of the overlying time-stratigraphic unit is formed by the DFR 12 (Vandergrachtella scopulorum Zone). The base of the Famennian constitutes the upper boundary of the upper unit. Respectively, these three units coincide with the Flume Formation, an interval comprising the Cairn Formation plus the lower portion of the Southesk Formation, and the upper portion of the Southesk Formation.

The following comments serve to illustrate the pertinent field characteristics of these components of the Fairholme Group, in stratigraphically ascending order.

The Flume Formation

This formation comprises the earliest Frasnian sediments within the area and has a constant thickness of 115 feet. The Flume is overlain by the Cairn Formation and underlain by the breccias and dolomites of the Cambrian system. The upper boundary is defined at the uppermost occurrence of black chert nodules and lenses, parallelling bedding planes in the dolomite sequences (fig. 6). The formation consists predominantly of fossiliferous and biostromal dolomites in the studied area, indicating deposition on a broad stable shoal in relatively shallow marine water. The basalmost portion of the Flume consists of dolomitic siltstone and silty, argillaceous dolomite, indicative of extremely shallow water and partially subaerial conditions.

Interfingering of these silty, unfossiliferous dolomites

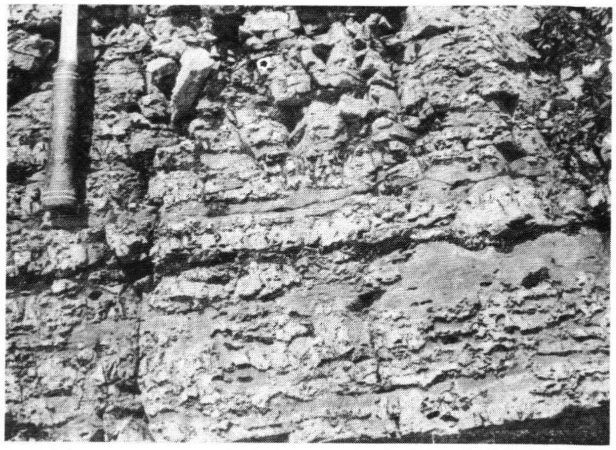


Fig. 6. Flume Formation, Penny Creek (JD9-F60). Chert lenses and nodules in dark colored Amphipora-stromatoporoid biostromal dolomite.

with fossiliferous to biostromal dolomites has been indicated by regional control. Therefore, it is considered useful to regard these lithologies as distinct facies types.

(1) Terrigenous clastics facies. — The dolomitic siltstone is rarely exposed in the thesis area; good exposures occur in Cripple Creek (JD6-F60) and South Ram Ridge (JD12-F60, fig. 7). The sequence, over-

Fig. 7. Calcareous, silty dolomite flags of the terrigenous clastics facies. South Ram Ridge (JD12-F60).

lying the breccias of the Cambrian erosion surface, is composed of buff calcareous shales and laminated dolomitic siltstones. Truncation of the laminae indicates minor disconformities, while slump structures suggest deposition on a slight slope. Thin streaks of green shale occur in Tina Creek North (JD8-F60). This sequence represents the initial marine transgression during the Frasnian.

Aitken (1966) introduces the Yahatinda Formation for similar silty dolomite and dolomitic siltstone strata separating pre-Devonian from Frasnian sequences along the mountain front. He recognizes two "facies"; i.e. a thicker (and older) channel facies and a thinner (and younger) non-channel facies. Regionally, the age of the Yahatinda ranges from late Lower Devonian (based on fossil fish) to early Upper Devonian (based on plant remains and fossil spores).

The thin terrigenous clastics sequence of the Cripple Creek area fits Aitken's descriptions of the non-channel facies of the Yahatinda for which a littoral-marine environment is postulated. The absence of any diagnostic fossil content in these beds at Cripple Creek precludes an age determination but an early Upper Devonian age is most likely.

The biostromes of the Upper Flume show a marked vertical variation (appendix 4). The basal portion of the biostromes contains abundant *Amphipora*, which are accompanied by small nodular stromatoporoids at the top. The middle portion is essentially composed of an agglomeration of large spherical, hemispherical or tear-shaped stromatoporoids. The upper portion of the biostromes shows a decrease in size of the stromatoporoids and reoccurrence of *Amphipora*. The latter occur exclusively in the uppermost beds of the biostrome. A marked lateral faunal variation is also apparent. The centres of the biostromes are predominantly composed of an agglomeration of stromatoporoids while the flanks are characterized by a mixture of *Amphipora* and stromatoporoids. This assemblage grades laterally into fossiliferous beds with an exclusive *Amphipora* fauna. The fauna occurs in an extremely fine to medium crystalline, brownish-grey to black dolomite. The light-weathering colours of the faunal component are in sharp contrast to those of the dark dolomite matrix (fig. 9).

The biostromal beds are of limited lateral and vertical extent (appendix 4) and are separated by light grey unfossiliferous dolomite beds (fig. 8). These barren beds are more resistant to erosion and weather out as thin ledges, which can be traced laterally over considerable distances.

It is often possible to distinguish the cherty dolomites of the Flume Formation from the non-cherty biostromal carbonates of the overlying Cairn by color variations in the covering lichen. The chert nodules and silicified dolomites are covered by a green variety, while the non-cherty dolomites are overgrown by red or orange lichen. This color variation can often be distinguished from a considerable distance and is a useful aid in reconnaissance mapping.

The fauna of the Flume Formation is generally poorly preserved due to partial or complete dolomitization. Composition is generally based on shape or outline of the fossils. An exception is present in Boundary Creek (JD1, JD2-F60), where part of the Flume occurs in limestone facies. This section displays interesting depositional features and the internal structure of the organisms is well preserved. The limestone interval grades upwarts into a dolomite section via a transition zone, containing calcareous stromatoporoids in a dolomitized matrix. The preservation of the calcitic stromatoporoids allows taxonomic determination and a comparison of the collections with those of equivalent beds in the subsurface (e.g. chapter VIII; Swan Hills) will be useful. The chert in the Flume Formation at Boundary Creek occurs in the matrix surrounding the stromatoporoids. The areal extent of the limestone facies is very limited and the equivalent beds in Deadfall Creek (JD3-F60) occupy an intermediate position between those studied in Boundary (JD1-, JD2-F60) and Nell Creek (JD4, JD5-F60). The section in Deadfall Creek shows progressive dolomitization and is useful in interpreting "ghost features" in the completely dolomitized section at Nell Creek.

The Cairn Formation

The Cairn Formation is herein redefined to present a better understanding of its depositional history. McLaren (1955) describes the Cairn Formation as a sequence of dark brown and black, organic dolomites. This definition leads to difficulties in defining its upper boundary.

Dark colored, very fossiliferous and biostromal carbonates occur at several stratigraphic levels. The extreme is present in the North Ram River section (JD13, JD13A-F60), where such carbonates immediately underlie the Alexo Formation (appendix 3).

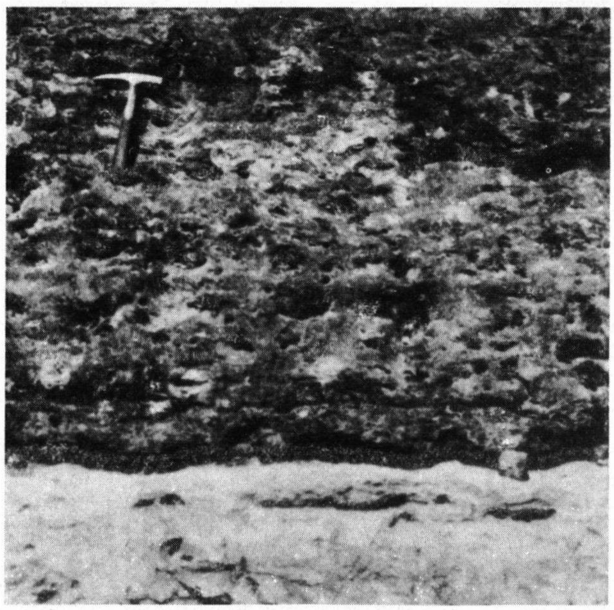


Fig. 8. Cairn biostrome, JD11-F60 (494-500 feet). Typical biocycle from bottom to top:

(1) light grey barren beds
(2) *Amphipora* beds
(3) stromatoporoid beds
(4) *Amphipora* beds

It is proposed to restrict the Cairn Formation to the predominantly dark colored, non-cherty dolomites with a distinct *Amphipora*-stromatoporoid assemblage in the basal portion of the Fairholme. The Cairn Formation, so revised, has a consistent thickness in the Cripple Creek area (appendix 3) and the proposal offers a solution to the dispute between McLaren and Taylor. The Cairn Formation (revised) overlies cherty carbonates of the Flume Formation and is overlain by dark colored biostromal dolomites with a coral-brachiopod assemblage (e.g. North Tina Creek, JD8-F60). This latter sequence is placed in the Southesk Formation (appendix 3) and constitutes one of its several facies.

The thickness of the Cairn cannot be established in the northern and southernmost portions of the area. The formation is only partially exposed at the second ridge

Fig. 9. Biostromal unit of mixed massive stromatoporoids with numerous *Amphipora*. Note dolomite blebs in centre of several stromatoporoids. North Ram River (JD13, JD13A-F60).

north of North Ram River and at South Ram River (JD14-F60), due to tectonic disturbances. The accompanying cross section (appendix 3) shows the consistent thickness of the Cairn Formation (revised) in the remainder of the area. Thicknesses range from 350 to 375 feet, indicating that the formation was laid down as a blanket deposit. Lateral and vertical facies changes, within the formation, are numerous but of very minor extent, usually involving a variation in bioclastic

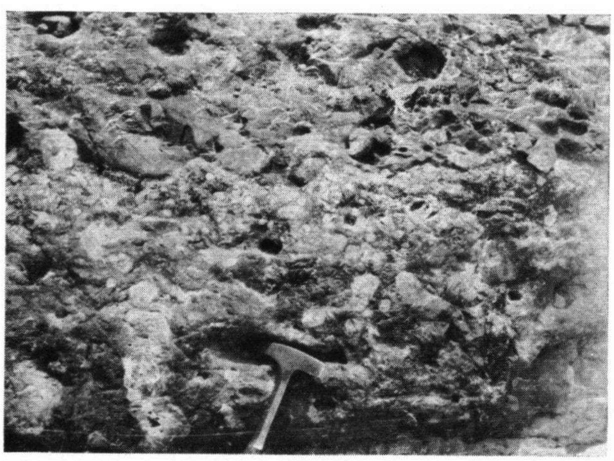


Fig. 10. Upper and middle portion of typical Cairn biostrome, respectively characterized by an *Amphipora-Thamnopora*, and stromatoporoid assemblage. Note vugs probably after leached stromatoporoids. Douglas Creek (JD19C-F60).

admixture within the dolomite matrix and faunal content. However, regional studies indicate a major lateral facies change, to argillaceous limestone and calcareous shale, outside the thesis area at Wapiabi Creek and in the Flathead-Crowsnest Pass areas (chapter VIII).

The faunal aspects of the Cairn are identical to those of the biostromes in the Flume Formation and no additional description is required.

The Southesk Formation

The Southesk is redefined in accordance with the revision of the underlying Cairn Formation. The formation is overlain by dolomitic siltstones of the Alexo Formation and underlain by dark colored dolomites of the Cairn (revised) with its stromatoporoid-*Amphipora* fauna. The revision suggests that this assemblage is much less important in the Southesk than it is in the Cairn. The regional validity of this observation has been tested by microscopic studies of selected Devonian outcrop sections in the northwestern portion of Southern Alberta. Results indicate that scattered *Amphipora* occur in post-Cairn sediments. Globular stromatoporoids, main builder of the Cairn biostromes, are rather rare in the Southesk, while thin lamellar species occur more often.

It is unknown whether this observation was not made, or not stressed by previous workers. MacKenzie (1965), in a most recent article on the Fairholme carbonate-shale transition at Mount MacKenzie (fig. 4), states that the Southesk can be separated from the Cairn Formation on the basis of its "lighter color and smaller *Amphipora*-stromatoporoid content". His stratigraphic sections illustrate this conclusion quite clearly and his lithologic descriptions record only one Southesk interval with globular stromatoporoids. Therefore, it may be deduced that MacKenzie defines the Southesk Formation on the same criteria as those proposed by the present author for the Cripple Creek area.

Apparently, a similar situation occurs in the Miette reef complex (Mountjoy, 1965; 53° 07′ N, 117° 45′W). The top of the Cairn Formation (op. cit.: fig. 8) coincides with the stratigraphically uppermost occurrence of "mainly stromatoporoidal carbonates," while "coralline carbonates" predominate in the overlying Southesk Formation. However, the general validity of this conclusion cannot be established for the entire Southesk Formation within the area. Complete dolomitization and subsequent leaching result in intervals consisting of non-descript crystalline and vuggy dolomites. The outlines of the vugs indicate a fossil-leached origin and it is possible that they are partially after stromatoporoids.

Moreover, globular stromatoporoids are reported from the time-equivalent Leduc Formation of the subsurface (Klovan, 1964; chapter VIII).

The DFR 12 (Vandergrachtella scopulorum Zone) has been established over the entire map area. The faunal assemblage occurs in a characteristic sequence of nodular, argillaceous limestone and calcareous shale, indicated as the "Cripple Tongue" (appendix 3).

The occurrence of this easily recognizable marker horizon is utilized to subdivide the Southesk Formation into three slices. The lower Southesk includes the interval from top Cairn Formation to the base of the Cripple Tongue. The latter constitutes the middle Southesk, while the upper Southesk comprises the interval from top Cripple Tongue to base Alexo Formation (i.e. base Famennian).

The Southesk Formation displays a classic example of interfingering facies, well defined by lithological and faunal criteria. The following facies have been established:

(1) dark brown to black, bituminous shale facies; barren or with sparse pelagic fauna;
(2) greenish-grey to dark grey, calcareous shale facies; barren or with sparse pelagic fauna;
(3) medium grey to buff, nodular, argillaceous limestone and calcareous shale facies;
(4) light grey to medium grey coralline limestone facies;
(5A) dark brown or light grey organic (ecologic) biostromal dolomite facies; the sequences, placed in this facies, contain intervals of barrier edge carbonate sands (facies 5B);
(6) light grey, slightly fossiliferous dolomite facies with a mixed coral-gastropod-ostracod faunal assemblage;
(7) light grey, laminated dolomite facies with an algal -gastropod-ostracod assemblage.

The following comments illustrate the criteria on which this facies differentiation is based.

(1) *Dark brown to black, bituminous shale facies; barren or with a sparse pelagic fauna,* and
(2) *greenish grey to dark grey, calcareous shale facies; barren or with a sparse pelagic fauna.*

Continuous shale exposures are rare due to their recessive nature. These facies have a very limited distribution within the map area. A well-exposed section is present at North Ram River (JD13, JD13A-F60, appendix 3, fig. 11).

The shales of this locality possess a dark grey color and a calcareous content of less than 5 %. They are essentially non-bituminous and are assigned to facies 2. In the excellent shale exposures along Wapiabi Creek (see chapter VIII), the section shows a basal interval of dark grey and black shales. A similar color variation occurs in the subsurface, where the brownish black shales of the Duvernay are overlain by the greenish-grey shales of the Ireton Formation (Andrichuk, 1954, 1958; McCrossan, 1959). It has been suggested that this color variation is caused by variation in water circulation and aeration. The dark grey and black colors are postulated to indicate poor circulation, causing a certain degree of restriction, while the green variety is indicative of areas with good circulation. This relationship between color variation and degree of circulation has been used in the past to detect Fairholme carbonate complexes. The black shales were suggested to occur in "cul-de-sacs adjoining reef promontories". Correlations on the accompanying cross section (appendix 3) show the absence of a cul-de-sac in front of the carbonate mass in the Cripple Creek area and a gradual thinning of the shales towards the southeast, without significant reversals, is indicated.

Fig. 11. Calcareous shales at North Ram River (JD13-F60). Note bedding plane markings on slab to right of hammer.

Large samples of the shales were collected at five foot intervals at North Ram River (JD13, 13A-F60) to facilitate a study of the microfauna. The microfaunal assemblage consists of *Tentaculites*, ostracods, marine algae, foraminifera. An interesting feature is that the inner space of the *Tentaculites*, etc. has been subsequently filled with sediments and finer organic debris. This observation indicates that deposition was rather slow during a long period of time and explains the flooding of the interval with a prominent microfauna.

A literature study reveals the tendency of previous workers to exaggerate the amount of shales. This observation is illustrated by Belyea's descriptions of Cripple Creek (northwest); i.e. Tina Creek North (JD8-F60). Belyea (1958) suggests the presence of a thick sequence of shales on an accompanying illustration. Detailed examination reveals that in reality only 70 feet of the Southesk Formation occurs in shale facies (appendix 3), the remainder consists of non-argillaceous, fossiliferous, and biostromal limestones. It is rather dangerous to determine the presence of shales on the basis of weathering characteristics or on covered intervals. The inclusion of argillaceous limestones may result in an erroneous interpretation of the bathymetric and environmental conditions.

(3) *Medium grey to buff, nodular, argillaceous limestone-calcareous shale facies.*

This facies replaces the calcareous shales progressively towards the southeast. Strata, equivalent to the shale sequence at North Ram River (JD13, 13A-F60), occur partially in nodular limestone-calcareous shale facies at Joan's Ridge (JD15, 15A-F60).

The transition between the shales and limestones is gradational and the definition of facies boundaries is difficult in intervals with interfingering lithologies.

The nodular argillaceous limestone-shale facies consists of interbedded light to medium grey limestones and medium grey calcareous shales.

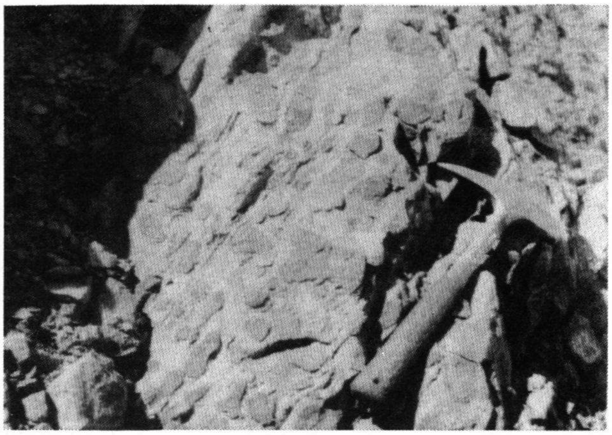


Fig. 12. Limestone nodules in argillaceous matrix. Cripple Tongue in Tina Creek North, JD8-F60 (1030 feet).

The nodular appearance of the limestones has led various authors to imply deposition on a gradual slope and subsequent slumping of the sediments. This explanation is not generally accepted and the nodular appearance is probably caused by a diagenetic concentration of the lime component. A chronological review of the various mechanisms, considered responsible for the characteristic nodular texture, is supplied in the next chapter.

The limestone contains varying amounts of argillaceous material and a characteristic fauna composed of brachiopods, crinoids, and bryozoa. Solitary corals are rare and constitute only a minor admixture.

The facies is restricted to the lower and middle portions of the Southesk Formation within the confines of the area. In the lower Southesk it occurs between North Ram River (J13, 13A-F60) and Tina Creek North (JD8-F60), and occupies an intermediate position between the calcareous shales and a coralline limestone facies (appendix 3).

In the middle Southesk, the facies occurs between North Ram River and Nell Creek (JD4-F60) and is indicated as the Cripple Tongue (appendix 3). At its type locality, at Gertie Creek (JD10-F60), the Cripple Tongue is 96 feet thick. A gradual thinning towards the southeast is indicated. Continuous exposures are rare and the unit weathers back conspicuously between the more resistant, cliff-forming carbonate sequences of the basal and upper Southesk. The Cripple Tongue includes two limestone bands which can be traced over the entire map area and serve as useful markers. The intercalated shales contain an abundance of limestone nodules, which weather out and form a rubble over the shaly intervals (fig. 13).

Fig. 13. Limestone nodules weather out and form a rubble over less resistant shale beds. Joan's Ridge, JD15-F60, Cripple Tongue.

Studies of large fossil collections from the Cripple Tongue, establish the DFR 12 (Vandergrachtella-Tenticospirifer Zone), equivalent to the MacGeea proteus Zone of Warren and Stelck (1950, 1956).

The presence of a biostratigraphic time line in a carbonate complex with such pronounced facies variations is of particular interest. The accompanying stratigraphic cross section (appendix 3) emphasizes this time line by using the base of the Cripple Tongue as datum.

Following is a summary of the most prominent faunal components (determinations by Dr. G. O. Raasch and Dr. B. S. Norford):

Brachiopoda

Atrypa hackberryensis Stainbrook
Cyrtospirifer whitneyi
Schuchertella cf. prava Hall
Schizophoria cf. Iowaensis
Gypidula cornuta Hall
Nervostrophia sp.
Atrypa ciliipes Crickmay

Corals

Acinophyllum stramineum (Billings)
Tabulophyllum sp.
Thamnopora sp.
Alveolites sp.
Hexagonaria sp.
Coenites sp.
Syringopora sp.
Aulopora sp.
Phillipsastrea cf. woodmani (White)
Cladopora sp.

The presence of the argillaceous limestone-calcareous shale facies in the upper portion of the Southesk has been established by regional studies in the Wapiabi Creek and Flathead-Crowsnest Pass areas (chapter VIII).

(4) *Light to medium grey coralline limestone facies.*

The facies is composed of medium to thick bedded, light and medium grey limestone, in sharp contrast with the nodular, thin bedded argillaceous limestone-calcareous shale facies, which it progressively replaces in a southern direction. The contact between the two facies is gradational. Shale intercalations, which are

characteristic of the nodular limestone-calcareous shale facies, disappear gradually into the coralline limestones.
These lithologic variations cause a differentiation in weathering pattern. Sequences characterized by interfingering of the two facies are readily recognized by a repetition of recessive and resistant carbonate units (Disaster Creek, JD16-F60; appendix 3).

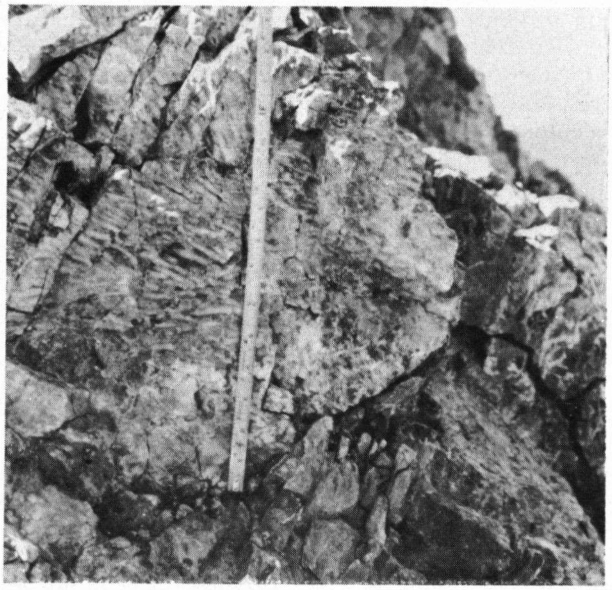


Fig. 14. Disphyllid colonies in coralline, biostromal (slightly dolomitic) limestone at Penny Creek (JD9-F60).

The faunal assemblage shows a pronounced decrease in the brachiopod-gastropod-crinoid component and an increase in coral content (fig. 14). The facies is characterized by the occurrence of biostromes composed of *Thamnopora, Alveolites, Aulopora,* disphyllid corals and globular favositids with a slight brachiopod-gastropod admixture. These biostromes have been studied in detail in Tina Creek South (JD7-F60) and Tina-Cripple sections (JD17-F60). The results suggest a vertical and lateral gradation in their faunal content (appendix 5).
The basal portion and the flanks of the biostromes are characterized by a high percentage of globular and platy Alveolites while the upper and central portions are essentially composed of Thamnopora, disphyllids, and solitary rugose corals.
A gradual increase in the brachiopod-crinoid admixture occurs towards the northwest; e.g. the admixture is more pronounced in Penny Creek (JD9-F60) than in Tina Creek North (JD8-F60).
The only unquestionable occurrence of globular stromatoporoids, in the Southesk Formation of the map area, has been established in a thin bed of coralline limestone at North Ram River (JD13, JD13A-F60) and Ann Creek (JD18-F60). The type section of the coralline limestone is located at Tina Creek North (JD8-F60). The calcilutite matrix is subject to progressive dolomitization as indicated by varying amounts of isolated dolomite rhombs.
The distribution of the coralline limestone facies (4) in the middle Southesk is restricted to the area between Nell Creek (JD4, JD5-F60) and Deadfall Creek (JD3-F60). The "Cripple Tongue" in this area is entirely composed of limestones with dolomite intercalations. Shales, which characterize the unit in the northern portion of the map area, are absent. The unit has therefore undergone a facies change from nodular argillaceous limestone and calcareous shale facies (3) in the northwestern portion of the map area to coralline limestone facies in the southeastern part between Nell Creek (JD4, JD5-F60) and Deadfall Creek (JD3-F60). This lithologic change is accompanied by a faunal gradation. The crinoid-brachiopod fauna of the northern portion is gradually replaced by a coral-brachiopod fauna towards the southeast.
Excellent faunal collections from coralline limestone sequences at Penny Creek (JD9-F60) yielded:

Alveolites sp.
Coenites sp.
Syringopora sp.
Hexagonaria sp.
Tabulophyllum sp.
Thamnopora sp.

(5A) *Variety A: dark brown biostromal dolomite facies.*
This facies occupies an intermediate position between the coralline limestone and the light colored dolomite facies, which is so characteristic of the Southesk Formation between Cripple Creek (JD6-F60) and South Ram (JD14-F60). The dark brown biostromal dolomite facies occurs both in the lower and upper portions of the Southesk Formation (i.e. respectively in the Leduc and Nisku equivalents).
Its distribution in the lower Southesk covers the entire area under discussion with the exception of the northernmost section (North Ram River, JD13, JD13A-F60). Its distribution in the upper portion of the Southesk (Nisku Formation) covers the entire area without exception (appendix 3).
The type section of the dark brown biostromal dolomite is located at Tina Creek South (JD7-F60) and is divisible into three units.
The basal unit, composed of very finely crystalline brown dolomites, overlies the Cairn Formation. Its faunal content consists of a coral-brachiopod assemblage, in sharp contrast with the *Amphipora*-stromatoporoid biostromes of the Cairn. The middle unit is very fossiliferous and biostromal. Transitional gradations between dark brown and light grey biostromal dolomites occur near the top. The upper unit is characterized by prolific coral biostromes. Globular favositids and platy *Alveolites* occur abundantly. The brachiopod-crinoid admixture is almost negligible. A careful examination, to detect a possible occurrence of the *Amphipora*-stromatoporoid assemblage, was unsuccessful.
Dolomitization has practically destroyed all internal

structure. Partial leaching of the organisms gives rise to vuggy and cavernous porosity (fig. 16). The leaching, often restricted to the centres of the organisms, is controlled by a similar process as described for the Cairn biostromes. The rims of the organisms are often preserved as dolomitic peripheries surrounding the vugs. A microscopic study of the rim material indicates the absence of concentric layers and definite coralline texture is occasionally observed. Globular favositids, or vugs after these organisms, are often described as stromatoporoids in routine reconnaissance studies. Transverse sections through platy *Alveolites* occur as thin sticks or threads in outcrop and are often reported as *Amphipora*. The only undisputed *Amphipora* occurrence in the Southesk is at the base of the formation in Boundary Creek (JD1-F60), interval 1143'-1153' (appendix 3). The interval is part of a dark brown dolomite sequence containing Aulopora and disphyllid corals in both overturned and growth position. The brachiopod admixture contains geopetal sediment infill.

Previous workers include the dark colored coralline dolomites in the Cairn Formation. This usage leads to the conclusion that the Cairn thickens towards the edges of the carbonate complexes.

The dark biostromes of the Southesk Formation (fig. 15) are of limited lateral and vertical extent and are surrounded by less fossiliferous dolomites. The matrix does not vary and is essentially composed of dolomitized carbonate mud with varying amounts of bioclastic debris.

The dark colored fossiliferous dolomites, surrounding the biostromes, have been closely examined in order to detect a possible increase in bioclastic debris, derived from the adjacent biostromes by mechanical abrasion (facies 5B). However, no pronounced increase could be established although the majority of organisms of some biostromes occur in overturned position and could have been rolled around by the waves. The biostromes form relatively thin coatings or low knolls on a rather smooth sea bottom.

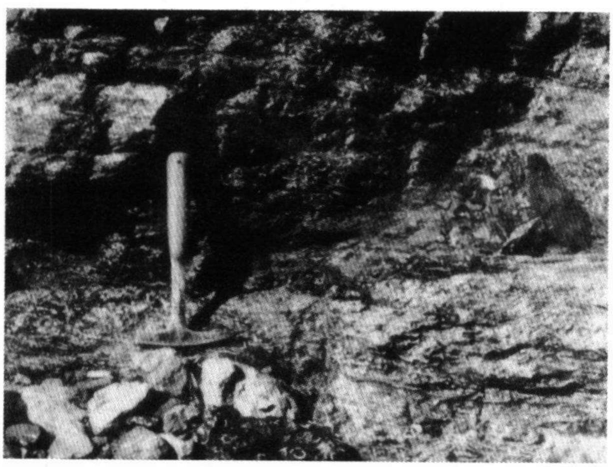


Fig. 15. Prolific *Alveolites-Thamnopora* beds. Tina/Cripple Creek, JD17-F60.

The distribution of the dark brown biostromal dolomite facies in the upper portion of the Southesk Formation (i.e. Nisku equivalent) represents Belyea and McLaren's Grotto Member. It is present in the entire area from North Ram River (JD13, JD13A-F60) to South Ram River (JD14-F60), (appendix 3).

Belyea (1958) describes the Grotto Member at Cripple Creek (JD6-F60) and deviates from the sequence at the type section by including a basal sequence drastically different in faunal and lithological aspects. The present author proposes a return to the type section and restricts the Grotto to the upper portion of Belyea's sequence. The Grotto, so defined, is composed of dark grey and brown dolomites with a pronounced coral assemblage. The basal interval (Belyea, 1958) represents the nodular argillaceous limestone-calcareous shale facies (3) in the middle portion of the Southesk Formation, i.e. the Cripple Tongue (fig. 20).

The lithology and fauna of the Grotto Member are identical to those of the dark brown biostromal dolomite in the lower Southesk. A distinction between the two dolomites is only possible when the intervening nodular limestones and shales of the Cripple Tongue (DFR 12) are present. Separation is impossible in the area southeast of Nell Creek (JD4-F60), where the Cripple Tongue grades into dark brown biostromal dolomite facies (e.g. South Ram River, JD14-F60, appendix 3).

Consequently, the term Grotto can only be used in the northwestern and central portions of the map area. The term is useful to emphasize the correlation between the Nisku of the subsurface and the upper Southesk of the outcrop and the presence of a well defined biostratigraphic time line in the middle portion of the Southesk. Therefore, the present author proposes to retain the term Grotto but the similarity with the biostromal dolomite facies in the lower Southesk should be kept in mind.

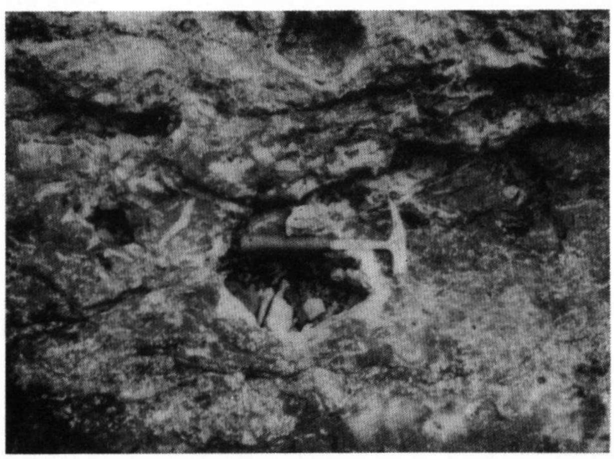


Fig. 16. Biostrome at Tina/Cripple (JD17-F60). Large coral colonies, *Alveolites* sp., solitary rugose corals, *Thamnopora*, disphyllid corals. Hammer rests on cavern, which originated by leaching of coral colony as indicated by coralline texture of the light grey rim.

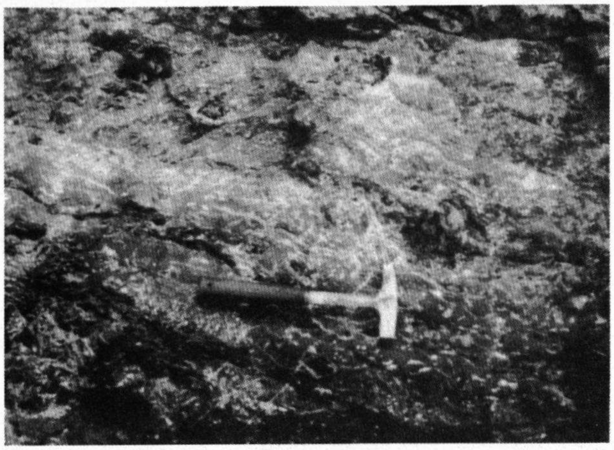


Fig. 17. Coral biostromes: *Thamnopora* sp., *Alveolites* sp., disphyllid corals.

(5B) *Variety B: light grey biostromal dolomite facies with a prominent coral-stromatoporoid (?) assemblage.*
The dark brown biostromal dolomite facies grades into medium grey to very light grey dolomites at Tina Creek South (JD7-F60) and Tina/Cripple (JD17-F60) (fig. 18). Crystallinity of these light colored dolomites ranges from extremely fine to very coarse. Light colored dolomites occur both in the lower and upper portions of the Southesk (appendix 3, i.e. the Peechee and the Arcs Member) (Belyea and McLaren, 1957). The distribution of the light colored dolomites in the lower Southesk is restricted to the southern portion of the area between Tina Creek South (JD7-F60) and South Ram River (JD14-F60). Their occurrence in the upper portion of the Southesk covers the entire map area, immediately underlying the Alexo Formation. Light grey dolomites characterize the upper Fairholme carbonate complexes of the Rocky Mountains and the Leduc Formation of the subsurface. Regional studies indicate that the Southesk Formation in the centres of the carbonate complexes consists almost entirely of light grey dolomites. Their white to pale yellow color and craggy weathering features are characteristic.

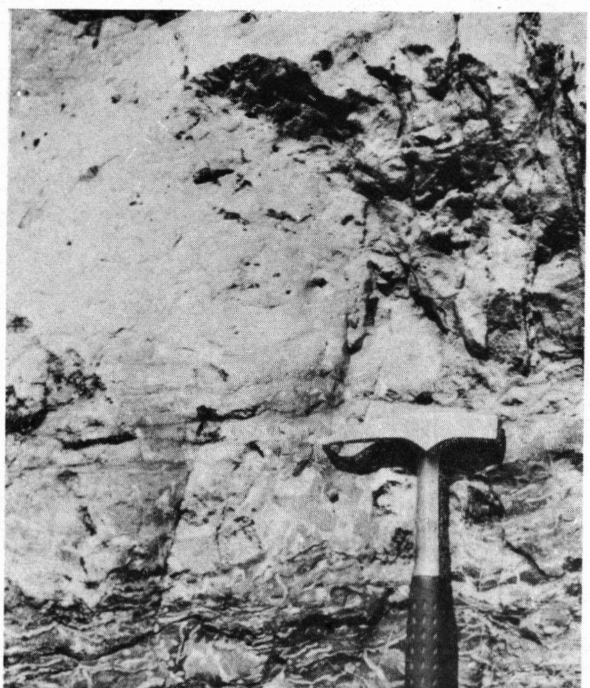


Fig. 18. Gradational facies change between dark brown and light grey biostromal dolomites at Tina/Cripple, JD17-F60.

The light colored dolomites, in contrast to the dark brown biostromal dolomites, are non-calcareous within the studied area. The complete dolomitization is associated with, and possible caused by, a total absence of argillaceous material. The textures of the original sediments have practically been obliterated and their definition is often difficult or impossible.
The light colored dolomite stringers in the lower Southesk at Tina Creek South (JD7-F60) and Tina/Cripple (JD 17-F60) interfinger with dark brown biostromal dolomites. The *Thamnopora-Alveolites* fauna of the dark dolomites is also present in the light grey dolomites and a similar dolomite groundmass is indicated. These observations suggest the absence of essential primary variations between the dark brown and light grey dolomites in this area.
The interfingering of the two dolomite types occurs at several stratigraphic levels, indicating a gradual facies change rather than a genetic reef-off reef relationship. Belyea (1958) uses the latter to explain the juxtaposition of light and dark dolomites in this area. The biostromal character of the dark dolomites and their gradational transition into similar light colored dolomites appear to contradict this postulation.
The dolomites are light to medium grey and weather with a white to pale yellow color. The crystallinity

Fig. 19. Tongue of light grey biostromal dolomite showing cavernous porosity and exfoliation. Note dark brown biostromal dolomites in uppermost portion of photograph. Cripple Creek North (JD6A-F60).

varies from very fine to very coarse, silt and argillaceous admixture is negligible or absent. The facies is restricted to the area between Tina Creek South (JD 7-F60, fig. 19) and Gertie Creek (JD 10-F60). The light grey Southesk dolomites in this area are characterized by their highly vuggy aspects and the lack of distinct bedding planes.

The following criteria are used to postulate a biostromal origin.

(a) The similarity in faunal assemblage, bioclastic content and rock matrix in the dark biostromal dolomite and light colored dolomites and their gradational contact at Tina Creek South (JD7-F60). This biostromal character of the light grey dolomite is postulated to extend further southeastward.

(b) The highly vuggy nature of the light grey dolomites in the area between Tina Creek South and Gertie Creek is readily explained by the same processes that led to identical vuggy porosity development in the dark brown biostromal dolomites at Tina-Cripple (JD17-F60), where the relation between vuggy porosity and biostromal coralline content was substantiated by direct observations.

(c) The Southesk Formation at Cripple Creek (JD6-F60) is characterized by repeated sequences of dark brown biostromal and light grey dolomites identical to the situation at Tina Creek South.

However, a comparison between these two sections indicates a progressive increase of the light grey dolomite component towards the southeast. The massive, extremely vuggy and highly porous nature of these dolomite sequences between Tina-Cripple (JD17-F60) and Gertie Creek (JD6-F60) has been reported by various authors. Belyea (1958) uses these observations to postulate a biohermal buildup at Cripple Creek. A downward reef slope, a belt of reef talus and fore-reef deposits were reported to occur over a short lateral distance. The present author prefers to characterize the situation as a sequence of biostromes.

The basal portion of the Southesk Formation at Cripple Creek (JD6-F60) is characterized by a repetition of dark and light grey dolomites and indicates a gradual transition rather than a biohermal rim (appendix 3). This does not preclude the presence of local, small carbonate buildups. A light grey dolomite bank, surrounded by dark brown organic dolomites, occurs in Penny Creek (JD9-F60, appendix I). Another bank, also enclosed in dark brown biostromal coralline dolomites, occurs in Cripple Creek North (JD6A-F60; Peechee on fig. 20).

The distinction between bedded and unbedded or massive sequences, in the basal portion of the Southesk Formation, is often used as a criterion to distinguish between off-reef and biohermal reef deposits. The field observations indicate that the light grey dolomites are almost invariably well bedded in thick or massive units. Stratification is often obscured, however, by peculiar weathering effects. The dolomites weather by exfoliation of sheets paralleling the surface (fig. 21). This process results in the formation of rounded masses, lending a false impression of lack of bedded structure.

The addition of a stromatoporoid component to the faunal assemblage is not based on actual field observa-

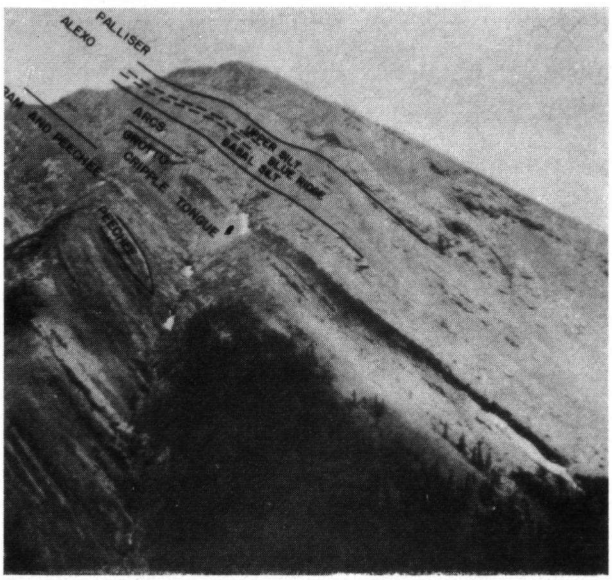


Fig. 20. Part of the section at Cripple Creek North. Note the thin Blue Ridge limestone member of the Alexo Formation and the two thin limestone bands in the Cripple Tongue. The Basal Southesk consists of interbedded light and dark colored biostromal dolomite sequences.

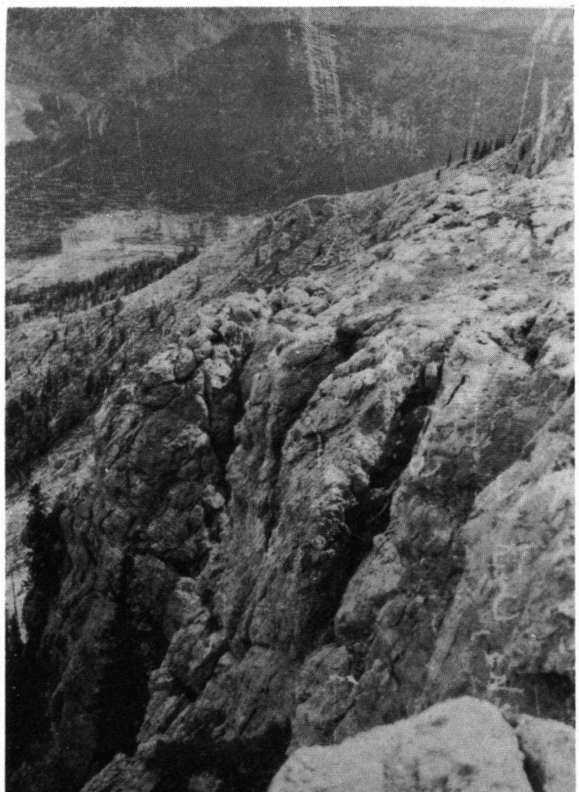


Fig. 21. Impressive sequence of light grey dolomite in basal Southesk at South Ram Ridge (JD12-F60). Note weathering by exfoliation.

tions. The similarity of faunal assemblages in the interfingering dark brown and light grey biostromal dolomites, at Tina Creek South (JD7-F60) and Tina-Cripple (JD17-F60), strongly suggests that the vugs in the light grey dolomites of the time-equivalent basal Southesk at Cripple Creek (JD5-F60) have originated by leaching of globular favositids and coral colonies. Moreover, the author was unable to locate unquestionable stromatoporoids at Cripple Creek. However, stromatoporoids constitute an integral part of the faunal assemblage in the upper portion of the time-equivalent Leduc Formation of the non-dolomitized Redwater reef complex (Klovan, 1964; chapter VIII of this thesis). It is therefore probable that at least part of the vugs at Cripple Creek represent leached stromatoporoids and consequently this class of Hydrozoa is tentatively included in the faunal assemblage of this facies. The light grey biostromal reef facies is absent in the upper portion of the Southesk (Arcs Member) in the map area (appendix 3).

6. *Light grey, slightly fossiliferous dolomite facies with a mixed coral-gastropod-ostracod fauna.*

Field observations (appendix 3) indicate a slight, but consistent, thinning of the Southesk Formation towards the southeast (i.e. further onto the shelf). This thinning is accompanied by a progressive decrease in the dark brown biostromal dolomite content of both the lower and upper Southesk. Moreover, the characteristic vuggy and biostromal aspect of the light grey dolomites changes to a slightly fossiliferous (and consequently less vuggy) variety in the area between Douglas Creek (JD11-F60) and Deadfall Creek (JD3-F60). In contrast to the Tina-Cripple Creek area, stratification is well developed and exfoliation less common. A pronounced differentiation in both composition and amount of the faunal content is indicated. The highly fossiliferous to biostromal dolomites, characteristic of the Tina-Cripple Creek area, are practically absent between Gertie and Deadfall Creek. The predominant coral-stromatoporoid (?) assemblage in the former area is gradually being replaced by a mixed coral-gastropod-ostracod fauna in the latter. These observations suggest a marked change in the depositional milieu.

Slabbed and polished rock surfaces show the presence of fine to coarsely crystalline sparry dolomite blebs. These intervals are designated as "birdseye" dolomite. Folk (1959) has suggested several possible origins for such features:

(1) precipitation of spar in animal burrows,

(2) recrystallization of carbonate mud in irregular patches,

(3) slumping or mud-cracking in relatively soft sediments,

(4) precipitation of spar in narrow tubes resulting from escaping gas bubbles,

(5) reworking and redeposition of soft sediments resulting in a carbonate type with vague intraclasts, and irregular patches of spar.

The present author observed two major types of birdseyes. The first variety occurs irregularly throughout the host rock, ramifying in all directions. A partial interconnection via thin films of sparry dolomite is often present. They are considered to represent the infills of bottom scavengers, probably worms.

The second, more common, variety consists of irregularly lenticular blebs. They vary in length from a fraction to several millimeters. A definite alignment is indicated. The long axis coincides with the bedding. The blebs occur between the pellets, never across them. The platy alignment suggests that these birdseyes are not due to boring organisms. Some of the blebs taper out laterally to a thin thread, which often expands again to another birdseye. This observation may suggest a partial collapse of the cavity, prior to infill, under the weight of the overlying deposits.

There are at least five possible origins. They might be considered to originate by algae, gas bubbles, replacement, diagenetic recrystallization or shrinkage.

Ham (1954) described similar birdseye limestones in the Ordovician of the Arbuckle Mountains and concludes that the blebs are caused by bluegreen algae. The present author favours a similar origin for the Frasnian birdseye dolomite within the map area. However, all traces of algal filaments in the birdseyes have disappeared. It appears likely that the platy birdseyes represent infill along local planes of weakness. Splitting of the sediment can be explained by gas generation caused by algal decay or by desiccation.

Folk (1959) makes the significant interpretation that birdseye structures are associated with shallow water, intermittently exposed deposits.

Wolf (1965) describes and classifies numerous types of "open-space structures such as birdseyes and stromatactis" in an excellent paper on the Devonian algal reefs of New South Wales (Australia). The birdseyes in the Lower Devonian Nubrigyn reef complex are mainly confined to algal bioherms and biostromes. Wolf concludes that the presence of birdseyes may be used as a shallow-water indicator, essentially restricted to the littoral (i.e. intertidal) zone.

Therefore, concensus of opinion indicates that the presence of birdseyes denotes a very shallow water environment with intermittent exposure to the atmosphere.

The term calcispheres has been applied to single-chambered, calcareous spheres ranging from 50 to 300 microns. Their systematic position has been a controversial matter for the last 150 years. Foraminifera, rhabdoliths, coccoliths, lepidodendroid plants, and algae have been proposed as a possible source.

Rupp (Shell Canada Limited, personal communication) noted a striking resemblance between the fossil calcispheres and the reproductive cysts of four present-day species of green dasycladacean algae, which flourish in shallow water in Florida Bay. A similar origin and environmental milieu is proposed for the Frasnian calcispheres in the thesis area.

The lower Southesk contains local breccias of limited lateral and vertical extent (fig. 22). Brecciated inter-

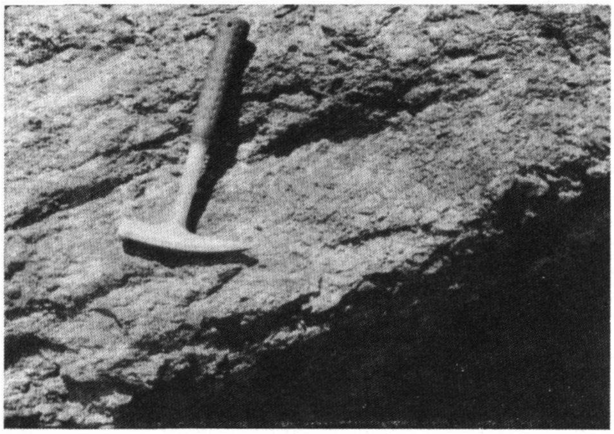


Fig. 22. Sedimentary breccia (solution breccia?) in light grey dolomite sequence of the basal Southesk at Douglas Creek (JD11-F60; 1645 feet).

vals were traced from Douglas Creek (JD11-F60) to Nell Creek (JD4, 5-F60). Recognition is difficult due to "healing processes" which tend to blend the fragments with the surrounding matrix.

The distribution of this facies in the upper portion of the Southesk (i.e. Arcs Member) has not been established within the investigated area.

7. *Light grey, laminated dolomite facies with an algal-gastropod-ostracod assemblage.*

The light grey dolomite sequence in the basal Southesk Formation between Deadfall Creek (JD3-F60) and South Ram River (JD14-F60) displays yet another facies (appendix 3).

Well preserved algal structures are recognized despite complete dolomitization. The observations indicate a gradual change in the faunal assemblage of the light grey dolomite sequences in the southeastern portion of the Bourgeau-Hummingbird carbonate complex.

The following lithologies are indicated.

Very finely laminated algal deposits. — These structures are well exposed in Deadfall Creek (JD3-F60). The deposits are generally referred to as "algal mats"

Fig. 23. Laminated beds of probable algal origin associated with algal breccias and oncoliths. South Ram River (JD14-F60).

(fig. 23). The actual algal films are not preserved. The varved dolomites represent the fine layers of carbonate mud which was trapped by the algae.

These structures have been described as algal stromatolites (Logan, Rezak, Ginsburg; 1962) and are classified as algal boundstone in Dunham's carbonate classification (chapter IV). The laminated deposits occur at several stratigraphic levels in Deadfall Creek (JD3-F60) and Boundary Creek (JD2-F60) and thicknesses vary from 8 to 50 feet. The algal beds are separated by light grey dolomites with a tightly interlocking crystalline texture. Klovan (1964) reports similar laminated limestones in the "back reef facies" of the subsurface Leduc Formation in the Redwater reef complex (see chapter IX of this thesis). Algal filaments have been observed in these undolomitized sequences to which the name "laminates" is assigned.

Hemispheroidal algal structures. — The stromatolites contain occasional hemispheroidal bodies (6 inch diameter). The curvature of the lamellae of these bodies increases upwards. The structures are well preserved in Boundary Creek (JD1, JD2-F60; fig. 24). The algal mats, deposited in very shallow water, have been subject to periods of subaerial desiccation. This process introduced cleavages and cracks. The algal hemispheroids and the intervening cleavages were subsequently buried and filled in. Logan, Rezak and Ginsburg (1962) proposed a new classification of algal structures, based upon geometric form. They distinguish two basic geometric units, i.e. hemispheroids and spheroids. The three main categories are:

(1) laterally linked hemispheroids;
(2) discrete vertically stacked hemispheroids;
(3) discrete spheroids.

The hemispheroidal structures at Boundary Creek (JD1, 2-F60) are assigned to the first category.

Spheroidal algal balls around a foreign nucleus. — Well preserved algal balls occur in the basal portion of the Southesk Formation along the Onion Lake Road (South Ram River, JD14-F60; fig. 25). The nucleus is invariably composed of fossil detritus (gastropods and brachiopods). These features are known as oncoliths and are assigned to the "discrete spheroid" category of

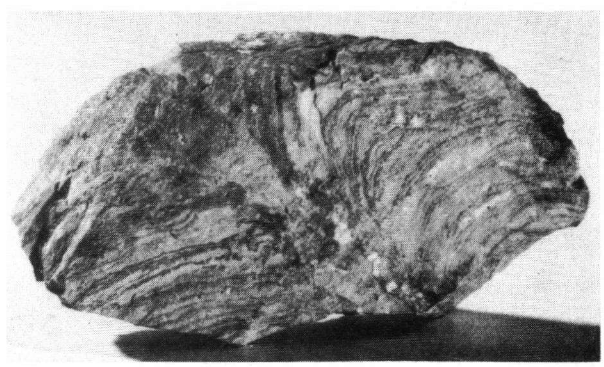


Fig. 24. Hemispheroidal algal balls showing cleft filled with sediments. Boundary Creek (JD2-F60).

the Logan, Rezak, Ginsburg classification. The algal balls originated by growth of laminations around a shell fragment, which is being rolled about by submarine agitation. Ginsburg postulates their generation in permanently submerged shoal waters or areas low in the intertidal zones. Kaufmann (1964) describes various forms from the Upper Devonian Souris River Formation (i.e. Beaverhill Lake equivalent) of Saskatchewan.

Algal breccias. — Brecciated intervals occur in the basal Southesk at Boundary Creek (JD2-F60) and South Ram Ridge (JD12-F60). The fragments consist of laminated, very finely to finely crystalline dolomite and vary from 1/2 to 5 inches. The edges of the fragments are angular to subangular, suggesting a limited amount of transport (fig. 26).

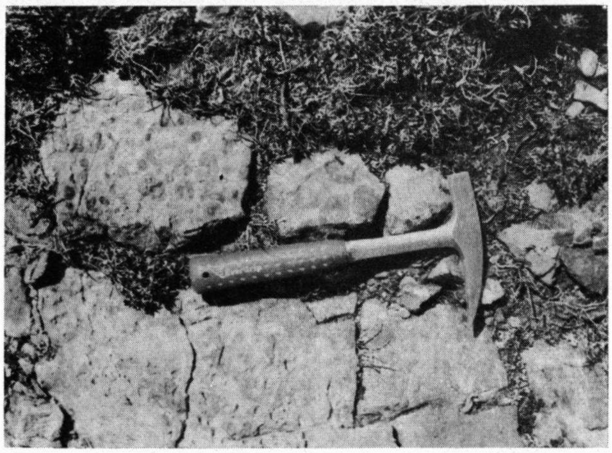


Fig. 25. Algal pisolites, South Ram River, JD12-F60.

Fig. 26. Algal breccia, South Ram Ridge, JD12-F60.

Stromatactis. — The algal structures along Onion Lake Road are accompanied by *Stromatactis* (South Ram River, JD14-F60; fig. 27). These cavities, partially filled with internal sediment, seem to constitute a common feature in carbonate muds and have been described in bioherms of Mississippian age in Montana, Oklahoma, New Mexico, and Britain. They also occur in Devonian bioherms in Belgium and Australia. The features consist of an upper portion filled with white, coarse dolomite crystals and a basal portion composed of geopetal sediment infill. Dimensions vary from 1/2 to 2 inches (vertical) and from 2 to 4 inches (lateral). The basal border is generally sharp while the upper boundary is quite irregular.

Fig. 27. Laminar *Alveolites* and *Stromatactis* in basal Southesk Formation. Stromatactis represents primary voids filled with geopetal sediments and coarse, white dolomite crystals. South Ram River, JD14-F60.

There is no general agreement regarding the origin of the cavities. Bathurst (1959) considers the vugs as solution voids, indicative of subaerial exposure. French and Belgian workers consider the original form of the cavities as organisms. Others visualize a multiple origin. All agree that the last step in the development of such features takes place by filling of the voids by internal sediment and by precipitation of coarsely crystalline calcite in the remaining void space. Subsequent leaching of the upper portions gives rise to vugular porosity.

The light grey dolomite sequences of the upper portion of the Southesk Formation (i.e. Arcs Member) are also assigned to the light grey laminated dolomite facies. The member consists of barren, well-bedded and locally laminated, very fine to coarsely crystalline dolomites. The conspicuous role of algal components, which characterize the facies in the lower Southesk, is greatly reduced in the upper portion.

The facies gradation, from dark biostromal to light grey slightly fossiliferous and algal dolomites in the lower Southesk, is repeated in the upper portion of the formation (appendix 3). Moreover, this transition occurs approximately in the same region, i.e. the Cripple Creek-Tina Creek portion of the area.

The upper Southesk occurs over the entire thesis area with a constant thickness of approximately 200 feet. This sequence, both over- and underlain by planes of time equivalence, occurs predominantly in a dark brown biostromal dolomite facies, i.e. Grotto Member, in the northwestern portion, between North Ram River (JD13, 13A-F60) and Tina Creek North (JD8-F60; fig. 28). Light grey dolomites, in the upper Arcs Member, constitute a relatively minor component.

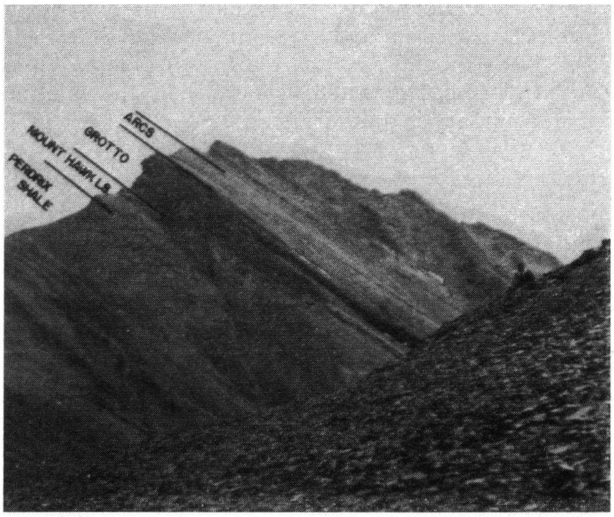


Fig. 28. Looking southeastwards at first ridge northwest of North Ram River. Note thin Arcs (light grey laminated dolomite) and thick Grotto development (dark biostromal) in the Upper Southesk (Nisku equivalent). The basal portion of the Southesk Formation occurs in calcareous shale (Perdrix) and nodular argillaceous limestone—calcareous shale facies (Mount Hawk).

The reverse is true in the southeastern portion of the area, between Tina Creek North and South Ram River (JD14-F60), where the light grey dolomites of the Arcs Member predominate and only a thin Grotto is present (fig. 29).

Well pronounced interfingering of dark brown biostromal and light grey, slightly fossiliferous dolomite sequences occurs in the area between Tina Creek South (JD7-F60) and Cripple Creek North (JD6A-F60; appendix 3; fig. 30).

The coincidence of similar facies changes, in the lower and upper portions of the Southesk Formation, suggests a direct relationship between the facies distribution patterns. Areas in which the lower Southesk occurs in dark biostromal dolomite facies, or consists of repeated sequences of dark and light grey dolomites, are characterized by an interfingering of Arcs and Grotto dolomite types. Areas in which the lower Southesk occurs in light grey dolomite facies are characterized by a thick Arcs Member in the upper Southesk.

This postulated facies relationship, between the upper and lower Southesk, is substantiated by observations

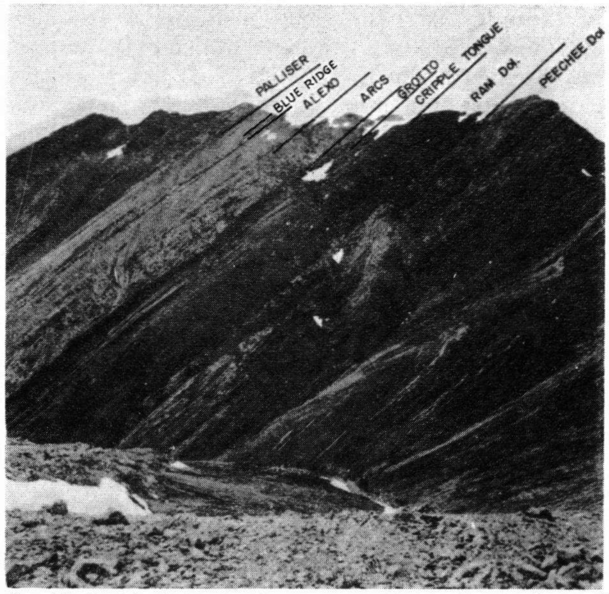


Fig. 29. Typical Upper Devonian sequence in the central portion of the area. Note the thick Arcs dolomite member and thin Grotto dark biostromal dolomite member in the upper portion of the Southesk Formation (Nisku equivalent). The resistant Blue Ridge Member (restricted platform limestone) of the Alexo Formation and the two thin open marine limestone bands in the Cripple Tongue are well exposed.

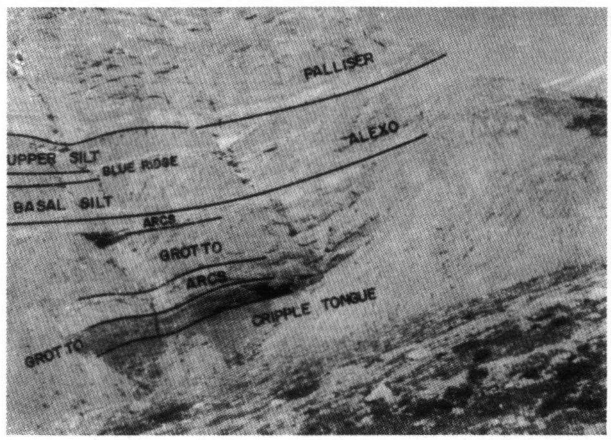


Fig. 30. Upper Southesk (Nisku equivalent) in Tina Creek South (JD7-F60). Upper portion of photograph shows massive Palliser cliff, underlain by Alexo Formation with typical threefold division. The light grey band (in central portion of photograph) consists of Arcs dolomite, underlain by a largely covered sequence of Grotto dolomite. The covered interval is underlain by a sequence of which the upper half consists of Arcs and the basal portion of Grotto dolomite.

of other workers in various areas, e.g. Price (1964) in the Flathead-Crowsnest Pass (chapter VIII of this thesis).

3. THE POST-FAIRHOLME SEQUENCE

The Frasnian Fairholme Group is overlain by the Famennian Alexo and the Palliser Formation, in stratigraphic ascending order.

The Alexo Formation, 170 feet thick at Cripple Creek, is unfossiliferous and displays a characteristic threefold division (fig. 29). The upper and lower members, respectively 68 and 82 feet thick, consist of buff, yellow and pale greenish-grey dolomite silt, sand, and mudstones. They weather recessively and with a characteristic yellow color. The middle member is more resistant and consists of pelletal limestones. Choquette (1956) has introduced the name Blue Ridge for this carbonate sequence.

Correlations between the Alexo Formation of the outcrop sections and the subsurface Winterburn Group are indicated on appendix 2.

The thickness of the Alexo does not vary within the limits of the area. The typical weathering aspects are used extensively for mapping purposes.

The Palliser Formation, of late Famennian age, overlies the Alexo (figs. 29 and 30). The Palliser has not been studied due to tectonic complications. A thickness of 880 feet has been established in a section 1½ miles northwest of North Ram River (JD13, 13A-F60). The formation is readily divisible into two easily recognized members, i.e. the recessive Costigan and resistant Morro Member, in stratigraphically descending order. The Costigan totals 210 feet at the aforementioned locality, and consists of thin-bedded, argillaceous and silty, fossiliferous limestone. The Morro is 670 feet thick and is essentially composed of tight, slightly dolomitic, pelletal limestones. Correlations between the Palliser Formation of the southern Rocky Mountains and the subsurface Wabamun Group are indicated on appendix 2.

Mississippian, Permo-Pennsylvanian and Triassic sediments occur along the northern flank of Cripple Creek. This sequence falls outside the scope of this thesis and the lithologic descriptions are omitted.

CHAPTER VI

STRATIGRAPHY: MICROSCOPIC DESCRIPTIONS

The following photographs, and corresponding descriptions, illustrate the microscopic characteristics of the various facies. Primary sedimentary textures, important criteria for facies delineation, can be recognized in most rock sequences, despite the destroying effects brought about by complete dolomitization.

Facies 1: *dark brown to black, bituminous shale, barren or with a sparse pelagic fauna.*

Facies 2: *greenish grey to dark grey, calcareous shale, barren or with a sparse pelagic fauna* (fig. 31).

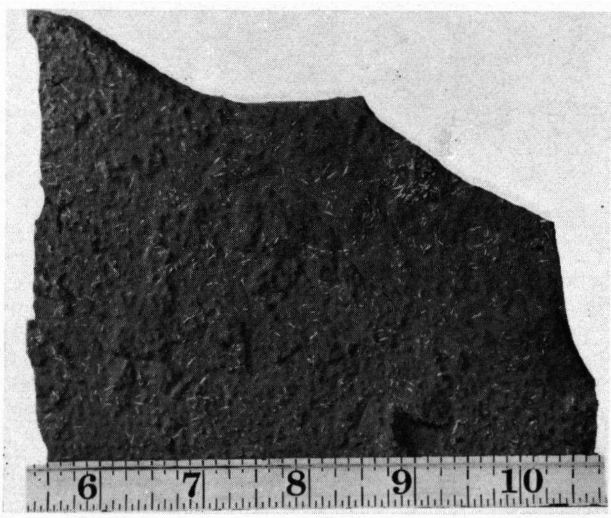


Fig. 31. Shale, medium dark grey, slightly calcareous (less than 5 %), thinly laminated to varved, trace of fibrous organic compound, numerous *Tentaculites*. North Ram River (JD13, 13A-F60). File No. 5080-20[3].

[3] File numbers refer to negatives deposited with Shell Canada Limited, Calgary, Alberta. Scale depicted is graduated in inches.

It is apparent, under a high magnification, that a great proportion of the component particles are quartzose and fall within the size limits of the very fine silt. Variations in fissility are probably due to varying carbonate content. The essential absence of burrows and common occurrence of *Tentaculites* are noteworthy. Ostracods and linguloid, chitinous brachiopods constitute a very minor, but ubiquitous admixture. Pyrite occurs either as disseminated grains "floating" in the shale matrix or as perfect replacement of shell material. Two possible sources are suggested for the extremely finely disseminated calcite content:

(a) the presence of pelagic *Tentaculites* indicates that the bottom sediments were subject to a shower of skeletal debris from the overlying waters,

(b) some carbonate may be due to winnowing of the adjacent limestone belts.

Fig. 32. Limestone, medium and dark grey, argillaceous (30 %), excellent nodular texture, exclusive brachiopod-crinoid assemblage: wackestone. North Ram River (JD13, 13A-F60). File No. 5080-12.

Facies 3: *medium grey to buff, nodular, argillaceous limestone — calcareous shale facies* (fig. 32-34).

The origin of the nodular texture is of interest and several possible modes of origin have been postulated.

(a) Submarine flow and penecontemporaneous brecciation of partially consolidated lime muds, with the flow structure being subsequently accentuated by compaction of the sediment.

(b) Compaction in the partly consolidated sediment, whereby bands of rock with the same composition as the nodules, are squeezed to form the nodules. More argillaceous interbeds are forced around the nodules and display flow structures.

(c) Recrystallization of the partially consolidated rock, whereby recrystallization forms the limestone clots or nodules in an argillaceously-enriched matrix. Subsequent compaction of the rock could form the flow structure in the less consolidated matrix.

(d) Due partially to either (b) or (c) and possibly (a), followed by stylolitic solution, which enriched the argillaceous content of the matrix.

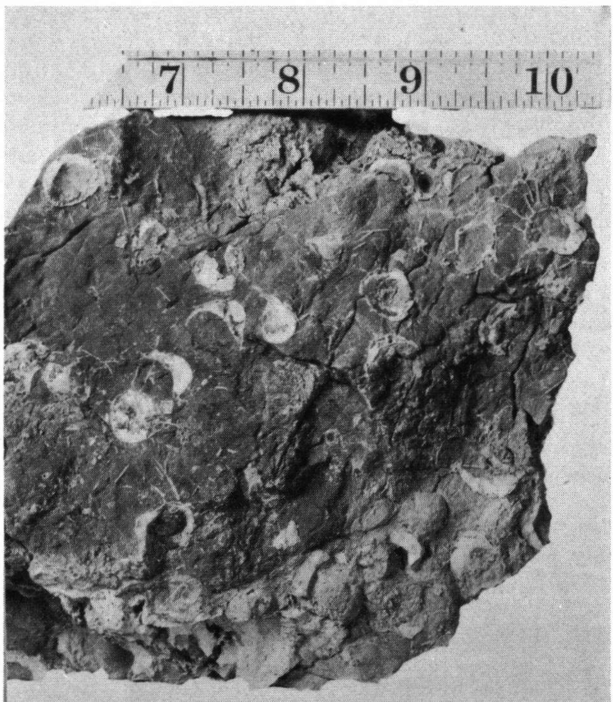


Fig. 33. Limestone, buff, extremely finely crystalline, argillaceous (15 %), 10 % floating bioclastic debris (brachiopod spines), exclusive brachiopod-crinoid assemblage, wackestone. Cripple Creek (JD6-F60). File No. 5080-28.

McCrossan (1958) studied the nodular, sedimentary boudinage in the time-equivalent Ireton Formation of the subsurface. He concluded that these structures were formed by compaction of the limey beds, sandwiched between more argillaceous and plastic beds. As these fine muds, unconfined laterally, were subject to compaction, they spread plastically toward the slightly lower parts of the sea bottom. Lateral flow, as a result of density differences in the sediment, is also postulated. The more plastic clayey beds dragged the surface and created tension in the limey beds. As the unconfined mass spread laterally, the beds began to pull apart and thinned at points of weakness until, eventually, they ruptured to form separate lenses. Increasing depth of burial and hydrostatic pressure would further distort the lenses. The more shaley beds, which were slower to cement, would be squeezed around them.

Experimentally, Ramberg (1955) produced similar boudinage structures in a competent layer, sandwiched between incompetent ones, when acted upon by compressional stresses perpendicular to the layering. Murray (1965) expresses yet another possible mode of origin. He studied identical limestone-shale sequences in the Waterways Formation of the subsurface. Murray invokes disruption of stratification by burrowing organisms. He points out that skeletal remains are most common in the nodular limestone, but essentially absent in the more laminated intervals. He suggests

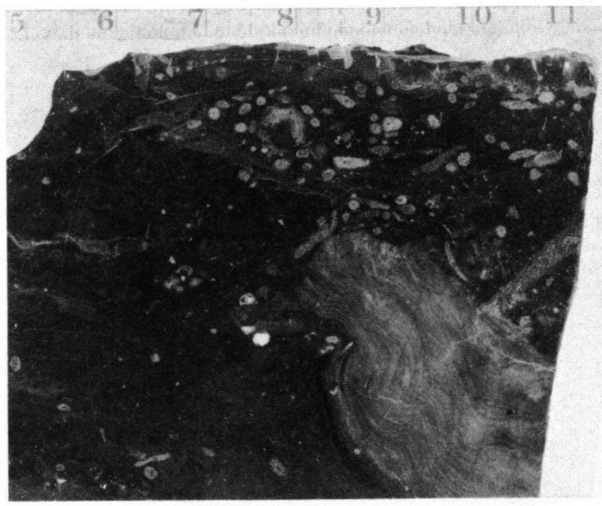


Fig. 34. Limestone, medium and dark grey, argillaceous (15 %) dolomitic (20 %) due to very finely disseminated floating dolomite rhombs, exclusive *Amphipora*-stromatoporoid assemblage: wackestone. The medium grey carbonate occurs as irregular nodules, lumps and masses. These carbonate blebs are surrounded by more argillaceous, dark grey carbonate and dark grey, calcareous shale intercalations. This nodular rock type constitutes the basalmost portion of the Flume and the Cairn biostromes, immediately overlying the light grey, unfossiliferous dolomite sequences. Indirect evidence of burrowing can often be deduced from local concentrations of pelletal carbonate mud, which cross the stratification. Black chert nodules are common in the Flume Formation. A secondary origin is indicated by the excellent preservation of the primary carbonate textures within the chert. Certain intervals show a marked elongation of the nodules usually in a direction parallel to the bedding planes. Secondary pyrite is common and occurs both in the carbonate nodules and the matrix. Douglas Creek (JD11-F60). File No. 5080-13.

that this observation indicates an important factor in the formation of these segregations. The role of compaction is not denied but burrow mottling is also deemed significant.

Grundel and Rosler (1963) studied the Upper Devonian nodular limestones of Thuringia (Germany). Their investigations show that the total carbonate

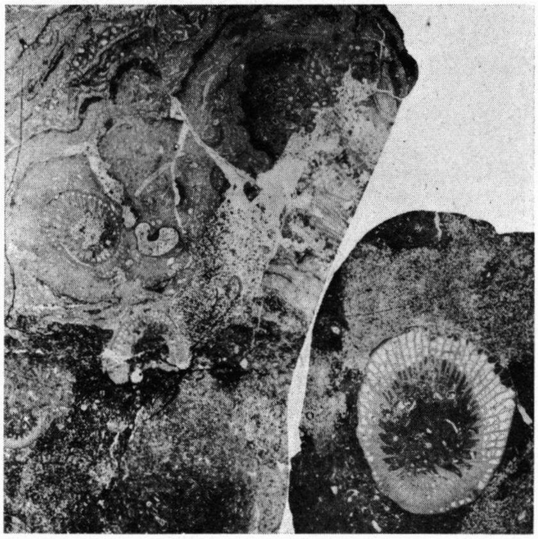


Fig. 35. Limestone, light to medium grey, calcilutite matrix with varying amounts of bioclastic debris (10-50 %), argillaceous content is negligible, platy alveolitids and globular favositids are accompanied by large rugose corals and coral colonies. A gastropod-brachiopod-crinoid admixture is common; wackestone with isolated packstone accumulations. North Tina Creek (JD8-F60). File No. W1028B, W1026A, W1057A.

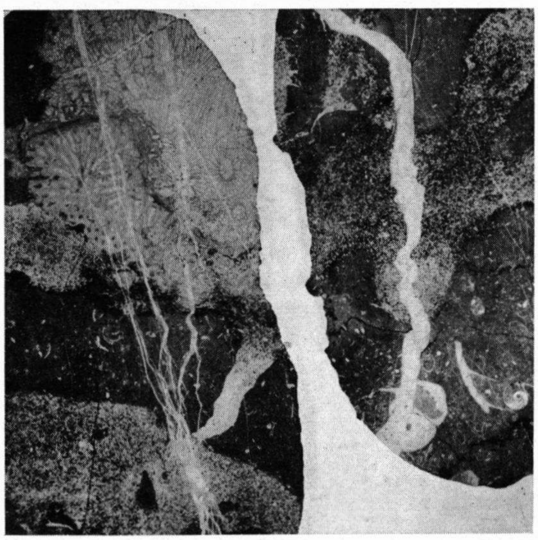


Fig. 36. Limestone, light to medium grey, calcilutite matrix with faintly pelletal or grumulous texture, varying amounts of bioclastic debris (5-25 percent), argillaceous content is negligible, prominent coralline assemblage with slight gastropod-brachiopod-crinoid admixture; wackestone grading to packstone. North Tina Creek (JD8-F60). File No. W 1026B, 1025C.

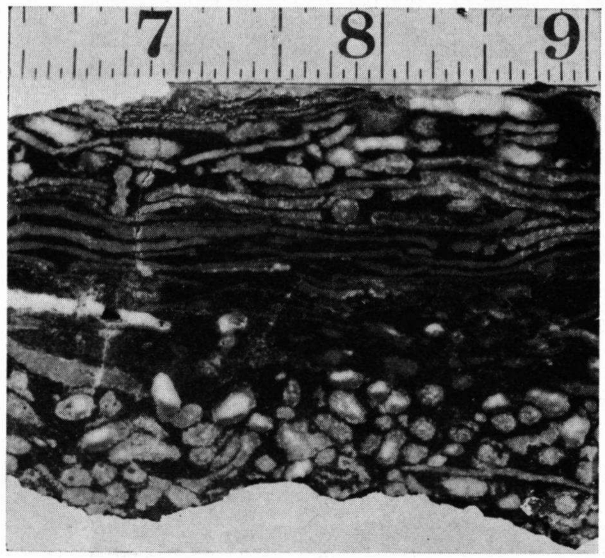


Fig. 37. Dolomite, dark grey, brownish-grey waethering, extremely finely crystalline, with abundant *Thamnopora*-platy alveolitid assemblage. Leaching of part of the faunal content is indicated by the presence of geopetal sediment infill and clear secondary coarse, white dolomite. This rock type constitutes part of the Southesk biostromes in the Tina Creek south (JD7-F60) — Cripple Creek (JD6-F60) region; packstone. Tina Creek South (JD7-F60). File No. 5080-47.

content, size and number of nodules, as well as the vertical separation of nodule layers and the clay content of the nodules, have definite mutual relations. During sedimentation, a thin oxidation zone was followed by a reduction zone, where H_2S and ammonia were formed. Both substances considerably increase the solubility of $CaCO_3$. At the boundary between the oxidation and reduction zone, H_2S was destroyed by oxidation.

Within the oxidation zone, the ammonium compounds are subject to bacterial nitrification. These processes produce a decrease in solubility of $CaCO_3$. Calcite is concentrated in individual centers, which afterwards become nodules. Therefore, the formation of limestone nodules is an early diagenetic process in unsolidified sediments.

Facies 4: *light to medium grey coralline limestone* (figs. 35 and 36).

Facies 5: *dark brown biostromal dolomite facies* (figs. 37-41).

Two varieties can be distinguished, one dominated by a coralline assemblage (variety A), the other by an *Amphipora*-stromatoporoid assemblage (variety B).

Facies 6: *light grey, slightly fossiliferous dolomite with a mixed coral-gastropod-ostracod fauna* (figs. 42 and 43).

Facies 7: *light grey, laminated dolomite facies with an algal-gastropod-ostracod assemblage* (figs. 44- 50).

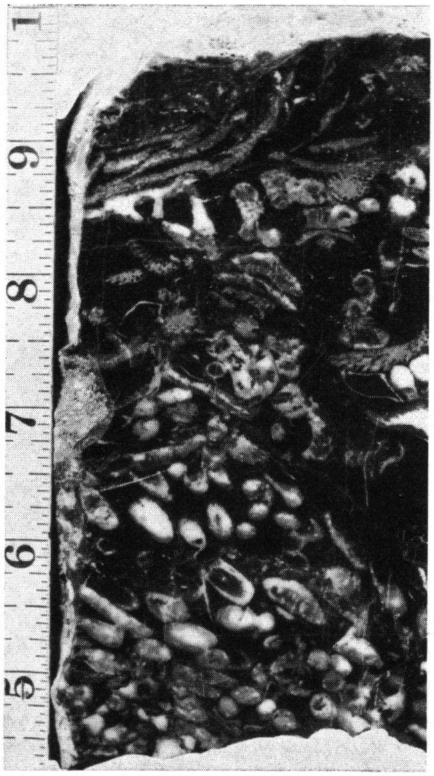


Fig. 38. Dark brown biostromal dolomite facies; variety A: coralline assemblage. Dolomite, dark grey, brownish-grey weathering. Inter-coralline matrix consists of extremely finely crystalline carbonate mud. Leaching processes are indicated by occurrence of geopetal infill and presence of coarse, white dolomite; packstone. Tina/Cripple Creek (JD17-F60). File No. 5080-38.

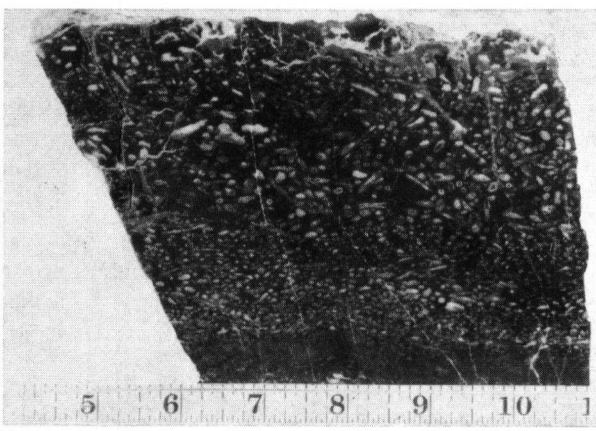


Fig. 39. Dark brown biostromal facies; variety B: *Amphipora-stromatoporoid* assemblage. Dolomite, dark grey, brownish-grey weathering, extremely finely crystalline matrix, abundant *Amphipora*. This rock type is representative for the basal and uppermost portions of the Flume and Cairn biostromes; packstone. Douglas Creek (JD11-F60). File No. 5080-64.

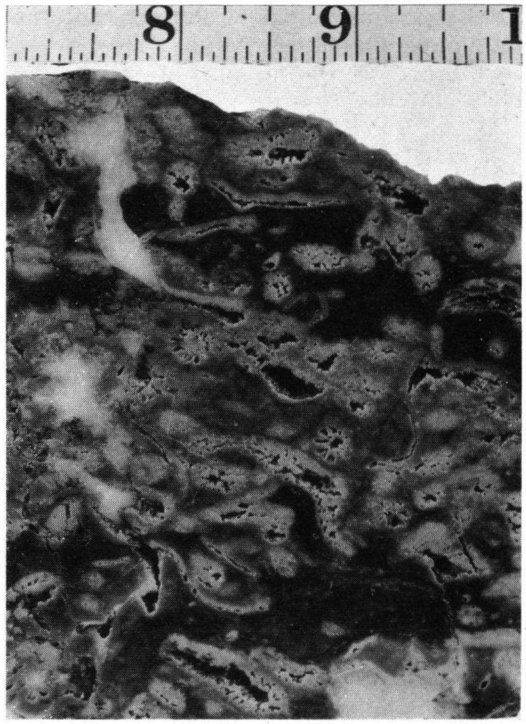


Fig. 40. Dark brown biostromal dolomite facies; variety A: coralline assemblage. Dolomite, dark grey, brownish grey weathering, extremely finely crystalline lutite matrix, with varying amounts of floating bioclastic debris. Abundant corals, which have been subject to partial leaching, give rise to vuggy porosity. Tina Creek South (JD7-F60). File No. 5080-57.

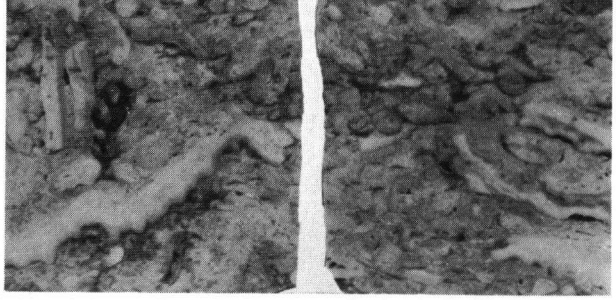


Fig. 41. Light grey biostromal dolomite with a prominent coral-stromatoporoid assemblage (variety A). Shell, Malmo 1A (subsurface control).) File No. 5080-58.

The following fauna has been identified by Dr. G. O. Raasch. Corals: *Acinophyllum* („*Dishphyllum*") *catenatum* (Smith), cf. *Characterophyllum nanum* (Hall and Whiff), *Thamnopora polyforata* (Schlotheim), *Alveolites*. Stromatoporoids: *Trupetostroma* (?) *Stachyoides* (?) sp. Massive Algae (?)

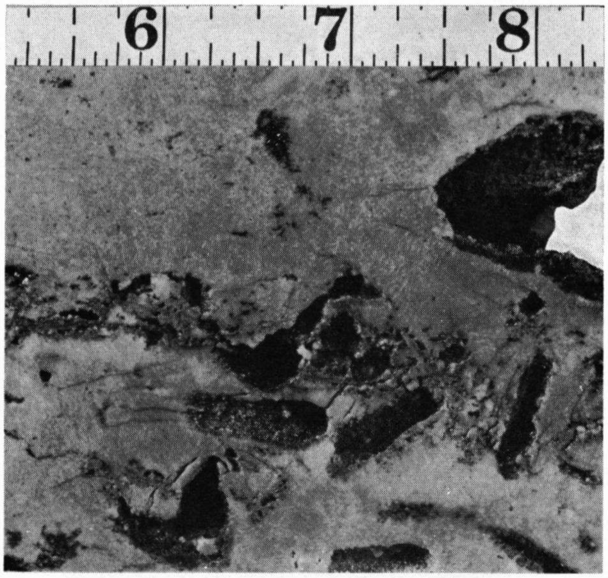


Fig. 42. Dolomite, light grey, finely crystalline, non-calcareous and non-argillaceous. Faunal content (approximately 5 %) has been removed by secondary leaching. The predominance of stick-shaped vugs suggests a coralline origin; wackestone. Douglas Creek (JD11-F60). File No. 5080-79.

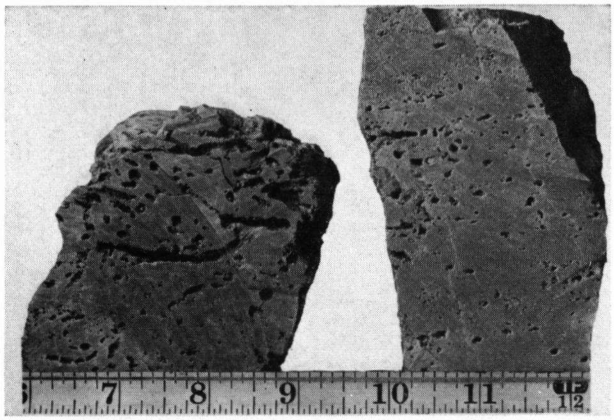


Fig. 43. Dolomite, very light grey, finely crystalline. Faunal content has been removed by secondary leaching. The amount, outline and position of the vugs indicate an approximate 10 percent coralline content, floating in a carbonate mud matrix. Primary depositional textures in the matrix have been obliterated by complete dolomitization; wackestone. Ann. Creek (JD18-F60). File No. 5080-67

Fig. 44. Dolomite, light grey, very finely crystalline, unfossiliferous, excellently laminated. Dolomitic birdseyes show a definite alignment parallel to laminae and are probably due to rotting of algal partings; boundstone (?) (facies 7, variety A). Boundary Creek (JD1, 2-F60). File No. 5080-65.

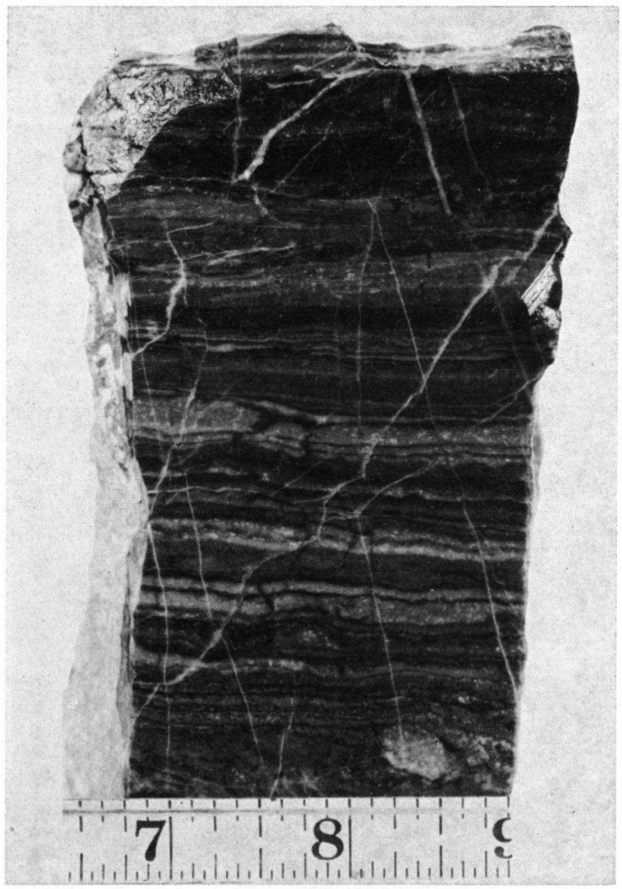


Fig. 45. Dolomite, light to dark grey, extremely to very finely crystalline, excellently laminated, small dolomitic birdseyes, stromatolitic boundstone (facies 7, variety A). Boundary Creek (JD1, 2-F60). File No. 5080-49.

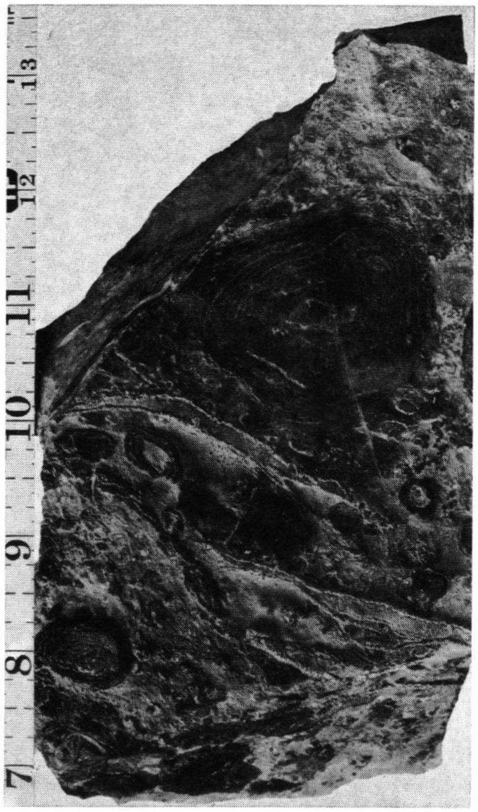


Fig. 46. Spheroidal algal balls around a foreign nucleus (facies 7, variety B). South Ram River (JD14-F60). File No. 5080-8.

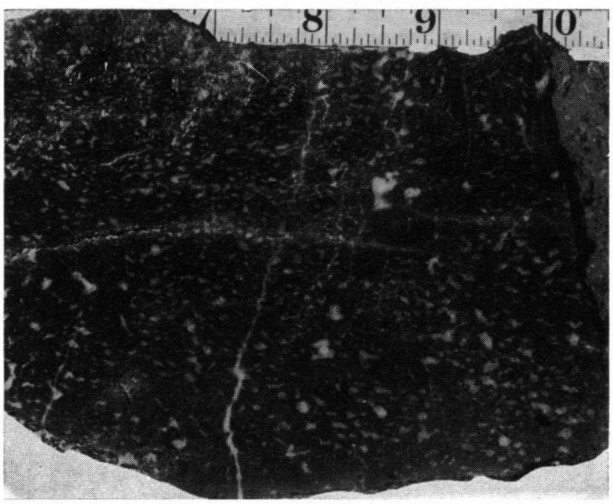


Fig. 47. Dolomite, medium grey, very finely crystalline, unfossiliferous, abundant sparry dolomite blebs (birdseyes) (facies 7, variety C). Boundary Creek (JD1, 2-F60). File No. 5080-5.

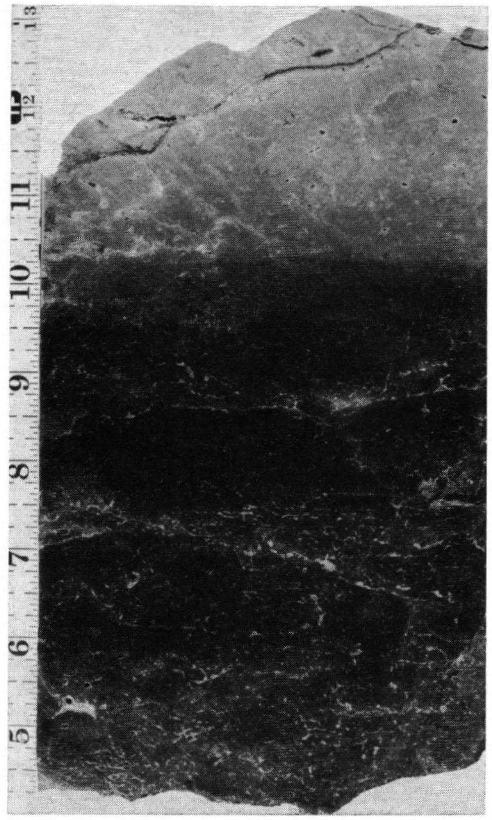


Fig. 48. Gradational contact between dark and light grey dolomite, very finely crystalline, well laminated, unfossiliferous, abundant small sparry dolomite birdseyes with a prevalent alignment parallel to laminae. Birdseyes may be caused by rotting of algal filaments; algal stromatolitic boundstone (facies 7, variety C). Deadfall Creek (JD3-F60). File No. 5080-87.

Five varieties can be distinguished within this facies:

variety A: very finely laminated algal deposits,

variety B: spheroidal algal balls around a foreign nucleus,

variety C: birdseye dolomite,

variety D: non-descript dolomite,

variety E: Stromatactis dolomite,

Chronological review of Stromatactis. — Dupont (1865) describes *Stromatactis* as a "flowering of calcite off a linear base". The upper portion is indicated as "digitated and very irregularly denticulated".

Lecompte (1938, 1958) describes *Stromatactis* in bioherms of Frasnian age in the Belgian Ardennes. *Stromatactis* is considered to be associated with an "organic phenomenon" although no organic structure is present in thin sections.

Lowenstam (1950) reports *Stromatactis* in Niagaran reefs in Illinois and describes layers of "rigidly welded skeletons of resistant frame builders".

Bathurst (1959), in his study of the knoll reefs of Lancashire, Yorkshire and Derbyshire, describes "thin layers and irregular masses of coarse calcite". The features are indicated as "reef tufa" or "fibrous calcite".

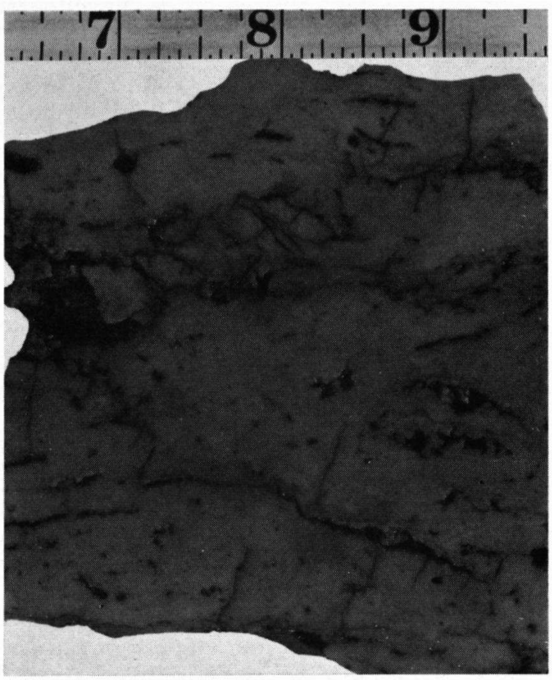


Fig. 49. Dolomite, very light grey, cream to white weathering, unfossiliferous, ghost textures suggest pelletal to grumulous carbonate mud origin: mudstone. (Facies 7, variety D: non-descript dolomite.) Deadfall Creek (JD3-F60). File No. 5080-87.

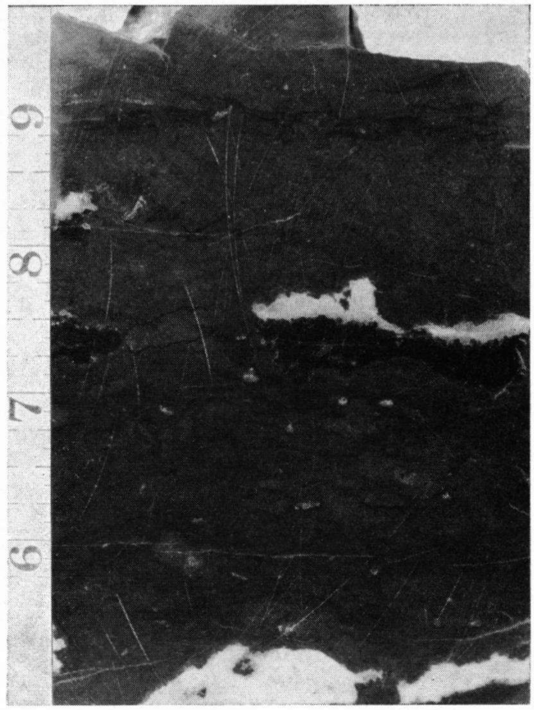


Fig. 50. Dolomite, medium grey, very finely crystalline unfossiliferous, containing *Stromatactis* consisting of an upper sparry dolomite portion and a basal part filled with geopetal sediment (facies 7, variety E). South Ram River (JD14-F60). File No. 5080-30.

Lees (1961) reports "reef tufa", composed of patches and sheets of calcite, in the Waulsortian reefs of southern Ireland. The "reef tufa" is equivalent to the "sparry calcite" of Pray (1958) and *Stromatactis* of Lecompte, Lowenstam, and Bathurst. Lees considers "reef tufa" as a sparry calcite infill of formation voids. Philcox (1964) studied two Frasnian lime mud build-ups near Winnifred Pass, 70 miles northwest of Jasper, Alberta (fig. 4). The principal rock type is an unsorted, light coloured biomicritic limestone. Cavities of several types formed during deposition of the sediments. All types were filled similarly, shortly after formation. The principal cavity is indicated as *Stromatactis* and interpreted as the cavity left by the decay of a slimy algal mat after burial.

Wolf (1965) presents a detailed description of *Stromatactis* occurrence in the Lower Devonian Nubrigyn reef complex of New South Wales (Australia). These structures, characterized by horizontal to sub-horizontal bottoms and irregular upper surfaces, formed by filling of original cavities. The occurrence of several types, sizes and shapes of *Stromatactis* are explained by variations in the nature and origin of the cavities within the host rock. Subaerial weathering is held responsible for their genesis. In the Nubrigyn Formation, *Stromatactis* occur most commonly in algal-precipitated and algal-bound carbonate muds. Wolf considers *Stromatactis* as a reliable indicator of the environmental milieu, essentially restricted to the littoral (i.e. intertidal) zone.

CHAPTER VII

CLASSIFICATION AND ENVIRONMENTAL INTERPRETATION OF THE FAIRHOLME FACIES, THEIR DEPOSITIONAL HISTORY AND PALEOGEOGRAPHIC SETTING

1. CLASSIFICATION AND ENVIRONMENTAL INTERPRETATION OF THE FAIRHOLME FACIES

The various facies of the Southesk Formation occur within well-defined, segregated areas of distribution and each facies is characterized by distinct lithological and faunal criteria. This facies differentiation indicates pronounced variations in the environmental milieu during Southesk time. In contrast, the Flume and the Cairn Formation occur essentially in identical facies over the entire map area and are not suited for differentiation of environmental milieu.

The following comments emphasize the environmental conditions resulting in different facies expression. The facies names are revised to include an environmental connotation and a number is assigned to each facies for classification and identification purposes.
The accompanying schematic cross-section (appendix 6) illustrates the proposed environmental facies names and their classification. Pertinent depositional, lithological and faunal characteristics are arranged in systematic order.

Facies 1, dark brown to black, bituminous shale facies, barren or with a sparse pelagic fauna

The absence of benthonic fauna, the local occurrence of a sparse pelagic fauna and the relatively high carbon-kerogen content, indicate the prevalence of toxic, stagnant conditions. The influence of marine currents was negligible or absent, as witnessed to by the millimeter laminations. This facies is the end product of deposition under inhospitable, restricted marine conditions and, for the sake of brevity, will be indicated as *facies 1: restricted marine shale (euxinic)*.

Facies 2, greenish grey to dark grey, calcareous shale facies, barren or with a sparse pelagic fauna

The calcareous content, absence of appreciable kerogen content, and the gradational transitions into argillaceous, shelly limestone indicate non-restricted, open marine conditions. The influence of marine currents was negligible as indicated by the laminated and varved texture and rare occurrence of thin-shelled, chitinous brachiopods. A slow rate of deposition is suggested. McCrossan (1958) reaches the same conclusion for the time-equivalent Ireton formation of the subsurface on the basis of a detailed petrographic study. Loranger (1954) postulates an open marine environment on the basis of the microfaunal content. Consequently, the facies will be indicated as *facies 2: open marine shale.*

Facies 3, medium grey to buff, nodular, argillaceous limestone-calcareous shale facies

This facies is characterized by the common occurrence of a rich and varied benthonic fauna. Nodular wackestones predominate. Deposition took place in relatively deep water without appreciable turbulence. These waters were poorly aerated, leading to the demise of an important stromatoporoid-coral content. An unrestricted, open marine environment is indicated and the facies will be designated as *facies 3: open marine carbonate-shale.*

Facies 4, light to medium grey, coralline limestone facies

This facies is characterized by the near-absence of argillaceous admixture and a marked increase in coralline content in comparison to the open marine carbonate-shale facies. The predominance of carbonate mud suggests a low degree of turbulence, which is supported by the in-situ position of a great portion of the coral colonies in the biostromes. Large colonial corals, up to five feet in diameter, grew as flattened, hemispherical forms which attained stability with their flat bases. Large overturned specimens were observed but little or no evidence of fragmentation was indicated, suggesting the short-lived nature of the more violent waves. These strata accumulated as a coralline bank below effective wave base. A relatively shallow water depth and a well-aerated milieu is indicated. Moderate stirring and abrasion by storm activity occurred occasionally. The facies will be indicated as *facies 4: open marine carbonate.*

Facies 5A, dark brown and light grey to white biostromal dolomite facies

This facies, represented by the *Amphipora*-stromatoporoid biostromes in the Flume and the Cairn Formation and by the coral biostromes in the Southesk Formation, displays the organic, ecologic reef portion of the facies spectrum. Complete dolomitization has resulted in destruction of most sedimentary textures. However, the indicated predominance of carbonate mud matrix, associated with varying amounts of bioclastic debris, suggests a relatively low degree of turbulence or winnowing within the map area. This conclusion is supported by the absence of carbonate detritus, i.e. broken-up biostromal rubble transported into deeper water. Detailed studies in areas with lesser degree of dolomitization have resulted in definition of barrier edge *detrital carbonate* (*facies 4A*), *barrier edge carbonate sand* (*facies 5B*) and *barrier edge carbonate mud* (*facies 5C*). An example of this situation is supplied by Klovan's study of the time-equivalent Leduc Formation in the Redwater area of the Alberta Basin (see chapter VIII of this thesis). Another example has been studied in the Fairholme Group of the Wapiabi Creek area (chapter VIII of this thesis). However, this subdivision cannot be established in the Cripple Creek map area and the dark brown biostromal dolomites are indicated as *facies 5A: organic ecologic reef.* The light grey, biostromal dolomite with a coral-stromatoporoid (?) fauna is also assigned to facies 5A, although extensive leaching and lack of color contrast between fossil content and matrix preclude definite support for this postulation.

Facies 6, light grey, slightly fossiliferous dolomite with a mixed coral-gastropod-ostracod fauna

A marked decrease in overall macrofaunal content, near-exclusive predominance of carbonate mud, income of an appreciable gastropod-ostracod assemblage and presence of birdseyes, indicate a slightly restricted depositional environment. Only a slight degree of turbulence is indicated, except during occasional storms which resulted in brecciation. A slight increase in salinity is suggested by the paucity and composition of the faunal assemblage. These sequences will be designated as *facies 6: semi-restricted carbonates.*

Facies 7, light grey, laminated dolomite facies with an algal-gastropod-ostracod assemblage

The faunal differentiation, initiated in the semi-restricted dolomites, is quite pronounced in the laminated dolomite facies. Algal structures and brecciated intervals indicate deposition in very shallow water. As a rule, the only evidence of life, preserved in the laminated dolomite sequences, are occasional burrows. The presence of mud cracks and evidence of vadose leaching (stromatactis) indicate periodic desiccation. The virtual absence of macrofossils is due to poor aeration and restricted water circulation. These intervals, characteristic for the southeastern portion of the map area, are assigned to *facies 7*: *restricted carbonates*.

Stratigraphic information of time-equivalent sequences in the subsurface of eastern Alberta and Saskatchewan indicate the presence of additional facies, which have been included in appendix 6. The reader is referred to the *Geological History of Western Canada* (Alberta Society of Petroleum Geologists, 1964) for more detailed information. A short description of these facies, absent in the Fairholme of the thesis area, will suffice to illustrate this supplement to the Upper Devonian facies spectrum.

The Duperow Formation of the Canadian prairie provinces, Montana and the Dakotas, displays a repetition of orderly-arranged facies units. These sedimentary rhythms, due to oscillating environmental conditions, contain anhydritic dolomites as well as laminated anhydrite and vari-colored sand-silt-shale sequences. Characteristically, these intervals occur in the upper portions of the individual rhythms. A tidal flat complex of carbonates and evaporites, occasionally interrupted by terrestrial conditions, is indicated. Respectively, these sequences are assigned to: *facies 8*: *evaporitic carbonates*, *facies 9*: *evaporites*, *facies 10*: *terrigenous clastics*.

2. DEPOSITIONAL HISTORY

Important conclusions regarding the depositional history during Frasnian time can be drawn from the areal distribution and environmental interpretation of the Fairholme facies. Several distinct stages of development are indicated. The facies distribution is readily explained by an initial period of transgression followed by a terminating regression.

The initial transgressive period resulted in the development of extensive *Amphipora*-stromatoporoid biostromes overlying the Cambrian erosion surface. These biostromes characterize the Flume and the Cairn Formation within the area and indicate differential subsidence of the region in comparison to the adjacent shale provinces of the subsurface in the Alberta basin. The transgressive period persisted during early Southesk time and resulted in deposition of open marine calcareous shales over the Cairn biostromes in the northwesternmost portion of the area described in this thesis. The occurrence of open marine carbonate-shale intervals in the Cripple Tongue of Middle Southesk time, overlying the organic reef dolomites and the semi-restricted dolomites of the Lower Southesk in the central and southeastern portions of the map area, denote the termination of the transgressive period.

The following regressive period, initiated during late Southesk time, is indicated by the occurrence of organic ecologic reef dolomites, i.e. the Grotto Member of the uppermost Frasnian. The overlying restricted dolomites of the Arcs Member substantiate the continuation of this regression. The influx of terrigenous clastics, quartz silt and vari-colored argillaceous material, in the Alexo Formation (early Famennian) denotes the most advanced stage in this overall regressive period. The presence of intra-formational breccias, mudcracks and rare salt casts, indicate intermittent periods of non-deposition and desiccation. Link (1950) has postulated a similar transgressive aspect for the Leduc- and regressive aspect for the Nisku Formation of the subsurface.

It must be emphasized that this major twofold division represents only a gross and simplified picture. The lithologic and faunal variations in the Cairn and the Southesk biostromes, ranging from open marine carbonate-shale to restricted carbonates, permit a much more refined rhythmic delineation of minor transgressive and regressive pulses.

3. PALEOGEOGRAPHIC SETTING

Several important conclusions regarding the paleogeographic setting of the area described in this study during Fairholme time can be drawn from the spatial distribution of the facies.

A review of the geologic literature reveals a general confusion in the application of paleogeographic terms. Loose and undefined usage of such terms as basin, slope, shelf and platform by various authors results in contradictions. Therefore, it is desirable to calibrate the paleotopographic nomenclature with recently established physiographic definitions. The present author proposes to use the definitions supplied by Heezen et al. (1959), resulting from the continuous echo-sounding measurements of the bottom topography of the North Atlantic. This application will result in elimination of such nondescript terms as "basinal", often encountered in carbonate studies.

The continental margin, separating the continent from the ocean, is divisible into three parallel categories. The relatively flat portions of the submerged continental platform constitute category I, which is subdivisible into the continental shelf, epicontinental marginal sea and continental margin plateau. The steep slopes, which border the continental block, constitute the provinces of category II. The continental slope constitutes the most important province of this category. At the base of the continental slope a gentle gradient continues to the abyssal ocean floor.

This lower portion of the continental margin constitutes category III, with the continental rise as most important province. In summary, the most common type of continental margin consists of a continental shelf, continental slope and continental rise. Therefore, these three provinces warrant a closer examination.

The continental shelf is a shallow (averaging less than 100 fathoms), gently-sloping (less than 1:1000) surface of low local relief (less than 10 fathoms), which extends from the shore line to the shelf break, where the seaward gradient sharply increases. The width of continental shelves ranges from a few miles to more than 200 miles.

Epicontinental marginal seas are those shallow seas (less than 1500 fathoms) which lie on the continental blocks and can be distinguished from the continental shelves by their greater depth (usually greater than 100 fathoms).

A marginal plateau is a shelf-like feature, which lies at greater depths than the continental shelf and is separated from the continental shelf by an incipient continental slope. These features generally lie at depths greater than 100 fathoms and less than 1200 fathoms.

The continental slope is that relatively steep (3°-6°) portion of the seafloor which lies at the seaward border of the continental shelf. It typically drops from depths of 50-100 fathoms to depths of 750-1750 fathoms. The top of the slope is usually well marked by a relatively sharp shelf break.

The continental rise lies at the base of the continental slope. Gradients range from 1:100 to 1:700. The depth on the continental rise ranges from 750 to 2800 fathoms.

Study of recent marine carbonate sediments indicate that three broad classes are present. Calcareous oozes, chiefly *Globigerina* ooze, are typical for the ocean basins. Toward the sides of the ocean basins, at the continental slopes, the *Globigerina* ooze grades into terrigenous muds or into carbonates with a benthonic assemblage. The carbonates of the continental shelves have been the subject of recent extensive studies. The Great Bahama Bank constitutes the best known example and has supplied a wealth of information. Organic reefs are present in the Bahamas but form only a small part of the total carbonate deposit, the remainder being predominantly composed of bioclastic attrition material, chemically precipitated limestone and carbonates of unknown origin.

Extensive carbonate deposits, in a continental shelf-epicontinental sea setting, occur in all geologic systems. These carbonates of the geologic record display all or most of the characteristics of the recent shelf carbonates.

The carbonate-shale sequences of the Fairholme Group in the Canadian Rocky Mountains present an additional example of deposition in a continental shelf-epicontinental marginal sea setting. The depositional slope is very gentle and gradual within the confines of the area and a distinction between top-, fore-, and bottom-set sediments is non-existant. The facies spectrum, ranging from open marine calcareous shales to restricted dolomites, represents the lithological and faunal record of deposition on this gently-sloping shelf.

A progressive deepening in a northwesterly direction during Southesk time is indicated. This deepening is associated with a persistent increase of argillaceous material and pelagic fauna. The relief between the carbonate shelf and surrounding seafloor was very slight but sufficient to present deposition of argillaceous material on the shelf. The orderly arrangement and interfingering relationship of the facies belts over a lateral distance of approximately eight miles, the absence of appreciable amounts of barrier edge detritus and the slight but persistent rate of thinning in the Southesk, support a progressive southeastward shallowing.

Wells (1956) has concluded that Paleozoic and Mesozoic corals grew to a maximum depth of 50 meters, in well-oxygenated and gently circulating waters.

Lecompte's studies of the Frasnian in the Belgian Ardennes indicate that massive stromatoporoid reefs were constructed above wave-base, while tabulate and colonial coral reefs were constructed below wave-base.

These conclusions support the postulation that the entire central and southern portion of the Cripple Creek map area persisted around, or above wave-base level during Frasnian times. The degree of differential compaction between the calcareous shales and the rigid carbonates, is not sufficient to significantly affect the postulation of an epicontinental marginal sea in the northwesternmost portion of the area during early and middle Southesk time.

The differentiation of the Frasnian sediments in the Canadian Rocky Mountains appears to have been controlled by depth of water, rate of subsidence and the amount of argillaceous material transported into the area.

Small differences in relief of the sea floor allowed initiation of biostromal development on shallow shoal areas. The Cripple Creek area formed part of such a shoal during early Fairholme time as indicated by the predominance of fossiliferous and biostromal carbonates in the Flume and the Cairn Formation.

Regional variations in the thickness of the Flume Formation indicate the Cripple Creek area and its surroundings to be located on an inherited structural high trend. Regionally, this postulation is also substantiated by sparse faunal control. The DFR 3 (Ladogioides kakwaensis Zone) occurs both to the west, in the westerly portion of the Eastern Ranges, and to the east in the basal portion of the Beaverhill Lake Group of the subsurface. However, this zone is absent in Cripple Creek area, where the DFR 4 (Allanaria allani Zone) represents the earliest Frasnian deposition.

Deposition of marine shales terminated biostromal development in the northwestern portion of the area, resulting in distinct differentiation of the Brazeau, and Bourgeau-Hummingbird carbonate provinces separated by the Cline clastic embayment during early Southesk time (fig. 51).

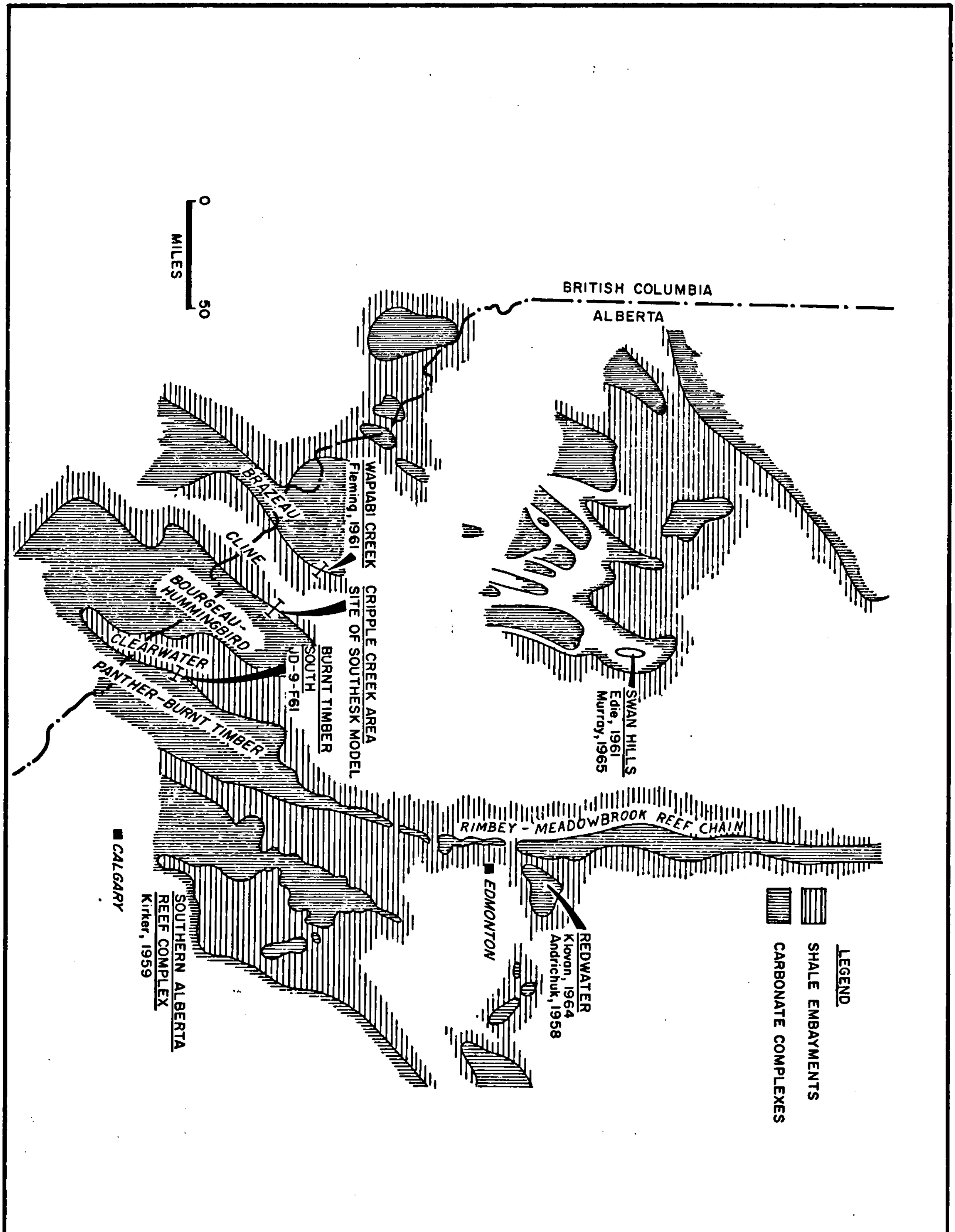


Fig. 51. Distribution of Devonian carbonate complexes, Alberta, Canada.

CHAPTER VIII

A COMPARISON OF THE CRIPPLE CREEK CARBONATE-SHALE MODEL WITH ADDITIONAL FAIRHOLME TRANSITIONS IN THE CANADIAN ROCKY MOUNTAINS

The carbonate-shale transition in the Cripple Creek area is characterized by its gradual aspect. A buffer zone, consisting of open marine limestone-shale (facies 3), open marine coralline limestone (facies 4), and dark brown biostromal dolomite (facies 5), separates open marine calcareous shale (facies 2) at North Ram River (JD 13, 13A-F60) from light colored dolomites at Cripple Creek (JD 6-F60). This *gradual* type of carbonate-shale transition is referred to as the "Cripple Creek type".

Regional studies have indicated the presence of other transition types in the Fairholme of the Rockies. Therefore, three additional Fairholme transitions will be described, primarily to illustrate the variation in environmental conditions and paleogeographic setting during Frasnian time. The available information on these three additional transitions is less detailed than that on the Cripple Creek area and some problems must remain unsolved.

1. THE FAIRHOLME CARBONATE-SHALE TRANSITION AT WAPIABI CREEK

Fairholme carbonates are exposed along the Bighorn Range, as far southward as Wapiabi Creek, and constitute part of the major Brazeau carbonate complex, 36 miles northwest of Cripple Creek (figure 51).

A most spectacular carbonate-shale transition occurs along Wapiabi Creek. The author, accompanied by Dr. A. J. Wells of Bataafse Internationale Petroleum Maatschappij, visited the area during the 1960 field season and established the major stratigraphic relations at that time. The area was revisited during the 1961 season and three outcrop sections were measured by C.W. Fleming of Shell Canada Limited. The following observations are essentially based on Fleming's fieldwork.

Generally speaking, the Wapiabi transition differs diametrically from the Cripple Creek area. Light grey dolomites of the Southesk Formation are well exposed along the north bank of the creek (fig. 53), while dark and greenish grey calcareous shales and argillaceous carbonates occur along the south flank (fig. 52). The horizontal distance, separating these lithologies, amounts to only one-quarter mile.

The following summary includes the most salient features.

(1) The light colored dolomite sequence at Wapiabi Creek (northwest) is well bedded in thick units. Massive bioherms are absent (fig. 53). Locally, weathering by exfoliation obscures stratification and has led previous workers to report bioherms (Belyea, 1954, 1958).

(2) The reported stromatoporoid-*Amphipora* content in the Southesk Formation is not verified. The only recognizable organism in the light colored dolomites is indicated by faint outlines, showing concentric rings (*Collenia* type alga?). Positive determination is impossible due to complete dolomitization.

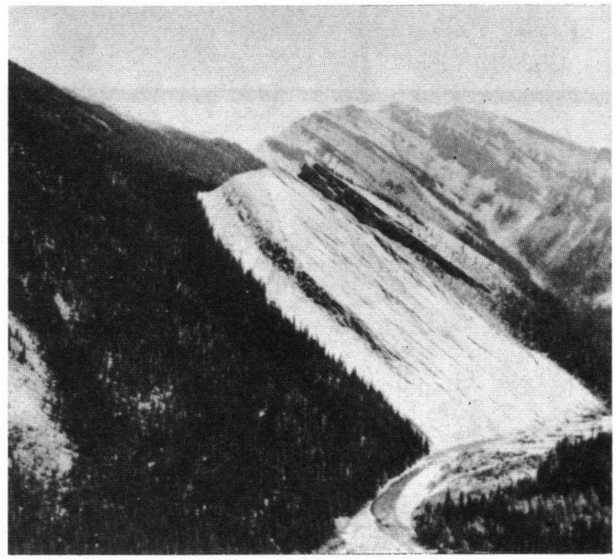


Fig. 52. Looking southeastwards across Wapiabi Creek. Thick sequence of pale greenish-gray open marine shales (Wapiabi Creek south; WF1-F61) in close contact with light colored dolomites on northwest side of Wapiabi Creek north; (WF5-F61).

Fig. 53. Looking northwestwards across Wapiabi Creek and Fairholme carbonate complex. Note stratified nature of light grey dolomite and the absence of bioherms. Wapiabi Creek north (WF 5-F61); eastern periphery of Brazeau carbonate complex.

(3) The transition from open marine shales to light colored dolomites takes place within a quarter mile and without a buffer zone of intervening carbonates.

(4) An interval of barrier edge detritus (facies 4A) is exposed along a southeastern tributary of Wapiabi Creek (fig. 54). The debris is mainly composed of crinoid ossicles, accompanied by *Thamnopora* admixture. The interval shows well-developed foreset bedding. Each set of beds has been levelled off before subsequent deposition with a different angle of dip. Several truncated surfaces are exposed. An angular disconformity occurs between the detritus and the overlying marine shales, which closely conform with the upper surface of the foreset beds. The detritus has been deposited as a bioclastic calcarenite and not as large cemented blocks. Dolomitization is complete, except for thin stringers, which interfinger with the surrounding shales. The presence of marine shales prevented dolomitization of these limestone streaks. A distance of only a few hundred yards separates the bioclastic debris from a complete light grey dolomite section. The occurrence of carbonate detritus indicates the presence of topographic relief between the carbonate and the shale provinces. This relief, sufficient to prevent deposition of argillaceous material on the carbonate shelf, did not exceed a few tens of feet. The carbonate detritus surrounds the light grey carbonates as an apron with increasing thicknesses away from the shale province. Therefore, the thickness of the detritus section can be used as an indicator of the proximity to the carbonate shelf.
The following faunal assemblage has been established in the detrital carbonate sequence (determinations by Dr. G. O. Raasch):

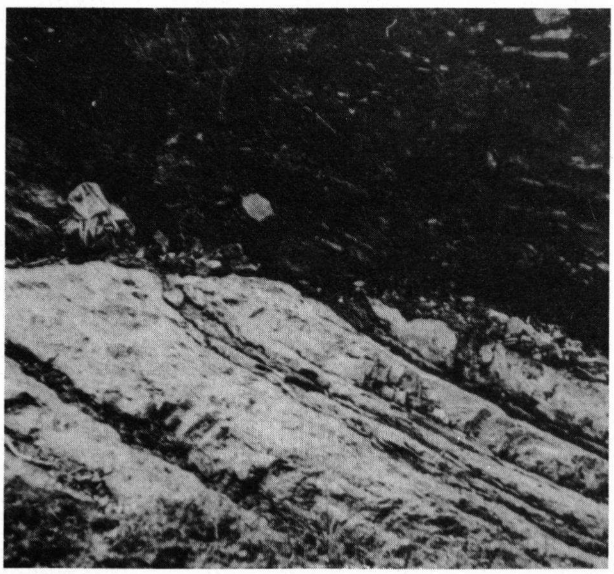


Fig. 54. Southeast tributary of Wapiabi Creek. Carbonate detritus (facies 4A), showing large scale cross bedding. Dip section of ripples. Wapiabi Gap (WF2-F61).

Tentaculites sp.
Nervostrophia sp. (incomplete)
Warrenella sp.
Spinatrypa albertensis
Atrypa sp. (*devoniana*?)
Atrypa pronis Stainbrook
Disphyllum (*Synaptophyllum*)
Thamnopora sp.
Mictophyllum (?) or *Tabulophyllum* (?)

The DFR 5 (Leiorhynchus athasbaskense Zone) is indicated (appendix 1).
McCrossan (1959) and Klovan (1964) have established similar detrital aprons surrounding the peripheries of the Leduc carbonate shelves in the subsurface (see Chapter IX of this thesis). The Duvernay fragmental limestone of the subsurface is analogous to, and contemporaneous with the bioclastic debris in the Wapiabi Creek area.

(5) The shales, interfingering with the carbonate detritus, contain pyrite concretions and an impoverished fauna composed of rare dwarfed brachiopods and fenestellid bryozoa. The abrupt juxtaposition of the carbonates and shales in the Fairholme Group of the Wapiabi Creek area is striking and this type of transition is referred to as the "Wapiabi type".

2. THE FAIRHOLME CARBONATE-SHALE TRANSITION IN THE FLATHEAD-CROWSNEST PASS AREA OF ALBERTA AND BRITISH COLUMBIA

Price (1964) reports on the Fairholme Group in the Flathead-Crowsnest Pass Area, approximately 185 miles southeast of Cripple Creek (fig. 4). A direct comparison between the two areas is hindered by introduction of a local stratigraphic nomenclature in the Flathead region. Therefore, it is necessary to correlate Price's nomenclature with the standard Fairholme sequence to arrive at plausible conclusions.
The Cambrian Elko Formation constitutes the pre-Devonian sequence in this area. The Elko consists of resistant, grey, unfossiliferous dolomites, which grade downward into green shales with a Middle Cambrian trilobite fauna (Aitken, 1966). Locally, a fossil regolith underlies the Fairholme Group. As in the Cripple and Wapiabi Creek areas, an important hiatus between the Fairholme and the pre-Devonian sequence is indicated. Pre-Fairholme deformation was restricted to gentle epeirogenic tilting.
Price introduces the Hollebeke Formation as the basal unit of the Fairholme Group in the Flathead-Crowsnest Pass area. The formation is divided into two members. The lower member (100-220 feet) consists of limestone, dolomite, dolomitic sandstone and limestone-dolomite breccias. Price's lithologic descriptions indicate the predominance of restricted carbonates.
The breccias represent solution-collapse phenomena, caused by solution of intercalated evaporites. Deposition took place in a restricted shallow-water environment, characterized by intermittent hypersaline conditions. The accompanying correlation diagram (fig. 55) shows the apparent absence of chert in the lower

member of the Hollebeke. This absence precludes a direct correlation with the Cripple Creek area. However, a correlation with the Flume Formation is indicated by the reported presence of *Atrypa multicostellata* Kottlowski. Raasch places this brachiopod in the DFR 4 (*Allanaria allani* Zone) (appendix 1). These observations indicate a major facies change within the Flume Formation between the Cripple-Wapiabi Creek area and the Flathead-Crowsnest Pass region. The organic reef dolomites (facies 5A) of the thesis area are replaced by restricted carbonates and evaporites (facies 7,8,9). It may be concluded that the Flathead-Crowsnest Pass area, was located farther onto the carbonate shelf than the Cripple-Wapiabi Creek area during early Frasnian time.

The upper member of the Hollebeke Formation consists of cryptocrystalline limestones. Limestone-dolomite breccias occur locally. The thickness of the upper member varies from 200 feet in the eastern part to 580 feet in the west. Dolomitic mottling, horizontal lamination, algal stromatolites, stromatoporoids and *Amphipora* are reported. Calcispheres, pellets and pseudo-oolites are common. These observations suggest a restricted carbonate facies (facies 7). The breccias indicate intermittent highly saline conditions and evaporite deposition.

The faunal content consists of:

Atrypa multicostellata Kottlowski
Atrypa sp.
Spinatrypa sp.
Eleutherokomma reidfordi Crickmay
Antrypis sp.
Productella sp.
Smithiphyllum imperfectum Smith
Thamnopora sp.

Price expresses difficulty in correlating the upper member of the Hollebeke Formation with the Fairholme sequence to the north. The lithologic differences prevent him from making a direct correlation. The reported faunal assemblage includes elements ranging from the DFR 4 (Allanaria allani Zone) to the DFR 8 (Leiorhynchus carya Zone). Therefore, the present author proposes a direct correlation with the post-DFR 4 Cairn Formation of the Cripple Creek-Wapiabi Creek areas. The different lithologies indicate a major facies change between the two areas. The restricted carbonates (facies 7) in the Flathead area are replaced by the organic ecologic reef dolomites (facies 5) at Cripple Creek. This conclusion indicates a more shelfward position for the Crowsnest Pass area during Cairn time. These postulated facies gradations in the Flume and Cairn illustrate the regional range of facies variations in these formations, which is absent in the local Cripple Creek area.

The Hollebeke Formation is overlain by the Mount Hawk or by the Borsato Formation, consisting respectively of argillaceous limestones and brownish dolomites. Price follows the North American stratigraphic nomenclature and the Mount Hawk and the Borsato Formation are distinguished on lithologic criteria, although they are indicated as time equivalents.

The Mount Hawk Formation is indicated as the "basin margin facies". Lithologically, the formation consists of obscurely bedded, very finely crystalline, argillaceous limestones. The formation is between 400 and 480 feet thick and quite recessive. The following faunal assemblage is reported from the lower half of the formation:

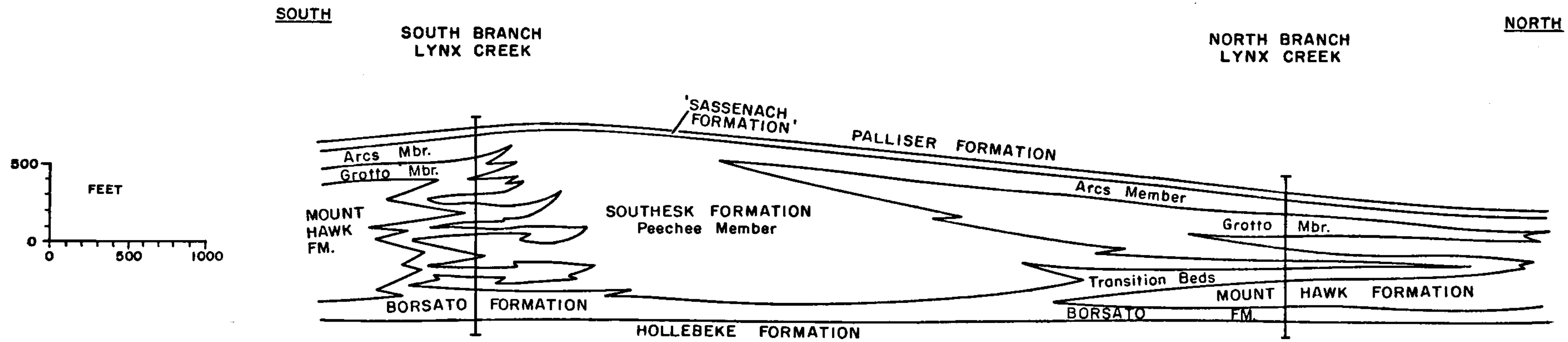
Calvinaria albertensis Warren
Atrypa cf. *varicostata* Stainbrook
Warrenella nevadensis Walcott
Atrypa cf. *A. devoniana* Webster (DFR 11, 12)
Cyrtina sp.
Leptostrophia sp.
Spinatrypa sp.
Thamnophyllum sp.

The upper half of the formation yielded:

Gruenwaldtia americana Stainbrook (DFR 9)
Devonoproductus cf, *D. vulgaris* Stainbrook (DFR 10)
Schizophoria cf. *S. amanaensis* Stainbrook
Gypidula cf. *G. munda* Calvin
Mictophyllum cf. *M. modicum* Smith
Thamnophyllum sp.
Tabulophyllum sp.

A Frasnian zonal range from DFR 9 (Leiorhynchus albertense Zone) to DFR 12 (Vandergrachtella scopulorum Zone) is indicated, which coincides with that of the Southesk Formation in the Cripple Creek area (appendix 1). Therefore, the Mount Hawk Formation of the Flathead-Crowsnest Pass area represents the time and facies equivalent of the open marine carbonate-shale facies (group 3) of the Southesk Formation in the Cripple Creek area.

The accompanying correlation diagram (fig. 55) illustrates the interfingering relation between the Mount Hawk and the Borsato Formation. The dark brown, coarse dolomites of the latter overlie the Hollebeke Formation in the Flathead Range. The dolomites are fetid and display druse-lined vugs, parallel with the bedding. *Amphipora*, relics of stromatoporoids and tabulate corals are reported. Brown or black shales occur as partings or as intercalations. The thickness of the Borsato varies between 60 and 230 feet. The faunal content is reported as non-diagnostic for zonal differentiation. The descriptions lack sufficient detail to determine whether the *Amphipora*-stromatoporoid component is restricted to the basal portion of the Borsato and the coralline component to the upper portion. If so, the Borsato would straddle the Cairn-Southesk boundary of the Cripple Creek area. The accompanying correlation diagram (fig. 55) substantiates this postulation. The interfingering of the Mount Hawk- and Borsato Formations in the middle Fairholme is identical to the repeated sequences of open marine carbonate-shale (facies 3) and dark biostromal dolomite (facies 5) in the Cripple Creek area. The great thickness variation of the Borsato (between 60 and 230 feet) is comparable with the thickness variation of the dark brown biostromal dolomite sequences in the area



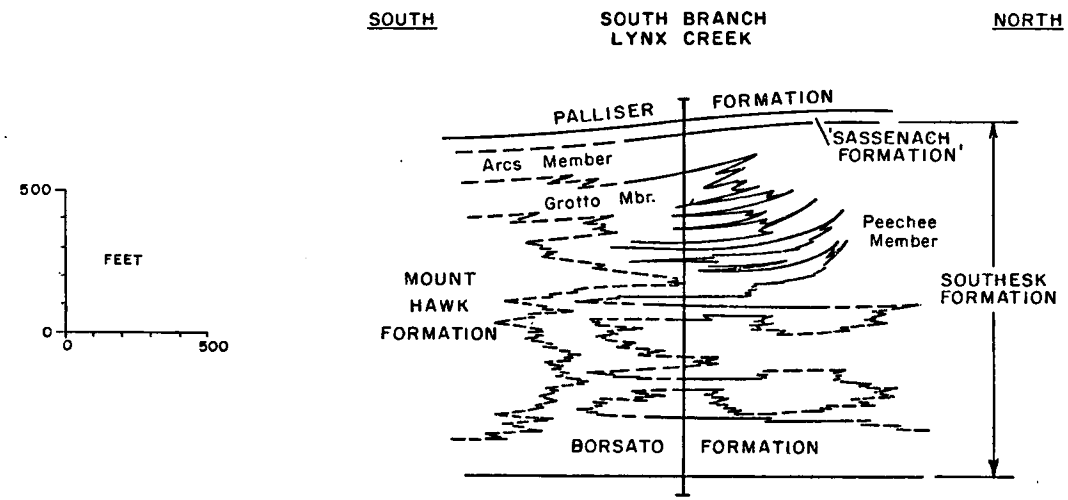


Fig. 55. Correlation diagram across reef front between south and north branches of Lynx Creek, Flathead Range, Alberta (upper diagram), with sketch of detail of reef front relationships at south branch of Lynn Creek (lower diagram).

between Tina Creek North (JD 8-F60) and Tina-Cripple Creek (JD 17-F60). Price describes the sheet-like occurrence of the Borsato, overlying the Hollebeke, as "dark organic biostromal dolomites at the base of the reef margin complex and extending beyond the periphery of the reef". This situation is analogous to the sheet-like occurrence of the organic ecologic reef facies (group 5) at the base of the light grey dolomite sequences in the central and south-eastern portions of the Cripple Creek area.

Price reports bituminous inclusions in the Borsato dolomites and concludes that they represent dolomitized equivalents of sediments that contained abundant organic matter. The formation is essentially composed of biostromal dolomites and related skeletal calcarenites. The dark biostromal dolomite sequences in the Lower Southesk of the Cripple Creek area display identical lithologies.

The Southesk Formation is composed of light grey, coarsely crystalline, vuggy, massive dolomites. Dolomitization has destroyed all traces of any organic structures which may have occurred in the rocks.

These descriptions fit those of the light grey dolomite (facies 5, 6, 7) of the Southesk Formation in the Cripple Creek Area.

This correlation between the two areas is further substantiated by the accompanying correlation chart (fig. 55). The interfingering of the Borsato and the Southesk Formation in the Flathead-Crowsnest Pass area is identical to the intercalated dark and light biostromal dolomite sequences in Tina-Cripple Creek South (JD 17-F60). Like in the Cripple Creek area, the upper portion of the Fairholme Group consists of a lower brown dolomite sequence, designated as the Grotto Member, and an upper, very light grey, coarsely crystalline dolomite interval, designated as the Arcs Member.

The thickness of the Grotto Member varies between 60 and 100 feet and consists of dolomites similar to the dark organic dolomites of the Borsato. The thickest sections are reported to occur immediately adjacent to the "reef front", where the Grotto Member cannot be separated from the organic dolomites of the Borsato. The present author arrived at the same conclusions in describing the dark biostromal dolomite sequences in the lower and upper portions of the Southesk Formation in the Cripple Creek area. However, the presence of the Cripple Creek Tongue permits separation between the organic dolomites of the Grotto Member and Lower Southesk in the thesis area.

The Arcs Member is reported to occur as a widespread blanket of bedded dolomites at the top of the Fairholme Group. The homotaxial position, identical lithologies, and absence of faunal content in the Arcs dolomites of both the Flathead-Crowsnest Pass and Cripple Creek area permit a direction correlation.

The post-Fairholme sequence consists of thin-bedded to platy, silty and laminated, very finely crystalline carbonates. Mud cracks are common. Price introduces the term Sassenach Formation for this sequence. The Sassenach Formation is overlain, with sharp and apparently concordant contact, by brownish grey carbonates of the Palliser Formation.

The accompanying correlation diagram (fig. 55) shows two types of carbonate-shale transition. The southern transition, at the south branch of Lynx Creek, is more abrupt than the northern transition at the

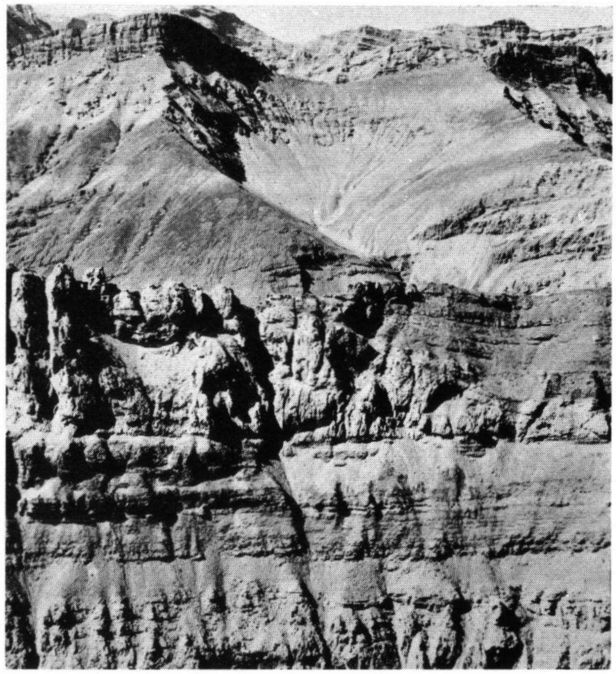


Fig. 56. Burnt Timber South (JD9-F61). Closeup of northeastern transition of Panther-Burnt Timber carbonate complex at Burnt Timber South (JD9-F61). Note the wedge of light colored dolomite (facies 4A 5) in the Southesk Formation. Thin stringers of light dolomite extend into the dark, open marine carbonates to the right. *Receptaculites* beds plaster the light dolomites as a thin veneer, while crinoids and brachiopods predominate in the open marine, argillaceous carbonates.

north branch. The former is related to the Wapiabi type, while the latter is comparable with the gradual Cripple Creek transition.

A narrow bufferzone of dark organic dolomites, separating open marine carbonate and shale from light grey dolomite sequences at Lynx Creek South, indicates that this transition occupies an intermediate position between the gradual Cripple and abrupt Wapiabi types. The presence of open marine limestone (facies 3) in close proximity to the light grey dolomites (facies 5, 6) at Lynx Creek South is another indication that the transition is less abrupt than Wapiabi, where this position is occupied by thick open marine shale sequences (facies 2).

The total thickness of the Fairholme, in the clastic sections at both Wapiabi and Flathead, is much thinner than that of the corresponding carbonate sections. Price contributes this thinning to actual relief, between the carbonate and clastic provinces, slightly modified by differential compaction. The presence of relief is further substantiated by the occurrence of barrier edge detrital carbonates (facies 4A), swept from the carbonate shelf.

3. THE FAIRHOLME CARBONATE-SHALE TRANSITION AT BURNT TIMBER SOUTH

The third additional carbonate-shale transition is exposed at Burnt Timber South (JD 9-F61), 60 miles southeast of Cripple Creek, on the northeastern periphery of the Panther — Burnt Timber carbonate shelf (Fig. 51). Time-equivalent open marine shale (facies 1 and 2) and open marine limestone-shale sequences (facies 3) occur at Mount Oliver (JD 8-F61), 3 miles northwest of Burnt Timber south. Thick open marine carbonate sequences occur immediately in front of the Burnt Timber South section and a general facies gradation from open marine limestone to open marine dolomite is indicated (fig. 56). Crinoids and brachiopods are common to abundant but are gradually replaced by a near-exclusive *Receptaculites* assemblage. These *Receptaculites* beds occur as a thin veneer, plastered against a pronounced wedge of light grey dolomites. The transition is more abrupt than the Cripple Creek type. Repeated sequences of dark and light colored dolomites characterize the Southesk Formation. The dark biostromal intercalations (facies 5A) disappear over a short lateral distance to the south. Thin beds of light colored barrier edge detrital carbonate (facies 4A) taper off into the open marine, *Receptaculites*-bearing dolomite. An additional interesting observation is the predominance of light colored dolomites (group 6, 7) in the upper portion of the Cairn at Burnt Timber South, suggesting a facies change from the normal, dark brown, *Amphipora*-stromatoporoid biostromal dolomites (group 5A) at Cripple Creek.

4. GENERAL REMARKS

The foregoing stratigraphic and environmental descriptions have resulted in the delineation of a range of carbonate-shale transitions, with the extremely gradual Cripple Creek and extremely abrupt Wapiabi Creek types as end-members. However, these end-members occur on different carbonate shelves, respectively on the western periphery of the Bourgeau-Hummingbird, and the northeastern rim of the Brazeau shelf.

Subsequent studies (Fleming, oral communication) established a Cripple Creek type transition along the northwestern rim of the Brazeau carbonate complex in the general Mackenzie Mountain area (fig. 4). Therefore, the carbonate-shale transitions, along the periphery of the Brazeau complex, grade from a Cripple to a Wapiabi type.

A similar conclusion may be drawn from Price's work in the Flathead-Crowsnest Pass area (fig. 55). The southern transition, at south branch of Lynx Creek, is more abrupt than the northern transition at the north branch.

All gradations between the Cripple- and Wapiabi type transitions must occur somewhere along the periphery of a carbonate complex.

The following comments will attempt to explain the areal distribution of these various types of transition in terms of paleogeographic setting during Southesk time. However, the amount of information is very sparse and a statistical approach is precluded.

It is obvious that carbonate sediments, once formed, are subject to the same mechanical processes as all other sediments. Detrital carbonates, washed off the shelf into adjacent and slightly deeper areas, are subject to local hydrodynamic conditions. This is equally valid for those carbonate sequences which were generated (in situ) off the shelf areas. Prevailing current-direction constitutes the main agent. Sediments may be expected to accumulate in the relatively quiet zones on the leeward side of the carbonate shelf. Channels between the carbonate shelves may be the sites of strong and scouring currents. Examples of leeward accumulations behind islands are quite common at present. Many islands and shoals in the Persian Gulf have a tail of sediment, extending in a down-wind direction. Lime mud accumulations on the leeward side of Andros Island have been reported by Ginsburg and Illing. Such lime mud accumulations occur also in sheltered embayments.

These observations are utilized by the present author to explain the areal distribution of the various types of carbonate-shale transitions around the peripheries of the Fairholme carbonate shelves.

The Cripple Creek type transition is postulated to occur in areas on the leeward side of the Fairholme shelves. These locales were protected from the influence of direct wind and current action and are characterized by a gradual transition from carbonate to shale.

The Wapiabi Creek type transition occurs in windward areas, which were directly subject to wind and current action. This transition is characterized by an abrupt change from clastics to carbonates and by the presence of carbonate detritus.

The abrupt Wapiabi transition, located on the northeastern rim of the Brazeau carbonate shelf suggests the predominance of northeasterly winds during Southesk time. This postulation is supported by the presence of the gradual Cripple Creek transition at the western periphery of this carbonate complex in the general Mount Mackenzie area (fig. 4; Mackenzie, 1965). This author reports the presence of a bufferzone of open marine carbonates separating open marine shales from light colored dolomites.

Additional support for the postulation of a northeasterly wind and current direction is supplied by the gradual transition in the Cripple Creek map area, on the southwestern rim of the Bourgeau-Hummingbird carbonate shelf.

A review of the geological literature indicates that several authors reached the same conclusion in studies of time-equivalent subsurface formations.

Andrichuk (1958) explains the location of the Redwater carbonate complex of the Leduc formation by facies differentiation within the underlying Cooking Lake (fig. 51, appendix 1). The Cooking Lake forms the platform for the Leduc carbonate buildup and is

largely composed of non-biostromal carbonates in the general area. However, a pronounced algal-stromatoporoid biostromal facies belt occurs approximately 10 miles northeast of and parallel to the overlying Leduc biostromal buildup. Therefore, a southwesterly migration of biostromal carbonates is indicated. Andrichuk explains the migration by the prevalence of northeasterly winds.
Kirker (1959) indicates a similar situation in the area bordering the Southern Alberta reef complex (fig. 51). A belt of organic shoals occurs in the Cooking Lake Formation, six to eight miles north of and parallel to the overlying Leduc reef.
Edie (1961), in his study of the Swan Hills oilfield (fig. 51), indicates a marked accumulation of "essentially horizontally deposited reef debris", and associated argillaceous limestones, along the southwest margin of this carbonate buildup. Therefore, the southwest side constitutes the leeward side and a northeasterly wind and current action is indicated.

CHAPTER IX

THE CARBONATE MODEL CONCEPT AND ITS APPLICATION

The amount of information on carbonate stratigraphy and petrology, accumulated during the last 20 years, is overwhelming. Generally, such a rapid accumulation results in creating confusion. The petrographic nomenclature changed with each classification and this practice led to a semantic problem. Although this difficulty has not been entirely solved, a more or less uniform and universally recognized nomenclature has been established.
These initial petrographic studies, based on detailed microscopic descriptions, have resulted in the definition of some ten major facies divisions (appendix 6). Each of these is well-documented by a series of lithological and faunal criteria.
Presently, detailed studies of the spatial arrangement of the carbonate facies have replaced and complimented the earlier studies. The efforts of the petroleum industry are directed towards locating facies belts with favourable reservoir potential. A certain degree of predictability would be present if the major facies belts occupy a more or less fixed position on the carbonate shelves.
The results of these investigations have led to the definition of a "well-tempered" depositional carbonate pattern, which is designated as "the carbonate model". It must be emphasized that this model is based on years of carbonate experience. The parameters, used in this model, have been established empirically, by searching for similarities in depositional texture, faunal assemblage and sedimentary characteristics.
The merits of such a model are obvious. Once the uniformity of the model has been established, by comparison of various individual carbonate sequences of widely different geographic setting and age, it is possible to greatly reduce or eliminate the semantic problem and to stress the limited number of parameters of each particular facies. Facies terms are known and understood, enabling clear communications. The carbonate petrographer is constantly watching for particular parameters, which make it possible to rapidly define the major facies and their environmental implications.
The construction of such a carbonate model develops along the lines of an evolutionary process; i.e. from a simple idea, based on sparse surface and/or subsurface control, to a detailed illustration, as more and more information becomes available. The development of a model goes through several phases. A broad concept, such as a regional facies change from carbonate to shale or from carbonate to evaporite, constitutes the first step and may be based on only a few control points. Even at this early stage, some of the major facies divisions should be recognized, suggesting the presence of other possible facies belts. The concept develops into a "local model" as additional surface and subsurface control becomes available. At this point, enough material has been studied to recognize all main carbonate facies and their lateral and vertical distribution patterns. A reasonable picture has now been established, which presents a working hypothesis. The final step in the model construction is reached when a detailed microfacies picture can be presented.
In summary, a conceptual carbonate model constitutes a synthesis of all pertinent data, necessary to represent the areal configuration, composition and environmental milieu of the major facies, into a simple and orderly form. Experience has shown that the carbonates of western Canada fit into a unified model, as presented on appendix 6. This conclusion indicates the primary advantage of the unified model. It stresses the basic similarity of carbonate sequences of various age and location. It eliminates the view that each carbonate study is unique.
The delineation of the major carbonate facies belts does not mean that all of these must be present in each carbonate sequence. Several facies may be absent. For instance, comparison between the gradual Cripple Creek and the abrupt Wapiabi Fairholme transition indicates the absence of the open marine carbonate and organic ecologic reef facies at Wapiabi and the near-absence of barrier-edge detrital carbonate at Cripple Creek.
The author proposes to show that this unified model concept can be applied profitably on a world-wide basis to various carbonate sequences.
The accompanying chart (appendix 7) shows the application of the model concept to additional western Canadian carbonate sequences, reported in the geologi-

cal literature, and to carbonates in Europe and Canada's Northland. The following comments serve to outline the most pertinent geological data.

(1) Dooge, 1966
The observations within the area described in this thesis are summarized.

(2) Price, 1964
The reader is referred to Chapter VIII for additional details (see fig. 4 for geographic location).

(3) Klovan, 1964
This study, of the subsurface Upper Devonian Redwater reef complex, is based on the examination of diamond cores from 37 wells (appendix 6). The Redwater reef, in contrast to the vast majority of subsurface and surface complexes, has not been subject to subsequent dolomitization. Consequently, the preservation of original sedimentary textures, faunal content and petrological characteristics, is excellent. This circumstance renders the complex particularly suited for detailed petrological and paleontological studies. Klovan restricts the study to the upper-most 150 feet of the Leduc Formation. His results indicate the presence of 7 major facies belts "from the basin, across the reef, to the lagoon".

(a) *Megalodon* facies — occurring along the outer edge of the complex,

(b) tabular stromatoporoid facies — immediately reefward from the outer edge of the complex,

(c) organic-reef facies,

(d) massive stromatoporoid detritus facies — located lagoonward from the organic reef,

(e) skeletal calcarenite facies — intimately associated with the organic-reef facies,

(f) back-reef facies — making up the bulk of the complex,

(g) *Amphipora* facies — occurring in the central part of the complex.

Klovan concludes that the presence of shallow-water organic reefs led to restricted water movement on the complex, so that islands and tidal flats developed behind them. The back-reef areas are characterized by non-skeletal sediments and a sparse fauna. In the interior parts of the complex, a shallow restricted lagoon developed, in which *Amphipora* flourished.

(4) *Murray, 1965*; *Edie, 1961*
The Swan Hills and Judy Creek oilfields (fig. 51) produce from carbonate sequences, encased in open marine carbonates and shales of probable early Late Devonian age.
Murray (1965) reports on the "basin facies" of the sequence; i.e. the Waterways Formation. Nodular, argillaceous lime muds and calcareous shales predominate. Skeletal open marine carbonate intercalations are common. The faunal assemblage consists of brachiopods, echinoderms, gastropods, bryozoa, ostracods and *Tentaculites*. Murray interprets the depositional environment as varying from:

(a) quiet stagnant water below wave base, bottom conditions are inhospitable to benthonic life,

(b) better-oxygenated conditions allowing development of a bottom community.

Edie (1961) reports on the facies distribution of the carbonate complex. Essentially, this complex consists of a basal transition zone, grading into a carbonate platform. The various facies of the main phase of reef development occur above this basal complex.
Edie visualizes a build-up of successively smaller atoll-like layers. Precipitation of calcium carbonate within the lagoonal area of each layer kept pace with growth of the outer organic lattice. Within the reef mass, six depositional environments, characterized by specific suites of fossils, are recognized.

(a) *Windward (northeast) side of carbonate complex*:

(1) light buff, highly permeable calcirudites, 60-100% bulbous stromatoporoids and *Amphipora*, rare *Thamnopora*-type corals, lamellar stromatoporoids, minor crinoid ossicles, articulate brachiopods, rare rugose cup corals, ostracods;
(1A) in situ lamellar stromatoporoids with interbedded talus, black shale partings, dips ranging from 5-15 degrees;
(2) "black reef", 70 % dark grey, bulbous stromatoporoids and 5 % *Amphipora* with black shale matrix;
(3) light grey to buff, slightly argillaceous, extremely finely crystalline limestone, 10-30 % fossils composed of *Thamnopora*-type corals, *Amphipora*, lamellar stromatoporoids, minor crinoid ossicles, articulate brachiopods, rare rugose cup corals and ostracods.

(b) *Lagoonal (central) portion of complex*:

(4) light buff, lithographic to pelletal limestone with local intraformational conglomerate, 5-30 % *Amphipora*, rare ostracods and gastropods;
(5) dark brown, slightly argillaceous lime muds, 2 % black shale partings, 10-40 % *Amphipora*, rare bulbous stromatoporoids and ostracods.

(c) *Leeward (southwest) side of complex*:

(6) Dark brown, argillaceous lime mud, 10 % thin beds bituminous black shale, rare chert nodules, 2 % crinoid ossicles and articulate brachiopods, rare (locally 10-20 %) *Thamnopora* type corals, *Amphipora*, rare stromatoporoids, rugose cup corals, ostracods and gastropods.

(5) *Jux, 1960*
This study reports on reef development in the mountains of the Rheinisches Schiefergebirge.
Small reefs appear during early Middle Devonian (Couvinian). Various reef types are described, e.g. biohermal mounds of *Hexagonaria* corals, biostromal sheets of corals and hydrozoa, and massive stromato-

poroidal limestone build-ups. These reefs are encased in sandstones. Transition zones, consisting of thin-bedded argillaceous limestone and calcareous shale, are common. The distribution pattern of these reefs is explained by differentiation in sedimentary troughs and positive areas.
Well developed biostromal development occurs in the Givetian. Coral and hydrozoan biostromes and massive stromatoporoidal build-ups are described. These autochthonous reefs grade laterally into thick-bedded bioclastic limestone, thin-bedded argillaceous limestone, and cherty shale. Closely spaced and widespread biostromes give rise to massive limestones.
The Middle Devonian reefs developed in the "zone of turbulence" (Lecompte, 1954, 1958).
Frasnian biostromes, exposed in the general area, are assigned to the coralline zone of Lecompte. This differentiation is based on bathymetric variations. The Givetian reefs thrived in very shallow water, whereas the Frasnian biostromes grew in slightly deeper water, below effective wave base.

(6) *Dooge and Raasch, 1966.*

The Lower Devonian in the Yukon and Northwest Territories displays a facies spectrum ranging from continental clastics to open marine shales. Each facies is characterized by distinct lithologic and faunal criteria, reflecting deposition of a transgressive sea onto a shallow shelf. A narrow belt of extremely fossiliferous to biostromal carbonates separates open marine graptolitic- and *Tentaculites*-bearing shales (in the west) from laminated, restricted dolomites (in the east). Of particular interest is the extensive occurrence of solution-collapse breccias in the outcrop sections of the eastern portion of the Territories (facies 9). Brecciation is probably due to leaching of evaporite intercalations, which are present in nearby subsurface control points.
A detailed study of the Lower Devonian carbonate-shale transition has been carried out by the present author at Royal Creek (northern Yukon; 63° 30' - 65° N and 135° 05' - 135° 20' W). Closely-spaced, and well-exposed outcrop sections have supplied significant information on the intercalation of shelly and graptolitic faunas and on the position of the Siluro-Devonian boundary (paleontology by Dr. G. O. Raasch).
The Lower Devonian carbonate-shale transition is abrupt in the Royal Creek area. The contact between the two depositional provinces is well exposed on opposite flanks of a cirque. The close juxtaposition of time-equivalent shales and pure carbonates suggests the presence of (minor) relief between the two.

(7) *Lecompte (1954-1958)*

These classical studies, on the paleoecology of the Devonian reefs of the Ardennes, illustrate both the vertical sequence within the biostromal and biohermal carbonate mass and the pattern of concentric biofacies in contemporaneous sediments surrounding the bioherms.
Lecompte stresses the bathymetric pattern of the dominant forms. Stromatoporoids constitute the most numerous animal in the shallowest depths, followed by corals and brachiopods and, finally, a pelagic fauna in the deepest portions of the Devonian seas. Massive, globular stromatoporoids predominate in the shallowest turbulent zone, while the lamellar variety flourishes in a slightly deeper water. Corals progress, through branching and solitary forms, to even deeper levels. The role of algae is not considered in detail, but Lecompte concludes that they played an important role in the construction of the bioherms, if one accepts Lecompte's "*Stromatactis*" as an alga.
The presence of "deep" coral bioherms, as well as shallow stromatoporoid reefs, are indicated. Intermediate forms occur where a bioherm starts to grow in relatively deep water and reaches the shallow, turbulent zone near sea level. This gradation results in a faunal variation from coralline to stromatoporoidal.
The accompanying chart (appendix 7) shows the assignment of the facies belts, in these widely diverging carbonate provinces, to their appropriate slot in the proposed unified model. It is hoped that this classification may contribute to the understanding of carbonate deposits.

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