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THE LOWERMOST PALEOZOIC McNAUGHTON FORMATION AND EQUIVALENT CARIBOO GROUP OF EASTERN BRITISH COLUMBIA: PIEDMONT AND TIDAL COMPLEX

F.G. Young

Energy, Mines and Resources Canada
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Preface

This report describes the stratigraphy, sedimentology and petrography of the McNaughton Formation, the lowest formation of the Gog Group, and equivalent rocks of the Cariboo Group, in an area northwest of Jasper National Park and east of Prince George. These rocks comprise a Lower Cambrian terrigenous clastic succession which occurs on both the east and west sides of the Rocky Mountain Trench. The origin of this major topographic feature has long been a subject for debate and the present study, one of the first to examine concurrently both sides of the Trench has disclosed new evidence which should help solve the puzzle.

The results of Dr. Young's investigations shed new light on the growth and structural history of this part of the Cordilleran mountain belt during the early Paleozoic and also on the surface processes and climates that prevailed at that time. They also support the concept of the West Alberta Arch, a major structural element which is thought to have influenced sedimentation in the Deep Basin area of Alberta during the Paleozoic.

The information and conclusions presented in this report should prove useful in the exploration for both mineral and hydrocarbon resources thus meeting a major objective of the Geological Survey of Canada, the identification of our energy and mineral resources.

D.J. McLaren
Director General
Geological Survey of Canada

Ottawa, November 1978

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THE LOWERMOST PALEOZOIC McNAUGHTON FORMATION AND EQUIVALENT CARIBOO GROUP OF EASTERN BRITISH COLUMBIA: PIEDMONT AND TIDAL COMPLEX

Abstract

In the upper Fraser River region of British Columbia, the McNaughton Formation and correlative parts of the Cariboo Group make up a complex prism of terrigenous clastic sediments which were deposited in the early Paleozoic miogeocline of western North America. The McNaughton Formation consists principally of medium- to coarse-grained quartzite in eastern outcrops where it is approximately 1300 m (4265 ft) thick; westward it becomes finer grained and interbedded with pelite in the western Rocky Mountains, where it is 2200 m (7217 ft) thick in the Robson Trough. Abrupt thinning occurs over McBride Arch in the vicinity of the Rocky Mountain Trench, west of which the correlative Cariboo clastic succession gradually thickens again to 1000 m (3280 ft).

Eight lithofacies are identified and described from the McNaughton Formation. Markov chain analyses of vertical sequences of these facies are used to aid in interpreting depositional environments and to establish facies associations. The main associations include fan-delta, piedmont, piedmont-estuary transition, estuary-tidal flat, and tidal inlet-subtidal. The sandy piedmont plain was modified by numerous, braided, shallow, poorly channelled streams which changed courses frequently and in which transverse bars were prominent. The distal margins of the piedmont merge imperceptibly into sand-choked estuarine channels and tidal flats. Tide-influenced, shallow-marine pelite-quartzite facies filled the Robson Trough. The abundance of quartz pebbles and the mixed altered and unaltered feldspar grains in the McNaughton quartzite, as well as their drab colouration, point to the existence of a warm, humid climate and a source-area of high relief. Mineral species in the quartzite as well as the great volume of alluvial deposits indicate considerable uplift of the adjacent Hudsonian cratonic margin.

The Cariboo clastic succession, consisting of the upper Yankee Belle, Yanks Peak, and Midas Formations, includes the same eight facies recognized in the McNaughton, as well as four others. Paleocurrents, red-bed thicknesses, lithofacies trends, and largest clast-size distributions in the middle part of the Cariboo clastic sequence all indicate that an isolated uplift northwest of McBride Arch shed clastic detritus southward onto the Cariboo shelf. There it was reworked by strong tidal currents into shallow-marine sandbars.

Tidal flat and shoal-water sediments were deposited over the McBride Arch which acted as a partial barrier between the McNaughton and Cariboo dispersal systems.

Résumé

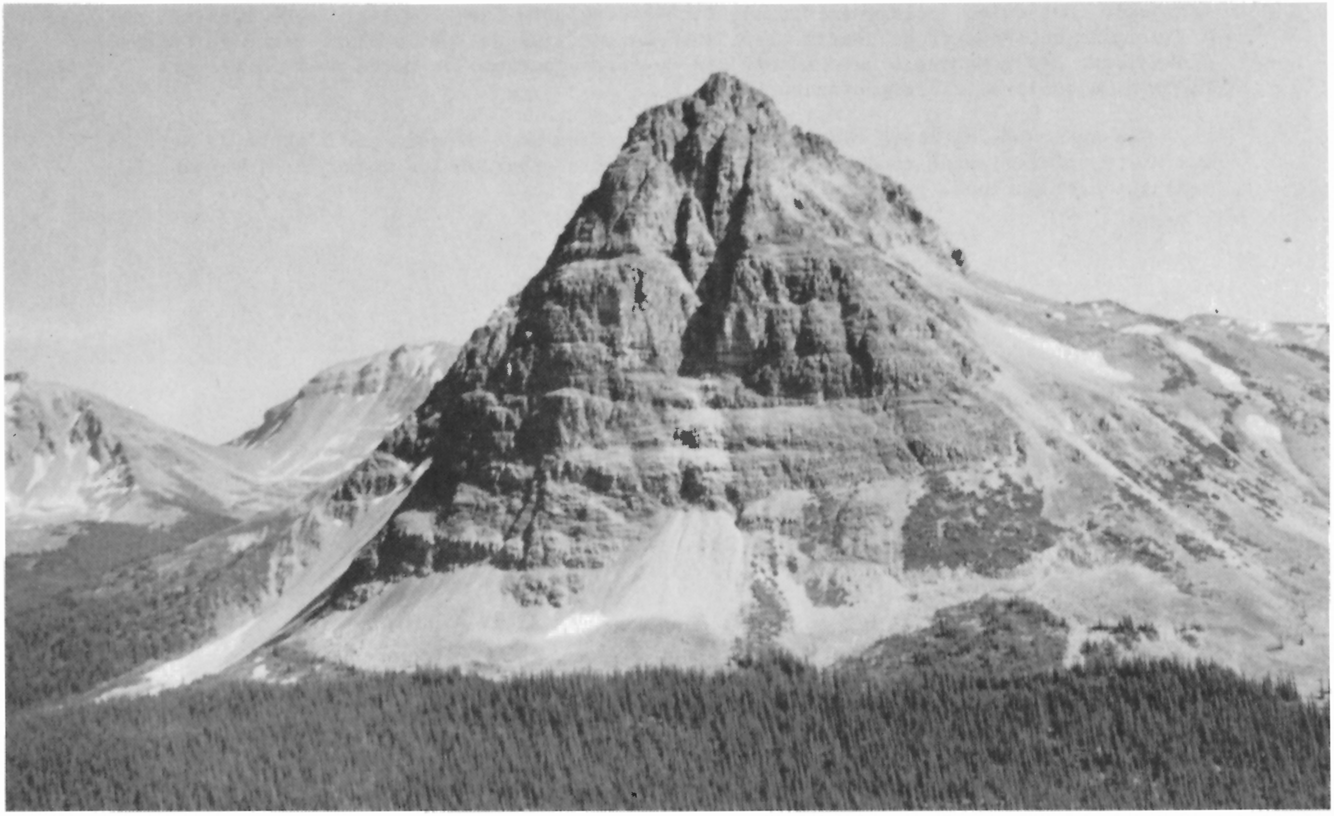
Dans la région de l'amont de la rivière Fraser en Colombie-Britannique, la formation de McNaughton et les parties corrélatives du groupe de Cariboo forment un prisme complexe de sédiments clastiques terrigènes, qui se sont déposés dans le miogéosynclinal du Paléozoïque inférieur de l'ouest de l'Amérique du Nord. La formation de McNaughton est principalement formée de quartzite à grains moyens à grossiers, dans les affleurements situés à l'est, où son épaisseur atteint approximativement 1300 m (4265 pieds); elle est caractérisée par des grains plus fins, et se trouve intercalée avec des pélites à l'ouest, dans les montagnes Rocheuses occidentales, où son épaisseur atteint 2200 m (7217 pieds) dans la dépression de Robson. On observe un amincessement brusque au-dessus de l'arche de McBride, à proximité du sillon des montagnes Rocheuses, à l'ouest de laquelle la succession clastique correspondante de Cariboo s'épaissit graduellement jusqu'à atteindre de nouveau 1000 m (3280 pieds).

On a reconnu et décrit huit lithofaciès dans la formation de McNaughton. On a fait appel à des analyses par la chaîne de Markov des successions verticales de ces faciès, afin de pouvoir interpréter les milieux de sédimentation, et d'établir des associations de faciès. Parmi les principales associations, on peut citer: cône-alluvial-delta, piémonts alluviaux, la transition piémont-estuaire, estuaire-zone tidale et passe-zone subtidale. La plaine de piémont sableuse a été modifiée par de nombreux cours d'eau anastomosés peu profonds, caractérisés par l'irrégularité de leurs chenaux, et les fréquentes variations de leur cours, ainsi que des bancs de sable transversaux trés visibles. Les marges du

piémont passent imperceptiblement à des chenaux d'estuaire engorgés de sable, et des zones tidales. Un faciès à quartzites et pelites marines peu profondes et influencé par les marées occupait la dépression de Robson. L'abondance de galets de quartz et le mélange de grains de felspath altérés et non altérés dans le quartzite de McNaughton, ainsi que leur coloration terne, indiquent que le climat a été chaud et humide, et que la zone d'où sont issus les matériaux avait un relief prononcé. Les minéraux présents dans le quartzite et le volume important de dépôts alluviaux indiquent que la marge de craton adjacent d'Hudson a subi un soulèvement considérable.

La succession clastique de Cariboo, qui comprend la partie supérieure de la formation de Yankee Belle, la formation de Yanks Peak, et la formation de Midas, inclut les mêmes huit faciès identifiés dans la formation de McNaughton, ainsi que quatre autres. Les paléocourants, l'épaisseur des red beds, les tendances des lithofaciès, et la répartition des fragments les plus gros dans la partie médiane de la succession clastique du Cariboo indiquent tous qu'un soulèvement isolé, localisé au nord-ouest de l'arche de McBride, est à l'origine de l'apport de débris clastiques au sud, jusque sur la plate-forme de Cariboo. Ceux-ci ont été remaniés à cet endroit par de forts courants de marée pour former des flèches de sable à faible profondeur.

Des sédiments de zones tidales de hauts-fonds se sont déposés sur l'arche de McBride, qui s'est partiellement comportée comme une barrière séparant les voies de dispersion de McNaughton et Cariboo.



FRONTISPIECE. Mount Jobe, British Columbia: This exposure, 600 m thick, of McNaughton quartzite at Latitude 53°39'N, Longitude 119°54'W, is typical of the prominent character of the formation in the Rocky Mountains. GSC 199280.

THE LOWERMOST PALEOZOIC McNAUGHTON FORMATION AND EQUIVALENT CARIBOO GROUP OF EASTERN BRITISH COLUMBIA: PIEDMONT AND TIDAL COMPLEX

CHAPTER I

INTRODUCTION

Lower Cambrian strata in the mountainous upper Fraser River area of eastern British Columbia and west-central Alberta comprise a thick, well-exposed series of piedmont-alluvial, estuarine, intertidal, shallow-marine, and deep-marine lithofacies. In the Rocky Mountains, the Gog and upper Miette Groups embrace this series and are correlative with the Cariboo Group in the Cariboo Mountains which lie to the southwest. In this report are summarized the sedimentology, regional stratigraphy and tectonic characteristics of the main clastic prism of this series--the McNaughton Formation and its western equivalents, the upper Yankee Belle, Yanks Peak, and Midas Formations. A series of depositional models of the early Cordilleran miogeocline is generated from various lines of evidence, including facies analyses, stratigraphic sequences, petrography, paleocurrents, and grain size data.

AREA OF INVESTIGATION

The area of investigation includes much of the drainage basin of the upper Fraser River above its great bend, and lies between Latitudes 52°45, and 54°30, North (Fig. 1). The 16 km (10 mile) wide Rocky Mountain Trench cuts through the area from southeast to northwest, and separates the Rocky Mountains in the northeast from the Cariboo Mountains and Interior Plateau to the southwest. The Fraser River flows northwestward through the trench at an elevation of about 700 m (2300 ft) above sea level, and the mountains on each side of it rise to elevations generally between 2000 and 2400 m (7000-8000 ft). Mount Robson at 3955 m (12 972 ft) and Mount Sir Alexander at 3275 m (10 700 ft) above sea level are the highest peaks in the area.

Field observations made by the writer and others both southeast and northwest of the study-area also were incorporated into the formulation of regional paleogeography and depositional history.

ACCESS

The area is accessible by highways approaching from all four cardinal compass points--from the north via Highway 97, from the west via Highway 26, from the south via Highway 5, and from the east via Highway 16. The latter is the only major road passing through the area, and it follows approximately the Fraser River from Jasper to Prince George. A few logging roads provide limited access to the outcrops of interest. Horse trails and hiking trails are rare in this region, but more are being blazed with each passing year. The remoteness of the interiors of the mountain ranges practically necessitates the use of helicopters, which are available for charter in Prince George, Valemount and Hinton.

A main line of the Canadian National Railway also follows the Fraser River from Jasper to Prince George, and passengers may detrain at many small stations along the route within the study-area.

PREVIOUS WORK

Prior to this study, no regional stratigraphic analyses had been made of the Gog or Cariboo Group, nor had any attempts been made to understand their inter-relationships. Recently, a Ph.D. thesis on the sedimentology of the Gog Group in the Banff-Jasper Parks region was completed by P. Palonen (1976) at the University of Calgary. These two analyses were conducted independently; however, some of Palonen's observations and conclusions are cited here in order to illustrate similarities or differences in depositional conditions between the two study-areas.

Earlier works on the Lower Cambrian and Proterozoic rocks of the Canadian Rocky Mountains include those of C.D. Walcott (1913), who established a sequence of formations, L.D. Burling (1923), who modified Walcott's nomenclature, and C.F. Diess (1940), who described the section near Mount Assiniboine. R.D. Hughes (1955) proposed new formational names for Lower Cambrian strata in the Sunwapta Pass area, but these names were unnecessary because the earlier terminology of Walcott and Diess was found applicable throughout the Jasper and Banff regions (Mountjoy, 1962; Price and Mountjoy, 1966).

In the course of mapping the eastern half of the Mount Robson map-area (83E), Mountjoy (1962, 1964) modified Walcott and Burling's units and published additional stratigraphic data. The only published information arising from numerous commercial geological surveys northwest of the Jasper area is the valuable report by Slind and Perkins (1966) of Shell Canada Limited. They proposed a subdivision of the Proterozoic rocks and figured stratigraphic cross-sections of lower Paleozoic rocks for the Rocky Mountains between Pine Pass and Jasper.

In the western part of the area, geological studies have been confined largely to the Cariboo gold district, southwest of Bowron Lakes Park. The earliest work describing the geology of this area is that of A. Bowman (1889) of the Geological Survey of Canada, who established a series of formations. Later studies by W.A. Johnston and W.L. Uglow (1926), also of the Survey, resulted in a revised sequence which was used until the detailed work of S.S. Holland (1954) and A. Sutherland-Brown (1963) established the nomenclature used in this report.

R.B. Campbell, while doing regional geological mapping in the 1960's, again revised the stratigraphic succession of the Cariboo Group. This was due largely to his discovery of a second carbonate formation not recognized by previous students of the deformed rocks in the Cariboo gold district. During a reconnaissance

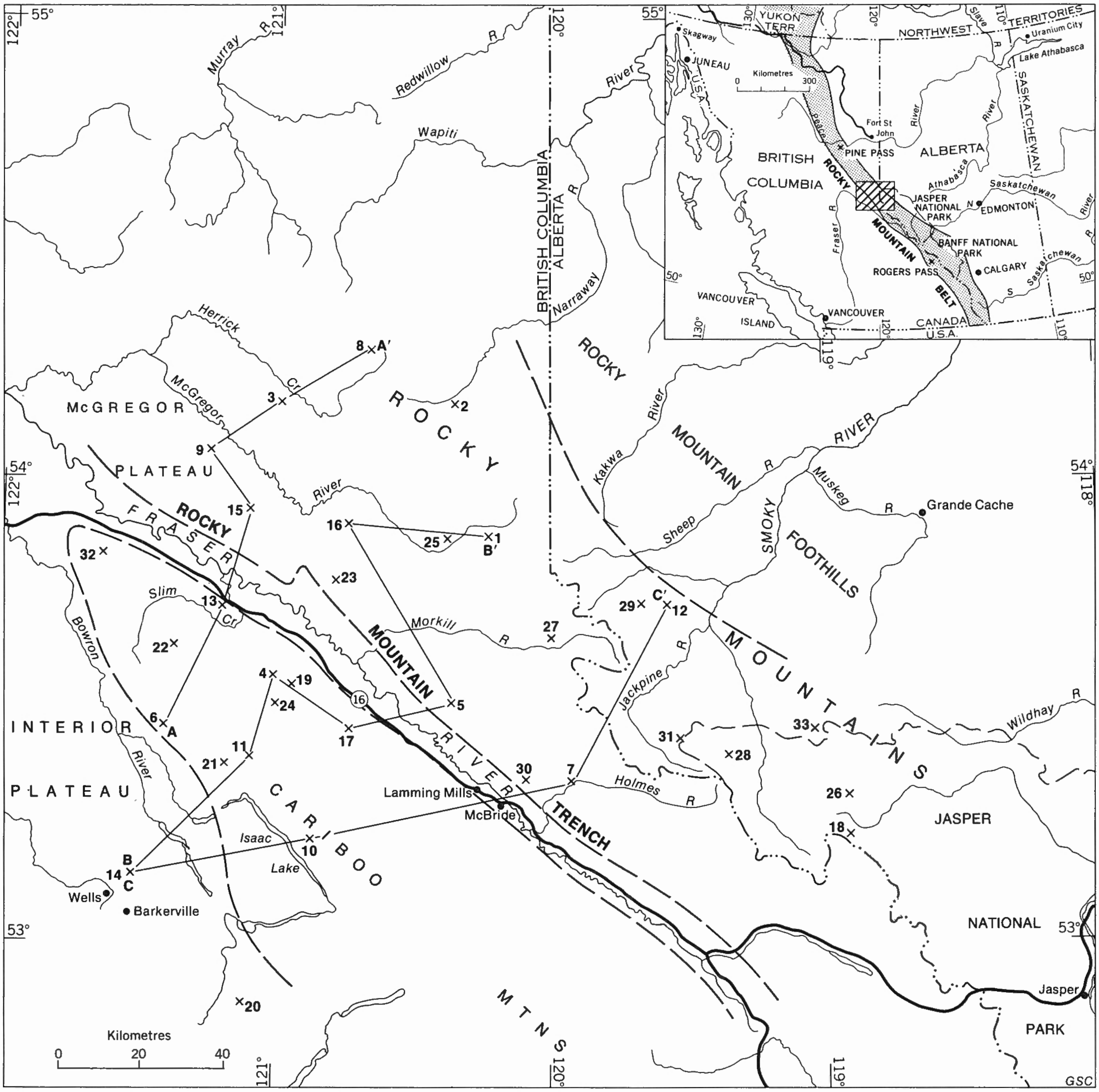


FIGURE 1. Index map showing location of study-area, physiographic elements, stratigraphic control points and lines of profiles. (Numbers refer to sections and localities listed in Appendix A).

of the northern Cariboo Mountains in 1966, Mountjoy recognized the similarity of the higher carbonate unit to the Mural Formation of the Rocky Mountains, and of the Yanks Peak Quartzite to the McNaughton Formation. The need for a regional stratigraphic study to correlate the strata from one range to the other across the Rocky Mountain Trench was realized, and led to the present study.

The writer's Ph.D. thesis (Young, 1969) was concerned principally with the problem of correlation, and a summary account of stratigraphic and sedimentological findings was given in the geological report on the McBride map-area by Campbell *et al.* (1973). The present report integrates data and interpretations from the Ph.D. thesis with data gathered subsequently, and highlights the sedimentology of the McNaughton Formation and correlative units in the Cariboo Mountains.

ACKNOWLEDGMENTS

The writer is grateful to both E.W. Mountjoy and R.B. Campbell for conceiving the original project and suggesting it to him as a Ph.D. thesis. Campbell's assistance and guidance in the field seasons of 1967 and 1968 were of inestimable value. The guidance and encouragement of E.W. Mountjoy, who supervised the thesis project at McGill University, also are acknowledged with sincere gratitude. He also offered unpublished stratigraphic data, photographs, and observations on the structural geology of the region.

Short periods of field work were undertaken in 1970, 1971 and 1973 while the writer was a guest in the camps of G.C. Taylor and D.F. Stott. The writer is grateful to them both for recommending continued patronage of the project by the Geological Survey of Canada.

Grateful recognition is made of the assistance given by all those who helped with the field work, especially C.P. Watson, P. Tredger, B. Bimm, K.R. Wood, Z. Hadnagy and T.P. Poulton.

Thanks are extended also to Shell Canada Limited for the use of unpublished stratigraphic information on upper Proterozoic and Lower Cambrian rocks of the Rocky Mountain region and for the loan of rock specimens.

The constructive critical reviews of this manuscript by J.D. Aitken and R.L. Christie led to great improvements in its organization and clarity, and to substantial refinements of some of my original opinions.

CHAPTER II

STRUCTURAL AND STRATIGRAPHIC SETTINGS

TECTONIC AND STRATIGRAPHIC BACKGROUND

Gabrielse (1972) and Monger *et al.* (1972) interpreted the Purcell Supergroup, and Stewart (1972) the Windermere Supergroup, to mark initial sedimentation into a newly formed oceanic rift in late Proterozoic time. Although attractive in terms of modern plate tectonics theory, this hypothesis is not supported strongly by evidence in the rocks themselves. The Purcell and particularly the Windermere provide no evidence of an extensive landmass throughout the length of the Cordillera which may have formed a source-area on the western side of the supposed rift. Nor is there evidence that the Proterozoic sedimentary rocks rest on oceanic crust; on the contrary, in the southern Canadian Cordillera, fragmentary data suggest the existence of a widespread granitoid substratum (Campbell, 1973; Wanless and Reesor, 1975).

The Windermere basin in the southeastern Canadian Cordillera resulted from profound subsidence of the craton margin following the East Kootenay Orogeny (White, 1959), which deformed and uplifted parts of the Purcell Supergroup. The thick sequence of shale, immature terrigenous clastics, and minor amounts of carbonate rock that forms the Windermere Supergroup was deposited in a trough extending throughout the length of the Cordillera (Gabrielse, 1972). The continental-terrace wedge that was built out from the craton margin during Windermere time consists of a general sequence of facies that is surprisingly similar throughout the Cordillera. This sequence consists mainly of deep-water sediments, including diamictites and poorly sorted grit beds in the lower but major part of the succession, followed by a thick shale division containing local, shallow-water carbonate units near the top of the sequence (Young *et al.*, 1973). Maximum thickness of the Windermere in the southern Cordillera apparently occurs within the western part of the study-area, where 6 km (3.7 miles) of sedimentary rocks accumulated (Fig. 2).

In this early history of the Cordilleran miogeocline, the Gog Group constitutes a depostional interval of transitional character between mainly deep water sedimentation below, and dominantly platform carbonate deposition above (Fig. 2). The Gog Group and its equivalents in the Cariboo Group form a second, dominantly quartz-clastic continental-terrace wedge of principally alluvial and shallow-marine character. The various small uplifts west of the craton-margin and the larger upwarp of the margin itself, expressed in the stratigraphy of the McNaughton Formation and its equivalent to the west, attest to the mildly unstable tectonic condition of the region during this transitional period.

The Gog quartzite outcrops fairly continuously in the Rocky Mountains from the type section at Mount Assiniboine, south of Banff, Alberta, northwest to the Pine Pass area (Fig. 1), a distance of 700 km (435 miles). Farther northwest, the Gog grades into the upper part of the Misinchinka Group (Gabrielse, 1975). In the Rogers Pass area (Fig. 1, inset map), 320 km (19.9 miles) southwest of the study-area, similar rocks of equivalent age and in various states of metamorphism are known as the Hamill Group.

A thick sequence of Middle Cambrian to Lower Ordovician carbonate and shale formations, ranging from the Tatei-Chetang Formation at the base to the Skoki Formation at the top, conformably overlies the Gog Group. This sequence is markedly cyclic in character (Aitken, 1966), and represents prolonged sedimentation on a shallow-marine shelf, largely uncontaminated by arenaceous terrigenous clastics.

The Gog and Windermere sequences thin abruptly eastward within the thrust belt of the Rocky Mountains (*see* Wheeler *et al.*, 1972, Fig. 3). Although the relationship of the Gog quartzite to the Basal sandstone unit of the Alberta Basin is not well established (Pugh, 1971, 1975), it is believed that east of the mountains the oldest strata above the Precambrian basement are Middle Cambrian in age (Aitken, 1968; Pugh, 1971, 1975).

Stratigraphy of McNaughton Formation and related units

Upper Miette Group

The stratigraphy of the upper part of the Miette Group is complex, as shown by the local distribution of various units and their wide variations in thickness (Young, 1972b); thus, more field studies are required before formal nomenclature can be established.

In the southern Pine Pass area, northwest of the study-area, a unit of interbedded pelite and quartzite, approximately 300 m (984 ft) thick, was mapped as upper

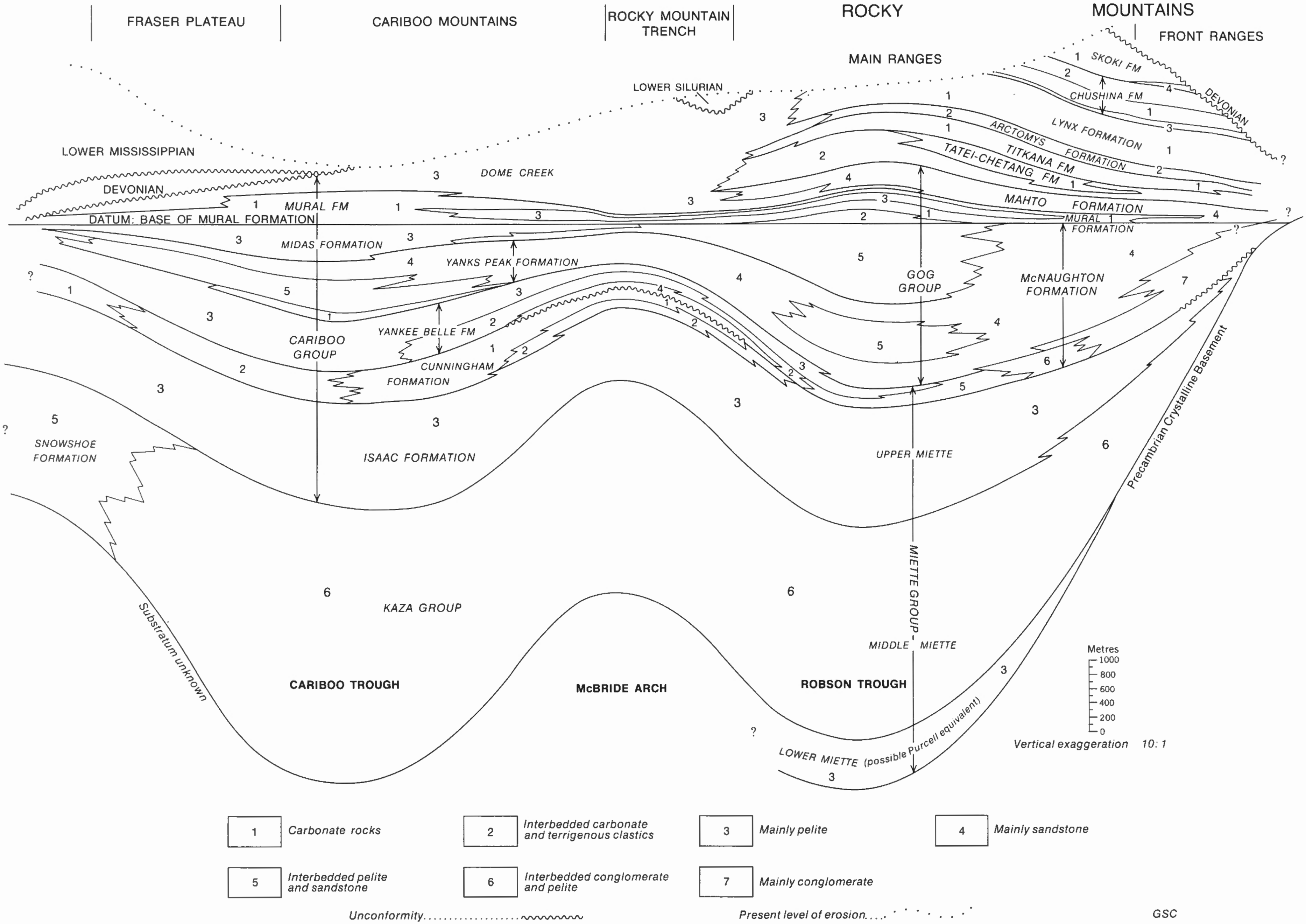


FIGURE 2. Restored stratigraphic profile of Hadrynian to Ordovician rocks, eastern Cordillera at approximate Latitude 54°N.

Miette Group (G.C. Taylor, pers. com., 1973). However, abundant *Cruziana* trails and other trace fossils of Lower Cambrian affinity have been found by the writer in these rocks, and these beds can be assigned now to the upper McNaughton Formation. Hence, the suggestion by Slind and Perkins (1966) that the McNaughton thins to 261 m (855 ft) at Pine Pass must be amended to at least 560 m (1837 ft). However, the absence of an exposed base of the formation in the Murray Range at Pine Pass still leaves open to question the actual thickness of the McNaughton in that area.

McNaughton Formation

The McNaughton Formation is the lowest and thickest formation of the Gog Group (Table 1) in the Rocky Mountains northwest of Jasper National Park. Its type section is located at Mount McNaughton, near the headwaters of the Fraser River, at approximately Latitude 53°00'N, Longitude 118°45'W.

The basal contact of the McNaughton Formation generally is abrupt and, locally, there is obvious scouring of underlying Miette Group pelite. The lowest beds of a continuous, dominantly conglomerate or quartzite succession define the base of the McNaughton, and this succession commonly overlies a thick slaty shale unit belonging to the Miette Group. This definition differs somewhat from that used by Palonen (1976) in the Jasper Park region. He placed feldspathic, conglomeratic quartzite of the Jasper Formation, a unit probably correlative with the basal conglomeratic part of the McNaughton Formation of this study, within the Miette Group. This decision was based largely on the presence of an unconformity at the base of the Gog Group in the Lake Louise area (Aitken, 1969), and the absence of the Jasper Formation above the unconformity in that area. However, in the Jasper area (Charlesworth *et al.*, 1967) and at localities farther northwest (this study), the Jasper Formation or its equivalents commonly grade upward over a thick interval from feldspathic, conglomeratic quartzite into nearly pure quartzarenite (*see* Fig. 4, Bastille Creek section), and evidence for an unconformity at the top of the feldspathic quartzites is entirely lacking. Hence, inclusion of these rocks into the Gog Group is essential for geological mapping and basin analysis.

In the Robson Synclinorium, the basal contact is more difficult to define because of numerous arenaceous rocks in the immediately underlying Miette Group. It seems probable that the contact is diachronous from east to west (Fig. 2), such that the basal McNaughton beds are older in the eastern part of the area than those in the western part. Direct evidence for this hypothesis is lacking, but the suggestion is based on the depositional model which is developed in this paper. Evidence for a regional disconformity is lacking, although great variations in the thickness of the upper shale unit of the Miette Group in eastern outcrops support the conclusion for the existence of an interval of erosion at the top of the Miette prior to McNaughton deposition in that area. This is parcticularly true also over McBride Arch (Fig. 2), along the outcrop belt parallel and immediately adjacent to the east side of the Rocky Mountain Trench. Sudden changes in thickness of the McNaughton along this belt (Fig. 6) indicate that parts of the arch were uplifted and eroded prior to and during McNaughton sedimentation.

The McNaughton Formation is capped, in the northern half of the area, by a bed, 1 to 5 m (3.3-16.4 ft) thick, of hematitic sandstone, which may be a paleosol. The basal calcareous sandstone and shale of the Mural Formation concordantly overlie this iron-rich bed, and the Mural, in turn, grades upward into quartzite of the Mahto Formation.

Cariboo Group

Strata correlative with the McNaughton Formation in the Cariboo Mountains form part of the Cariboo Group which includes, in ascending order, the Isaac, Cunningham, Yankee Belle, Yanks Peak, Midas, Mural and Dome Creek Formations (Table 1). The clastic part, of interest in this report, comprises the upper Yankee Belle, Yanks Peak, and Midas Formations. Other parts of the group include units of various types of limestone, dolostone, and shale. The entire group was deposited essentially without interruption, except for a local disconformity between the Cunningham and Yankee Belle Formations, and attains a maximum thickness of 5100 m (16 732 ft) in western Cariboo Mountains (Fig. 2).

Subdivisions and correlations

Correlations between the McNaughton Formation and equivalent parts of the Cariboo Group are based primarily on the biostratigraphic and lithologic correlation of the Mural Formation, which directly overlies each sequence. Below the Mural, correlations are based on lithologic similarities and stratigraphic sequence and, thus, are not completely reliable. However, an especially convincing correlation between the Rocky Mountain and Cariboo Mountain sequences can be made based upon the succession at Holy Cross Mountain (Fig. 1, Sec. 23) (Young, 1972b). There, the thick unit of greenish-grey phyllite that underlies the McNaughton quartzite greatly resembles the Yankee Belle Formation. The phyllite unit is in turn underlain by 67 m (220 ft) of quartzitic sandstone, beneath which lie 135 m (443 ft) of dolostone and sandstone, both of which appear at the base of the Yankee Belle Formation on the opposite side of the Rocky Mountain Trench.

In this report, the McNaughton Formation and its western counterparts were divided into three intervals with similar thicknesses. Correlations of the boundaries of these intervals were made on cross-sections illustrating all important measured sections (e.g. Figs. 3-5). These intervals are termed informally the lower, middle and upper sequences, respectively. The lower sequence refers to the basal part of the McNaughton Formation, the upper part of the Miette Group in places, the upper part of the Yankee Belle Formation, and approximately the lowest third of the Yanks Peak Formation. The middle sequence includes the upper two thirds of the Yanks Peak Formation and the middle third of the McNaughton, approximately. The Midas Formation and upper third of the McNaughton constitute the upper sequence.

All three sequences generally commence at their bases with marine shale, which overlies littoral or nonmarine facies at the top of underlying sequences. These are interpreted as regional transgressions, above which progradation of coarse clastic sediments followed almost immediately in the cases of the lower two sequences. Progradation is not evident in the upper subdivision in the study-area. Sequence uniformity and

CARIBOO MOUNTAINS

Era	Period	Group	Formation	Lithology
PALEOZOIC	UPPER AND LOWER CAMBRIAN	CARIBOO GROUP	DOME CREEK FORMATION (0-200 m)	
			Gradational contact	
	LOWER CAMBRIAN		MURAL FM (150-600+ m)	Limestone, dolostone, shale, minor siltstone
			Conformable contact	
	? LOWER CAMBRIAN		MIDAS FM (90-300+ m)	Shale, siltstone, minor sandstone
			Conformable contact	
			YANKS PEAK FM (0-580 m)	Grey, white, pink,quartzite, minor silty shale
			Gradational contact	
			YANKEE BELLE FM (270-900 m)	Interbedded shale, siltstone, limestone, minor sandstone and dolostone
			Gradational to disconformable contact (?)	
PROTEROZOIC	HADRYNIAN		CUNNINGHAM FORMATION (? 60-550 m)	Limestone, minor grey shale; dolostone near Rocky Mountain Trench
			Gradational contact	
			ISAAC FM (? 900-1500 m)	Grey to black phyllite and shale, minor siltstone, sandstone and limestone
		Gradational contact		
		KAZA GROUP (includes SNOWSHOE FM) (3600+ m)		Alternating units of feldspathic grit and grey phyllite or schist; minor limestone and conglomerate
Base not exposed				

ROCKY MOUNTAINS

Era	Period	Group	Formation	Lithology
PALEOZOIC	MIDDLE CAMBRIAN	TATEI-CHETANG FORMATION (60-360 m)		Banded slaty shale, argillaceous limestone, micritic limestone, maroon to grey-brown shale; shaly facies on Bearpaw Ridge?
		Conformable contact		
	LOWER CAMBRIAN	GOG GROUP	MAHTO FM (245-300 m)	Grey to pink quartzite, minor siltstone and shale
			Gradational contact	
			MURAL FM (215-380 m)	Limestone, dolostone, green to grey shale, sandstone, minor siltstone
			Conformable contact	
	? LOWER CAMBRIAN		McNAUGHTON FORMATION (600-2300 m)	Quartzite, feldspathic and pebbly at base; interbedded shale and fine-grained quartzite (Holmes River Member)
		Locally disconformable contact		
		MIETTE GROUP (WINDERMERE SUPERGROUP)	Undivided quartz sandstone; olive to brown mudstone; trails (0-550 m)	
			Conformable contact	
PROTEROZOIC	HADRYNIAN		BYNG FM (0-300 m)	Dolostone, pale grey and yellow, in part sandy
			Unnamed grey mudstone, siltstone, and minor sandstone, in part calcareous at top (210-550 m)	
			Conformable contact	
			MIDDLE MIETTE (2100-2700± m)	Coarse, arkosic, partly pebbly sandstone (grit), grey phyllitic shale
			Conformable contact	
			LOWER MIETTE (600-1200± m)	Black slaty shale
Base not exposed				

GSC

TABLE 1. Table of formations.

the presence of medium-scale cycles in the Cariboo Group permit fairly straightforward correlations among sections in the Cariboo Mountains, but the absence of these features in the McNaughton Formation results in considerable uncertainty and subjectivity. Eastern sections in particular were subdivided arbitrarily into three approximately equally thick parts, at changes in the vertical succession of facies.

The lower sequence is characterized by the presence of green quartzite and phyllitic shale, and the common appearance of limonitic patches and speckles in the arenaceous rocks. The limonite is apparently due to the weathering of pyrite crystals, ferroan carbonate cements, and detrital heavy minerals in these rocks. An overall coarsening-upward, probably shoaling trend forms the lower sequence in western sections of the McNaughton Formation and its equivalent strata in the Cariboo Group.

The middle sequence includes the majority of the Yanks Peak Formation and the middle, generally arenaceous part of the McNaughton Formation. Yellowish-grey to flesh-coloured quartzites are typical of this interval in the McNaughton whereas, in the Yanks Peak, red beds are common.

The upper sequence consists of relatively large amounts of shale, evidently due to a greater marine influence during deposition of the upper McNaughton and Midas Formations. Burrows and trails are far more abundant in this interval than in the underlying ones, and include *Cruziana,* which are unique to this interval.

Thickness variations

An isopach map (Fig. 6) was constructed from available measured sections, including several supplied by Shell Canada Limited, as well as mapping and air photo data, in order to illustrate large-scale variations in the thickness of the McNaughton Formation and the correlative part of the Cariboo Group. These variations reflect major morphologic elements of the sedimentary basin, since no significant erosion occurred within or at the top of the succession.

The McNaughton gradually thickens toward the southwest to a maximum of 2250 m (7400 ft) in a trough-like feature that trends parallel to the depositional strike and coincides approximately with the Robson Synclinorium (Campbell *et al.*, 1973). Hence, it is named here the Robson Trough (Fig. 2). Abrupt thinning of the succession southeast of this trough marks the flank of the McBride Arch, a positive, domal element centred approximately within the present-day Rocky Mountain Trench. The sudden thickness changes along the axis of the Robson Synclinorium near McBride are attributed to mapped north-trending normal faults which were active probably just prior to McNaughton deposition. Other ancient faults may be present around the periphery of the arch, but have not been identified. An important aspect of this arch, highlighted by the 500 m contour northwest of McBride, is that its axis, which runs oblique to the Rocky Mountain Trench (Fig. 6), apparently has not been offset, indicating that strike-slip displacements have not taken place within the trench.

A slight trough, here named the Cariboo Trough, is indicated in the western Cariboo Mountains where at least 1200 m (4000 ft) of the Cariboo clastic units are preserved (Fig. 2). The 500 m contour that passes through the Wells area probably approximates the margin of the shallow-marine shelf on which these clastics were deposited, as rocks of deep-water aspect become abundant in this vicinity and farther west. This line agrees approximately with the locus of the shelf edge during Mural time as suggested by the presence of archaeocyathids (Stelck and Hedinger, 1975). More data are needed to confirm the indication that the northern Cariboo Mountains occupy the site of a westward-projecting salient or plateau along the ancient continental margin.

Age

The McNaughton Formation and equivalent units in the Cariboo Group lie directly below strata containing the oldest shelly fossils in the region. The latter include trilobites and archaeocyathids, assigned to the *Fallotaspis* Zone of the Early Cambrian by Fritz (1975), whereas the McNaughton occupies most of an unnamed zone characterized by metazoan trace fossils (Young, 1972a) in its marine facies. Such a zone is typical of transitional intervals between the Proterozoic and Cambrian around the world (Daily, 1972; Stanley, 1976), but there is as yet no international agreement on either a suitable name, or the time-stratigraphic placement of this interval. Most workers (e.g. Cowie and Glaessner, 1975) agree that a definition based on fossil remains with a suitable stratotype is desirable, and the McBride area sequence has been suggested casually (Cloud, 1973) as a possible stratotype for North America.

More small fossils as well as trace fossils (Palonen, 1976) are being discovered continually in this sequence, and more field work and research are required to document the local biostratigraphy. Forms resembling *Platysolenites* sp. were found in upper Miette Group strata by the writer during the early stages of field work, and Professor Durham (written com., 1976, 1977) has found fossils resembling *Campitius* and *Volborthella* spp. from the upper Miette. This is also the stratigraphic interval in which abundant intrastratal trails, including *Didymaulichnus miettensis* Young, are common. Because these fossils are typical of the Tommotian and even younger stages of the Lower Cambrian (Daily, 1972), the entire McNaughton Formation, as well as the upper part of the Miette Group down to a level equivalent to or coincident with the top of the Byng Formation [carbonate division of the Windermere Supergroup (Young *et al.*, 1973)], may be equivalent to the Russian Tommotian Stage. However, because of the present uncertainty regarding the base of the Cambrian, the McNaughton is designated here "?Early Cambrian" in age. The writer follows the proposal of Cloud (1973) that this fossiliferous interval be placed within the Paleozoic Era; hence, the Proterozoic-Paleozoic boundary also is placed tentatively at the top of the Byng Formation.

STRUCTURAL SETTING

The study-area straddles the Rocky Mountain, Rocky Mountain Trench, and Cariboo Mountain structural belts. The general structural characteristics of each of these belts are given in the following sections, and some of the current tectonic models are discussed. New observations on structural features in the western Rocky Mountains are described and used to support the tectonic model proposed by Campbell (1973). From this model a palinspastic base map was constructed for the Rocky Mountain structural belt.

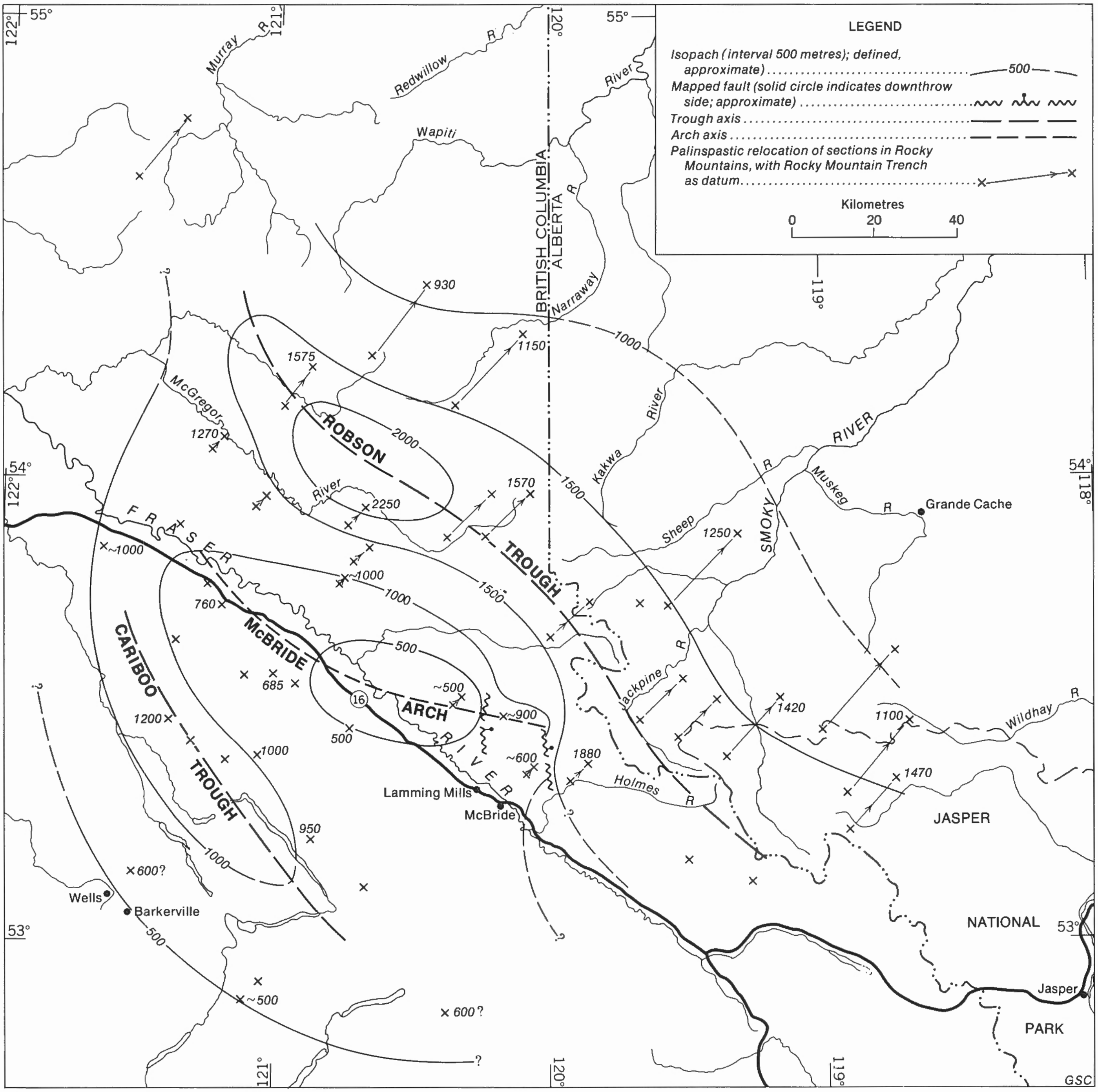


FIGURE 6. Isopach map of McNaughton Formation and correlative units of the Cariboo Group.

Northern Cariboo Mountains and Rocky Mountain Trench

A series of northwest-plunging anticlinoria and synclinoria that are well defined in the south but flatten out and become indistinct northward comprises the primary structural elements of northern Cariboo Mountains. Vertical faults trending mainly northwest and north become more numerous northward in the brittle rocks of the Cariboo Group. Campbell (1970) believes that these faults represent brittle fracture of the youngest rocks above plastically deformed, more deeply seated rocks which appear at the surface, up-plunge to the south.

Because the Cariboo Mountains have not undergone significant compression, no palinspastic restoration was attempted for that area.

The structural complexities within the Rocky Mountain Trench are largely undeciphered due to poor bedrock exposures, but extremely sheared rocks with vertically oriented, probably compressional elements seem to be dominant. Faults in the Rocky Mountain Trench are not necessarily more significant than those in the adjacent Rocky Mountains or Cariboo Mountains, although stratigraphic differences between the Cariboo and Gog Groups (Fig. 2) suggest the possibility that the trench is the locus of major fault displacements. Because of the present lack of understanding about the structural makeup of the trench, a palinspastic reconstruction is not attempted here.

The Cariboo Mountains and Rocky Mountain Trench merge gradually northwestward into the Interior Plateau (Fig. 1), which is predominantly forested, and affords little information on stratigraphy or structural geology.

Rocky Mountains

Description and tectonic models

The Rocky Mountain structural belt (Marginal Zone) within the study-area is dominated by northwest-trending anticlinoria and synclinoria on which are superimposed numerous steep faults. In the central Rocky Mountains along the northeast margin of the Gog outcrop belt, supracrustal shortening along imbricate thrust slices is indicated from geological and geophysical evidence (Price and Mountjoy, 1970). Toward the Rocky Mountain Trench the rocks become increasingly deformed in association with closely spaced, overturned folds and steep faults. Structural dislocations and strain phenomena in this area obscure primary sedimentary structures important to sedimentological analyses.

The study-area is located in a zone transitional structurally between the southern and northern Rocky Mountains. Thrusting and detachment of supracrustal rocks from the basement characterize the mode of mass transfer in the southern Rocky Mountains, whereas folding and faulting played equal roles in the deformation of the northern Rockies (Stott and Taylor, 1972).

Campbell (1973) believes that, in the present area, a tectonic belt including the core zone (Omineca Crystalline Belt) of the Columbian Orogen, the Rocky Mountain Trench, and the Rocky Mountain Main Ranges was influenced predominantly by vertical crustal movements, and was not moved eastward by an amount equal to the shortening in the thrust belt of the eastern Rocky Mountains. This hypothesis requires updoming of the Precambrian basement, at least within the core zone of the orogen. Evidence that upwelling of the crystalline basement indeed occurred subsequently was provided by a zircon age of 1960 m.y. from gneiss of the Shuswap Metamorphic Complex (Wanless and Reesor, 1975). Campbell indicated a fundamental boundary between an area in which vertical tectonism dominated and one displaying mainly northeastward thrusting. This boundary lies along the line of major faults (e.g. Snake Indian, Backrange Faults) that separate the Main Ranges from the Front Ranges, and which themselves exhibit reverse separation.

An alternative model of deep-seated tectonics advocated by Price and Mountjoy (1970) involves crustal shortening along imbricate thrust sheets, which merge downward in a zone of major detachment on the upper surface of the crystalline basement. Mountjoy suggested that the thrust faults extend beneath the Rocky Mountain Trench well into the Cariboo Mountains (*see* Campbell *et al.*, 1973, p. 73; Wheeler *et al.*, 1972, Fig. 3, Sec. P-P'). The amount of shortening determined from balanced cross-sections provided by the Price and Mountjoy model is considerably greater than that required by Campbell's model. New evidence is presented below that favours Campbell's model, and supports its usage in the palinspastic reconstruction proposed for stratigraphic mapping of the McNaughton Formation.

New observations of structures in western Rocky Mountains near Latitude 54° North

Since the publication of the report on the geology of the McBride map-area (Campbell *et al.*, 1973), the writer has made several observations of structural elements in the Rocky Mountain Trench and in the Torpy River area which allow revisions to published cross-sections, and bear on the problem of palinspastic reconstruction. On the ridge immediately northeast of lower Torpy River (approximately Lat. 53°57'N, Long. 121°06'W), McNaughton strata form a syncline overturned toward the southwest, and not a monoclinal panel dipping southwesterly as shown on Map 1356A (*in* Campbell *et al.*, 1973) (Fig. 6b). Beds of McNaughton quartzite outcrop low on the valley wall immediately southwest of Torpy River, and dip at low to moderate angles beneath younger lower Paleozoic rocks.

Outcrops on low ridges and in the ballast quarry of the Canadian National Railway near lower Ptarmigan Creek in the Rocky Mountain Trench also were re-examined. The writer believes that the limestone in the ballast quarry east of Highway 16 is of the Cunningham Formation, and not the Mural Formation as depicted on Map 1356A (*op. cit.*). Also, most of the ridge west of the highway consists of deformed rocks of the Yankee Belle Formation rather than the Yanks Peak Formation. These observations require alterations of structural profiles D-D' (left end), J-J' (right end) in Campbell *et al.* (1973), and B-B' (included as right end of Fig. 6a, this report).

The structural profile (Fig. 7a) constructed from new data as outlined above reveals that folds are more important in the western Rocky Mountains near Latitude 54° North than hitherto recognized. Southwestward overturning of many of these folds would be dynamically consistent with a low-angle, westward-dipping décollement, but also would be expected if the central to eastern parts of the Main Ranges in this area had been uplifted. This uplift may have been localized in part along the Snake Indian Fault, the hanging wall of which, at Latitude 54°15'N, consists of a sequence of limestone and dolomite (Taylor, 1971; pers. com., 1973), possibly pre-Windermere in age. Basement rocks, which probably lie not far below the exposed Proterozoic carbonate beds, likely would have been involved in such an uplift.

Basement involvement in the Mesozoic tectonic deformation of this region also is favoured because of disruption of the basement surface during late Proterozoic faulting and differential subsidence. Abrupt and large thickness variations of the McNaughton Formation along its western outcrop belt (Fig. 2) in Robson Synclinorium attest to this instability. The presence of small cross-cutting faults at the loci of some of these thickness changes [e.g. the fault mapped 11.3 km (7 miles) northeast of McBride] suggests that they may be ancient features, active during sedimentation in earliest Cambrian time. Although they may be listric in nature and peter out within the Miette Group, these faults also may have involved the crystalline basement. The inferred irregularity of the basement surface imposes serious constraints on the possibility of its passiveness during Columbian and Laramide compression of the crust.

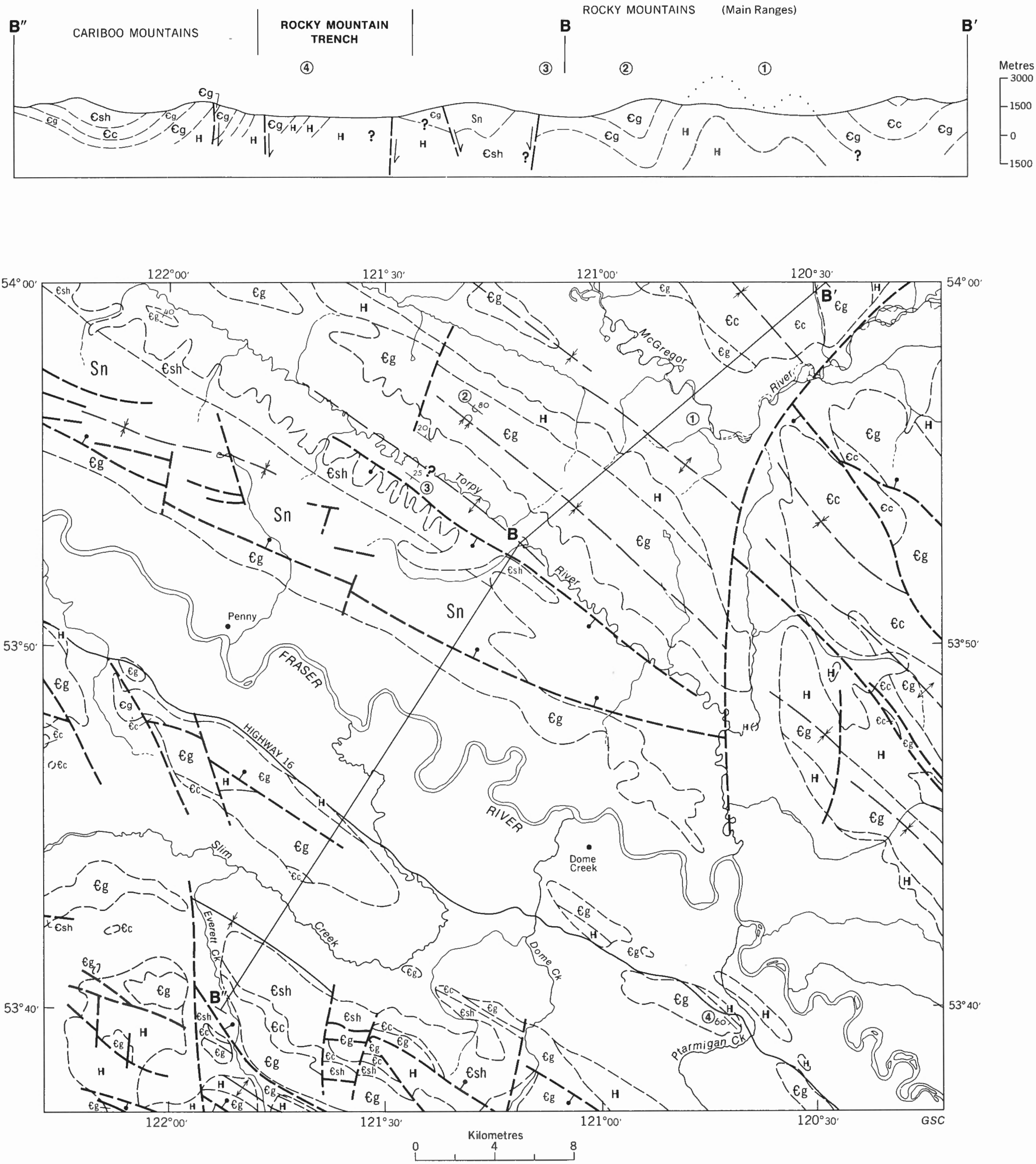


FIGURE 7. Revised structural geology of northern McBride map-area (after Campbell *et al.*, 1973).

In view of the above geometric features, as well as the supportive arguments given by Campbell (1973), his tectonic model is favoured by the writer, and is used herein to construct a palinspastic base-map.

Palinspastic reconstruction

Palinspastic extension of the crust in the Rocky Mountain portion of the study-area is required to allow for post-depositional northeast-southwest shortening. This reconstruction simply expands the Rocky Mountain portion of the basin to its original extent and does not reposition localities to their original sites with respect to the Canadian Shield. Thus, localities in the Rocky Mountains are shifted northeastward with respect to the northeastern margin of the Rocky Mountain Trench, which is used as a datum (Fig. 6). Campbell's tectonic model is used as a basis for this reconstruction, utilizing his figured structural profile and its derived palinspastic stratigraphic cross-section (Campbell, 1973, Figs. 3, 4).

Displacements were determined by opening folds without accounting for penetrative strain and, east of Snake Indian Fault, by measuring the overlap of strata between the hanging walls and foot walls of thrust faults. By this method, localities within the Main Ranges are extended 1.35 times their present distance from the trench, and those in the Front Ranges, 1.5 times. Hence, the Mount De Veber section, which is the farthest from the trench, is restored to a distance of 77 km (48 miles) as compared with its present distance of 53 km (34 miles) from the trench.

Sn	*Silurian (mainly Nonda Formation)*
Ꞓsh	*Cambrian and ? Ordovician shale (Dome Creek Fm, unnamed unit)*
Ꞓc	*Cambrian carbonate rocks mainly (Mural, Titkana, Lynx, Mahto Fms)*
Ꞓg	*Lower Cambrian quartzite (McNaughton, Yanks Peak, Midas Fms)*
H	*Hadrynian (Yankee Belle, Cunningham, Isaac Fms, Miette Group)*

Geological boundary (approximate)

Bedding top known (inclined) 20

Trend line (section only)

Fault (solid circle indicates downthrown side)

Anticline axis

Syncline axis

Line of section B B'

NOTES

No reverse fault required here, as on Map 1356A, and cross-section B-B', in Campbell *et al.* (1973) ..... ①

Structure revised from recent field observations - steep to overturned eastern limb of fold in McNaughton Fm ..... ②

Gog Group quartzite (McNaughton or Mahto) outcrops in valley floor, dips gently to moderately southwest ..... ③

Cunningham and Yankee Belle Formations underlie mapped Yanks Peak Formation near Ptarmigan Creek ..... ④

Legend for Figure 7 *GSC*

CHAPTER III

SEDIMENTOLOGY OF THE McNAUGHTON FORMATION

INTRODUCTION

The sedimentology of the rocks under review is discussed in two chapters, the first dealing with the McNaughton Formation, and the second with equivalent formations to the west in the Cariboo Group. The sedimentological analyses in these chapters include descriptions and interpretations of major facies, followed by the development of depositional models by means of vertical sequence analysis. In the case of the McNaughton Formation, Markov chain analyses are used to indicate cyclic trends and facies associations. Sections on the petrography of these rocks provide data on which to base interpretations of source-area characteristics, weathering processes, and climate. Finally, a series of basin models is integrated from all lines of evidence, providing interpretation of source-area and depositional environments, paleodispersal trends, and major physical processes active during deposition.

The McNaughton Formation of the study-area is divided here, as an aid to sedimentological description, into eight facies. These include:

(i) the conglomeratic quartzite,

(ii) the planar crossbedded quartzite,

(iii) the massive quartzite,

(iv) the festoon crossbedded quartzite,

(v) the interbedded quartzite-pelite,

(vi) the flaser quartzite,

(vii) the mixed pelite-sandstone, and

(viii) the pelite facies.

The conglomeratic quartzite facies is subdivided into two subfacies, including the alternating conglomerate-pelite, and the uniform conglomeratic quartzite subfacies. Two other facies were noted outside the limits of the study-area and are described following the descriptions of the above in order to help complete the picture of the McNaughton Formation. The first of these is a red, trough crossbedded quartzite facies, similar to the red-bed facies of the Cariboo Group, and the second is a carbonaceous shale-siltstone-sandstone facies.

In the following sections, several descriptive classifications are used. Bedding thicknesses are classified according to the scheme proposed by McKee and Weir (1953) and, in addition, massive bedding is used to denote beds thicker than 1.5 m (5.0 ft). Several classifications of cross-stratification are currently in vogue and the one used here, adapted from Dalziel and Dott (1970), is relatively simple. The four main types of crossbedding include:

(i) planar-parallel (or planar-tabular),

(ii) planar-wedge,

(iii) trough-parallel, and

(iv) trough-wedge (or festoon).

Size classes of cross-stratification follow the recommendations of Conybeare and Crook (1968), as below:

Small scale	- up to 5 cm (<2 in) thick
Medium scale	- 5 cm to 2 m (2 in-6.5 ft) thick
Large scale	- 2 to 8 m (6.5-26 ft) thick
Very large scale	- over 8 m (>26 ft) thick

The Wentworth grade scale for grain sizes is employed throughout.

FACIES DESCRIPTIONS AND INTERPRETATIONS

Conglomeratic quartzite facies

Conglomeratic quartzite was observed only in the easternmost outcrops of the McNaughton Formation, and occurs only at the base of the formation (Fig. 2). An abrupt, locally erosional contact separates this facies from underlying pelitic strata of the Miette Group.

Conglomeratic quartzite alternates with units of pelite and argillaceous sandstone at Bastille Creek, where these rocks form a member 253 m (830 ft) thick (Fig. 8). This member is overlain by a uniform conglomeratic quartzite, 177 m (384 ft) thick, which in turn grades gradually upward into planar crossbedded quartzite. The uniform mode is the more typical subfacies, and is described and interpreted separately from the alternating conglomerate-pelite subfacies.

Alternating conglomerate-pelite subfacies

The alternating conglomerate-pelite subfacies consists of lenticular conglomeratic units, varying from a few to 40 m (130 ft) thick, which interfinger with similarly thick units of unfossiliferous, thinly bedded, silty shale and sandstone (Fig. 8) (*see* Pelite Facies below).

The conglomeratic facies includes quartz-pebble, sandy conglomerate (Figs. 9, 10) and pebbly, granular, feldspathic, quartzitic sandstone, generally medium to very coarse grained, and poorly to moderately sorted. Large rip-up clasts of shale are common in the lower parts of conglomeratic units, or immediately above thin shale interbeds within these units. Some beds display thick graded sets, but most appear homogeneous, or show irregular vertical and lateral textural variations between granular sandstone and pebble conglomerate (Fig. 10). Some massive beds are capped by a few centimetres of laminated, silty sandstone. No cross-stratification was observed in these units, and no data on pebble orientations are available.

Conglomeratic units and individual massive beds typically have abrupt basal contacts which, in part, show broad, shallow groove-casts up to 2 m (6.5 ft) in width. These features, as well as truncated stratification of underlying beds, and large tabular shale-clasts, attest to scouring by the flow that entrained the rudaceous sediments.

Uniform conglomeratic quartzite subfacies

Uniform conglomeratic quartzite forms thick to massive beds stacked almost without interruption in units up to 205 m (670 ft) thick as in the Mount De Veber area (Fig. 5). Two main textural types of quartzite are present, including a moderately well sorted, coarse-grained quartzite with pebbly layers, and a poorly sorted, granular-pebbly variety having 10 to 20 per cent sericitized mud matrix.

The first type appears mainly homogeneous in texture, except for crude horizontal lamination, which is commonly near tops of beds, and the presence of fine-grained sandstone at the tops of beds. Basal scours are present, but uncommon. In places, graded sets, approximately 6 cm (0.2 ft) thick, are superimposed one above the other within thick beds. Pebble layers, only one clast-diameter thick, occur commonly but irregularly and consist of faceted quartzose pebbles up to 60 mm (2.4 in) long in apparently random orientations. Pebbles also exist in isolation within coarse-grained quartzite. One observed bed of granular quartzite exhibited low-angle, trough crossbedding, a structure likely the result of migrating dunes (Harms *in* Harms *et al.*, 1975).

The poorly sorted quartzite is relatively uncommon, appears in massive beds, and is similar to the conglomeratic quartzite of the alternating conglomerate-pelite subfacies.

Interpretation

It is difficult to be certain of the origin of the alternating conglomeratic quartzite-pelite subfacies based solely on features in the quartzite beds. The lack of crossbedding, the graded sets, the scoured basal contacts, and the homogeneous character suggest a resedimented origin (Walker *in* Harms *et al.*, 1975), but a more definite interpretation requires taking into account the stratigraphic context of the facies, reviewed later in the paper.

The crude lamination common in the uniform conglomeratic quartzite subfacies suggests high-velocity currents of the upper flat-bed phase (Southard *in* Harms *et al.*, 1975). Other evidence of strong traction currents includes asymptotic crossbedding, and pebble layers of single-clast thickness, possibly representing lag deposits.

The uniform conglomeratic quartzite subfacies grades upward into and interfingers with planar crossbedded quartzite. The gradational vertical succession from one subfacies into another at the base of the McNaughton implies that they share a close genetic relationship, which is discussed later in the report.

Planar crossbedded quartzite facies

Description

Planar crossbedded quartzite is the dominant facies of the McNaughton Formation in its eastern outcrops and forms most of the formation there. In the western Rocky Mountains, this facies comprises much of the lower sequence of the formation and forms single units ranging in thickness from 100 to 450 m (328-1475 ft). In nearly all sections studied, the massive quartzite facies and interbedded quartzite-pelite facies interfinger with, or grade vertically into, the planar crossbedded quartzite. Because of continuous gradations between facies, the planar crossbedded quartzite facies is difficult to distinguish, in places, from either of the former two, or from the festoon crossbedded quartzite facies.

FIGURE 8. Basal McNaughton Formation near Bastille Creek (Sec. 1; Figs. 1, 4) showing contact with Miette Group (arrow). Lenticular conglomeratic quartzite units alternate with pelite in interpreted fan-delta facies association above the contact. Uniform conglomeratic quartzite forms the unit at the summit of the ridge. GSC 199286.

This quartzite generally is well stratified, forming monotonous sequences of medium-bedded to massive beds (Fig. 11). Most of the beds are tabular, while others are discernibly wedge-shaped, or exhibit a pinch-and-swell form. Rare, discontinuous interbeds of silty shale or argillaceous sandstone, seldom greater than 0.3 m (1 ft) thick, typically are associated with this facies.

Planar crossbedding is the hallmark structure of this facies. Sets of planar cross-strata are stacked one above another and generally display planar, nearly parallel contacts (Fig. 12). Small-scale scours are minor and large-scale scours rare. Set thicknesses range mainly between 0.15 and 1.0 m (0.5-3.3 ft), with a few sets attaining thicknesses of 1.2 m (4 ft). Dip-directions of foresets are typically unimodal and consistent among sets at a given locality. At some localities, beds 1 m (3.3 ft) thick consist of a basal planar cross-laminated set overlain by a horizontally stratified set.

Trough crossbedding is relatively uncommon in this facies and is associated with planar crossbedding and scoured bedding contacts. Isolated, single lenticular sets up to 1 m (3.3 ft) thick occur, while some quartzite beds consist of composite planar and trough cross-bedded sets. A few very thick beds display crude lamination which is discernible because of subtle variations in grain-size.

Shaly intercalations in this facies are olive-grey, generally silty or silt-laminated, and rarely graded. Thin bands or beds of argillaceous, micaceous sandstone sometimes are included in these shaly interbeds. In one section, 10 m (33 ft) thick, rhythms are formed by repetitive, upward transitions from abundant shale and thin quartzite interbeds into pure, thickly bedded quartzite.

Load-casts, shale-clasts, and deformed lamination were observed only rarely, and no trace fossils were seen in this facies.

The quartzite of the planar crossbedded facies is typically pale grey to brownish grey, and rarely greenish grey in colour. In eastern outcrops in the lower half of the McNaughton, coarse to very coarse grain sizes prevail, with granule and rare pebble layers present, especially at the bases of beds and sets. Here the rock is slightly feldspathic and cemented by quartz overgrowths and minor sericitized argillaceous matrix. In the upper part of the formation and in western occurrences of the facies, the quartzite tends to be fine to medium grained, moderately to well sorted, highly quartzose, and hence very mature.

A granulometric analysis of Sample 446 YA-11 (Fig. 24) from the basal McNaughton Formation at the Holmes River section (Fig. 1, Loc. 7; Fig. 5) reveals a strong bimodality, reflecting a large, coarse traction-load population, a large suspension population, and a relatively small saltation population. Similar grain-size distributions have been attributed to fluvial deposition by Glaister and Nelson (1974, Fig. 5) and Moiola and Weiser (1968). On the other hand, an analysis of Sample 445 YA-2 from the upper McNaughton Formation of the Mount De Veber area (Fig. 24) indicates that this arenite is unimodal, well sorted, and medium to coarse grained, possibly due to reworking in a littoral

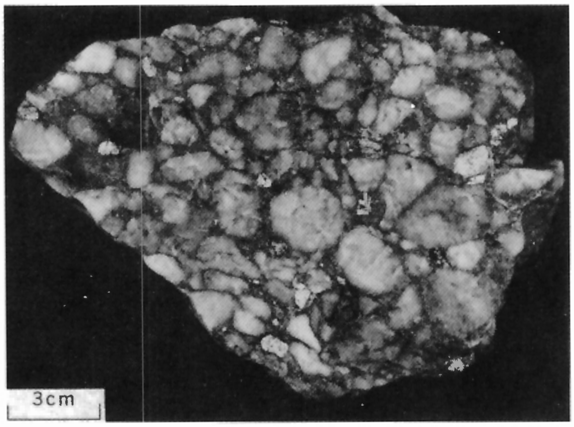


FIGURE 9. Clast-supported pebble conglomerate from base of the McNaughton Formation, Bastille Creek section. Vein quartz is predominant; feldspar is minor constituent. GSC 199268.

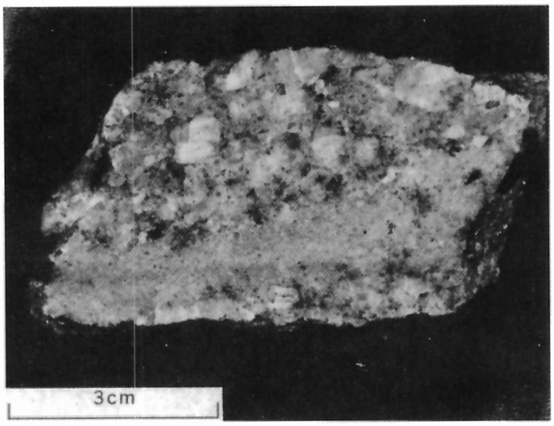


FIGURE 10. Greenish-grey conglomeratic quartzite from near base of the McNaughton Formation, Banff-Jasper Highway road cut near Athabasca Falls. GSC 199269.

environment. This sample was taken from a single bed of massive quartzite within a sequence dominated by the crossbedded quartzite, and illustrates the close relationship between these two facies.

Interpretation

The abundant planar crossbedding of this facies can be attributed to migrating sand waves (Southard *in* Harms *et al.*, 1975) of the type observed between current ripples and dunes in the progression of bed-forms associated with increasing current strength over a granular bed in the lower flow regime. Set thicknesses, planar internal laminae, and non-tangential relationships between laminae and basal surfaces of sets are typical features of straight-crested sand waves (*op. cit.*) or transverse bars of braided streams (Smith, 1970). Low-angle wedge sets and minor trough crossbedding noted in this facies probably represent transitional sand wave-to-dune and true dune bedforms, developed at higher current velocities than sand waves in sands of a given grain size. The horizontally laminated sets and beds represent either lower or upper flat bed phases; small-scale cross-lamination, associated with current ripples, is virtually absent because ripples do not form on granular materials coarser than about 0.6 mm (Costello, 1974). Flow depths probably were at least twice as great as the thicknesses of individual sets (Harms *in* Harms *et al.*, 1975).

Shaly interbeds attest to more tranquil depositional conditions, probably occurring during waning current flows and in standing pools of water.

Assemblages of planar crossbedding and horizontal stratification have been found associated commonly with sandy, braided rivers (Williams, 1966; Smith, 1970, 1972). Narrowly dispersed paleocurrent readings, such as those recorded from this facies, suggest migration of straight- to sinuous-crested transverse bars (Smith, 1972), as opposed to the more dispersed foreset orientations associated with combinations of transverse, linguoid, and longitudinal bars observed in modern braided streams (Walker, 1976). The postulated fluvial origin of this facies is supported by its lack of trace fossils and the few granulometric analyses.

Massive quartzite facies

Description

The massive quartzite facies appears in all sections studied as single beds or as homogeneous units ranging in thickness from about 10 to 160 m (33-526 ft). It is associated commonly with the planar crossbedded quartzite and the interbedded quartzite-pelite facies and, in some cases, displays characteristics gradational into those of either of these facies.

Its distinguishing characteristic is its imposing, massive units, as much as 8 m (26 ft) thick, which form very resistant, thick ledges on mountain-side outcrops. Thinner beds of less than 1 m (3.3 ft) in thickness also occur. Shale lenses and irregular shale partings occur within some units of massive quartzite at a few localities. Most units, particularly the thicker ones, have sharp basal contacts, and many display abrupt upper contacts as well. Others have upper contacts that are gradational into burrowed forms of the interbedded quartzite-pelite facies.

Few sedimentary structures are visible in this quartzite, partly because lichens grow extensively on this type of rock, and partly because of its uniform grain size and colour. A crude or vague parallel lamination is discernible in some massive beds. Both tabular and trough crossbedding, and distinct lamination rarely are present.

This quartzite is typically white weathering, with fresh surfaces appearing greyish white or rarely pale green. This lack of colour is due mainly to the rock's purity--quartz sand cemented entirely with quartz overgrowths. Grain sizes range from very fine to coarse, but all beds are well sorted, as exemplified by the granulometric analysis of Sample 445 YA-2 (Fig. 24). Some beds contain small quantities of very coarse grained sand or granules, in part concentrated on the upper surfaces of beds.

FIGURE 11. Monotonous succession of regularly bedded, mainly planar crossbedded quartzite from middle of the McNaughton Formation, Bastille Creek section. GSC 199284.

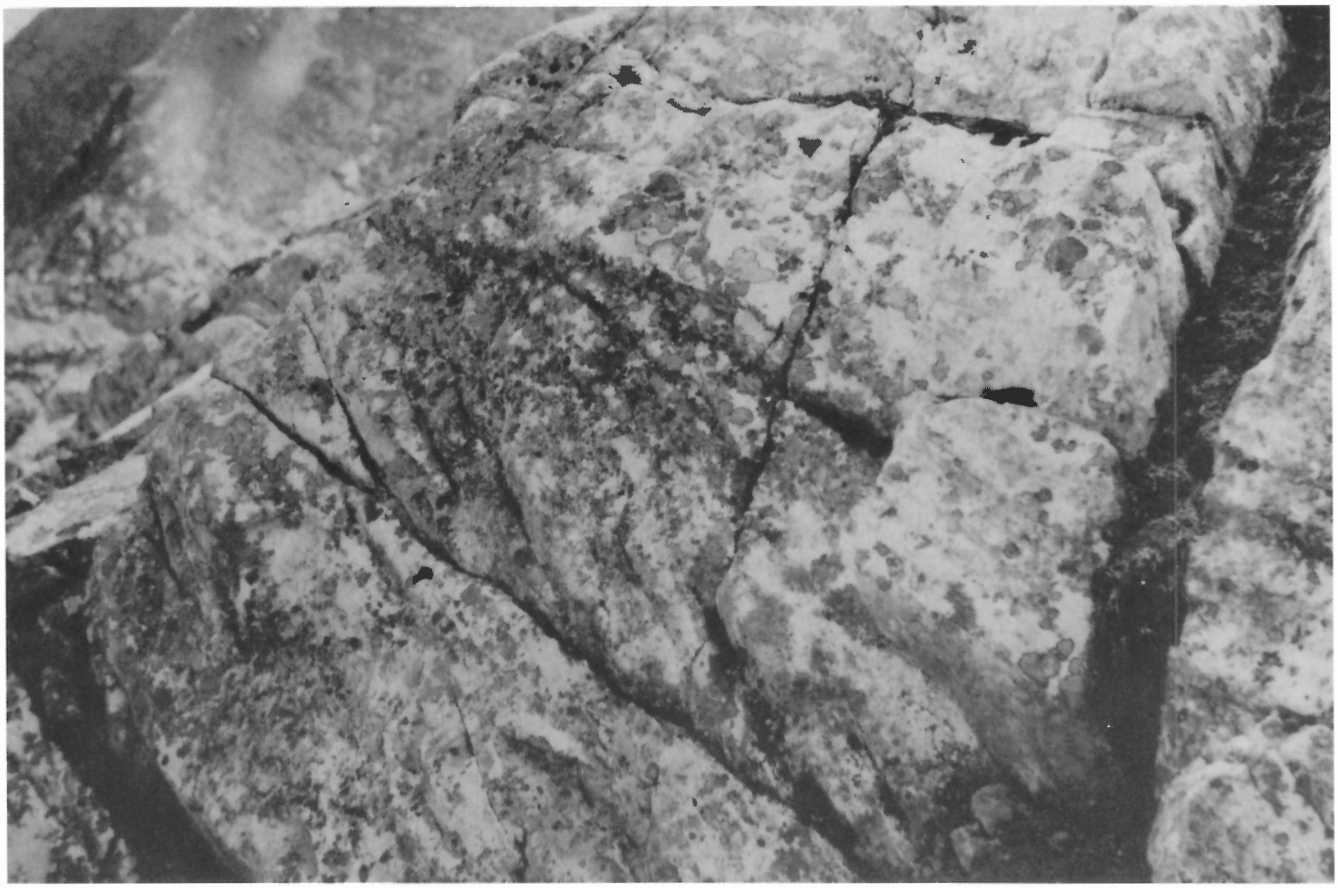


FIGURE 12. Close-up view of planar, crossbedded quartzite in stratigraphic section illustrated in Figure 11. Approximately 1.5 m of section shown. Note typical, extensive lichen cover. GSC 199287.

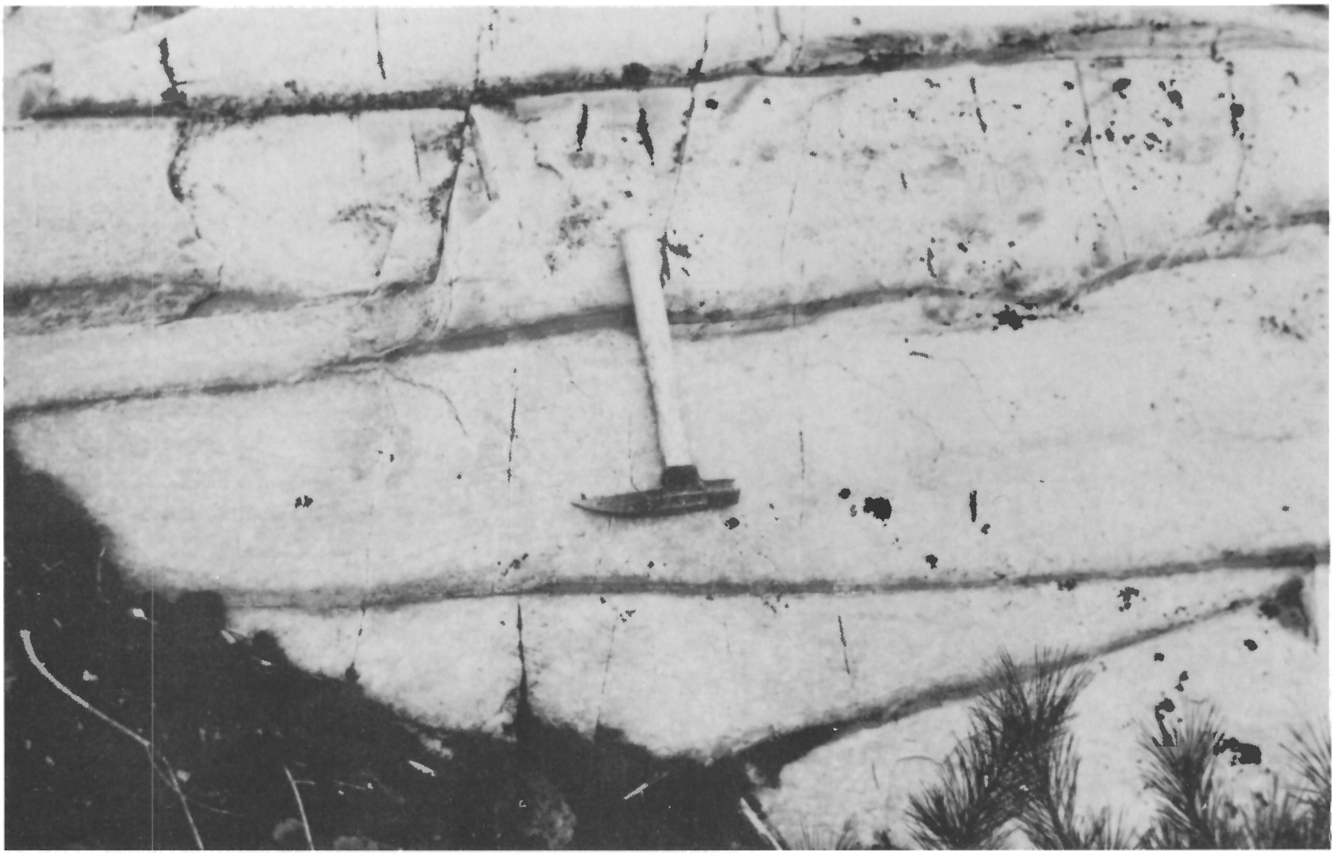


FIGURE 13. Thick mud drapes on lenticular quartzite beds of festoon crossbedded facies, lower McNaughton Formation, Holmes River section. GSC 199283.

Interpretation

The paucity of sedimentary structures in this facies offers little on which to base an interpretation. The massive beds and well-sorted, mature character of the quartzite indicate fairly constant, dynamic conditions. Some combination of the beach and aeolian dune-field environments seems to be the most likely origin of the massive quartzites.

Festoon crossbedded quartzite facies

Description

The festoon crossbedded quartzite facies occurs only in western sections of the McNaughton Formation, chiefly in its lower half. The thickest known development of this quartzite is in the Torpy River section, where it is 95 m (310 ft) thick, and it forms the bulk of the lower McNaughton division. Elsewhere, it is relatively minor volumetrically, and comprises units ranging in thickness between 10 and 65 m (33 and 213 ft).

Basal contacts of this facies are mainly abrupt, whereas upper contacts are either abrupt or gradational. Other facies commonly associated with it include the massive quartzite, interbedded quartzite-pelite, and mixed pelite-sandstone facies.

The beds of this quartzite are lenticular, in part undulose, and generally thick, with minor thin to medium beds. The primary cause of lenticular bedding is scouring and subsequent infilling by trough crossbedding. The festoons include low-angle wedge-shaped sets, and small- to medium-scale trough co-sets, all of which are outlined commonly by shale partings and beds, comprising mud drapes and large-scale flasers (Fig. 13). Interbeds of argillaceous siltstone or sandstone are present in some places. Corrected crossbed orientations are widely variable, and there are many examples of herringbone sets, having bimodal distributions with modes almost 180° apart. Other sedimentary structures include shale-clasts, parallel lamination, graded sets, tabular cross-bedding, and vertical burrows (*Skolithos* and *Monocraterion*).

The quartzite is fine to coarse grained, moderately to well sorted, quartzose with siliceous cement, and pale grey, pink or green in colour. Some scour-pockets are filled with granule-size material or enrichments of dark heavy minerals.

Interpretation

The large scours and various types of wedge- and trough-shaped crossbedding that are characteristic of this quartzite facies bespeak of strong, erosive currents and possibly the passage of dune-like bedforms (Harms and Fahnestock, 1965). Mud drapes lining scours and flaser-like partings within sets of cross-laminae indicate conditions of alternating quiescent and active flow. Reversing currents were present according to the widely dispersed and bimodal paleocurrent orientations. All of these features suggest a nearshore tidal regime, in which ebb and flood tidal currents run almost counter to each other (Klein, 1967), and are separated by interludes of slack water. The dominance of sand, the festoon crossbedding, the scours and shale-clasts indicate concentrated flow conditions, such as might be expected within tidal channels and inlets (Kumar and Sanders, 1974). Vertical burrows and the close relationship to the mixed sandstone-pelite facies support a nearshore marine interpretation.

Interbedded quartzite-pelite facies

Description

The interbedded quartzite-pelite facies is dispersed throughout the McNaughton Formation in its western outcrops, but in eastern sections it is restricted to the upper 200 m (655 ft). It forms units ranging in thickness between 10 and 50 m (33 and 164 ft), and commonly grades upward and downward into either shalier or more quartzitic facies.

The interbedded quartzite-pelite facies is part of a continuum of mixed rock types ranging from practically all quartzite at one extreme to dominantly mudstone at the other. It is defined arbitrarily as consisting of greater than 50 per cent quartzite beds, with lesser proportions of pelitic interbeds. Interbedded facies dominated by pelitic sediments generally belong to the mixed pelite-sandstone facies.

The quartzite beds of the interbedded facies are mainly thin to medium bedded, and have sharp contacts with pelitic interbeds. Thick beds are present rarely, and are generally crossbedded in compound planar or trough sets. The thinner beds are evenly laminated or apparently homogeneous, and in part contain flasers and uneven shale microlaminae. Bioturbated fabrics, contorted lamination and, rarely, closely packed vertical burrows (*Skolithos*) were observed in the quartzite beds. The quartzite is very fine to medium grained, well sorted, very quartzose, and greyish white to pale green in colour.

Pelitic interbeds consist of various combinations of slaty shale, silty mudstone, siltstone and argillaceous sandstone. The latter two may form lighter toned bands and small lenses within the medium grey to black mudstones. Some mudstone beds contain small, silt-filled burrow structures like those described from the mixed pelite-sandstone facies. Pelite bedding thickness lies commonly within the range of 0.1 to 1.0 m (0.3-3.3 ft).

The alternation of quartzite and pelite beds is rhythmic in places. In some rhythms, quartzite beds increase in proportion and become thicker upsection (sandier upward rhythms) while, in others, shale becomes thicker and more abundant upsection (shalier upward rhythms).

Interpretation

Both the arenaceous and pelitic components of this facies possess burrow structures and bioturbation fabrics, providing evidence of shallow-marine conditions during deposition. In many examples tide-influenced environments are indicated by flasers, lenticular bedding, and tidal bedding (Wunderlich, 1970). The presence of distorted laminae and beds in these examples supports a tidal-flat interpretation, because slumping is sometimes present in the prograding banks of tidal channels (Reineck, 1967). The presence of medium-scale crossbedding also implies the intermittent passage of strong currents which were able to transport sand in straight- to sinuous-crested sand waves and dunes.

In other examples of the facies, beds of laminated quartzite alternate with beds of burrowed pelite. These rhythms comprise parallel-laminated to burrowed sets, commonly observed in recent sediments in the inner neritic zone (e.g. Swift, 1970; Reineck and Singh, 1972) and found in ancient sediments ranging in age throughout the Phanerozoic Eon (Goldring and Bridges, 1973). Their origin is attributed generally to storms and/or strong tides, which generate waves and bottom currents powerful enough to scour nearshore sands and muds, and entrain them seaward by various modes of transport (Reineck and Singh, 1972; Howard, 1972).

Flaser quartzite facies

Description

The flaser quartzite facies appears primarily in the intermediate to western exposures of the McNaughton Formation and grades into, or interfingers with, the mixed pelite-sandstone, the interbedded quartzite-pelite, and the massive quartzite facies. It forms units which range in thickness from 30 to 140 m (100-460 ft) and commonly include thin tongues of one or more of the above facies.

Abundant irregular, dark grey shale microlaminae form intricate, anastomosing arrays within the quartzite beds of this facies. Many of these partings outline cross-lamination within beds, and are thus flaser structures (Fig. 14). Thin, uneven to irregular bedding and moderate resistance to erosion result from these fine networks of shale partings. Some medium to thick beds of quartzite showing delicate, even lamination (Fig. 15) or, rarely, planar crossbedding are associated in places with the shale-parted quartzite beds. Interference ripple marks, burrows and trails, and silt dykelets are structures observed on bedding planes of this facies. Burrowed shale beds containing sandstone or siltstone lenses (Fig. 16) are commonly interbedded, and occur in variable proportions gradational into the mixed pelite-sandstone facies.

The quartzite of this facies is typically very fine to fine grained, in part silty, very quartzose except for micaceous laminae, and moderately to well sorted. A few beds containing very coarse sand grains were noted. Medium to dark brownish grey colours are common, resulting from the weathering of ferrous minerals.

Interpretation

The preponderance of well-sorted sand in this facies, together with the presence of crossbedding and *Skolithos* and *Monocraterion* burrows (Fig. 17), indicate moderately agitated, marine conditions, probably close to shore. The multitudinous shale laminae, however, point to intermittent slack water from which very thin

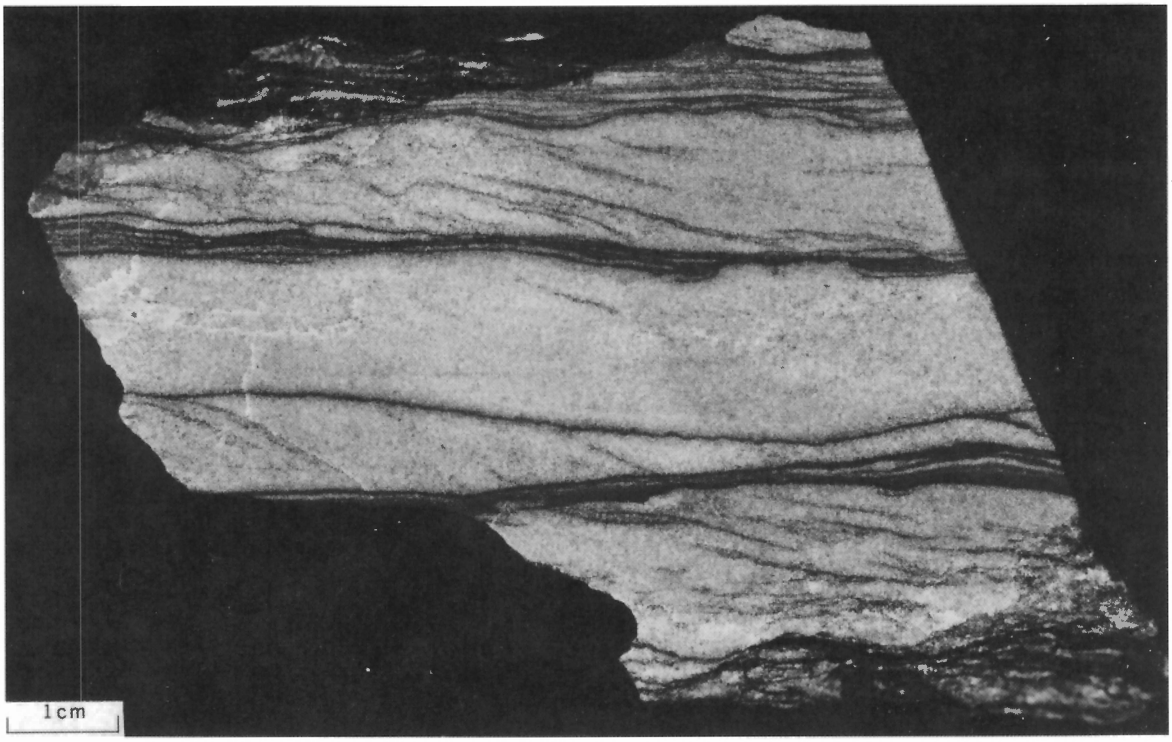


FIGURE 14. Very fine grained flaser quartzite facies, McNaughton Formation, Dezaiko Range section. Slabbed hand specimen. GSC 199278.

FIGURE 15. Shale flasers and reactivation surfaces in flaser quartzite facies, McNaughton Formation, Dezaiko Range. GSC 168839.

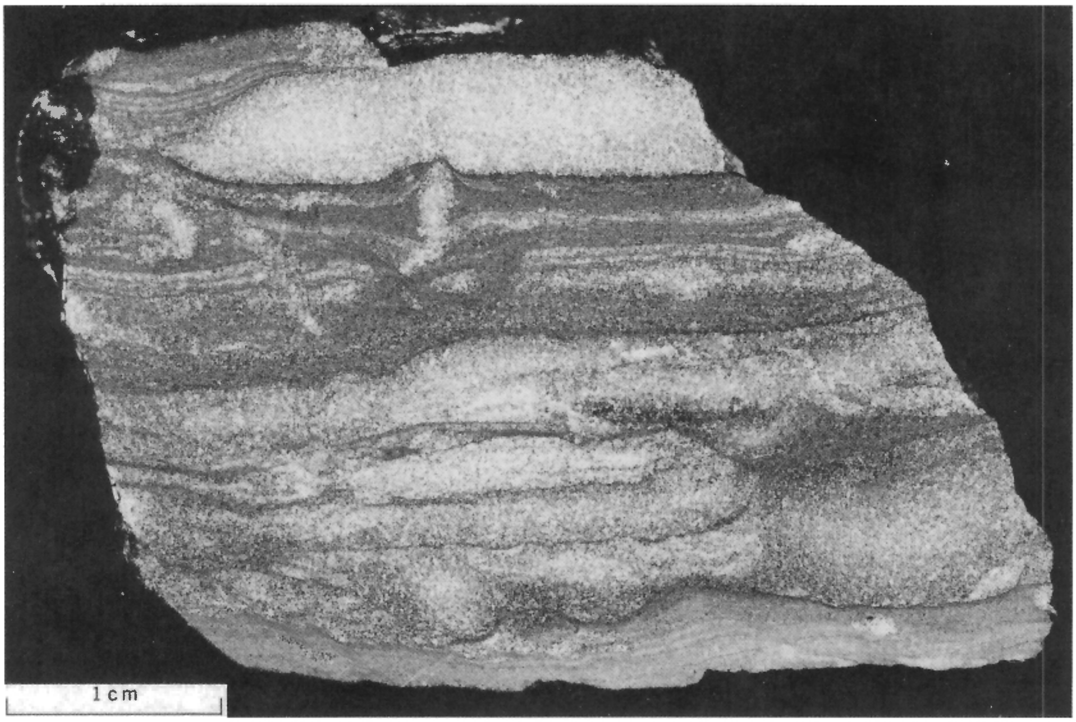


FIGURE 16. Flaser quartzite specimen showing lenticular bedding, silt microlaminae, deformed dykelets and burrows; considered to represent an intertidal depositional setting. Middle McNaughton Formation, Walker Creek section. GSC 199274.

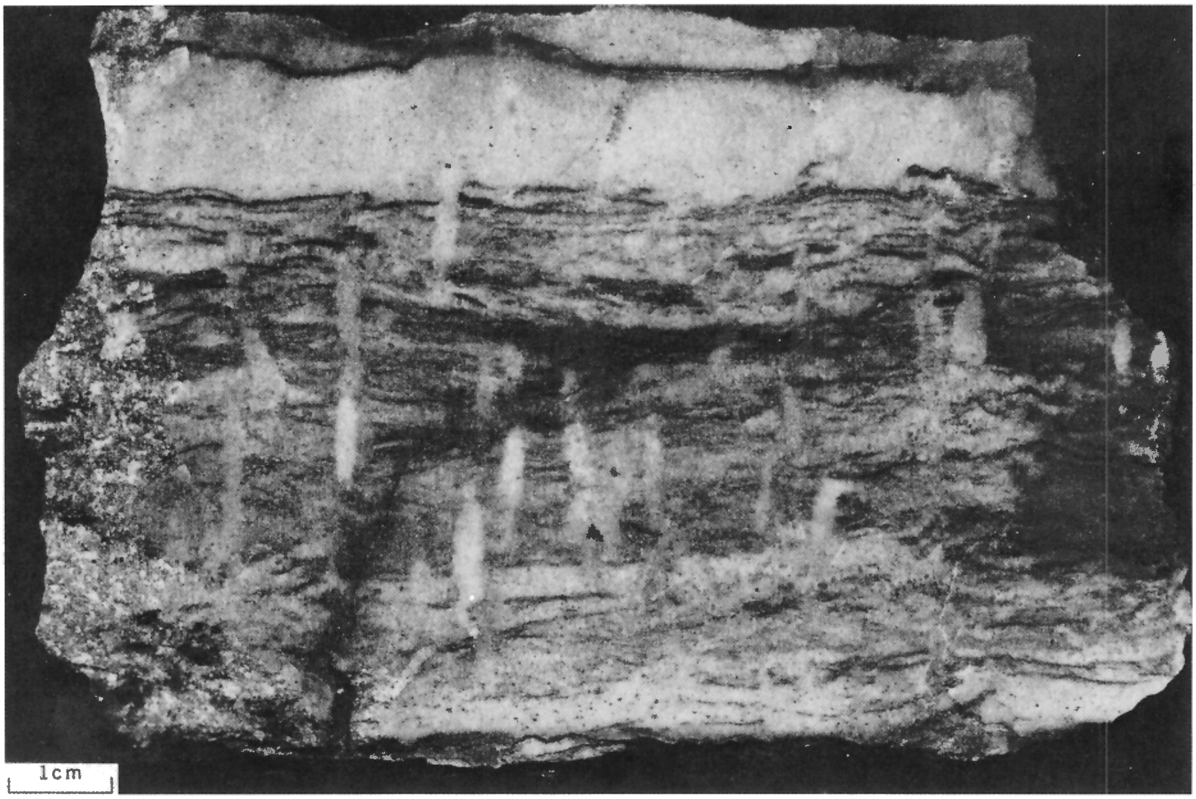


FIGURE 17. Flaser quartzite facies revealing *Monocraterion* escape burrows. McNaughton Formation, Dezaiko Range section. GSC 199275.

layers of suspended fines settled out. The intertidal zone is an environment in which such variable conditions exist. Ancient and recent tidal-flat sediments contain all of the structures observed in this facies (Ginsberg, 1975). The complex alternations of sand and mud, the interference ripple marks, and the modified original bedforms comprising these beds suggest deposition of intertidal sand-bars (Klein, 1970) or sand-flats (Kellerhals and Murray, 1969).

Mixed pelite-sandstone facies

Description

Appearing only in the central and western outcrop belts of the McNaughton Formation, the mixed pelite-sandstone facies comprises the bulk of the Holmes River Member. At the Holmes River section, the total thickness of this facies is over 800 m (2440 ft), which is 95 per cent of the latter member. Facies that interfinger with the mixed pelite-sandstone facies include the festoon crossbedded quartzite facies, the flaser quartzite facies, and the interbedded quartzite-pelite facies. Gradational contact relationships among these facies are most common, but abrupt contacts with the festoon crossbedded facies also are present.

Pelitic rocks predominate in this facies, and form very thin to medium beds of lenticular to irregular outline. Silt commonly appears in thin laminae, bands, lenticular beds (isolated ripples and ripple-trains), dykelets, and load-casts within dark grey to black slaty shale. Very thin interbeds, bands, and laminae of siltstone and claystone, comprising the "tidal bedding" of Wunderlich (1970), are common within mudstone intervals. Finely laminated, silty sandstone may be mixed with the pelites as thin interbeds, which in places are irregularly truncated or disturbed by soft-sediment slumping. Thin to thick beds of quartzite occur sporadically in the sequence in many sections, and form white resistant ledges within the generally dark brown weathering and recessive pelitic rocks (Fig. 18).

The various pelitic and arenaceous rock types comprising this facies seem to be arranged generally in irregular vertical sequences, although no detailed studies of these sequences were undertaken to test this impression. Cycles approximately 10 m (33 ft) thick were observed to recur in vertical sequences in part of the Holmes River section (Fig. 19a). They consist of a basal thick bed of fine-grained sandstone, overlain by a series of repeated small-scale rhythms (Fig. 19b), followed upward by several metres of almost uniform shale. The small-scale rhythms (Fig. 19b) consist of several centimetres of homogeneous sandstone at the base, overlain by microlaminated siltstone, and followed by shale containing silt lenses or dykelets. This rhythmic pattern breaks down with the disappearance of the upper shaly component of the larger scale rhythms. Instead, simple variations in the proportions of siltstone and shale versus fine quartzite in vertical sequence are more typical of the facies.

An interesting suite of small-scale sedimentary structures exists within this facies. These include soft-sediment deformational structures, current ripple marks and lineations, parallel laminations, and bioturbation structures.

The deformational structures include load-casts, boudins, folded silt blebs and burrow-fillings (Fig. 20), and compressed silt dykelets (Fig. 21). The latter are very similar to those described from the Devonian Caithness Flagstone Series by Donovan and Foster (1972), and the Scottish Dalradian Supergroup by Anderton (1976). The latter are abundant and appear on bedding planes as short, slightly curved, stick-like markings, occurring either as branches from a central, larger dykelet, or as isolated, lenticular forms. In cross-section, the dykelets are deformed invariably into complex ptygmatic folds (Figs. 21, 23), probably as a result of compaction of the shale during early diagenesis, later complicated by the development of slaty cleavage.

In many places this subfacies contains silt-filled burrow structures that are circular in plan view (Fig. 22), and generally oval and vertically compressed in cross-section (Fig. 23). The writer was unable to find an established ichnofossil name for this burrow and refers to them herein as spheroidal burrows. Rare horizontal trails, poorly preserved, were observed in this facies. At some localities, such as the Torpy River section, biogenic structures are absent.

Interpretation

The interlaminated and thinly interbedded character of most of this facies indicates extremely variable depositional conditions, in which currents strong enough to carry along arenaceous particles alternate with slack water, from which suspended fines settled out. Such conditions occur in shallow offshore zones, tidal flats, and alluvial flood-basins. The great thickness of this facies in some localities and the presence of burrows practically rule out the possibility of a flood-basin setting. Hence, storm- and tide-influenced environments are strongly favoured and are supported by the stratification, structures, and vertical sequences noted above.

The fining-upward rhythms described from the Holmes River section are very similar to those described by Klein (1971, 1975) and Anderton (1975), which both writers attributed to regressive tidal flat sedimentation. In their model, lower tidal flat sands (bars, flats, channels) grade landward--and upward in the regressive sequence--into interbedded sand and mud of the mid-flat environment which, in turn, grades landward or upward into the high tidal flat muds. In Anderton's example the presence of pseudomorphs of gypsum rosettes and fine parallel lamination in the upper mudstone support his interpretation. Perhaps significantly, the silt dykelets described above are absent in the upper mudstone of Anderton's example.

The regressive tidal-flat model is not considered likely in the present case for the following reasons:

1. These rhythms are the exception rather than the rule in very thick sequences of this facies. The great thicknesses themselves cast doubt upon tidal-flat sedimentation.

2. Because pelitic rocks in the McNaughton Formation become gradually more abundant from east to west--in a proximal to distal sense--and the mixed pelite-sandstone facies grades into thick pelite facies of the distal sections, it seems most likely that both facies are of subtidal origin.

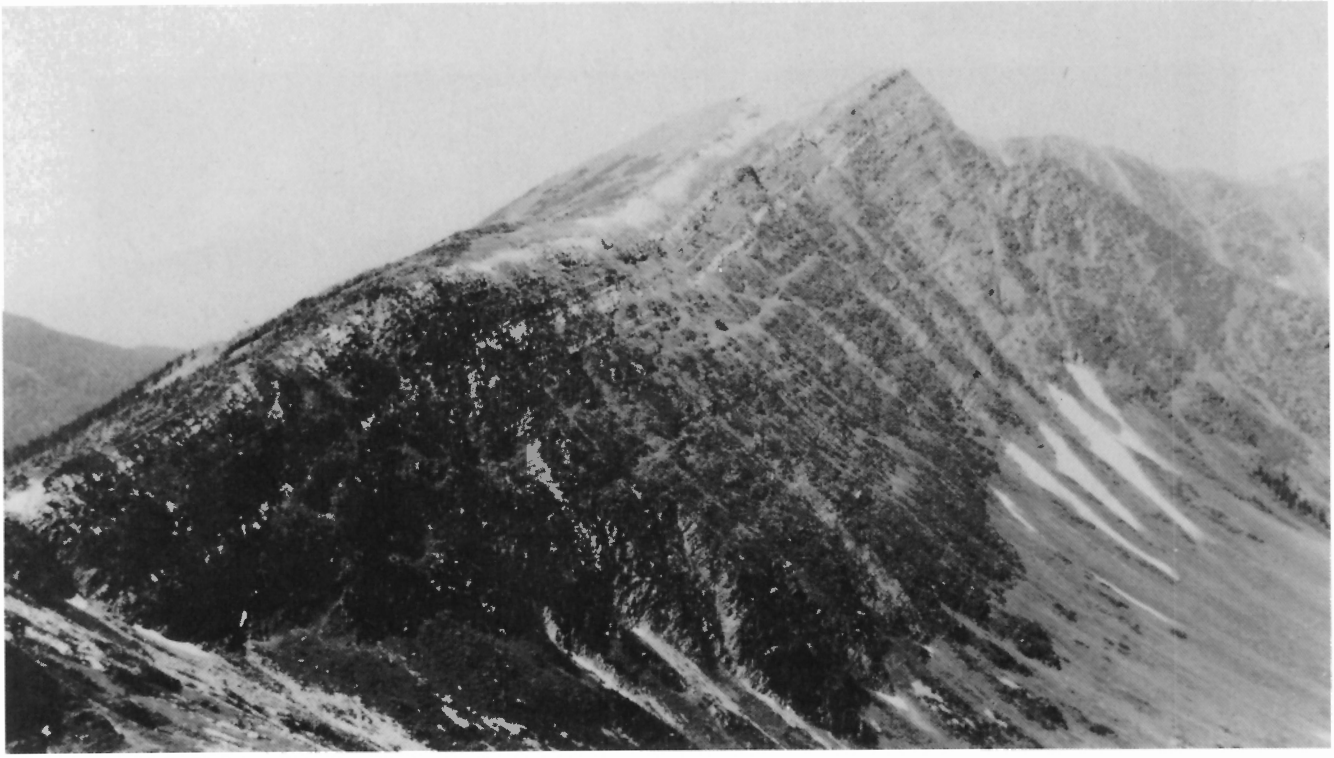


FIGURE 18. Dark-weathering Holmes River Member of McNaughton Formation at Walker Creek section. Most of this member at this locality is a mixed pelite-sandstone facies. GSC 199285.

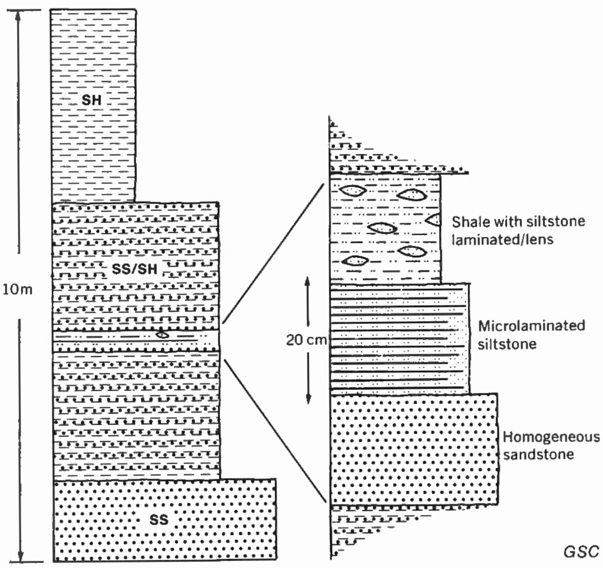


FIGURE 19. Graphical representation of medium- and small-scale rhythms in mixed pelite-sandstone facies at Holmes River section.

3. The deformed silt dykelets abundant in this facies have been attributed with good reason by some workers (e.g. Donovan and Foster, 1972) to subaqueous shrinkage, possibly caused by sudden changes in salinity of overlying waters, such as those involved in large-scale nearshore tidal currents.

4. Several other facies are considered to be of intertidal origin, and the tidal influence on McNaughton sedimentation is well established. Hence, offshore, subtidal sediments also can be expected to reflect the influence of tidal currents.

The small-scale rhythms and repetitions of fine and arenaceous sediments typical of this facies are similar to storm-generated graded rhythmites (Reineck and Singh, 1972), and parallel-laminated to burrowed sets (Howard, 1972) common in offshore and lower shoreface environments. These composite sets possibly are induced by storm tides which are capable of carrying huge clouds of suspended sediments seaward from the coastal area and scouring and reworking bottom sediments by the passage of large wavelength swells. Resulting deposits are upward-fining composite sets as bottom currents wane, and increasingly finer matter settles out of the suspension cloud with time.

In summary, a subtidal, shallow offshore origin is favoured for the majority of the mixed pelite-sandstone facies, particularly for those units greater than 100 m (328 ft) thick in the distal sections. It is important to note that small syneresis cracks--now deformed silt dykelets--and "tidal bedding" can occur in offshore facies, and are not diagnostic of themselves, or together, of intertidal sedimentary environments.

FIGURE 20. Plastically deformed sand lenses and burrow-fillings in mixed pelite-sandstone facies, McNaughton Formation, Holmes River section. GSC 199279.

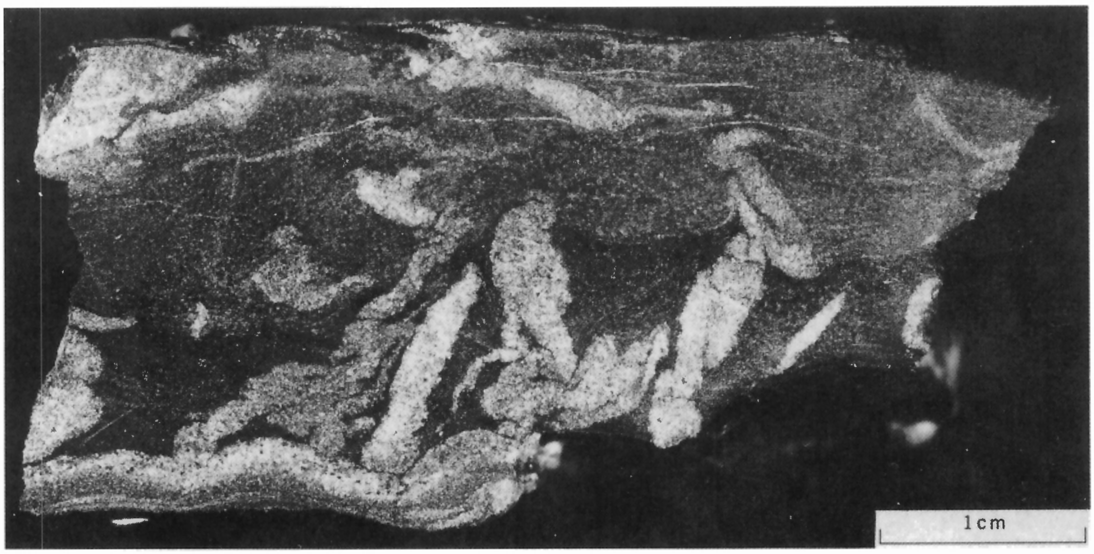


FIGURE 21. Mixed pelite-sandstone facies showing deformed sand dykelets, McNaughton Formation at Mount Dudzic, Rocky Mountains near Latitude 55°N. GSC 199277.

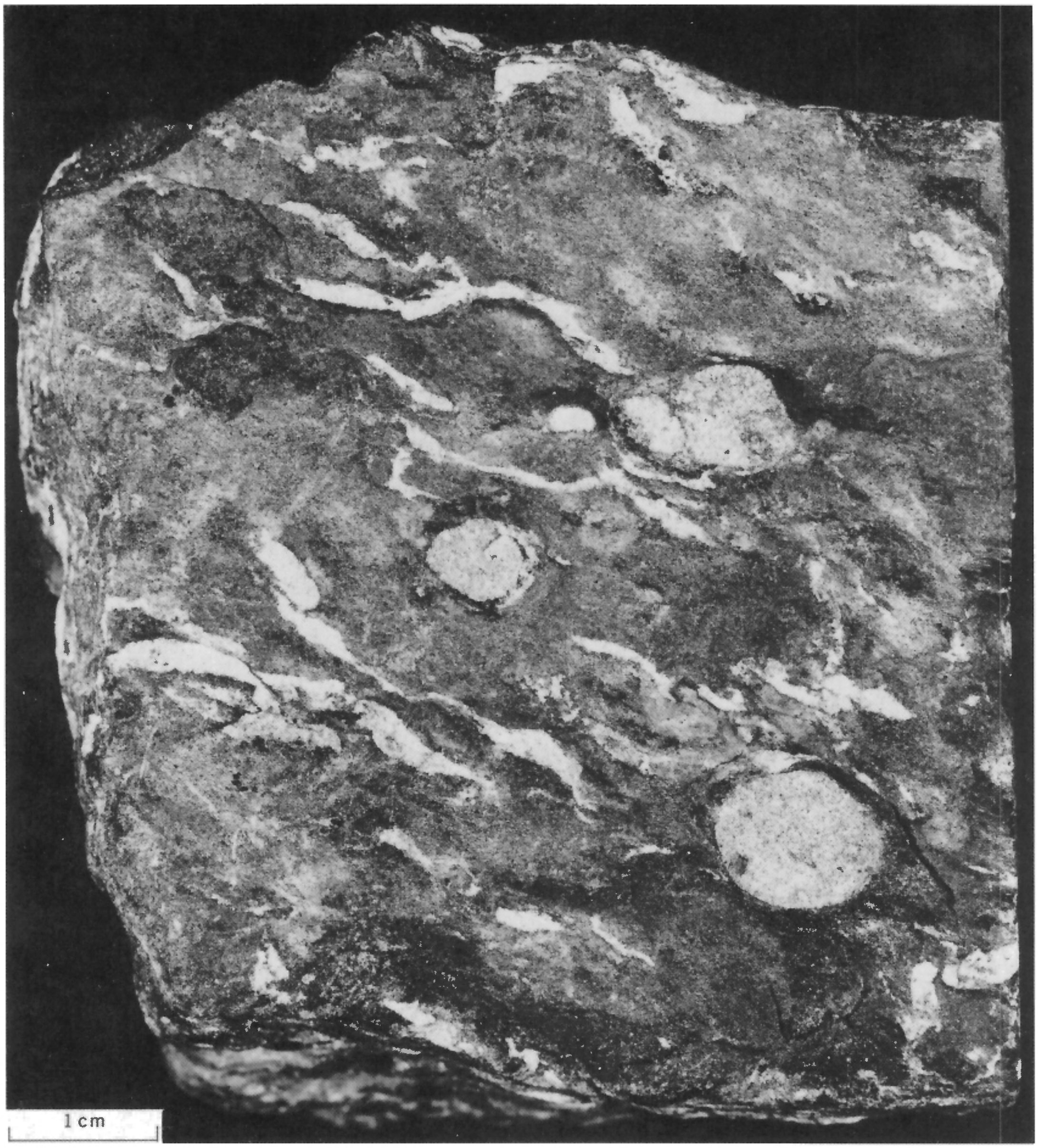


FIGURE 22. Bedding plane view of specimen of mixed pelite-sandstone facies, showing sand dykelets and spheroidal burrow-fillings. McNaughton Formation, Dezaiko Range. GSC 199276.

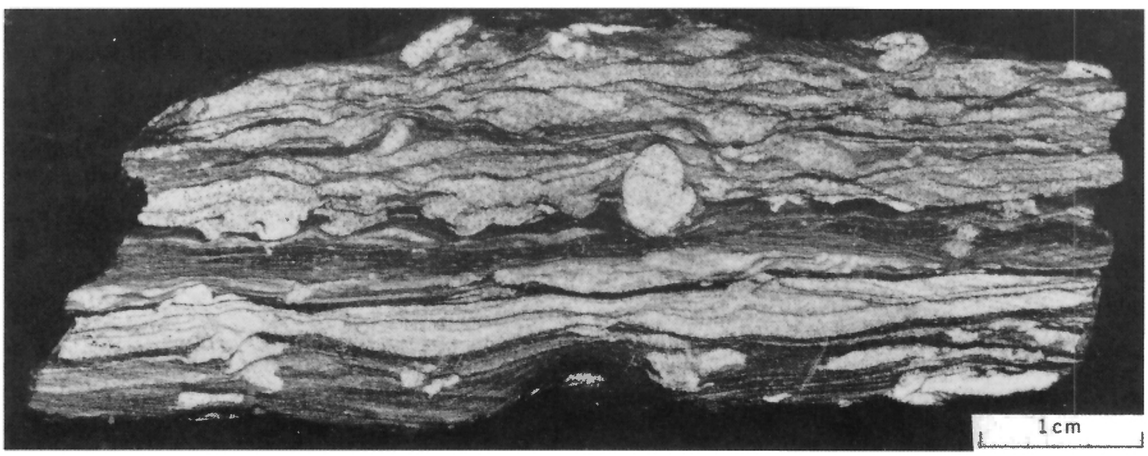


FIGURE 23. Sectional view of specimen in Figure 22, showing intricate, anastomosing shale microlaminae, flattened dykelets and spheroidal burrow-fillings. GSC 199272.

Pelite facies

Pelitic rocks are volumetrically unimportant in the McNaughton Formation and are present primarily as interbeds, partings, and laminae within the various arenaceous facies described above. Nearly pure pelite units do exist, however, in the lower sequence, alternating with conglomeratic rocks in eastern outcrops, and in the upper sequence of western sections, alternating with the mixed pelite-sandstone facies and others that contain shale. They range in thickness from a few to 135 m (445 ft) in the sections studied and consist of various proportions of shale, silty shale, and siltstone, with minor argillaceous sandstone and quartzite in some cases.

Pelites at the base of the McNaughton tend to be micaceous and silt-rich, appear to be thickly bedded or non-bedded, and contain thin bands and lenses of clean silt or sand. These rocks are pale greenish grey to medium grey, and weather commonly to deep orange-brown hues. This colouring is due largely to the oxidation of pyrite, microscopically disseminated in the pelites, or appearing as small crystals. Bedding is thin and somewhat indistinct where interbeds of argillaceous sandstone are present. These interbeds exhibit low-angle cross-lamination, and rare quartzite beds are typically horizontally laminated.

Pelite forms a unit about 135 m (445 ft) thick near the top of the McNaughton in the McGregor Range (Fig. 1, Loc. 9; Fig. 3), and consists mainly of thin-bedded, medium to dark grey shale. Siltstone is interbedded with the shale in lenses, laminae, and uneven, very thin beds. Silt-filled burrows are common in this unit.

The pelite facies undoubtedly resulted from the deposition of finely suspended material in a quiet, marine environment. This is indicated by its grey colouration, the presence of burrows, and the association of many pelitic units with shallow-marine facies.

Miscellaneous facies

Two other major facies were noted from outside the limits of the study-area and are described briefly below.

The first is a red, trough crossbedded, quartzite facies that was observed at Athabasca Falls (Lat. 52°39'45"N, Long. 117°52'30"W) on the Banff-Jasper highway in Jasper National Park. This facies is approximately 100 m (330 ft) thick there and apparently lies at or near the base of the McNaughton. The quartzite is coarse grained to granular, poorly sorted, and is predominantly festoon crossbedded in lenticular sets, mainly 10 to 15 cm (0.3-0.5 ft) thick. Some thicker sets of planar crossbedding with tangential bottom-sets also are present. This facies has most of the characteristics of deposits in braided-stream channels.

The second facies occurs northwest of the study-area in northern Monkman Pass and southern Pine Pass map-areas below sandstone of the upper McNaughton Formation, which formerly was believed to comprise the entire formation (Slind and Perkins, 1966). It consists of carbonaceous shale, siltstone and sandstone interbeds that are rich in trace fossils, particularly *Cruziana* ex gr. *C. fasciculata* Seilacher, of general Early Cambrian age, and probably formed by trilobites (Seilacher, 1970). This facies is about 300 m (1000 ft) thick at Mount Murray (Lat. 55°27'30"N, Long. 122°39'W) and, in turn, is underlain by 65 m (216 ft) of fine- to coarse-grained, quartzose sandstone containing *Skolithos* burrows, typical of the Gog Group. The carbonaceous facies is thin bedded, extensively burrowed, and exhibits silt dykelets, mud-cracks, fine carbonaceous shale laminae and lenticular cross-laminated beds of sandstone. It is very similar to, and grades into, the mixed pelite-sandstone facies described below. The sedimentary structures and thin stratification noted are reminiscent of tidal-flat deposits (Ginsburg, 1975).

PETROGRAPHY OF McNAUGHTON QUARTZITES

Macroscopic petrographic observations were made on all McNaughton quartzites and microscopic studies were perfomed on 25 thin sections in order to outline main characteristics and trends in composition, granulometry, and colour. This information is used to interpret the climate, topography, and bedrock characteristics of the source-area, and to map sediment dispersal patterns in the receiving basin. Regional petrographic trends of the McNaughton are later compared with those of the Yanks Peak-Midas depositional system.

Composition

The McNaughton quartzites are typically very quartzose in all parts but the lower sequence and eastern middle portion (Table 2). Microscopic examination reveals that the quartz is derived mainly from igneous plutons and hydrothermal veins (Folk, 1968), with a minor amount from older quartzites. McNaughton quartzarenites are tightly cemented by quartz overgrowths and minor sericitic to chloritic matrix. Polygonization and interpenetration of quartz grain-boundaries become increasingly important from east to west, culminating in metamorphic schistose quartzites in western ranges and in the Rocky Mountain Trench. It is interesting to note that detrital feldspar grains in these western quartzites are scarcely affected by recrystallization. The quartzite cliffs in the lower walls of the Rocky Mountain Trench near McBride are feldspathic, white, schistose quartzites, allowing them to be assigned to the lower part of the McNaughton Formation.

Pebbles in the conglomeratic quartzite facies of eastern sections are 99 per cent quartz--mainly vein-quartz with minor quartzite--and vary in roundness from subrounded to well rounded. Quartz-pebble shapes were determined to be mainly "compact bladed" and "compact elongated" (mean maximum projection sphericity: 0.71) according to the sphericity-form diagram of Folk (1968).

Feldspar content is greatest near the base of the McNaughton in the conglomeratic quartzites of eastern sections (Table 2) and gradually decreases in relative abundance upward, until it disappears in the middle of the formation. For example, in the Bastille Creek section, feldspar makes up 15 per cent of the particulate part of the quartzites in the basal conglomeratic member, declining gradually upward to 1.2 per cent in the middle of the formation. Feldspar content is less in the lower sequence of western sections than in eastern ones, and disappears upward within the lower sequence.

The feldspar component includes at least 20 per cent plagioclase, much of which is untwinned. Potash feldspar is most common in the grain-size range of 1 to 8 mm. A large proportion of the feldspar is white, apparently due to both vacuolization and kaolinitization

				Per cent of Particulate fraction					Per cent Matrix fraction			
Sample	Section	Interval	Facies	% Part.	Quartz	Fspar	Lith	Other	% Matrix	Seric	Quartz	Other
440 YA-2	1	lower	A	82.6	74.1	14.8	7.0	4.1	17.4	15.8	0.8	0.8
440YA-10	1	middle	B	81.5	94.4	1.2	4.3	0	18.5	13.8	2.9	1.8
HL-12	8	lower	?	72.3	91.0	5.7	2.4	0.9	27.7	0.4	22.8	4.5
HL-40	8	middle?	?	73.3	100	0	0	0	26.7	1.0	24.7	1.0
HL-57	8	middle?	?	74.7	100	0	0	0	25.3	1.0	22.6	1.7
309 YA-25	16	lower	B	78.6	89.0	9.5	1.3	0.2	21.4	6.9	14.5	0
309 YA-33	16	middle	E	77.7	99.7	0	0	0.3	22.3	12.3	7.4	2.6

GSC

TABLE 2. Modal analyses of McNaughton quartzites.

resulting from weathering prior to deposition. Also, some grains of feldspar, including plagioclase, are relatively clear and unweathered. According to Folk (1968), such mixing of weathered and fresh feldspar grains may be due to the erosion of an area of high topographic relief. This idea is supported by the abundance of pebbles in the feldspathic quartzites, and the sheer volume of coarse detritus in the McNaughton Formation.

Heavy minerals other than leucoxene are rare in quartzites of the eastern sections, but are common in the shallow-marine siltstone and fine-grained quartzite of western sections, where they appear both as a dispersed component and as concentrations within certain laminae. Minerals observed in thin sections include zircon, tourmaline, rutile, leucoxene, sodic amphibole, and several unidentified varieties. An incursion of dark green jadeite granules appears in the middle of the formation in Bastille Creek area.

The heavy and light mineral components of the McNaughton quartzites indicate an ultimate plutonic igneous and metamorphic source-terrain, which was very likely the western portion of the Churchill Province of the Canadian Shield, now buried by sedimentary rocks of the Interior Plains. However, the abundance and volume of quartz sand in the McNaughton Formation suggest that some proportion of its supply came from earlier deposited sandstones, such as the Proterozoic Athabasca and Thelon Formations, which formerly blanketed great areas of the Canadian Shield (Fraser *et al.*, 1970). The underlying Miette Group itself may have been uplifted and eroded, thereby supplying detritus into the McNaughton basin. Because of its proximity, the Miette would have supplied this detritus very early in the deposition of the McNaughton, but the similar abundance of feldspar in the basal McNaughton and the middle and upper Miette suggests that no recycling occurred. Also, the apparent lack of blue quartz in the Gog Group, characteristic of Windermere clastics, indicates that the latter was at best a minor supplier of sediment, even at the beginning of McNaughton deposition.

According to the composition and roundness studies of over 200 different conglomerate deposits by Dal Cin (1968), Cailleux (1964), and Tricart (1958), the high proportion of quartz in the pebble-size fraction indicates warm and humid climatic conditions in the area of alluviation. The presence of shallow-marine bank-carbonates and mixed carbonate-clastic facies immediately below the McNaughton Formation and its western equivalents indicates the existence of marine waters, probably associated with the warm, humid climate of the surrounding region.

Granulometry

Most of the grain-size and sorting characteristics of the quartzites have been discussed previously within the context of each facies. Four granulometric analyses were undertaken to aid in the interpretation of several facies. These were accomplished by measuring the maximum diameters of individual grains as they appeared in thin sections, utilizing various measuring devices attachable to a petrographic microscope. Cumulative size frequency (weight frequency) curves derived from these analyses were plotted and are shown in Figure 24.

Grain-size trends in McNaughton quartzites reflect initial high relief of the cratonic source-area and the predictable deposition of coarse detritus in proximal areas and finer materials basinward. The pebble and granule size-fractions are confined largely to the lower sequence of eastern sections. Asscociated quartzites in eastern sections are medium to coarse grained, the latter dominant in the lower part, but present only as tongues in the upper part of the formation. Westward, the basal quartzite member is dominated by medium-grained arenites, while the upper two thirds of the formation consist mainly of fine-grained quartzite, siltstone, and shale.

Helpful in determining paleodispersal trends within the depositional basin are isopleth maps (Figs. 39-41) of the coarsest observed particles. In the case of the McNaughton, the coarsest particles are present in the basal part of the formation, and their areal size distribution supports other data indicating clastic supply from the northeast. Much of the Yanks Peak Formation (middle sequence, Fig. 40), on the other hand, apparently was derived from a northern source-area. These paleodispersal trends are discussed in greater detail in the final chapter.

Maturity and drabness of McNaughton quartzite

The striking textural and mineralogical maturity of the McNaughton quartzite units above the basal member and, generally, within the distal-alluvial to shallow-marine facies is emphasized by the whiteness or, at best, pallid hues of these rocks. Thick alluvial deposits most commonly exhibit various reds and browns (Table 4) as a result of oxidative conditions producing iron oxides as grain coatings or matrix components. Why then is the McNaughton not red, at least within the study-area, although possessing many other features typical of a red-bed sequence?

To answer this question we have to examine the proposed causes of red-bed formation and see why these do not apply in the present case. The red pigment in sedimentary rocks is largely hematite, both as crystalline platelets and as amorphous or submicroscopic material. The hematite may originate in two main ways (Van Houten, 1973): (1) inheritance from red and reddish-brown soils in the source-area, or (2) post-depositional oxidation of ferrous minerals in the sediment. Red soils are produced in warm, seasonally humid climates, such as those found today in tropical

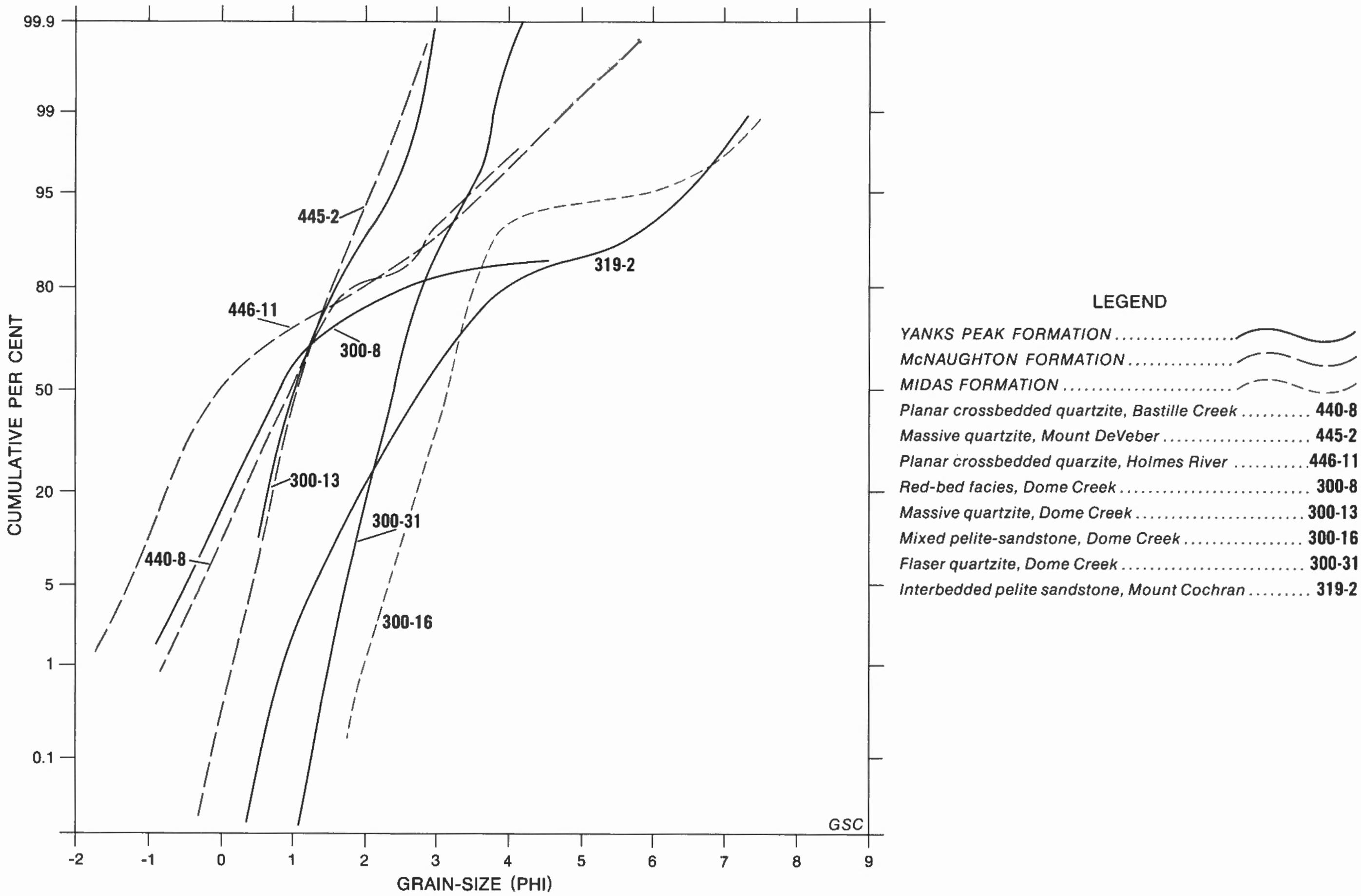


FIGURE 24. Frequency distributions of grain size.

uplands and savannas. Chemical and X-ray analyses of such soils from Colombia (Van Houten, 1972) indicate that most of the iron is tied up with clay minerals, and about half of it is in the form of brown, hydrated ferric oxid (limonite). Brown pigments tend to predominate in alluvial deposits derived from these uplands, but they are converted easily to hematite by dehydration and the absence of strongly reducing conditions (Berner, 1969).

The *in situ* formation of hematite pigment from the oxidation of ferrous detrital minerals in warm, arid climates has been documented by Walker (1967) from his studies of Recent to Pliocene alluvium of Baja California.

Preservation of red pigmentation in alluvial deposits is not always guaranteed. Bleaching processes leading to drab colouration are caused by chemical reduction, enhanced by decay of organic matter, and a high water table. The presence of abundant hematite and leucoxene in a drab deposit suggests post-depositional bleaching, because both these secondary minerals are formed in red savanna and desert soils (Van Houten, 1973).

The major factors causing drab, rather than red pigments in alluvial deposits (*op. cit.*) include: (1) a high water table, (2) high rainfall (non-seasonal), (3) low alkalinity and (4) low oxidation potential. In the case of the McNaughton Formation of the study-area, evidence has been cited already in support of a warm and humid climate in the source-area. The abundance of leucoxene and the presence of hematite and limonite in McNaughton quartzites support this interpretation and suggest further that conditions within the receiving basin, including those listed above, acted against the conversion of limonite to hematite and caused bleaching of introduced pigments. Primary among these factors was probably a high, steady rate of precipitation, giving rise to a high water table. Lack of land vegetation in earliest Cambrian time rules out any contribution to chemical reduction by decaying organic matter in a nonmarine setting.

High rainfall would help also to explain the mineralogical maturity of these rocks. Weathering and destruction of labile components in intermediate depositional sites are enhanced greatly by continual wetting and drying (Bradley, 1970). These conditions would be expected on the rainy, distal alluvial apron in the littoral areas in which much of the McNaughton sediments probably were deposited. In addition to this effect, the differential preservation of quartz over less resistant minerals would have been enhanced further on the McNaughton tidal flats, on which great distances of grain transport and abrasion occurred as in modern tidal regimes (Swett *et al.*, 1971).

FACIES ASSOCIATIONS, SEQUENCES AND INTERPRETATIONS

Having defined, described and made preliminary interpretations of each of eight facies recognized in the McNaughton Formation, naturally occurring facies associations and vertical sequence patterns must be established next. These facies relationships provide the basis for making final interpretations of depositional settings. Some of the facies are arranged in obviously paired vertical alternations, others in repetitive rhythms involving three or four facies, and still others in less distinct vertical sequences or associations. In order to bring to light all of these patterns, a statistical analysis was applied to the vertical facies successions of seven measured sections, which have a total thickness of 9625 m (31 560 ft).

Markov chain analysis

Discussion of method

The embedded Markov chain analysis, both in a simplified form as outlined by Selley (1970) and Walker (*in* Harms *et al.*, 1975) and in a more rigorous form as described by Miall (1973), is used here. Each yielded very similar results, the more rigorous form having the advantage of providing chi-square values which can be used to test the sequences for randomness. Detailed explanations of Markov chain analysis and its usage in geological studies are given in numerous papers and textbooks, including Harbaugh and Bonham-Carter (1970), Davis (1973) and Dacey and Krumbein (1970). Only a brief account of basic principles need be given here.

A Markov process is one "in which the probability of the process being in a given state at a particular time may be deduced from knowledge of the immediately preceding state" (Harbaugh and Bonham-Carter, 1970, p. 98). Thus, in a stratigraphic section consisting of numerous facies, any preferred ordering of upward facies transitions can be brought to light through the application of a Markov chain analysis.

The first step is to list all known facies transitions, generally in upward sequence (*see* Figs. 3-5) and, for convenience, to indicate the nature of contacts between each facies. These lists then can be combined and tabulated in a transition count matrix (Table 3) in which is recorded the number of times a given facies (column headings) overlies each of the other facies (listed in the rows). From this can be derived a second matrix depicting the probabilities of completely random transitions (computational details *in* Miall, 1973). A third matrix giving the actual probabilities of a given transition (transition probability matrices, Table 3) is then computed and constructed, from which is derived a final matrix that shows the differences between the actual probability and the random probability of each transition (difference matrices, Table 3).

The positive values in the difference matrix highlight a preferred order in the vertical successions (the Markov property), while negative values emphasize unlikely facies transitions. A facies relationship diagram, showing only the transitions indicated as non-random (positive), can be constructed from the difference matrix [*see* discussion by Walker (*in* Harms *et al.*, 1975)].

It is desirable that the sequences being analyzed are "stationary", that is, that they exhibit similar Markovian properties no matter what the location or partial stratigraphic interval. However, in the case of the McNaughton Formation, visual inspection of the available sequences indicates that they are non-stationary with respect to location and internal stratigraphy. This is commonly the case among stratigraphic sections of regional distribution or of considerable thickness (e.g. Casshyap, 1975) because of (a) different sedimentological conditions co-existing in various parts of a basin, and (b) secular changes in sedimentological "style".

In order to focus on the problem created at least by the first circumstance, two sets of stratigraphic sections were selected, each based on general location and the dominance of certain facies, and were analyzed separately. The first set includes two easternmost sections, which are dominated by rudaceous and arenaceous deposits, and represent the "proximal sector" of the McNaughton Formation. The second set comprises those sections in the northern part of the study-area which include an abundance of pelitic rocks. They are presumed to be in more basinward locales than sections of the first set (as will become clearer as more evidence is provided), and thus are called the "northern distal sector" of the McNaughton Formation.

In the subsequent discussions and in Figures 25 to 27, a shorthand reference to the various facies is used, according to the following scheme:

A - Conglomeratic quartzite

B - Planar crossbedded quartzite

C - Massive quartzite

D - Festoon crossbedded quartzite

E - Interbedded quartzite-pelite

F - Flaser quartzite

G - Mixed pelite-sandstone

H - Pelite

A computer programmable matrix analysis of contact relations, devised by A.D. Miall (Miall, in prep.) and kindly loaned to the writer, was used to determine whether all observed contacts between any two facies tended to be gradational or abrupt.

Analysis of all McNaughton sections

A Markov chain analysis of the entire formation indicated the presence of preferred upward facies transitions to a high degree of confidence (Table 3). These preferential transitions are summarized in the facies relationship diagram (Fig. 25a), which suggests certain associations and cyclical transitions. These must be checked against the original sequence data, however, because the analysis considers each facies transition in isolation from others, and certain transitions may be characteristic of particular areas or parts of the section. For example, Figure 25 suggests that facies A and H tend to alternate, with an occasional change from H to F. However, it is evident from graphic logs of facies transitions (Figs. 3-5) that facies A, H and F never form an association. Thus, it is instructive to analyze distinct parts of the formation, as suggested above, in order to see what rhythms and associations occur in each part.

TOTAL McNAUGHTON DATA

Transition count matrix

	A	B	C	D	E	F	G	H	Row sums
A	–	2	–	–	–	–	–	4	6
B	–	–	13	–	9	1	2	2	27
C	–	10	–	3	21	5	7	3	49
D	–	2	2	–	3	1	5	1	14
E	–	5	18	4	–	6	16	6	55
F	–	–	4	1	6	–	7	1	19
G	–	2	11	5	13	4	–	3	38
H	5	1	2	1	6	4	2	–	21

Total beds: 229

Transition probability matrix

	A	B	C	D	E	F	G	H
A	–	0.33	–	–	–	–	–	0.67
B	–	–	0.48	–	0.33	0.04	0.07	0.07
C	–	0.20	–	0.06	0.43	0.10	0.14	0.06
D	–	0.14	0.14	–	0.21	0.07	0.36	0.07
E	–	0.09	0.33	0.07	–	0.11	0.29	0.11
F	–	–	0.21	0.05	0.32	–	0.37	0.05
G	–	0.05	0.29	0.13	0.34	0.11	–	0.08
H	0.24	0.05	0.10	0.05	0.29	0.19	0.10	–

Difference matrix

	A	B	C	D	E	F	G	H
A	–	+0.21	-0.22	-0.06	-0.25	-0.09	-0.17	+0.57
B	-0.03	–	+0.24	-0.07	+0.06	-0.06	-0.11	-0.03
C	-0.03	+0.05	–	-0.02	+0.12	–	-0.07	-0.06
D	-0.03	+0.02	-0.09	–	-0.04	-0.02	+0.18	-0.03
E	-0.03	-0.06	+0.05	-0.01	–	–	+0.07	-0.01
F	-0.03	-0.13	-0.02	-0.01	+0.05	–	+0.19	-0.05
G	-0.03	-0.09	+0.03	+0.06	+0.05	+0.01	–	-0.03
H	+0.21	-0.08	-0.14	-0.02	+0.02	+0.10	-0.09	–

Chi-squared (Harbaugh and Bonham-Carter, 1970): 174.16
Degrees of freedom: 41
Transitions non-random at 99% confidence level

PROXIMAL McNAUGHTON SECTOR

Transition count matrix

	A	B	C	D	E	F	G	H	Row sums
A	–	2	–	–	–	–	–	4	6
B	–	–	10	–	2	–	–	–	12
C	–	9	–	–	4	1	–	–	14
D	–	–	1	–	–	–	–	–	1
E	–	1	4	1	–	–	–	–	6
F	–	–	–	–	–	–	–	–	0
G	–	–	–	–	–	–	–	–	0
H	5	–	–	–	–	–	–	–	5

Total beds: 44

Transition probability matrix

	A	B	C	D	E	F	G	H
A	–	0.33	–	–	–	–	–	0.67
B	–	–	0.83	–	0.17	–	–	–
C	–	0.64	–	–	0.29	–	–	–
D	–	–	1.00	–	–	–	–	–
E	–	0.17	0.67	0.17	–	–	–	–
F	–	–	–	–	–	–	–	–
G	–	–	–	–	–	–	–	–
H	1.00	–	–	–	–	–	–	–

Difference matrix

	A	B	C	D	E	F	G	H
A	–	+0.02	-0.37	-0.03	-0.16	–	–	+0.54
B	-0.19	–	+0.40	-0.03	-0.02	–	–	-0.16
C	-0.20	+0.24	–	-0.03	+0.09	–	–	-0.17
D	-0.14	-0.28	+0.67	–	-0.14	–	–	-0.12
E	-0.16	-0.15	+0.30	+0.14	–	–	–	-0.13
F	–	–	–	–	–	–	–	–
G	–	–	–	–	–	–	–	–
H	+0.85	-0.31	-0.36	-0.03	-0.15	–	–	–

Chi-squared: 87.5
Degrees of freedom: 29
Transitions non-random at 99% confidence level

NORTHERN-DISTAL McNAUGHTON SECTOR

Transition count matrix

	A	B	C	D	E	F	G	H	Row sums
A	–	–	–	–	–	–	–	–	0
B	–	–	3	–	6	–	2	1	12
C	–	1	–	2	17	4	6	2	32
D	–	1	–	–	3	–	1	1	6
E	–	4	14	2	–	6	14	6	46
F	–	–	4	–	6	–	6	1	17
G	–	2	10	1	12	4	–	1	30
H	–	–	1	1	4	4	2	–	12

Total beds: 155

Transition probability matrix

	A	B	C	D	E	F	G	H
A	–	–	–	–	–	–	–	–
B	–	–	0.25	–	0.50	–	0.17	0.08
C	–	0.03	–	0.06	0.53	0.13	0.19	0.06
D	–	0.17	–	–	0.50	–	0.17	0.17
E	–	0.09	0.30	0.04	–	0.13	0.30	0.13
F	–	–	0.24	–	0.35	–	0.35	0.06
G	–	0.07	0.33	0.03	0.40	0.13	–	0.03
H	–	–	0.08	0.08	0.33	0.33	0.17	–

Difference matrix

	A	B	C	D	E	F	G	H
A	–	–	–	–	–	–	–	–
B	–	–	+0.03	-0.04	+0.18	-0.12	-0.04	–
C	–	-0.07	–	+0.01	+0.16	-0.01	-0.06	-0.04
D	–	+0.09	-0.21	–	+0.19	-0.11	-0.03	+0.09
E	–	-0.02	+0.01	-0.01	–	-0.03	+0.03	+0.02
F	–	-0.09	–	-0.04	+0.02	–	+0.14	-0.03
G	–	-0.03	+0.08	-0.01	+0.03	–	–	-0.06
H	–	-0.08	-0.14	+0.04	+0.01	+0.21	-0.04	–

Chi-squared: 100.3
Degrees of freedom: 29
Transitions non-random at 99% confidence level

– Denotes no transitions or probabilities

GSC

TABLE 3. Markov matrices of McNaughton Formation.

Analysis of the proximal sector

Representatives of the proximal sector include the Mount De Veber and Bastille Creek sections (Figs. 4, 5) in the eastern ranges. Markov analysis of proximal sequences showed their facies transitions to be strongly non-random, probably due to the numerous alternations of A and H facies. There, these facies are not associated with the F-facies (Fig. 25), and the general facies relationship diagram can be modified to illustrate the dual association of facies H (Fig. 25b). Other preferred transitions in the proximal sector are fining-upward trends of A to B to C, and coarsening-upward trends of E to C to B. A matrix analysis of contact relationships indicates that these two types of cycles tend to be separated by sharp contacts.

Examination of graphic logs (Figs. 3-5) reveals how and where these indicated rhythms exist in nature. The A to B to C trend is a single, large-scale interval, 200 to 300 m (655-985 ft) in thickness near the bases of the two sections analyzed. About midway through these sections, the rhythmic alternation of B and C facies is common and comprises the bulk of the McNaughton in the eastern area. The coarsening-upward E to C to B rhythms occur only in the upper 100 to 150 m (330-490 ft) of the formation in this area, and are generally in the order of 25 to 50 m (82-164 ft) thick.

Analysis of the northern distal sector

The second group of McNaughton data to be analyzed separately consists of sections in the northern medial to distal sector, including those at Walker Creek, Dezaiko Range, McGregor Range and Torpy River (Figs. 3, 4). According to the Harbaugh and Bonham-Carter equation for chi-square (Miall, 1973), facies transitions within these sections are significantly different from random transitions, at a confidence level greater than 99 per cent (Table 3). Some interesting trends emerge from the analysis that are useful to this discussion.

The transition count matrix illustrates the absence of conglomeratic quartzite (A) from these sections and the non-association of the planar crossbedded (B) and flaser (F) quartzites. Several facies transitions seem to be rare or absent. Apparently preferred transitions are summarized in the facies relationship diagram (Fig. 27). Transitions shown are gradational except those abrupt or scoured contacts indicated by solid arrows, such as G to C, and C to E. Many pairs of transitions appear to be possible; however, the main rhythms and trends include:

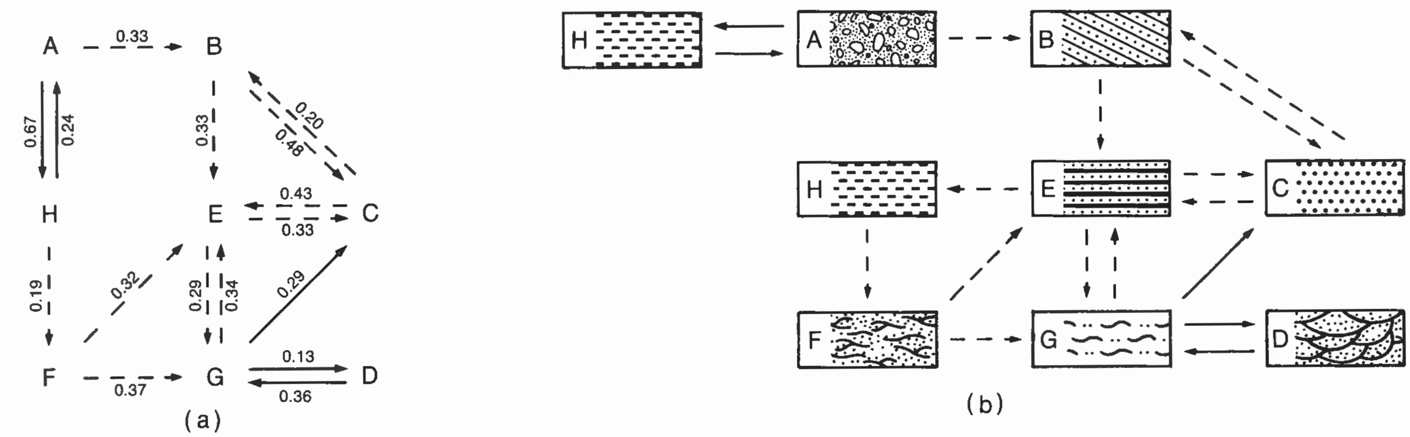


FIGURE 25. Facies relationship diagram for total McNaughton data: (a) uncorrected; (b) corrected

FIGURE 26. Facies relationship diagram of proximal McNaughton data

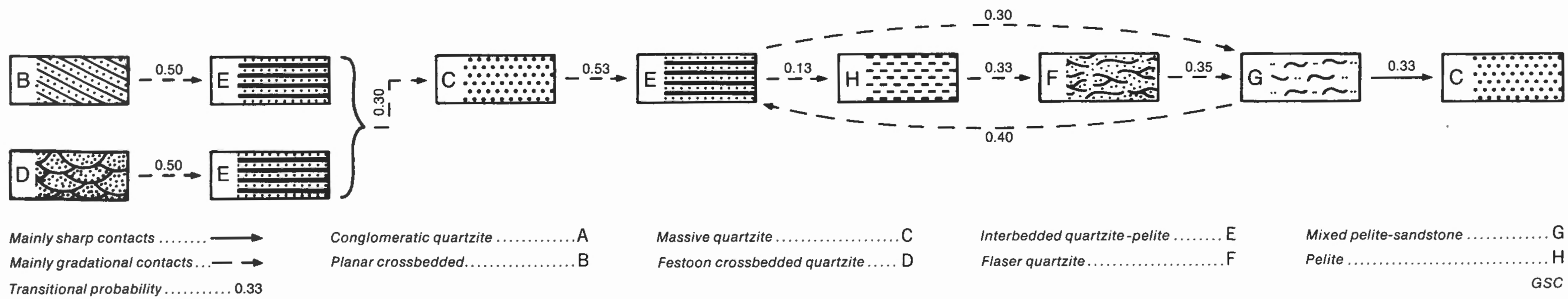


FIGURE 27. Facies relationship diagram of distal McNaughton data

(1) B to E,

(2) D to E,

(3) G to E and

(4) C to E to H to F to G (sometimes shortened to C to E to G).

A check of the graphic logs (Figs. 3, 4) indicates that paired transitions in isolation or in repeated alternations are common (e.g. the E to G to E to G cycles of the Dezaiko Range section). Rhythms of C to E to G, B to E to G, and D to E to G are also fairly common. The more complex trend (4) is not known to exist in any section, although the trend C to E to H to F to E occurs several times, and the sequence C to E to H to F to E to G occurs once. A comparison of these results with the analysis of the whole formation shows that the latter emphasized the upper portions of the complex rhythm, in the form H to F to G, or H to F to E to G. This analysis may indicate the existence of an ideal cycle or trend which rarely appears in its entirety in a given vertical sequence.

The preliminary facies relationship diagram derived from the analysis of all the data (Fig. 25a) now can be adjusted (Fig. 25b) to show the primary facies assemblages with their interpretations, and the dual association of the pelite facies (H). Each of these assemblages, plus some intermediate ones, and their characteristic internal rhythms, will be discussed and interpreted in the following section.

Preferred facies associations and sequence patterns

Having analyzed several vertical sequences of facies and determined preferred patterns and assemblages, their interpretations now can be made. The important facies associations are named genetically in order to emphasize the interesting range of depositional environments believed to be represented by the McNaughton Formation. They include the fan-delta, piedmont, estuarine-tidal flat, transitional piedmont-estuarine, and tidal inlet associations.

Fan-delta association

Repeated alternations of the conglomeratic quartzite and pelite facies at the base of the McNaughton Formation in eastern sections constitute the fan-delta association. This association forms a thick transitional unit between uniform pelites of the underlying Miette Group and the overlying, uniform conglomeratic quartzite of the McNaughton.

The conglomeratic quartzite facies described previously consists of massive, poorly sorted beds with scoured basal contacts, and bears a resemblance to conglomeratic "grits" of the underlying Miette Group. Many of the sedimentary features associated with these rocks are summarized in Figure 28. Pelites of the immediately underlying Miette Group are silty, partly burrowed, and contain horizontal trails (Young, 1972a). This facies was observed to be interbedded with well-sorted quartzite of nearshore origin in the vicinity of Mount De Veber and is assumed to represent moderately shallow offshore conditions. Hence the intertonguing conglomeratic quartzite and pelite facies probably represents subaqueous flows of coarse detritus entering a moderately shallow marine environment in the front of a developing alluvial system. As discussed below, this alluvial system is probably a series of coalescent alluvial fans; hence, where these fans empty into a body of water, by definition, a fan-delta results (McGowen and Scott, 1974). The numerous interfingering conglomeratic lenses and their gradually thinning distal margins suggest poorly channelized flows, in part stacked one above the other. The massive, poorly sorted character of the conglomerate suggests fluidized flows, or "grain-flows", which in part became turbidity currents that resulted in graded beds.

Piedmont association

The large-scale upward trend from conglomeratic quartzite (A) to planar crossbedded quartzite (B) to massive quartzite (C) is one in which mean grain sizes diminish, feldspar becomes less abundant, and general textural maturity improves. In most proximal sections of the McNaughton, the massive and crossbedded quartzites alternate irregularly over a major portion of the formation. The strip-log of the Mount De Veber section in Figure 5 illustrates this vertical facies pattern.

The predominance of planar crossbedded quartzite, previously interpreted as representing sandy, braided stream deposits, over intervals greater than 1 km (3300 ft) thick, suggests that they formed an alluvial fan complex. Because this complex developed adjacent to a nearby source-area of relatively high relief (*see* Petrography), it can be considered a piedmont. Stratigraphic and petrographic evidence discussed thus far indicates that a relatively sudden tectonic uplift occurred at the beginning of McNaughton time, causing rapid upbuilding and progradation of a piedmont plain. Initially, proximal alluvial sediments would have been deposited closely above marine sediments of the Miette Group along the flanks of the new uplift. As the piedmont plain was built up and prograded outward and the upland slopes retreated, increasingly distal alluvial sediments would appear at a given locality above earlier deposited proximal ones. This simplified sedimentation model explains the paradox of apparent transgression reflected in vertical facies sequences, and regression in terms of lateral facies relationships, and is discussed more fully in the final chapter.

The crude, horizontal lamination observed in the uniform phase of the conglomeratic quartzite facies, succeeded upward by planar-tabular crossbedded quartzite, follows the pattern of successive downstream changes in braided river deposits noted by Smith (1970). Smith observed that horizontal lamination is dominant in longitudinal bars, which tend to occur upstream from transverse bars, in which the dominant structure is planar crossbedding with unimodal orientations. A similar vertical sequence of dominant structures in part of the Dakota sandstone of New Mexico was interpreted as proximal braided-alluvial, tending toward distal braided-alluvial, by Gilbert and Asquith (1976).

It is interesting to compare the proximal McNaughton facies to other formations interpreted as dominantly alluvial-fan in origin (Table 4). In most ancient fan complexes, as in the McNaughton Formation, the mean grain size decreases upward. This is probably due to the gradual reduction in topographic relief, associated with downwasting and slope retreat of an initially uplifted terrain. Most complexes exhibit channels and trough

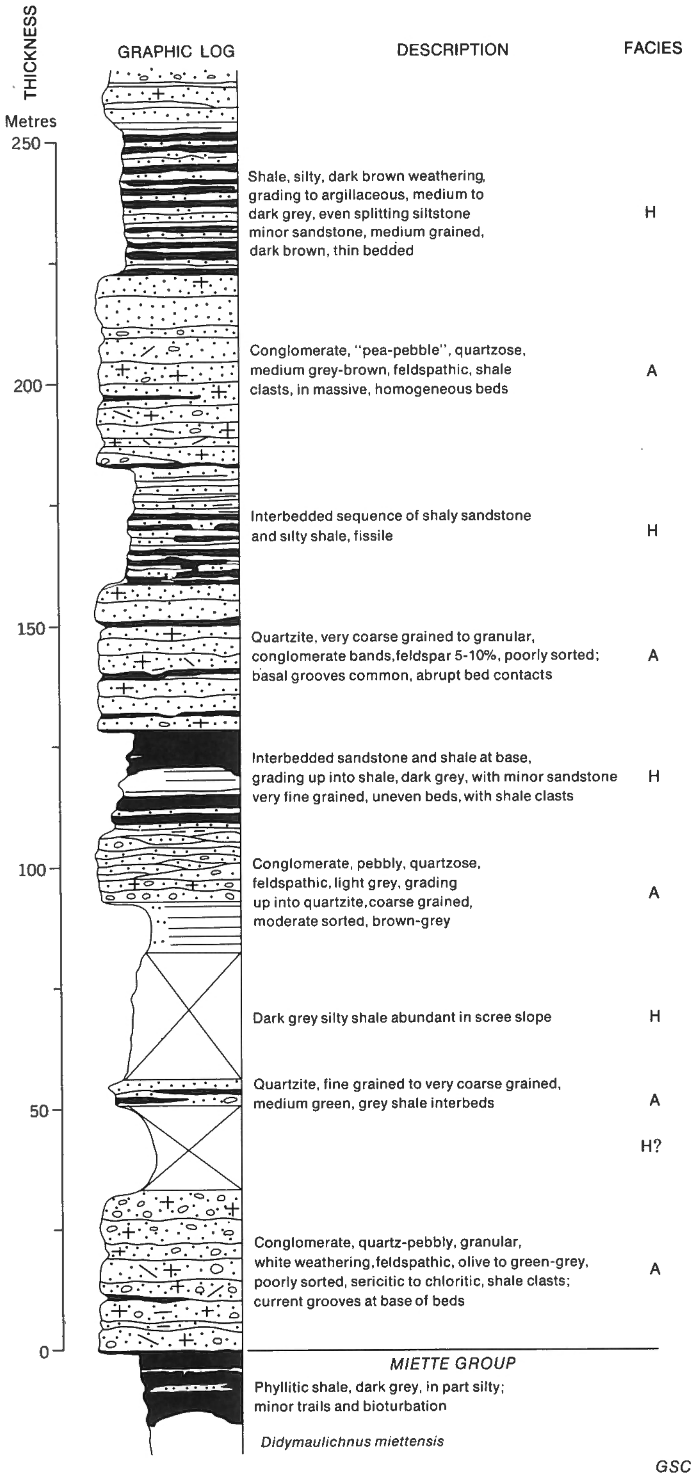


FIGURE 28. Lithology of basal McNaughton Formation at Bastille Creek; fan-delta succession.

crossbedding, although these features are not common in the McNaughton Formation of the study-area. Such features may be more typical of proximal parts of piedmont alluvium, whereas the McNaughton outcrops of the study-area may represent mainly medial to distal locales.

Formation	Sediment Colour	Thickness (km)	Sequence Trends	Channels	Trough x-bedding	Planar x-bedding	Graded Sets
Torridonian (Scotland) Williams, 1969;	red	2.5	fining-up	—	C	C	—
Old Red Sandstone (Norway) Nilsen, 1969;	brown, green	5.0	fining-up; coarsening-up	C	C	C	C
Fountain (Colorado) Hubert, 1960;	red	1.4	fining-up	C	C	—	P
Fundy (E. Canada) Klein, 1962;	brown, red	1.5	fining-up	C	C	C	P
Van Horn (Texas) McGowen and Groat, 1971;	red	0.3	fining-up	C	C	C	—
Missoula (Montana) Winston, 1973	red	3.0	coarsening-up	—	C	C	—
McNaughton (British Columbia)	drab	1.3	fining-up	P	P	C	P

Not mentioned, assumed rare... —   Present in minor amounts........P
Common.........................C   GSC

TABLE 4. Comparison of ancient alluvial fan complexes

The origin of the massive quartzite units of the McNaughton Formation within this framework remains uncertain. Interpretations of similar facies elsewhere provide some clues, but no completely parallel example has been found.

The interfingering relationship between the massive and crossbedded quartzite within the McNaughton resembles, to some extent, that of the Hawkesbury Sandstone of the Sydney Basin described by Conaghan and Jones (1975). The massive sandstone units of that formation display irregular, scoured, basal contacts, and contain shale breccias in their basal parts, whereas the massive McNaughton quartzite shows only sharp, apparently even, basal contacts, and no breccias. Nevertheless, most other features are similar. Conaghan and Jones ascribed the origin of the massive sandstones to upper flow regime conditions occasioned by floods, and the cross-bedded facies to aggradation of sand waves during the waning stages of flood conditions. A similar origin for some of the massive quartzite beds of the McNaughton seems reasonable.

The excellent size sorting of many examples of the massive quartzite and its association with the inter-bedded quartzite-pelite facies of possible shallow-marine origin suggest that it may have origins associated with littoral processes also. Here, an observation made by Meckel (1975) from the Colorado River delta is helpful.

The Colorado River delta occupies the head of the Gulf of California, the western flank of which is formed by mountains in an arid climate, and hence skirted by alluvial fan complexes. The distal parts of the fans merge with the delta-plain, which is characterized by large tidal ranges. Meckel found massive to horizontally bedded sand in chenier-like ridges and distal alluvial fan sand-bodies present where the alluvial fans abut and overlap the tidal-flat deposits. The origins of these sand-bodies apparently are linked with the action of waves and, possibly, wind during storms and associated high tides. Bigarella (1972) has pointed out that high

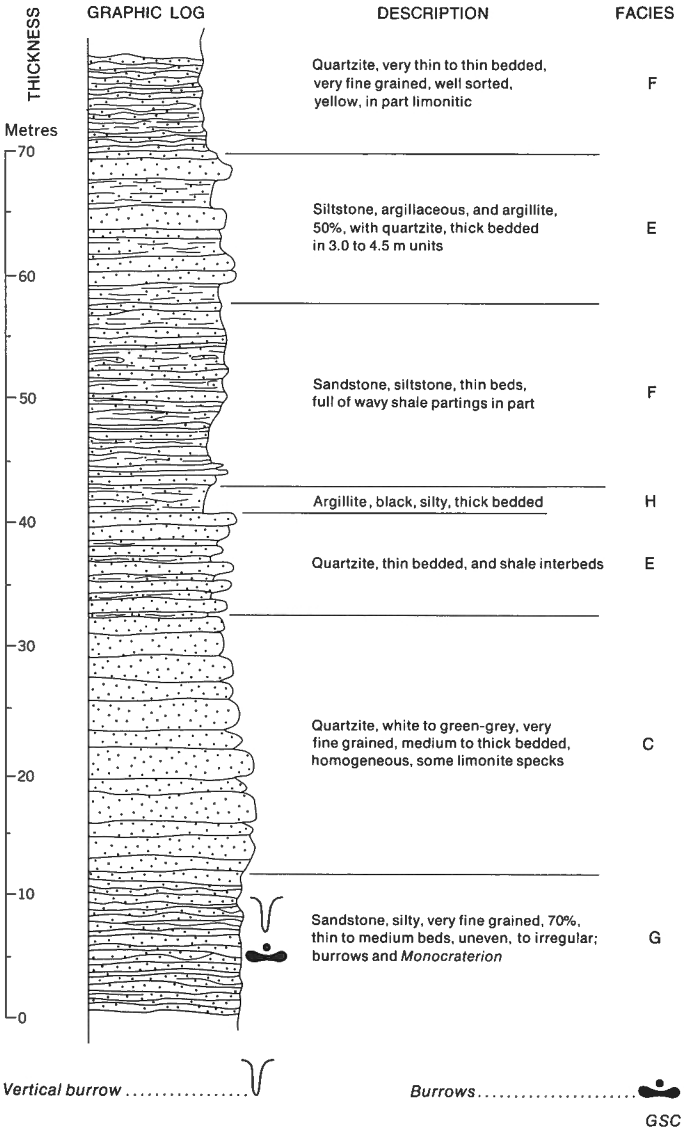


FIGURE 29. Lithology of eastuarine-tidal flat succession in lower part of McNaughton Formation at Walker Creek (Sec. 16).

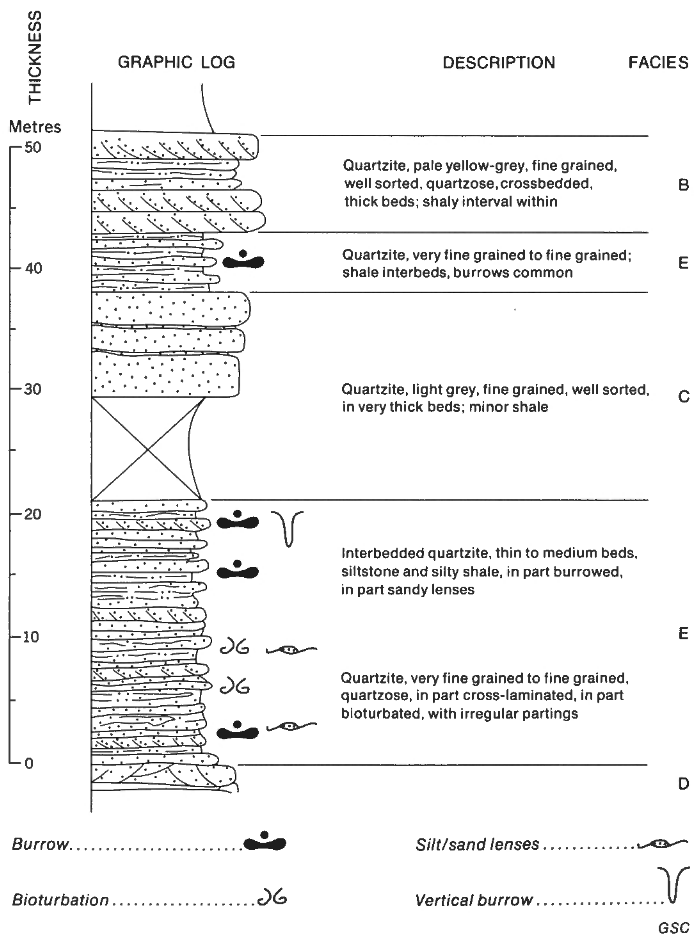


FIGURE 30. Detail of lithology of coarsening-upward rhythm in middle of McNaughton Formation, Dezaiko Range (Sec. 3).

rainfall and slumping induce homogenization of aeolian sand deposits. A similar setting to that of the southwestern Colorado River delta, but having greater precipitation, could account for some of the massive quartzite beds of the McNaughton Formation.

Estuarine-tidal flat association

As illustrated in Figure 29, a common association in outcrops of the medial zone includes the massive quartzite (C), interbedded quartzite and pelite (E), flaser quartzite (F), mixed pelite-sandstone (G), and pelite (H) facies. These may alternate in various ways, but commonly form fining-upward and coarsening-upward rhythms, occasionally in a continuous cycle, as suggested by the Markov analysis. Both types of rhythms, occurring in close association, have been noted in estuarine and tidal flat successions of the southwestern coast of the Netherlands (Terwindt, 1971) and the Colorado River delta (Meckel, 1975).

The fining-upward rhythms (generally represented by an upward transition from quartzite to mainly pelite) are extremely variable in thickness and probably represent either the lateral migration of channels or an increase in water depths, possibly associated with a marine transgression. Sharp, erosional basal contacts characterize the sequences of sand and shale caused by migrating channels (Meckel, 1975), hence transitional contacts, such as that at the base of the massive quartzite unit (Fig. 29), most likely represent the gradual emergence of a beach ridge or coastal barrier complex. Shale and quartzite interbeds at the top of this unit indicate an alternation of calm and active current regimes, as might exist in a zone where sand-spits and shallow embayments form the inner margin of a barrier island. The black pelite of the middle of the cycle was deposited, probably, in a backwater or lagoon unaffected by tidal currents.

The overlying coarsening-upward rhythm, involving mainly the mixed pelite-sandstone and flaser quartzite facies, represents gradually shoaling conditions, probably subtidal and sandy intertidal environments. Extensive sandy tidal flats comprise much of the distal delta-plain of many modern tide-dominated deltas (e.g. Burdekin River of Australia, *see* Coleman and Wright, 1975). In a sand-dominant clastic system like that of the Gog Group, similar sand-flats probably developed in shallow estuaries at the distal margins of the piedmont plain. The interbedded quartzite and pelite facies (E) that interfingers with the flaser quartzite facies (F) could be interpreted as fluvial flood deposits partly reworked by tidal currents, or as resulting from the migration and infilling of tidal creeks. The predominance of thick quartzite beds with sharp bases and the presence of burrows in some of the pelite favours the latter interpretation. Tidal creeks are apt to be shallow and free to migrate on a sand-flat, much as they are in modern Boundary Bay near the Fraser Delta (Kellerhals and Murray, 1969).

Another type of coarsening-upward rhythm involves the interbedded quartzite-pelite facies which grades upward into either the massive quartzite or planar cross-bedded quartzite facies. These are common in the upper 100 m (330 ft) of the McNaughton in the proximal zone, in parts of the Holmes River Member in more westerly sections (Fig. 29), and were described by Palonen (1976) in the lower Gog Group in northern Banff National Park.

In these rhythms, the interbedded quartzite-pelite facies typically is partly burrowed and some sandy pelite beds are bioturbated; small-scale cross-lamination is sometimes present, representing the passage of ripples in the thinly bedded quartzite. Other structures include fine, laminated sand-mud alternations, lenticular bedding, and vertical burrows. These features resemble those found in mixed sand-mud tidal flat deposits ("Misch" flat facies of Reineck, 1967). This interpretation is supported by the fact that this facies overlies a thick sequence of festoon quartzite facies and shale-interbedded equivalents in the Dezaiko Range section, which probably represent intertidal sand bars (Klein, 1970). The overlying massive quartzite unit is possibly a wind- or wave-reworked tongue of alluvial sand which encroached upon the tidal flats. A similar model can be invoked to explain the succeeding rhythm, except that in this rhythm the quartzite is crossbedded and contains a shaly interval. These beds may represent unreworked fluvial sands and muds, deposited at the distal end of an alluvial fan.

Transitional piedmont-estuarine association

In medial to distal successions, shalier upward rhythms are present in close vertical proximity to coarsening-upward rhythms and probably are allied to them. These rhythms are formed by an upward decrease in the thickness and scale of quartzite beds and contained structures, along with an upward increase in shale content and bed thickness. Mean grain sizes of arenaceous rocks may increase upward, as in the illustrated example (Fig. 31), rather than decrease. Basal contacts of these rhythms are mainly sharp, although not necessarily erosional.

The quartzite of the lower parts of these rhythms is generally a combination of massive and planar cross-bedded quartzite and probably was deposited as transverse bars and shallow channel-fillings at the distal margin of the alluvial fan complex. The overlying interbedded quartzite-pelite facies could represent a delta-front type of setting where fan channels entered shallow bays. The thin, irregular interbeds of the mixed pelite-sandstone facies (G) or the flaser quartzite facies (F) in the upper parts of the rhythms were deposited in shallow subtidal environments such as bays or lagoons, or on intertidal sand/mud flats. In the example (Fig. 31), as well as in the immediately underlying shalier upward rhythm, two features in the mid-portions of the rhythms in the interbedded facies favour intertidal conditions. The first is the presence of convoluted bedding, which sometimes forms on the prograding banks of tidal creeks (Reineck, 1967), and the second is the evidence of paleocurrents, opposed to those in the underlying fluvial sands, suggesting flood-tidal currents. Because of their abrupt appearance in the section, followed by gradual onlap of shallow marine conditions, these rhythms could represent periodic break-outs, or avulsion, of fluvial channels on the distal piedmont plain.

Tidal inlet association

Interfingering units of the festoon quartzite facies (D) amidst thick sequences of the mixed pelite-sandstone (G) are typical of the Holmes River Member in the Holmes River area of the Robson Syncline. The festoon quartzite overlies the pelitic rocks along a sharp, scouring contact, and generally has an abrupt upper contact as well (Fig. 32). As described previously, this quartzite probably represents a type of tidal channel because of its variable to bimodal crossbed orientations. Although the details of the Holmes River succession were studied inadequately, the sedimentary structures and lithologic associations of the festoon quartzite units suggest sequences very similar to those described for estuarine channels and tidal inlets in the literature.

Oomkens and Terwindt (1960) (*see* also Klein, 1967) described a vertical sequence of sediments from the estuarine arms of the Rhine and Meuse Rivers of the Netherlands. The sequence consisted of coarse sand and shelly debris at the base above an eroded surface, followed by festoon crossbedded sand which, in turn, is overlain by thin-bedded, evenly laminated sand with clay laminae. This was ascribed to the rapid lateral migration of the estuarine channel.

Kumar and Sanders (1974) described the vertical succession of sedimentary textures and structures resulting from the lateral migration of a tidal inlet between two barrier islands. They pointed out that, because of the deep scouring at the bases of these inlets, deposits filling these channels would have a high potential for preservation, whereas associated barrier island sands located above mean high tide level correspondingly may be preserved rarely. The deep channel fill of their inlet sequence consists of lenticular sets of cross-laminae, caused by deposition and partial erosion of reversing flood and ebb currents, similar to the structures observed in the festoon quartzite facies. The argillaceous sandstone intervals containing lenses of silty sand may represent the upper spit and tidal flat deposits of an inlet sequence. These successions appear to be stacked one above another in the example illustrated, and are overlain finally by offshore mixed pelite-sandstone facies. Continuous subsidence is evident from the thickness and vertical continuity of the marine facies of this section, allowing the main portions of the channel-filling sequences to be preserved.

The fact that these channels overlie and are overlain by the mixed pelite-sandstone facies indicates the close tie of the latter to nearshore processes and deposits, despite their "offshore" character, as argued earlier. It is suggested, therefore, that this facies represents the tide-influenced, subtidal facies of an estuary or semi-restricted basin.

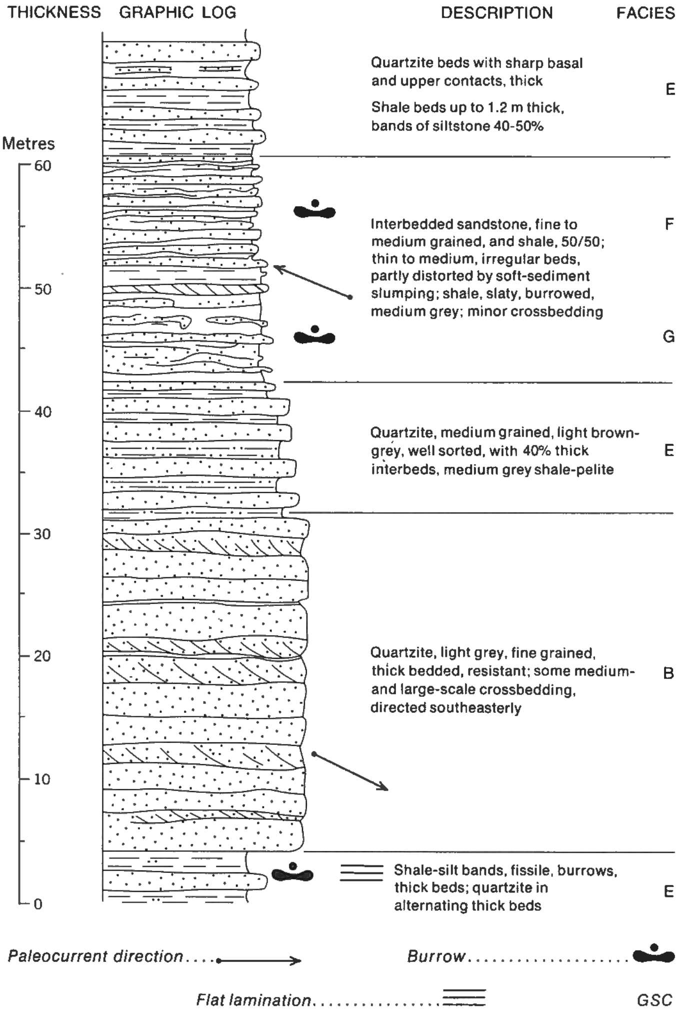


FIGURE 31. Detail of lithology of "shalier-upward" rhythm from piedmont-estuarine transition near top of McNaughton Formation, Dezaiko Range (Sec. 3).

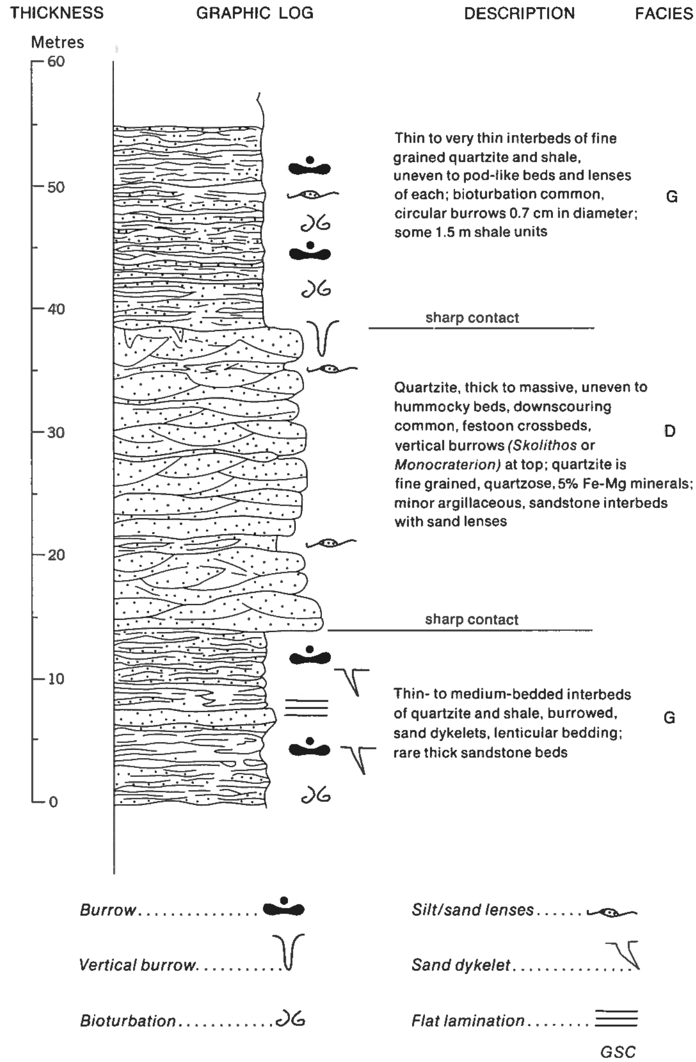


FIGURE 32. Lithology of tidal inlet sequence from middle of Holmes River Member, McNaughton Formation, Holmes River (Sec. 7).

Summary interpretation of depositional environments

The foregoing discussion of major facies associations and vertical sequences allows some modifications to be made of earlier interpretation of individual facies. The interbedded quartzite-pelite facies probably embraces several lithotopes, as might be expected from its somewhat heterogeneous definition, including the lower shoreface, delta-front, overbank alluvial, and mixed sand/mud tidal flat environments. All of them are characteristic of the transition zone between nonmarine and marine conditions. The mixed pelite-sandstone facies apparently represents subtidal, shallow bay to offshore environments in the main, although a few, relatively thin units of this facies may have been deposited on intertidal mud-flats.

The dominant influence of tidal currents in the deposition of medial and distal zones of the McNaughton Formation is clear, as is the role of braided streams in the deposition of the proximal to medial quartzites. The transition zone between the tidal and fluvial regimes is characterized by both fining-upward and coarsening-upward rhythms which represent merging, interfingering relationships between the two systems. Distributaries having erosional contacts with underlying or adjacent sediments are absent.

CHAPTER IV

SEDIMENTOLOGY OF UPPER YANKEE BELLE, YANKS PEAK, AND MIDAS FORMATIONS

Units in the Cariboo Group correlative with the McNaughton Formation include the upper Yankee Belle, the Yanks Peak, and Midas Formations, which together form a thick clastic succession in northern Cariboo Mountains. This western clastic succession is similar lithologically to that of the McNaughton Formation, but generally is thinner and exhibits more stratigraphic regularity than its eastern counterpart. Marker beds and large-scale sedimentary cycles can be correlated over most of the northern Cariboo Mountains within the clastic succession, allowing important observations on lateral facies changes to be made.

Stratigraphic control was established using seven principal measured sections (Figs. 3-5) and several partial, ancillary sections. Sedimentological data were obtained from these sections as from numerous isolated outcrops. The following facies analysis is not as rigorous as that given for the McNaughton Formation, and is intended primarily to complement the earlier review.

FACIES DESCRIPTIONS AND INTERPRETATIONS

All eight facies of the McNaughton Formation were observed in the clastic succession of the Cariboo Group. In addition, four new facies are described from the Cariboo Group. These include a red-bed facies, an interbedded shale-siltstone-sandstone facies, an evenly bedded quartzite facies, and a carbonate facies. Descriptions of the facies common to both successions and their inter-relationships with the unique Cariboo facies provide added insights into the interpretations of many of the McNaughton facies.

Facies similar to those of the McNaughton Formation

Conglomeratic quartzite facies

Only the uniform conglomeratic quartzite subfacies of this facies group was observed in the Cariboo Group and, in all three places where it was seen, it occurs in the upper Yanks Peak Formation, representing the middle sequence. It forms a unit 89 m (292 ft) thick at the Mount Amos Bowman section east of Isaac Lake, and is there both underlain and overlain by the interbedded quartzite-pelite facies. At the Slim Creek section, it forms a pink to red unit, 29 m (95 ft) thick, and grades upward into the red-bed facies. Pebbly sandstone, conglomerate, and minor red shale interbeds constitute a poorly exposed unit of undetermined thickness at Sugarbowl Mountain.

These conglomeratic rocks occur far to the west of similar rocks of the McNaughton Formation, which are confined to its easternmost outcrops and the lower sequence. This distribution suggests that the Yanks Peak clastics represent a separate dispersal system from that of the McNaughton, at least in part. This possibility is enlarged upon later in the report.

The conglomeratic quartzite of the Yanks Peak Formation is thick bedded to massive and contains minor, thinner interbeds of shale, siltstone, and/or fine-grained sandstone. In the northernmost Cariboo Mountains, these interbeds are red due to the presence of hematite in the rock-matrix. Most beds appear quite homogeneous, except for some vague parallel laminations. Planar cross-stratification is rare, as are shale rip-up clasts.

Grain-size distributions of much of the quartzite are obviously bimodal; granules and pebbles form a coarse mode that is fairly distinct from a well-sorted, medium sand size mode. Some of the conglomeratic rocks are poorly sorted and contain considerable amounts of clay-silt matrix. Pebble or granule conglomerate layers rarely are present within the quartzite beds.

The conglomeratic quartzite facies contains approximately 10 per cent pink feldspar of coarse sand and granule grades. Minor amounts of red jasper and relatively soft, green material, tentatively identified as jadeite, occur in the granule fraction. Pebbles in the Yanks Peak, as in the McNaughton Formation, almost invariably are quartz.

The rudaceous grain sizes, the association with red beds, and the high feldspar content support the earlier interpretation of fluvial deposition. The crude, parallel lamination of this facies possibly represents longitudinal bars or plane-bed conditions caused by rapid flow in the lower part of the upper flow regime (Harms and Fahnestock, 1965).

Planar crossbedded quartzite facies

The Cariboo Group lacks thick successions of planar crossbedded quartzite, unlike the McNaughton Formation. This facies appears mainly as tongues within massive quartzite or red beds of the Yanks Peak Formation. For example, it forms a 31 m (102 ft) thick unit in the lower Yanks Peak of the Dome Creek section (Fig. 4), and the upper 14 m (46 ft) of another 30 m (100 ft) thick unit in the middle of the Yanks Peak in the Zig Zag Ridge section (Fig. 4).

In all examples of this facies, minor thin beds of argillaceous siltstone or laminated sandstone are interspersed with thick, planar-tabular sets of cross-stratification. A few massive beds of quartzite, consisting of sand coarser than the associated cross-stratified beds, generally are present.

The planar crossbedded quartzite facies probably originated as migrating transverse bars and sand waves in fluvial channels. The finer grained interbeds may represent periods of reduced flow rates and flows of shallow depth.

Massive quartzite facies

The massive quartzite facies exists mainly at or near the top of the Yanks Peak Formation (middle sequence), and near the top of the lower sequence. In several sections, units approximately 100 m (330 ft) thick are present; crossbedding appears in the upper 10 to 15 m (33-49 ft) of some of these units.

Correlations between closely spaced sections of the Yanks Peak Formation in the Dome Creek area (Fig. 4) suggest that the massive quartzite changes facies laterally into the planar crossbedded and the red-bed facies (described below). Vertical contiguity and gradations among these facies also lend support to the idea that they are laterally contiguous, by reason of Walther's Law of Correlation of Facies (Middleton, 1973).

Most examples of this quartzite are massively bedded and consist of well-sorted, medium- to coarse-grained, pure quartz arenite, which is white or pale pink. Sedimentary structures are rare, but those observed include lag lenses of granules or pebbles, in part sigmoidal in shape, and indistinct coarse lamination.

These features indicate a highly agitated environment of deposition, such as that found in a fluvial channel or along a beach. Grain-size distributions of two specimens of massive quartzite (Fig. 24) support a beach origin by comparison with other deposits (Glaister and Nelson, 1974). However, more current-formed and biogenic structures would be expected in the latter environment. Grain-size distributions similar to those of beach sands may result from strong currents in the upper flow regime within fluvial channels, where they are likely to be coarser than most beach sands, or upon subtidal sand waves (Off, 1963). In all these environments, flat-bed or antidune bed-forms may be present, resulting in poorly developed lamination or homogeneous fabrics.

Festoon crossbedded quartzite facies

Good examples of the festoon crossbedded quartzite facies exist in the lower part of the Yanks Peak Formation (upper part of the lower sequence) along the northwestern flank of the Cariboo Mountains. On the ridge above lower Slim Creek (Fig. 3), festoon crossbedded quartzite forms a unit approximately 125 m (410 ft) thick. Within the interior of northern Cariboo Mountains, this facies is rare, and is not recorded anywhere from the middle and upper correlation divisions. In two recorded instances, it grades abruptly upward into the red-bed facies.

Festoon crossbedding in sets of various thicknesses is the main characteristic of this facies. Foreset dip-directions are typically bimodal and, in places, are arranged in herringbone co-sets (Fig. 33). Most paleocurrent distributions are almost bipolar but, in at least one example, the modes are less than 180 degrees apart. Ripple marks with shaly coatings and mudcracks are present in thinly bedded examples of this facies. As in the McNaughton Formation, pinch-and-swell bedding, varying from thin to massive, is associated with this quartzite. Shaly partings and interbeds are minor and, in some cases, are burrowed. The quartzite is fine to coarse grained, moderately to well sorted, and includes lag lenses of very coarse particles at the bases of some scours.

The bimodal paleocurrents, mature texture of the quartzite, and rare bioturbation indicate shallow-marine depositional conditions, dominated by tides. Tidal inlets, channels, sandbars and sand-flats could all be represented within the festoon crossbedded quartzite. The significance of the vertical transition from this facies into the red-bed facies will be discussed in a later section.

Interbedded quartzite-pelite facies

The interbedded quartzite-pelite facies forms units that are interspersed throughout the western clastic succession, being particularly common in the lower Midas Formation and in central to southern outcrops of the Yanks Peak Formation. Some units are up to 55 m (180 ft) thick, but most are 20 to 28 m (65-91 ft) thick. Rocks of the interbedded quartzite-pelite facies occur as tongues between quartzite units, and as a transitional facies between pelitic and quartzitic rocks. A close association with the flaser quartzite facies is evident from numerous vertical sequences in which these two facies alternate with gradational contacts.

The interbedded quartzite-pelite facies typically consists of fine-grained, in part silty, evenly laminated, limonitic, quartzitic sandstone and interbeds of micaceous siltstone and dark grey shale. The sandstone is thin to medium bedded, whereas the pelite is thin bedded and commonly bioturbated. Thick-bedded, medium- to coarse-grained quartzite may be present and, in some samples, is the primary rock-type.

The alternating beds of laminated fine sandstone and micaceous, burrowed pelite are reminiscent of shallow-subtidal, marine deposits of modern and ancient stormy coastal areas (Goldring and Bridges, 1973).

Flaser quartzite facies

The flaser quartzite facies appears principally in the Midas Formation and was noted twice in the lower Yanks Peak Formation. In these formations it consists mainly of quartzitic sandstone, with discontinuous shale partings (a type of flaser). It grades into the mixed pelite-sandstone facies, which is defined as consisting of at least one half pelite beds. Units of flaser quartzite may be up to 40 m (130 ft) thick.

Bedding in this facies is typically uneven to irregular and thin, owing to the abundance of fine, wavy shale partings. Further irregularity is caused by bioturbated fabrics, horizontal trails, and vertical burrows, such as *Monocraterion*, in quartzite beds. Some quartzite beds contain black shale-chips, many of which are oval in outline, and extremely thin. The latter may represent compressed and carbonized life-forms, but these objects merit detailed study to confirm their origin.

The close association of the flaser quartzite with pelite, mixed pelite-sandstone, and interbedded quartzite-pelite, and the presence of bioturbation, indicate a shallow-marine origin. Whether or not it originated in the intertidal zone, as postulated for this facies in the McNaughton Formation, is open to question, because many sedimentary structures observed in the McNaughton were not evident in the flaser quartzite of the Cariboo Group. However, shale partings in a quartzite facies record alternating energetic and quiescent conditions, which would be expected in a depositional site influenced by tidal currents or periodic storms.

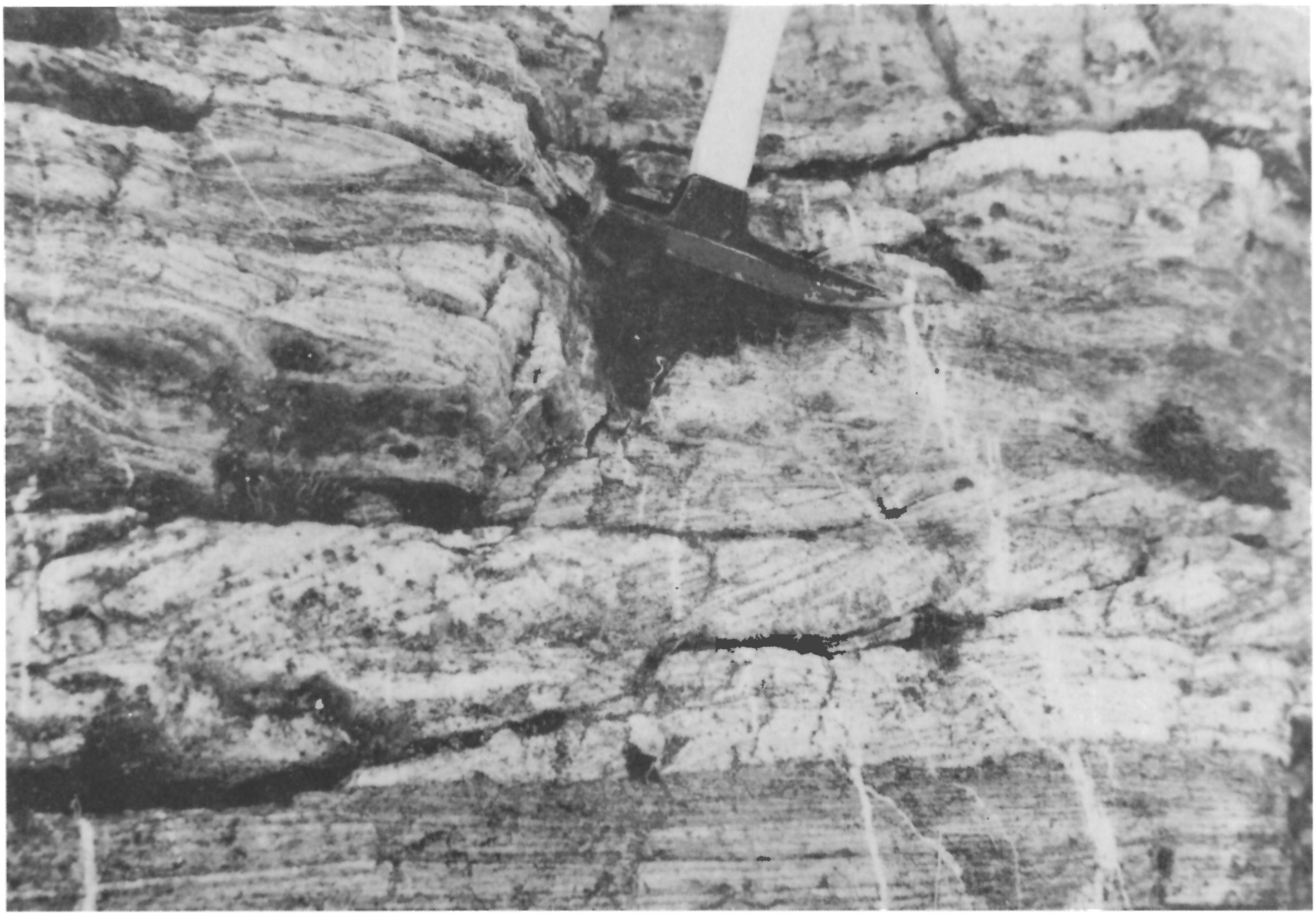


FIGURE 33. Cross-lamination and parallel lamination enhanced by hematite concentrations in festoon crossbedded quartzite facies, Yanks Peak Formation, Slim Creek section. GSC 199281.

Mixed pelite-sandstone facies

The mixed pelite-sandstone facies forms the basal 100 m (330 ft) or more of the Midas Formation in the western Cariboo Mountains and is present higher in the formation to the northeast. It appears but rarely in the Yanks Peak Formation, and only in the western part of the area. Interfingering facies include the pelite and interbedded siltstone-shale-sandstone facies, and massive or planar crossbedded quartzite with minor amounts of shale which commonly underlies the mixed facies.

The mixed facies consists of thin interbeds of dark grey shale, light grey or green siltstone, and minor very fine grained, limonitic sandstone. Silt-filled burrows (Fig. 34) and deformed silt lentils and dykelets are common; flasers and associated micro-cross-lamination are relatively rare. Parallel-laminated to burrowed sets (Goldring and Bridges, 1973) are discernible in a few localities (Fig. 35).

A variant of this facies is present rarely in the upper Midas Formation, and is similar to the carbonaceous mixed facies observed in the upper McNaughton Formation at Mount Murray (Ch. III), north of the study-area. *Cruziana* trails and other trace fossils abound on the shaly undersurfaces of silty sandstone beds in this subfacies.

The sedimentary structures and associations of this facies in the Cariboo Group are consistent with the subtidal, shallow-marine (i.e. offshore) interpretation advocated for it in the McNaughton Formation.

Pelite facies

Included in the pelite facies of the Cariboo clastic succession are uniform shale (usually phyllitic or slaty), shale with minor beds of siltstone or fine-grained sandstone, and massive siltstone, which is discussed below as a separate subfacies. The pelite facies is present in two principal stratigraphic levels in the succession: at its base (Yankee Belle Formation), and at or near its top (Midas Formation). The basal pelite unit varies in thickness from 30 to 140 m (100-460 ft) and consists of light greenish grey argillite or slaty shale which grades upward into massive siltstone or interbedded siltstone and shale. At one locality the basal shale is blood red in the lower 33 m (110 ft), becoming green above. The upper pelite unit also becomes coarser upward and is light greenish grey in northwestern Cariboo Mountains, but in the western outcrops it is a dark grey, upward-fining sequence, 120 m (400 ft) thick.

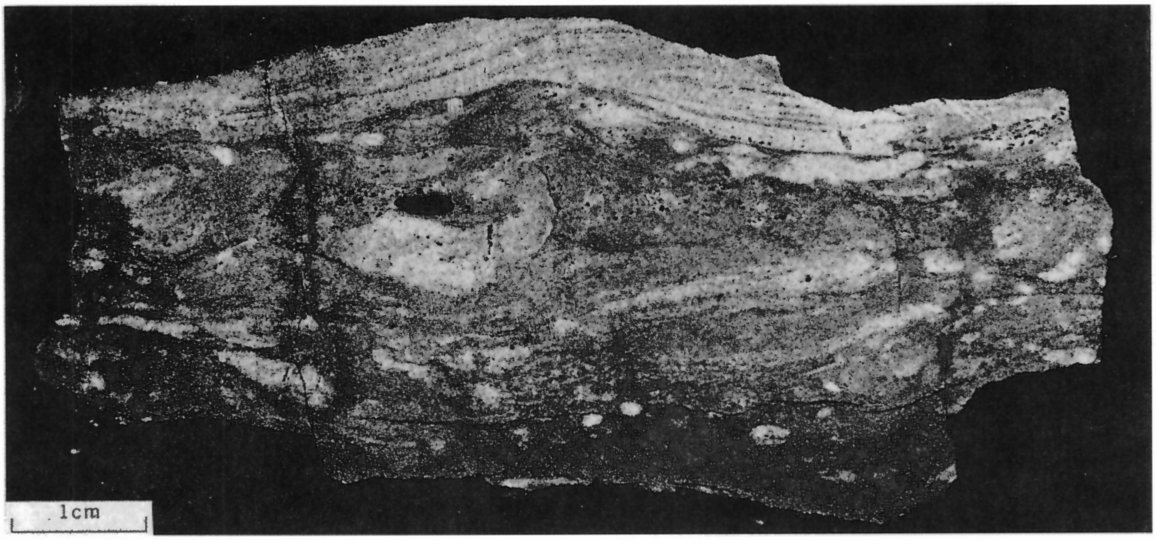


FIGURE 34. Silt-filled burrows, deformed silt lenses, and ripple cross-lamination in mixed pelite-sandstone facies of Midas Formation, "Marten Pass". GSC 199273.

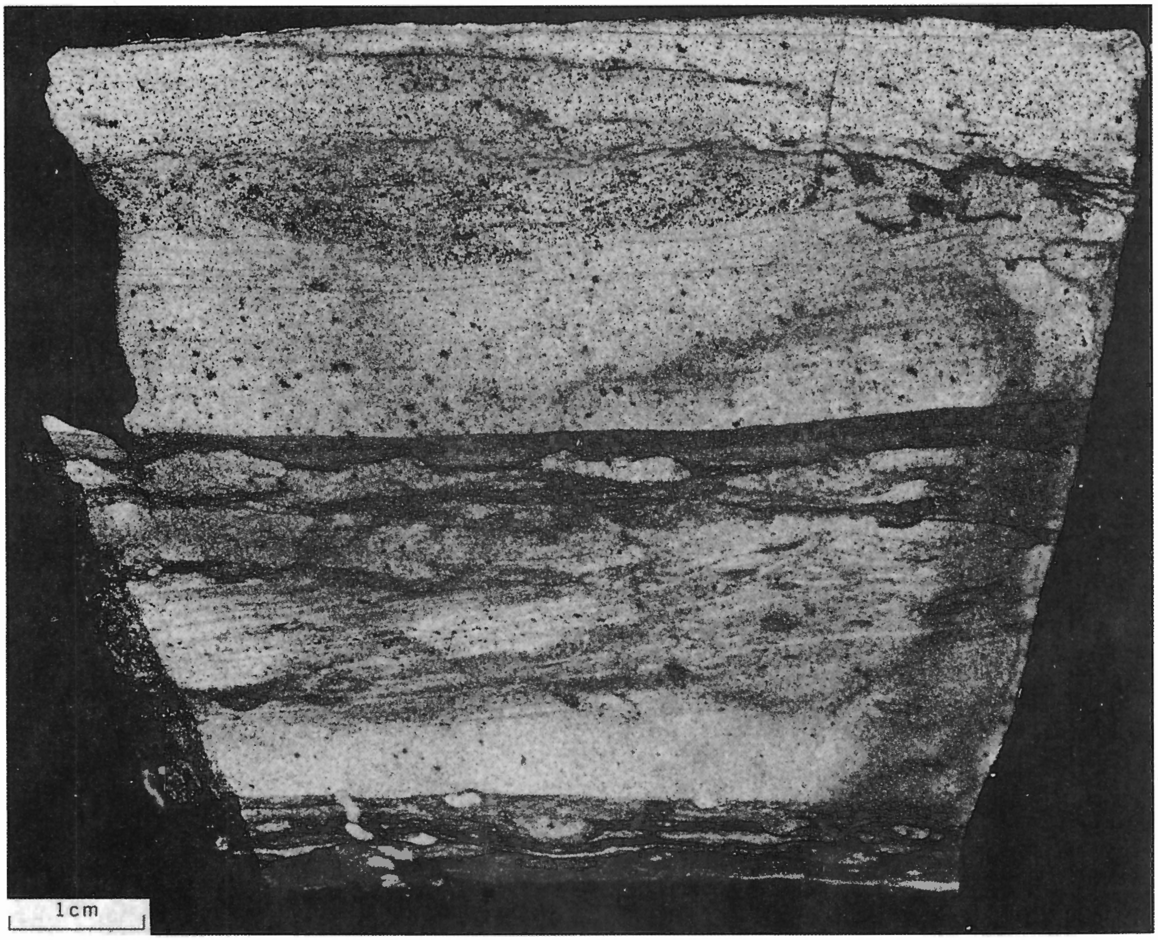


FIGURE 35. Parallel and inclined lamination and small burrows in specimen of mixed pelite-sandstone facies, Midas Formation, Haggen Creek section. GSC 199271.

In the Wells area, the Yankee Belle Formation consists principally of greenish-grey and maroon-grey phyllitic shale, believed to be correlative with the upper Yankee Belle and lower Yanks Peak Formations of northern Cariboo Mountains.

The massive siltstone subfacies is typically greenish grey, non-laminated, and includes rocks ranging from silty mudstone to argillaceous, very fine grained sandstone. It forms discrete units within the Yanks Peak Formation, and also the middle parts of coarsening-upward pelite-arenite cycles. Small amounts of fresh, probably authigenic plagioclase were identified in some of these rocks. In places, interbedded, laminated shale separates thick to massive beds.

Massive siltstone commonly lies between laminated shale below and well-sorted arenite of shoal-water origin above. At two localities, the overlying rocks include oolitic dolomite or algal-grain limestone, which also attest to shallow-marine conditions. This intermediate position in probable shoaling-upward cycles suggests that the siltstone originated on the outer shelf or in the clinoform zone.

Facies peculiar to the Cariboo clastic wedge

Red-bed facies

Red beds appear exclusively in the middle and upper Yanks Peak Formation, and only in the northernmost part of the Cariboo Mountains. This facies consists of red, hematitic sandstone in medium to thick, partly lenticular beds, and 20 to 40 per cent red shale and siltstone interbeds. It intertongues with massive, white quartzite, planar crossbedded quartzite, and the interbedded siltstone-shale-sandstone facies. Red-bed rock-units range in thickness to at least 70 m (230 ft), as in the Mount Cochran area north of Isaac Lake.

Fining-upward rhythms were not noted and evidently are rare or poorly developed. Instead, simple alternations of maroon shale, very thin bedded siltstone, and thick-bedded sandstone are typical. Many sandstone beds are lenticular (Fig. 36), probably originating as scour-fillings. Trough cross-stratification of small and medium scale is common, and foreset dip-directions are unimodal at specific localities. Tabular sets of cross-beds with tangential lower bounding contacts are present in some thick beds of sandstone, which elsewhere are parallel-laminated.

The sandstone varies within a few metres of thickness from very fine to very coarse grained, displaying moderate sorting and commonly a small population of very coarse and granular sizes (Fig. 24, Sample 300 YA-8). Feldspar is a minor constituent of most red-bed sandstones, but is absent in one analyzed specimen from Mount Cochran (Table 5, Sample 319 YA-5).

The grain-size distributions of sandstones in the red-bed facies, the presence of unidirectional, festoon crossbedding, and the hematite stain in these rocks all point to fluvial depositional conditions in a highly oxidizing environment. The predominance of arenaceous clastics and their great variation in grain size indicate extremely variable and episodic stream discharge, such as that found in a braided stream. The close interrelationship of the red beds with the massive and planar crossbedded quartzites suggests the possibility that the latter represent torrential flow conditions in main channels, whereas the red beds represent extremely variable flows alternating with periods of nonflow, as might be expected in side channels and ephemeral streams.

Interbedded shale-siltstone-sandstone facies

The interbedded shale-siltstone-sandstone facies occurs within the Yanks Peak Formation throughout northern Cariboo Mountains and forms thick transition zones at the top of the Yankee Belle Formation along the eastern flank of the Cariboo Mountains, and at the top of Yanks Peak Formation along their western flank. An example of the former is 85 m (280 ft) thick at Zig Zag Ridge where it is overlain by sandy limestone or sandstone of the basal Yanks Peak Formation. A representative of the upper Yanks Peak transition zone is 80 m (262 ft) thick on "Haggen Ridge" and is overlain there by pelite of the Midas Formation.

This facies consists of thin, uneven beds of siltstone, shale, argillaceous sandstone, and clean, very fine to coarse-grained sandstone, forming a disordered vertical sequence. Bed contacts generally are abrupt (Fig. 35), and marked by the presence of fine, shaly partings.

Many argillaceous beds contain silt-filled burrows, or are completely bioturbated (Fig. 37). Some siltstone beds exhibit trails, small symmetrical ripple marks, and oval carbonaceous imprints.

A sandstone sample from Mount Cochran (Fig. 24, Sample 319 YA-2) is poorly sorted and has a high silt-clay population (20%). It consists of 4 per cent feldspar and 61 per cent quartz, with the remainder cement, sericitic matrix, and miscellaneous lithic grains. This is somewhat less mature chemically than the average Yanks Peak arenite (Table 5).

Because the interbedded facies just described forms transition zones between pelite on one hand, and massive quartzite, red beds, or evenly bedded quartzite on the other, it is clearly shallow marine in origin, an interpretation substantiated by the presence of bioturbation structures. In some cases, parallel-laminated to burrowed sets (Goldring and Bridges, 1973) are present, but the common interruption of the sequence of fine clastic strata by coarse-grained sandstone must be due to proximity of the site to sporadic high-intensity currents, perhaps induced on a shoreface by heavy seas during storms, or on a delta-front during floods.

Evenly bedded quartzite facies

Evenly bedded quartzite is present at various stratigraphic levels in the Yanks Peak Formation as resistant units 55 to 70 m (180-230 ft) thick. This quartzite commonly interfingers with or grades upward into massive or planar crossbedded quartzite, and is both underlain and overlain by shalier rocks such as the interbedded quartzite-pelite facies.

This quartzite facies is characterized by its thick, even beds, some of which consist of planar-tabular crossbedding sets approximately 1 m (3.3 ft) thick. Vague parallel lamination is the only other structure recorded from these rocks, and this is obscured by the absence of grain-size or colour variations. Paleocurrent distributions determined from such crossbeds at Mount Amos Bowman are unimodal, but widely dispersed about the mean.

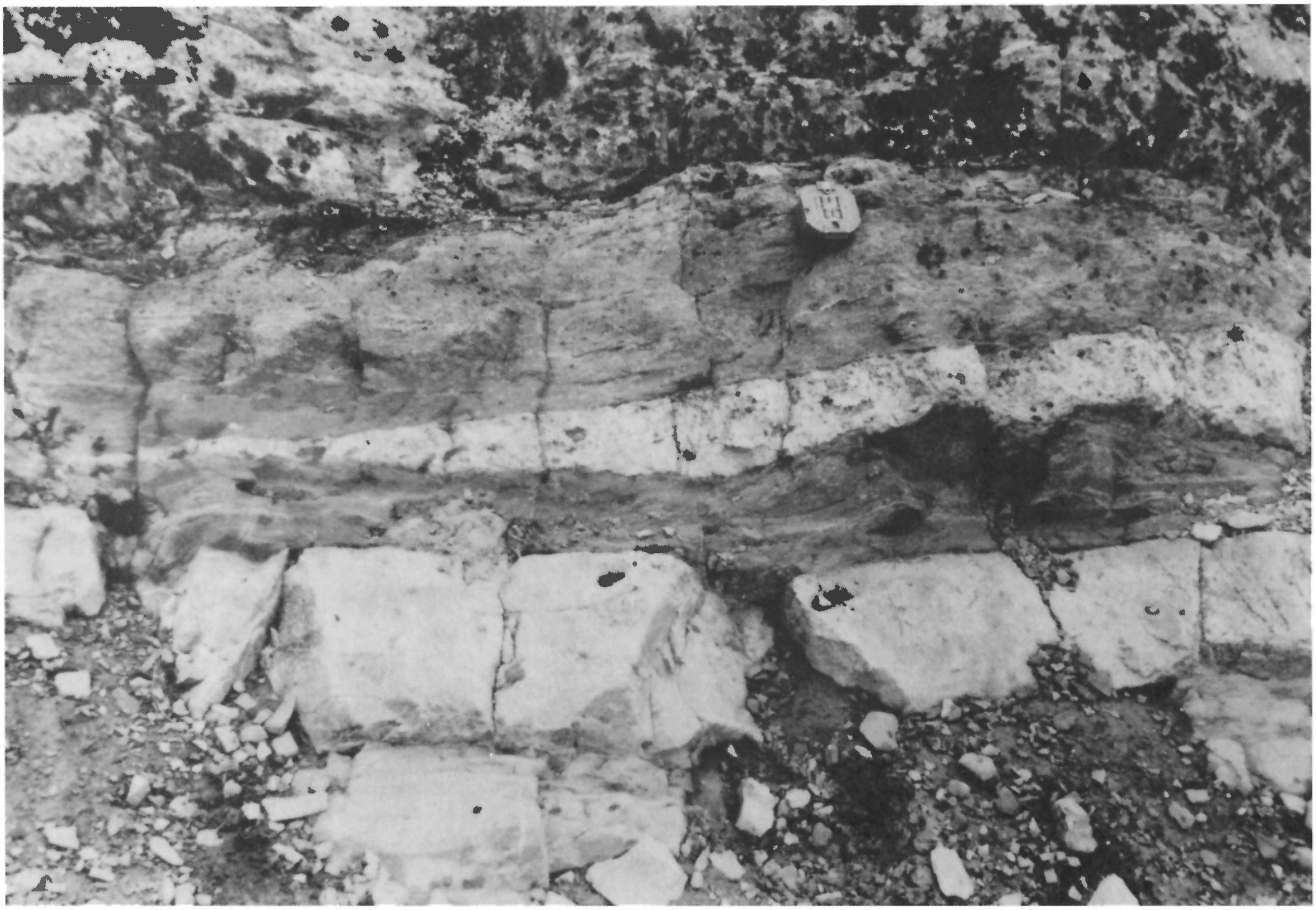


FIGURE 36. Thin lens of conglomeratic quartzite in red siltstone and shale unit, Yanks Peak Formation, Dome Creek section. GSC 199282.

				% of Particulate frac.				% of Matrix fraction			
Sample	Section	Interval	Facies	% Part.	Quartz	Fspar	Other	% Matrix	Seric	Quartz	Fe-Ox
300 YA-16	4	upper	G	65.0	85.0	2.1	12.9	35.0	7.8	24.1	3.1
300 YA-15	4	upper	F	60.6	79.3	7.3	13.4	39.4	20.9	8.3	10.2
300 YA-13	4	middle	C	71.4	99.4	0.6	0	28.6	0	28.6	0
300 YA-12	4	middle	C	64.2	69.5	15.5	15.0	35.8	35.2	tr	0.6
300 YA-8	4	middle	RB	82.0	92.5	6.9	0.6	18.0	15.7	tr	2.1
317 YA-7	10	middle	A	82.2	97.5	0.5	2.0	17.8	7.2	10.6	0
319 YA-5	11	middle	RB	73.0	95.6	0	4.4	27.0	7.0	20.0	0
319 YA-2	11	lower	IBD	73.0	83.3	4.9	11.8	27.0	14.0	13.0	0
300 YA-6	4	lower	C	59.4	92.9	4.6	2.5	40.6	40.6	0	0

GSC

TABLE 5. Modal analyses of Cariboo Group arenites

Laminated sandy siltstone and greenish-grey shale are present rarely as thin interbeds. At nearly every locality visited, the quartzite is medium grained and moderately to well sorted.

This facies clearly is similar to the massive quartzite facies, yet there are sufficient differences in stratification to distinguish the two. This is made evident particularly by weathering characteristics at the top of the Yanks Peak Formation at Zig Zag Ridge, where massive quartzite forms a very resistant capping unit (Fig. 38) that lies above less resistant quartzite beds of the evenly bedded facies.

The even, parallel lamination and good sorting exhibited by this quartzite indicate strong currents in the depositional environment. Traction currents of relatively high velocities and moderate depths probably account for the indistinct, even lamination (Harms *et al.*, 1975, p. 50). The close association of this facies with shalier rocks of shallow-marine origin suggests a similar affinity. The zone of breaking surf (middle to upper shoreface) could generate currents required to produce flat-beds in well-sorted sands, but would have to be especially powerful and semi-continuous to result in repetitive thick beds of these sand deposits. Another possible mode of origin is as marine sand waves (Off, 1963), which are formed by strong tidal currents on shallow shelves onto which arenaceous detritus is being introduced (Klein, 1976).

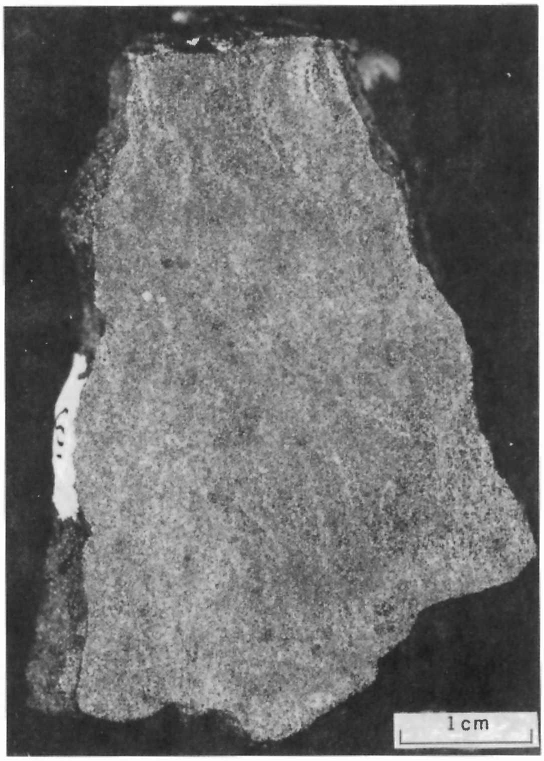


FIGURE 37. Bioturbated fabric in dark brown, pyritic sandstone from upper Yanks Peak Formation at Haggen Creek section. GSC 199270.

FIGURE 38. Exposure of Yanks Peak Formation at Zig Zag Ridge (Sec. 17). Very resistant cliff near top of mountain consists of massive quartzite, 30 m thick; this is overlain by argillaceous rocks of the Midas Formation. GSC 203211.

Carbonate facies

Various kinds of carbonate rocks occur in the lower sequence at approximately the same stratigraphic level in several widely scattered sections (Figs. 3, 4). This facies varies in thickness from 20 to 36 m (65-118 ft). Carbonate rocks are unknown in the middle and upper sequences, but are the principal facies of the overlying Mural Formation.

Included within the carbonate facies are micritic limestone, algal-coated-grain limestone, oolitic and intraclastic sandy dolostone, and crystalline dolostone. The micritic limestone is more or less sandy in the eastern Cariboo Mountains, and grades laterally and vertically into calcareous, well-sorted, fine- to coarse-grained sandstone. The oolitic dolostone is sandy, and interbedded with minor amounts of fine-grained sandstone. At the Everett Creek locality (Fig. 1, Loc. 22), the dolostone unit is capped by a bed, 1.5 m (5 ft) thick, of massive, ochrous dolostone, resembling a hardground. The rounded, pellotoidal and coated grains, some of which have crystalline interiors and thin micritic outer envelopes, are similar to those common in underlying limestones of the Yankee Belle and Cunningham Formations. The coatings are probably of algal origin.

The presence of ooids, algal grains, intraclasts and well-sorted quartz sand in these carbonate rocks indicates that they originated on marine shoals in relatively clear, warm water. Such conditions may have evolved on a slowly developing terrace wedge, as indicated by the position of these rocks at the top of a thick coarsening-upward cycle. The oolitic dolostone and sandstone may have been deposited in a nearshore setting, in an area sheltered from the direct input of clastic detritus.

PETROGRAPHY OF CARIBOO CLASTIC ROCKS

A petrographic reconnaissance of rocks comprising the Cariboo clastic succession was undertaken in order to determine general compositional characteristics and trends, and to obtain granulometric analyses of arenites from certain facies. To accomplish this, 37 thin sections were prepared and examined; of these, 9 underwent composition analyses, and 7 granulometric analyses, all by point-counting.

Composition of quartzites

Quartz is the principal component in arenites of the Cariboo Group. Quartzites from outcrops along the western flank of the Rocky Mountain Trench and west of the Cariboo Mountains exhibit sutured grain-boundaries in thin sections. Within the mountains, quartz overgrowth cements, sericitized detrital matrix, and mild straining of grains are common features of these rocks.

Approximately 99 per cent of all coarse sand grains, granules, and pebbles are quartz. Microscopic examination reveals that a large proportion of the quartz is metamorphic quartzite, and the remainder plutonic and hydrothermal quartz. Metamorphic quartzite includes stretched and composite-grain varieties, and constitutes between 5 and 20 per cent of fine- to coarse-grained arenites. Large grains of orthoclase, granite, jasperoid, jadeite and sedimentary chert are rare.

The proportion of feldspar varies erratically, both areally and stratigraphically (Table 5). In contrast to its upward-diminishing abundance in the McNaughton Formation, feldspar is present throughout the Cariboo succession, except for the upper half of the Midas Formation. Very fine and fine-grained quartzites contain the greatest proportion of feldspar, ranging up to 25 per cent (estimated) of the particulate components, whereas it is rare or absent in quartzites coarser than medium-grained. This distribution also differs greatly from that of the McNaughton Formation. Scarcely any feldspar is present in the Yanks Peak Formation in the south-western part of the study-area, and most of it occurs in northeastern Cariboo Mountains. Microcline and orthoclase are dominant, while plagioclase is relatively minor. Most feldspar grains are somewhat vacuolized, but many are fresh.

Heavy and accessory mineral species include tourmaline, leucoxene, zircon, hornblende, chloritoid, chlorite, magnetite, rutile, muscovite, garnet, and clastic carbonate. These are most abundant in silty and very fine grained quartzites, especially those in the upper part of the lower sequence.

The suite of minerals and rock fragments in the Cariboo clastic wedge indicates ultimate derivation from a mixed igneous and metamorphic terrain, such as the Canadian Shield. Feldspar, metamorphic quartzite, and hornblende appear to be more abundant in the Cariboo Group quartzites than in the McNaughton quartzites.

Autochthonous particles, including shale-clasts and probable phosphatic pellets, are common in some argillaceous sandstones of the Midas Formation. These are dark brown to black, and almost opaque in thin section. One specimen from the Dome Creek section was estimated to contain 25 per cent phosphatic grains; otherwise, phosphate content is relatively low according to qualitative X-ray analyses (Appendix B).

Various forms of iron oxides are present in these rocks, including non-crystalline limonite, and honey-brown to red-brown crystals of goethite and hematite. Leucoxene also is common and is present as irregular patches and discrete grains.

Granulometry of Cariboo clastic rocks

Seven granulometric analyses, including five of Yanks Peak quartzites, were undertaken in order to provide quantitative data. These analyses were performed by eye-piece micrometer measurements of the widest diameter of grains viewed in thin sections. Corrected cumulative weight-frequency curves (Fig. 24) of these analyses indicate that size-sorting of Yanks Peak quartzites ranges from poor to moderate (standard deviation: 0.70 to 2.0 phi). Bimodal size-distributions partly account for this relatively poor sorting.

Maximum grain-sizes observed within each correlation division were plotted on isopleth-paleocurrent maps (Figs. 39-41). The lower sequence contains rocks the maximum clast sizes of which roughly increase from west to east. In the middle sequence, however, maximum sizes increase from south to north, with pebbles measuring 45 mm in diameter in the Slim Creek area. A north to northeasterly trend of increasing sizes is evident also in rocks of the upper sequence (Midas Formation).

VERTICAL SEQUENCES AND LATERAL FACIES TRANSITIONS IN CARIBOO SUCCESSION

Lower sequence

Unique to the lower sequence are the festoon cross-bedded quartzite facies and the carbonate facies, both of which comprise the upper shallow-marine portions of shoaling-upward cycles. The lower sequence consists of three major cycles of this type, the upper two of which merge and become indistinguishable in eastern sections. The lowest cycle includes shale at the base and commonly is capped by carbonate rocks. Intermediate facies consist of the interbedded shale-siltstone-sandstone facies in eastern sections, massive siltstone in central areas, and phyllitic shale in western parts of the Cariboo Mountains. This lateral change in facies reflects bottom conditions of increasingly high energy in the offshore environment from west to east.

The upper two cycles include the festoon crossbedded quartzite, flaser quartzite, and mixed pelite-sandstone facies, and reflect the influence of tides, especially in the northeastern outcrop area. Southward in the Isaac Lake area, the upper cycles are dominated by massive and evenly bedded quartzites, and relatively thin, deeper water phases are represented by the interbedded quartzite-pelite facies. These rocks reflect a very dynamic current regime, probably greatly influenced by tides and shoaling waves.

Middle sequence

The middle sequence also consists of three cycles, involving alternations of arenaceous, shallow-marine or fluvial facies, and pelitic, offshore facies, particularly in the central and western Cariboo Mountains. These cycles lose their identity within alluvial facies which predominate northward and eastward.

In eastern sections, red-bed facies of alluvial origin directly overlie festoon crossbedded quartzite of tidal-flat origin in the lower sequence; however, to the west, the lowest cycle consists of planar crossbedded quartzite or evenly bedded quartzite above offshore facies. Hence, the planar crossbedded and evenly bedded quartzite appear to be distal from the red-bed and conglomeratic quartzite facies.

Upper sequence

The upper sequence, represented by the Midas Formation in the Cariboo Mountains, comprises an overall fining-upward trend in some sections but, in others, no such trend is evident. Relatively thin cycles and rhythms of pelitic and arenaceous facies are present, but they seem to be developed only locally.

Large-scale trends in Cariboo clastic succession

An overview of the general vertical sequence of the Cariboo clastic succession reveals that it consists of a single cycle of regression and marine transgression, commencing at its base with offshore marine shale. Progradation of the alluvial deposits basinward occurred in rhythmic steps and culminated in the lower to middle part of the middle sequence. After this culmination, increasingly deeper marine conditions ensued, at first manifested as highly reworked beach sands (top of the Yanks Peak Formation) followed by offshore pelitic sediments (Midas Formation). The top of the Midas is generally a dark grey or greenish-grey marine shale, thus completing the cycle.

CHAPTER V

PALEOGEOGRAPHY

The paleogeography of the study-area in earliest Cambrian time is derived from paleocurrent and paleodispersal trends and lithofacies distributions. A discussion of the former for each sequence is presented first, followed by a survey of lithofacies distributions and thicknesses. Finally, a history of the evolution of the main paleogeographic elements is given, integrating all observational information and derived inferences. This is illustrated with a series of maps and cross-sections.

PALEOCURRENTS AND PALEODISPERSAL TRENDS

The directions in which sediment was dispersed were determined mainly from measurement of paleocurrent directions, distribution of the largest clast-sizes, and the spatial relationships of lithofacies. In the present study, only a reconnaissance survey of paleocurrent directions was made, providing minimal evidence for dispersal patterns. Therefore, paleocurrent data are combined with data on maximum grain size, obtained from Shell Canada and personal observations, and plotted on maps of each interval (Figs. 39-41). The paleocurrents and isopleth contours together reveal the major trends of paleodispersal for each sequence.

Paleocurrent data at each station were examined for bimodality, and a vector calculated for each mode. The strength of each vector was determined using equations outlined by Curray (1956), and was used to determine the lengths of vectors on the maps (Figs. 39-41). Vector strength is a measure of dispersion of the directional measurements about the mean; hence, a relatively short vector denotes a station with a large variance in readings. Finally, determinations of statistical significance were calculated using the Rayleigh test, also outlined by Curray (*op. cit.*).

Lower sequence

Paleocurrents are directed generally toward the southwest (Fig. 39) in the lower sequence, although there are a few exceptions to this trend. Bimodal distributions are common in this interval in the Cariboo Group and presumably reflect the influence of tidal currents that reworked the sediments of this area.

Maximum particle sizes diminish generally southwestward, except for the anomalously fine-grained rocks over the McBride Arch just east of the Rocky Mountain Trench. The presence of these finer sediments eastward of coarser, tidally reworked sediments of the Cariboo Group suggests two possibilities: (1) either that the rocks over the Arch may be correlated with a higher, finer part of the upward-fining lower sequence, or (2) that they represent high, intertidal flats.

The latter possibility is supported by the presence of festoon crossbedded quartzite in the deformed McNaughton Formation in this area (Fig. 4, Fleet Creek section; Loc. 5). Because the lower sequence thins markedly over this feature, it is interpreted as a topographic high, at each end of which subsiding areas attracted sediments from the McNaughton dispersal system and shunted them into the Cariboo system. This concept is supported by the through-going fine-pebble isopleth contour at the northwestern end of the anomaly. The largest pebbles occur in the areas of the Kakwa River and Sheep Creek, as they do also in each of the succeeding intervals. This area is here termed the Kakwa dispersal salient.

Middle sequence

Paleocurrent data from the middle interval, although sparse, indicate generally southwesterly directed currents (Fig. 40). These are in agreement with isopleth trends, which reveal three major dispersal features. The most important of these are two distinct dispersal salients, one in the Kakwa area, and the other in the western McGregor Plateau. Maximum clast sizes decrease radially away from the Kakwa salient and sand no coarser than medium grained lies over McBride Arch and northwestward to McGregor Range. West of the Rocky Mountain Trench, however, maximum particle sizes increase toward the north, and medium pebble sizes are encountered in the Yanks Peak Formation in northernmost Cariboo Mountains. This distribution, together with a northward increase in the thickness of red beds (Fig. 40), indicates the existence of a source-area west of, and distinct from, the main pericratonic upland that supplied detritus to the McNaughton Formation.

An apparent clash of trends is evident in the McGregor Plateau area. This problem is not resolved by supposing the correlations are wrong, because a match of the Yanks Peak dispersal pattern against either the lower or upper sequences of the McNaughton fares no better than that shown on the present map. A partial solution to the problem can be offered by suggesting that considerable crustal shortening has occurred in a zone more or less coincident with the Rocky Mountain Trench. Removal of the Cariboo sequence a modest distance westward with respect to the western McNaughton outcrops would allow more room between the Yanks Peak dispersal pattern and the distal McNaughton. Even so, it is remarkable that the McNaughton Formation in the McGregor Range seems so unaffected by the Yanks Peak source-area, which lay not far to the west.

Upper sequence

No paleocurrent directions were recorded from the Midas Formation, and those from the upper McNaughton Formation are quite variable (Fig. 41). However, they appear to trend roughly perpendicular to maximum grain-size contours, and indicate that currents were flowing away from the Kakwa dispersal salient in proximal areas. The McBride Arch does not appear to have influenced dispersal of the coarsest particles in this interval, although thickness data show that it remained a relatively positive area. Coarsest detritus in the Midas Formation is depicted as being derived from the McNaughton dispersal system; evidence is lacking for a source-area beneath McGregor Plateau as in the case of the middle sequence. Although more data from the northernmost Cariboo Mountains are required to confirm this conclusion, thickening of the generally shaly Midas northward supports this interpretation.

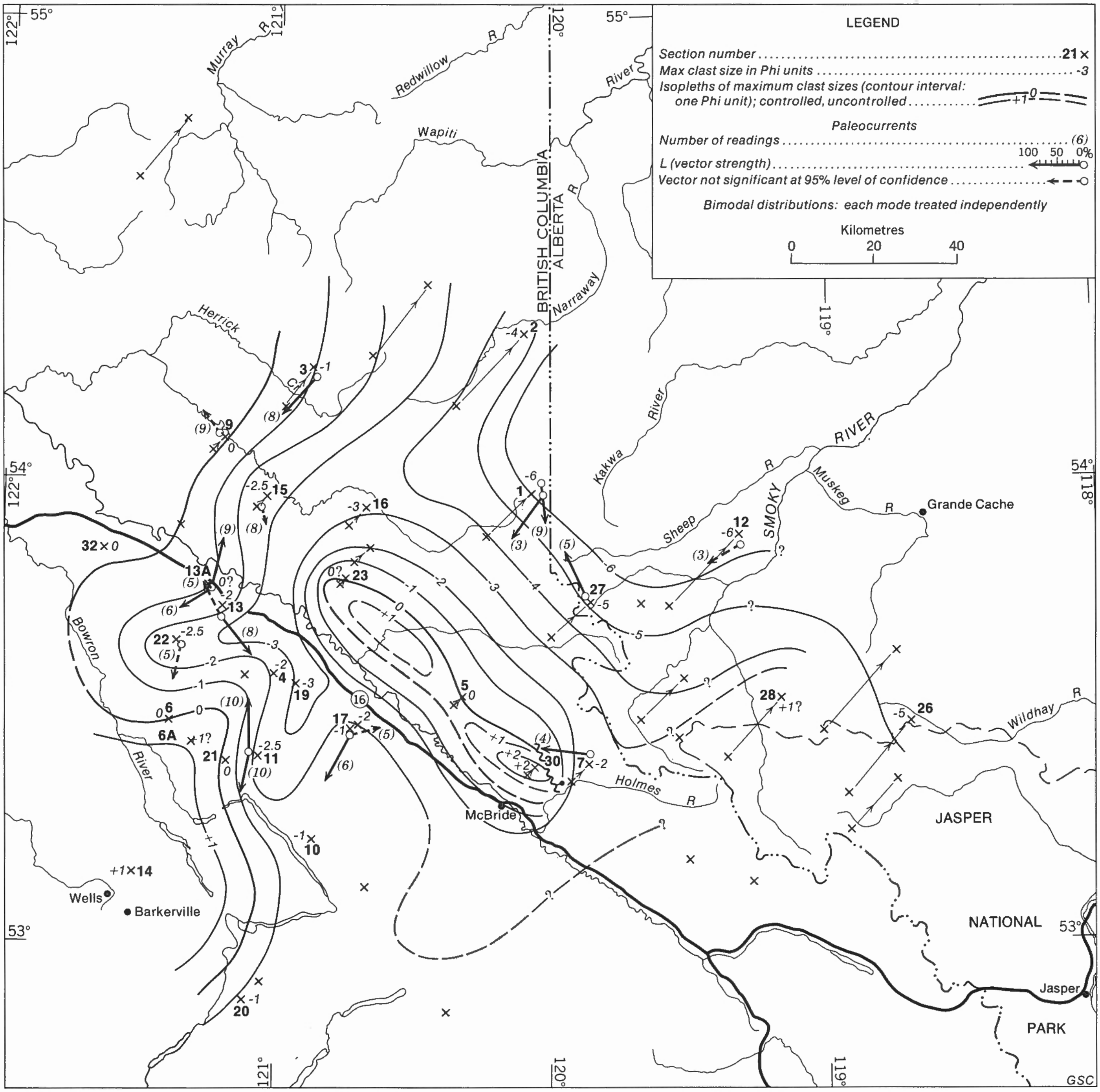


FIGURE 39. Paleodispersal map of lower sequence of McNaughton and Yanks Peak Formations.

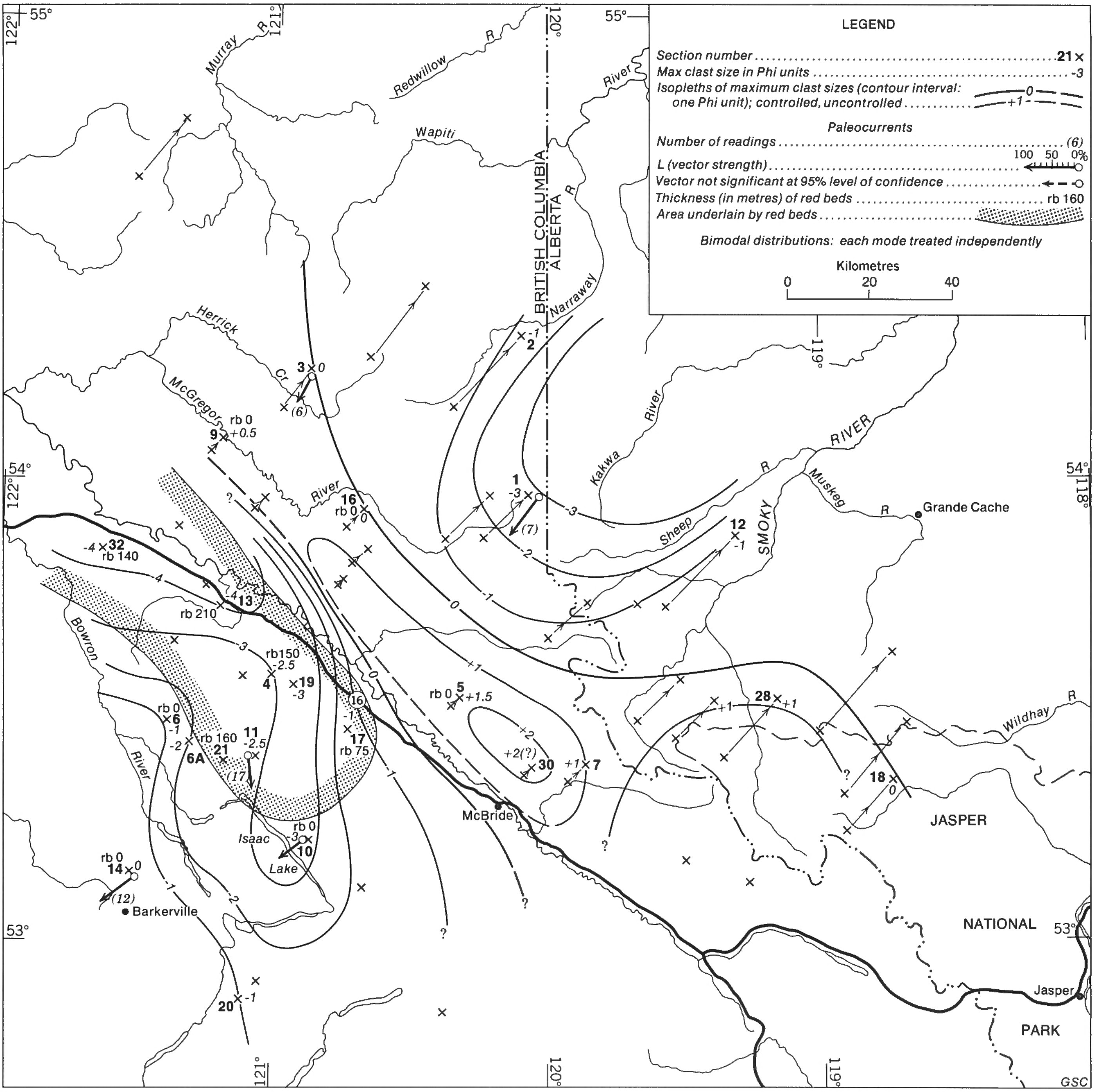


FIGURE 40. Paleodispersal map of middle sequence of McNaughton and Yanks Peak Formations.

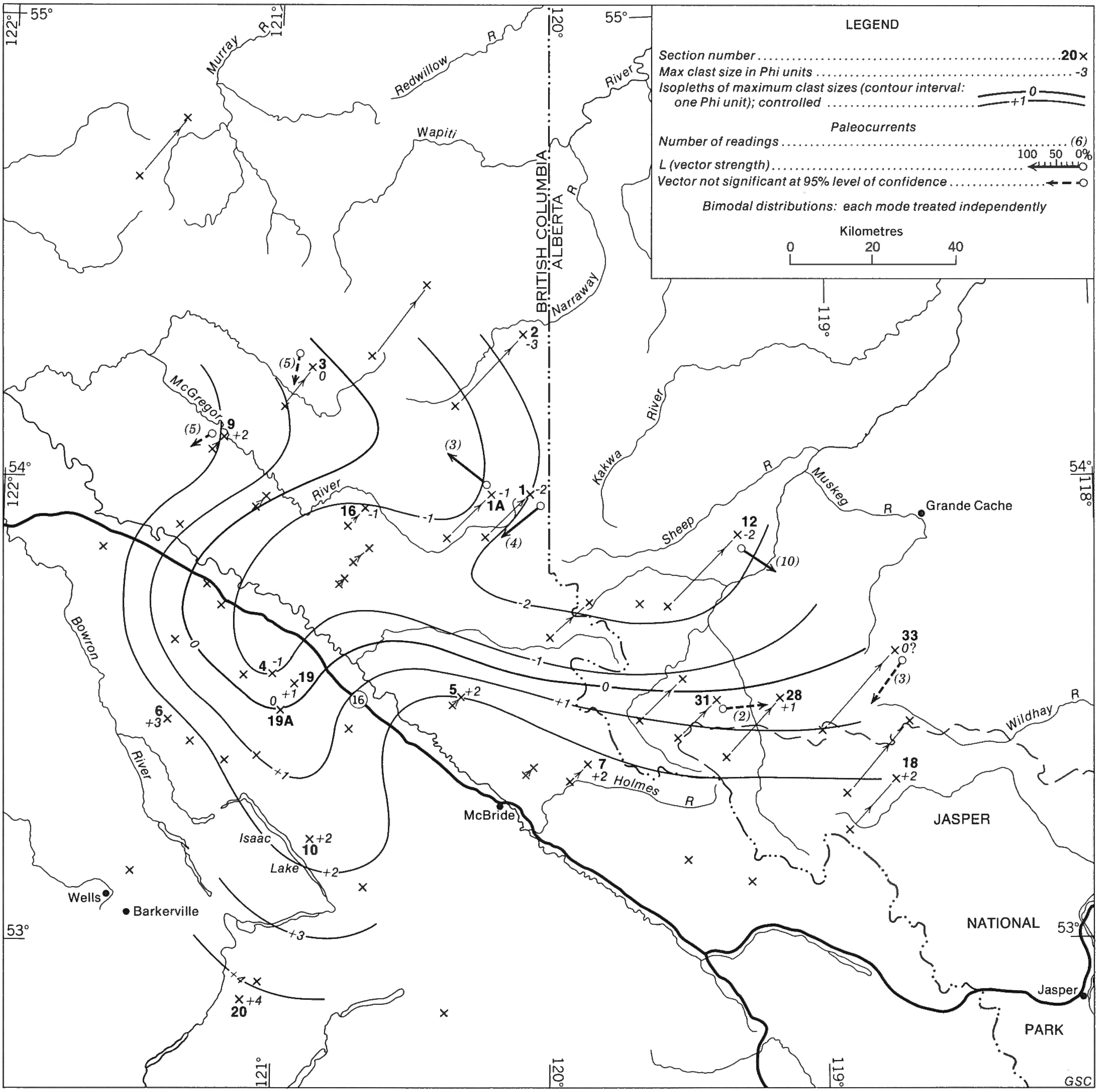


FIGURE 41. Paleodispersal map of upper sequence of McNaughton and Midas Formations.

LITHOFACIES DISTRIBUTIONS AND PALEOGEOGRAPHIC EVOLUTION

Simplified lithofacies maps for each sequence are used here to illustrate the distribution of depositional environments. The described facies were classified into four lithotopes: fluvial, beach/sandbar, tidal and open marine (Table 6). Those facies denoted by an asterisk in the table were assigned secondarily to alternative lithotopes wherever internal features or associations of individual stratigraphic units appeared to justify this.

At each control section, cumulative thicknesses of each lithotope within each sequence were determined, and posted on the lithofacies maps (Figs. 42-44) as percentages of the entire sequence thickness. Boundaries between dominant single or paired lithotopes are outlined on the maps, using the paleodispersal and isopach maps as guides. Major depositional and tectonic elements for each interval are labelled.

Paleogeography prior to deposition of the McNaughton Formation

Basin geometry was inherited from the results of minor tectonic upheavals that took place during the latter stages of Windermere deposition, particularly those occurring at the close of Cunningham and Byng carbonate sedimentation. Tectonic elements created during this time were more or less maintained throughout the remainder of Windermere time and during most of McNaughton time. A minor uplift, the McBride Arch, divides the Robson Trough from the Cariboo Trough (Fig. 2), and was emergent at the end of Cunningham time.

The Robson Trough and adjacent McBride Arch effectively segregated the stratigraphy and sedimentation style of the uppermost Miette Group from the Yankee Belle Formation of the Cariboo Group. During this interval of time, tectonic instability is evident in the Rocky Mountain area by the variableness of upper Miette stratigraphy (Young, 1972b) and the presence of diamictites and coarse grain-flows in proximal areas. This instability culminated in the tectonic uplift of the craton margin, expressed in the basin as the abrupt appearance of McNaughton conglomerate and quartzite.

The Cariboo basin was apparently shelf-like in configuration during Yankee Belle time, and comparatively stable, as evidenced by the numerous cycles of marine clastics and carbonates within it (Campbell *et al.*, 1973).

Paleogeography of the lower sequence

As indicated previously, the lower sequence consists of a single regressive cycle, expressed as a coarsening-upward sequence in the Cariboo Mountains and western Rocky Mountains. In the eastern part of the Rocky Mountains, the base of this cycle is partly rudaceous (e.g. Fig. 4, Walker Creek and Bastille Creek sections), probably due to initial surges of coarse detritus from newly formed uplands into the adjacent marine basin. These were interpreted as fan-delta deposits, and are overlain by arenaceous sediments interpreted as originating on a piedmont plain.

Only the upper, climactic part of the sequence is portrayed on the lithofacies map (Fig. 42). Arenaceous fluvial sedimentation stretched westward to the present Rocky Mountain Trench, forming a vast piedmont plain at the foot of an uplifted cratonic margin. Coarse, gravelly braided streams traversed down the eastern part of the piedmont apron while, in the western part, streams intertongued with sandy tidal flats and channels.

Relatively fine grained intertidal sedimentary rocks appear over McBride Arch, which may have been partly emergent during this interval. Unfortunately, deformation of the thin McNaughton Formation in this part of the Robson Synclinorium obscures primary features pertinent to stratigraphy and sedimentology.

West from the axis of the McBride Arch, a tide-dominated shelf gradually deepened westward. The mapped belt of the beach/sandbar lithotope includes a few carbonate banks within it. The massive and bedded quartzite facies dominant within this group at first were thought to represent mainly beach deposits, but their distribution and association, as shown on this map, indicate that they are described more reasonably as submerged offshore sand-bodies. Such features have been described variously as sand waves (Off, 1963), subtidal sand bodies (Klein, 1976) and marine-bar sands (Brenner and Davies, 1974). Sedimentary structures documented in ancient examples of marine sandbars (Spearing *in* Harms *et al.*, 1975) include trough crossbedding and parallel-laminated to burrowed sets, but the massive bedding of the Yanks Peak examples are taken herein to be more akin to the major foreset facies of the Precambrian Skallneset sandstone of Norway (Hobday and Reading, 1972).

A thick sequence of marine shale, siltstone and fine-grained sandstone lies west of the shelf deposits, and possibly represents shelf-slope and basin (bathyal?) deposits.

There is no evidence in the sedimentary record of the lower interval for the northern landmass that is so clearly evident in the subsequent interval, as described below.

Paleogeography of the middle sequence

The distribution of lithotopes in the middle sequence (Fig. 43) supports the contention, made earlier (*see* Fig. 40), that two major source-areas existed during this time -- the cratonic margin in the east and an insular uplift northwest of McBride Arch. Because there is no evidence of this outer landmass within the upper sequence, it seems to represent a single episode of uplift, erosion, and marine transgression during middle sequence time.

LITHOTOPE			
FLUVIAL	BEACH BAR	TIDAL	MARINE
Conglomerate quartzite	Massive quartzite	Festoon crossbedded quartzite	Pelite
Planar crossbedded quartzite	Evenly bedded quartzite	Interbedded quartzite-pelite	Interbedded quartzite-pelite*
Massive quartzite	Alternating conglomerate-pelite subfacies †	Flaser quartzite	Carbonate
Red-bed facies		Mixed pelite-sandstone	Mixed pelite-sandstone*

† Included in this group only because of shoreline connotation

* Secondary assignment

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TABLE 6. Classification of facies

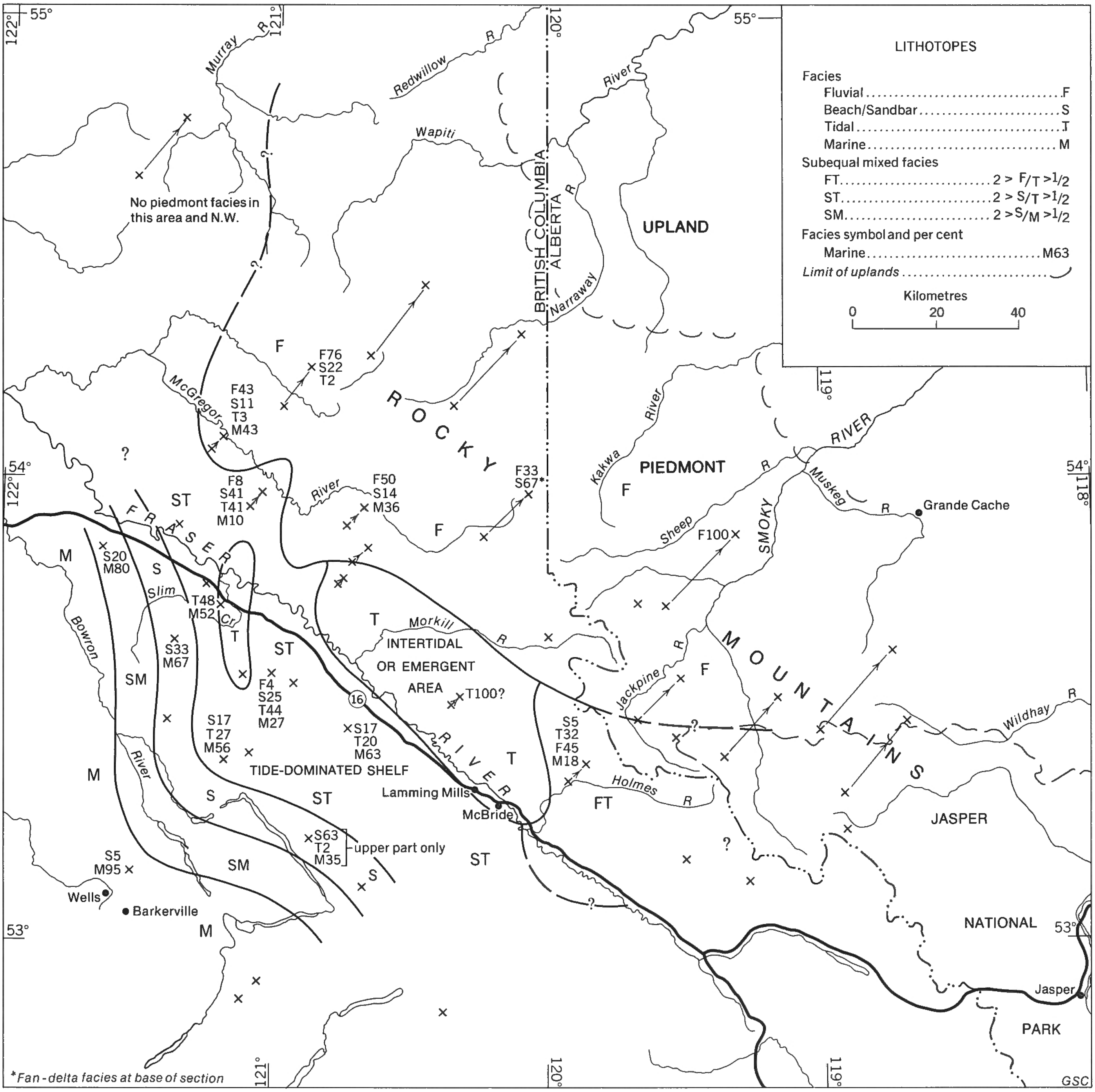

FIGURE 42. Lithofacies and paleogeographic map of lower sequence, McNaughton and Yanks Peak Formations.

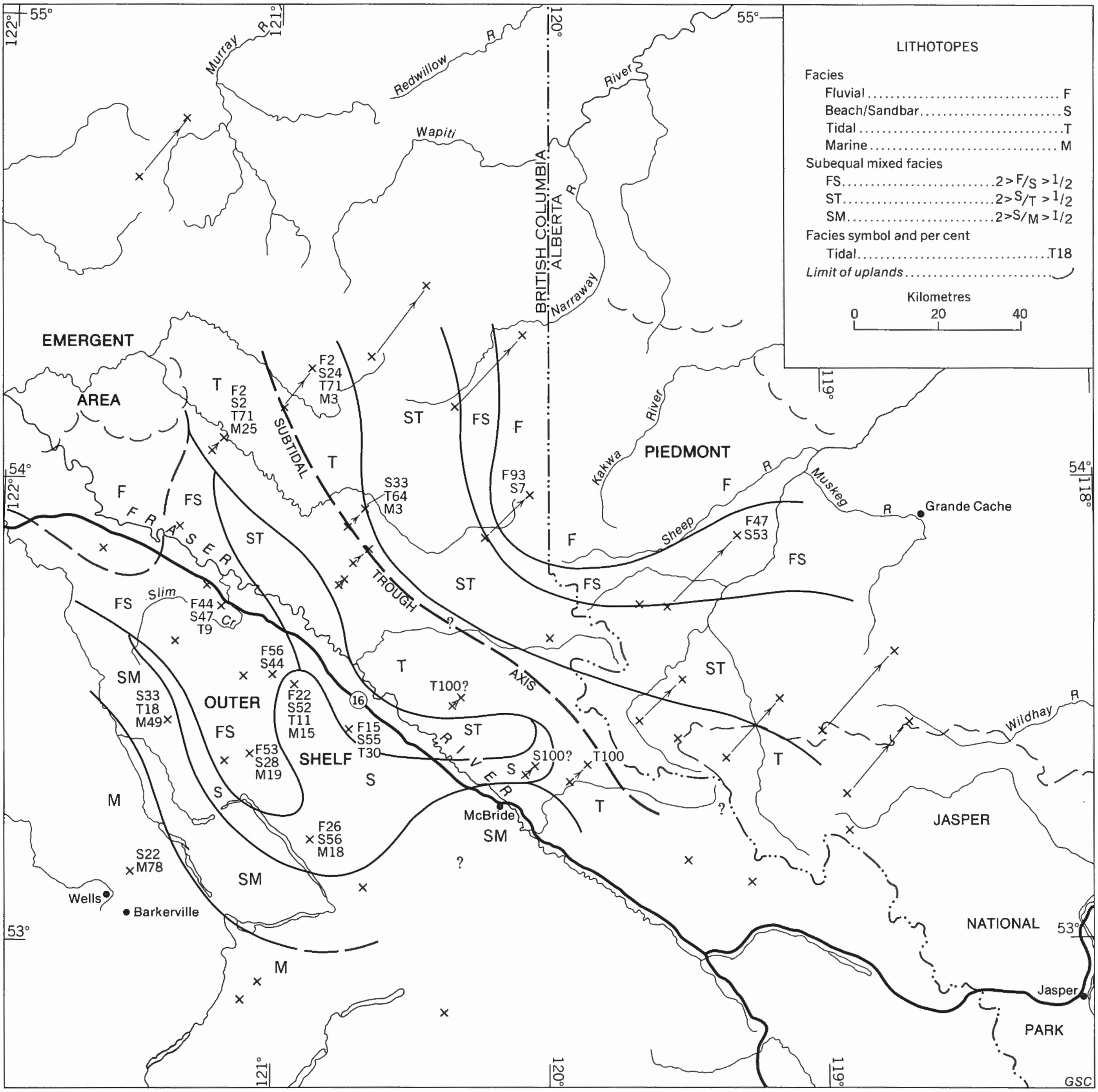

FIGURE 43. Lithofacies and paleogeographic map of middle sequence, McNaughton and Yanks Peak Formations.

McBride Arch still acted as a partial barrier between the McNaughton and Yanks Peak depositional systems, and an outer shelf persisted in the Cariboo basin. East of the arch, the Robson Trough continued to subside differentially, and absorbed much of the detritus entering from the eastern piedmont.

Sedimentary rocks laid down in the Robson Trough are dominated by subtidal mixed pelite-sandstone facies, and subtidal to intertidal arenaceous facies. Tidal currents obviously played an important role in this trough, and were probably reinforced by the elongated shape of the trough, and its position landward of McBride Arch.

In this sequence, much of the beach/bar lithotope more likely represents nearshore and littoral zone sand than that of the lower interval, because this lithotope forms a fringe around the mixed fluvial-beach/bar areas in the present case, unlike the lower one. In the interior part of the outer shelf, however, where tidal influence is known to have been present, some of the beach/bar lithotope may represent marine sandbars.

Paleogeography of the upper sequence

A simple facies-pattern relative to that of the middle sequence developed in the upper interval (Fig. 44), although an inner trough and outer shelf were still in existence as indicated by thickness variations. Relatively little clastic debris accumulated on the outer shelf, presumably because the Robson Trough trapped most of the sediment shed from the eastern source-area.

While the eastern piedmont plain maintained its position, the western clinoform may have shifted slightly eastward because both the Midas and Mural Formations are relatively thick in western Cariboo Mountains, and consist primarily of deep-water facies.

By the end of McNaughton and Midas time, the basin apparently had been filled with muddy sediments and the eastern source-area was greatly subdued, not shedding significant amounts of clastic debris. The sea may have receded from much of the area at the termination of this sequence, resulting in the formation of an iron-rich (Appendix B) soil just prior to the transgression heralding the commencement of Mural deposition.

SEDIMENTOLOGICAL MODEL OF THE McNAUGHTON-CARIBOO BASIN

A sedimentological model of the basin represented by the McNaughton Formation and the Cariboo clastic succession can be devised to accommodate the data described in previous sections. Independent types of data, such as paleocurrent directions, largest clast sizes, thickness, and lithofacies distribution show good agreement regarding basin geometry, source-area conditions, sedimentary environments, and paleodispersal. Some aspects of this model have been noted already; the entire model, with its tectonic setting and evolutionary history, is discussed herein.

Major tectonic elements of the basin, including Robson Trough, McBride Arch and Cariboo Trough, were established at least as early as late Hadrynian (Windermere) time (Fig. 45A), and probably earlier (Fig. 2). McBride Arch remained relatively positive (but mainly submerged), and Robson Trough negative, throughout the time of McNaughton deposition, whereas the Cariboo Trough evolved into an outer, stable shelf in latest Windermere time (Cunningham and Yankee Belle Formations).

Tectonic uplift of the cratonic borderland must have occurred toward the end of Windermere time, thereby supplying the voluminous coarse terrigenous detritus to the flanking miogeoclinal basin (Fig. 45B). The apparently abrupt thinning of both the Windermere and Gog Groups east of their outcrop belt suggests that they abutted against a steeply rising upland, probably an ancestral form of the West Alberta Arch (Van Hees, 1964). The composition of the McNaughton quartzite and conglomerate attests to a mixed igneous and metamorphic source-terrain, presumably the Canadian Shield, which may have been partly covered by terrigenous sediments and sedimentary rocks.

The abundance of quartz pebbles and the mixture of altered and unaltered feldspar in the lowest part of the McNaughton Formation indicate the source-area had considerable topographic relief and a warm, humid climate. The chemical maturity, leucoxene content, and drab colouration of the McNaughton quartzites suggest that the flanking piedmont also was subject to a wet, non-seasonal climate.

Paleodispersal within the McNaughton Formation in a southward direction is reflected by paleocurrents, largest clast-size distributions, and lithofacies trends at all stratigraphic levels. The Kakwa dispersal salient was a local depocentre lying directly updip (eastward) from the McBride Arch. Initial progradation of the McNaughton piedmont was directed into this area (Fig. 45B), as indicated by the presence of subaqueous, conglomeratic fan-delta deposits in the Bastille Creek area. The preexisting, shallow Robson Trough filled rapidly with coarse detritus and, with the emergence of the McBride Arch, piedmont growth was forced basinward (southwestward) as far as the present-day Rocky Mountain Trench in the upper part of the lower sequence (Fig. 45B), then retreated northeastward to the eastern flank of the Robson Trough during the remainder of the McNaughton depositional interval.

The McNaughton piedmont was very arenaceous, and was crisscrossed by a multitude of rapidly shifting, shallow, braided channels. Longitudinal bars predominated in headward areas, but were replaced gradually downstream by transverse bars and straight-crested sand waves. The lack of terrestrial vegetation at this time allowed unhindered channel migration and rapid surface run-off (Schumm, 1968), which, in a wet climate, probably gave rise to wide sheet-floods, similar to one observed and described by Inglis (1967) on the Kosi River fan in northern India.

At its distal margin, the McNaughton piedmont merged almost imperceptibly with tidal-flat or estuarine deposits throughout the formation. Scoured distributary channels were absent, and the transition from alluvial to estuarine environments took the form of sand-wave choked, tide-dominated distributaries, similar to those of the Burdekin River delta (Coleman and Wright, 1975). Feldspar and other labile components were destroyed completely in the sandy, tidal transition zone. Sandy tidal flats developed adjacent to major channel-mouths, and graded into mud flats away from debouching streams. During the progradational climax of the lower sequence, sands from the McNaughton dispersal system were transported onto the Cariboo shelf where they were reworked into

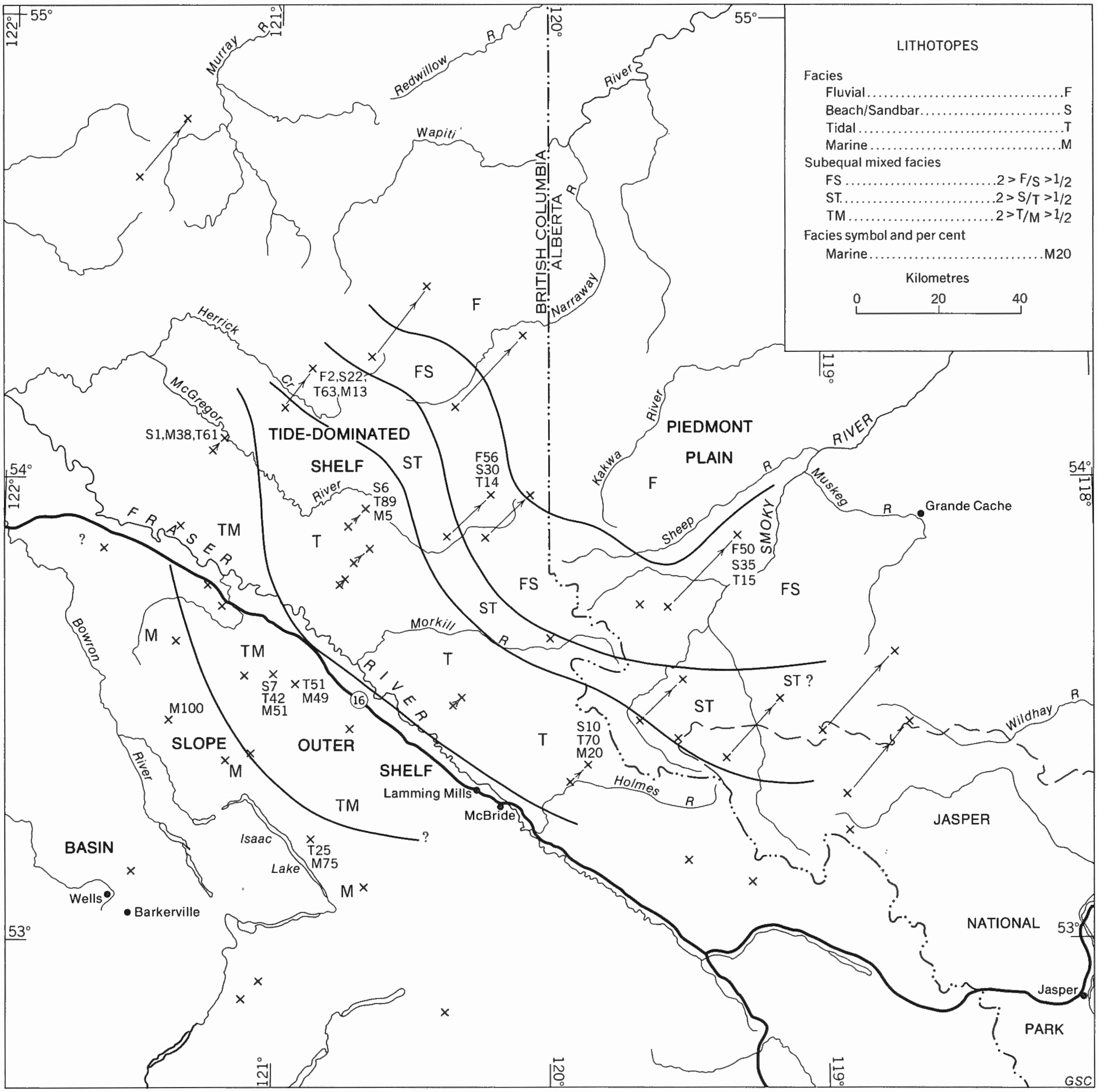

FIGURE 44. Lithofacies and paleogeographic map of upper sequence, McNaughton and Midas Formations.

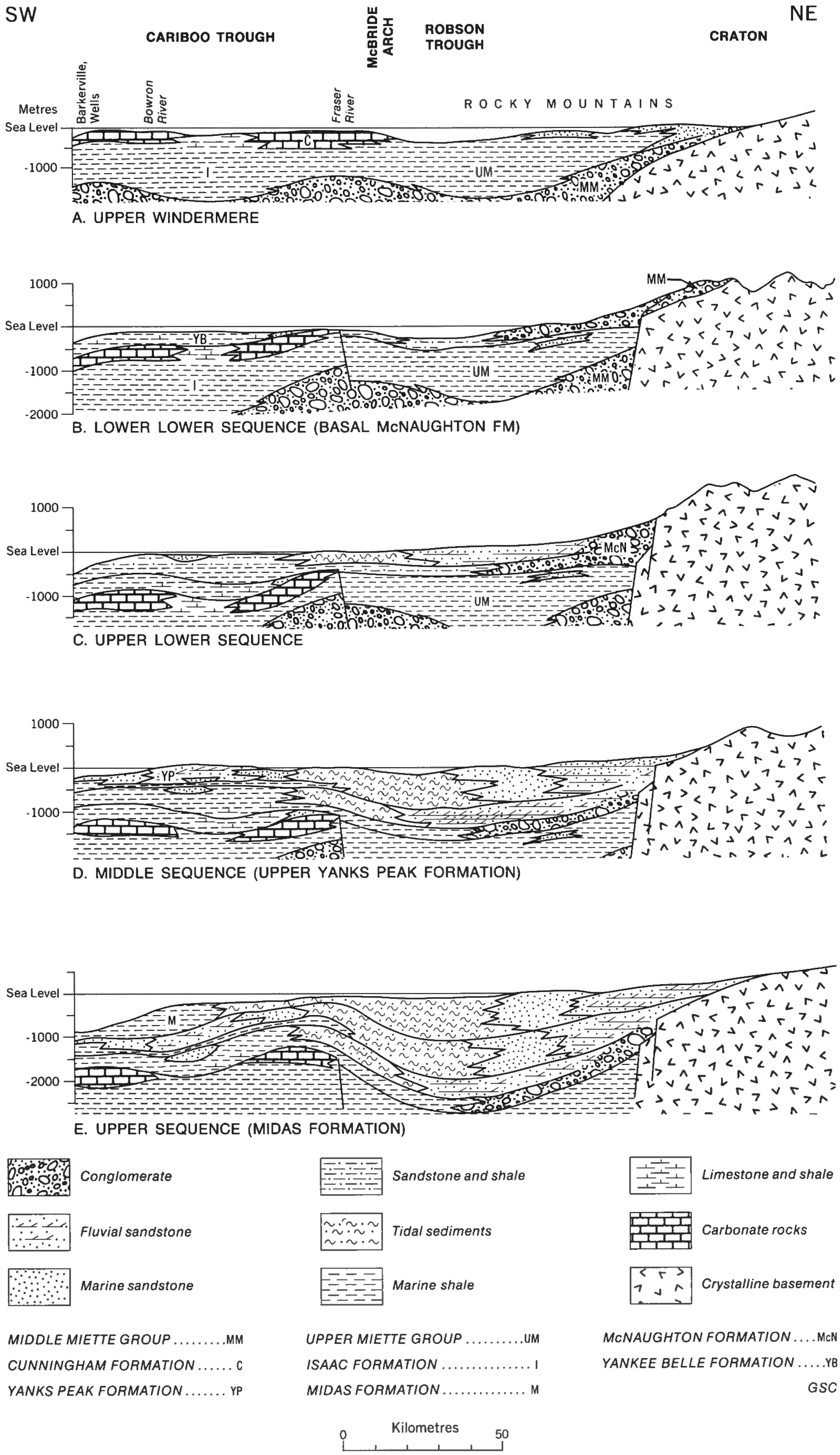

FIGURE 45. Diagrammatic restored sections across Robson and Cariboo Troughs during earliest Cambrian time

tidal marine sandbars. When the piedmont subsequently retreated to the northeast, muddy subtidal facies were formed in the Robson Trough and graded into alluvial sediments in a constantly shifting zone of tidal flats, tidal channels, and beach ridges.

Tides played an important role in the transporting and reworking of sediments in this miogeoclinal basin, as their effects are evident in subtidal trough sediments, open shelf sands, and in alluvial fan channels. These tides may have been strong because of coastline configurations, or because of generally higher tidal ranges during early Paleozoic time. The documentation of tide-dominated sedimentation in upper Proterozoic and lower Paleozoic formations from various parts of the world [e.g. Scotland (Klein, 1970), western U.S.A. (Klein, 1975), eastern U.S.A. (Goodwin and Anderson, 1974)] lends credence to the latter supposition.

During deposition of the middle sequence, the McBride Arch effectively separated the McNaughton from the Yanks Peak depositional system. An emergent area in the vicinity of McGregor Plateau shed coarse clastic debris southward onto the Cariboo shelf. Red beds common in this system indicate less intense and perhaps more seasonal precipitation than that experienced by the McNaughton system.

Composition of Yanks Peak quartzites indicate that the McGregor uplift exposed a significant amount of meta-quartzite as well as plutonic igneous rocks, or sedimentary rocks derived primarily from them. Because of the lack of outcrops and the preponderance of metamorphic rocks in the McGregor Plateau, the nature of this shortlived uplift remains a mystery.

By the beginning of upper sequence time, the McGregor uplift either subsided or was destroyed by erosion and the cratonic upland in the east was subdued considerably (Fig. 45E). Thus, less clastic debris was supplied to the Cariboo shelf than previously, because the Robson Trough continued to trap most of the sediment derived from the cratonic upland. Weak tidal currents reworked sand and mud in the Robson Trough and westward to the middle part of the Cariboo shelf.

Finally, clastic supply dwindled to insignificant amounts, Robson Trough apparently was filled with sediment, and the sea withdrew from the eastern part of the basin for a brief interval. An iron-enriched soil formed on the youngest sediments of the McNaughton (Appendix B), as well as on the Midas in places, before the sea again encroached eastward. This transgression resulted in carbonate sedimentation over most of the study-area, indicating that the cratonic source-area remained very subdued during the deposition of the Mural Formation.

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APPENDIX A

NAMES AND LOCATIONS OF STRATIGRAPHIC SECTIONS

Principal measured sections

	Name	Latitude	Longitude
1.	Bastille Creek	53°53'N	120°12'W
2.	Blue Lake (Shell)	54°09'N	120°18'W
3.	Dezaiko Range	54°10'N	121°00'W
4.	Dome Creek	53°36'N	121°01'W
5.	Fleet Creek	53°31'N	120°23'W
6.	"Haggen Ridge"	53°28'N	121°24'W
7.	Holmes River	53°20'N	119°48'W
8.	Horseshoe Lake (Shell)	54°17'N	120°41'W
9.	McGregor Range	54°04'N	121°15'W
10.	Mount Amos Bowman	53°13'N	120°51'W
11.	Mount Cochran	53°24'N	121°05'W
12.	Mount DeVeber	53°43'N	119°36'W
13.	Slim Creek	53°44'N	121°11'W
14.	Summit Creek	53°09'N	121°31'W
15.	Torpy River	53°57'N	121°06'W
16.	Walker Creek	53°54'N	120°46'W
17.	Zig Zag Ridge	53°28'N	120°46'W

Secondary sections and localites

18.	Abdul Creek (Shell)	53°15'N	118°54'W
19.	"Black Ridge"	53°34'N	120°57'W
20.	Black Stuart Mountain	52°53'N	121°02'W
21.	Dominion Creek	53°23'N	121°08'W
22.	Everett Creek	53°39'N	121°22'W
23.	Holy Cross Mountain	53°46'30"N	120°47'W
24.	"Marten Pass"	53°32'N	121°02'W
25.	McGregor River	53°53'N	120°21'W
26.	Monte Cristo Mountain (Shell)	53°21'N	118°54'W
27.	Morkill River	53°40'N	120°00'W
28.	Mount Chown (Shell)	53°26'N	119°25'W
29.	Muddywater River	53°44'N	119°39'W
30.	Northwest McBride Peak	53°22'N	120°05'W
31.	Resthaven Mountain	53°27'45"N	119°33'W
32.	Sugarbowl Mountain	53°51'N	121°39'W
33.	Azure Lake	53°28'N	119°01'W

APPENDIX B

X-RAY COMPOSITIONAL ANALYSES OF SELECTED SPECIMENS

A thin hematitic iron formation caps the McNaughton Formation in the northern part of the study-area. This unit is approximately 2 to 5 m (6.7-16.9 ft) thick and is, in part, calcareous, arenaceous, and magnetitic. Its lateral extent, position at the base of the marine transgression that gave rise to the Mural Formation, and its iron content suggest an origin as a lateritic paleosol. X-ray analyses of three specimens from widely separated localities, including one from Cariboo Mountains, indicate a very low grade iron ore (Tables 7, 8).

Sample Section †	Chlorite	Illite	Quartz	Feldspar	Calcite	Dolomite	Siderite	Hemaite*	Magnetite
294 YA-1	13		83				3	1	
298 YA-14	22	1	57			3	17		
482 YA-1	9	9	60		5	4		4	9
462 YA-19	10		69	1	6	7		7	
300 YA-15	16	2	66	4			1	11*	

† All specimens from Midas Formation or upper part of McNaughton — *GSC*

* Reported as goethite and pyrite

TABLE 7. X-ray mineralogical analyses

Sample Section	100°C (g) Sample wt.	1000°C Sample wt.	(g) L.O.I.%	Base on 100°C L.O.I.%	Total Carbon	Organic Carbon	Mineral Carbon	P_2O_3 †	SiO_2	K_2O	CaO	Al_2O_3	Fe_2O_3	TiO_2	Total
294 YA-1 *	0.4006	0.3854	0.0152	0.379	0.54	0	0.54	0.80	74.66	0.06	1.30	3.34	15.18	0.07	99.00
298 YA-14*	0.4015	0.3598	0.0417	10.39	2.70	0	2.70	0.45	53.55	0.66	2.26	3.34	24.25	0.13	97.03
482 YA-1 *	0.4002	0.3749	0.0253	6.32	1.61	0	1.61	0.37	52.19	0.98	6.26	3.80	28.18	0.12	98.22
462 YA-19*	0.4001	0.3618	0.0383	9.57	2.21	0	2.21	0.51	57.44	0.40	8.09	3.73	20.00	0.14	99.88
300 YA-15		XRF Scan only			?	0	?	min	maj	maj	maj	maj	maj	min	

L.O.I. = $CO_2\uparrow + Fe\downarrow + H_2\uparrow$ $CO_2\uparrow = CO_2$ Driven off into air $Fe\downarrow$ = Gain in wt. due to $Fe^{2+} \rightarrow Fe^{3+}$ $H_2O\uparrow$ = Crystal lattice water

* Quantitative estimates were made using the $Li_2B_4O_7$ fusion technique based on reference standard AGV-1 (Aug. 25, 1976)

† Phosphate present probably amorphous, and possibly collophane — *GSC*

TABLE 8. X-ray fluorescence elemental analyses

A few thin sections of dark brown, argillaceous sandstone of the Midas Formation reveal black opaque pellets in the rock. These are identified previously (Campbell *et al.*, 1973) as phosphatic pellets but, because X-ray analyses of two specimens (Tables 7, 8) reveal only minor quantities of phosphate in these rocks, some doubt is cast on their identification. However, the phosphate that is indicated may well be associated with the opaque pellets which are largely masked by the abundance of quartz and chorite. These pellets may be locally enriched, particularly along the northeastern flank of the Cariboo Mountains where the Midas is thin.

The X-ray analyses were performed by A.G. Heinrich at the Institute of Sedimentary and Petroleum Geology in Calgary.