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# TRIASSIC ROCKS OF THE SOUTHERN CANADIAN ROCKY MOUNTAINS

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## ABSTRACT

Triassic rocks in the southern Canadian Rockey Mountains comprise the Spray River Group, which is divided into the lower Sulphur Mountain Formation and the upper Whitehorse Formation. The Sulphur Mountain Formation consists of grey to rusty brown weathering siltstones, sandstones, silty limestones, dolomites, and shales that comprise, in ascending order, the Phroso Siltstone, the Vega Siltstone, the Whistler, and the Llama Members. In the eastern Front Ranges and subsurface of the Foothills between Athabasca and Bow Rivers, the Vega Siltstone Member is characterized by a light grey to buff-weathering dolomite lentil herein named the Mackenzie Dolomite. The Whitehorse Formation consists of pale-weathering, variegated dolomites, limestones, sandstones, siltstones, and intraformational and/or solution breccias, which are, throughout most of the region, divided into the Starlight Evaporite and Winnifred Members. In the Athabasca-Bow River region, the Starlight Evaporite Member contains a resistant light grey to buff-weathering sandstone lentil, herein named the Olympus Sandstone.

Petrographic examination of Sulphur Mountain and Whitehorse strata indicates a composition of detrital quartz, orthoclase, microcline, and plagioclase feldspar, collophane, layered silicates such as muscovite, clay, and clay-like minerals, opaque and accessory minerals such as pyrite, hematite, zircon, tourmaline, rutile, apatite and organic carbonaceous matter. Dolomite and calcite form significant concentrations, occurring

as cement and matrix in the siltstones of the Sulphur Mountain Formation, and as well rounded detrital grains, ooliths, pellets, clasts, and skeletal fragments in both the Sulphur Mountain and Whitehorse Formations. Gypsum occurs sparingly. The limited mineral variety and concentration suggest that the rock components were derived from a source area of low relief, consisting of pre-existing sediments.

Studies of HCl insoluble residues from the Sulphur Mountain Formation indicate a decrease in carbonate concentration toward the presumed source of detrital sediments in the east and northeast. Analyses of sedimentary directional structures in the overlying Whitehorse Formation suggest formation probably by longshore currents from the west and northwest.

Sediments of the Sulphur Mountain Formation were deposited mainly in a shallow-water neritic environment, which in some regions probably formed part of a series of coalescing delta complexes, along the eastern margin of the Cordilleran Geosyncline. Sediments of the Whitehorse Formation are postulated to have been deposited in an arid to semi-arid, shallow water, intertidal or lagoonal environment.

# INTRODUCTION

Triassic rocks in the Rocky Mountain Foothills and Front Ranges of west-central Alberta and southeastern British Columbia (Fig. 1) comprise a thick and variable sequence of marine strata which crop out along a series of northwesterly trending valleys and mountain ridges.

This bulletin is based on field work carried out in the Athabasca River-Crowsnest Pass area (Fig. 1) during the summers of 1966, 1967 and 1971, extending and concluding work begun in 1962. The purpose of the investigation was to obtain detailed information on the character, structure, distribution, age, and stratigraphic relationships of Triassic rocks in the area and, also, to determine if rock-stratigraphic units established north of Athabasca River (Gibson, 1968b, 1969) could be identified and extended into the Athabasca-Crowsnest area to the south. The purpose of the laboratory research was to study the megascopic and microscopic aspects of the rocks and to outline and interpret the environment and history of deposition of Triassic rocks in the region.

The stratigraphy and part of the petrology were documented in two earlier preliminary Geological Survey Papers (Gibson, 1968b, 1969 ). The following report supplements earlier work by emphasizing the petrology of the Triassic succession in the region. New stratigraphic information obtained during the 1971 field season from the Foothills and Front Ranges between North Saskatchewan and Panther Rivers (Fig. 2) also is included as well as a brief review of the stratigraphy and nomenclature used in the earlier papers.

## PREVIOUS WORK

### ATHABASCA-BOW RIVER REGION

Triassic rocks of the region were first described by McConnell (1887) during a geological investigation of part of the Rocky Mountains near Banff, although he considered the strata to be of Carboniferous age. Dowling (1907) studied the same succession and assigned a Permian-Triassic age. Later, Lambe (1916), on the basis of fossil identifications, proved the rocks to be of Triassic age. Kindle (1924) subsequently named this rock sequence the Spray River Formation. In 1927, Warren described a section of the Spray River Formation in Spray River gorge near Banff and, in 1945, divided the formation into two members, a lower Sulphur Mountain Member, and an upper Whitehorse Member, designating Spray River gorge as the type locality for the lower Sulphur Mountain Member. To the north, MacKay (1929a, b) mapped the distribution of Triassic rocks in the Foothills Belt near Cadomin and Mountain Park. Allan and Carr (1947) described the Triassic stratigraphy of the Highwood-Elbow River area south of Banff. Crockford (1949) undertook a similar Triassic stratigraphic study in the Ribbon Creek area south of Banff. Best (1958) designated and described a type section for the Whitehorse Member of the Spray River Formation on Whitehorse Creek near Cadomin, Alberta. Irish (1951) and Mountjoy (1960) elevated the Whitehorse and Sulphur Mountain Members to formational status in the Jasper region north of Athabasca River, and this usage subsequently has been extended

into the report area by the writer and other geologists. Reports of other investigations which include brief descriptions, discussions and/or maps of Triassic rocks in the Athabasca-Bow River region occur in papers and geological maps by Clark (1948), Crockford and Clow (1955), Crockford (1956), Hunt (1956), Mountjoy (1960), Shafiuddin (1960), Price and Mountjoy (1971) and Price and Ollerenshaw (1971). A synthesis of all published Triassic stratigraphic information in Western Canada, including information on the present report area, was made by Barss, et al. (1964), and included information gathered up to the end of 1962.

## CROWSNEST PASS REGION

MacKay (1932), during an investigation of coal deposits in the region, recorded 350 feet of sandstones and quartzites of probable Triassic age near Crowsnest Station. Telfer (1933) measured and briefly described a succession of Triassic strata north of Crowsnest Pass, and considered these rocks equivalent to the Spray River Formation of the Banff region. Other occurrences of Triassic strata in the Crowsnest Pass area have been mapped and/or reported by Newmarch (1953), Crabb (1957), Norris (1958), Douglas (1958), and Price (1962, 1965).

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field work. The writer also extends his appreciation to Crowsnest Industries for permission to use private logging roads along Elk River valley.

X-ray and chemical analyses on selected samples of the Sulphur Mountain and Whitehorse Formations were provided by A. E. Foscolos of the Geological Survey. Other laboratory support was provided by Miss A. Renn (insoluble residue analyses) and Mr. O. McEwan (thin sections).

The writer was ably assisted in the field by D. Spray in 1966, D. K. McAlpine in 1967, and J. M. Ross in 1971.

All fossils collected in the field were identified and dated by E. T. Tozer of the Geological Survey.

## STRATIGRAPHY

The detailed stratigraphy of Triassic rocks in most of the Athabasca River-Crowsnest Pass region was described by the writer in two earlier preliminary reports (Gibson, 1968b, 1969); however, an area bounded by the Foothills and Front Ranges between North Saskatchewan and Bow Rivers had not been studied during the earlier investigations and therefore was examined during the summer field season of 1971.

The following summary of Triassic stratigraphy is presented in order to familiarize the reader with the lithology and nomenclature characteristic of the region, and to provide a background for the introduction in this report of additional stratigraphic information and resulting modification of statements and interpretations made in earlier reports. In addition, stratigraphic

cross-sections between the Front Ranges, Foothills and Foothills subsurface are included, as well as some isopach maps of the more important units, members, and formations (Figs. 3 to 13).

The nomenclature and unit boundaries defined in this paper are, with minor revisions, those proposed by the writer in the area north of Athabasca River (Gibson, 1968a). Two distinctive lithofacies described in an earlier paper (Gibson, 1968b) now are given a more formal definition as lentils or facies of the Sulphur Mountain and Whitehorse Formations.

## SPRAY RIVER GROUP

Triassic rocks in the Athabasca River-Crowsnest Pass region comprise the Spray River Group which is divisible into two distinctive formations, a lower Sulphur Mountain and an upper Whitehorse (Pl. I, A). Each formation is further characterized by intervals of distinctive lithology that generally facilitate subdivision into members. In the Rocky Mountain Foothills and Front Ranges the Spray River Group ranges in thickness from a minimum of 285 feet (935 m) near Highwood Pass south of Bow River (Sec . 67-18, Figs. 2 and 7), to a maximum of 2,440 feet (8,003 m) at Mount Olympus (Sec. 66-4, Figs. 2 and 4), near the headwaters of Brazeau River. Throughout most of the report-area, Spray River strata disconformably overlie chert, cherty dolomite, and sandstone of the Permian Ishbel Group (Pl. I, B). However, at some eastern localities Spray River rocks rest disconformably on cherty dolomites of the Mississippian Rundle Group (Pl. I, A). The

Spray River Group is disconformably overlain by the Jurassic Fernie Formation and the Whitehorse Formation is progressively truncated from northwest and west, to southeast and east (Pl. I, A). Figure 8 is an isopach map of the Spray River Group in the Athabasca River-Crowsnest Pass area.

## Sulphur Mountain Formation

The Sulphur Mountain Formation, with type section at Spray River gorge near Banff, comprises a grey to rusty brown weathering sequence of calcareous and dolomitic siltstone and sandstone, silty limestone and dolomite, and shale, ranging in thickness from 330 feet (1,082 m) at Burns Creek (Sec. 67-29, Figs. 2 and 6), to more than 1,627 feet (5,337 m) on Forsyth Creek northwest of Crowsnest Pass (Sec. 67-27, Figs. 2 and 6). Figure 9 is an isopach map of the Sulphur Mountain Formation in the report area, illustrating a general thickening from east to west across the structural trend of the Rocky Mountain Foothills and Front Ranges. Geological maps of the region, of a standard to permit a general palinspastic reconstruction, are not yet available. Figure 9 and the other isopach maps of this report are presented,therefore, on a non-palinspastic base; thickness anomalies therefore may be caused by tectonic dislocations, and do not necessarily record depositional events. In the Brazeau River area, Douglas and Norris (in MacKenzie, 1965) estimated relative travel and overlap of major fault slices to be in the order of a maximum of 10 to 25 miles (16 - 40 km).

Throughout much of the report-area, the Sulphur Mountain Formation can be divided readily into four members which are, in ascending order; Phroso Siltstone, Vega Siltstone, Whistler, and Llama. However, in the eastern Foothills and the region south of Bow River, the upper two members are difficult to recognize because of facies changes and the results of pre-Jurassic, and post-Laramide erosion. In part of the Athabasca-Bow River region, the Vega Siltstone Member contains a distinctive, pale-weathering dolomite facies, herein named the Mackenzie Dolomite Lentil.

## Phroso Siltstone Member

The Phroso Siltstone Member (Pl. I, B) comprises a recessive, shaly- to flaggy-weathering assemblage of grey-brown to dark grey quartz siltstones and silty shales, with intercalated very fine-grained quartz sandstone beds near the base at some localities. The strata are carbonaceous-argillaceous, very dolomitic, and south of Bow River commonly contain thin interbeds of very calcareous siltstone. The Phroso Siltstone Member varies in thickness from a minimum of 100 feet (328 m) at Picklejar Creek (Sec. 67-18, Figs. 2 and 7), to a maximum of 800 feet (2,624 m) at Ross Creek (Sec. 67-21, Fig. 2).

The contact of the Phroso Siltstone Member with the underlying Permian Ishbel Group is disconformable, with the contact at most localities characterized by a cherty, quartzose, phosphatic pebble conglomerate, ranging in thickness from a few inches to 1 foot (3.28 m). In the more easterly sections north of Bow River, the Phroso Member disconformably overlies dolomites of the

Mississippian Rundle Group (Pl. I, A). The contact with the overlying Vega Siltstone Member is conformable and commonly distinct. However, at some localities, especially south of Bow River, the contact is gradational with strata characteristic of the Phroso and Vega Siltstone Members interdigitating through several feet.

In an earlier preliminary report (Gibson, 1968b, p. 5), the writer considered a distinctive dolomite facies in the Cadomin area to be a facies of the Phroso Siltstone Member. However, as a result of subsequent field work, and a re-examination of the two earlier stratigraphic sections, the dolomite lithofacies is now included in the Vega Siltstone Member, and will be discussed later in the text.

In the Athabasca River-Crowsnest Pass area the Phroso Siltstone Member contains few fossils. At Spray River gorge near Banff, the pelecypod Claraia stacheyi Bittner was collected and the strata containing this fossil were assigned an Early Triassic Griesbachian age by Tozer.

## Vega Siltstone Member

The Vega Siltstone Member (Pl. I, B) consists of a greyish to rusty brown weathering sequence of carbonaceous-argillaceous, dolomitic, calcareous quartz siltstone, silty limestone, and shale. Locally, beds of very fine-grained dolomitic quartz sandstone, and sandy to silty dolomite are intercalated in parts of the member. At some western sections south of Bow River, the lower half of the Vega Member is unusually calcareous. The calcite occurs

as cement in some of the siltstones, and as finely crystalline to bioclastic limestone interbeds with the siltstones. The Vega Member contains a distinctive light grey weathering dolomite lithofacies, herein named the Mackenzie Dolomite Lentil, in some areas of outcrop and in the subsurface of the Rocky Mountain Foothills and Front Ranges of the Athabasca-Bow River region. At Picklejar and Burns Creeks (Fig. 1) south of Bow River, the Vega Member is capped by a similar light grey weathering silty to sandy dolomite and dolomitic sandstone unit up to 55 feet (180 m) thick. This southern lithofacies, although resembling in lithology the Mackenzie Dolomite, occurs stratigraphically much higher in the Vega Member. In the writer's opinion the two dolomite facies are separate units in the Vega Member, with the dolomite lithofacies at Picklejar and Burns Creeks being younger in age. However, because of the wide geographic distance between the two occurrences and the apparent absence of the dolomite lithofacies in the intervening areas (Fig. 10), it is possible that the two dolomite units are contemporareous. The Vega Siltstone Member ranges in thickness from a minimum of 170 feet (558 m) at Mackenzie Creek Gap (Sec. 71-8, Figs. 2 and 3), to a maximum of 1,190 feet (3,903 m) at Forsyth Creek (Sec. 67-27, Figs. 2 and 6).

The Vega Siltstone Member is conformably overlain by the Whistler or Llama Members throughout most of the report area. At most localities north of Bow River, the member is overlain by the recessive sequence of dark grey dolomitic siltstone to silty dolomite of the Whistler Member. This siltstone and dolomite unit commonly contains a thin band of phosphatic pebble

conglomerate and sandstone at its base, making the contact between the two members easy to place. The contact with the overlying Llama Member, at sections where the Whistler Member is absent, is placed at a generally distinct colour and composition change between the two members. At three localities south of Bow River (Secs. 67-14, 67-16 and 67-17), the upper part of the Sulphur Mountain Formation is eroded, and the Vega Siltstone Member is disconformably overlain by the Jurassic Fernie Formation. The Vega Member rests conformably and gradationally on the Phroso Siltstone Member.

The Vega Siltstone Member contains few fossils. Those identified by Tozer include the pelecypod Posidonia cf. P. mimer Oeberg (GSC loc. 79364) and the ammonite Euflemingites cf. E. cirratus (White) (GSC loc. 79361) of Early Triassic Smithian age, and the ammonite Eumorphotis multiformis Bittner (GSC locs. 88058, 79363) and the pelecypod Anodontophora sp. (GSC loc. 79363) of probable Early Triassic age.

## Mackenzie Dolomite Lentil

The name Mackenzie Dolomite Lentil is proposed here for a sequence of light grey to buff-weathering dolomite and minor siltstone and sandstone in the lower part of the Vega Siltstone Member (Pl. I, E). The lentil is exposed in two areas, the Cadomin-Mackenzie Creek area, and the Snow Pass-Cascade River area near Banff (Figs. 7 and 10). Strata characteristic of the lentil were described first by Best (1958) in the North Saskatchewan-Athabasca River area. He subdivided the Sulphur Mountain Member into three units,

one of which he called the Middle Dolomite unit. Because of the distinctive nature of the dolomite lentil, and its apparent lateral continuity throughout much of the Foothills subsurface north of Bow River, the writer proposes to assign the dolomite lentil a formal name, the Mackenzie Dolomite, and designate a type locality in the Nikanassin Range, 1 3/4 miles (3 km) southeast of Mackenzie Creek Gap (Fig. 3, Sec. 4).

The Mackenzie Dolomite comprises a relatively thin sequence of medium-bedded, light grey to yellowish grey, slightly calcareous, silty to sandy dolomite with, locally, interbeds of very dolomitic quartz silstone and very fine grained sandstone near the upper and lower contacts. The dolomite is mainly medium to coarsely crystalline, with thin intervals containing abundant dolomitized bioclasts in the upper half of the unit. Most of the carbonate has been recrystallized including much of the bioclastic brachiopod-pelecypod shell fragments, such that in thin section only ghost outlines are discernible (Pl. III, A). The dolomite in part is very vuggy and porous (Pl. III, B), and contains well-rounded detrital grains of quartz, and feldspar - up to 30 per cent by volume - and trace amounts of collophane, pyrite, and other common heavy minerals (Pl. VI, A, B). The interbedded sandstones and siltstones are quartzose, and cemented with finely to medium crystalline, recrystallized dolomite and calcite. Feldspar, rutile, zircon, tourmaline, pyrite, and collophane constitute the remaining secondary minerals of the detrital interbeds.

Figure 10 is an isopach map of the Mackenzie Dolomite, and illustrates thickness trends, distribution, and general shape of the dolomite unit in the report-area. The map, prepared on a non-palinspastic base, illustrates that the member occurs as three lenses. These lenses are believed to be depositional features, modified by, but not created by, tectonic dislocations. In the Kananaskis-Highwood River area, a dolomite lithofacies has been noted at the top of the Vega Member, in contact with the Fernie Formation (Secs. 67-18, 67-29, Figs. 2, 6, 7). However, this dolomite unit, because of its isolated nature and stratigraphically higher occurrence in the Vega Member, is not included in the Mackenzie Dolomite, but is considered as a separate shallow water carbonate accumulation, probably younger in age. All thickness values on figure 10 are based on available surface and subsurface information.

The Mackenzie Dolomite Lentil ranges in measured thickness from a minimum of 12 feet (39 m) at Fiddle Pass (Sec. 66-1, Fig. 2), to a maximum of 80 feet (262 m) at the type locality near Mackenzie Creek Gap (Sec. 71-8, Fig. 2). In the subsurface to the east the dolomite lentil has a recorded thickness of as much as 160 feet (525 m) (Fig. 10).

The lower contact of the Mackenzie lentil with the main lithofacies of the Vega Siltstone Member is generally sharp and distinct. It is placed where the dark-weathering, carbonaceous-argillaceous siltstones of the Vega Member change abruptly into the lighter weathering silty dolomites and dolomites of the Mackenzie Dolomite. The upper contact is placed at a prominent litho-

logical change, where the light-weathering dolomites change to more thickly bedded and darker weathering siltstones of the main Vega lithofacies. At Snow Pass (Sec. 71-7, Fig. 2), the contact is gradational through several feet of beds.

No identifiable fossils were collected from the dolomite.

## Whistler Member

The Whistler Member (Pl. I, F) consists of a recessive, generally shaly-weathering sequence of dark grey to black, carbonaceous-ferruginous, silty dolomite and dolomitic quartz siltstone, ranging in measured thickness from a minimum of 43 feet (141 m) at Snow Pass (Sec. 71-4, Figs. 2 and 5), to a maximum of 75 feet (246 m) at Jacques Creek near Athabasca River (Sec. 66-9, Fig. 2). The strata are commonly thin to indistinctly bedded, and characteristically contain thin, regular to slightly crenulated, light grey laminations.

The Whistler Member has a limited lateral distribution in the report-area and is confined mainly to the Rocky Mountain Front Ranges north of Bow River. The member, however, extends as far south as Spray River gorge near Banff (Fig. 2). The restricted distribution is attributed in part to syndepositional thinning and in part to a probable facies change to the Llama Member. Figure 11 is an isopach map of the member showing its thickness and distribution in the area.

The Whistler Member appears to conformably overlie the resistant siltstones of the Vega Member at most localities. However, because

of a phosphatic pebble conglomerate commonly found at the base of the member in some parts of the region, there is a possibility of a small unconformity or diastem between the two members. The contact with the overlying Llama Member is conformable and distinct and is placed at the first occurrence of a resistant, medium- to thick-bedded sequence of siltstones and silty dolomites characteristic of the Llama Member.

The Whistler Member is sparsely fossiliferous in the report area, containing compressed, generically indeterminate ammonites of the family Beyrichitinae. However, Daonella sp. (GSC loc. 88056), collected at South Elliot Peak (Sec. 71-1, Fig. 2), indicates an Anisian age according to Tozer.

## Llama Member

The Llama Member (Pl. I, F, H) comprises a resistant, thin- to thick-bedded sequence of silty to sandy dolomite, dolomitic siltstone and, locally, interbeds of silty shale and fine- to very fine grained quartz sandstone. Strata of the member weather a characteristic yellowish grey-brown, with the colour becoming progressively paler from the base to top, a feature attributable to a decrease in carbonaceous-ferruginous matter.

The Llama Member was earlier described by the writer (Gibson, 1968, p. 9) to contain a very dolomitic siltstone to very fine grained sandstone lithofacies at the top of the member at Burns Creek (Sec. 67-29, Fig. 2). In view of subsequent field investigations north of Bow River, and subsequent assignment of the silty dolomite unit to the Vega Siltstone Member of Picklejar Creek,

the light yellow weathering dolomitic siltstone-sandstone lithofacies at Burns Creek is now thought to be part of the Vega Member, and not the Llama Member as earlier stated.

The Llama Member ranges in measured thickness from 9 feet (30 m) on Fiddle River (Sec. 63-23, Figs. 2 and 3), to more than 200 feet (656 m) at Smith-Dorrien Creek (Sec. 67-32, Fig. 2). The recorded thickness at the latter locality is 210 feet (689 m), and the thickness of missing strata was estimated to be between 25 and 50 feet (82 - 164 m). As with other members of the Sulphur Mountain Formation, the Llama Member increases in thickness from east to west.

The contact between the Llama Member and the overlying Whitehorse Formation ranges from sharp and distinct to gradational. In the western localities of the report area, the contact is generally sharp and abrupt, and is placed at a prominent colour and composition change between the Llama Member and the Whitehorse Formation (Pl. I, F, H). The gradational contact is found at most eastern sections, and is placed on the basis of and within a zone of maximum colour and composition change. Barss et al. (1964) have suggested the possibility of a disconformity between the Sulphur Mountain and Whitehorse Formations, however, during field investigations by the writer no convincing evidence was found to indicate an unconformity. The contact with the underlying Whistler Member is generally sharp and distinct. Where the Whistler Member is absent because of a facies change, the Llama Member conformably overlies the Vega Siltstone Member.

In the Athabasca River-Crowsnest Pass area, fossils are scarce and preservation is poor. Those collected from the member include the ammonite Gymnotoceras sp., and the pelecypod Daonella sp. (GSC loc. 79368), and indeterminate spiriferid and lingulid brachiopods, and pelecypods, with a suggested Middle Triassic Anisian age.

## Whitehorse Formation

The Whitehorse Formation (Pl. I, A, G), with type section near Cadomin (Sec. 66-11, Fig. 2), comprises an assemblage of pale-weathering, variegated dolomites, limestones, quartz sandstones, and intraformational and/or solution breccias. Lenticular gypsum-anhydrite strata as much as 145 feet (476 m) thick occur near Athabasca River. The formation ranges in thickness from a minimum of 20 feet (66 m) at Lodgepole River (Sec. 67-22, Figs. 2 and 7), to a maximum of 1,370 feet (4,494 m) at Mount Olympus (Sec. 66-4, Figs. 2 and 7). South of Bow River, the Whitehorse Formation is relatively thin and is limited to the more westerly sections of the area. It appears to have undergone extensive pre-Jurassic and post-Laramide erosion. Figure 12 is an isopach map of the Whitehorse Formation showing its thickness and distribution in the report-area.

In the northern half of the report-area, the Whitehorse Formation is divisible into three distinct stratigraphic units which, in ascending order, are the Starlight Evaporite Member, the Olympus Sandstone Lentil, and the Winnifred Member. The Olympus Sandstone is a prominent resistant lentil within

the Starlight Member. Because of the thinness and restricted distribution of the Whitehorse Formation south of Bow River, the formation is not amenable to stratigraphic subdivision.

The contact between the Whitehorse and the underlying Sulphur Mountain Formation is gradational at some localities and abrupt at others. The Whitehorse is disconformably overlain by the Jurassic Fernie Formation (Pl. I, A, G).

## Starlight Evaporite Member

The Starlight Evaporite Member (Pl. I, F, G, and H) contains the largest variety of rock types of any unit of the Spray River Group. It consists of a buff, yellow, light grey to reddish brown weathering sequence of interbedded carbonates, sandstones, siltstones, intraformational and/or solution breccias, with minor amounts of gypsum. The gypsum was observed at Helmet Mountain (Sec. 66-3, Fig. 2) as a lens 145 feet (476 m) thick. The carbonate consists of limestone and dolomite with the latter generally forming the most abundant rock type in the member. The dolomite is finely crystalline and, locally, very sandy to silty. The limestone is quartzose, thin to thick bedded, locally "chalky", and commonly porous because it is less well cemented than the dolomite. At Lodgepole River (Sec. 67-22, Figs. 2 and 7), the entire Whitehorse Formation [21 ft. (69 m)] consists of dense limestone with scattered skeletal grains and has a subconchoidal fracture. The sandstones and siltstones, which sometimes form a prominent lithofacies of the Starlight Member (i.e. the Olympus Sandstone Lentil), are quartzose, and cemented mainly by silica but

locally by calcite and dolomite. The intraformational and/or solution breccias (Pl. III, C) in some of the thicker western sections form diagnostic facies. They are massive weathering, medium to thick bedded, generally porous and crumbly, and yellow to reddish brown in colour. The breccia is composed of angular clasts of sandy limestone, dolomite and calcareous ferruginous sandstone, cemented with medium to coarsely crystalline calcite.

The Starlight Member ranges in measured thickness from a minimum of 20 feet (66 m) at Lodgepole River (Sec. 67-22, Figs. 2 and 7), to a maximum of 1,320 feet (4,330 m) at Mount Olympus (Sec. 66-4, Figs. 2 and 7). The Starlight Member increases in thickness from east to west, across the structural trend of the region.

Abrupt facies changes are characteristic of the Starlight Member so that, except for the Olympus Sandstone, lithologic correlation is impossible even between closely spaced sections.

In the Front Ranges north of Bow River, the Starlight Member is conformably and gradationally overlain by the Winnifred Member (Pl. I, G). The contact is assigned on the basis of a marked lithological contrast between the two members. At the more eastern localities north of Bow River, the member is disconformably overlain by the Jurassic Fernie Formation. South of Bow River, the undifferentiated Whitehorse Formation is considered to be equivalent to the Starlight Member. There, the strata are disconformably overlain by the Jurassic Fernie Formation.

Fossils are rare in the Starlight Member. Those collected include indeterminate gastropods, rhynchonelloid brachiopods, and the pelecypods Alectryonia? sp. (GSC loc. 79362), and Hoernesia sp. (GSC loc. 79366). Tozer suggests a Middle to Late Triassic age for strata containing the latter two fossils.

## Olympus Sandstone Lentil

At many localities north of Bow River, the Starlight Evaporite Member contains a distinctive, lenticular sandstone unit, herein designated the Olympus Sandstone Lentil (Pl. I, H). The type section assigned to the lentil is located at Mount Olympus, near the headwaters of Brazeau River (Sec. 66-4, Figs. 2 and 7). The Olympus Sandstone, formerly referred to as the "Quartzite Facies" (Gibson, 1968b, p. 11), comprises a resistant, generally cliff-forming sequence of buff- to yellow-weathering slightly dolomitic quartz sandstone with, locally, intercalated beds of sandy dolomite. The sandstone is mainly fine to medium grained, with the detrital fraction composed of subangular to well-rounded grains of quartz and feldspar (Pls. III, F, and IV, A, D, and E). The feldspar ranges up to 25 per cent of the detrital fraction, but averages an estimated 10 per cent by volume. The sandstone is cemented with silica and to a lesser degree with dolomite. The dolomite is finely crystalline and in some areas contains a large concentration of dolomite-supported quartz and feldspar. The dolomite interbeds occur in the thicker, more massive exposures of the unit.

The maximum measured thickness of the lentil is 457 feet (1,499 m) at Snow Pass (Sec. 71-4, Figs. 2 and 5). The Olympus lentil thins and disappears in all directions as a result of a facies change. The type section at Mount Olympus is 256 feet (840 m) thick. Figure 13 is an isopach map of the lentil showing its thickness and distribution in the report-area. The configuration of the lentil is considered to be a depositional feature, modified by, but not created by tectonic dislocations.

At most localities the upper and lower contacts of the lentil are conformable and distinct. The contacts are placed at a well-defined lithologic change between the more porous sandy carbonates and dolomitic sandstones of the underlying and overlying Starlight lithofacies, and the resistant, well-indurated sandstones of the Olympus Lentil. At Snow Pass, the lower contact is gradational, and the upper contact is disconformably overlain by black shales of the Jurassic Fernie Formation (Fig. 7, Sec. 7).

No fossils have been collected or reported from the lentil.

## Winnifred Member

The upper member of the Whitehorse Formation comprises a relatively thin, medium- to thick-bedded, resistant sequence of medium to pale grey, sandy to silty to slightly calareous dolomite, with minor interbeds of dolomitic quartz siltstone to very fine grained sandstone. Thin intercalated beds of intraformational dolomite conglomerate are found at some localities (Pl. I, G).

Strata of the Winnifred Member have been recognized only as far south as North Saskatchewan River (Fig. 7). The maximum measured thickness of the member is 145 feet (476 m) at Fiddle Pass (Sec. 66-1, Fig. 2) (Pl. I, A). The member thins and disappears toward the east and southeast (Fig. 7) owing mainly to pre-Jurassic erosion.

The Winnifred Member is disconformably overlain by the Jurassic Fernie Formation. The contact at most sections is characterized by a phosphatic, quartzose pebble conglomerate, as much as 6 inches (15 m) thick at the base of the Fernie Formation. However, where the conglomerate is absent, the contact is placed at a marked lithological change between the resistant silty to sandy dolomites and siltstones of the Winnifred Member, and the dark grey to black-weathering shales, siltstones, and interbedded limestones of the basal Fernie Formation.

The Winnifred Member contains few identifiable fossils in the report-area. The pelecypod Pleuromya? sp. was collected at Fiddle River, but is not useful as a precise indicator of age.

## ECONOMIC GEOLOGY

### PETROLEUM AND NATURAL GAS

Petroleum and natural gas prospects in the Triassic rocks of the Athabasca River-Crowsnest Pass area appear limited to the porous sandstone and carbonate strata of the Whitehorse Formation, and the Mackenzie Dolomite Lentil of the Vega Siltstone Member of the Sulphur Mountain Formation. The

Whitehorse Formation contains many porous horizons especially in the Starlight Evaporite Member of the thicker western sections. Unfortunately, the porosity of these sandstones and carbonates decreases eastward, and the Whitehorse Formation in many wells of the subsurface consists of dense, nonporous limestone, dolomite and sandstone. The Olympus Sandstone Lentil of the Starlight Member has the physical configuration and general lithological attributes of a potential sandstone reservoir, however, at most localities examined, the sandstone displays no obvious porosity. Where the sandstone has a high dolomite content, the rock has poor to fair porosity. The Olympus Sandstone may, however, become more porous towards its eastern margin (Fig. 13), but it is not known to extend east of the Front Ranges.

The most promising unit for future hydrocarbon exploration, especially natural gas, is the Mackenzie Dolomite of the Vega Siltstone Member. The dolomite is, in part, very porous and permeable and is underlain and overlain by good carbonaceous source rocks of the main Vega Siltstone lithofacies. The most porous zones, some of which contain solidified, black vitreous pyrobitumen matter, are located in the thinner exposures of the lentil. These zones occur in the intercalated bioclastic beds, where shells and shell fragments have been leached and have undergone severe recrystallization. Several wells have penetrated the dolomite lentil, however, only a few have encountered encouraging results. At B.A. et al. Mountain Park, the dolomite lentil produced gas at the rate of 13 MCF per day. Other wells in the area were dry or recovered only salt and gassy water. North of Edson, Alberta, gas is being produced from a dolomite unit which may be equivalent to the Mackenzie Dolomite.

In the Highwood-Sheep River area south of Bow River (Fig. 2), a small dolomite lens at the top of the Vega Siltstone Member (Secs. 5 and 12, Figs. 6 and 7) is slightly porous and contains black, vitreous, pyrobitumen-filled vugs. Because of the lack of drilling to the east of the measured sections, stratigraphic control is lacking and the precise subsurface extent of the dolomite is unknown. However, like the Mackenzie Dolomite to the north, this dolomite unit may be worthy of consideration as a potential hydrocarbon reservoir.

## GYPSUM AND PHOSPHATE

White gypsum was recorded at Helmet Mountain in Jasper National Park (Sec. 66-3, Fig. 2) in a lens 145 feet (476 m) thick. Granular phosphate and phosphatic pebble conglomerate occur at the base of the Whistler Member of the Sulphur Mountain Formation at some western localities. However, like the gypsum, the phosphate is best developed in and generally restricted to Jasper National Park and therefore is not available for economic development.

## BUILDING STONE

Another feature worthy of economic consideration in the report-area is the presence of Triassic building stone commonly referred to as "Rundle Rock". The flaggy-weathering siltstones of the Vega Member have been extensively used to face buildings, construct floors, patios, and fireplaces in the Jasper, Banff, and Calgary areas. The best stone is generally found south of Bow River in the Canmore and Kananaskis River areas. Because of

the thin- to medium-bedded nature of the siltstone and thin shale partings between much of the strata (Pl. I, D), the rock splits easily into 2- to 4-inch (5 - 10 cm) thick slabs suitable for the above-mentioned construction purposes.

## PETROLOGY

Little petrologic research has been done on Triassic rocks in the Athabasca River-Crowsnest Pass area. Shafiuddin (1960) made a detailed petrologic study of Triassic rocks of the type Sulphur Mountain and Whitehorse Formations at Banff and Cadomin, respectively. Some petrologic information also was provided by Barss et al. (1964), and Gibson (1968a, b) during regional stratigraphic investigations, which included part of the present report-area.

The following discussion includes a detailed description and analysis of the detrital and chemical mineralogy. A mineralogical modal and maximal grain size analysis was undertaken on selected samples of the Spray River strata; however, results generally proved inconclusive and tended only to confirm trends revealed by the other studies.

### DESCRIPTIVE MINERALOGY

Sedimentary rock classifications by Wentworth (1922) and Folk (1964) were followed throughout the investigation except when working with the carbonate rocks. For these no classification was satisfactory because of the recrystallized nature of the limestone and dolomite. A classification of carbonates used previously by the author (Gibson 1971), although applicable to some carbonate rock types, proved difficult to use in others (i.e. recrystallized dolomite), and therefore was not adopted during this study.

## Quartz-chalcedony

The most abundant detrital mineral constituent of Triassic rocks in the Athabasca River-Crowsnest Pass area is quartz. It comprises 75 to 80 per cent of the detrital components, ranging in size from medium to coarse silt and medium-grained sand. The average grain size in the Sulphur Mountain Formation creates difficulty in classifying strata in the field, because the average grain diameters are close to the sand-silt boundary of the Wentworth size classification (Pettijohn, 1957, p. 18). In contrast, the detrital quartz of the Whitehorse Formation has a slightly larger average grain size, with most grains in the sand-size range. The average grain size of detrital quartz in the Whitehorse Formation is estimated to be 0.10 mm, although grains in the Olympus lentil are slightly larger, averaging 0.15 mm in diameter. Most quartz in the Sulphur Mountain Formation is angular to subangular displaying a prominent quartzitic texture (Pls. III, D, and V, A, B, C). In contrast, the quartz of the overlying Whitehorse Formation is subrounded to well rounded, generally occurring as isolated "floating" grains dispersed in a matrix of calcite or dolomite (Pl. III, E). However, like those of the Sulphur Mountain Formation, the detrital grains of the Olympus Sandstone are characterized by a well-developed quartzitic texture (Pl. III, F) with welded contacts.

Most quartz displays straight to slightly undulose extinction, and contains scattered authigenic inclusions such as crystals of apatite, pyrite, carbonate, and acicular crystals of rutile? (Pl. VII, A). The type of extinction and the presence of inclusions appear to be related to the size of the detrital grain.

Anderson and Picard (1971), in a study of Triassic and Permian siltstones from Wyoming and South Dakota, found that the presence of non-undulatory extinction and the number of inclusion-free quartz grains, though variable, generally increased with a decrease in grain size in silt-size strata. This observation proved to be true generally for Triassic siltstones in the Athabasca River-Crowsnest Pass area. The fine- to medium-grained quartz of the Whitehorse Formation was commonly characterized by slightly undulose extinction. Recent research has demonstrated that the combined criteria of inclusions and type and degree of extinction in quartz grains, as a means of determining the genesis of quartz grains in a sandstone or siltstone, must be used with caution (Blatt and Christie, 1963; Blatt, 1967; and Anderson and Picard, 1971). Other sedimentary criteria must be considered now in conjunction with the inclusion-extinction criteria, when making provenance interpretations for detrital quartz.

The alteration of detrital quartz is common in most siltstones of the Sulphur Mountain Formation, and the finer grain sizes of the Whitehorse Formation. The alteration is manifested by carbonate "etching" and replacement of siliceous detrital grains (Pls. III, E, and IV, B), and by the presence of sutured contacts between some quartz grains of the Olympus Sandstone Lentil (Pl. IV, A, E). The larger grains are less affected by carbonate replacement, a characteristic readily apparent in quartz grains of the Whitehorse Formation. The general nature, geochemistry, and evidence of the carbonate replacement process has been discussed and illustrated by

Carozzi (1960), Walker (1957, 1960), Siever (1962), Glover (1964), Peterson and von der Borch (1965), Sharma (1965), and Gibson (1971). It must be emphasized, however, that some of the "corroded" or "etched" quartz is probably the result of an optical illusion effect (Folk, 1964, p. 67), where the adjacent crystalline carbonate overlaps the edges of the small detrital grains. The dissolved silica from the diagenetic alteration probably serves as a silica source for overgrowths and cement in strata displaying quartzitic textures. Euhedral overgrowths are common in some sandstones and sandy carbonates of the Whitehorse Formation, and to a lesser degree in the siltstones of the Sulphur Mountain Formation (Pl. IV, C). The contact between the overgrowth and parent grain is usually marked by a thin "dust" rim of reddish brown iron staining or by small opaque iron minerals and liquid? bubble-like inclusions (Pl. IV, C, D). Where the sandstones and siltstones have a predominant silica cement or have undergone silicification (i.e. the Olympus Sandstone), the actual boundaries between the overgrowths, if present, and parent grains are difficult to observe (Pl. IV, A, E).

Chert or chalcedony occurs as fracture fillings, scattered subrounded grains, and as a replacement of carbonate shells and shell fragments in some of the dolomite lentils and thin beds of the Sulphur Mountain Formation (Pl. IV, F). In a recent paper, Folk and Pittman (1971) report that chalcedony with length slow optical properties is associated with sediment deposition under evaporitic conditions. In testing this observation on Triassic chalcedony samples in the report area, the writer found that most grains had length fast

optical properties. However, near the top of the Vega Member at Burns Creek (Sec. 67-29, Fig. 2), chalcedony-filled fossil shells in a dolomite lens showed both length fast and length slow optical properties. These observations were made at the top and bottom of a single bed. If the Folk-Pittman hypothesis is valid, part of the bed, consisting of a few centimetres in the representative thin section, may have formed under evaporitic conditions, whereas the remainder of the sample formed under normal shallow marine conditions.

## Feldspar

Feldspar grains in the Triassic strata of the region display many of the textural and diagenetic features common to quartz, and form up to 33 per cent by volume of the detrital minerals. However, the average concentration more commonly ranges between 10 and 15 per cent by volume. Most feldspars were stained with sodium cobaltinitrite (Chayes, 1952) to facilitate their optical identification.

Orthoclase, the most common feldspar, ranges in volume between 5 and 15 per cent. It is dispersed throughout the rock succession, but has a slightly larger concentration in strata of the Sulphur Mountain Formation. Subhedral to euhedral crystals and overgrowths, some with good Carlsbad twinning, were observed in many sandstones, siltstones, and carbonates (Pl. V, A).

Plagioclase, the second most common feldspar, generally was found difficult to identify in thin section because of its optical similarity to quartz and orthoclase when lacking polysynthetic and albite twinning. Chemical

analyses by A. E. Foscolos[1] of the Geological Survey on selected samples of siltstone and sandstone of the Vega Siltstone and Olympus Sandstone units revealed a plagioclase concentration between 1 and 11 per cent by weight of the samples analysed. In comparison, thin section examination of the same samples indicated a volumetric plagioclase concentration between 0 and 3 per cent of the rock constituents. This difference in concentration between point-counting and chemical analysis of the same samples suggests that untwinned plagioclase can be mistakenly identified as quartz. Plagioclase grains with 010 cleavage and good polysynthetic twining had a chemical composition in the albite-oligoclase range (Pl. V, B, C). In contrast to the orthoclase, overgrowths and authigenic crystals were not common.

Microcline forms an ubiquitous but quantitatively insignificant mineral of the clastic components, rarely exceeding 2 per cent by volume of the feldspars (Pls. IV, E, and V, D, E). It is commonly found in the Sulphur Mountain Formation as angular to subangular grains.

Most feldspar has undergone some diagenetic alteration, the most evident being replacement by carbonate minerals (Pl. V, D, E). However, in some sandstones and siltstones the feldspars show incipient alteration. This feature is particularly evident in the sandstones of the Starlight Evaporite Member.

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[1]For analytical method <u>see</u> Foscolos <u>et al</u>., (in preparation).

## Collophane

Collophane, a cryptocrystalline isotropic varietal mineral of the apatite group, occurs sparingly throughout much of the Sulphur Mountain Formation, in concentrations rarely exceeding 1 per cent by volume. However, at a few of the thicker western sections in the region, such as Helmet Mountain, Elliot Peak, and Elk Range (Fig. 2), collophane concentrations were estimated in thin sections to be approximately 30 per cent of the mineralogy. The phosphatic zones are commonly lenticular, erratic in their distribution, and rarely occur in beds more than 6 inches (15 cm) thick. They are found best developed at the base of the Whistler, near the top of the Vega, and in the basal few feet of the Llama Member. Phosphate is generally absent from the Whitehorse Formation with the exception of a few phosphatic lingulid shell fragments in the Winnifred Member, and in some of the dense sandy carbonates of the Starlight Member.

Collophane most commonly occurs as thin, elongate, laminated shreds or shell fragments probably derived from lingulid brachiopods (Pls. V, F, and VI, A, B). These blue-black shell fragments are found throughout most strata of the Sulphur Mountain Formation. At some localities, they form dense, black, wavy laminations or bands up to 1 inch (3 cm) thick. Granular phosphate occurs as elongate pellets, well-rounded grains, and concentrically banded ooliths (Pl. VI, C, D, E). The ooliths, ranging in diameter between 0.20 mm and 0.30 mm, occur with subangular quartz and feldspar grains. The ooliths commonly contain nuclei of quartz, feldspar, dolomite, and pyrite (Pl. VI, C, E).

Most of the granular phosphate contains small ferruginous (probably pyritiferous) inclusions. In addition, collophane occurs as replacement patches in dolomite. As with other minerals of the Spray River Group, the phosphate has been diagenetically replaced by carbonates. Plate VI, E shows dolomite replacing a phosphatic oolith.

Layered silicates (mica, clay and clay-like minerals)

The layered silicates, comprising the micas, chlorite-glauconite, and true clay minerals, form a ubiquitous, but generally quantitatively insignificant, concentration in the Triassic rocks of the report-area, rarely exceeding 5 per cent of the total mineral constituents. The silicate minerals were identified by means of their optical characteristics and X-ray diffraction patterns.

Mica, occurring as small detrital flakes or grains of muscovite,forms the most common and conspicuous mineral of the assemblage. The muscovite, up to 0.065 mm in longest apparent dimension, occurs mainly in the dark grey carbonaceous-ferruginous laminations of the siltstones and shales of the Sulphur Mountain Formation. Most grains are aligned parallel to the bedding and laminations, suggesting a detrital derivation and deposition in a low energy environment. The muscovite concentration decreases from the base upward in the Sulphur Mountain Formation, and is observed rarely in the Whitehorse Formation. Biotite was noted in an angular clast of an intraformational breccia of the Starlight Evaporite Member.

Chlorite and glauconite are grouped and treated as a single mineral constituent because of their small grain size, similar colour and optical properties. One or both constituents may be present in a given sample. The chlorite-glauconite is found mainly in the siltstones of the Sulphur Mountain Formation, but does occur in some sandstones of the Olympus lentil, and some of the intraformational and/or solution breccias of the Starlight Member.

Kaolinite, a 1:1 layered silicate, was found in the breccias and sandstones of the Whitehorse Formation. It occurs as conspicuous flakes and as matrix in some of the silty and sandy clasts of the intraformational and/or solution breccias. Most kaolinite probably has originated from the post-depositional decomposition or alteration of feldspar minerals.

X-ray diffraction analyses indicate the presence of illite, a 2:1 layered silicate, but the diffraction pattern may be due in part or wholly to muscovite and glauconite, both of which are 2:1 layered silicate minerals. The general masking effect by carbonaceous-ferruginous matter largely prevented optical identification of the clay and clay-like minerals, with the exception of muscovite and some of the chlorite-glauconite.

## Opaque and accessory minerals

The opaque constituents consist of iron sulphides and organic-carbonaceous matter, both of which are responsible for the dark colour of Sulphur Mountain strata. Pyrite, averaging less than 2 per cent by volume, occurs as micro-aggregates and small euhedral cubes. In strata of the Phroso Silt-

stone Member it forms thin lenticular laminations up to 1/2 inch (2 cm) thick (Pl. VI, F). The pyrite is found mainly in the Sulphur Mountain Formation, but does occur sparingly in some sandstone and breccia facies of the Whitehorse Formation. Some of the black opaque matter may be "hydrotroilite", a non-crystalline iron sulphide found in some sedimentary clastic deposits (Brenner, 1970). "Hydrotroilite" is not detectable by X-ray analysis. Ferric oxide-hematite staining is responsible for the reddish brown colour of the "red-bed" facies in the Starlight Member. It commonly is found coating detrital grains and breccia clasts, and has formed as a result of oxidation of iron-bearing minerals, possible pyrite and clay, in a subaerial environment.

Black to brown carbonaceous matter confirmed by D.T.A. and X-ray diffraction techniques is confined mainly to strata of the Sulphur Mountain Formation. It occurs as thin laminations and as disseminated aggregates and grain coatings, generally mixed with pyrite and clay minerals (Pls. IV, E, and VII, D). Combined with pyrite, the two components have been estimated to comprise 30 per cent of the total mineral content in some strata of the Phroso Siltstone and Whistler Members.

The accessory minerals, which include, in order of relative abundance, zircon, tourmaline, rutile, and apatite, do not exceed 1 per cent by volume of the mineral suite. Like the opaque minerals, they are most commonly found in the siltstones of the Sulphur Mountain Formation. Colourless to pale pink zircon, ranging in size from 0.03 mm to 0.10 mm, occurs as subrounded grains and, rarely, as subhedral to euhedral crystals. Pleochroic, reddish

brown to bluish green tourmaline occurs as subhedral to euhedral detrital and authigenic grains and crystals up to 0.22 mm in diameter. Most tourmaline consists of elongate grains bounded by smooth parallel sides and well-rounded ends. Rutile, which is reddish brown to amber, occurs in the siltstones of the Sulphur Mountain Formation; however, acicular crystals (rutilated quartz) have been observed as inclusions in some of the larger quartz grains of the Whitehorse Formation (Pl. VII, A). Apatite occurs as small, colourless, euhedral to subhedral authigenic crystal inclusions in many detrital grains of quartz and feldspar.

## Gypsum

Gypsum occurs sparingly in the Triassic rocks of the Athabasca River-Crowsnest Pass area. At Helmet Mountain (Sec. 66-3, Fig. 2) an exceptionally thick, 145 foot (476 m) lens with interbedded dolomites was observed in the Starlight Member of the Whitehorse Formation. Elsewhere, the mineral occurs in trace amounts in some solution breccias of the Starlight Member, and as thin lenticular laminae in some siltstones of the Vega Member of the Sulphur Mountain Formation. At Burns Creek (Sec. 67-29, Fig. 2) a thin, siliceous bioclastic dolomite lens (Pl. IV, F) near the top of the Vega Siltstone Member contains suspected traces of white gypsum. This gypsum is associated with light grey to white chert with optical properties indicative of formation under evaporitic conditions (Folk and Pittman, 1971).

The gypsum is fibrous to prismatic, commonly forming a "felted" interlocking crystal mosaic. The thin gypsiferous laminations, observed in the siltstone of the Sulphur Mountain Formation, consist of fibrous crystals oriented perpendicular to the bedding and laminations. This gypsum represents a probable replacement of carbonate, rather than a sedimentary chemical precipitate. Some of the Starlight Member breccias contain angular clasts of soft, silty limestone and dolomite with traces of gypsum. This gypsum probably represents an original precipitate formed in a highly saline, evaporitic shallow-water environment. For a more detailed account of the Triassic gypsum occurrences and associated sedimentary breccias in the vicinity of the report-area, the reader is referred to reports by Govett (1961) and Gibson (1971).

## Carbonate

Carbonate minerals are abundant in the Triassic rocks of the Athabasca River-Crowsnest Pass area. In order of relative abundance they are dolomite, calcite, and possible siderite. The carbonate occurs in part as detrital grains, ooliths, pellets, clasts, and skeletal fragments in both the Sulphur Mountain and Whitehorse Formations. On the other hand, the sandstones and siltstones of the Sulphur Mountain Formation contain carbonate which may have originated as cement or matrix but cannot be so identified because of recrystallization. Carbonate minerals north of Athabasca River (Gibson, 1971) were largely recrystallized with consequent obliteration of many

original textures and structures. The carbonate minerals in the present report-area show a similar degree of recrystallization and, consequently, display many textural similarities.

Dolomite forms the predominant carbonate and occurs as anhedral to subhedral crystals ranging between 0.03 mm and 0.10 mm in diameter (Pl. VII, B). Dolomite in this size range is mostly found in the Vega Siltstone Member, whereas the finer size classes occur mainly in the subconchoidal fracturing dolomites of the Starlight and Winnifred Members of the Whitehorse Formation. These smaller crystal sizes may represent a replacement of the calcite or aragonite mud that is commonly associated with shallow water evaporitic sediments.

Euhedral to subhedral rhombic dolomite crystals, some of which display well-developed zoned overgrowths (Pl. VII, C), are common in many siltstones of the Sulphur Mountain Formation. Euhedral overgrowths also are found on many well-rounded "ghost-like" detrital dolomite grains of the same siltstones (Pl. VII, D). The rhombic crystals, overgrowths, and zoning are readily apparent in thin section because of opaque carbonaceous-ferruginous staining and inclusions between the grains and between the various overgrowth stages. Most of the dolomite contains ferruginous inclusions. The textural relationships of these authigenic crystals and overgrowths to the host strata, coupled with the repeated overgrowth and recrystallization stages outlined by opaque to semi-opaque carbonaceous-ferruginous staining, suggest that the euhedral

crystals and some recrystallization took place after consolidation of the main sediment, at a time when the host rock was sufficiently porous and permeable to permit migration of the carbonate solutions and carbonaceous-ferruginous matter through the detrital framework. The occurrence of well-rounded relict carbonate grains, pellets, and associated sedimentary structures and textures suggests that some or much of the carbonate was deposited as a detrital component with the quartz and feldspar. On the other hand, recrystallization has destroyed most of the evidence for a detrital versus non-detrital origin of the dolomite.

Most dolomite in the report area is considered to be of secondary origin, having replaced calcite or aragonite; however, some of the dolomitization may have been penecontemporaneous as shown by the intraformational and/or solution breccias of the Starlight Evaporite Member. These breccias contain angular clasts of silty dolomite, cemented by medium to coarsely crystalline calcite. The dolomite of the clasts may represent a penecontemporaneous replacement of calcite or aragonite, a replacement which took place before brecciation of the sediment. If, however, some of the carbonate was indeed a detrital product from a pre-existing carbonate, some of the present carbonate may have been dolomitized before transport to the present site of deposition. No evidence was found to indicate the original composition of the carbonate before recrystallization.

Calcite is confined mainly to strata of the Whitehorse Formation, but does occur as a cementing and/or matrix constituent with dolomite in strata

of the Sulphur Mountain Formation south of Bow River. It has not been observed in significant concentrations in any of the siltstones, sandstones, or shales of the Sulphur Mountain Formation north of Bow River.

The most common variety of calcite observed occurs as a coarsely crystalline, recrystallized mosaic ranging in size from 0.03 mm to 0.13 mm in diameter, sometimes referred to a "pseudosparite" (Folk, 1959, p. 33; Gibson, 1971, p. 12). It results from the indiscriminate recrystallization of grains, skeletal fragments, and cement, to the extent that only scattered "ghost-like" outlines of the original textures remain. In contrast to dolomite, most calcite displays well-developed lamellar twinning, and is characterized by a lack of carbonaceous-ferruginous staining and inclusions. In addition, overgrowths and euhedral crystals were conspicuously absent. The cement of many of the intraformational and/or solution breccias of the Starlight Member is composed of "pseudosparite" and in some cases probable sparite.

Skeletal fragments form the second most common variety of calcite and are most prevalent in the limestones of the Sulphur Mountain Formation south of Bow River. The bioclasts consist mainly of elongate, angular to well-rounded pelecypod and/or brachiopod and possible ostracode shell fragments, all of which have been recrystallized. In places the internal shell structure and outline have been almost eliminated, leaving only a ghost-like outline of the original shell fragment (Pl. VII, E). Other bioclasts included crinoid columnals and columnal fragments, small echinoid spines, and

possible algal-coated? breccia clasts. The algal? coatings were observed on some subrounded clasts of the intraformational breccias of the Starlight Evaporite Member (Pl. VII, F).

Well-rounded grains and spheres, composed mainly of calcite, were noted in both the Whitehorse and Sulphur Mountain Formations but generally forming a minor textural component of the carbonate mineralogy. The grains, up to 0.31 mm in diameter, locally are silty, and occur in the intraformational breccias and conglomerates of the Whitehorse Formation (Pl. VIII). At Forsyth and Smith-Dorrien Creeks (Secs. 67-27, 67-15, Fig. 2), small spherical calcite grains ranging in diameter between 0.065 mm and 0.162 mm were observed in the silty carbonaceous limestones and calcareous siltstones of the Phroso and Vega Siltstone Members of the Sulphur Mountain Formation (Pl. VIII, D). These grains generally are composed of a single calcite crystal, are inclusion free, and some of them display a thin concentric rim or band. The genesis of the spheres is not known, but they may represent recrystallized ooliths or calcispheres. The angular nature of the associated quartz and feldspar grains in the host strata suggests that the sediment has not undergone much wave agitation during deposition, which favours a calcisphere origin for the spherical, generally structureless grains.

Traces of possible siderite were observed at some eastern localities in the siltstones of the Vega Siltstone Member. In thin section the siderite? is brownish grey with an optical relief higher than other carbonates of the same thin section.

## INSOLUBLE RESIDUE ANALYSIS

Strata of the Sulphur Mountain Formation were subjected to an insoluble residue analysis in order to try and outline the clastic-to-carbonate mineral relationships, the nature and probable direction of the sediment dispersal system, the sea bottom environment, and the nature of the adjacent land areas. Furthermore, it was anticipated that a comparison could be made with results obtained from a similar analysis on Sulphur Mountain rocks north of Athabasca River (Gibson, 1971). The carbonaceous-argillaceous-ferruginous concentration of most Sulphur Mountain strata made standard microscope point-counting techniques unreliable with respect to the carbonate concentration of the siltstones and sandstones. For example, thin sections were made from two samples of the Vega Siltstone Member collected at Snow Pass (Sec. 71-4). Point counts were then made, after which the samples were subjected to an insoluble residue analysis. Point-counting revealed carbonate concentrations of 41.7 per cent and 14.3 per cent by volume, whereas chemical analysis of the same two rock samples indicated values of 24.4 per cent and 28.3 per cent by weight respectively. Because of the random or unpredictable interfingering nature of terrigenous clastic and carbonate strata and the occurrence of relatively pure carbonate strata, insoluble residue studies were not undertaken on strata of the Whitehorse Formation.

Representative samples of the Sulphur Mountain Formation were selected from successive 25- to 50-foot (82 - 164 m) thick stratigraphic intervals where possible. Because of the weathering and general talus cover of the Phroso and

Whistler Members (Pl. I, B, F), representative samples were difficult to obtain and, consequently, insoluble residue control is poor. Standard disaggregating techniques were not applicable because of the quartzitic textures and secondary silicification of many siltstones and sandstones of the Sulphur Mountain Formation. Consequently, all samples were crushed and pulverized, then treated with HCl and analysed according to the techniques of Ireland (1958). The insoluble residue values were processed statistically to obtain the mean and standard deviation from the mean for the total Sulphur Mountain Formation, and for each of the formation members where practical (Tables 2, 3). The mean values for the total formation and its more important members were plotted then and contoured on base maps of the area (Figs. 14 to 19) to facilitate visual comparison between the 16 localities examined.

The mean insoluble residue values for the Sulphur Mountain Formation (Table 3) range in concentration from a low of 52 per cent at Burns Creek to a maximum of 75 per cent at Cadomin. The average concentration for the total Sulphur Mountain Formation in the report area is 65 per cent by weight. This value indicates a generally high carbonate concentration for the siltstones and sandstones of the Sulphur Mountain Formation. Figure 14 is an isopleth map showing the distribution of mean insoluble residue values and isopleth trends for the Sulphur Mountain Formation based on values obtained at 16 localities. Figure 14 indicates a relatively high insoluble residue concentration in the eastern part of the North Saskatchewan-Athabasca River area.

The isopleths show a general concentration decrease from east to west suggesting a possible shoreline and detrital source area to the east and/or northeast. A similar trend is apparent to the south in the remainder of the area. The two anomalous configurations shown near Cadomin and the headwaters of Highwood River are the result of including samples of the Mackenzie Dolomite and the upper Vega Siltstone Member in the analysis. The inclusion of these values (mainly dolomite) lowered the mean insoluble residue values for the Sulphur Mountain Formation at these localities.

Insoluble residue isopleths for the Phroso, Vega, and Llama Members show similar concentration trends as outlined in the total Sulphur Mountain Formation (Figs. 15, 16, 17). The average residue values for the 16 localities show a general decrease in concentration from east to west. It must be emphasized, however, that even though isopleth configurations of the Phroso and Llama Members are similar to the Vega Member and the total Sulphur Mountain Formation, these isopleths are based upon fewer sections and analyses because of poor field exposures and a consequent lack of rock samples. However, with these limitations in mind, a generally higher average insoluble residue concentration is found for samples of the Phroso Siltstone Member, especially in the northern part of the report area. The unusual isopleth configuration for insoluble residue values of the Llama Member in the Athabasca River area (Fig. 17) is thought to result from the proximity of the Whitehorse Formational contact. As the contact is approached, the Llama Member generally contains more dolomite and dolomitic siltstone-sandstone interbeds. Thus, where a

complete stratigraphic section occurs with a Whitehorse contact, the average insoluble residue value is low because of the dolomite and dolomitic siltstone-sandstone interbeds. Where a stratigraphic section terminates in the Llama Member because of pre-Jurassic and/or post-Laramide erosion, the average values are generally much higher because the carbonate concentration decreases downward in the Llama Member.

Insufficient data are available from the Whistler Member to plot meaningful residue concentrations on a base map. However, in contrast to the Whistler Member values north of Athabasca River (Gibson, 1971, p. 26), the average values to the south appear to be much higher.

## PALEOCURRENT ANALYSIS

Throughout the Athabasca River-Crowsnest Pass area sedimentary directional structures are scarce, and are confined mainly to the sandstones and siltstones of the Starlight Evaporite and Vega Siltstone Members. Preservation is poor, and reliable field azimuth values are difficult to obtain and interpret. However, the few values recorded in the report area do give some indication of the nature and direction of sediment transport and the probable type of paleoenvironment in which the sediments were deposited. All reliable directional structure attitudes were recorded in the field. Wherever practical, three azimuth values were recorded for each outcrop locality and plotted on figure 18. Similarly, if only one value was obtainable it too was incorporated into the analysis. All field values were rotated using a Schmidt equal area stereonet to correct for the tilting of the rocks in the area.

Crossbedding is the most common and best preserved directional structure in the Triassic strata. It occurs in beds up to 3 feet (17 m) thick, in the fine- to medium-grained sandstones of the Olympus lentil of the Starlight Evaporite Member, and in the dolomitic quartz sandstones near the base of the Starlight Member (Pl. II, E). Most crossbedding is of the simple type showing well-developed truncation at the top and asymptotic tangency at the base. The corrected values on figure 18 indicate a general current transport direction for the sands of the Whitehorse Formation toward the east and southeast. The configuration, texture, and transport direction suggest that sediment movement may have been in part due to longshore or littoral drift currents, paralleling the eastern basin margin. Crossbedding in the Sulphur Mountain Formation is of smaller scale and is generally referred to as micro-cross-lamination (Gibson, 1971). The poor field preservation and small size made reliable azimuth values difficult to obtain. The smaller size and association with finer grained sediments suggest that most of the micro-cross-lamination in the Sulphur Mountain Formation formed under different environmental conditions than the crossbeds of the Whitehorse Formation.

Oscillation and interference ripple-marks (Pl. II, G) were noted on some well-exposed bedding surfaces of the Sulphur Mountain Formation at Cadomin and at Bighorn and Sheep Creeks. Other directional structures observed, although not common, were flute casts, groove casts, and bounce casts, all found in talus samples of the Vega Siltstone Member.

Paleocurrent studies north of Athabasca River indicated a general current transport direction from the east and northeast for sediments of the Sulphur Mountain Formation (Gibson, 1971, p. 32). Paleocurrent values recorded from the Whitehorse Formation north of Athabasca River suggested a current transport direction from the north to northeast. However, as noted above, most sands of the Whitehorse Formation in the Athabasca River-Crowsnest Pass area appear to have been transported from the north and northwest. These values were recorded mainly from the Olympus Sandstone, whereas the values recorded to the north were from sandstones scattered throughout the formation.

## PALEOENVIRONMENTS OF TRIASSIC SEDIMENTATION

Few suggestions have been made concerning the depositional history of Triassic rocks in the Athabasca River-Crowsnest Pass area other than an inference of deposition under shallow or deep water conditions. Barss *et al.* (1946), Nelson (1970), and Gibson (1968a, 1971) have suggested the nature of the paleoenvironment and conditions of deposition for Triassic rocks in part of the present report-area, as well as other regions of the Western Canada sedimentary basin. Triassic rocks generally have proven difficult to relate to modern-day environments, especially the strata of the Sulphur Mountain Formation. The difficulty may result from a lack of comparative studies or perhaps the Triassic rock succession has unique characteristics not yet described in the literature. The following paleoenvironmental inter-

pretation is based largely on the mineralogical, paleontological, and sedimentological character of the Triassic rocks and their relationship and similarity to features in recent depositional environments. This discussion and interpretation must, therefore, be considered only as a working hypothesis subject to revision or amendment when additional criteria and observations become available.

Triassic rocks in the report-area form a westward-thickening wedge of marine sediments deposited in what is commonly referred to as the Cordilleran Miogeosyncline. The eastern margin of the geosyncline and its configuration and lateral extent is generally well defined; however, the western margin remains speculative. Nelson (1970, p. 111) depicted a relatively narrow Triassic seaway during Early and Middle Triassic time in the report-area, with extensive land areas to the west in much of the present British Columbia interior. This interpretation caused difficulty in trying to account for the composition and sediment types or lack of sediment types in the report-area and other areas of Western Canada in which Triassic rocks occur. Nelson (1970, p. 111) does, however, mention another possible interpretation of the configuration of the ancient Triassic seas and landmass areas. He suggests that the depositional basin may have been more extensive to the west, thus implying a less extensive landmass area in much of the present British Columbia interior. On the basis of Triassic investigations in the report-area and other areas of Alberta and British Columbia (Gibson, 1971), the writer favours the second interpretation of Nelson. The high concentration

of quartz in relation to other detrital minerals (feldspar and chert), the absence of rock fragments and ferromagnesian minerals, the occurrence of westerly dipping crossbeds, westerly thickening stratigraphic units, and a westerly decreasing insoluble residue concentration for sediments of the Sulphur Mountain Formation combine to suggest a provenance area to the east for most of the clastic sediments; an area of probable low relief and mature topography, composed of pre-existing sediments. No convincing evidence has yet been found to indicate a sediment source area to the west, a feature one would expect in order to account for the narrow Triassic seaway and extensive adjacent western land-mass areas figured by Nelson.

Prior to Triassic deposition, the Athabasca River-Crowsnest Pass area underwent extensive erosion or non-deposition because much of the Permian Ishbel Group is missing from the eastern part of the report area. The Permian strata underlying Triassic rocks in much of the area are interpreted by Rapson-McGugan (1970) to indicate shallow-water deposition in an evaporitic environment comparable to that existing today along the coast of Baja, California.

## Sulphur Mountain Formation

### Phroso Siltstone Member

Following a period of pre-Triassic erosion and/or non-deposition, Triassic seas transgressed,probably from the west or northwest, over a surface having generally low relief and composed mainly of sandstones and carbonates of Permian and Mississippian age. Field and laboratory evidence suggests

that most silts, sands, shales, and carbonates of the Sulphur Mountain Formation were deposited in a shallow-water shelf environment, similar in some ways to modern shallow shelf areas off the eastern Atlantic coast of the United States and possibly the Wash and Wadden Sea areas of Western Europe.

The Phroso Siltstone Member contains sedimentary characteristics that sometimes are found in two modern sub-environments of shallow shelf areas, namely, the tidal flat environment, and the delta environment. However, exact comparisons to either of these sub-environments are difficult to make because of a lack of some critical diagnostic criteria in the Triassic strata. For example, recent tidal flat environments are described as containing from 3 to 7 micro-environments (van Straaten, 1961; and Evans, 1965) extending seaward as distinctive sedimentological zones, some of which are incised by tidal channels and meandering creeks. These diagnostic criteria have not been observed in the Phroso Member. Recent deltas generally are characterized by a limited areal extent, and commonly contain clays, clay-size and interdistributary bay sediments and associated structures which, so far, have not all been recognized in the Triassic rocks. The following discussion of field and laboratory data from the Phroso Siltstone strata suggests a sedimentary model comparable to that of a modern shallow-water shelf environment containing tidal flat-deltaic and possible estuarine complexes. The shallow water (less than 10 feet) or intertidal portions of this environmental model are not exposed and may not be preserved in the subsurface because of post-Triassic uplift and erosion, thereby accounting for the absence of some

of the diagnostic criteria outlined above. It must be noted that other paleo-environmental interpretations may be possible for the deposition of Phroso strata (i.e. deposition under normal marine conditions in a deep water environment); however, the contained fauna and sedimentary evidence now preserved in the Phroso strata of the Athabasca River-Crowsnes Pass area, as interpreted by the writer, favour a shallow water origin.

The concentration and preservation of dark grey to brown ferrunginous-organic carbonaceous matter in Phroso strata suggest deposition in a restricted marine environment, where the iron and organic plant matter were buried before complete oxidation. Berner (1970) reported that sedimentary iron sulphate or pyrite and organic matter were forming in the tidal flat and adjacent subtidal areas of Long Island Sound on the east coast of the United States. The pyrite results from a reaction between ferruginous minerals and hydrogen sulphide, the latter constituent derived from the decomposition of the organic matter in the sediment. However, some of the pyrite in the Phroso Member is an authigenic constituent formed after consolidation and cementation of the sediment. Siltstones of the Phroso Member contain recrystallized carbonate in a concentration sufficient to serve as a supporting matrix to detrital quartz and feldspar grains. Microscopic examination of some of these very dolomitic siltstones reveals that some of the carbonate consists of well-rounded relict grains (Pl. VIII, E, F), suggesting a detrital origin for some and possibly all of the carbonate cementing the siltstones. Thin limestone interbeds are found with the siltstones south of Bow River,

and may indicate deposition in an environment away from the influence of a major river system. Small spherical grains of calcite were observed in some silty limestones at Smith-Dorrien Creek (Pl. VIII, D). These grains represent possible calcispheres and accordingly are interpreted to indicate shallow water deposition (Kummel and Teichert, 1971).

Sedimentary structures such as regular to wavy lenticular laminations, micro-cross-laminations, and ripple-marks are found throughout the member. Similar structures are common to sediments of recent deltas, tidal flats, and shallow water subtidal areas. The cross-laminations and ripple-marks generally occur in the eastern parts of the region, the area of shallowest water according to the present hypothesis. The fine, regular and lenticular laminations are more common in the western sections of the region, and represent formation under slightly deeper water conditions, at depths generally below effective wave base.

The Phroso Member is sparsely fossiliferous, containing some poorly preserved indeterminate pelecypods, ammonites, and possible ostracodes in the thicker more westerly sections of the area. However, at most eastern and some western localities, blue-black phosphatic lingulid shell fragments were observed in the siltstones. These shell fragments are angular, and consequently have not been subjected to sedimentary reworking or long distances of transport. Investigations by Craig (1952), Ferguson (1963), Rhodes and Bloxam (1969), Paine (1970) and Detterman (1970) reveal that inarticulate brachiopods such as lingulids are generally characteristic of intertidal or

subtidal depositional areas where the water is marine or slightly brackish. Recent lingulids are commonly found flourishing in or near outlets of large river systems in water usually less than 25 feet (46 m) deep. Lingula occurrences, however, have been reported from water up to 200 feet (9,508 m) deep. Coleman et al. (1970) describe and illustrate lingulid brachiopod mounds on the tidal flats of the Klang Delta of Malaysia. Thus, the presence of lingulid shells and shell fragments in the Phroso and other members of the Sulphur Mountain Formation represents the most convincing evidence available for a shallow water subtidal origin for the sediments in the Athabasca River-Crowsnest Pass area. The sparse occurrence of compressed ammonites and pelecypods in the more westerly sections of the report area may indicate slightly deeper water conditions.

The composition of the sediment may reflect the nature of the climate, the topography, and the probable nature of the source material at the time of deposition of the Phroso strata. The occurrence of unoxidized organic-ferruginous material suggests a period of continuous sedimentation with rapid sediment input and burial, while the occurrence of Lingula shells and shell fragments indicate a tropical or subtropical climate (Ferguson, 1963) with an average or relatively high rainfall. The rapid sediment input results in the organic-ferruginous matter being buried quickly before complete oxidation. The fine grain size and relatively high quartz concentration and general lack of ferromagnesian and other heavy minerals in the sediment suggest that the Phroso sediments were derived from a pre-existing sediment or sedimentary rock in a topographically low-lying source area.

## Vega Siltstone Member

The siltstones, sandstones, shales, and carbonates of the Vega Member were, with minor exceptions, deposited under environmental conditions similar to those postulated for the underlying strata of the Phroso Siltstone Member. Shallow water conditions prevailed throughout most of the area; however, textural parameters in the Vega siltstones suggest the possibility of a slight marine regression in comparison to Phroso time. The siltstones of the Vega Member are slightly coarser grained than those of the Phroso Member. However, this grain size increase may equally reflect an increased gradient in the source rivers and streams.

Mineralogical and textural evidence supporting a shallow water origin for sediments of the Vega Member is provided by the occurrence of well-rounded relict grains of dolomite and limestone associated with carbonate-supported grains of quartz and feldspar (Pl. VIII, E), as described in the Phroso Member, fragmented and abraded fossil shells forming thin bioclastic limestone and dolomite interbeds at some localities south of Bow River. The carbonate interbeds may reflect deeper water conditions, away from the influence of major sediment transporting streams. In addition, carbonaceous-ferruginous concentrations show a proportionate decrease over that in sediments of the underlying Phroso Member, possibly indicating sediment deposition under less restricted, more oxygenated marine conditions. Furthermore, the carbonate minerals, mainly dolomite, form a relatively higher concentration in Vega than Phoso strata. The increased carbonate

concentration in Vega siltstones reflects a reduction in the detrital supply from the eastern landmass as a result of a changing climate or possibly the result of an increased supply of detrital carbonate. At most eastern sections north of Bow River, dolomite forms a very distinctive lithofacies and is called the Mackenzie Dolomite. Examination of several thin sections of the Mackenzie lentil shows a texture of subangular to well-rounded relict grains, large subrounded intraclasts, and faint outlines of whole and fragmented pelecypod shells (Pl. III, A). In addition, the dolomite contains well-rounded grains of phosphate, and blue-black lingulid shell fragments (Pl. VI, A, B). The texture, mineralogy, fauna, and lenticular shape of the Mackenzie Dolomite suggest that the dolomite lentil represents a possible shell bank, similar to those found today on some tidal flat areas (van Straaten, 1961; Evans, 1965). The skeletal material has been extensively recrystallized, such that most bioclasts and detrital grains are difficult to recognize. Conversely, the dolomite lentil may only represent a shallow water evaporitic dolomite. Traces of gypsum and optically "length slow" chert were observed in a thin dolomite lens at the top of the Vega Member at Burns Creek. Folk and Pittman (1971) interpret the occurrence of "optically slow" chert in a sediment to indicate formation in an evaporitic environment.

Distinctive bedding, laminations, and sedimentary structures provide further evidence of a shallow water origin for most sediments of the Vega Member. The bedding generally consists of rhythmic alternations of

resistant, faintly to non-laminated, medium to thick siltstone beds, and finely laminated to micro-cross-laminated, recessive siltstone to shaly siltstone beds (Pl. I, D). Some of the thick beds contain flute, groove, and bounce casts, and good crossbedding, all structures which are sometimes characteristic of turbidites in deep water; however, these structures may occur in other types of unrelated environments. Because graded bedding, a mixed or displaced fauna, and other sedimentary characteristics of deep water turbidites are lacking, the Vega Member is thus interpreted to have been deposited under shallow water conditions. The thin, finely laminated, more carbonaceous-ferruginous beds were deposited by gravity settling during slightly more tranquil conditions. Crossbedding (Pl. II, H), mudcracks, and oscillation ripple-marks were observed at Snow Pass (Sec. 71-4, Fig. 2), supporting the hypothesis of a shallow-water, neritic origin for Vega Siltstone strata.

Phosphatic lingulid shells and shell fragments (Pls. II, C, and III, A) were observed in the Mackenzie Dolomite and some siltstones of the Vega Member, thus indicating similar paleoenvironmental conditions to those postulated for the underlying Phroso Member. Worm and/or other burrowing trails (Pl. II, D) were observed in finely laminated siltstones of the member, implying a relationship to similar structures in recent tidal flat and subtidal environments.

The rhythmic bedding, sedimentary structures, and general composition of Vega strata indicate a probable climate change in the report-area. The thicker non-laminated siltstones represent periods of high sediment

discharge or flooding by streams, ultimately resulting in the formation of thick beds. The flute, groove, and bounce casts may have formed by shallow water currents initiated by gravitational slumping. In contrast, the thinner, more finely laminated, carbonaceous-ferruginous strata represent deposition under more tranquil normal marine conditions, with little to no sediment input from the mainland river systems. The thinner beds represent periods of low rainfall and runoff. With the reduced supply of detrital sediments, tidal currents and waves rework, sort, and redistribute the sediment. The composition of the Vega strata reflects a source area underlain by sedimentary rocks. The end of Vega time heralds the beginning of a generally prominent sedimentological and faunal break in most of the Athabasca River-Crowsnest Pass area.

## Whistler Member

Following deposition of the Vega Member, the region may have been subjected to a short interval of non-deposition and/or erosion, which is suggested by the occurrence, in some areas, of a zone of granular phosphate and phosphatic pebble conglomerate at the base of the Whistler Member. However, on the basis of fossil collections from areas north of Athabasca River, Triassic fossil zones appear complete between the Lower and Middle Triassic rock succession. The magnitude of this diastem, if it does in fact exist, is probably small.

The Middle Triassic epoch began with a slight deepening of water, the extent and nature of which was such that in western areas of the region the waters were slightly deeper than those to the east, where the strata change facies to coarser grained, more dolomitic sediments typical of the Llama Member. In the deeper water regions, the strata are characterized by fine, light grey laminations lacking obvious organic carbonaceous-ferruginous inclusions. These light grey laminations represent periods where oxidation was strong enough to remove the dark coloured carbonaceous-ferruginous matter, or periods of strong winnowing action by marine currents and waves, removing the dark matter. Because of the predominant concentration of dark grey carbonaceous-ferruginous matter, and noticeable lack of fossil assemblages, deposition of most Whistler strata in the western part of the region occurred in an oxygen deficient environment. The occurrence of well-rounded phosphate grains, clasts, and ooliths (Pl. VI, C, D, E) in the member suggests that at times the sediments were deposited in very shallow water, in an active wave energy environment. South of Bow River, the Whistler equivalent contains lenses and thin limestone interbeds, some of which contain well-preserved ammonites. This region, as discussed previously, probably represents a deeper water environment.

Climatic conditions continued to change during Whistler time. The thin development and thin-bedded nature of the member suggests a low sediment input and rate of detrital sedimentation to the west, while localities to the east show a marked increase in carbonate concentration and a corresponding

decrease in dark coloured organic-ferruginous matter in Whistler equivalent strata. This observation suggests a much reduced detrital sediment input and river discharge into the basin, probably the result of reduced rainfall and consequent desert-like conditions in the eastern landmass area. Alternatively, one might suggest that the decrease in organic carbonaceous-ferruginous matter is the result of a decreasing organic bloom in the eastern part of the basin, or alternatively is the result of a turnover of bottom waters in a restricted environment changing conditions from those of anaerobic to aerobic. However, evidence supporting these alternative interpretations has not been found by the writer. The composition of the detrital sediments again implies a provenance of pre-existing sediments.

## Llama Member

Triassic seas began to shallow and regress during deposition of Llama and Llama-equivalent sediments in the report and other areas of western Alberta and northeastern British Columbia. Semiquantitative maximal grain size analyses on selected samples of the Sulphur Mountain Formation revealed an average maximal grain size increase in strata of the Llama Member over strata of the underlying members. The shallowing sea was accompanied also by a decrease in concentration of detrital quartz, feldspar, and carbonaceous-ferruginous matter, and a proportionate increase in concentration of carbonate minerals from the base to the top of the member. The occurrence of well-rounded to subangular grains of quartz and feldspar in recrystallized dolomite

Pl. V, B, C), well-rounded relict grains of dolomite in the siltstones, and the presence of thin bands of intraformational dolomite conglomerate again provide evidence for a shallow water origin for the Llama sediments. The intraformational conglomerate occurs as thin interbeds, and indicates that the area was exposed periodically to the atmosphere, permitting desiccation and fragmentation of the dolomite. Well-preserved blue-black Lingula and lingulid and orbiculid phosphatic shell fragments were observed at many sections near the base of the member (Pl. V, F). These shells and shell fragments, as discussed previously, indicate sediment deposition under shallow marine or brackish to near brackish water intertidal to subtidal conditions.

During Llama time, the climate changed from one of temperate to tropical conditions, with an average or high rainfall, to one of arid or semi-arid conditions, with generally low rainfall. The vertical reduction in concentration of detrital quartz, feldspar, and carbonaceous-ferruginous matter suggests that river systems, as a consequence of reduced rainfall throughout Llama time, were greatly reduced in their capacity to carry and transport sediments into the deposition basin. Alternatively, one might argue that the dispersal energy in the marine or shallow water environment increased greatly thereby removing most of the detrital clastic material. However, the nature and composition of the strata do not support this hypothesis. Most Llama strata are thick and structureless, with little to no evidence of strong

current activity. With the reduced fresh water input into the basin, shoreline and tidal flat salinities would increase slightly, and thus remove the favourable brackish water environment conducive to the development and existence of the phosphatic inarticulate brachipod fauna. The Sulphur Mountain period thus ended with the Athabasca River-Crowsnest Pass area showing a complete paleoclimate reversal, from one of moderate or high rainfall and moderate to high river discharge and detrital sediment input in Early Triassic time, to one of low rainfall and small river discharge in late Middle and early Late Triassic time.

In summary, the sediments of the Sulphur Mountain Formation were deposited in shallow water on a marginal shelf which in some regions probably formed part of a series of coalescing delta complexes along the eastern margin or miogeosynclinal part of the Cordilleran Geosyncline.

## Whitehorse Formation

### Starlight Evaporite Member

The contrast in composition and sedimentary character between the Whitehorse and Sulphur Mountain Formations suggests a significant paleoenvironmental change at the end of Sulphur Mountain time. The seas continued to regress at the end of Llama time, leaving shallow lagoons, extensive intertidal flat areas, and subaerially exposed barrier islands. The depositional environment may have been similar in some ways to those existing today in

the Texas Gulf Coast (Kwon, 1969; Shepard and Moore, 1955), Persian Gulf (Evans, 1966; Evans et al., 1969), and Baja, California (Phleger and Ewing, 1962; Thompson, 1968) coastal areas. All three areas contain sediments having many characteristics common to the Starlight strata.

The Starlight Evaporite Member consists of light grey to buff, to pale reddish brown and green limestones and dolomites, sandstones, intraformational conglomerates and/or solution breccias, and some gypsum. The predominant limestones and dolomites have been recrystallized and commonly contain well-rounded grains of quartz and feldspar (Pl. III, E). Some dolomites are composed of well-rounded grains, ooliths, and pellets. The limestone and dolomite conglomerate and/or breccia clasts are frequently soft, chalky, very ferruginous and argillaceous, and reddish brown to bright yellow in colour. In addition, some of the clasts are composed of ooliths and pellets, some of which appear to contain algal rims (Pls. VII, F, and VIII, A). The conglomerates and/or breccias are most common at western localities north of Bow River. The occurrence of the gypsum, intraformational and/or solution breccias, "red beds", oolitic, and very finely crystalline carbonates suggests deposition under very shallow water evaporitic conditions in a broad intertidal and/or lagoonal environment. The occurrence of phosphatic lingulid shells and shell fragments at Sheep and Bighorn Creeks, two of the most eastern localities in the area, suggests the possibility of slightly brackish water conditions resulting from large periodic influxes of fresh water into the tidal flat-lagoonal area. At Lodgepole River (Sec. 67-22, Fig. 2), the

southernmost section in the report area, the total Whitehorse Formation consists of limestone with fragmented pelecypod and/or brachiopod, and gastropod shells. This region represents a less restricted or slightly deeper water area, although an area shallow enough to be subjected to strong wave and current activity.

Sandstones occur as thin to medium beds throughout the Starlight Member; however, in the North Saskatchewan River area, they comprise a distinctive body, up to 450 feet (1,476 m) thick, called the Olympus Sandstone Lentil. This sandstone represents an offshore bar or barrier island system, formed by wave and longshore currents travelling parallel to the coast. The Olympus Sandstone contains crossbedding, and well-developed oscillation ripple-marks at some localities.

An unconformity has been postulated by some workers (Barss et al., 1964) between the Sulphur Mountain and Whitehorse Formations. If one accepts the foregoing shallow water-evaporitic interpretation, stratigraphic evidence supporting the unconformity is easy to find. However, the magnitude of the unconformity, if it does exist, is considered by the writer to be small. The abrupt lithologic changes, both vertically and laterally, throughout the Starlight Member, indicate the possibility of numerous small diastems or periods of slight erosion and/or non-deposition, but nothing of the magnitude of an unconformity.

The foregoing discussion thus supports the hypothesis of a shallow water evaporitic depositional environment in an arid to semi-arid climate,

with river discharge reduced to periodic flooding into the intertidal and/or lagoonal area. At most times during Starlight sediment deposition, the waters were warm, very saline, and not conducive to the support of a flourishing fauna.

## Winnifred Member

The final stages of Triassic deposition took place in the shallow waters of a transgressing sea. The carbonates, siltstones, sandstones, and minor intraformational conglomerates of the Winnifred Member were deposited in the waters of an intertidal to subtidal environment, with water depths generally deeper than those postulated for the Starlight Evaporite strata. The carbonates are granular to very finely crystalline, and frequently contain large well-rounded grains of detrital quartz and feldspar. At many localities dolomitic siltstones, fine-grained sandstones, and silty dolomites contain dark grey organic carbonaceous-ferruginous inclusions, indicating a return to normal marine conditions and a temperate climate. Some of the sandstones display graded bedding, and contain well-rounded grains of carbonate with the quartz and feldspar.

Winnifred strata generally are confined to the thicker western sections north of Bow River, because the uplift, erosion, and/or non-deposition at the end of the Triassic Period was probably more extensive in the areas to the south than to the north. This major unconformity coincides with a prominent conglomerate bed at the base of the Fernie Formation, and a marked lithologic and faunal break between the Jurassic and Triassic systems.

In summary, most sediments of the Whitehorse Formation are postulated to have been deposited in an arid to semi-arid, shallow water, intertidal and/or lagoonal environment.

## REFERENCES


Allan, J. A., and Carr, J. L.
1947: Geology of Highwood-Elbow area, Alberta; Res. Council Alberta, Rept. 49.

Anderson, D. W., and Picard, M. Dane
1971: Quartz extinction in Siltstone; Bull. Geol. Soc. Am., v. 82, p. 181-186.

Barss, D. L , Best, E. W., and Meyers, N.
1964: in Geological history of western Canada; R. G. McCrossan and R. P. Glaister, eds., Calgary, Alberta, Alberta Soc. Petrol. Geologists, p. 113-136.

Berner, R. A.
1970: Sedimentary pyrite formation; Am. J. Sci., v. 268, p. 1-23.

Best, E. W.
1958: The Triassic of the North Saskatchewan-Athabasca Rivers area; Alberta Soc. Petrol. Geologists, Guidebook; Eighth Ann. Field Conf., p. 39-49.

Blatt, Harvey
1967: Original characteristics of clastic quartz grains; J. Sediment. Petrol., v. 37, p. 401-424.

Blatt, Harvey, and Christie, J. M.
1963: Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks; J. Sediment. Petrol., v. 33, p. 559-579.

Carozzi, A. V.
1960: Microscopic sedimentary petrography; New York and London, John Wiley and Sons, Inc., p. 1-193.

Chayes, F.
1952: Notes on staining of a potash feldspar with sodium cobaltinitrite in thin section; Amer. Mineralogist, v. 37, p. 337-340.

Clark, L. M.
1948: Geology of the Rocky Mountain Front Ranges near Bow River, Alberta; Bull. Am. Assoc. Petrol. Geologists, v. 33, p. 614-633.

Coleman, J. M., Gagliano, S. M., and Smith, W. G.
1970: Sedimentation in a Malaysian high tide tropical delta; in Deltaic sedimentation modern and ancient, James P. Morgan, ed.; Soc. Econ. Paleontologists Mineralogists, Spec. Publ. no. 15, p. 185-197.

Crabb, J.
1957: A summary of the geology of the Crowsnest coal field and adjacent areas; Alberta Soc. Petrol. Geologists, Guidebook, Seventh Ann. Field Conf., p. 77-85.

Craig, G. Y.
1952: A comparative study of the ecology and palaeoecology of Lingula; Trans. Edin. Geol. Soc., v. XV, p. 111-119.

Crockford, M. B. B.
1949: Geology of Ribbon Creek area, Alberta; Res. Council Alberta, Rept. 52.

1956: The Canmore coal basin; Alberta Soc. Petrol. Geologists, Sixth Ann. Field Conf., p. 92.

Crockford, M. B. B., and Clow, W. H.
1955: Triassic and Jurassic formations of southern Alberta; Alberta Soc. Petrol. Geologists, Third Ann. Field Conf., p. 60-67.

Detterman, R. L.
1970: Sedimentary history of the Sadlerochit and Shublik formation in northeastern Alaska; in Proc. Geological Seminar on the north slope of Alaska, Pacific Section, W. L. Adkinson and M. M. Brosgé, eds., Am. Assoc. Petrol. Geologists, p. 01.

Douglas, R. J. W.
1958: Mount Head map-area, Alberta; Geol. Surv. Can., Mem. 291.

Dowling, D. B.
1907: Report on the Cascade Coal Basin, Alberta; Geol. Surv. Can., Publ. 949, 37 p.

Evans, G.
1965: Intertidal flat sediments and their environments of deposition in the Wash; Quart. J. Geol. Soc. London, v. 121, p. 209-245.

1966: The recent sedimentary facies of the Persian Gulf region; Phil. Trans. Roy. Soc. London, Ser. A, p. 291-298.

Evans, G., Schmidt, V., Bush, P., and Nelson, H.
1969: Stratigraphy and geologic history of the Sabkha, Abu Dhabi, Persian Gulf; Sedimentology, v. 12, p. 145-159.

Ferguson, L.
1963: The paleoecology of Lingula squamiformis Phillips during a Scottish Mississippian marine transgression; J. of Paleontology, v. 37, p. 669-681.

Folk, R. L.
1959: Practical petrographic classification of limestones; Bull. Am. Assoc. Petrol. Geologists, v. 43, p. 1-38.

1964: Petrology of sedimentary rocks; Austin, Texas, Hemphill's Bookstore.

Folk, R. L., and Pittman, J. S.
1971: Length-slow chalcedony: A new testament for vanished evaporites; J. Sediment. Petrol., v. 41, p. 1045-1058.

Foscolos, A. E., Stott, D. F., and Proctor, R. E.
Layer lattice silicate assemblages, mineralogy and inorganic geochemistry of Lower Cretaceous shales of northeastern British Columbia; Geol. Surv. Can., Paper (in preparation).

Gibson, D. W.
1968a: Triassic stratigraphy between the Athabasca and Smoky Rivers of Alberta; Geol. Surv. Can., Paper 67-65.

1968b: Triassic stratigraphy between Athabasca and Brazeau Rivers of Alberta; Geol. Surv. Can., Paper 68-11.

1969: Triassic stratigraphy of the Bow River-Crowsnest Pass region, Rocky Mountains of Alberta and British Columbia; Geol. Surv. Can., Paper 68-29.

1971: Triassic petrology of Athabasca-Smoky River region, Alberta; Geol. Surv. Can., Bull. 194.

Glover, J. E.
1964: Universal stage in studies of diagenetic textures; J. Sediment. Petrol., v. 34, p. 851-854.

Govett, G. J. S.
1961: Occurrence and stratigraphy of some gypsum and anhydrite deposits in Alberta; Res. Council Alberta, Bull. 7.

Hunt, C. W.
1956: Panther dome: A minor orogen of the Canadian Cordillera; Guidebook, Sixth Ann. Field Conf., Alberta Soc. Petrol. Geologists.

Ireland, H. A.
1958: Insoluble residues: Subsurface geology in petroleum exploration; Colorado School of Mines.

Irish, E. J. W.
1951: Pierre Greys Lakes Map-area, Alberta; Geol. Surv. Can., Mem. 258.

Kindle, E. M.
1924: Standard Paleozoic section of the Rocky Mountains near Banff, Alberta; Pan-American Geologists, v. 42.

Kummel, B., and Teichert, C.
1970: Stratigraphy and paleontology of the Permian-Triassic Boundary Beds, Salt Range and Trans-Indus Ranges, West Pakistan; in Stratigraphic boundary problems: Permian and Triassic of West Pakistan; B. Kummel and C. Teichert, eds.; Univ. of Kansas Press, p. 1-110.

Kwon, H. J.
1969: Barrier Islands of the northern Gulf of Mexico coast. Sediment source and development; Louisiana State University Coastal Studies Institute, Tech. Report no. 75.

Lambe, L. M.
1916: Ganoid fishes from near Banff, Alberta; Trans. Roy. Soc. Can., Ser. 3, sec. 4, v. 10, p. 37-38.

MacKay, B. R.
1929a: Mountain Park Sheet; Geol. Surv. Can., Map 208A.

1929b: Cadomin Sheet; Geol. Surv. Can., Map 209A.

1932: The Mesozoic-Paleozoic contact and associated sediments, Crowsnest District, Alberta and British Columbia; Geol. Surv. Can., Summ. Rept. Pt. B.

MacKenzie, W. S.
1965: The geology of the Southesk Cairn carbonate complex; University of Toronto, Ph.D. thesis.

McConnell, R. G.
1887: Report on the geological structure of the Rocky Mountains; Geol. Nat. Hist. Surv. Canada, Ann. Rept. 1886, Pt. D.

Mountjoy, E. W.
1960: Structure and stratigraphy of the Miette and adjacent areas, eastern Jasper National Park, Alberta; University of Toronto, Ph.D. thesis.

Nelson, S. J.
1970: The face of time, the geological history of western Canada; Alberta Soc. Petrol. Geologists, Calgary, Alberta, p. 111-113.

Newmarch, C. B.
1953: Geology of the Crowsnest coal basin, with special reference to the Fernie area, Brit. Columbia Dep. Mines, Bull. 33.

Norris, D. K.
1958: Beehive Mountain, Alberta and British Columbia, 82J/2 E 1/2; Geol. Surv. Can., Paper 58-5.

Paine, R. T.
1970: The sediment occupied by recent lingulid brachiopods and some paleoecological implications; Palaeogeography, Palaeoclimatology, Palaeoecology, v. 7, p. 21-31.

Peterson, M. N. A., and von der Borch, C. C.
1965: Chert: modern inorganic deposition in a carbonate-precipitating locality; Science, v. 149, no. 3691, p. 1501-1503.

Pettijohn, F. J.
1957: Sedimentary petrology; Harper Geoscience Series, 2nd ed., p. 18.

Phleger, F. B., and Ewing, G. C.
1962: Sedimentology and oceanography of coastal lagoons in Baja California, Mexico; Bull. Geol. Soc. Am., v. 73, p. 145-182.

Price, R. A.
1962: Fernie Map-Area, east half, Alberta and British Columbia, 82G E 1/2; Geol. Surv. Can., Paper 61-24.

1965: Flathead Map-Area, British Columbia and Alberta; Geol. Surv. Can., Mem. 336.

Price, R. A., and Mountjoy, E. W.
1971: Geology, Canmore, Alberta (East and West); Geol. Surv. Can., Maps 1265A, 1622A, and structure sections.

Price, R. A., and Ollerenshaw, N. C.
1971: Geology, Scalp Creek (East and West), Alberta; Geol. Surv. Can., Maps 1275A, 1276A.

Rapson-McGugan, J. E.
1970: The diagenesis and depositional environment of the Permian Ranger Canyon and Mowitch Formations, Ishbel Group, from the southern Canadain Rocky Mountains; Sedimentology, v. 15, p. 363-417.

Rhodes, F. H. T., and Bloxam, T. W.
1969: Phosphatic organisms in the Paleozoic and their evolutionary significance; in Phosphate in fossils; Proc. of the North American Paleont. Convention, Pt. K, Allen Press Inc., Lawrence Kan; p. 1485-1514.

Shafiuddin, M.
1960: Spray River Formation near Banff and Cadomin; University of Alberta, M.Sc. thesis.

Sharma, G. C.
1965: Formation of silica cement and its replacement by carbonates; J. Sediment. Petrol., v. 35, no. 3, p. 733-745.

Shepard, F. P., and Moore, D. G.
1955: Central Texas Coast sedimentation; Bull. Am. Assoc. Petrol. Geologists, v. 39, p. 995-1053.

Siever, R.
1962: Silica solubility, 0° - 200°C, and the diagenesis of siliceous sediments; J. Geol., v. 70, p. 127-148.

Telfer, L.
1933: Phosphate in Canadian Rockies; Bull. Can. Inst. Mining Met., v. 36, p. 566-605.

van Straaten, L. M. J. U.
1961: Sedimentation in tidal flat areas; J. Alberta Soc. Petrol. Geologists, v. 9, p. 203-226.

Walker, T. R.
1957: Frosting of quartz grains by carbonate replacement; Bull. Geol. Soc. Am., v. 68, p. 267-268.

1960: Carbonate replacement of detrital crystalline silicate minerals as a source of authigenic silica in sedimentary rocks; Bull. Geol. Soc. Am., v. 71, p. 145-152.

Warren, P. S.
1927: Banff area, Alberta; Geol. Surv. Can., Mem. 153.

1945: Triassic faunas in the Canadian Rockies; Am. J. Sci., v. 243, p. 480-91.

Wentworth, C. K.
1922: A scale of grade and class terms for clastic sediments; J. Geol., v. 30, p. 377-392.