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TRIASSIC PETROLOGY OF ATHABASCA–SMOKY RIVER REGION, ALBERTA

D. W. Gibson

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By
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PREFACE

Triassic rocks in the Foothills Belt and eastern Rocky Mountains of Alberta have long been recognized as an interesting and variable sequence of strata, but little detailed information has been obtained on the stratigraphy and petrology of this succession. Triassic strata in northeastern British Columbia are important reservoirs for oil and gas. The occurrence of strata of a similar age in western Alberta necessitated a detailed investigation to evaluate their potentialities as source rocks and reservoirs for oil and gas.

This report describes and interprets the stratigraphic, sedimentologic, and petrologic features necessary for the economic evaluation of the Triassic rocks in the Smoky–Athabasca River region of Alberta.

Y. O. FORTIER,
Director, Geological Survey of Canada

OTTAWA, December 6, 1968

BULLETIN 194 — Petrographie der Trias im Gebiet von Athabasca - Smoky River (Provinz Alberta)

Von D. W. Gibson

Eine petrographische Untersuchung der Spray-River-Gruppe wird dazu verwandt, die Ablagerungsverhältnisse und Ursprungsgebiete zu bestimmen.

БЮЛЛЕТЕНЬ 194 — Петрология триассовых отложений в районе рек Атабаска-Смоки, в провинции Альберта

Д. В. Гибсон

Петрологическое изучение пород группы реки Спрай с целью определить источники и условия отложения осадочных материалов.

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Abstract

The Triassic Spray River Group between Athabasca and Smoky Rivers, Alberta, is subdivided into two main and contrasting lithofacies. The lower part, the Sulphur Mountain Formation, consists of a dark grey-brown to rusty brown weathering, thin- to medium-bedded sequence of siltstones, silty dolomites, shales, and fine-grained sandstones that comprise, in ascending order, the Phroso Siltstone, the Vega Siltstone, the Whistler, and the Llama Members. The upper part of the group, the Whitehorse Formation, consists of a grey to buff weathering assemblage of limestones, sandy limestones, dolomites, and intraformational breccias comprising, in ascending order, the Starlight Evaporite, the Brewster Limestone, and the Winnifred Members.

The Sulphur Mountain and Whitehorse Formations are composed mainly of quartzose and dolomitic siltstones, dolomites, and limestones, which contain pyrite and traces of collophane, gypsum, and resistant heavy minerals. Mineral variety and concentration suggest that the allochthonous minerals were derived from a source-area of low relief, consisting of pre-existing sediments of a composition similar to an orthoquartzite or protoquartzite. The Sulphur Mountain Formation was selected for more detailed study because its members can be easily traced throughout the area studied. The mineralogical analyses and the percentage of insoluble residue in the rocks suggest a decrease in carbonate concentration to the northwest. A notable increase in grain size above the Whistler Member, coinciding with the beginning of a pronounced marine regression, is also indicated. The analysis of sedimentary directional structures such as micro-cross-laminations, crossbedding, ripple-marks, flute casts, groove casts, and bounce casts, is consistent with the east to northeast sediment source suggested by the mineralogical composition of the strata.

It is postulated, on the basis of the accumulated field and laboratory data, that sediments of the Sulphur Mountain Formation formed during minor marine transgressions and regressions in a shallow shelf, deltaic type of environment analogous, in some ways, to those off the mouths of the present Mississippi and Niger Rivers. In contrast, sediments of the Whitehorse Formation were probably deposited in a more restricted, shallow-marine environment comparable, in some ways, to the Texas Gulf Coast area of the United States.

Résumé

Le groupe de Spray River du Trias, situé entre les rivières Athabasca et Smoky, en Alberta, est subdivisé par l'auteur en deux principaux faciès lithologiques contrastants. La partie inférieure du groupe, la formation de Sulphur Mountain, consiste en une succession de siltstones, de dolomies limoneuses, de schistes argileux et de grès

finement grenus, en stratification de mince à épaisseur moyenne, que les intempéries ont altérés du brun-gris foncé au brun-rouille; la succession comprend, en ordre ascendant, les siltstones de Phroso et de Vega et les niveaux de Whistler et de Llama. La partie supérieure du groupe, la formation de Whitehorse, consiste en un assemblage, altéré de gris à chamois, de calcaires, de calcaires arénacés, de roches dolomitiques et de brèches interstratifiées comprenant, en ordre ascendant, les dépôts d'évaporites de Starlight, le calcaire de Brewster et les niveaux de Winnifred.

Les formations de Sulphur Mountain et de Whitehorse sont composées surtout de siltstones dolomitiques et quartziques, de dolomies et de calcaires; ces roches contiennent de la pyrite et des traces de collophane, de gypse et de minéraux lourds résistants. La diversité et la concentration des minéraux semblent indiquer que les minéraux allochtones proviennent d'une région à bas relief où gisaient des sédiments préexistants de composition similaire au quartzite d'origine sédimentaire ou au grès-quartzite. L'auteur a choisi d'approfondir l'étude de la formation de Sulphur Mountain parce qu'elle offre des niveaux faciles à retracer dans la région. L'analyse minéralogique et la proportion de résidus insolubles des roches semblent indiquer une diminution de la concentration en carbonates en direction nord-ouest. Il semble également qu'il y ait augmentation notable de la dimension des grains dans les couches supérieures au niveau de Whistler, indication d'une régression marine prononcée. L'analyse des structures sédimentaires directionnelles, telles la stratification entrecroisée à l'échelle microscopique, la stratification entrecroisée, les rides de plages, les rainures d'érosion, les empreintes de sillons et de rebond justifie l'hypothèse d'une source sédimentaire de l'est au nord-est que suggère la composition minéralogique des strates.

Se fondant sur les données recueillies sur le terrain et en laboratoire, l'auteur prétend que les sédiments de la formation de Sulphur Mountain se sont déposés lors de transgressions et de régressions marines mineures dans un milieu bas de type plate-forme deltaïque assez semblable aux embouchures actuelles du Mississippi et du Niger. Par contraste, les sédiments de la formation de Whitehorse ont probablement été déposés dans un milieu marin plus restreint et peu profond ressemblant en quelque sorte à la côte du golfe du Mexique au Texas, aux États-Unis.

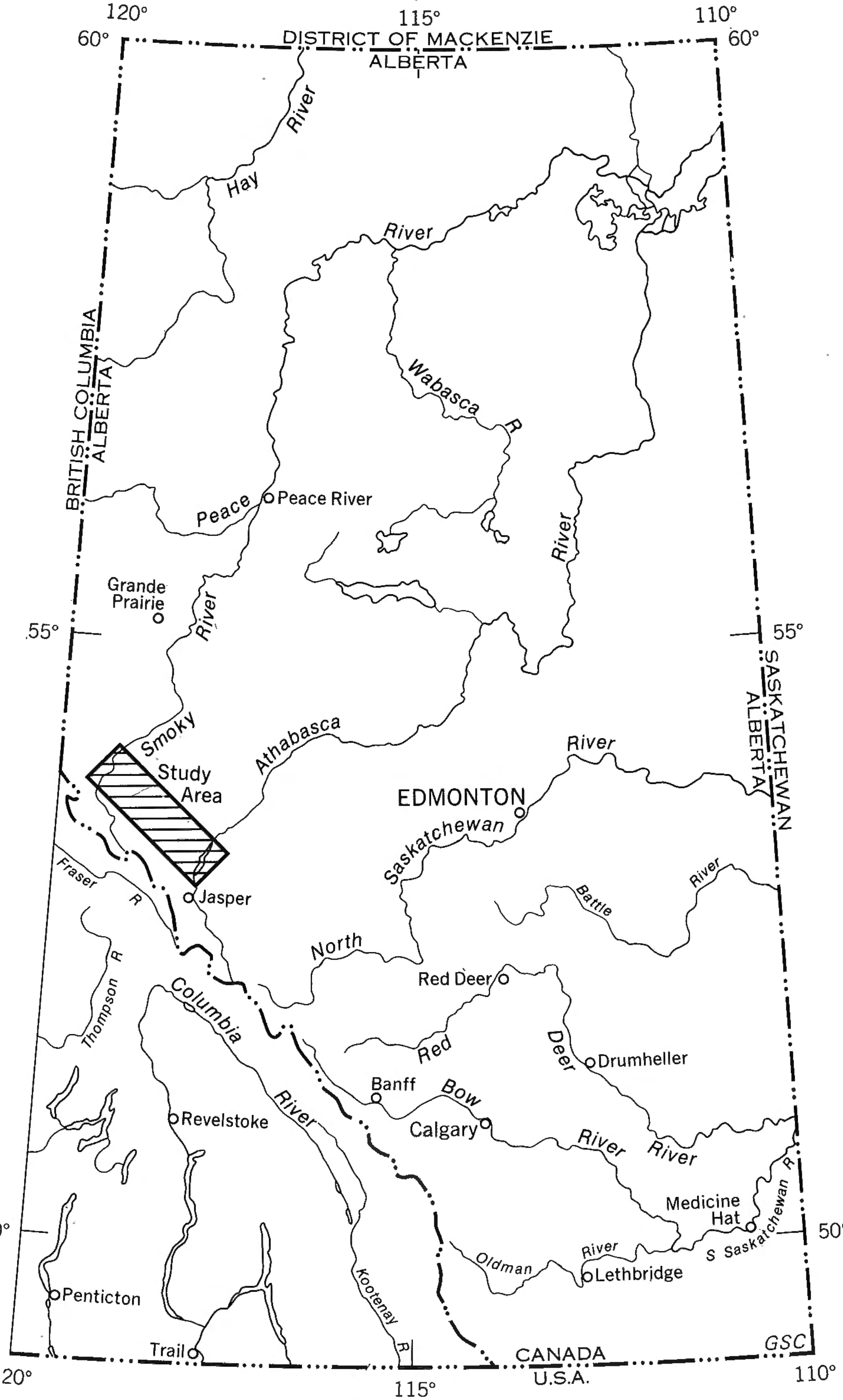

FIGURE 1. Index map showing location of study-area.

INTRODUCTION

Triassic rocks between Athabasca and Smoky Rivers have long been recognized as an interesting and variable sequence of strata, but little detailed stratigraphic and petrologic research had been attempted before 1960. The writer began a detailed investigation of these strata in 1962 (Fig. 1) to: (1) solve some of the existing stratigraphic and nomenclatural problems in the region; (2) correlate the Triassic succession of the Athabasca–Smoky River region with both the Banff area of Alberta to the south and the Peace River area of British Columbia to the north; (3) collect the macrofaunal and microfaunal assemblages of the rock succession; (4) study the megascopic and microscopic features of the sedimentary petrography; (5) 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 a Geological Survey Paper in 1968 (Gibson, 1968). This report supplements the earlier report by emphasizing the petrology of the Triassic succession. In addition, a brief review of the stratigraphy and nomenclature used in the earlier paper is presented.

Five analytical studies were undertaken as the main objectives of the petrological phase of the investigation: (1) a descriptive mineral analysis was made, using thin sections cut from representative samples and employing standard analytical and descriptive techniques; (2) a maximal grain size study, using techniques introduced by Pelletier (1958) and Carozzi (1958), was made on samples of the Sulphur Mountain Formation; (3) insoluble residue analyses of the members of the Sulphur Mountain Formation were made with the aim of detecting sedimentation trends; (4) a mineralogical modal analysis was attempted on selected samples of the Llama Member; (5) the final study involved analysis and interpretation of directional current structures observed and recorded during field investigations.

Field Work and Acknowledgments

Research for this report was based mainly on the study of fifty stratigraphic sections, measured during the summers of 1962 and 1963. All samples, tentatively classified in the field, were subjected to more refined microscopic classification in the laboratory. Oriented specimens containing directional structures such as crossbedding, flute casts, and groove casts, were taken for further laboratory examination. Gross structures were measured and recorded in the field.

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Author's address: Institute of Sedimentary and Petroleum Geology,
3303 33rd Street, N.W., Calgary, Alberta.

Nine complete stratigraphic sections were selected for detailed petrographic examination. Thin sections were made from samples selected at 25-foot intervals except where such intervals were covered or inaccessible. A descriptive qualitative and semi-quantitative mineralogical study was made of all thin sections cut from rock samples of the area.

This report is based on research done as part of a Ph.D. dissertation submitted to the University of Toronto. The research was prepared under the general supervision of F. W. Beales, to whom the writer is indebted. Thanks are accorded E. W. Mountjoy of McGill University (formerly of the Geological Survey of Canada) for introducing the writer to the problem, and assisting with and discussing initial field preparations.

A. E. Foscolos of the Geological Survey of Canada confirmed the presence of clay minerals and organic carbonaceous matter in a few selected samples of the Sulphur Mountain Formation, using X-ray diffraction and DTA methods.

In the field the writer was ably assisted by G. R. Dodd and R. H. Hoogerbrug in 1962, and by W. J. Clack and J. M. Park in 1963.

STRATIGRAPHY

The following brief summary of the Triassic stratigraphy in the Athabasca–Smoky River region of Alberta is presented to familiarize the reader with the nomenclature and lithology characteristic of the region.

Triassic strata between Smoky and Athabasca Rivers outcrop in northwesterly trending valleys and mountain ridges in two broad physiographic units: the Alberta Foothills Belt, and the Front Ranges of the Rocky Mountains. These rocks comprise the Spray River Group, which is divisible into a lower Sulphur Mountain Formation and an upper Whitehorse Formation. Each formation is divisible into distinct members (Table I).

Sulphur Mountain Formation

The Sulphur Mountain Formation (Gibson, 1968) comprises a dark grey to rusty brown weathering sequence of siltstones, silty dolomites, and silty carbonaceous shales, from 490 feet thick at the headwaters of Levi Creek, to 1,280 feet on Whistler Creek (Fig. 2). The formation is divisible into four members which are, in ascending order, Phroso Siltstone, Vega Siltstone, Whistler, and Llama.

Phroso Siltstone Member

This member (Gibson, 1968) comprises a recessive, shaly to flaggy weathering assemblage of generally thin bedded, grey-brown to dark grey, carbonaceous-argillaceous[1], pyritiferous, micromicaceous siltstones, and silty shales (Pl. I F). Dolomitic siltstone and sandstone beds as much as 4 inches thick occur in parts of the unit in the eastern region of the study-area.

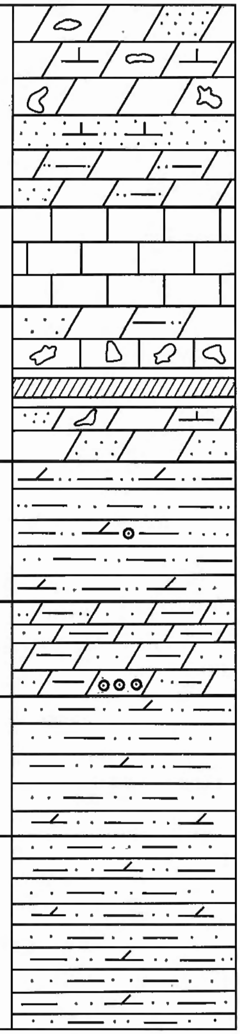
The Phroso Siltstone Member, 386 feet thick at the type locality, has a minimum thickness of 150 feet at the head of Levi Creek, and a maximum thickness of 463 feet in the vicinity of Blue Creek (Fig. 2). These thicknesses were measured at the eastern and western extremities of the study-area and indicate a stratigraphic thinning to the northeast.

The contact of the Phroso Siltstone Member with the underlying Ishbel or Rundle Groups is unconformable. Sections east of the Persimmon, Starlight, and De Smet Ranges (Fig. 2) overlie cherty dolomites of the Rundle Group, whereas sections west of these ranges overlie brown, cherty sandstones of the Ishbel Group. The contact with the overlying Vega Siltstone Member is conformable and distinct, although in some eastern sections it is gradational.

[1]Because of the colour-masking effect, and intimate association of the organic carbonaceous matter with the clay minerals, it was not possible to distinguish the organic and argillaceous constituents using a petrographic microscope. One or both constituents may be present in a given sample.

TABLE I | *Triassic formations and members in the Athabasca–Smoky River area*

Series	Group	Formation	Member
UPPER	SPRAY RIVER GROUP	WHITEHORSE FORMATION	Winnifred Member
UPPER	SPRAY RIVER GROUP	WHITEHORSE FORMATION	Brewster Limestone Member
UPPER / MIDDLE	SPRAY RIVER GROUP	WHITEHORSE FORMATION	Starlight Evaporite Member
MIDDLE	SPRAY RIVER GROUP	SULPHUR MOUNTAIN FORMATION	Llama Member
MIDDLE / LOWER	SPRAY RIVER GROUP	SULPHUR MOUNTAIN FORMATION	Whistler Member
LOWER	SPRAY RIVER GROUP	SULPHUR MOUNTAIN FORMATION	Vega Siltstone Member
LOWER	SPRAY RIVER GROUP	SULPHUR MOUNTAIN FORMATION	Phroso Siltstone Member



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Vega Siltstone Member

This member (Gibson, 1968) consists of well-indurated, cyclical alternations of medium grey, carbonaceous-argillaceous, pyritiferous, dolomitic siltstone to silty dolomite, and shale (Pl. I E). Thin-bedded[1], well-laminated, carbonaceous-argillaceous fissile to shaly, dolomitic siltstones, and silty quartzose shales, are intercalated throughout the unit, decreasing in frequency from the base upward.

The Vega member ranges from 160 feet thick on Wildhay River (Fig. 2), to 442 feet on the northeast flank of Llama Mountain anticline. The thickness of the type section on Mowitch Creek is 284 feet.

The Vega Siltstone Member is conformable or gradational to the underlying Phroso Siltstone Member. The contact with the overlying Whistler and Llama Members is probably conformable, and is coincident with the first occurrence of a prominent lithologic change. The contact with the Whistler Member is generally placed at the base of a fossiliferous, intraformational, phosphatic pebble-conglomerate from 2 to 6 inches thick and fossiliferous in places. Furthermore, a distinct compositional change occurs, which in the field is shown by the colour and weathering nature of the Whistler Member. The contact with the Llama Member, at sections where the Whistler Member is absent, is placed at a generally distinct colour and compositional change between the two members.

Whistler Member

This member (Gibson, 1968) is characterized by a recessive sequence of silty, carbonaceous-argillaceous, medium to dark grey weathering dolomite. A few intercalated beds of resistant dolomite occur but normally these are thin and frequently indistinct. The resistant beds are usually confined to the upper part of the member and contrast markedly with the recessive strata. The intercalated beds are commonly lenticular to nodular, as much as 6 inches thick, and locally very calcareous. They contain, in places, a prolific fauna of Middle Triassic ammonites, pelecypods, and brachiopods.

A maximum thickness of 140 feet is attained by the Whistler Member on Blue Creek (Fig. 2), and a minimum measured thickness of 12 feet on Mount Greenock. The member is absent at two sections, and may be absent in other areas southeast of Athabasca River, because of syndepositional thinning and a probable facies change to the Llama Member.

The member appears to conformably overlie the Vega Siltstone Member. However, because of the intraformational phosphatic conglomerate at the base of the former, the possibility of an unconformity between the two members should not be dismissed. The upper contact with the Llama Member is conformable and distinct or may be gradational. Generally, it is conformable and is placed at the first occurrence of a resistant, thick, massive sequence of siltstones and silty dolomites. The gradational contact, confined to the eastern sections, is characterized by a zone 10 to 25 feet thick of interfingering lithofacies of the Whistler and Llama Members. The contact is arbitrarily placed in the centre of this sequence.

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[1]Thin-bedded = less than 3 inches between bedding planes.
Medium-bedded = 3 inches to 2 feet between bedding planes.
Thick-bedded = more than 2 feet between bedding planes.

Llama Member

This member (Gibson, 1968) consists of an assemblage of medium to dark grey-brown and yellow-brown, carbonaceous-argillaceous, silty to sandy, quartzose dolomite, and dolomitic siltstone, with some local, interbedded, fissile, carbonaceous, silty shale. The interbedded shale is sparsely distributed in the member, and commonly occurs in the eastern sections. This shale probably represents a facies of the Whistler Member.

The Llama Member ranges in thickness from a minimum of 28 feet in the eastern parts of the region at Adam's Lookout and Fiddle River, to a maximum of 490 feet at Dinosaur Pass (Fig. 2). These values indicate a progressive and rapid thickening to the southwest.

The member is overlain conformably and gradationally by the Starlight Evaporite Member of the Whitehorse Formation. The contact is generally gradational but because of lithologic change is easily recognized by contrasting medium greys and browns of the Llama Member with the light greys and yellows of the Starlight Member. The colour change ranges through an interval of 25 to 35 feet in some sections. In the thinner eastern sections the colour change zone is narrower and consequently distinct. The contact is often accompanied by an abrupt lithologic change. The upper beds of the member consist of dolomitic siltstone and very fine grained sandstone, whereas the basal strata of the Starlight Evaporite Member of the Whitehorse Formation consist of thinner beds of sandy, fine- to medium-grained quartzose limestone and dolomite.

Whitehorse Formation

The Whitehorse Formation consists of a sequence of light weathering, variegated, locally sandy, limestones and dolomites, with small amounts of calcareous and dolomitic sandstones, and solution breccias. Locally, lenticular gypsum-anhydrite beds occur in the lower part of the formation and form distinctive sedimentary units as much as 200 feet thick. The formation ranges in thickness from a minimum of 82 feet at the headwaters of Levi Creek, to a maximum of 1,650 feet at Dinosaur Pass (Fig. 2). The Whitehorse Formation overlies the Sulphur Mountain Formation conformably and gradationally, and is in most areas overlain unconformably by the Nordegg Member of the Jurassic Fernie Formation.

The Whitehorse Formation in the Athabasca–Smoky River region is divisible into three distinct and generally persistent members (Gibson, 1968). They are, in ascending order, the Starlight Evaporite, the Brewster Limestone, and the Winnifred (Table I).

Starlight Evaporite Member

This member consists of a complex sequence of buff, yellow, light grey to reddish brown weathering, interbedded, interfingering, and lenticular carbonates, sandstones, siltstones, shales, and solution breccias, with local intercalated beds and lenses of gypsum.

The carbonate consists of limestone and dolomite in about equal proportions with perhaps a slight increase in the amount of limestone in the western sections. The limestone is generally quartzose, thin- to thick-bedded, locally "chalky", poorly indurated, and commonly forms the cement of the solution breccias. Dolomite occurs as thin to medium beds intercalated throughout the unit. Calcareous and dolomitic, very fine to

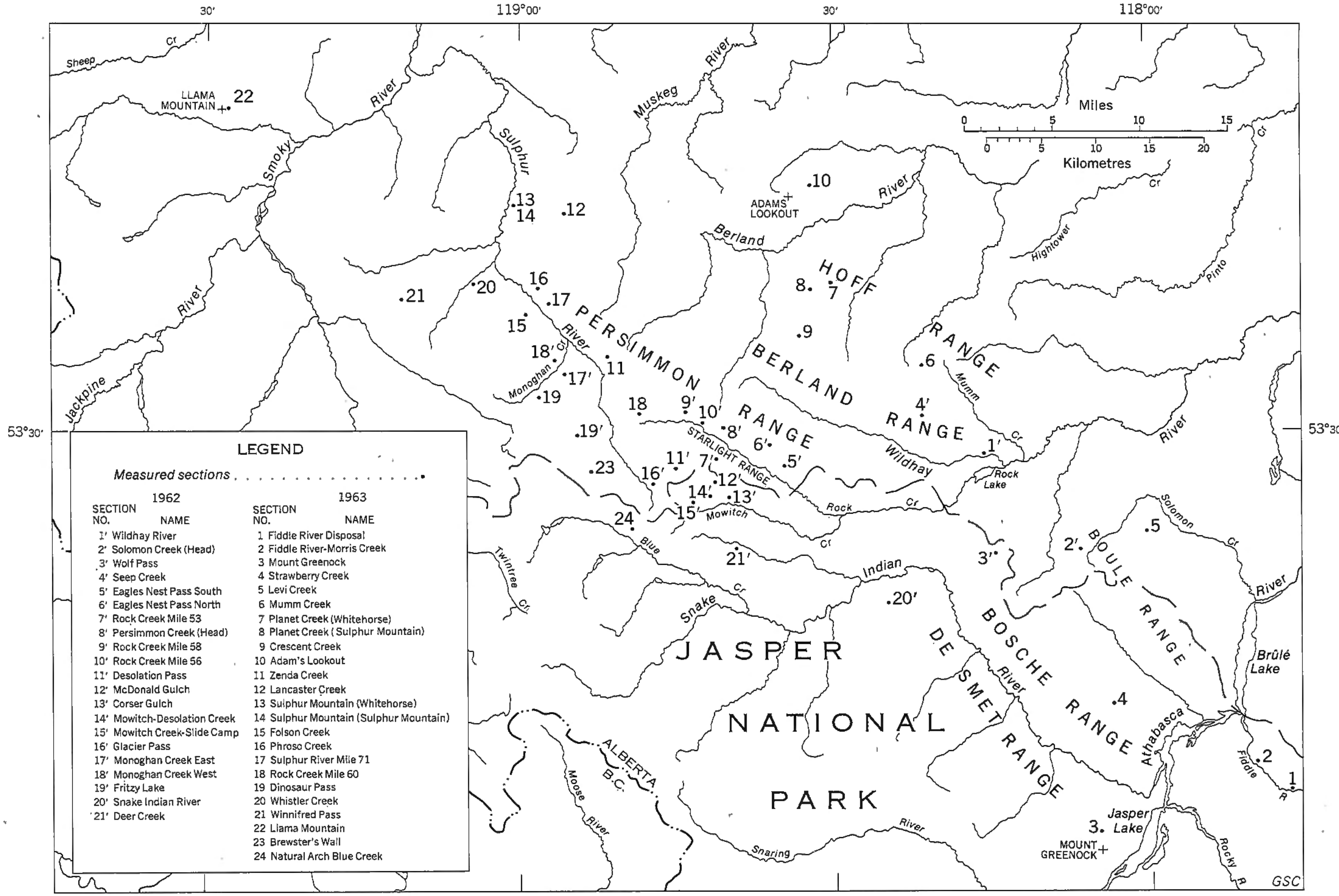


FIGURE 2. Locations and names of Triassic sections.

fine-grained quartz sandstone and minor amounts of siltstone are sparingly distributed in the unit, forming in part a "red bed" facies in some eastern and western sections of the region. The solution breccias are generally medium to thick bedded. The angular clasts consist of sandy (quartzose), ferruginous limestone and dolomite cemented with medium to coarsely crystalline calcite. Gypsum occurs as thin, regular to lenticular beds as much as 6 inches thick, and as thick lenses as much as 200 feet thick.

The Starlight Evaporite Member increases in thickness from east to west, normal to the formational trend of the region. The minimum reliable thickness measured was 103 feet at Adam's Lookout (Fig. 2). The maximum measured thickness of 760 feet occurs at Dinosaur Pass.

The member overlies, conformably and gradationally, the Llama Member of the Sulphur Mountain Formation. Sections west of the Persimmon, Starlight, and De Smet Ranges, have a sharp and abrupt contact with the overlying member. Across the contact the lithology changes from recessive yellow to light grey, "chalky," sandy to silty, limestones, dolomites, and solution breccias of the Starlight Evaporite Member, to resistant, cliff-forming, bioclastic, medium grey weathering limestones of the Brewster Limestone Member. East of the Persimmon, Starlight, and De Smet Ranges, the Brewster Limestone Member is absent and the Starlight Evaporite Member is overlain by the Winnifred Member. The contact is gradational through an interval of usually less than 15 feet. There is generally a marked lithologic contrast between the two members, but this is not so prominent as that found in the western sections overlain by the Brewster Limestone Member.

Brewster Limestone Member

This member comprises an assemblage of resistant, medium to dark grey weathering, medium- to thick-bedded, relatively pure, pelletoid, fossiliferous limestones (Pl. I A), with intercalated, slightly silty to sandy quartzose dolomite in some eastern sections. This latter feature is illustrated at section 8 on the Persimmon Range (Fig. 2). There, the member is divisible into two distinct dark weathering limestone units, separated by a thin, 3-foot thick band of light yellow-grey weathering, slightly silty to sandy, quartzose dolomite. The dolomite probably represents a thin tongue of the Starlight Evaporite Member. Stratal interfingering may also be present at other eastern sections, but has not been recognized owing to talus cover.

The Brewster Limestone Member has a limited distribution in the Jasper area (Fig. 2). It is confined to the region west of the Persimmon, Starlight, and De Smet Ranges, and represents one of the thinnest members of the Triassic succession, ranging from a maximum 205 feet at Brewster's Wall, to a minimum measured thickness of 11 feet near Ram Pass on the southwest side of Snake Indian River (Fig. 2). East of the Persimmon, Starlight, and De Smet Ranges the member is absent, owing to syndepositional thinning and to a probable facies change to the Starlight Evaporite Member.

Where the member is typically developed, both upper and lower contacts are sharp and conformable. The lower contact with the Starlight Evaporite Member is placed at a lithological and faunal change between the two members. The upper contact with the Winnifred Member is conformable and is placed at a prominent lithologic change between the two members.

Winnifred Member

A homogeneous assemblage of strata consisting of resistant to slightly recessive, medium- to thick-bedded, yellow to dark grey weathering, sandy to silty dolomite and limestone comprises the Winnifred Member. Intercalated beds of collapse breccia, "shale," and phosphatic quartzose sandstone occur sparingly in the thicker sections within the area. Dolomite is the dominant lithologic type. Locally, in the western sections it is very quartzose and phosphatic; in the eastern regions it is thick to medium bedded, and commonly displays a mottled coloration. Limestone, commonly rich in quartz, forms the second most abundant lithologic type within the member. The quartz content locally approaches 50 per cent of the rock. Sandstone, forming a small part of the total assemblage, is concentrated in the western part of the study-area. The sandstone beds are usually cemented with calcite, and rarely with dolomite. They are poorly indurated and recessive. "Shales," sparingly distributed in the member, are actually sandy to silty, argillaceous, fissile dolomites. Small amounts of solution breccia are found in a "red bed" facies of some western sections. These breccias differ from those of the Starlight Evaporite Member, commonly being a reddish brown with locally small amounts of green and yellow. Such colours generally are not found in the Starlight Evaporite Member, with the exception of the exposure on Fiddle River (Fig. 2).

The Winnifred Member ranges in thickness from a maximum of 735 feet at Dinosaur Pass, to a minimum of 9 feet on Wildhay River near Rock Lake (Fig. 2). Despite the thickness recorded in the west, pre-Jurassic erosion is suggested by a phosphatic, sandy, quartzose conglomerate at the top of the member. The thicker sections appear to be confined to the Colin Thrust Sheet (*see* Mountjoy, 1962, p. 49 for location) but exact thickness relations of the member in the adjoining thrust sheet tc the west are masked by the Chetamon Thrust Fault, which truncates the upper part of the member.

The Winnifred Member is overlain unconformably in all sections by either the Nordegg or the Rock Creek Member of the Jurassic Fernie Formation. It is overlain in the central and western region by a phosphatic, quartzose, chert-pebble conglomerate, from 2 inches to 2 feet thick. The strata overlying the conglomerate consist of slightly silty carbonaceous limestone, with small amounts of interbedded black, fissile shale typical of the Fernie Formation. This conglomerate was not observed east of the Persimmon, Starlight, and De Smet Ranges, although a marked lithologic contrast exists. The lower contact is everywhere conformable and distinct.

PETROLOGY

Descriptive Mineralogy

Most stratigraphic and petrologic research in the Triassic System of western Canada has been confined to the Peace River district of northeastern British Columbia, by such workers as Pelletier (1960, 1961, 1963, 1964), Clark (1961), Goruk (1963), and Colquhoun (1960, 1962). In west-central Alberta, Shafiuddin (1960) made a petrologic study of two Triassic sections at Banff and Cadomin, and Govett (1961) undertook a study of the gypsum deposits in Alberta, including the deposit at McDonald Gulch (Fig. 2). A synthesis of all published Triassic stratigraphic and some petrologic information in western Canada, including information on the current study-region, was made by Barss, *et al.* (1964). This summary included information gathered up to the end of 1962. The present study provides additional data not available from previous stratigraphic and petrologic investigations in the Athabasca–Smoky River region of Alberta.

The detrital and chemical mineralogy is similar for all members in the Triassic succession of the region, differing only in the relative proportions present at various locations within the formations and members. Two of the most common and important minerals are quartz and carbonate; their relationship is discussed in detail. The next group considered is the accessory minerals. These generally form less than 10 per cent of the total composition of each sample. The final discussion concerns three of the more important and interesting rock types in the Triassic assemblage: collapse breccias, gypsum, and phosphate-bearing rocks.

Standard field classifications of sedimentary rocks were followed throughout the study, with the exception of the carbonate rocks, for which a more detailed classification proposed by Wolf (1963) was adopted. This classification applies only to carbonates examined in thin section.

Quartz

The most common terrigenous detrital mineral observed in the Spray River Group is quartz. This comprises on the average, 80 per cent of the detrital population. In the Sulphur Mountain Formation grain sizes generally range between 0.02 and 0.50 mm, with an average of about 0.06 mm. This average value causes difficulty in classifying the rock, because it is close to the sand–silt boundary of the Udden size classification (Pettijohn, 1957, p. 18). Results based on visual examination of many thin sections indicate that quartz grains of the Sulphur Mountain Formation display a unimodal frequency, whereas those of the Whitehorse Formation appear to have a bimodal frequency distribution. The grain diameters in the Whitehorse Formation are more variable and reflect a wider range of lithologic types. The average diameter of the quartz fraction is approximately 0.070 mm. As noted, the quartz generally displays a bimodal size distribution, with one mode between 0.050 and 0.070 mm, the other ranging from 0.150 to 0.175 mm. The lower size range is most prevalent.

Most grains are subangular to angular, with some in the Whitehorse Formation classed as subrounded to well rounded. Because of the smallness of the grains and the occurrence of quartzitic textures (Pl. I B), it was not possible to obtain quantitative roundness estimates. The pronounced angularity of the quartz grains in the Spray River Group, and in particular the Sulphur Mountain Formation (*see* Pl. I G, H), is considered a function of size, rather than a product of transport distance and sedimentary reworking. The quartz is characterized by straight or slightly undulous extinction and is commonly free of obvious solid inclusions except for rare occurrences of apatite, mica, and pyrite. These petrologic relationships suggest that most of the quartz found in the Triassic rocks of the region would be classed as "common" or "plutonic" quartz (Folk, 1964).

Microcrystalline quartz or chert, rarely exceeding 1 to 2 per cent by volume, occurs throughout the succession but its concentration is highest in the Whitehorse Formation. It occurs as subangular to well-rounded grains, lenses, nodules, and as cement in some of the granular phosphate facies of the Whitehorse Formation.

Common characteristics of the detrital quartz fraction are authigenic overgrowths and quartzitic textures; the former are particularly abundant in the Whitehorse Formation, the latter in the Sulphur Mountain Formation (*see* Pl. II A, B, C, D). Quartz overgrowths are well developed in the quartz sandstone facies, in contrast with sandy carbonate facies of the Whitehorse Formation. Two types of overgrowths have been noted: the first occurs as euhedral outgrowths from a well-rounded detrital core into a carbonate cement or empty void (Pl. II A, B, C); the second consists of an irregular to well-rounded rim of quartz, separated from the parent grain by a "dust rim" that generally consists of small opaque minerals and liquid inclusions usually less than a micron in diameter (Pl. II D). All overgrowths are in optical continuity with the host grain. The silica forming the overgrowths was probably derived from the solution of very fine quartz grains originally present as matrix.

Another interesting and prominent feature of the quartz fraction is the serrated outline of the grains as seen in thin section (Pl. II D, E, F). The serrated edges are best displayed on grains smaller than 100 microns, although they occur to a lesser degree on grains exceeding 200 microns. The serrated grains are commonly cemented with fine to medium crystalline dolomite. As the illustrations show (Pl. II D, E), the serration is mostly the result of epigenetic replacement by a carbonate mineral. However, serrated or corroded outlines may result from other processes. Carozzi (1960, p. 18), reported that serrated or frosted grains may result from incipient crystal growths. Also, Glover (1964) observed corroded or serrated edges in some carbonate-cemented sandstones, but upon detailed microscopic examination using a universal stage, concluded that the irregular surface phenomena were due to thin section manufacture and grain orientation. Many of the apparently corroded grains were damaged euhedral authigenic overgrowths. Evidence seeming to support the carbonate replacement hypothesis in the Triassic strata is: (1) the general occurrence of serrated edges on many of the small angular and large well-rounded grains; (2) the partial or complete replacement of overgrowths, together with the partial replacement of the parent grain; (3) the occurrence of carbonate-filled, V-shaped indentations penetrating grain boundaries; (4) the presence of small, remnant quartz grains surrounded by dolomite more coarsely crystalline than the enclosing carbonate cement; (5) the occurrence of "frosted" grains in some insoluble residue samples of the Whitehorse Formation—a feature considered evidence of subaqueous solution or carbonate corrosion, in contrast with the commonly accepted eolian origin; and (6) the common occurrence of quartzitic textures and secondary overgrowths in the carbonate-cemented siltstones of the Sulphur Mountain Formation. This phenomenon could be evidence of precipitation and redeposition of silica that was originally derived from the replacement of quartz grains by carbonate under different environmental conditions. Some of the quartz serration in the finer size-fraction is thought by the writer to be attributable to thin section preparation, and to the effect of optical illusion (Folk, 1964, p. 67). However, owing to the large amount of serration of the entire detrital fraction found throughout a thick stratigraphic succession, corrosion and replacement appear to be the most likely explanation of the textures observed. Recent investigations by Walker (1957, 1960), Carozzi (1960), Siever (1962), Peterson and von der Borch (1965), and Sharma (1965), have demonstrated that carbonate replacement of quartz can and does occur under modern environmental conditions, and furthermore is probably far more common in ancient sedimentary deposits than previously acknowledged.

The large quartz content, in relation to other detrital minerals, indicates that most quartz has originated from a pre-existing sedimentary sequence, possibly from the sedimentary quartzites of the Ishbel Group.

Carbonate

Carbonate minerals form the most abundant mineral group by volume in the Triassic sequence. They occur mainly as dolomite and calcite, with possible traces of siderite. Most carbonate minerals observed in the study were recrystallized to such a degree that few original textures and structures were preserved. Classification following microscopic examination was based on that proposed by Wolf (1963) for limestones and dolomites (Table II).

TABLE II *Carbonate classification used in microscope study (modified after Wolf, 1963)*

CALCITE			DOLOMITE	
Authigenic Constituents	Recrystallized or Grain Growth Constituents	Size	Authigenic or Replacement Constituents	Recrystallized or Grain Growth Constituents
Sparite	Pseudosparite	>0.02 mm	Dolosparite	Pseudodolosparite
Microsparite	Pseudomicrosparite	0.02 mm to 0.005 mm	Microdolosparite	Pseudomicrodolosparite
Micrite	Pseudomicrite	<0.005 mm	Dolomicrite	Pseudodolomicrite

GSC

Dolomite, occurring mainly as cement, forms the dominant carbonate mineral of the succession. Four main types were recognized. The first and most common variety was microdolosparite, consisting of grains and crystals ranging from 5 to 20 microns, and averaging 10 microns in diameter. It commonly occurs in the upper part of the Winnifred Member (Pl. I D) as small, euhedral crystals, often stained and coated by carbonaceous or pyrobitumen residues. This texture, restricted to the Winnifred

Member, consists of two stages of recrystallization and replacement. The first stage involved dolomite replacement or crystal growth of the euhedral carbonate rhombs. The second stage followed with the replacement of calcite by dolomite, which now forms the dominant cement. Dolomicrite is the second type, and is commonly confined to the Winnifred Member of the Whitehorse Formation. However, it also occurs as intercalated beds in the gypsum deposits of the Starlight Evaporite Member. The third type observed was dolosparite, which occurs as cement in the "red bed" facies and collapse breccias of the Starlight Evaporite Member. It consists of an interlocking, subhedral mosaic, exhibiting sharp rhombic outlines. The last type is dolithite (Folk, 1959), which consists of well-rounded grains or fragments ranging between 0.10 and 0.20 mm in diameter. These are generally confined to the Whitehorse Formation, and occur as "ghost-like" spherical grains or elongate pellets.

All dolomite observed in this study is considered to be of secondary origin, having replaced calcite or aragonite. However, because of its fine crystalline nature and fine grain size, and intimate association with evaporitic sequences, the dolomicrite has in some instances been considered as primary in origin (Weber, 1962). The general opinion among many geologists, however, is that primary dolomite does not occur in nature. Recent studies by Gwinn and Clack (1964) have shown examples of dolomite that probably replaced calcite immediately after deposition.

Three varieties of calcite were observed: pseudosparite, pseudomicrosparite (Table II), and detrital organic fragments. It occurs sparingly throughout the Sulphur Mountain Formation, but is present in large amounts in the Whitehorse Formation, particularly in the Starlight Evaporite and Brewster Limestone Members. The most common variety of calcite is pseudomicrosparite, a cementing mineral composed of an interlocking mosaic of crystals averaging 0.01 mm in diameter. Twinned pseudosparite showing good cleavage also occurs as cement, but is generally confined to the collapse breccias of the Starlight Evaporite Member. The third variety occurs as conspicuous detrital organic fragments in various conditions and stages of preservation. These rarely exceed 1 mm in diameter, and most fragments are about 0.50 mm. Well-rounded and elongate pelletoid grains, ranging in size from 0.10 to 0.30 mm, were frequently observed in the Brewster Limestone Member.

Feldspar

Feldspar constitutes about 5 to 10 per cent of the total grains observed, and occurs as three varieties. The most commonly observed feldspar, orthoclase, ranges in concentration from 1 to 14 per cent of the mineral suite, and averages 8 per cent by volume. Plagioclase, with a composition in the albite–sodic oligoclase range, forms the next most abundant variety, although it never exceeds 1 per cent of the grains observed. The last variety consists of microcline which, like plagioclase, constitutes less than 1 per cent of the mineral suite. The feldspar is subangular to subrounded, displays a "quartzitic texture" in part, and has an average diameter generally smaller than the average diameter of the accompanying quartz grains. Most of the feldspar grains exhibit serrated grain boundaries, suggesting carbonate replacement. Overgrowths are not common. However, some grains of microcline were observed in which the grid-twinning was continuous into the overgrowth but did not appear to be in optical continuity with the parent grain. The generally small amount of feldspar suggests either a long period of abrasion, which differentially eliminated or reduced the feldspar content because of its poor durability, or a source area of pre-existing sediments containing little feldspar. The latter explanation is considered to best fit the available evidence when taken in conjunction with other minerals of the clastic succession.

Mica

Mica is a minor but ubiquitous mineral of the Sulphur Mountain Formation, and is sparingly distributed in the Whitehorse Formation. It occurs as conspicuous flakes or grains of muscovite, rare biotite, and possible sericite, in concentrations as much as 5 per cent by volume. The mica averages 0.075 mm in longest apparent dimension and is generally aligned parallel to the bedding and laminations, suggesting a detrital derivation. The amount of mica in the Sulphur Mountain Formation shows a progressive decrease from the base to the top of the formation. This feature suggests a progressive increase in energy conditions during Early and Middle Triassic time.

Clay Minerals

Closely associated with, and related to the micas, are the layered silicates or clay minerals. They are generally confined to the siltstones and shales of the Sulphur Mountain Formation. A few random samples from the Sulphur Mountain Formation were prepared for analysis by an X-ray diffractometer. The results indicated the presence of three clay mineral groups which are, in order of decreasing abundance, illite (2:1 layered silicate), kaolinite (1:1 layered silicate), and chlorite (2:2 layered silicate). The largest clay mineral concentration was recorded from samples of the Phroso Siltstone Member, and the smallest concentration from samples analyzed from the Vega Siltstone Member. Because of the masking effect and intimate association of organic carbonaceous matter and opaque ferruginous minerals, quantitative or qualitative microscopic identification was not possible.

Collophane

A varietal designation within the apatite group of minerals, collophane is a common although generally quantitatively insignificant mineral throughout the Triassic rocks of the Athabasca–Smoky River region. It is prevalent, however, at one or two horizons within the Winnifred and Whistler Members where it occurs in beds as much as 6 inches thick, of granular, cherty phosphate. It is usually light to dark brown, and yellowship brown in thin section, but appears as black, bituminous grains and nodules in outcrop. Because of its cryptocrystalline size, collophane is generally isotropic in thin section; it may show a weak birefringence due to strain, as was noted in some of the fossil shell fragments. Under microscopic examination five distinct forms were recognized: (1) well-rounded, ovoid pellets; (2) well-rounded and concentrically banded pellets and grains with cores or nuclei of quartz, feldspar, pyrite, and carbonate minerals (Pl. III); (3) elongate shreds or banded shell fragments, derived from lingulid and orbiculid brachiopods; (4) irregular replacement patches or blebs in which the collophane is present as a replacement of carbonate or is itself a direct precipitate; and (5) organic fragments in which collophane has replaced calcite or aragonite.

All grains, pellets, oölites, and organic fragments are well sorted and are as much as 500 microns in size, but average approximately 100 microns.

The general nature and mineralogical associations of the collophane, such as the large size, oölitic nature, abraded pelletoid grains and shell fragments, and its ability to coat presumed shallow-water detrital grains, suggest that the mineral formed under shallow-water conditions. Bushinski (1964) has proposed a source and mechanism by which phosphates are deposited under shallow-water conditions. The phosphate in the Triassic succession of the Athabasca–Smoky River region may have had a similar genesis, because types and structures suggested and illustrated by Bushinski closely resemble those described by the writer. Briefly, this genesis would imply the inflow of water from rivers containing a large amount of phosphorus in solution, and by upwellings from deeper parts of the sea. The dissolved phosphorus would then be concentrated by organisms which on dying would fall to the seafloor, and upon decomposition would be dispersed in the sands and silts of local basins. The phosphate would later become associated with pellets, oölites, concretions, cement, and various pseudomorphs, by normal sedimentary processes, and by later diagenetic and epigenetic replacement. The occurrence of collophane in the lower members of the Sulphur Mountain Formation suggests deposition in a shallow-water, but restricted depositional environment. Similarly, shallow-water deposition is suggested for the Winnifred Member, because of the contained phosphate and associated ripple-marks and crossbedding.

Gypsum

Allan (1933) first recorded gypsum in a deposit near the headwaters of Mowitch Creek (Fig. 2). Since then, several additional Triassic occurrences have been discovered in the Athabasca–Smoky River region. The writer noted five local occurrences within the study-area. These occur at Brewster's Wall, Sulphur Mountain, Monoghan Creek, Corser Gulch, and McDonald Gulch (Fig. 2). Other small deposits in the region not examined by the writer are listed by Govett (1961) and Mountjoy (1962, p. 65).

The gypsum and possible anhydrite occur as beds averaging 1 foot to 2 feet, but ranging up to 12 feet thick, as displayed at McDonald Gulch. The gypsum deposits are generally lenticular, and can rarely be traced from section to section. An exception occurs in the Starlight Range at McDonald Gulch and Corser Gulch, where gypsum can be traced along strike for 2 miles. Thin, regular to lenticular, dense, light grey, vuggy dolomite, with some calcareous sandstone beds, are intercalated with the gypsum in the thicker deposits. The gypsiferous facies, being incompetent, is susceptible to tectonic disturbance.

Gypsum occurs as fibrous to prismatic crystals as much as 800 microns long and as small irregular grains. In general, it forms a "felted" interlocking mosaic, intimately associated with recrystallized dolomite. In the thicker deposits it is relatively pure, but contains scattered grains of quartz, weathered authigenic pyrite, and dark red hematitic patches similar in composition to some of the fragments or clasts in the collapse breccias of the Starlight Evaporite Member. The gypsum is white with occasional red and pink tinting. White, "sugary" to crystalline gypsum is frequently observed filling small vugs, pores, and fractures in the associated beds of dense dolomite. In some thin sections gypsum is seen to closely resemble microcrystalline quartz or chert. This feature is attributed to the thinness of the sample slice, which causes the gypsum to approximate the birefringence of chert. Govett (1961, p. 16) reported the occurrence of cherty limestone beds in the gypsum deposit at McDonald Gulch. However, detailed field and microscopic examination of the gypsum and associated beds showed no chert and little limestone in the section. Govett may have mistaken gypsum for chert.

Opaque Minerals

The opaque mineral suite consists of organic carbonaceous matter, authigenic pyrite, pyrobitumen residue, and hematite associated with "red bed" facies. Pyrite is the most abundant mineral of the group and occurs as irregularly formed microaggregates and rare cubes. It is present in concentrations of as much as 10 per cent, but the average is 1 to 2 per cent by volume. This mineral is most common in strata of the Sulphur Mountain Formation, and particularly in the Phroso Siltstone Member. Laminations containing a large amount of pyrite have been observed as much as half an inch thick, and traceable for horizontal distances as much as 100 feet. Carbonaceous matter is found associated with pyrite and clay minerals, but does not exhibit any particular size or shape; it generally coats other grains or serves as matrix. The carbonaceous matter is most prevalent in the lower members of the Sulphur Mountain Formation and the upper part of the Winnifred Member in the Whitehorse Formation. Black, opaque pyrobitumen residues occur in a few samples from the top of the Winnifred Member in some of the eastern sections. These residues appear as fillings in vugs and pores and as a mottling in some of the dense microdolosparite rock specimens. Hematite occurs as a reddish brown mineral associated with all the "red bed" facies of the Whitehorse Formation. It coats terrigenous grains and fills small pores and voids. The ferric oxide is postulated to have originated mainly as a result of post-depositional alteration of iron-bearing minerals under the influence of a hot dry climate. Evidence supporting this origin is supplied by the close association of the "red beds" with collapse breccias and gypsum beds.

Miscellaneous Minerals

This group comprises the "heavy minerals", none of which exceeds 1 per cent of the total mineral suite. It includes zircon, tourmaline, apatite, and rutile. The mineralogy of the group is generally the same throughout the Triassic sequence, although differences in concentration occur. Zircon, the most commonly observed mineral of the group, varies from clear to faint shades of pink, and ranges in size from 35 to 150 microns. The average size is estimated at 60 microns. Tourmaline represents the second most abundant mineral of the group and averages 15 to 20 per cent by volume. Colours or varieties noted were, in order of abundance, yellowish green, dark green, and reddish brown. The grains are generally equidimensional to elongate, well rounded, and occur in the same size range noted for zircon. Rutile occurs as yellow, subrounded grains, sparingly distributed throughout the succession. Apatite occurs as authigenic, elongate, colourless crystals in the carbonate cement, and as small inclusions in detrital grains of quartz and feldspar.

Shafiuddin (1960) used tourmaline to correlate and determine the provenance of the sediments of the Spray River Group in the Banff–Cadomin area of Alberta. He concluded that the tourmaline concentration increased rapidly at the expense of zircon near the base of the Whitehorse Formation, and furthermore, that the base of the Whitehorse Formation was older at Cadomin than at Banff. He based his conclusion on the tourmaline–zircon frequency. The writer's visual comparisons of the Athabasca–Smoky River material, with estimation standards, did not suggest any orderly trend in tourmaline or zircon concentration.

Collapse Breccia

Collapse or solution breccias (Pl. V) are a diagnostic feature of the Triassic strata in most regions of Alberta and parts of northeastern British Columbia. The breccias are confined to two homotaxial formations. In Alberta they are found in the Whitehorse Formation whereas in the Peace River region of northeastern British Columbia they are confined to the subsurface Charlie Lake Formation.

The breccias, restricted largely to strata of the Starlight Evaporite Member, are characterized by conspicuous angular clasts and blocks, ranging from a quarter inch to blocks 3 feet in greatest apparent diameter. The average size ranges from half an inch to an inch in diameter. The clasts vary from light to dark grey, to yellow, ochre, and reddish brown. Macroscopic fragments commonly constitute between 10 and 20 per cent of the rock. Four distinct clast types have been recognized in the facies of the Athabasca–Smoky River area: (1) The most common is angular, yellow-orange, and consists of ferruginous, argillaceous, quartzose, sandy limestone, and dolomite. It is poorly indurated, and has a cement composed of clay, minor gypsum, and recrystallized "granular" carbonate. These clasts are seldom preserved in thin section because of loss during manufacture. (2) The second type consists of equicrystalline, slightly iron-stained, recrystallized calcite, with local concentrations of quartz sand and silt. Generally, these breccia fragments are poorly consolidated, owing to the "granular" or sucrose nature of the calcite. In hand sample, they are grey to yellow-grey. (3) Limonite-stained, equigranular, pseudomicrite and dolomicrite comprise the third clast type. The size range is in the upper limit of the class (Table II). (4) The last type consists of ferruginous, micaceous, quartzose, recrystallized, "granular" calcite. It is generally laminated, with the laminae outlined by mica and iron minerals. In hand specimen the clasts are yellow-orange to ochre, similar in appearance to the first clast type discussed. All gradations of the four basic types were observed in the facies.

The matrix consists of smaller breccia clasts, averaging 0.35 mm in diameter, and sand- to silt-sized authigenic and detrital grains. The authigenic and detrital fraction consists of quartz and minor amounts of orthoclase feldspar, ranging in size from 0.035 to 0.80 mm. A distinct bimodal distribution is evident, with sizes ranging from 0.035 to 0.106 mm, and from 0.30 to 0.40 mm. The grains of the lower range are angular to subangular, and are severely corroded and replaced by carbonate minerals, whereas the larger grains are well rounded and display only a slight degree of carbonate corrosion. The detrital grains are generally inclusion free, except for some quartz grains containing fine needles of rutile. The cement consists mainly of pseudosparite and pseudomicrosparite (Table II) and rarely, euhedral crystals of dolomite. The "granular" nature of the cement indicates that it has undergone recrystallization. The colour varies from light grey to yellow-grey, to red and green. The last two colours are generally, but not always, confined to occasional breccias found in the Winnifred Member. Under microscopic examination it is difficult to differentiate some of the breccia fragments from the enclosing cement. However, a slight but perceptible difference can be observed between the degree of crystallization of the fragment and the cement.

The solution breccia is usually interbedded with sandy to silty limestone, dolomite, and minor amounts of sandstone, all of which resemble some of the clast types in the breccia facies and suggest a local derivation for the breccia clasts. Another characteristic of the breccia facies is the lack of collophane and pyrite, two minerals observed throughout the Triassic succession. The lack of heavy minerals and organic fossil fragments is particularly evident. This feature may be attributed to the postulated evaporitic environment.

Based on the nature and size of the clasts, the condition and type of matrix and cement, and the close association to gypsum deposits, the following hypothesis is presented to explain the genesis of the collapse breccias. With the encroachment of evaporitic environmental conditions, gypsum or anhydrite was deposited as lenses and thin beds of varying thickness, ranging from a few millimetres to lenses as much as 2 feet thick. Interbedded with the gypsum were thin beds of limestone, dolomite (in some places sandy to silty), and rarely, calcareous sandstone and siltstone. After deposition of the gypsiferous layers, evaporitic conditions were replaced temporarily with a return to normal shallow-water deposition in which normal carbonate minerals and calcareous sandstones were deposited. The area was then intermittently subjected to local uplift or marine regression, permitting exposure, oxidation, and partial induration of the sediment. During periods of normal marine conditions, solution of gypsum and subsequent collapse of the overlying bed would occur. The climate was probably arid, and little solution would have occurred during periods of emergence. Upon return to evaporitic conditions, the cycle was repeated. Under prolonged evaporitic conditions, thicker gypsum deposits would result which, upon return to normal marine conditions, might or might not be dissolved, depending on their thickness and on the variations in sediment cover. The yellow weathering nature of the fragments suggests subaerial exposure which permitted oxidation, similar to that now occurring on the tidal flats at Baja California. If gypsum solution had occurred after the complete induration of the sediments, some degree of slumping should be evident in strata overlying the breccia facies. This feature has not been observed in the Jasper region. Brecciation, therefore, is suggested as being penecontemporaneous with the deposition and consolidation of associated and interbedded limestones, dolomites, and sandstones. A similar genesis is suggested, assuming correlation of the breccias of the Starlight Evaporite Member with those of the subsurface Charlie Lake Formation of the Peace River district of northeastern British Columbia.

Insoluble Residue Analysis

Purpose

Insoluble residue studies are frequently limited to carbonate rocks because strata composed of essentially terrigenous detritus are generally not amenable to rapid disaggregation, owing to cementation by secondary or primary silica. It was hoped that an insoluble residue analysis of the Triassic rocks in the Athabasca–Smoky River region might help to ascertain clastic associations, current action, sea bottom environment, and adjacent land conditions. Such studies might also assist correlations based on lithologic similarity, and facilitate surface to subsurface correlation in the Athabasca–Smoky River region, as well as in other regions of Alberta and British Columbia. The homogeneous nature of the Sulphur Mountain Formation, with its generally large dolomite content, made it the most suitable unit for a detailed insoluble residue study. The fine-grained and masking nature of the clay–organic–ferruginous content made petrographic trend studies difficult, and generally impossible in samples of the Phroso Siltstone Member.

Procedure

Three part and twelve complete stratigraphic sections were selected to represent all important Triassic localities. Preliminary tests showed that complete disaggregation by means of acid digestion was not possible, owing to secondary silicification and a quartzitic texture. Consequently, all samples had to be crushed and pulverized. Standard acid digestion techniques were employed. Because of the corroded and carbonaceous-coated nature, the crushed and pulverized condition of the detrital insoluble fraction, and the preparatory time involved in the analyses, it was decided to omit microscopic examination of the insoluble residue. However, thin sections representing the analyzed samples were examined to establish the mineral composition.

The insoluble residue quantitative values were plotted as columnar sections (Fig. 3) to facilitate visual comparisons in outlining vertical variation between members. All values were statistically processed to obtain the mean and standard deviation of the mean of each member throughout the region (Table III). Maps of the area, showing location and mean value of the insoluble fraction of each member in the analysis, are shown in Figures 4 to 8.[1]

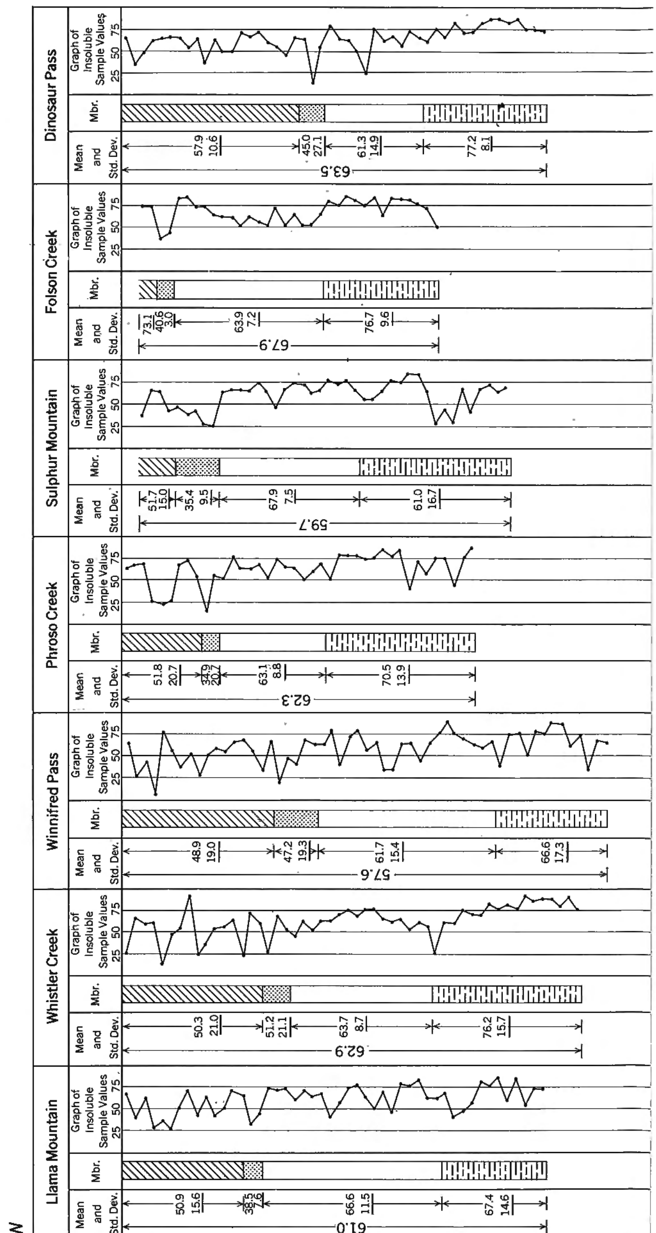
Results and Interpretation

1. Within the Sulphur Mountain Formation the average amount of insoluble residue content indicates an increase in concentration from the Llama Mountain–Sulphur River area, southeast to the Fiddle River region near Athabasca River (Fig. 4). Furthermore, a general increase in the amount of insoluble residue is suggested from west to east across the structural strike of the area. This feature, together with other pertinent stratigraphic data, suggest a shallowing or shoreline area east of the study-region. As in most comparable sedimentation studies, the terrigenous detrital material is generally found to decrease away from the source or provenance area.

2. A similar residue content distribution is suggested for each of the members in the Sulphur Mountain Formation, as shown by the values in the Vega and Phroso Siltstone Members. For example, in the Vega Siltstone Member in the northwest of the study-region, insoluble residue values ranging between 52 and 68 per cent were recorded; whereas to the southeast near Athabasca River, values ranging between 72 and 77 per cent were obtained.

3. Figure 3 illustrates that marked variations in the amount of insoluble residue do not occur across member boundaries as mapped and recognized in the field. This feature may, however, be partly attributable to the large sampling interval used in the analysis. The possibility of using an insoluble residue study as a means of confirming or correlating member contacts in the subsurface may therefore be worthy of further consideration.

[1]The structural complexity of the region precluded a thorough study of the major thrust sheets and consequently accurate palinspastic reconstruction was impossible. All the data maps presented here and the conclusions drawn regarding contemporary sedimentation, must be read with this serious tectonic distortion of the sedimentary picture in mind. For example, Douglas and Norris (*in* MacKenzie, 1965) estimated relative travel and overlap of major fault slices to be at least 10 to 25 miles in an area 50 miles to the southeast, that is tectonically comparable, in many ways, with the area studied for this report.



NW
Llama Mountain
Mean and Std. Dev.
Mbr.
Graph of Insoluble Sample Values
25 50 75
50.9
15.6
38.5
7.6
66.6
11.5
67.4
14.6
61.0
Whistler Creek
50.3
21.0
51.2
21.1
63.7
8.7
76.2
15.7
62.9
Winnifred Pass
48.9
19.0
47.2
19.3
61.7
15.4
66.6
17.3
57.6
Phroso Creek
51.8
20.7
34.9
20.7
63.1
8.8
70.5
13.9
62.3
Sulphur Mountain
51.7
15.0
35.4
9.5
67.9
7.5
61.0
16.7
59.7
Folson Creek
73.1
40.6
3.0
63.9
7.2
76.7
9.6
67.9
Dinosaur Pass
57.9
10.6
45.0
27.1
61.3
14.9
77.2
8.1
63.5

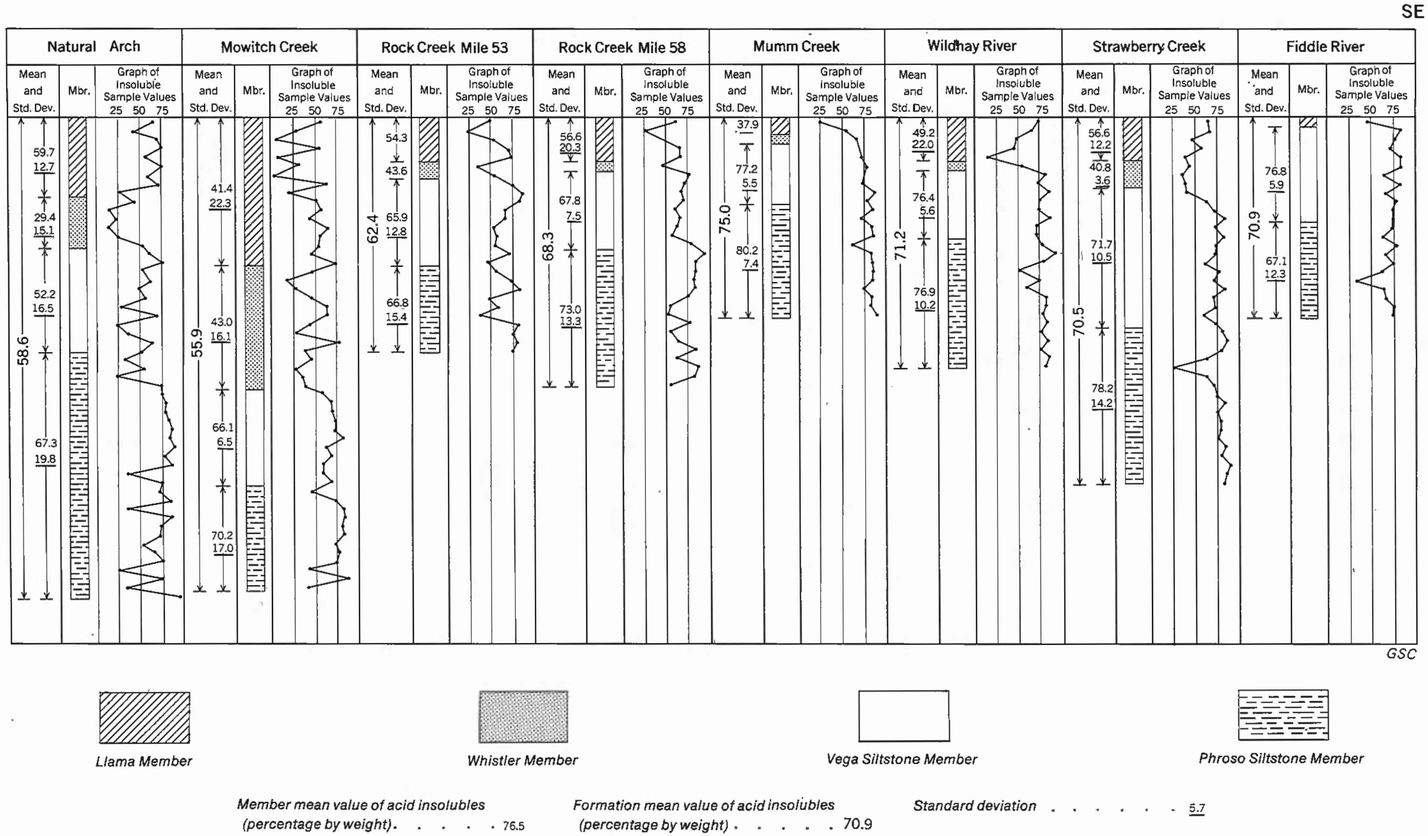


FIGURE 3. Columnar chart illustrating mean, standard deviation, and graph of the insoluble residue fraction from selected samples of the Sulphur Mountain Formation.

TABLE III *Data chart illustrating section location of mean and standard deviation of the mean of insoluble residue fraction of each member of the Sulphur Mountain Formation*

SECTION	MEMBER	NO. SAMPLES	MEAN	S.D.
Fiddle River	P	11	67.1	12.3
	V	11	76.8	5.9
	L	1	0.0	0.0
Strawberry Creek	P	18	78.2	14.2
	V	16	71.7	10.5
	W	3	40.8	3.6
	L	5	56.6	12.2
Wildhay River	P	15	76.9	10.2
	V	8	76.4	5.6
	W	1	0.0	0.0
	L	5	49.2	22.0
Mumm Creek	P	13	80.2	7.4
	V	6	77.2	5.5
	W	1	0.0	0.0
	L	2	37.9	——
Mile 58 Rock Creek	P	16	73.0	13.3
	V	9	67.8	7.5
	W	1	0.0	0.0
	L	4	56.6	20.3
Mowitch Creek	P	12	70.2	17.0
	V	11	66.1	6.5
	W	14	43.0	16.1
	L	17	41.4	22.3
Mile 53 Rock Creek	P	10	66.8	15.4
	V	10	65.9	12.8
	W	2	43.6	——
	L	5	54.3	——
Natural Arch	P	28	67.3	19.8
	V	12	52.2	16.5
	W	6	29.4	15.1
	L	9	59.7	12.7
Dinosaur Pass	P	14	77.2	8.1
	V	11	61.3	14.9
	W	3	45.0	——
	L	20	57.9	10.6
Folson Creek	P	13	76.7	9.6
	V	17	63.9	7.2
	W	2	40.6	——
	L	2	73.1	——
Phroso Creek	P	17	70.5	13.9
	V	12	63.1	8.8
	W	2	34.9	——
	L	9	51.8	20.7
Whistler Creek	P	17	76.2	15.7
	V	16	63.7	8.7
	W	3	51.2	——
	L	16	50.3	21.0
Winnifred Pass	P	13	66.6	17.3
	V	20	61.7	15.4
	W	5	47.2	19.3
	L	17	48.9	19.0
Sulphur Mountain	P	17	61.0	16.7
	V	16	67.9	7.5
	W	5	35.4	9.5
	L	4	51.7	15.0
Llama Mountain	P	12	67.4	14.6
	V	20	66.6	11.5
	W	2	38.5	——
	L	14	50.9	15.6

GSC

Phroso Siltstone Member . . . . P
Vega Siltstone Member V
Whistler Member . . . . W
Llama Member L

Mean value of Insoluble Residue Fraction (percentage by weight) . . MEAN
Standard Deviation of Mean . . . . . . S.D.

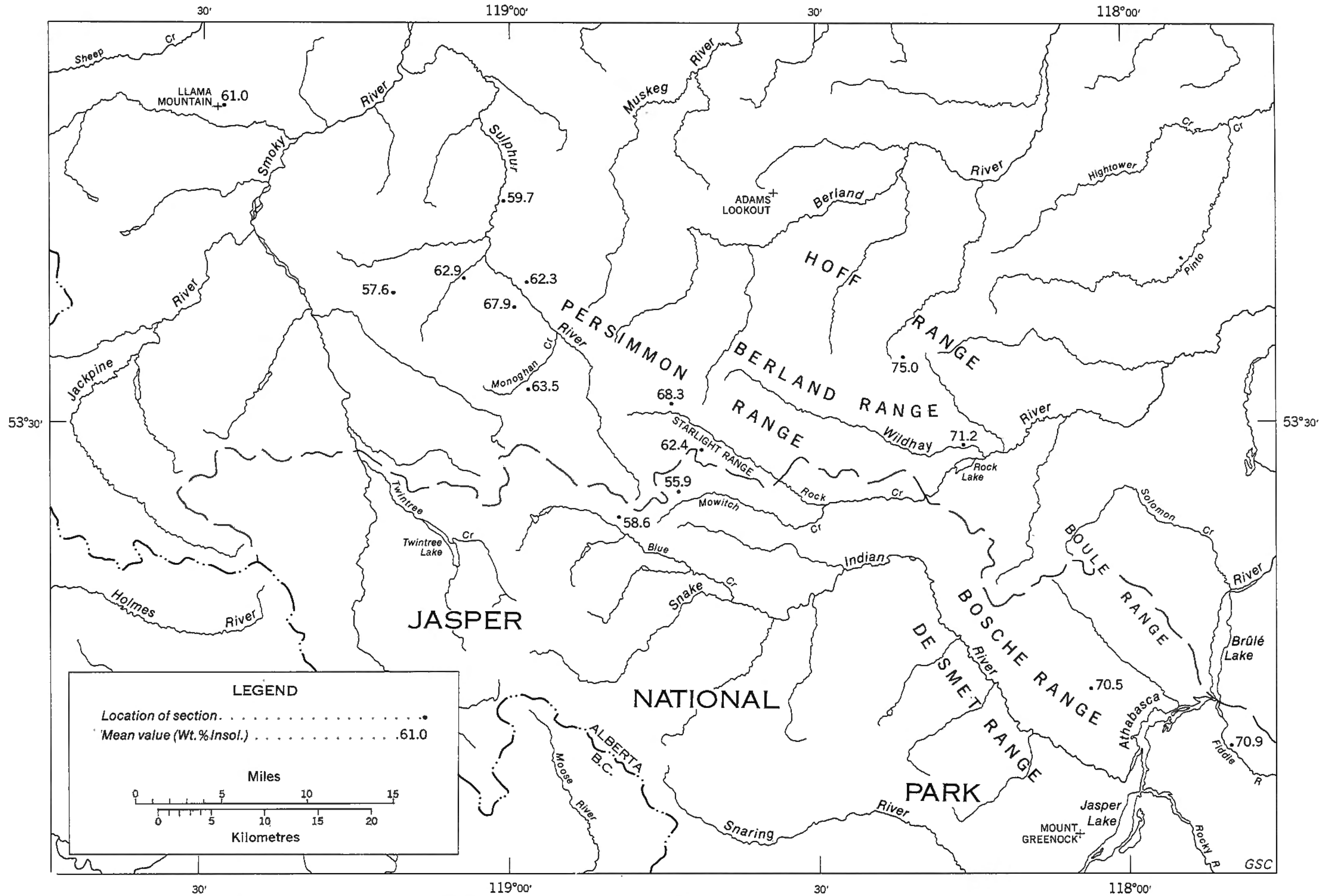


FIGURE 4. Location and mean values of the acid insoluble fraction of the total Sulphur Mountain Formation.

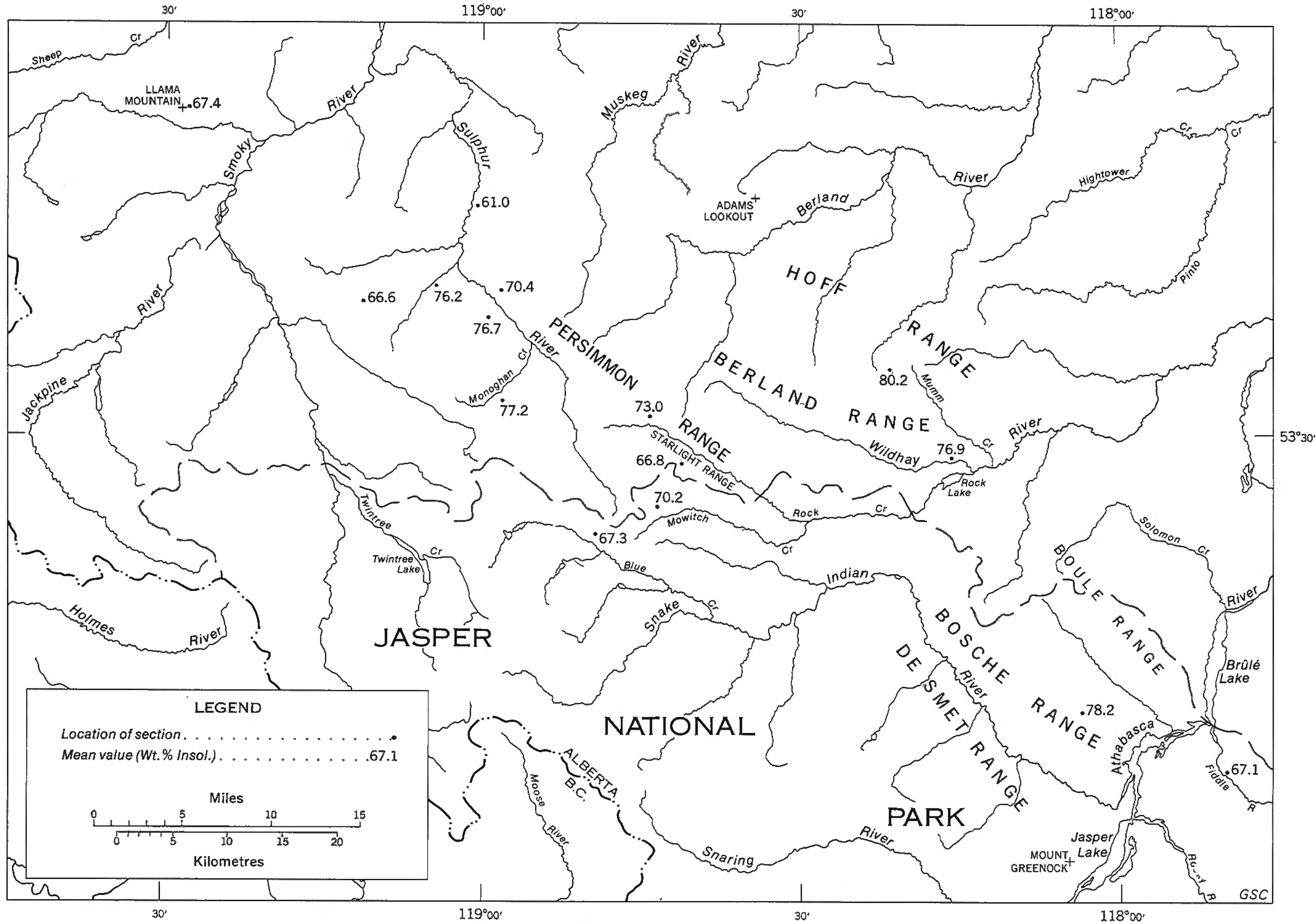


FIGURE 5. Location and mean values of the acid insoluble fraction in the Phroso Siltstone Member, employing data from Table III.

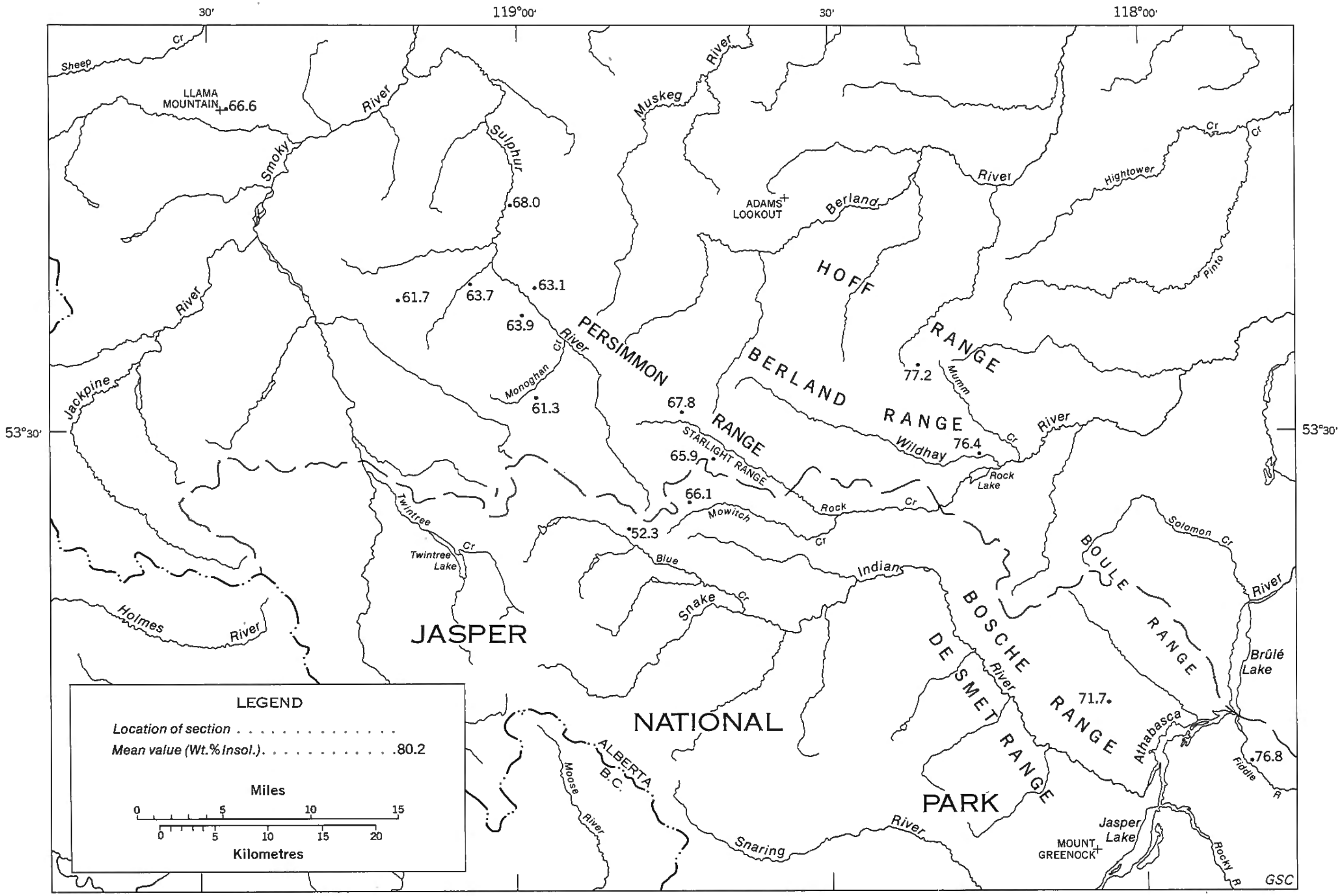


FIGURE 6. Location and mean values of the acid insoluble fraction in the Vega Siltstone Member, employing data from Table III.

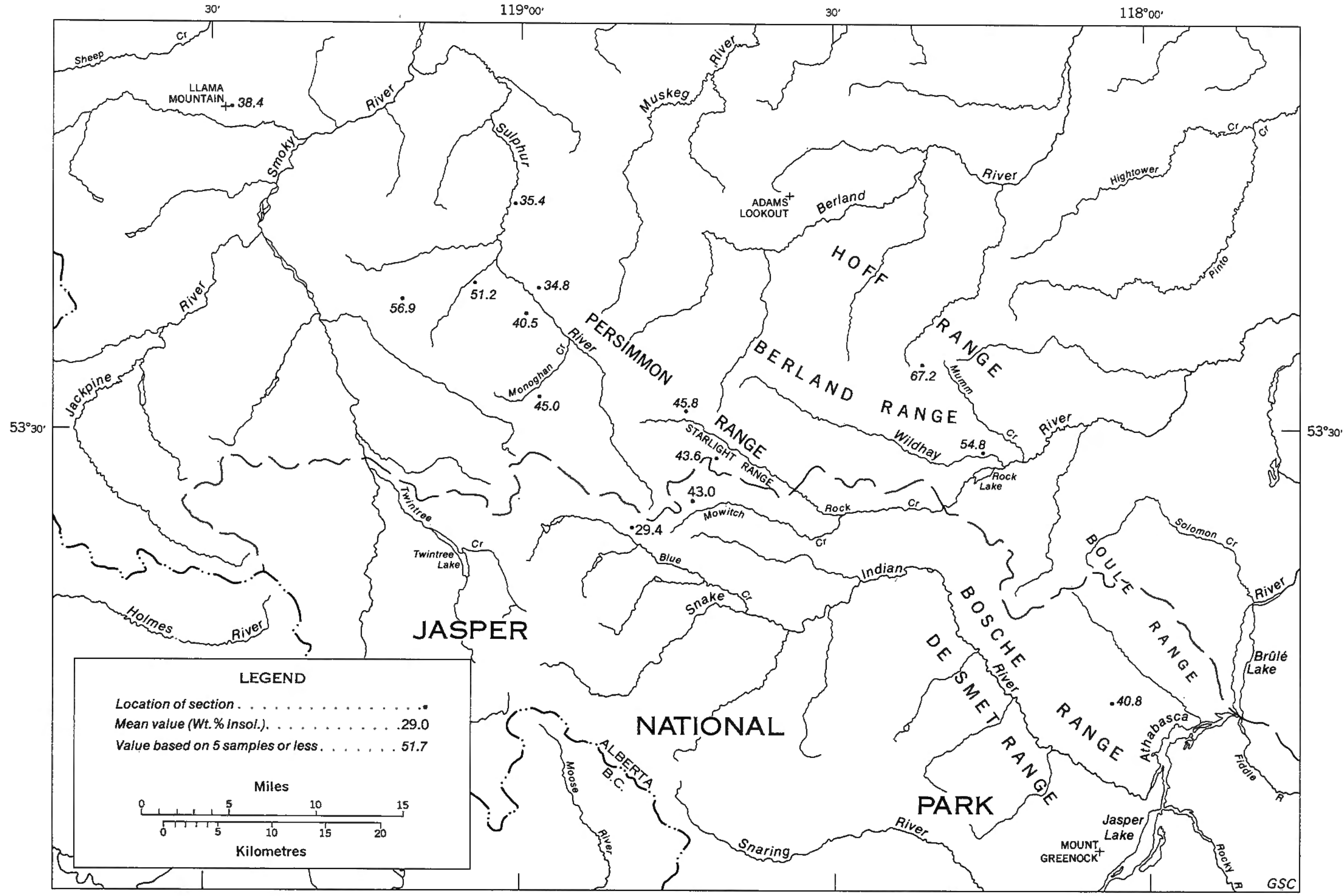


FIGURE 7. Location and mean values of the acid insoluble fraction in the Whistler Member, employing data from Table III.

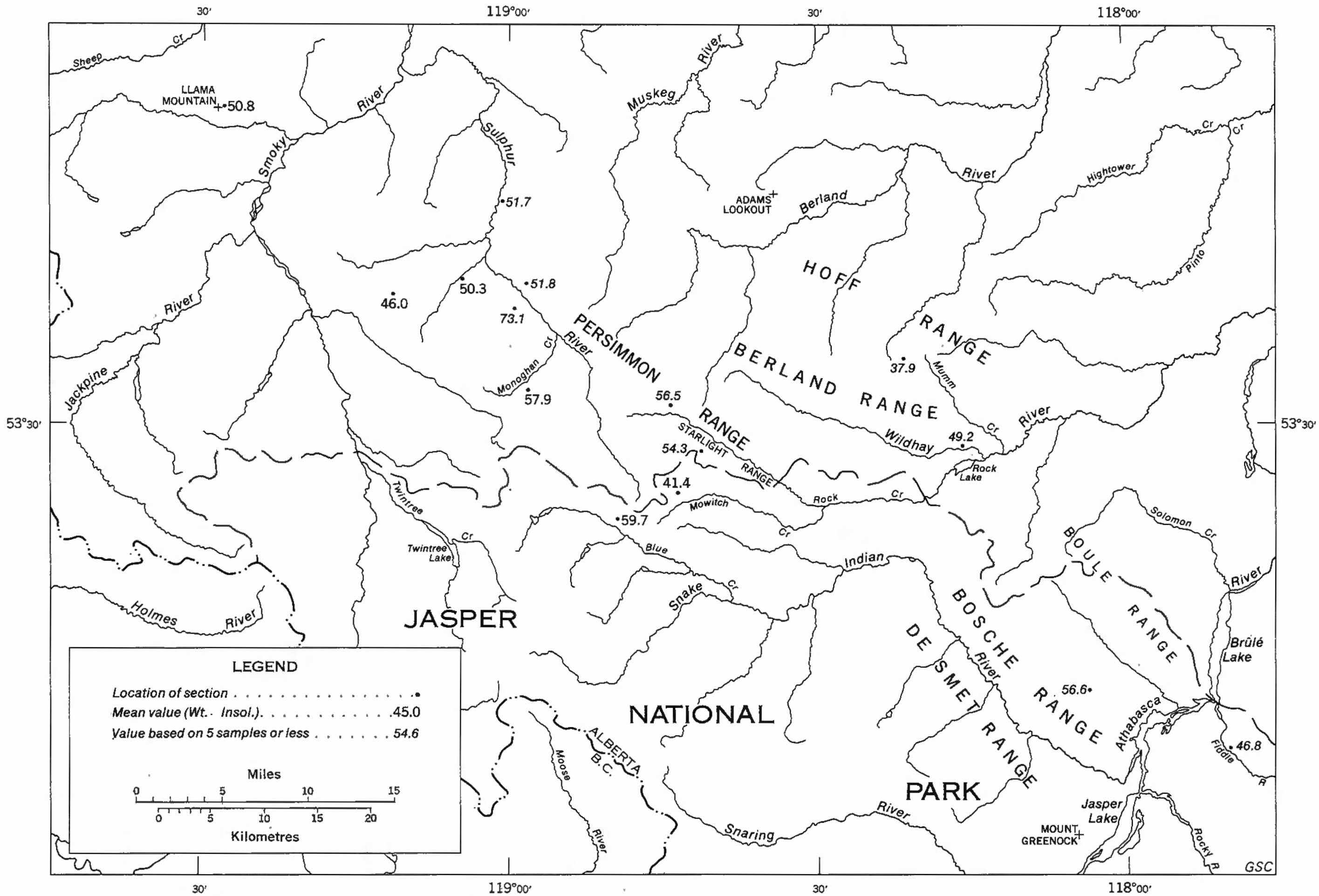


FIGURE 8. Location and mean values of the acid insoluble fraction in the Llama Member, employing data from Table III.

Maximal Grain Size Analysis

Purpose

Grain size analyses have generally been confined to sand-sized sediments because of the relative ease with which they can be examined and analyzed. Conglomerates have also been studied, but to a lesser degree. Grain size and the various measures derived from the statistical analysis of size distributions lend themselves to quantitative expression and can be plotted on maps and contoured. They reflect the energy gradients responsible for transportation and deposition of sand bodies and are therefore important in reconstructing paleoenvironments. The present study was initiated with the hope of solving the problem of establishing sedimentary trends, provenance area, and current transport direction in the Triassic rocks under investigation. Total size analysis studies of the rocks was not feasible because of diagenetic changes.

The idea of maximal grain size analysis was first demonstrated by Pettijohn (1957, p. 249). He suggested that a direct relationship existed between the mean grain diameter of a detrital population and the maximum grain in a sample; that is, the largest class or size measured varied directly with mean grain size of the parent population. Pelletier (1958) and Carozzi (1958) demonstrated this relationship in conglomerates and carbonate oöliths respectively. Similarly, Middleton (1962), using sand-sized grains, measured the maximum diameter of quartz grains in a turbidite sequence, and found a relationship between the coarsest grain diameter and its position within a bed. In almost all observations, the maximum grain size was found to be less at the top than at the base of the bed. The present investigation employed the above techniques, but the study was confined to silt and very fine grained sediments.

Procedure

To study and interpret the results of a maximal grain size analysis accurately it was first necessary to select samples amenable to correlation in the Athabasca–Smoky River region. The Sulphur Mountain Formation was the only such sequence that could be considered reliable, because the overlying Whitehorse Formation is characterized by heterogeneous carbonates and is noted for rapid facies changes within relatively short distances. Standard techniques of disaggregation having failed, a microscopic study of thin sections was necessary. Thin sections were systematically measured using a mechanical stage and eyepiece micrometer. The slides were traversed perpendicular to the bedding in such a manner that 100 grains were measured where possible, or an area of approximately 60 square millimetres was covered. At the start of the work all grains more than 40 microns in diameter were recorded and evaluated. Later, to lessen the effect of the smaller grains, only grains more than 70 microns were measured. All values were recorded and assigned to frequency intervals (Appendix A), and histograms and cumulative curves of the distributions were plotted. Average values were obtained for the 10, 5, and 3 coarsest grains, and plotted on a map of the area. All early work based upon a 40 micron cut-off was recalculated to the 70 micron cut-off, and cumulative curves prepared. From cumulative curves of the various samples analyzed the 20th percentile ϕ values were obtained following the method of Krumbein and Pettijohn (1938), and similarly plotted on a base map of the area.

The 20th percentile in the cumulative curves (Appendix B) was selected because it generally occurred close to a frequency interval containing a consistently high concentration of coarse grains.

Results and Interpretation

The results, as illustrated by Figures 9 and 10 and for all other stratigraphic intervals studied, do not suggest any significant lateral size gradations or concentrations in the region.[1] The only significant size variation recognized in the above experiment is shown by Table IV. The vertical position in the table is the same as that found in the field. A maximal diameter increase and ø decrease occurs above the Whistler Member, suggesting the beginning of a marine regression in the Whistler Member. Furthermore, the upper three values in the table demonstrate that one can readily observe a point or interval of maximum size increase, which may prove useful in defining member contacts in the subsurface.

TABLE IV *The mean Phi values of the 20th percentile, and the mean values of the three largest grain diameters from similar stratigraphic intervals arranged in order of stratigraphic position, demonstrating a prominent vertical grain size increase above interval D*

Interval	Location	Number of Sections Examined Per Interval	Mean Phi Value	Mean Grain Size 3 Largest Grains
A	150 feet above base of Whistler Member	14	3.10	0.155 mm
B	120 feet above base of Whistler Member	16	3.07	0.150 mm
C	20 feet above top of Whistler Member	16	3.10	0.144 mm
D	Top bed of Vega Siltstone Member	4	3.64	0.092 mm
E	20 feet below base of Whistler Member	3	3.77	0.082 mm
F	180 feet above Phroso Siltstone Member	3	3.90	0.071 mm
G	80 feet above Phroso Siltstone Member	4	3.80	0.085 mm
H	50 feet above Phroso Siltstone Member	4	3.79	0.082 mm
I	20 feet above Phroso Siltstone Member	4	3.63	0.096 mm

GSC

Mineralogical Modal Analysis

Purpose

Results of the insoluble residue analysis suggested a west to northwest increase in the carbonate or soluble mineral fraction. The purpose of this investigation was to ascertain if similar and more refined concentration values could be determined from individual point counts. This information would indicate the relative proportions of all minerals comprising any designated sample selected for observation, and would supplement the carbonate and insoluble residue information revealed by the percentage insolubles analysis of the Sulphur Mountain Formation. The Llama Member was selected for study because of its relatively coarse detrital grain size compared with the underlying three members; and because of the relative ease with which the member can be correlated from section to section, thus affording maximum reliability in sample selection from similar stratigraphic positions. The increase in diameter of the detrital content permitted a more rapid means of mineral identification in the microscopic study.

No modal analysis of the Whitehorse Formation was attempted because of its large carbonate content and the rapid facies changes in two of the three members. These attributes were considered more important than the much clearer thin sections of the Whitehorse Formation owing to the lack of organic carbonaceous and ferruginous matter.

[1] Sampling problems and the lack of a reliable palinspastic reconstruction of the area, render calculation of a formal statistical trend of dubious geological value.

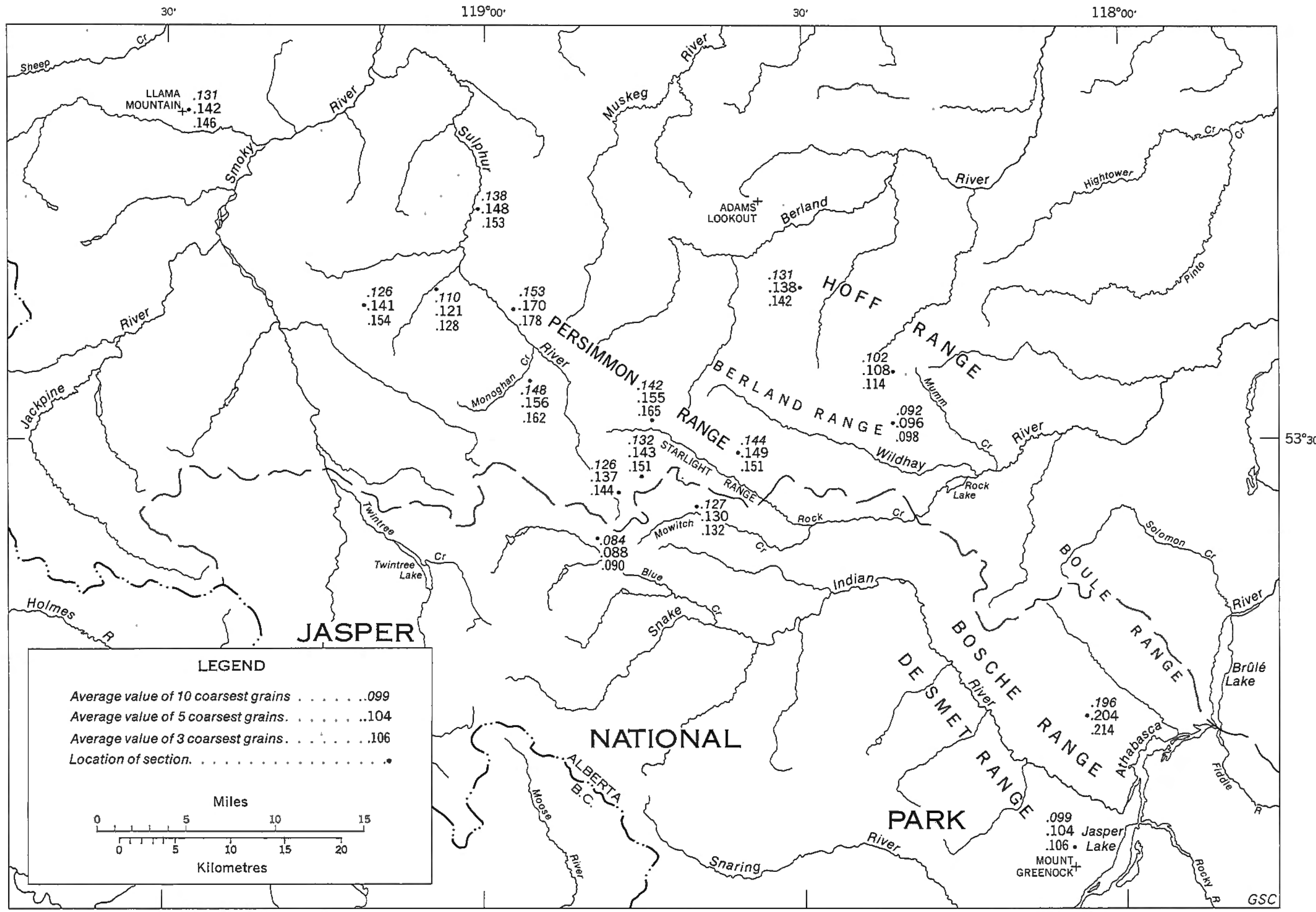


FIGURE 9. Maximal size distribution of average 10, 5, and 3 coarsest grain diameters from the zone 20 feet above the lower contact of the Llama Member.

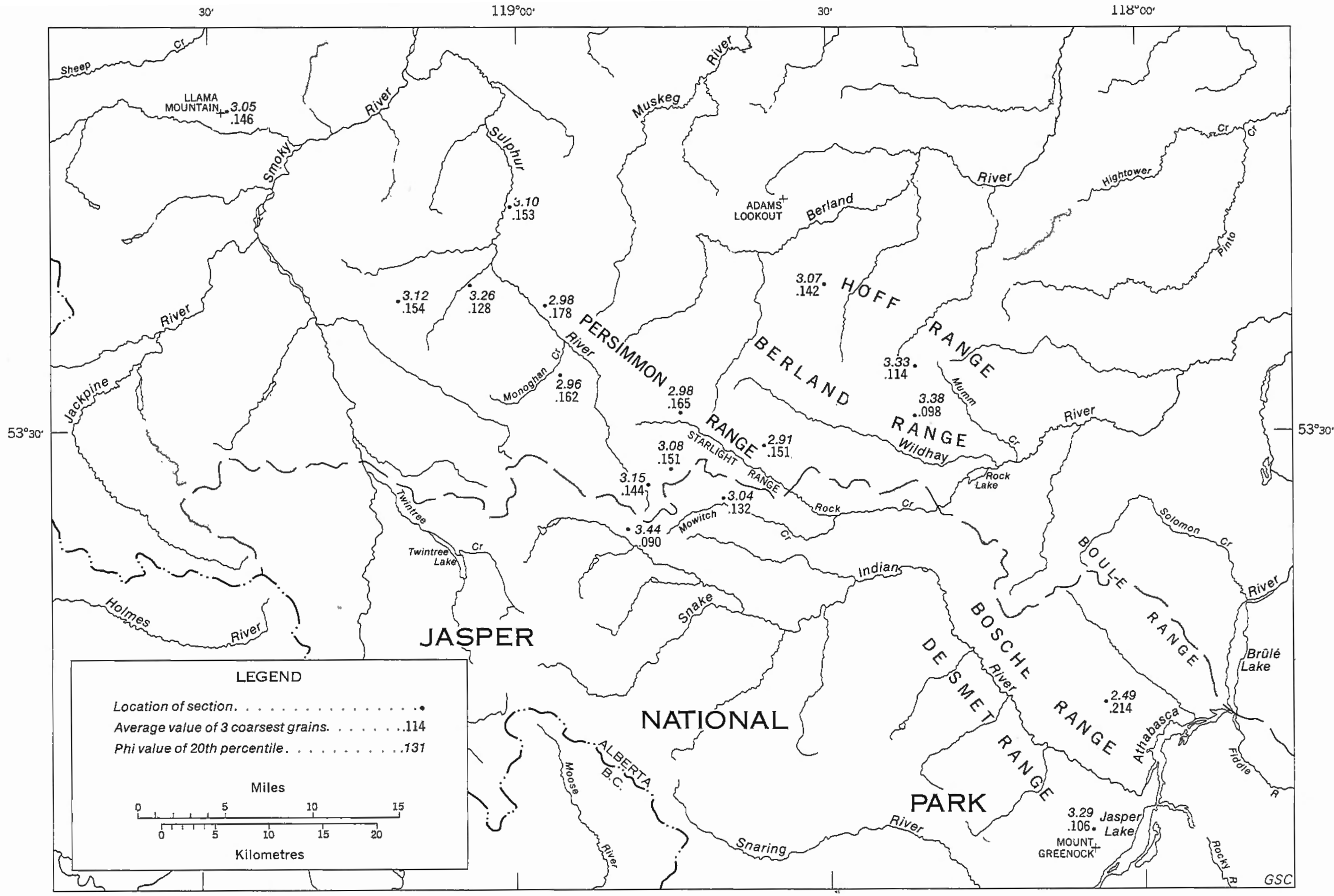


FIGURE 10. Size distribution of 20th percentile Phi values, together with average diameter of 3 coarsest grains, from the zone 20 feet above the lower contact of the Llama Member.

Procedure

Eight stratigraphic sections of the Llama Member, representing as closely as possible a cross-section of the study-area, were selected for analysis. Six mineralogical parameters were selected: (1) carbonate, consisting of cement and minor grains; (2) quartz, including cement and secondary overgrowths; (3) orthoclase feldspar, including microcline; (4) plagioclase feldspar; (5) opaque minerals, including pyrite, limonite, organic matter, and any other indeterminate opaque mineral; and (6) miscellaneous minerals, consisting of mica, collophane, clay, and any non-opaque heavy minerals. An individual frequency record was kept of each mineral in the last category. Three to six representative samples were selected at equally spaced intervals from the stratigraphic sections examined. These intervals generally represented the base, middle, and top of the member, to establish any vertical or lateral trends in the region.

Systematic microscope traverses were made perpendicular to bedding and laminations. One thousand point counts were made of each thin section. Values were recorded after five hundred counts and compared with those obtained after one thousand continuous point counts. In studies of this nature three hundred counts are usually considered to be sufficient for meaningful results, but because of the suspected low concentration of four of the six parameters under consideration, it was thought necessary to increase the number of counts.

All quantitative values obtained from the study were statistically processed employing a digital computer.

Results and Interpretation

Inspection of all the parameter values revealed no outstanding trends or significant concentrations in either a vertical or a lateral direction (*see* preceding footnote), except those for quartz and carbonate, which suggest a slight northwest trend similar to that indicated by the values obtained from the insoluble residue analysis.

Directional Current Analysis

Purpose

Directional structure studies have long been used as a means of determining the direction of current flow. Structures such as crossbedding, ripple-marks, flute casts, groove casts, and numerous others, have been used either singly or in combination, to ascertain the regional or local direction of sediment and current transport. The present study of paleocurrent indicators was initiated with the hope of determining: (1) the nature and direction of transport currents at the time of deposition of the silts and sands characteristic of the Sulphur Mountain Formation and part of the Whitehorse Formation; (2) some indication of the provenance of the sediments; and (3) the paleoenvironments in which the sediments were deposited. Detailed examination of the region's stratigraphy showed that directional current structures were not as numerous or obvious as had been suspected from previous reconnaissance and mapping surveys. Thus, a detailed statistical analysis was impossible. However, all structures and associated dimensions encountered throughout the course of field investigations were recorded, later analyzed, and interpreted in the laboratorv.

Direction current structures encountered in the Athabasca–Smoky River area during the course of field investigations were: crossbedding, ripple-marks, flute casts, groove casts, and bounce casts.

Crossbedding

All stratigraphic sections were searched in detail to obtain every possible measurement of crossbedding in the area. For consistency in the following discussion, the crossbedding classification of McKee and Weir (1953) is followed wherever possible.

Three main types of crossbedding have been recognized in the Athabasca–Smoky River area. Trough crossbedding is found in the Phroso and Vega Siltstone Members and represents the most common type found in the Triassic succession. This type is closely associated with, and in numerous instances is gradational with, both planar and simple crossbedding, also present in the area. Because of its size, the crossbedding is termed "micro-cross-lamination," a name suggested by Hamblin (1961) who defined it as a distinctive type of small-scale trough crossbedding. The writer proposes to enlarge the classification to include also the simple and planar types, and thus encompass any type of small-scale crossbedding, regardless of shape. The micro-cross-lamination in the Sulphur Mountain Formation is generally confined to thin beds rarely more than 6 inches thick. These beds are generally bounded at the top and bottom by dark grey films of very carbonaceous-argillaceous shaly siltstone and shale.

Crossbedding in the Whitehorse Formation is generally developed on a much larger scale. It is classified mainly as planar and simple, with minor amounts of trough crossbedding confined to the thinner, finer grained stratigraphic units of the Winnifred Member. Crossbedding in the Starlight Evaporite Member occurs in medium-grained sandstones, in beds ranging from 1 foot to 2 feet thick. The crossbedding is of the simple type except for one occurrence of planar crossbedding noted at Corser Gulch.

Procedure

The micro-cross-lamination of the Sulphur Mountain Formation is generally poorly exposed, and dips at such a small angle that oriented samples were taken to be later examined in the laboratory. An attempt was made to obtain at least three measurements for each outcrop location. However, outcrops containing only one or two attitudes were incorporated into the gross paleocurrent analysis. All oriented field samples were cut in the laboratory in as many directions necessary to obtain a three-dimensional view. All azimuth values were rotated, using a Schmidt equal area stereonet, to correct for the deformation and tilting of the Triassic strata. All dip values were plotted on rose diagrams grouped into 30-degree intervals. Next, all azimuth values were averaged by vector summation, using the techniques of Curray (1956) and Pincus (1956), and were plotted on two base maps of the area. From these plots the current direction responsible for the formation of crossbedding was ascertained. Data responsible for anomalous directions were re-examined. These data were rejected if found to be unreliable upon re-examination.

Results and Interpretation

Location of sections and their associated crossbed values for the Sulphur Mountain Formation are shown on Figure 11. Most of the values are from either the Phroso or the Vega Siltstone Member, with only three dip azimuths recorded from the Llama Member. The general paleocurrent trend is from an east to a northeast direction. Some

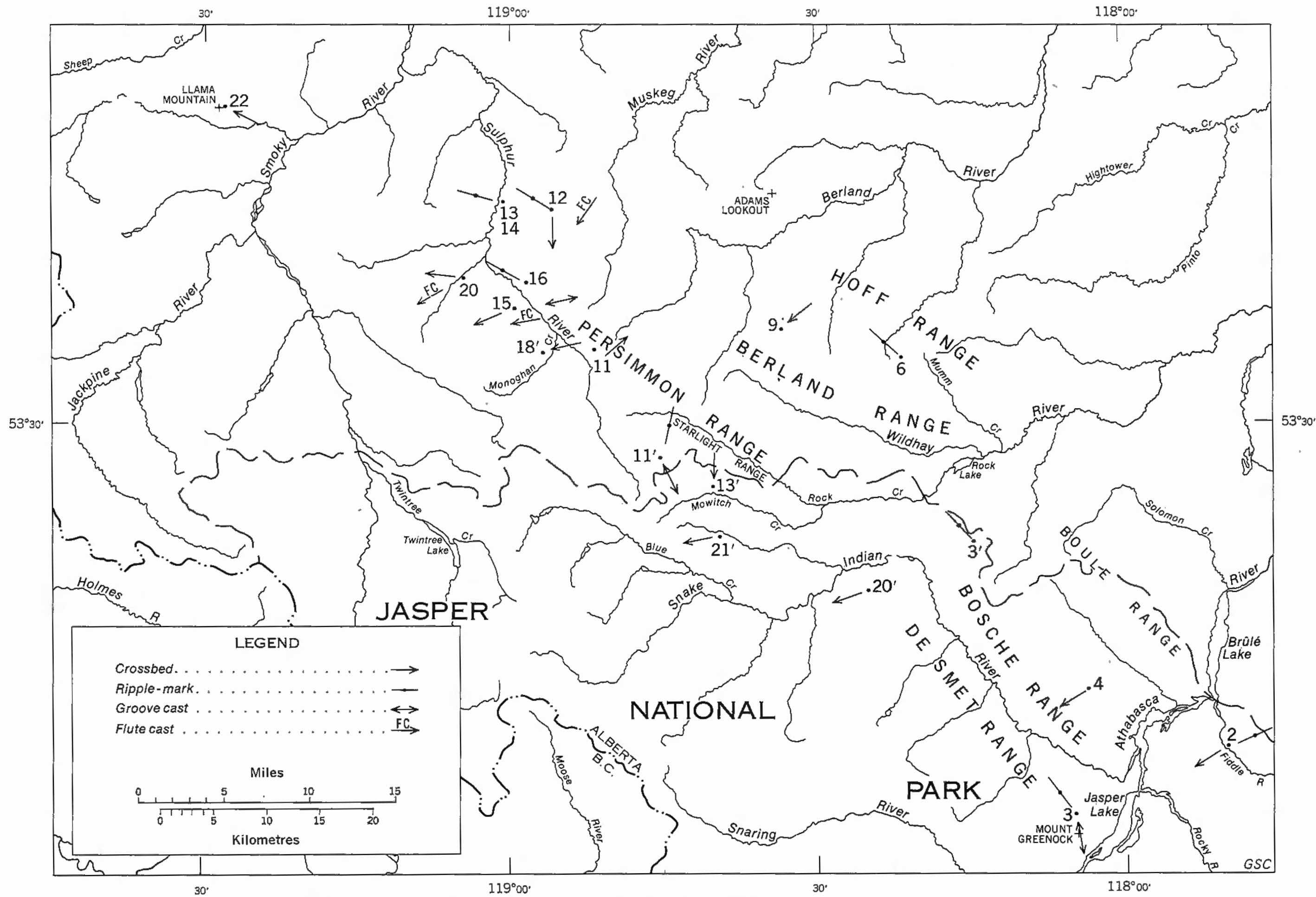


FIGURE 11. Corrected azimuths of directional structures in the Sulphur Mountain Formation.

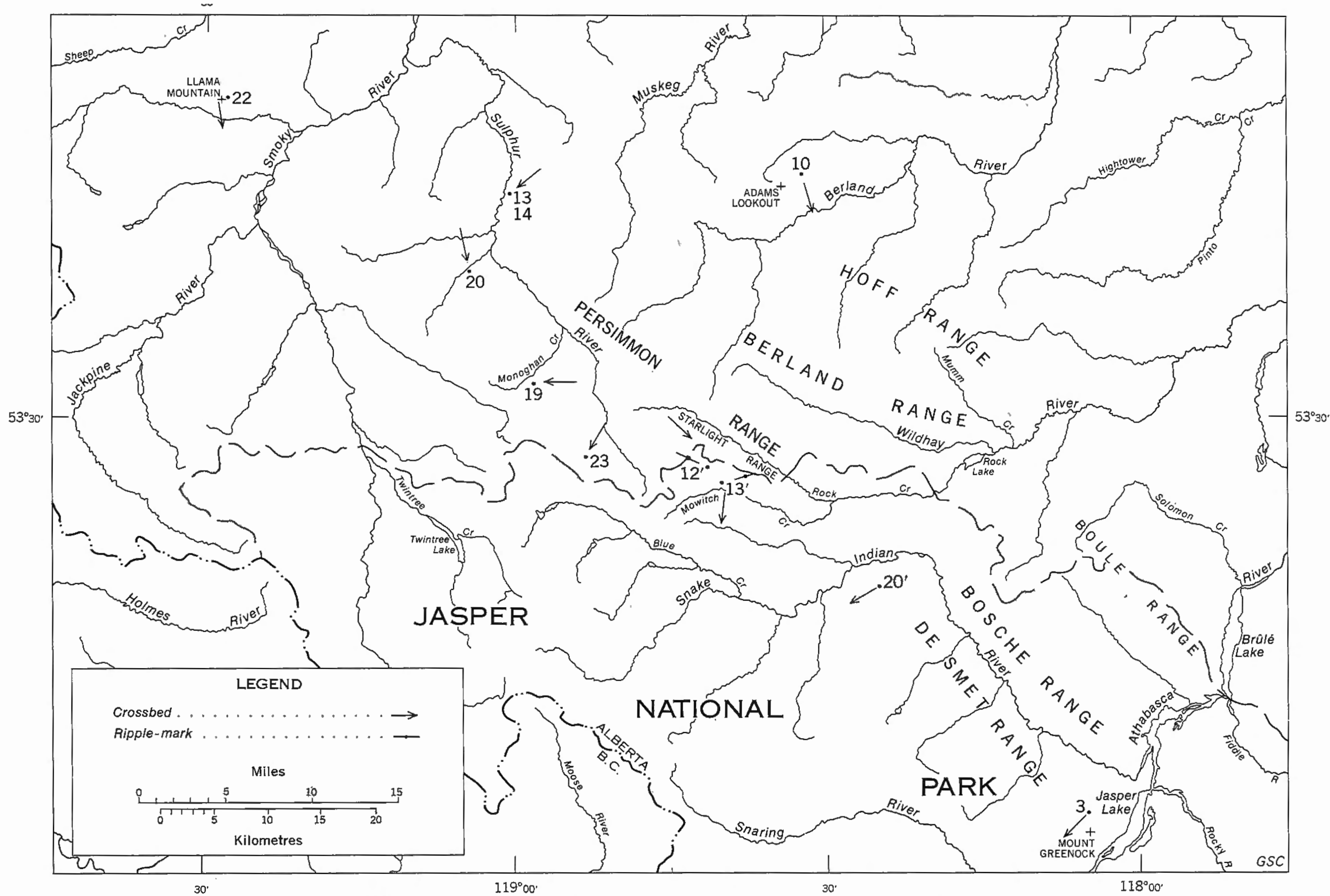


FIGURE 12. Corrected azimuths of directional structures in the Whitehorse Formation.

values (sections 15, 18, 20, 21, and 22) indicate that currents moved from a southeast direction. Section 11 illustrates a complete reversal in current direction. The results shown on Figure 11 indicate that sediments of the Sulphur Mountain Formation had in general a current transport direction from the east, and thus an easterly provenance.

Average dip azimuths of crossbeds observed in strata of the Whitehorse Formation are shown on Figure 12. From the limited number of values present, one can postulate a south to southwest current transport direction responsible for the formation of crossbedding. Current reversals contrary to the general trend are evident, and are illustrated by values at McDonald Gulch. However, the degree of similarity among values obtained is remarkable because of the limited number of crossbed azimuths recorded in the Whitehorse Formation.

The increased size and the fact that this type of structure is confined to medium- and coarse-grained sandstones suggest that the crossbedding in the Whitehorse Formation had an origin and depositional environment different from that found in the Sulphur Mountain Formation. Most crossbedding appears to have formed in shallow water under the influence of active or strong energy conditions. This is suggested by the coarse-grained and well-sorted nature of the sandstones, and by associated gypsum occurrences.

Ripple-Marks

Ripple-mark observations were generally confined to strata of the Vega Siltstone Member, although two ripple occurrences were noted in the Starlight Evaporite Member of the Whitehorse Formation. The amplitude of the ripples in most observations never exceeds half an inch and wave lengths range between 2 to 6 inches. All troughs and crests were notably rounded and symmetrical.

Procedure

The strike of the ripple-marks was recorded in the field. All values were plotted on a Schmidt stereonet, and then rotated to a horizontal position equivalent to the dip of the beds upon which they were formed. The tilt-corrected values were plotted on Figures 11 and 12, along with the other paleocurrent indicators.

Results and Interpretation

Figure 11 illustrates the tilt-corrected azimuth values of the ripple-marks recorded from the Sulphur Mountain Formation. Most ripple-marks in the Triassic succession are considered to have formed perpendicular to the prevailing current direction or prevailing wave orthogonals, and thus generally parallel to the strandline. The ripple azimuths on Figure 11 suggest that current and wave activity were from either east or west.

Ripple-marks, like crossbedding, can form an integral part of a detailed paleocurrent study if sufficient observations and measurements are taken to provide an adequate statistical base from which paleocurrent directions can be postulated. Ripple-mark observations in the Triassic succession of the Athabasca–Smoky River region are nowhere sufficiently abundant to use as current or strandline indicators. The few occurrences noted may, however, be used to substantiate conclusions based on the dip azimuths obtained from crossbeds.

Flute Casts

Procedure and Results

Flute casts (*see* Pl. IV), represent one of the most common types of "sole marks" in turbidite deposits, and have generally received wide acceptance as a reliable tool for indicating current directions responsible for the formation of turbidite sequences. However, they may also occur on "soles" of other sediment facies, such as limestone and sandstone, whose genesis is not the result of turbidity currents.

All field attitudes were obtained and recorded in a manner similar to that described for ripple-marks. Values were plotted on a Schmidt stereonet, and rotated about the strike of the bed to a horizontal position. The tilt-corrected azimuths were plotted on Figure 11, along with other paleocurrent indicators of the Sulphur Mountain Formation. Flute casts were not observed in the Whitehorse Formation. The plotted azimuth values at sections 12, 15, and 20, indicate a northwesterly current source. Although direct measurements of flute-cast orientations were limited in the field, numerous observations were made of well-preserved flute casts in the talus.

Groove Casts

Groove casts were also noted in the Sulphur Mountain Formation. They were observed only in the Vega Siltstone Member, where they generally range the full length of the exposed part of the bedding surface, which is commonly as much as 10 inches wide. The height varied between an eighth and a quarter of an inch.

All field observations of groove casts were recorded and analyzed in a fashion similar to that used in treating ripple-marks and flute casts. Figure 11 shows the location and nature of current movement responsible for the formation of the groove-cast structures. Current movement was from either the northwest or the southeast. However, when the azimuth values are interpreted with the other paleocurrent indicators, a north to northwest source direction is indicated.

Bounce Casts

These were observed only in talus of the Sulphur Mountain Formation. Bounce casts were not observed in outcrop. These structures resemble groove casts, except that they are developed on a much smaller scale. Samples observed in talus specimens were as much as 4 inches long, but the average was about 2 inches.

Summary

The foregoing paleocurrent analysis indicates a general current source to the east and northeast, and a strandline trending northwest. Exceptions to these trends exist (Figs. 11 and 12) and are to be expected in a study of this nature, regardless of the frequency of observations. In detailed sedimentological studies of modern sediments, crossbeds, ripple-marks, and other current structures not aligning themselves perpendicular or parallel to the direction of current transport may be observed.

PALEOENVIRONMENTS OF TRIASSIC SEDIMENTATION IN THE ATHABASCA–SMOKY RIVER AREA

Because of a general lack of recent sedimentological studies with which to compare ancient deposits, few suggestions have been made concerning the detailed depositional history of the Triassic succession in the Athabasca–Smoky River region, other than the inference of deposition under shallow- or deep-water conditions. It has proved difficult to establish a suitable modern-day analogy to this Triassic succession. Recently, however, Barss, *et al.* (1964), summarized ideas and hypotheses of other workers, including their own, in an attempt to unravel the complex Triassic depositional history of western Canada. In trying to compare ancient and modern sedimentary environments, difficulty may arise in matching sedimentary features between the two environments, and this was found to be so in the Athabasca–Smoky River region. The following discussion and interpretation, which is similar in part to that presented by Barss, *et al.* (1964), must therefore be considered only as a possible working hypothesis. Triassic strata in the Athabasca–Smoky River region were deposited in what is generally referred to as the Cordilleran Miogeosyncline. Mineral variety, concentration, thickness values, and a paleocurrent analysis, suggest that the allochthonous sediments of the Sulphur Mountain and Whitehorse Formations were derived from an east to northeast source area of low relief, consisting of pre-existing sediments of a composition similar to an orthoquartzite or protoquartzite (Pettijohn, 1957). Prior to Triassic deposition, a period of erosion occurred that removed the Ishbel Group from the eastern parts of the region.

Sulphur Mountain Formation

Phroso Siltstone Member

The Triassic period was initiated by a marine transgression, probably from the west, during which time strata of the Phroso Siltstone Member were deposited. The major depositional environment was probably similar to a marginal shallow-shelf area analogous to the present southeastern coast of the United States. Available evidence gathered from field and laboratory studies suggests that deposition took place in a restricted, shallow-water environment below wave base, or, where burial was sufficiently rapid to prevent decomposition of organic matter, at the sediment–water interface. Two modern sub-environments of a shallow shelf area exhibit some characteristics found in the sediments of the Phroso Siltstone Member. These are the "tidal flat environment" of the Dutch Wadden Sea area, and the "deltaic environment," recognized offshore from the mouths of Mississippi and Niger Rivers. Although certain similarities such as texture, sedimentary structures, bedding and laminations, suggest deposition in a tidal-flat environment (*see* Van Straaten, 1961; Potter and Glass, 1958), the typical features of such an environment (channel deposits, and a limited areal distribution) are lacking. From existing information, deposition in a shallow-shelf, deltaic-type of environment appears more appropriate. In sections along the northeastern fringes of the study-area, the Phroso Siltstone Member generally consists of alternating layers of coarse-grained, sandy silt, and finer material such as carbonaceous-ferruginous silty clay, or clayey silt. Furthermore, the Phroso strata contain well-formed laminations, some of which are horizontal and regular, others crossbedded, and some wavy and distorted. These characteristics are commonly found in the nearshore "delta-front" deposits of some modern deltas such as the Mississippi's (Scruton, 1955). Phroso strata of the thicker western sections have some characteristics attributable to deeper water deposition in a deltaic environment. In this region the succession is generally thicker, more massive, and displays less sharply defined vertical textural changes than Phroso strata in the thinner eastern sections. The Phroso strata at most western localities are postulated to have been deposited and distributed according to their settling velocities, rather than by current action. However, the sparse, non-laminated to faintly laminated interbeds of coarser grained siltstone within the regularly laminated stratigraphic sequence may be attributable to shallow-water turbidity currents. Deposition was generally rapid enough to exceed oxidation of the organic matter contained in the sediments. The water depth during sediment deposition was probably less than 20 fathoms, analogous to the depths at which the "delta-front" silts are being deposited by the Mississippi River.

The composition of the sediment reflects the nature of the climate, topography, and type of source material. The dominance of quartz as a major detrital constituent, and the presence of a carbonate cement, coupled with the fine size of the detrital material, suggest a topographically low-lying source area. The generally small amounts of feldspar and other less stable minerals indicate derivation from pre-existing sediments. Sedimentation was rapid enough to permit burial and preservation of some of the organic matter before being completely oxidized. The available evidence suggests that sediments of the Phroso Siltstone Member were deposited on a marginal shallow-shelf area, and have a greater resemblance to sediments of a modern deltaic environment than to a tidal flat environment.

Vega Siltstone Member

After deposition of the Phroso Siltstone Member the sea probably regressed slightly. The silts and very fine grained sands of the Vega Siltstone Member are slightly coarser than those in the underlying beds. The Vega sediments are characterized by a cyclical alternation, although not regular, in which thin bands of silty, argillaceous, organic sediment alternate with thicker, more massive beds of silt to very fine grained sand. The thicker, more resistant beds are considered to represent periods of rapid sediment influx. The fine, regular laminations are indicative of deposition mainly by gravity settling below wave base. Locally, however, the sediment was distributed by current and wave action as shown by ripple-marks and crossbedding. The general stratigraphic appearance suggests that deposition may have resulted from turbidity currents because of the occurrence of such structures as flute casts, groove casts, bounce casts, and cross-laminations, all features characteristic of flysch or turbidite deposits. Graded bedding and sole marks, however, occur in other types of unrelated environments. Because the coarse, graded beds and mixed or displaced fauna typical of deposits formed by turbidity currents are lacking, the Vega Siltstone Member is assumed to have been deposited under relatively shallow-water conditions in which the accumulating sediments were periodically disturbed by wave action. The mineralogical composition of the member reflects a source area of pre-existing sediments. The cyclical development suggests an alternating or fluctuating climatic regime such that during periods of high rainfall and consequent flooding, large quantities of sediment were brought into the depositional basin and distributed by weak marine currents, and possibly periodically by shallow-water turbidity currents. The end of Vega time is marked by a break in the faunal succession and by the occurrence of a phosphatic pebble-conglomerate. This suggests a possible depositional hiatus, and possibly a further slight marine regression.

Whistler Member

The Middle Triassic epoch in the Athabasca–Smoky River region was initiated by a transgression similar to that postulated for the Phroso period. The depositional environment is considered to have been similar to that of the Phroso Siltstone Member, except that sedimentation took place under deeper, more tranquil, euxinic conditions. The deposition of terrigenous sediment was very slow, as indicated by the sparse detrital content. The member generally contains well-rounded grains of phosphate in the basal part. The environment may therefore have been similar to that suggested by Bushinski (1964) in the genesis of shallow-water phosphate. The composition of the detrital constituents again implies a provenance of pre-existing sediments.

Llama Member

A regressive phase is postulated near the end of Whistler time. A maximal grain size study, which demonstrated an increase in average grain diameter upward in the member, suggests that in the beginning the regression was slow but later became more rapid. A change of climate and environment is suggested by the general nature of the sediments. The colour changes progressively from dark greys at the base to lighter greys and yellows toward the top, indicating a decrease in the carbonaceous and ferruginous content within the member. This feature may be indicative of arid conditions developing in the source area. However, the decrease in organic and iron sulphide content may be due to a larger amount of oxygen in the water or to a slow depositional rate, permitting normal oxidation to remove the organic and iron content. The latter explanation is favoured because of the postulated arid conditions that would have produced a decreased water flow in river systems, thus decreasing their carrying capacity, with a resulting decrease in the amount of detrital and organic material carried into the depositional area. Both the thick, generally unlaminated nature and the mineralogical composition of the strata suggest that beds of the Llama Member were deposited near shore in a shallow-water, marine environment.

Whitehorse Formation

Starlight Evaporite Member

At the end of Sulphur Mountain time, the regression continued and the sedimentary environment changed from a deltaic-type of shelf environment to a shallow-marine, lagoonal environment comparable in some ways with the area existing today off the Texas Gulf Coast. In early Whitehorse time, marine regression was at a maximum, leaving small isolated barrier bars irregularly distributed in the region. These bars served as restrictive barriers to water flow and, together with a dry climate, created evaporitic conditions. "Red beds," gypsum, and solution breccias were developed at this time. The isolated and sparse gypsum occurrences probably formed in small, isolated basins where hypersaline conditions existed as a result of restricted circulation caused by the offshore bars. Hematite staining associated with the gypsum and "red bed" facies is indicative of subaerial exposure with consequent oxidation and red coloration of the iron. Hunt and Ratcliffe (1959, p. 588) advocated a similar environment of deposition for strata of the correlative subsurface Charlie Lake Formation in the Peace River district of British Columbia. Similar suggestions were advanced by Pelletier (1960, 1961, 1963, 1964) and Armitage (1962). In contrast, Clark (1961, p. 129) postulated that breccias and mottling found in the Charlie Lake Formation of northeastern British Columbia had formed by submarine slumping, causing the brecciation and sediment mixing responsible for the present appearance of the strata. The breccias in the Athabasca–Smoky River region are in some places associated with gypsum, which suggests a genesis resulting from the solution of gypsum and the subsequent collapse of the overlying strata.

The transporting capacity of large river systems would be greatly diminished in a semi-arid to arid climate. This would account for the general decrease of terrigenous detritals and consequent relative increase in carbonate deposition. Climatic and environmental conditions were periodically changing throughout early and middle Starlight Evaporite time. The occurrence of an overlying thick sequence of relatively pure, detrital organic limestone is evidence that toward the end of the evaporitic period marine conditions, and possibly the climate, underwent a significant change.

Brewster Limestone Member

During the initial stages of Late Triassic (Karnian) sedimentation the sea transgressed toward the east, onlapping the sediments of the Starlight Evaporite Member. Much fragmented faunal material and the "ribbon-like" fibrous calcite in this member indicate that shallow-water conditions prevailed and that a prolific fauna developed and flourished along the margins of the depositional basin. However, these conditions were short lived. The seas again regressed, resulting in a shallowing of the water with associated water turbulence. The fauna was killed, comminuted in part by wave action, swept into the deeper parts of the shelf area, and deposited as a blanket over the carbonate strata of the Starlight sediments. At the close of Brewster time shallow-water, evaporitic conditions returned to part of the western region, as indicated by the occurrence of collapse breccias and "red beds."

Winnifred Member

During the final stages of Triassic deposition, marine conditions returned, with the seas transgressing from west to east. Shallow-water conditions are suggested by the occurrence of crossbedding and granular phosphate accumulations. Increasing amounts of organic matter are evident from the base to top of the Winnifred Member, indicating a departure from arid conditions. At the termination of the Triassic period, the Athabasca–Smoky River region underwent erosion, or a period of nondeposition. This is indicated by the presence of a conglomerate unit at the base of the Fernie Formation, and by the absence of Upper Triassic beds equivalent to the Pardonet Formation to the northwest.

CONCLUSIONS

The following conclusions are based on the foregoing petrologic investigation of Triassic strata in the Athabasca–Smoky River region of Alberta:

1. Strata of the Sulphur Mountain Formation consist of dark grey to rusty brown weathering siltstones, silty dolomites, shales, and minor amounts of sandstone. The Whitehorse Formation comprises a sequence of light weathering, variegated, locally sandy limestones and dolomites, with minor amounts of calcareous and dolomitic sandstones, and solution breccias.

2. Mineralogically, the Triassic strata comprise silt- to sand-sized, angular to well-rounded, partly "corroded," grains of quartz, orthoclase and plagioclase feldspar, recrystallized micritic to sparitic calcite and dolomite, and lesser quantities of collophane, pyrite, organic material, clay muscovite, gypsum, and common "heavy minerals" such as rutile, zircon, and tourmaline.

3. An insoluble residue study on samples from the Sulphur Mountain Formation indicates an increase in the average amount of insoluble residue from the Llama Mountain–Smoky River region southeastward towards the Fiddle River region near Athabasca River. A general increase in the amount of insoluble residue is implied from west to east across the structural strike of the area, indicating a sediment source area to the east and northeast.

4. A maximal grain size analysis on samples of the Sulphur Mountain Formation indicates a vertical increase in maximal diameter in all samples above the Whistler Member, which suggests the beginning of a marine regression commencing at the top of the Whistler Member time interval. No significant lateral size gradations or concentrations were noted in the area of study.

5. A paleocurrent analysis based on such structures as crossbedding, ripple-marks, flute casts, groove casts, and bounce casts, implies a general current direction from east and northeast to the west and southwest and a strandline trending northwest.

6. Sediments of the Sulphur Mountain Formation were deposited during minor marine transgressions and regressions on a marginal shallow shelf in some ways similar to a deltaic-type of environment. Sediments of the Whitehorse Formation are thought to have been deposited in a more restricted, shallow-marine environment similar in some ways to that of the Texas Gulf Coast area of the United States.

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APPENDIX A

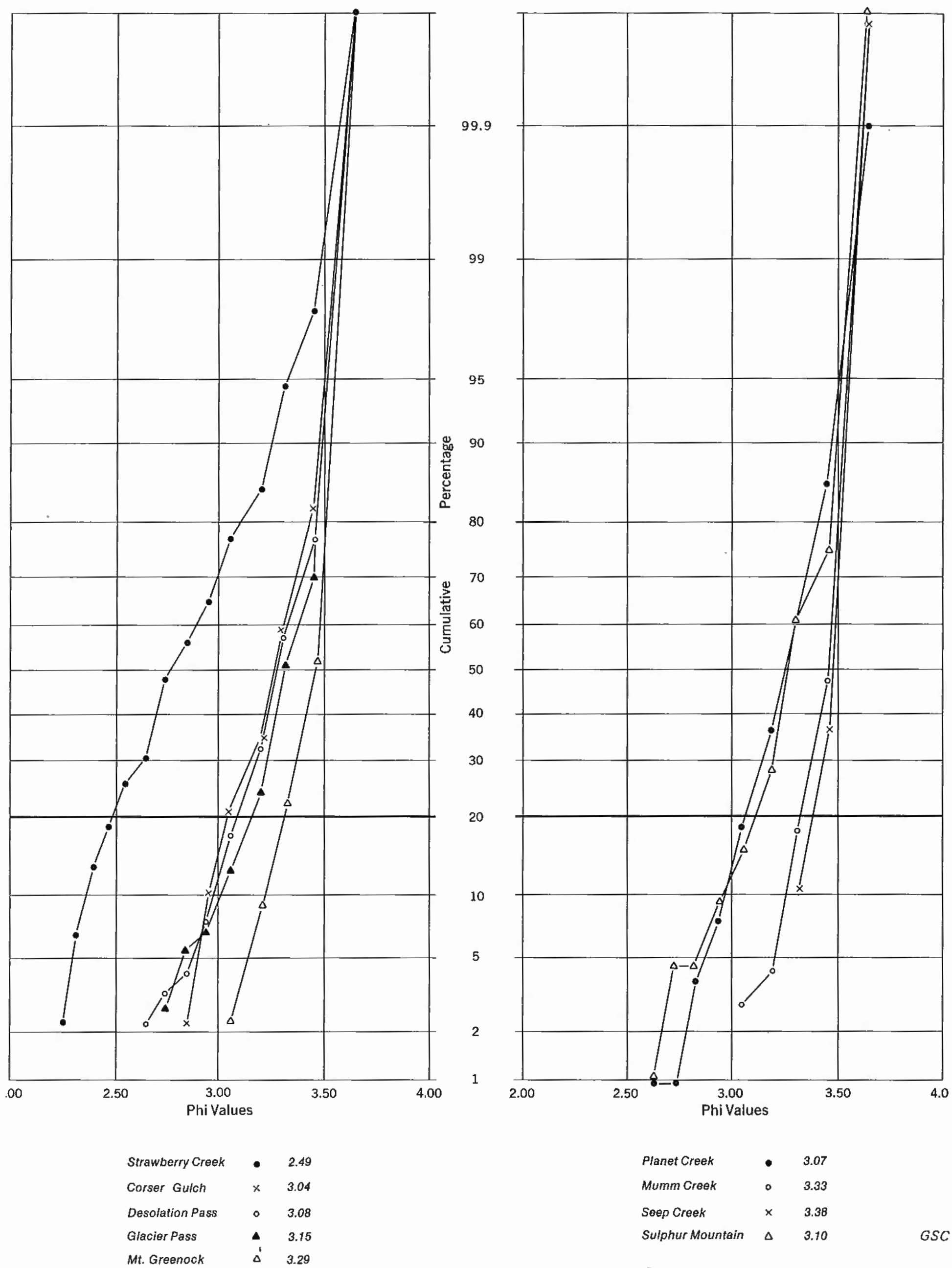
Data charts illustrating how the maximal grain size measurements were grouped into intervals using a sample truncation of 70 microns for the stratigraphic interval 20 feet above the base of the Llama Member.

INTERVAL IN MICRONS	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE	FREQUENCY	PERCENTAGE	CUMULATIVE PERCENTAGE
	PLANET CREEK			MUMM CREEK			SEEP CREEK			SULPHUR MOUNTAIN			LLAMA MOUNTAIN			MILE 71 ROCK CREEK		
71-80	15	15.7	99.9	38	52.8	100.0	30	63.8	100.0	26	24.8	100.0	16	18.4	100.0	12	14.3	100.0
81-90	26	25.4	85.2	21	29.3	47.8	12	25.6	36.2	16	15.2	75.2	22	25.3	82.0	16	19.1	85.9
91-100	24	23.6	59.8	10	13.9	18.1	5	10.6	10.6	33	31.4	60.0	24	27.6	56.7	20	23.8	66.8
101-110	18	17.6	36.2	1	1.4	4.2				14	13.3	28.6	7	8.4	29.1	12	14.3	43.0
111-120	11	10.8	18.6	2	2.8	2.8				6	5.7	15.3	12	13.8	20.7	11	13.1	28.7
121-130	4	3.9	7.8							5	4.8	9.6	2	2.3	6.9	4	4.8	15.6
131-140	3	2.9	3.9									4.8			4.6	3	3.6	10.8
141-150			.98							4	3.8	4.8	4	4.6	4.6	1	1.2	7.2
151-160	1	.98	.98							1	.95	.95				1	1.2	6.0
161-170																1	1.2	4.8
171-180																2	2.4	3.6
181-190																1	1.2	1.2
TOTAL COUNTED	102			72			47			105			87			84		
AVERAGE 10 COARSEST	0.131 mm			0.102 mm			0.092 mm			0.138 mm			0.131 mm			0.153 mm		
AVERAGE 5 COARSEST	0.138 mm			0.108 mm			0.096 mm			0.148 mm			0.142 mm			0.170 mm		
AVERAGE 3 COARSEST	0.142 mm			0.114 mm			0.098 mm			0.153 mm			0.146 mm			0.178 mm		
	MILE 58 ROCK CREEK			EAGLES NEST PASS			WHISTLER CREEK			MONOGHAN CREEK			DESOLATION PASS			CORSER GULCH		
71-80	11	12.5	100.0	8	7.9	99.8	21	50.0	100.0	12	9.2	99.9	21	22.8	100.0	16	18.0	100.0
81-90	21	23.9	87.5	15	14.8	91.9	10	23.8	50.1	21	16.0	90.7	17	18.5	77.3	20	22.5	82.2
91-100	17	19.3	63.6	19	18.8	77.1	6	14.3	26.3	25	19.1	74.7	24	26.1	58.8	22	24.8	59.7
101-110	12	13.6	44.3	15	14.8	58.3	2	4.8	12.0	27	20.6	55.6	14	15.2	32.7	12	13.5	34.9
111-120	13	14.8	30.7	20	19.8	43.5	2	4.8	7.2	24	18.3	35.0	9	9.8	17.5	10	11.2	21.4
121-130	7	8.0	15.9	11	10.9	23.7			2.4	7	5.3	16.7	3	3.3	7.7	7	7.9	10.2
131-140	4	4.5	7.9	6	5.8	12.8	1	2.4	2.4	7	5.3	11.4	1	1.1	4.4	2	2.3	2.3
141-150	1	1.1	3.4	5	4.9	6.9				6	4.6	6.1	1	1.1	3.3			
151-160			2.3	2	2.0	2.0						1.5	2	2.2	2.2			
161-170			2.3							2	1.5	1.5						
171-180	2	2.3	2.3															
TOTAL COUNTED	88			101			42			131			92			89		
AVERAGE 10 COARSEST	0.142 mm			0.144 mm			0.110 mm			0.148 mm			0.132 mm			0.127 mm		
AVERAGE 5 COARSEST	0.155 mm			0.149 mm			0.121 mm			0.156 mm			0.143 mm			0.130 mm		
AVERAGE 3 COARSEST	0.165 mm			0.151 mm			0.128 mm			0.162 mm			0.151 mm			0.132 mm		
	STRAWBERRY CREEK			WINNIFRED PASS			GLACIER PASS			MOUNT GREENOCK			NATURAL ARCH					
71-80	2	2.2	100.0	17	32.7	99.9	21	30.0	100.0	21	47.8	100.0	25	78.0	99.8			
81-90	3	3.3	97.9	16	30.8	67.2	13	18.6	70.1	13	29.6	52.3	5	15.6	21.8			
91-100	9	9.9	94.6	5	9.6	36.4	19	27.2	51.5	6	13.6	22.7	2	6.2	6.2			
101-110	7	7.7	84.7	6	11.5	26.8	8	11.4	24.3	3	6.8	9.1						
111-120	11	12.1	77.0	4	7.7	15.3	4	5.7	12.9	1	2.3	2.3						
121-130	8	8.8	64.9	1	1.9	7.6	1	1.4	7.2									
131-140	7	7.7	56.1			5.7	2	2.9	5.8									
141-150	16	17.6	48.4	1	1.9	5.7	2	2.9	2.9									
151-160	4	4.4	30.8	1	1.9	3.8												
161-170	7	7.7	26.4	1	1.9	1.9												
171-180	5	5.5	18.7															
181-190	6	6.6	13.2															
191-200	4	4.4	6.6															
201-210	1	1.1	2.2															
211-220			1.1															
221-230			1.1															
231-240	1	1.1	1.1															
TOTAL COUNTED	91			52			70			44			32					
AVERAGE 10 COARSEST	0.196 mm			0.126 mm			0.126 mm			0.099 mm			0.084 mm					
AVERAGE 5 COARSEST	0.204 mm			0.141 mm			0.137 mm			0.104 mm			0.088 mm					
AVERAGE 3 COARSEST	0.214 mm			0.154 mm			0.144 mm			0.106 mm			0.090 mm					

GSC

APPENDIX B

Cumulative frequency curves illustrating Phi values of 20th percentile with grain size truncation of 70 microns, for stratigraphic interval 20 feet above the base of the Llama Member.



99.9
99
95
90
80
70
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40
30
20
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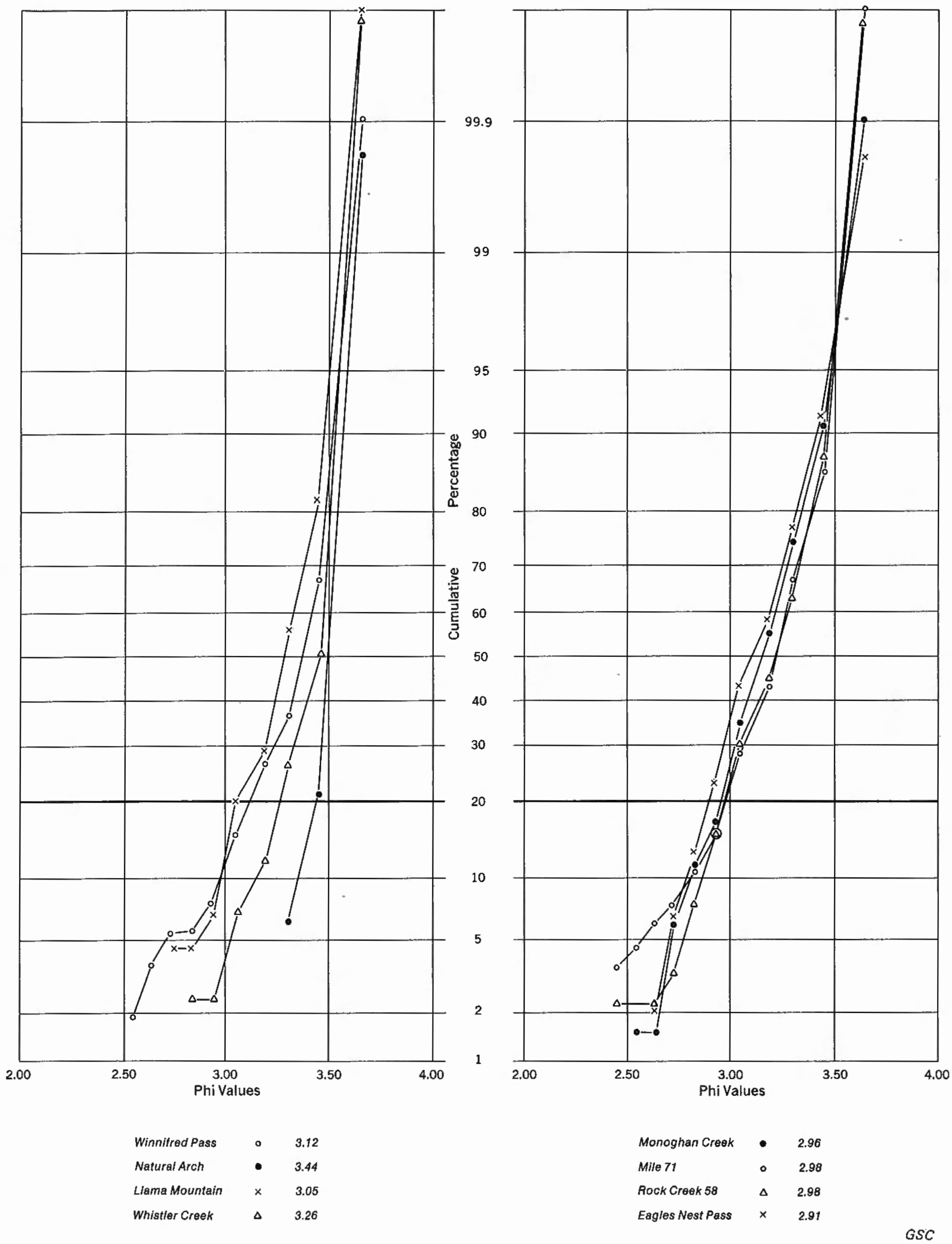
2
1
Cumulative Percentage
.00
2.50
3.00
3.50
4.00
Phi Values
2.00
2.50
3.00
3.50
4.0
Phi Values
Strawberry Creek ● 2.49
Corser Gulch × 3.04
Desolation Pass ○ 3.08
Glacier Pass ▲ 3.15
Mt. Greenock △ 3.29
Planet Creek ● 3.07
Mumm Creek ○ 3.33
Seep Creek × 3.38
Sulphur Mountain △ 3.10
GSC



99.9
99
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30
20
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2
1
Cumulative Percentage
2.00
2.50
3.00
3.50
4.00
Phi Values
Winnifred Pass o 3.12
Natural Arch • 3.44
Llama Mountain × 3.05
Whistler Creek △ 3.26
Monoghan Creek • 2.96
Mile 71 o 2.98
Rock Creek 58 △ 2.98
Eagles Nest Pass × 2.91
GSC

PLATES I–V

PLATE I. Descriptive Petrography

A. Organic carbonate detritus of Brewster Limestone Member illustrating crinoid ossicles, echinoid spines, and elongate pellets. (Dark material-collophane and carbonaceous material.)

B. Quartzitic texture showing welded nature of grain contacts; note angularity and corroded nature of grains. Vega Siltstone Member. Crossed nicols.

C. Same thin section as B, in plain polarized light.

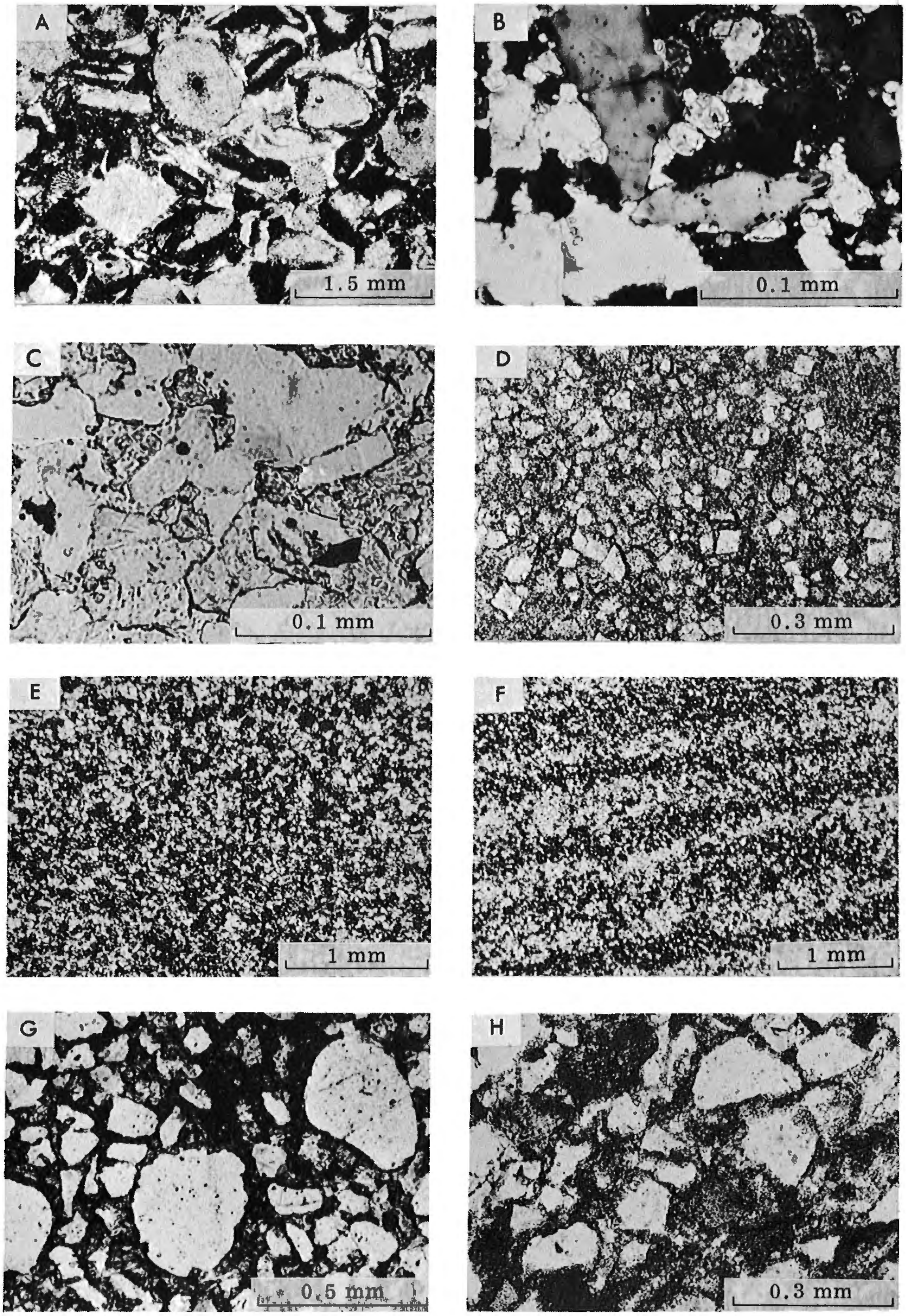
D. "Pseudogranular texture" illustrating euhedral to subhedral dolomite crystals in a pseudomicrosparite matrix. Winnifred Member.

E. Homogeneous siltstone of Vega Siltstone Member, showing dark carbonaceous-argillaceous-ferruginous nature of matrix.

F. Laminated siltstone of Phroso Siltstone Member, showing dark carbonaceous-ferruginous nature of laminae.

G. Idealized maximal grains showing incipient degree of carbonate corrosion; note angular nature of smaller grains.

H. Typical maximal grains used in analysis of Sulphur Mountain Formation; note angularity and corroded nature of grain boundaries.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B
0.1 mm
C
0.1 mm
D
0.3 mm
E
1 mm
F
1 mm
G
0.5 mm
H
0.3 mm

PLATE II. Carbonate-Quartz Authigenesis

A. Rounded quartz grain showing corroded edges with incipient development of a euhedral quartz overgrowth replacing calcareous pseudosparite matrix.

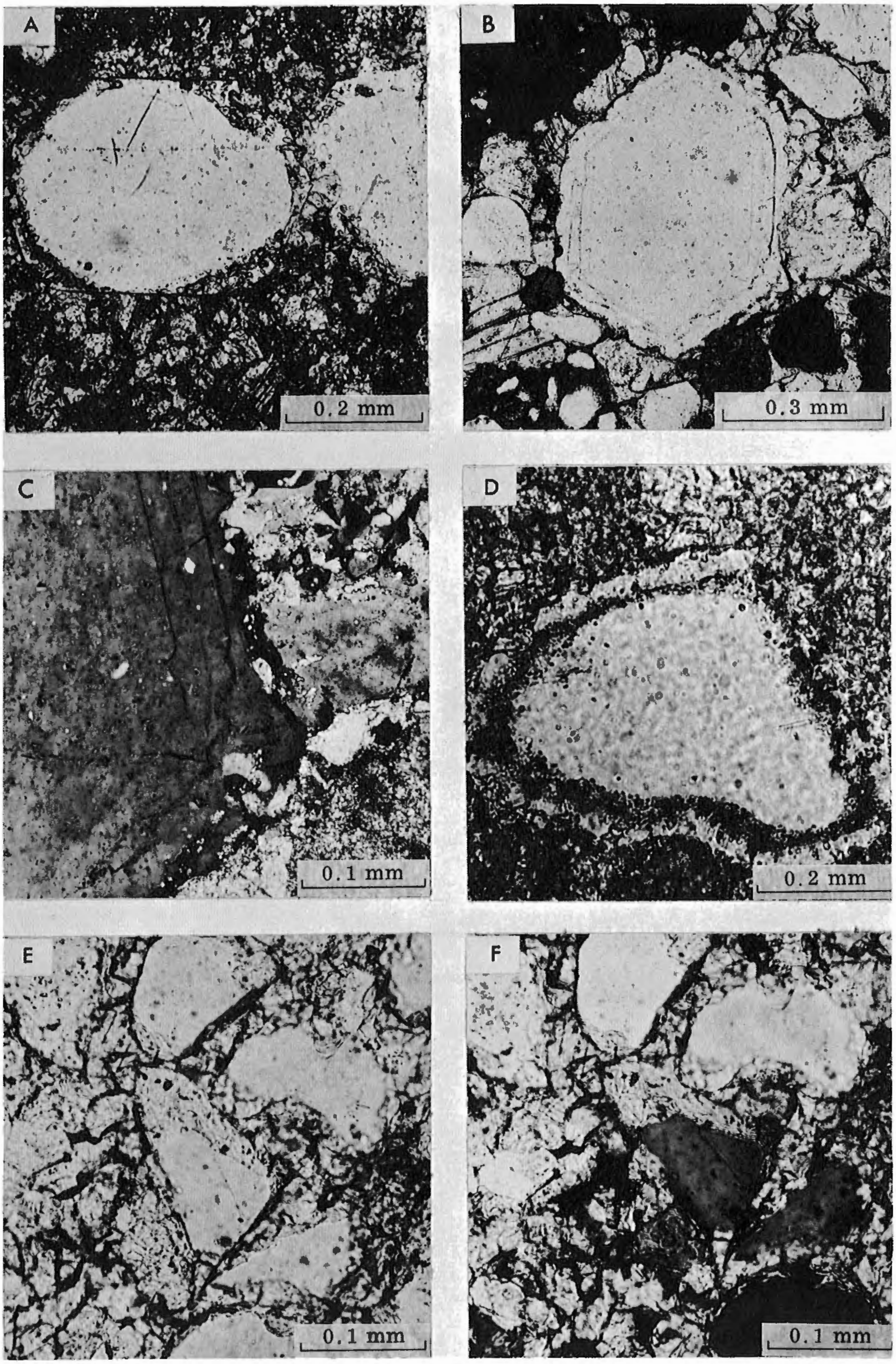
B. Zoned euhedral quartz grain showing three stages of overgrowth.

C. Enlargement of B showing overgrowths and quartz replacement of carbonate.

D. Rounded quartz grain illustrating replacement of overgrowth and part of grain by dolomite.

E. Rounded quartz grains being replaced by dolomite; note serrated edges of grains and ghost outline of original quartz grain.

F. Same thin section as E. Crossed nicols.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D
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E
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F
0.1 mm

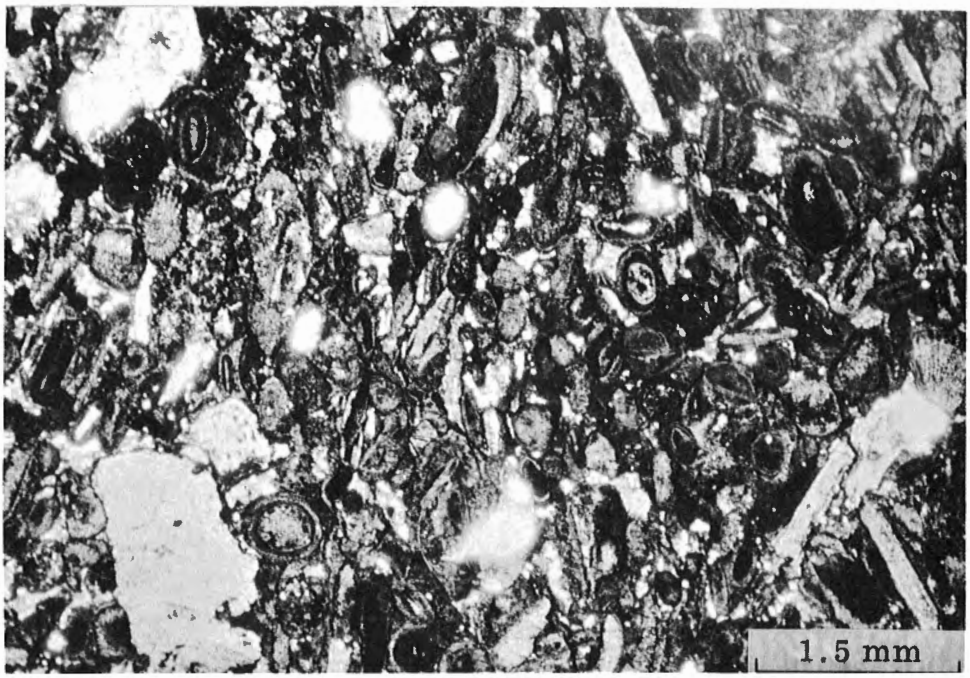

PLATE III. Thin section illustrating well-rounded and concentrically banded phosphatic grains from the Whistler Member, Mount Greenock.

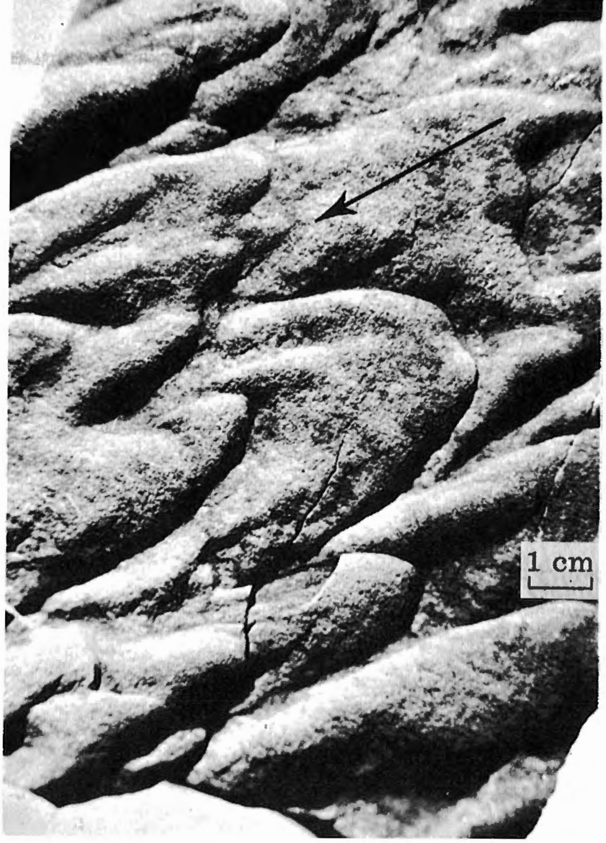

PLATE IV

Flute casts from Vega Siltstone Member, Lancaster Creek. Arrow indicates direction of current.

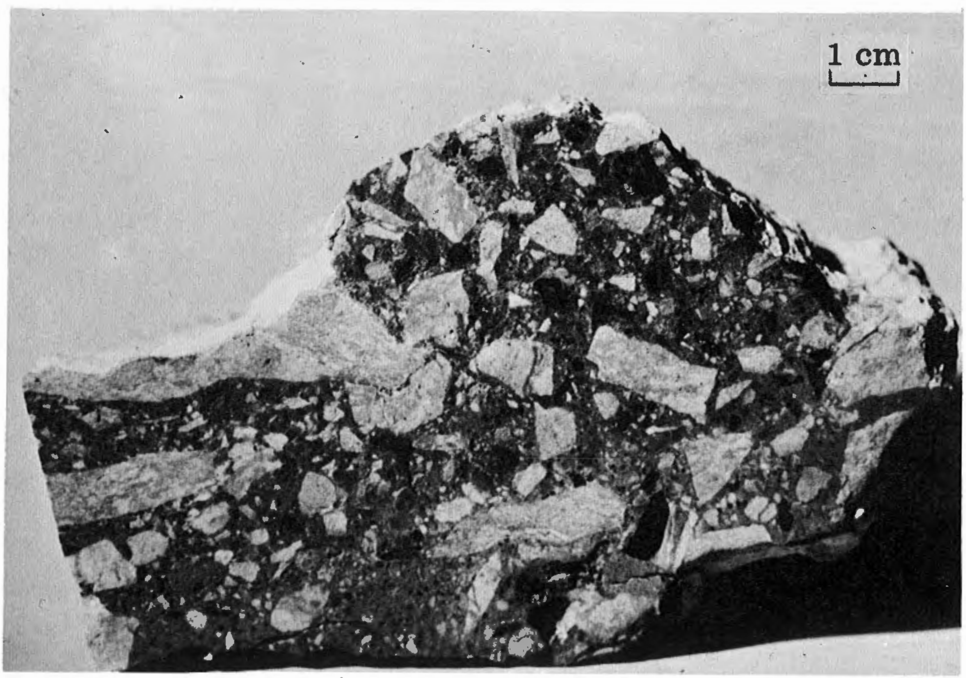

PLATE V. Collapse or solution breccia, illustrating different clast types and angular nature; Starlight Evaporite Member.

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